Modeling and Analysis of Alternative Concept of ITER Vacuum Vessel Primary Heat Transfer System

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Abstract

A RELAP5-3D model of the ITER (Latin for "the way") vacuum vessel (VV) primary heat transfer system has been developed to evaluate a proposed design change that relocates the heat exchangers (HXs) from the exterior of the tokamak building to the interior. This alternative design protects the HXs from external hazards such as wind, tornado, and aircraft crash. The proposed design integrates the VV HXs into a VV pressure suppression system (VVPSS) tank that contains water to condense vapour in case of a leak into the plasma chamber. The proposal is to also use this water as the ultimate sink when removing decay heat from the VV system. The RELAP5-3D model has been run under normal operating and abnormal (decay heat) conditions. Results indicate that this alternative design is feasible, with no effects on the VVPSS tank under normal operation and with tank temperature and pressure increasing under decay heat conditions resulting in a requirement to remove steam generated if the VVPSS tank low pressure must be maintained.

Keywords: Heat transfer; Alternative concept; Safety

1. Introduction

U.S. ITER (Latin for "the way") is responsible for design, engineering, and procurement of the ITER tokamak cooling water system (TCWS). The TCWS [1] is designed to provide cooling and baking for client systems, which include the first wall/blanket (FW/BLK), vacuum vessel (VV), divertor (DIV), and neutral beam injector (NBI). The VV primary heat transfer system (PHTS) removes heat generated in the VV during normal operation (10 MW of pulsed power) as well as the decay heat from the VV itself and from structures and components attached to the VV (FW/BLK and DIV), Refs. 1 and 2. The decay heat at time zero of the

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VV and all the attached structures is ~13 MW [3]. The VV PHTS has two safety functions: (1) contain contaminated cooling water and (2) provide passive cooling of decay heat during an accident event.

The current design of the VV PHTS consists of two independent loops, each loop cooling half of the VV with a nominal flow of 475 kg/s per loop of water at ~1.1 MPa and 100ºC for plasma heat removal. The total coolant flow for both loops is 950 kg/s. Both loops are required to remove the heat load during normal plasma operation. Under accident conditions, only one loop is needed to remove the decay heat of the complete VV and attached structures/components using only natural convection (no pump needed). The heat is transferred to air-cooled heat exchangers (HXs) located on the roof of the tokamak building.

The location of the HXs on top of the tokamak building is undesirable because they are vulnerable to external hazards (such as wind, tornado, aircraft crash). Failure of these HXs in their current location would allow radioactive material to be released directly into the environment. Placing the HXs inside the tokamak building will provide an additional barrier to radioactive material release into the environment in the event of an HX failure.

An alternative design has been investigated that places the HXs inside the building. The proposed alternative design will use an existing large volume of water located within the VV pressure suppression system (VVPSS) tank inside the tokamak building. The water-to-water HXs of the VV cooling loops will be placed inside the VVPSS tank.

A RELAP5 model was developed to investigate the thermal-hydraulic behavior of this alternative VV PHTS design by calculating the maximum temperature and pressure reached inside the VV and the VVPSS tank. This paper describes the current design, the alternative design, and the RELAP5 model and its results.

2. Description of the current design of the VV PHTS

The primary function of the VV PHTS is to remove nuclear heat during plasma operation and decay heat under accident conditions. The current VV PHTS design [1] is shown in Fig. 1. This figure shows the two VV PHTS cooling loops (each loop has three HXs [in green] on the roof of the building); the pressurizers (in purple), one for each loop; the pumps; one of the 18 VV half sectors; the distributor rings at the bottom; and the collector rings at the top.

Insert Fig. 1

During plasma operations, cooling water at 100°C is distributed to the 18 half sectors of the VV and is heated by ~2°C. Two cooling loops, each with a coolant mass flow rate of 475 kg/s, provide the cooling water to each half of the VV. The complete VV is divided into 18 parallel half sectors or segments (each half sector is 20° of the complete tokamak). Each VV cooling loop is attached to every other half sector. While both cooling loops are required during normal plasma operation, only one of the two cooling loops is needed to remove decay heat during abnormal operation. The nine half sectors of the nonoperating cooling loop will be cooled by the other nine half sectors of the operating loop, as each cooled half sector is welded to the noncooled half sectors. During abnormal operation, the coolant pumps will not be available and water will circulate by natural convection.

The system pressure at the VV inlet is regulated with a pressurizer (gas type) to 1.1 MPa during plasma and standby operations and to 2.4 MPa during baking. A pressure relief valve, which is vented to the normal ventilation and detritiation system (NVDS), is installed to prevent over-pressurization of the system. The pressure in the pressurizer is controlled by a pressure control valve at the pressurizer to allow discharge to the NVDS.

In the existing design, plasma heat is removed from the cooling water by the air-to-water HXs located on the roof of the building. Flow control valves and a bypass line with dual control valves (to meet the safety

requirement for redundancy) are provided to maintain a constant HX outlet temperature of 100°C during normal operation. The bypass line is also used during the standby and baking operations to allow the flow of water to bypass the main HX. During natural circulation, the control valve in the bypass line is closed so that all the flow goes through the HX.

A constant flow rate of 475 kg/s per loop is maintained by the main flow pump during plasma and standby operations. The pump maintains a constant flow rate of 250 kg/s during baking. A bypass line is installed around the main pump. This line contains dual check valves installed in parallel for safety and is used during natural circulation. The valves remain closed during plasma, standby, and baking operations and passively open during natural circulation to allow the free flow of cooling water. A check valve is installed downstream of the main pump to prevent backflow of the water during periods when the pump is not being used. A schematic of the current design is shown in Fig. 2.

Insert Fig. 2

A filter is located downstream of the pump in a small bypass line. About 10% of the total flow is bypassed through the filter. An electric heater is located downstream of the pump in a bypass line that opens only when the water has to be heated. The heater maintains a constant temperature of 200°C with less than ±2°C tolerance during baking and an inlet temperature of 100°C prior to plasma operations. The cooled water is sent through the piping manifold to cool the VV and some auxiliary systems.

3. Description of the VV PHTS alternative design

The proposed design change moves the HXs into the VVPSS tank [1] located at a high elevation in the building. The roof of the building is at an elevation of 33 m, the VVPSS tank is at an elevation of 24 m. The VVPSS tank is a horizontal tank, 6 m in diameter and 42 m long with a volume of 1,200 m^3. More than half of the tank (650 m^3) is filled with water. The main purpose of the tank is to quench the steam generated by a

large pipe break inside the VV. The tank is kept at a low pressure (4.2 kPa), and its water temperature is at 28°C (or less).

The proposed alternative design will use a double-jacket HX placed inside the water in the VVPSS tank. During normal plasma operation, the primary cooling water of the VV PHTS will circulate inside the HX tubes and will be cooled by component cooling water (CCW) circulating through the outer jacket channel. The CCW is at ~28°C; thus the outer jacket thermally isolates the HX primary tubes (at a higher temperature, ~100°C) from the VVPSS water (also at 28°C). When the VV PHTS performs its safety function or when there is a loss of off-site power, heat will be dissipated into the VVPSS water. The thermal capacity of the large water mass inside the VVPSS will be used to absorb the energy released during the accident transient or the decay heat of the VV and associated structures.

During abnormal operating conditions (safety function), the CCW will stop circulating inside the jackets, but the jackets will be full of water. The primary coolant heat will be transferred to the water in the jackets and from there to the water in the VVPSS tank. Water will circulate under natural circulation conditions in the VV cooling loop. The VV is the heat source (due to decay heat) and the VVPSS tank water is the heat sink under accident conditions.

The proposed HXs are water-to-water, more efficient than the previous air-to-water type located on the roof of the building. Therefore, they are smaller in size. They have been designed to remove 1.5 MW of power continuously for each VV coolant loop during normal plasma operation. The pulsed power is 5 MW per loop for 400 s with 1,400 s dwell time; the average power is

$$P_{ave} = 5\frac{400}{400+1400} = 1.1\ \text{MW}.$$

Thus the 1.5 MW HX design together with a large system thermal inertia (mainly due to the large structural mass of the VV) has sufficient capacity to remove the pulsed power of the VV.

4. RELAP5 model of the alternative VV PHTS design

The RELAP5-3D code [4], developed by Idaho National Laboratory, has been used to model this alternative design. RELAP5-3D is a three-dimensional (3-D) version of the RELAP5 code [5] developed by the U.S. Nuclear Regulatory Commission (NRC). It has added features over the NRC version such as 3-D hydraulic capabilities and space kinetics with the code NESTLE. It also has a graphical interface that permits visualization of the model and can show the values of some variables (temperature, pressure, velocity, void fraction, etc) in each volume or flow path as a function of time.

Each loop of the VV PHTS was modeled with three separate systems: the primary VV loop, the secondary double-jacket loop, and the water in the VVPSS tank. The fluid in each system is separated from the flow in each of the other systems, but there is thermal contact through the walls of the HX between the primary and secondary systems (double-jacket) and between the secondary and the water in the VVPSS tank. Each VV PHTS loop was modeled with a total of 95 volumes, 94 junctions, and 218 heat structures. The nine half sectors cooled by one VV PHTS loop were lumped into one control volume that was subdivided into 12 horizontal subvolumes. Figure 3 shows the RELAP5-3D nodalization of the three systems. The secondary system and the VVPSS tank system are represented at the top of the figure. The biggest part of the model is the primary system. The primary HX side, the pressurizer, the VV, the distributor and collector piping, and the pump leg are shown. The FW/BLK and DIV were also modeled as heat structures that radiate decay heat to the VV. The thermal shield and the cryostat were also modeled and thermally coupled to the VV via radiation.

Insert Fig. 3

Figures 4 and 5 show isometric views of the primary system model with the VV at the left, the HX and the pressurizer at the top right, and the piping in between. There is a bypass line for the HX and another bypass line for the pump (bottom right).

Insert Figs. 4 and 5

Some control systems were implemented in the HX to keep the primary coolant cold temperature above 100°C. If the temperature of the primary coolant leaving the HX is below 100°C, the HX primary is bypassed or the secondary flow is reduced until the temperature of 100°C is reached again. This is necessary because the HX is designed to remove 1.5 MW and the average power of the system is only 1.11 MW (Section 3).

5. RELAP5-3D results

Results for normal plasma operation are shown first. Figure 6 shows the power profile used. The first 1,000 s were run at a constant power of 1.5 MW to check the cooling capabilities of the HX, designed for 1.5 MW. At 1,000 s the first pulse of 5 MW was started. This power was maintained for 400 s (ended at 1,400 s run time). After that, dwell times of 1,400 s between pulses were used. A total of five pulses were simulated.

Insert Fig. 6

Figure 7 shows calculated coolant temperatures: into the VV (black), out of the VV (red), and out of the HX (green). The hottest temperatures were for the coolant leaving the VV (red). Each pulse produced peaks in the coolant temperatures. The first pulse increased the hot temperature up to 374.9 K; after that, the hot temperatures were under 374.5 K. After the third pulse the temperature oscillations were stable. The overall temperature variation was small, about 1.5 K, the temperature being controlled by the secondary flow.

Insert Fig. 7

Figure 8 shows the calculated temperatures for the VV structures; in this calculation six power pulses were simulated, starting at 600 s. The structure temperatures were about 10 K higher than the coolant temperatures. During normal plasma operation the temperature of the water in the VVPSS tank does not change because the CCW removes all the heat of the primary system through the jacket of the HX, isolating the VVPSS tank water from the primary system water.

Insert Fig. 8

Under decay heat conditions, the main pumps are not operating and coolant circulates by natural convection. Only one coolant loop (half of the VV) is used to remove the decay heat of the complete VV and its associated structures (FW/BLK and DIV). The second loop is assumed to be in the failed condition for safety analysis. The decay heat of the VV itself is small (26.5 kW at time zero), but the decay heat of the FW/BLK and DIV are very large (11.265 MW and 1.716 MW, respectively, both at time zero). Heat from these structures is transferred to the VV structures by radiation. Also, the VV radiates heat to the cold thermal shield, which is at 80 K, and the thermal shield radiates heat to the cryostat. Results for decay heat removal by natural circulation are shown in Figs. 9–10. In the safety analysis it was assumed that offsite power would be lost for 72 h (3 days) during the accident. The natural circulation within the VV PHTS must be sufficient to remove decay heat from the vacuum vessel and all internal components during this period without exceeding temperature limits. It can be assumed that after 72 h cooling to all components would be restored.

Insert Figs. 9 and 10

Figure 9 shows the temperatures of the coolant entering and leaving the VV during 345,600 s (96 h or 4 days) of decay heat operation. The calculations were run for one additional day (4 days instead of the 3 days of the required nonpower operation), and the results were totally acceptable. The coolant reached a maximum temperature of 413 K, which is acceptable. The structures reached higher temperatures, but all VV structures were under 450 K. The maximum natural convection coolant flow was about 16 kg/s (475 kg/s was the flow

with the pump on). The heat was ultimately transferred to the VVPSS tank. During the 4 days of simulated decay heat operation, VVPSS tank temperature increased by 25 K (Fig. 10) and pressure by 11.2 kPa. It was assumed that under abnormal operating conditions the vacuum system of the VVPSS tank would no longer be operating, the tank would be isolated, and tank pressure and temperature would increase as the tank water heated up. If the vacuum system continued operating, keeping the VVPSS tank pressure at 4.2 kPa, the water would reach saturation after 10 h and boiling would occur afterwards. The steam generated must be removed by the vacuum system and the water inventory would diminish with time. While the conditions in the VV were totally acceptable, the pressure, temperature, or water inventory changes in the VVPSS tank do not appear to be acceptable.

6. Summary and conclusions

A RELAP5-3D model of an alternative ITER VV PHTS design (with the HXs inside the VVPSS tank) has been developed and used to check the normal and abnormal operation (decay heat condition with no pumps) of the VV cooling system.

The model has demonstrated the feasibility of this alternative design under both normal and abnormal conditions. During normal operating conditions, the VVPSS tank water is not affected as it is thermally insulated from the primary system by the CCW double-jacket HX. During abnormal operating conditions, the VVPSS tank water acts as the heat sink for the decay heat from the VV and associated structures. Therefore, its pressure and water temperature increase significantly (by 11.2 kPa and 25 K, respectively). These changes in pressure and temperature in the VVPSS tank raised questions regarding acceptability. The resultant steam generation in the VVPSS tank would need to be removed by the vacuum system. The acceptability of the projected operations during abnormal conditions will be evaluated according to ITER Project Change Request procedures.

Acknowledgment

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Abbreviations:

BLK	blanket
CCW	component cooling water
DIV	divertor
FW	first wall
HX	heat exchanger
NBI	neutral beam injector
NRC	U.S. Nuclear Regulatory Commission
NVDS	normal ventilation and detritiation system
PHTS	primary heat transfer system
PSS	pressure suppression system
TCWS	tokamak cooling water system
VV	vacuum vessel

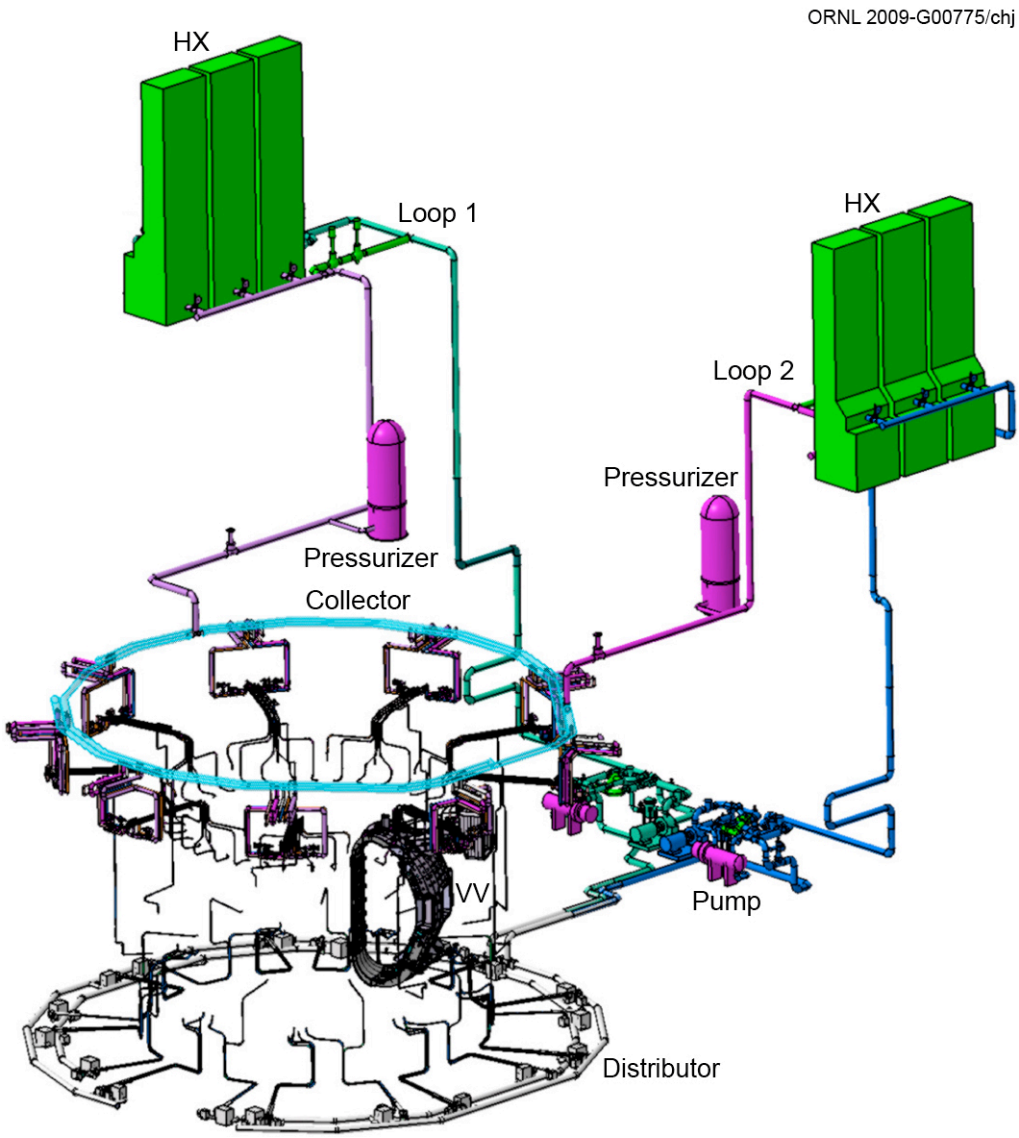
ORNL 2009-G00775/chj
HX
Loop 1
HX
Loop 2
Pressurizer
Pressurizer
Collector
VV
Pump
Distributor

Fig. 1.

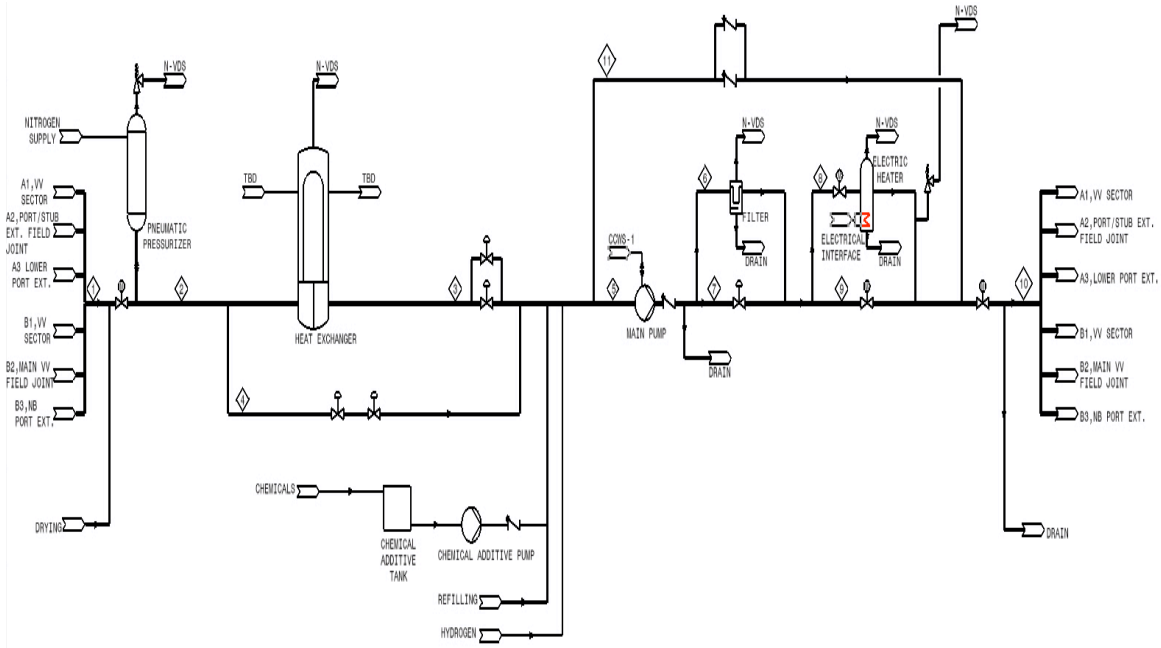
N-VDS
NITROGEN SUPPLY
A1,VV SECTOR
A2,PORT/STUB EXT. FIELD JOINT
A3 LOWER PORT EXT.
B1,VV SECTOR
B2,MAIN VV FIELD JOINT
B3,NB PORT EXT.
DRYING
PNEUMATIC PRESSURIZER
TBD
HEAT EXCHANGER
CHEMICALS
CHEMICAL ADDITIVE TANK
CHEMICAL ADDITIVE PUMP
REFILLING
HYDROGEN
CCMS-1
MAIN PUMP
FILTER
DRAIN
ELECTRIC HEATER
ELECTRICAL INTERFACE
A1,VV SECTOR
A2,PORT/STUB EXT. FIELD JOINT
A3,LOWER PORT EXT.
B1,VV SECTOR
B2,MAIN VV FIELD JOINT
B3,NB PORT EXT.

Fig. 2.

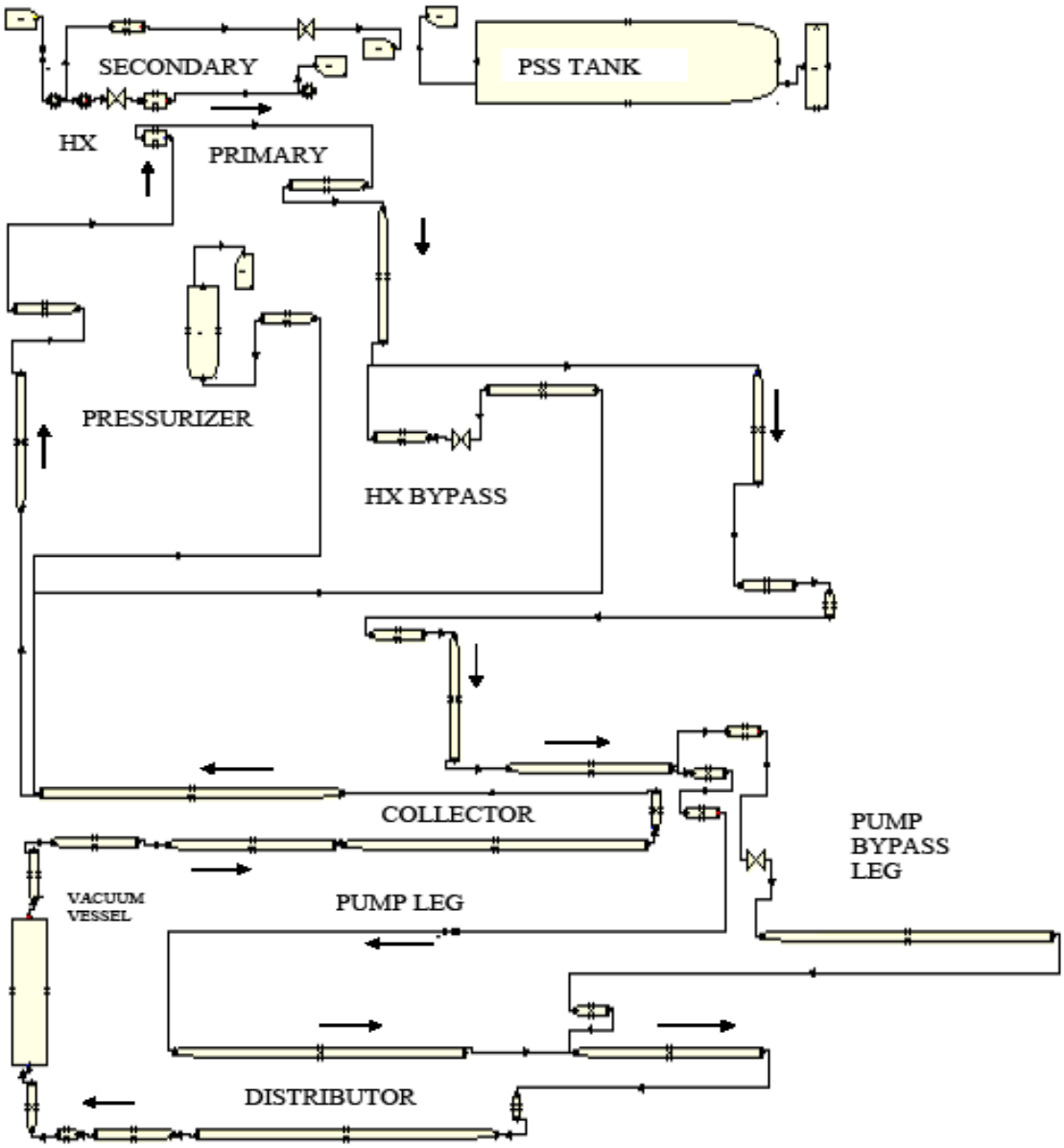
SECONDARY
PSS TANK
HX
PRIMARY
PRESSURIZER
HX BYPASS
COLLECTOR
PUMP
BYPASS
LEG
VACUUM
VESSEL
PUMP LEG
DISTRIBUTOR

Fig. 3.

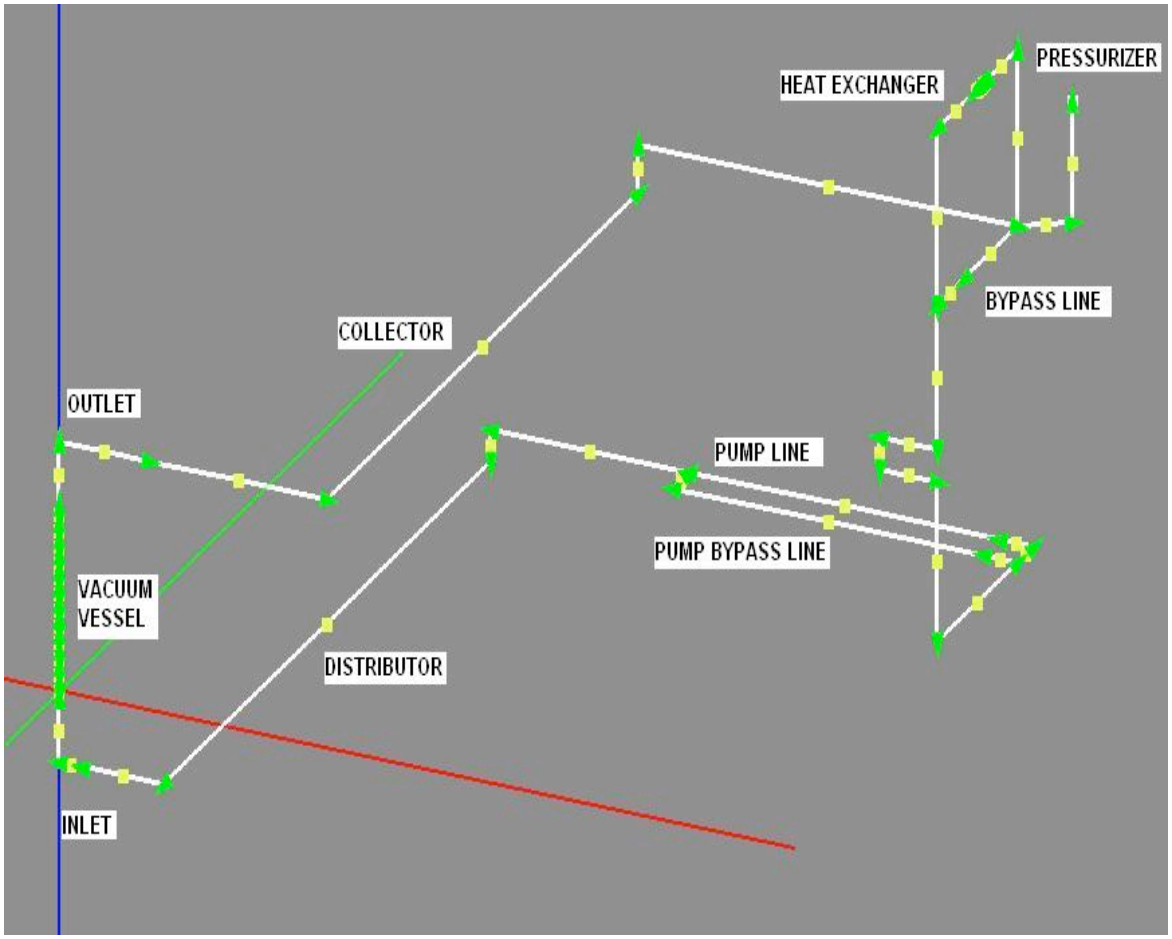
PRESSURIZER
HEAT EXCHANGER
BYPASS LINE
COLLECTOR
OUTLET
PUMP LINE
PUMP BYPASS LINE
VACUUM
VESSEL
DISTRIBUTOR
INLET

Fig. 4.

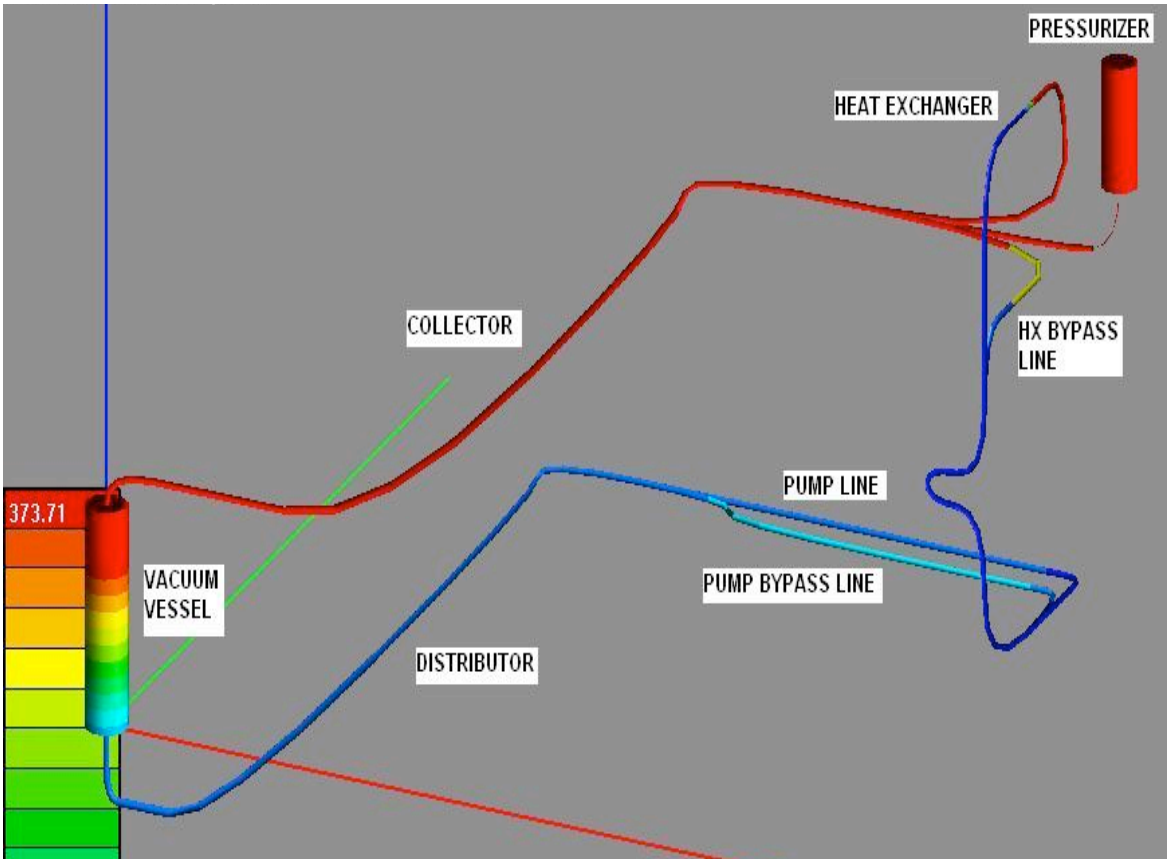
PRESSURIZER
HEAT EXCHANGER
COLLECTOR
HX BYPASS
LINE
PUMP LINE
373.71
VACUUM
VESSEL
PUMP BYPASS LINE
DISTRIBUTOR

Fig. 5.

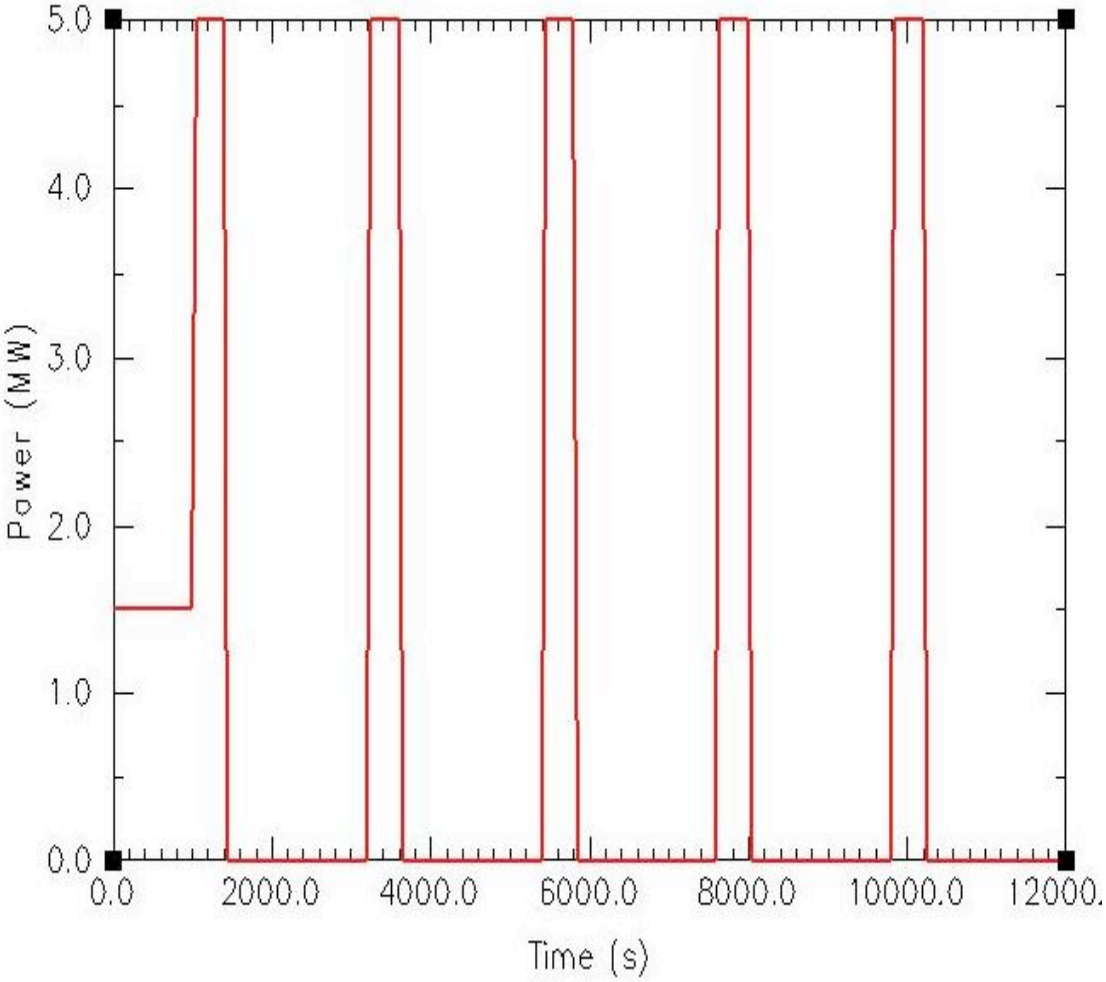
5.0
4.0
3.0
2.0
1.0
0.0
Power (MW)
0.0
2000.0
4000.0
6000.0
8000.0
10000.0
12000.
Time (s)

Fig. 6.

,

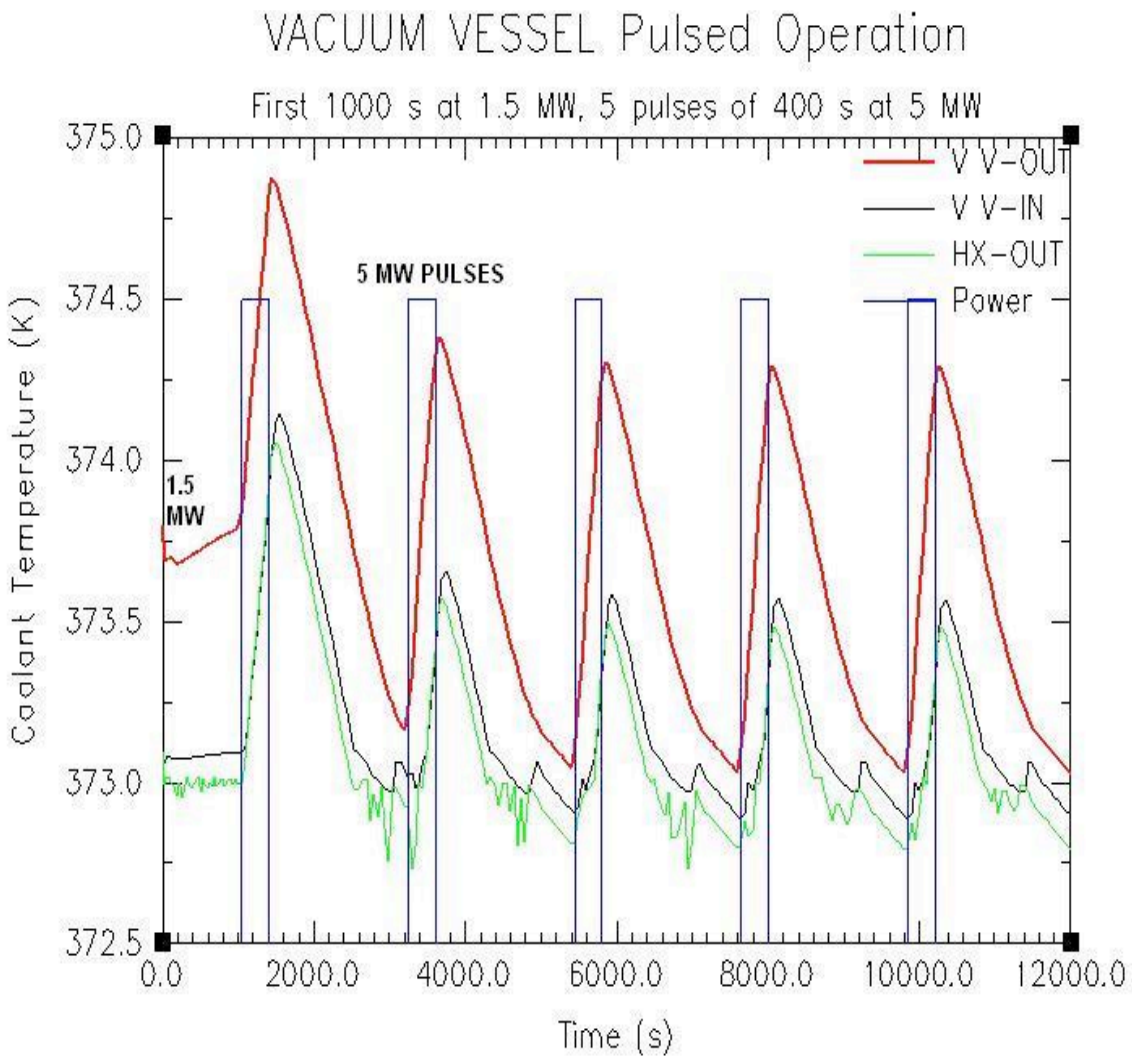
VACUUM VESSEL Pulsed Operation
First 1000 s at 1.5 MW, 5 pulses of 400 s at 5 MW
5 MW PULSES
1.5 MW
V V-OUT
V V-IN
HX-OUT
Power
Coolant Temperature (K)
375.0
374.5
374.0
373.5
373.0
372.5
0.0
2000.0
4000.0
6000.0
8000.0
10000.0
12000.0
Time (s)

Fig. 7.

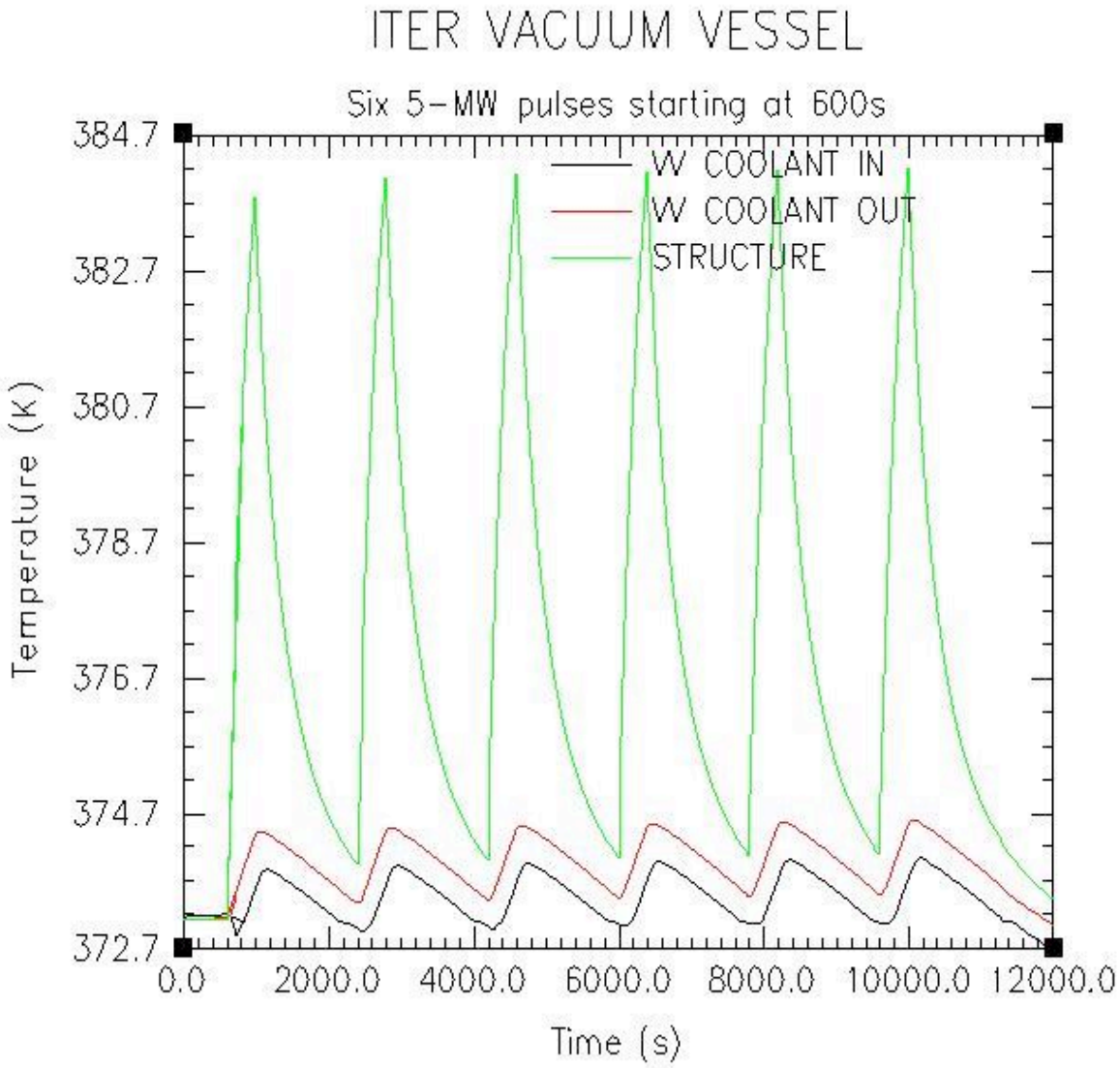
ITER VACUUM VESSEL
Six 5-MW pulses starting at 600s
W COOLANT IN
W COOLANT OUT
STRUCTURE
384.7
382.7
380.7
378.7
376.7
374.7
372.7
Temperature (K)
0.0
2000.0
4000.0
6000.0
8000.0
10000.0
12000.0
Time (s)

Fig. 8.

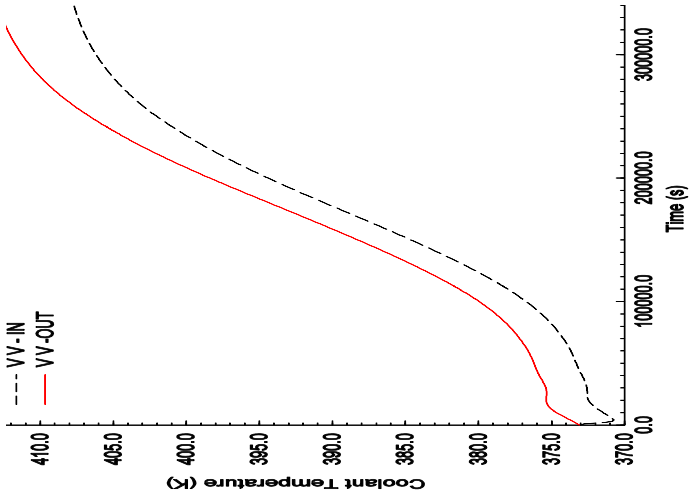
VV-IN
VV-OUT
410.0
405.0
400.0
395.0
390.0
385.0
380.0
375.0
370.0
Coolant Temperature (K)
0.0
100000.0
200000.0
300000.0
Time (s)

Fig. 9.

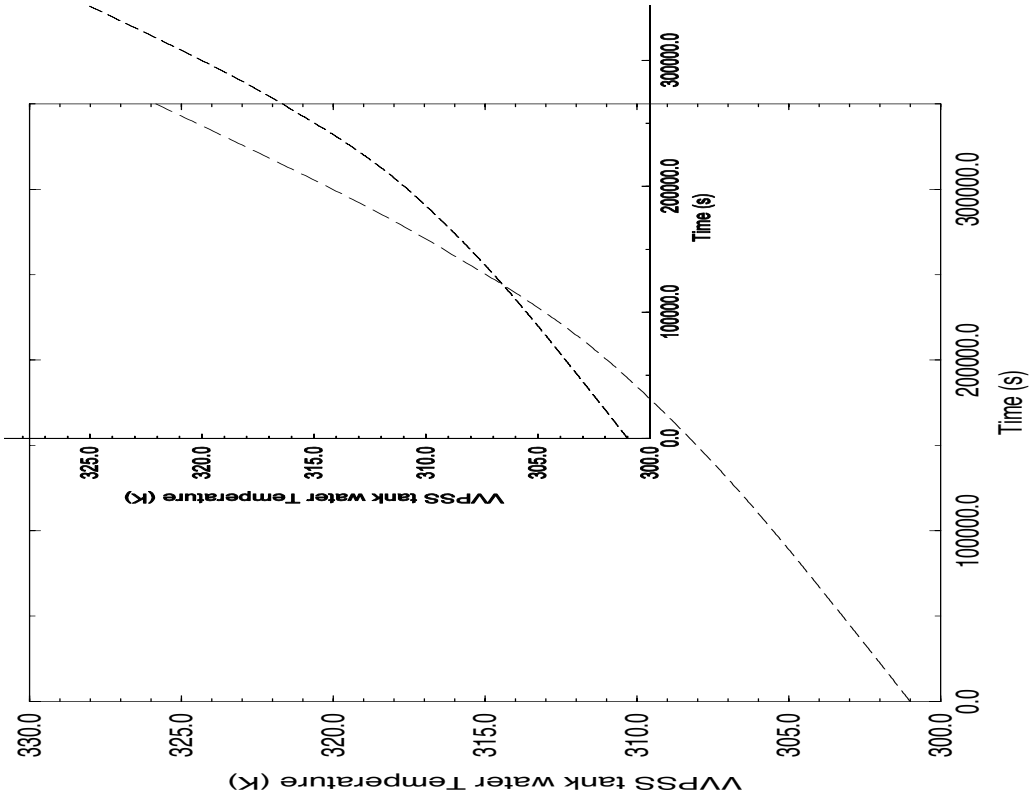
VVPSS tank water Temperature (K)
330.0
325.0
320.0
315.0
310.0
305.0
300.0
0.0
100000.0
200000.0
300000.0
Time (s)
VVPSS tank water Temperature (K)
325.0
320.0
315.0
310.0
305.0
300.0
0.0
100000.0
200000.0
300000.0
Time (s)

Fig. 10.

Figure Legends

Fig. 1. Current VV PHTS design (2 loops).

Fig. 2. Schematic of the current VV PHTS.

Fig. 3. RELAP5-3D nodalization of the alternative design.

Fig. 4. RELAP5-3D view of the alternative design primary system showing volumes and junctions.

Fig. 5. RELAP5-3D isometric view of the alternative design primary system.

Fig. 6. Power profile used for normal pulsed operation (5 MW pulses).

Fig. 7. Calculated coolant temperatures during normal pulsed operation.

Fig. 8. Calculated temperatures of the VV structures during pulsed operation.

Fig. 9. Coolant temperatures in and out of the VV during decay heat operation.

Fig. 10. Temperature of the water in the VVPSS tank during decay heat operation.

Approximate Figure sizes

Fig. 1 - 1/3 of one column = 1/6 pp

Fig. 2 – ½ of two columns = ½ pp

Fig. 3 – 1/3 of one column = 1/6 pp

Fig. 4 – 1/3 of one column = 1/6 pp

Fig. 5 – 1/3 of one column = 1/6 pp

Fig. 6 – 1/3 of one column = 1/6 pp

Fig. 7 – 1/3 of one column = 1/6 pp

Fig. 8 – 1/3 of one column = 1/6 pp

Fig. 9 – 1/3 of one column = 1/6 pp

Fig. 10 – 1/3 of one column = 1/6 pp