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Comparison of Alternatives to the 2004 Vacuum Vessel Heat Transfer System Design

February 2010

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COMPARISON OF ALTERNATIVES TO THE 2004 VACUUM VESSEL HEAT TRANSFER SYSTEM DESIGN

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ACRONYMS

A/W	Air to Water
ASN	French Nuclear Safety Authority
CCWS	Component Cooling Water System
CHWS	Chilled Water System
FC	Forced Circulation
HX	Heat Exchanger
NC	Natural Circulation
PCR	Project Change Request
PHTS	Primary Heat Transfer System
VV	Vacuum Vessel
VVPSS	Vacuum Vessel Pressure Suppression System

ABSTRACT

A study comparing different alternatives for the Vacuum Vessel Primary Heat Transfer System has been completed. Three alternatives were proposed in a Project Change Request (PCR-190) by relocating the heat exchangers (HXs) from the roof of the Tokamak building to inside the Vacuum Vessel Pressure Suppression System (VVPSS) tank. The study evaluated the three alternatives and recommended modifications to one of them to arrive at a preferred configuration that included relocating the HXs inside the Tokamak building but outside the VVPSS tank as well as including a small safety-rated pump and HX in parallel to the main circulation pump and HX.

INTRODUCTION

The Vacuum Vessel (VV) Primary Heat Transfer System (PHTS) removes heat generated in the VV during normal operation (10 MW, pulsed power) as well as the decay heat from the VV itself and from the structures/components attached to the VV (first wall, blanket, and divertor ~0.48 MW peak). Therefore, the VV PHTS has two safety functions: (1) contain contaminated cooling water (similar to the other PHTSs) and (2) provide passive cooling during an accident event.

The 2004 design of the VV PHTS consists of two independent loops, each loop cooling half of the 18 VV segments with a nominal flow of 475 kg/s of water at about 1.1 MPa and 100ºC. The total flow for both loops is 950 kg/s. Both loops are required to remove the heat load during normal plasma operation. During accident conditions, only one loop is needed to remove by natural convection (no pump needed) the decay heat of the complete VV and attached components. The heat is transferred to heat exchanger (HXs) located on top of the roof, outside the Tokamak building. These HXs are air-to-water (A/W) HXs.

Three alternatives have been proposed for this cooling system. For a detailed discussion of these alternatives, please refer to Project Change Request, PCR-190 (Ref. 1). A brief introduction is given here.

Alternative 1 includes only one main forced circulation loop with a small safety-rated pump in parallel with the main circulation pump. In addition, this alternative has two natural circulation safety loops. Both the safety and main loops supply water to the bottom of the VV with six branch lines and collect the heated water at the top of the vessel through six branches. The distribution headers are located in the lower pipe chase and the collection headers in the upper pipe chase. Each of these loops (one main and two emergency) has a HX mounted in the Vacuum Vessel Pressure Suppression System (VVPSS) tank. The main HX is cooled using either Component Cooling Water System (CCWS) or Chilled Water System (CHWS) water, and the emergency HXs are cooled by natural circulation of the VVPSS water. See Fig. 1 taken from PCR-190.

Alternative 2 is exactly the same as Alternative 1 except that there is only one emergency loop and one emergency HX. See Fig. 2 taken from PCR-190.

Alternative 3 also has one main forced circulation loop with a small safety-rated pump in parallel with the main circulation pump and one natural circulation safety loop. In this case, both the safety and main loops supply water to the top of the VV with three branch lines and collect the heated water at the top of the vessel through three branches. Here, the distribution header is located in the upper pipe chase as is the collection header. As before, each of these loops has a HX mounted in the VVPSS tank. The main HX is cooled using either CCWS or CHWS water, and the emergency HXs are cooled by natural circulation of the VVPSS water. See Fig. 3 taken from PCR-190.

The preferred configuration is developed by selecting specific attributes of the other configurations analyzed and the logic for selecting this configuration is discussed at the end of the document. It is a modification of Alternative 2 that eliminates the separate safety loop, but incorporates a small safety rated HX and pump in parallel with the main HX and pump. It uses 18 inlet and 18 outlet branches (as did the 2004 design) and locates the HXs outside of the VVPSS tank.

Tables 1 and 2 examine alternatives to the 2004 VV heat transfer system design that were proposed in PCR-190, as well as the preferred option.

Table 1. Comparison of Alternatives and the 2004 Design

Version	Main heat exchanger (HX) cooling	Number of forced circulation (FC) loops	Number of FC HX (location)	Major piping diameter	Mass flow in branch (kg/s)	VV pressure drop (ΔP) assuming same overall temperature rise (MPa) {alternate ΔP/2004 ΔP}	Half-segment-to-half-segment ΔT (assuming same overall temperature rise – 2°C)	Half-segment-to-half-segment ΔP (MPa) (normal operation – same mass flow)
2004	Air	2	2 (roof)	14”	950/18=53	0.05 {1}	0	0
Alternate 1	Water	1	1 (VVPSS)	20”	950/6=158	1.35 {27}	1.32	0.9
Alternate 2	Water	1	1 (VVPSS)	20”	950/6=158	1.35 {27}	1.32	0.9
Alternate 3	Water	1	1 (VVPSS)	20”	950/3=317	10.8 {216}	0.66	3.6
Preferred	Water	1	1 (building)	20”	950/18=53	0.05 {1}	0	0

Version	VV pressure drop (MPa) assuming the same half-segment flow rate {relative}	ΔT (°C) (overall/half-segment-to-half-segment) (assuming the same half-segment flow rate)	Half-segment-to-half-segment ΔP (MPa) (normal operation – same half-segment mass flow)	Half-segment-to-half-segment ΔP (MPa) (normal operation – Loss of coolant accident)	Number of natural circulation (NC) HXs	Half-segment jumpers needed (#)	How much coolant is lost in pipe break event?	Number of emergency loops
2004	0.05 {1}	2/0	0	~1.1	NC in FC piping	No	1/2	0
Alternate 1	0.15 {3}	6/4	0.1	0	2	Yes (12)	1/3	2
Alternate 2	0.15 {3}	6/4	0.1	0	1	Yes (12)	1/3	1
Alternate 3	0.3 {6}	12/4	0.1	0	1	Yes (15)	0	1
Preferred	0.05 {1}	2/0	0	0	0	No	1	0

Version	Reevaluation of in vessel cooling required?	Number of FC HXs	Scaled branch piping diameter	# branch pipes required
2004	No	2	1	18 in – 18 out
Alternate 1	Yes	1	√3	6 in – 6 out
Alternate 2	Yes	1	√3	6 in – 6 out
Alternate 3	Yes	1	√6	3 in – 3 out
Preferred	No	1	1	18 in – 18 out

Table 2. Performance of Alternatives Compared to the 2004 Design

Version	NC performance	Distribution/collector reconfiguration	Normal pumping power requirements (same mass flow)	FC cooling capability (same mass flow)	Emergency cooling pump required	Branch piping complexity	Number of welds
Alternate 1	Worse	~ Same	> 2004	More difficult	?	< 2004	< 2004
Alternate 2	Worse	~ Same	> 2004	More difficult	?	< 2004	< 2004
Alternate 3	Not possible	More difficult	>> 2004	More difficult	Yes	<< 2004	<< 2004
Preferred	Worse	Same	Same	Same	Yes	Same	< 2004

Version	Normal FC HX size (total area)	Draining	Cost
Alternate 1	< 2004	Worse	?
Alternate 2	< 2004	Worse	?
Alternate 3	< 2004	Worse	?
Preferred	< 2004	Same	?

DISCUSSION

1) **Location of Main Heat Exchanger –** The French Nuclear Safety Authority (ASN) expressed the concern that the VV PHTS only uses one confinement barrier between the radioactive material and the environment (Ref. 2). Additionally with the air-cooled HXs located on the roof, they are subject to many external events such as high winds and tornadoes (Ref. 3). Locating the main HXs inside the Tokamak building and using the CCWS as the primary heat sink during normal operation eliminates both of these concerns. Additionally, because the HX will now be water cooled on the secondary side, the size of the HX can be significantly reduced, potentially reducing cost.

2) **Heat Exchangers for Safety or Emergency Operation –** HXs for use during emergency conditions can be smaller, and similarly placed within the Tokamak building, eliminating the safety issue of a single confinement boundary for radioactive liquid, and also eliminating the problem with having to harden them to survive potential external events. These HXs could be cooled using CHWS water since it is a safety-class water system.

3) **Safety Classification for the Vacuum Vessel Cooling Water System –** All of the PHTSs have the safety function of containment of the water. The 2004 design of the VV system has the additional safety function of providing passive cooling in the event of a loss of offsite power event; therefore, two separate natural circulation cooling loops provide redundancy. In order to meet the requirements of a safety system, even when utilizing two redundant systems, these must not be subject to common cause failure. In the case of the VV cooling water system, the loops have been separated as much as possible by locating the air-cooled HXs at different locations on the roof; however, much of the piping is (e.g., distributors and collectors) are located close together and need to be isolated in order to prevent a break in one from damaging the other due to pipe whip. The VV branch piping located inside the cryostat is even more difficult to isolate, since it is not possible to provide intermediate support for them between the cryostat and the VV. In 2009, the ITER Safety Analysis and Assessment Group provided analysis which showed that the heat capacity of the VV structure is sufficient to absorb all of the decay heat radiated from in-vessel components to the VV walls. Introducing air into the cryostat after several days promotes additional passive heat transfer to the cold magnet structures and ultimate long-term removal of the decay heat. The significant difficulty of preventing common cause failure due to piping interactions during a break, along with the expectation that the vessel will be able to be cooled without water cooling (using the VV heat capacity and radiation), leads to the conclusion that a single safety-related cooling loop will be sufficient to provide a redundant cooling.

4) **Vacuum Vessel Pressure Drop –** The 2004 cooling system design has a pressure drop of <0.05 MPa, a temperature rise through the VV of 2ºC, a total flow rate through the VV of 950 kg/s (all 18–20 degree half-segments), with 18 inlet branches and 18 outlet branches, each inlet/outlet pair supporting one half-segment of the VV. Each of the three alternatives has a single forced convection-cooling loop supporting the VV.

   Alternates 1 and 2, as presented in Figs. 4 and 5, each have six inlet branches and six outlet branches with jumpers connecting three half-segments in series. To keep the temperature rise through the VV at 2ºC, alternative designs must maintain the same total mass flow rate through the VV. The flow rate through each half-segment is, therefore, 18/6 = 3 times higher than that of the 2004 design. Since pressure drop through each half-segment is approximately proportional to the square of the flow rate (assuming flow areas remain the same), then the pressure drop through each half-segment is nine times the 2004 design. Additionally, because Alternatives 1 and 2 connect three half-segments in series, the total pressure drop through the VV is, therefore, [9 × 3] 27 times that of the 2004 design.

Alternative 3 has three branch lines each feeding six half-segments (Fig. 6). Using similar arguments, the pressure drop through the VV for this case is [(18/3) × (18/3) × 6] 216 times the 2004 design. The pressure drop for alternative designs 1–3 is, therefore, excessive and would result in substantially larger pumps and increased cost. To avoid an increase in pump size, the flow rate through each half-segment could be reduced, resulting in an increase in temperature drop across the VV, or an increased number of branch lines. The number of branch lines would be increased to 18 inlets and 18 outlets for Alternatives 1 and 2 simply because the connections must be at the top and bottom of the half-segments. For Alternative 3 (assuming three half-segments in series are too many from the arguments above), the number must be increased to 9 inlets and 9 outlets (because two half-segments are in series and therefore must include a lower jumper since the inlets and outlets are both at the top of the vessel).

An alternative to keeping the same overall temperature rise through the VV would be to maintain the same mass flow through each of the half-segments. This would require a relaxation in the temperature rise requirement through the VV but would reduce the increase in pressure rise through the VV and piping. If the same mass flow through each half-segment were maintained, then for Alternatives 1 and 2, the pressure rise would increase by a factor of 3 since three half-segments would be connected in series. This would also cause an increase in temperature rise by [3 × 2ºC] 6ºC. The total mass flux through the VV would also be reduced by a factor of 3 to 317 kg/s. In the case of Alternative 3, if the mass flow through each half-segment remained the same, the temperature rise would increase by a factor of 6 to 12ºC and the pressure rise through the system would increase to [6 × 0.05 MPa] 0.3 MPa.

The preferred alternative maintains the 2004 VV pressure drop because jumpers are not proposed.

5) **Coolant Loss in Case of a Pipe Break Event** – The 2004 design has two totally independent cooling loops, and therefore a break in one of the loops would allow continued operation of the other (assuming no common cause failure – discussed in point 3 above). Also, in the event of a pipe break, water remains in every other half-segment in the 2004 design since each loop feeds every other 20 degree half-segment, and the half-segments are isolated from each other. All of the alternatives have only a single cooling loop, and a pipe break eliminates the possibility of any continued forced convection cooling after the break. However, because of the location of jumpers between half-segments in these designs, water will remain in some of the half-segments (others will drain in the event of a break). Table 1 indicates that water remains in two-thirds of the half-segments for Alternatives 1 and 2 in the event of a pipe break and in all of the half-segments for Alternative 3 (since both branch inlets and outlets are at the top of the vessel in this case).

   For the 2004 design, each alternating half-segment is fed from independent cooling water systems and is isolated from its neighbor. In the event of a pipe break in one of the coolant loops and the consequent drop in loop pressure, the pressure across the half-segment walls would become the total system gage pressure (unless some means is developed to decrease the pressure of the intact loop during the break event) and could potentially overstress the wall. Design alternatives have only one cooling loop eliminating the potential to overstress the wall because a break in this loop would result in uniform depressurization of all half-segments, and any differential pressures would be zero or at least of very short duration (on the order of the time required for the pressure wave to propagate through the branch piping).

6) **Draining and Drying** – The 2004 system drains from the bottom of the VV (or near the bottom). In Alternatives 1 and 3, three half-segments are in series with the inlet half-segment connected as before, and the other two half-segments connected by jumpers. Unless the lower jumper system can be designed to have a drain, all of the water in the second and third half-segments (going from inlet to

outlet) will have to be removed by gas overpressure, which could be used to clear the third half-segment and then by forced draining to clear the second half-segment. This will be significantly more difficult than in the 2004 design. Similarly, since Alternative 3 has both inlet and outlet branches connected at the top of the VV, it will all have to be forced drained to blow water out of all of the VV half-segments unless an independent draining system can be developed. This will also require considerable compressor power to get vapor velocities high enough in the VV half-segments to entrain all of the water. The preferred design would drain very similarly to the 2004 design since it retains branch piping to each of the half-segments. The only difference is that the preferred design has only one distribution and collection header, whereas the 2004 design had two independent header systems.

7) **Natural Circulation Capability** – The 2004 VV cooling water system is designed to operate under natural circulation conditions, and the design includes significant elevation changes between the VV and the air coolers on the roof. Additionally, the flow through the VV is upwards under all conditions. In Alternatives 2 and 3, the inlet and outlet lines of the emergency cooling system are at the bottom and top of the VV, respectively, so there is a distinct hot leg and cold leg which will induce natural circulation in the cooling loops. However, the center half-segment will be required to be in downflow. The buoyancy forces will therefore be against gravity and will tend to slow down the overall flow. Additionally, because the flows will be very low in the half-segment under natural circulation conditions, the possibility exists that internal flows may develop within this half-segment and cause significant degradation in local heat transfer. In Alternative 3, where both inlet and outlet coolant legs are located at the top of the vessel, there is no clear hot and cold leg. The possibility exists in this design that flows might reverse under some conditions, or never really establish “loop” natural circulation, which could lead to significant degradation in heat transfer within the half-segments. This design cannot produce dependable natural circulation.

   The preferred design does not have the natural circulation concern of Alternatives 2 and 3 above where there are three half-segments in series and one must operate in opposition to gravity during natural circulation. However, because the elevation difference between the VV and the HXs in the preferred design is smaller than in the 2004 design with the air-cooled HXs on the roof, the natural circulation performance would be expected to be worse than the original 2004 design.

   Present VV cooling requirements during emergency conditions specify a required coolant flow of 40 kg/s. Natural circulation calculations performed on the 2004 system with HXs located in the VVPSS tank indicate that only about 12 kg/s can be achieved (from RELAP5 calculations, Ref. 4). These calculations have used 350 mm main piping. This implies that the smaller piping anticipated for Alternatives 1 and 2 would be able to supply even less flow, and that a natural circulation loop of reasonable size would not be able to supply the required flow. Therefore, a small safety-class pump for emergency cooling will be necessary to meet this flow requirement.

   Additionally, recent calculations, which have assumed that there is no coolant available for the VV cooling and no coolant available to cool components internal to the VV, have shown that pure radiation from the VV to the thermal shield is sufficient to maintain the VV temperatures at acceptable levels (Ref. 4). This would imply that the emergency cooling system would not have to be considered a safety system.

8) **In-Vessel Cooling –** All of the alternatives have half-segments that operate under downflow conditions during normal operation. Flows in the VV are generally low because of the large flow area. Buoyancy forces can be important; however, in the 2004 design they are in the flow direction. In Alternatives 1–3, some of the half-segments are under downflow conditions, and buoyancy forces

would be acting opposite to the flow direction in those half-segments. For this reason, it would be necessary to reevaluate flows in these half-segments to ensure that the necessary cooling is still provided.

9) **Half-Segment-to-Half-Segment Pressure Drop and Temperature Differences** – The 2004 design has parallel flow through each of the half-segments, and temperature and pressure differentials across each half-segment are zero under normal operating conditions. Alternatives 1–3 have cooling of the half-segments in series and therefore increase both temperature and pressure differentials across the half-segments. Table 1 indicates differences assuming that the 2004 coolant temperature rise is maintained. Certainly, the high pressure differentials required to keep the same overall temperature rise would not be acceptable for normal operation.

10) **Heat Exchanger Location** – The HX physical location for Alternatives 1–3 is in the VVPSS tank. The elevation change between the VV and the VVPSS tank is slightly smaller than the 2004 elevation change, reducing the potential for natural circulation flow somewhat. Locating this HX physically within the VVPSS tank allows the VVPSS water to act as a heat sink during emergency conditions (the concentric tube design of this HX uses the CCWS as coolant during normal operation). During emergency operation, the VVPSS pressure must rise in order to prevent boiling since the VVPSS water is near saturation conditions normally. The VVPSS is to operate at 4.2 kPa and 28ºC, which is approximately 2ºC of subcooling in the water. Natural circulation calculations during a loss of offsite power event indicate the pressure of the VVPSS tank will increase to approximately 9.5 kPa after 72 hours. This pressure increase impacts the operation of the tank as a pressure relief system for the plasma chamber during normal operation and may not be desirable from that standpoint. This pressure increase was determined to be unacceptable (Ref. 5). The HXs could also be located outside this tank and cooled with CHWS (a safety-rated system). They should have a rather small footprint since the power requirements are relatively low and independent HXs could be used for normal operations using the CCWS and for the safety function using the CHWS. The proposed configuration discussed below incorporates this HX configuration.

11) **Jumpers and Branch Piping** – Jumpers are required in all three alternatives. Jumpers located at the top of the VV have been determined to be acceptable; however, locating jumpers at the bottom of the VV may prove difficult because of space limitations. No jumpers would be necessary for Alternatives 1 and 2 if the branch piping system of the 2004 design were maintained (18 inlet and 18 outlet). The VV cooling system also includes cooling branches for the lower port extension, the lower port, the lower port field joints, and the vessel field joints. Thus, even though the number of branches may be reduced, there will still be a significant amount of branch piping to be located. In designing Alternative 3, accommodation for these additional cooling systems would have to be made.

PROPOSED CONFIGURATION

The common cause failure discussion in discussion point 3 implies that multiple loops do not add to the overall safety of the system. Therefore, the multiple safety loops in Alternative 1 are not needed. Since the number of loops is the only difference between Alternatives 1 and 2, these systems are essentially the same. Discussion from this point forward will therefore include only Alternatives 2 and 3. Since natural circulation cooling will not meet the flow requirements during accident conditions, a safety-rated pumped system is necessary (discussion point 7). Flow requirements can be met using only the main loop and adding a small safety-rated pump and HX parallel to the main pump and HX [this configuration is similar to the parallel pump configuration shown in Fig. 4 of the PCR-190 (Ref. 1)]. The separate emergency loops can therefore be eliminated. In addition, the analysis in Ref. 4 shows that no water cooling at all is required in order to remove decay heat from the VV system and internal components, and therefore it may not be necessary to classify the small emergency pump and HX as safety systems. However, it may be desirable to design these systems with those features for investment protection. By locating both the main and safety HXs outside the VVPSS, overpressure of the VVPSS cannot occur because of the VV PHTS. Since the proposed configuration does not rely on natural circulation for making a safety case, these HXs can be located at any elevation where there is sufficient room. Because of the significant pressure drop introduced by operating several half-segments in series, either a relaxation of the overall temperature rise (now 2ºC) must be considered, or the present configuration of 18 inlet and 18 outlet branches can be maintained for Alternative 2. [The 2ºC temperature rise through the VV is determined by the heat deposited in the VV coolant and the coolant flow rate (950 kg/s)]. In the case of Alternative 3, nine inlets and nine outlets would be preferred to minimize pressure drop, and a flow path (or jumper system) at the lower portion of every other 20 degee half-segment would be required to allow flow between each paired half-segment. Alternative 3 has the added requirement of bringing cooling to the lower ports from an inlet header located in the upper pipe chase.

The preferred solution is Alternative 2 discussed in PCR-190 with four changes.

1) Elimination of the safety loop
2) Insertion of a safety-rated HX cooled by the CHWS in series with the safety pump (both pump and HX in parallel with the main pump and HX)
3) Both safety and main HXs outside of the VVPSS
4) 18 inlet and 18 outlet branches connected to the VV with no jumpers

Figure 7 shows this configuration. The separate safety loop design was eliminated because it could not be isolated from the main loop in the event of a pipe break and therefore would offer no additional protection for this event. In order to simplify the design, a small pump and HX system placed in parallel to the main pump and HX was designed to provide the required 40 kg/s, adding defense in depth under loss of power accident scenarios. This can be accomplished by providing appropriate safety-rated electrical power to the pump and using the CHWS on the secondary side of the HX. Because of overpressure or steam generation issues arising when the HXs are placed inside the VVPSS tank, both main and safety HXs should be placed outside the VVPSS tank. Because they are relatively small (the volume of the main HX is ~ 6000 liters and the emergency HX is ~ 60 liters) and the second coolant loop used in the 2004 design is eliminated with this alternative, space should be available to locate these HXs in the Tokamak building. By using the original configuration for branch piping (18 inlet and 18 outlet), the need for reevaluating the heat transfer inside the VV is eliminated since flow direction and velocities will be exactly the same as those in the 2004 design. There are no pressure and temperature differentials across half-segment walls that could lead to additional stresses in this region. Additionally, this configuration eliminates the need for half-segment to half-segment jumpers that potentially would be difficult to locate because of space limitations in the lower region of the VV. This preferred configuration is summarized in the last row of Tables 1 and 2.

A secondary solution might be Alternative 3 discussed in PCR-190 with four changes.

1) Elimination of the safety loop
2) Insertion of a safety-rated HX cooled by the CHWS in series with the safety pump (both pump and HX in parallel with the main pump and HX)
3) Both safety and main HX outside of the VVPSS
4) Nine inlet and nine outlet branches connected to the VV with either jumpers or direct connection between VV half-segment walls

The logic for this configuration is very similar to the preferred configuration discussed above; however, because both inlet and outlet branch piping are located at the top of the VV, either jumpers would be required at the lower portion of the VV to connect adjacent half-segments or direct connection between the VV half-segments using holes in the internal VV walls.

CONCLUSIONS

An evaluation of three proposed alternative configurations of the VV PHTS has been completed. These alternatives were presented in PCR-190. Eleven factors were considered in this evaluation including the location of the main HX, the pressure drop through the VV, the safety classification of the VV cooling water system, coolant loss in the event of a pipe break, and the ease of draining and drying the system, as well as several others. Based on these considerations, a fourth configuration is proposed that incorporates several features of those discussed in PCR-190 with some additional modifications. These include a single VV primary coolant loop with HXs located in the Tokamak building, a small safety rated pump and HX that bypass the main pump and HX during accident events, and branch piping serving each VV half-segment. This configuration both simplifies the piping system and improves safety.

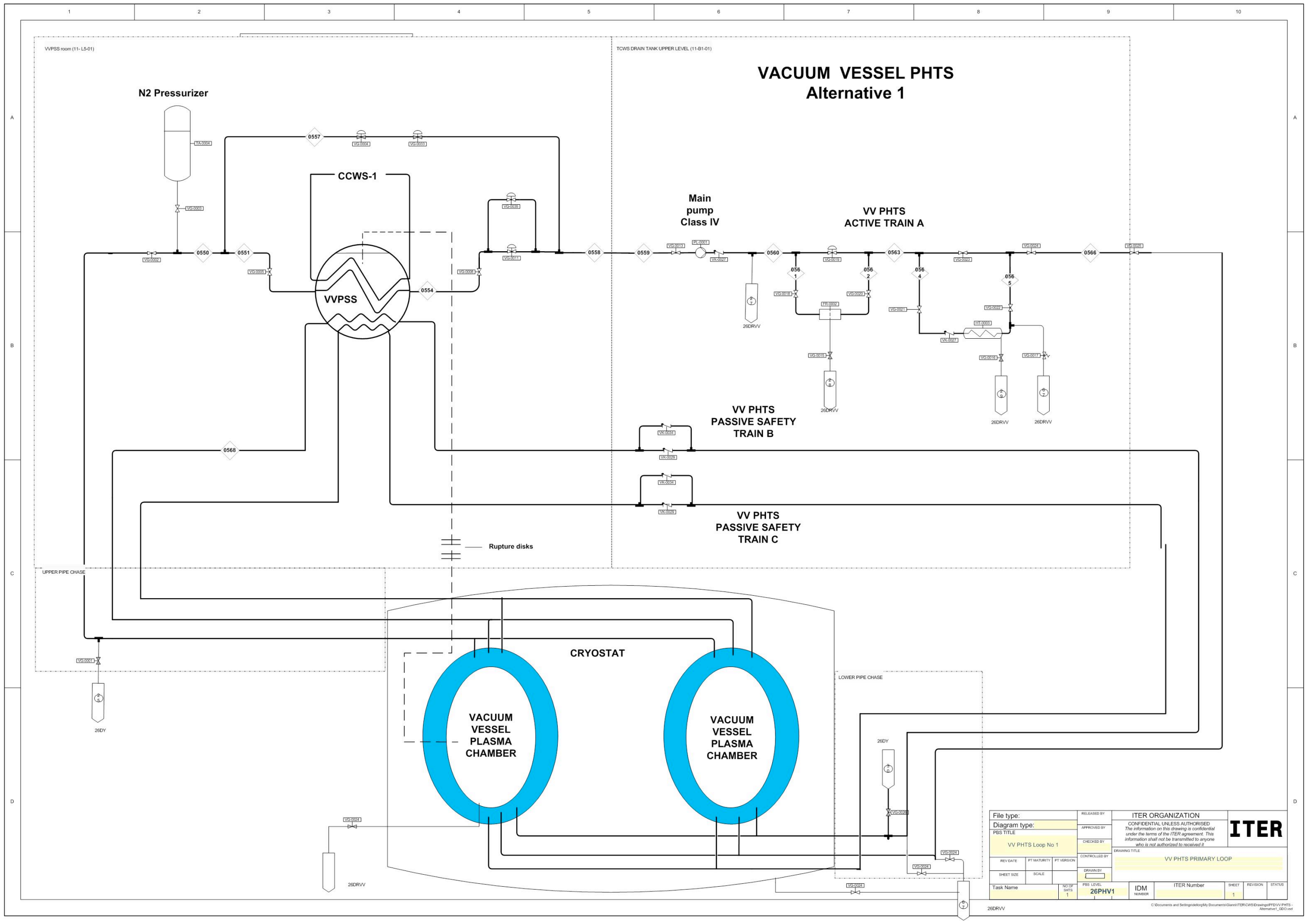

Fig. 1. Alternative 1 schematic – two safety loops.

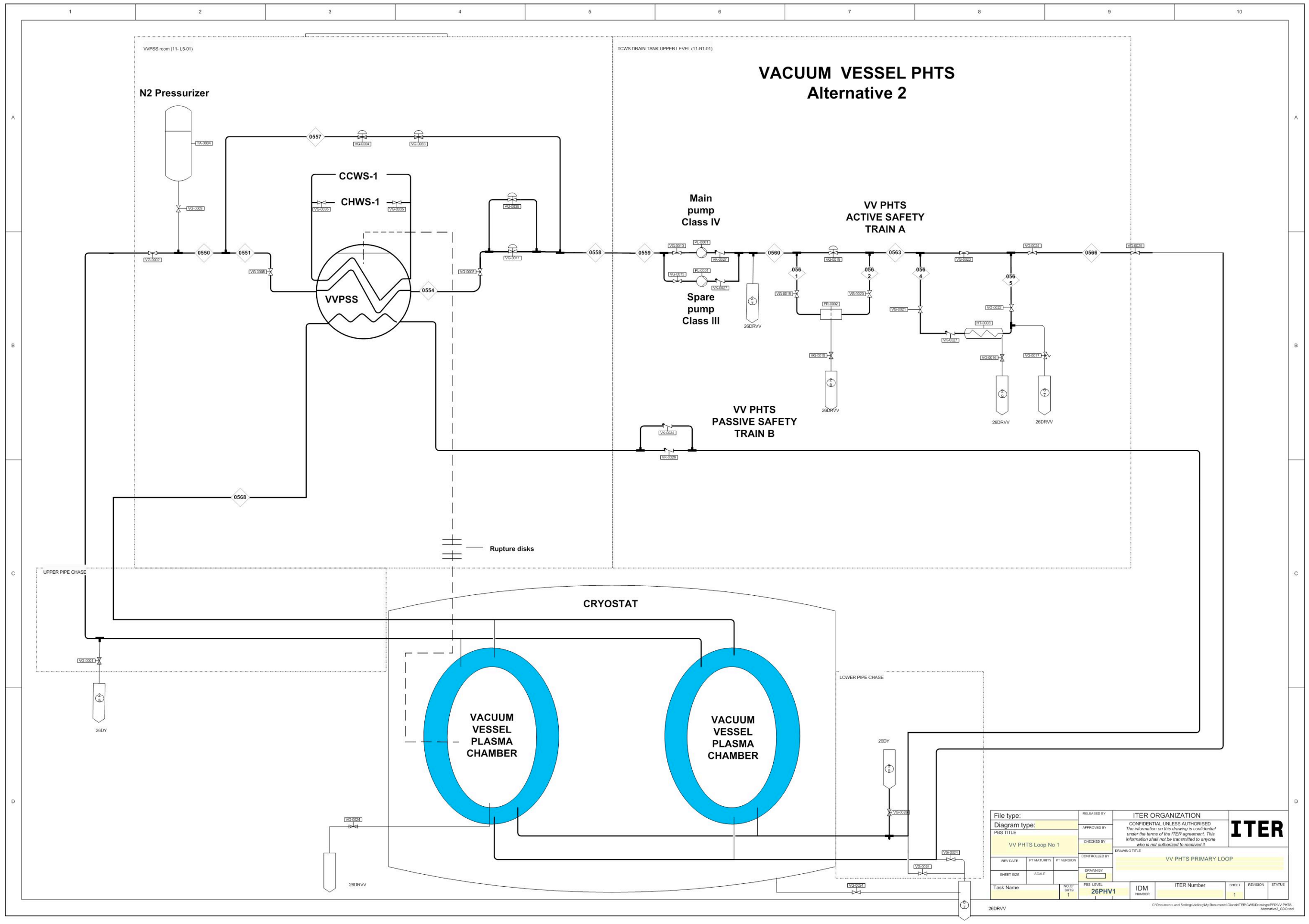

Fig. 2. Alternative 2 schematic – one safety loop.

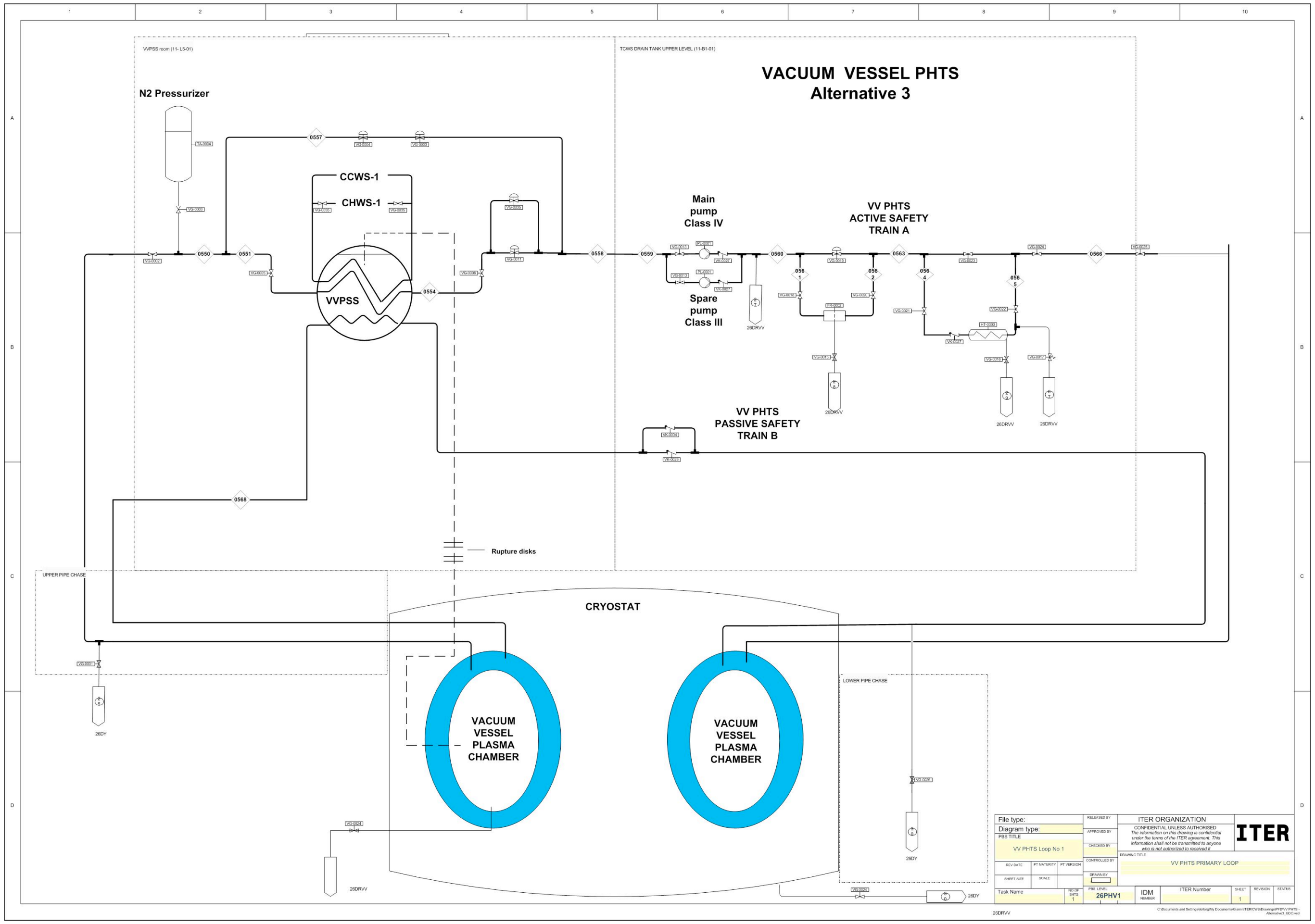

Fig. 3. Alternative 3 schematic – distributor and collector in upper pipe chase.

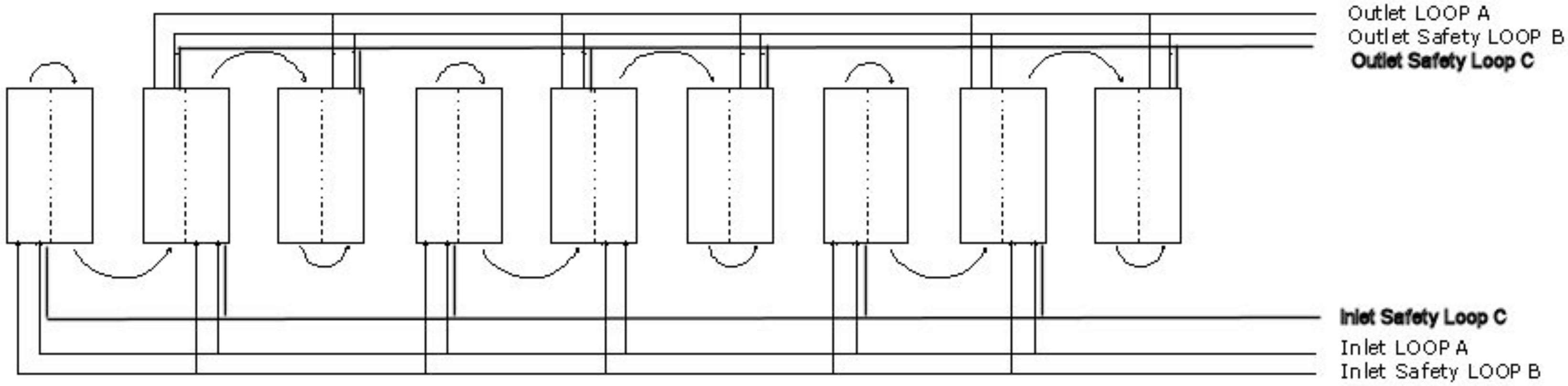

Fig. 4. Jumper configuration for Alterative 1.

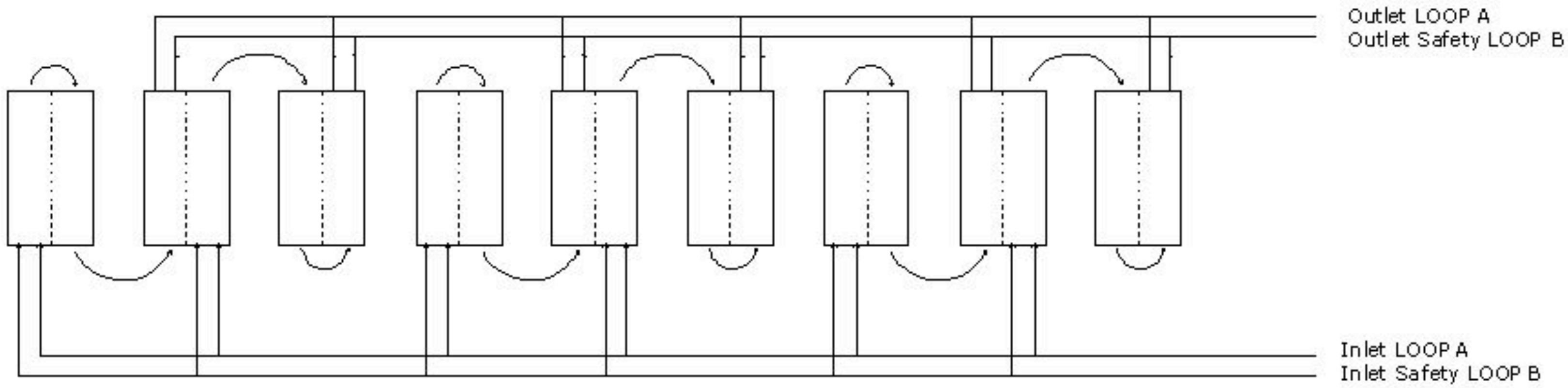

Fig. 5. Jumper configuration for Alternative 2.

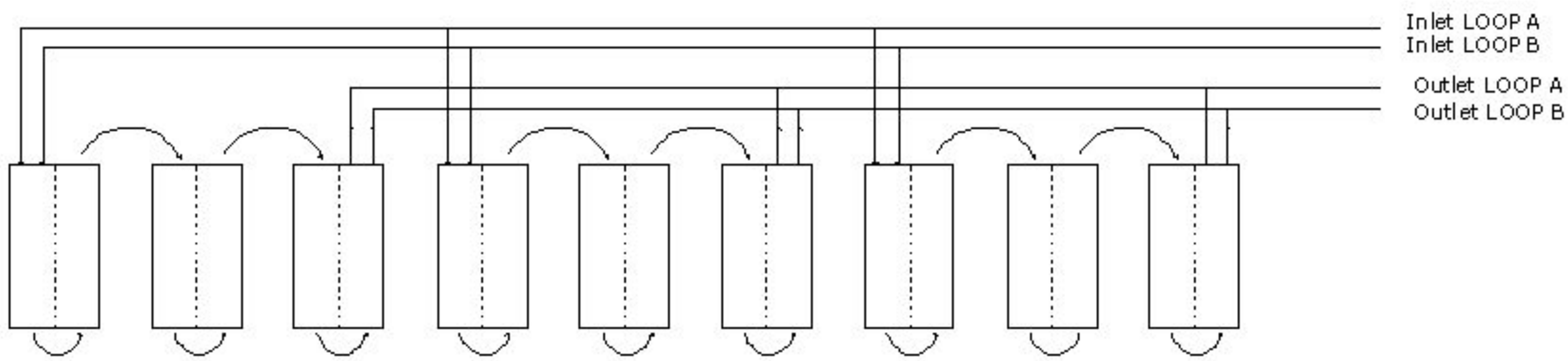

Fig. 6. Jumper configuration for Alternative 3.

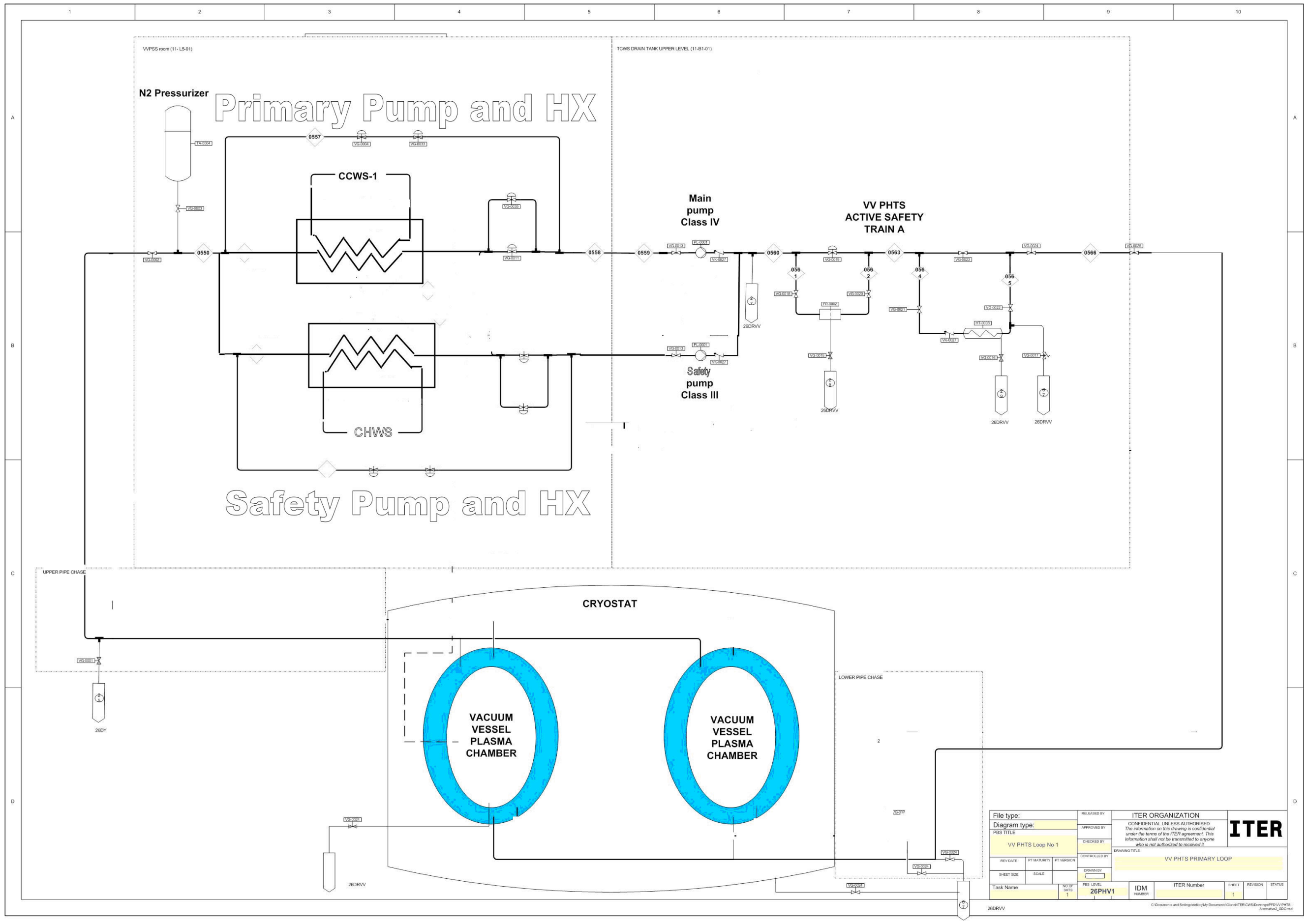

Fig. 7. Proposed configuration of VV PHTS.

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1. Giovanni Dell'Orco, *Optimization of the Vacuum Vessel (VV) Primary Heat Transfer System (PHTS)*, PCR-190, V2.6, August 2009.
2. Verbal communication, Jan Berry, U.S. ITER Cooling Systems, and Weil Taylor, ITER-IO, Safety Analysis and Assessment.
3. Burns and Roe, "Evaluate Vacuum Vessel PHTS Alternate Designs," Burns and Roe, ITER-RPT-005, April 2008.
4. L. Topilski, *Decay heat removal without active flow and natural circulation in the VV PHTS,* ITER_D_F67FP v 1.1, September 2009.
5. Juan Carbajo, et al., "Modeling and analysis of alternative concept of ITER vacuum vessel primary heat transfer system, ISFNT-9," Paper 06-014, ISFNT-9, Dalian, China, October 11–16, 2009.

APPENDIX A

QUALITATIVE EVALUATION OF VV COOLING SYSTEM OPTIONS OUTLINED IN PCR-190

Qualitative Evaluation of VV Cooling System Options Outlined in PCR-190

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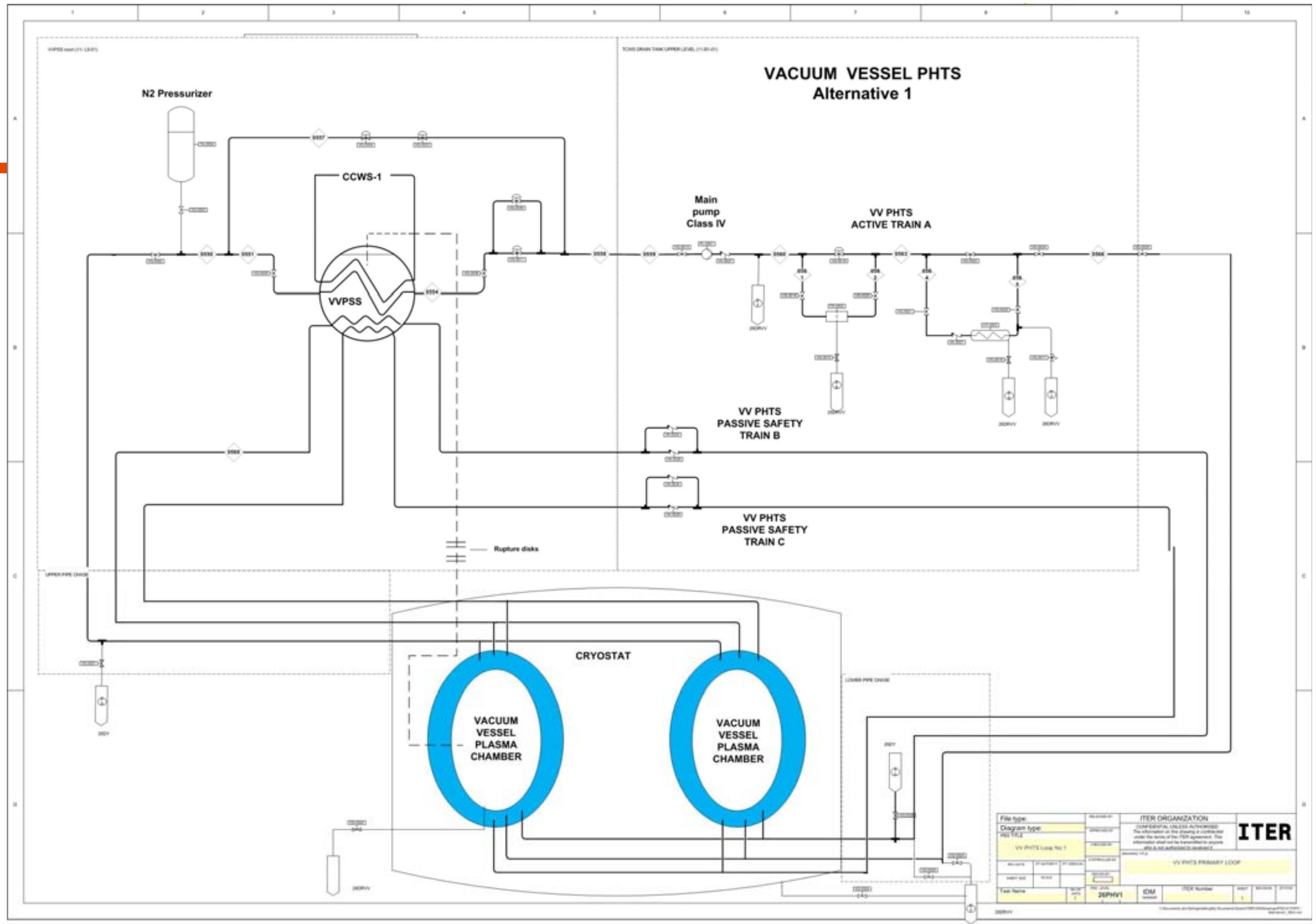
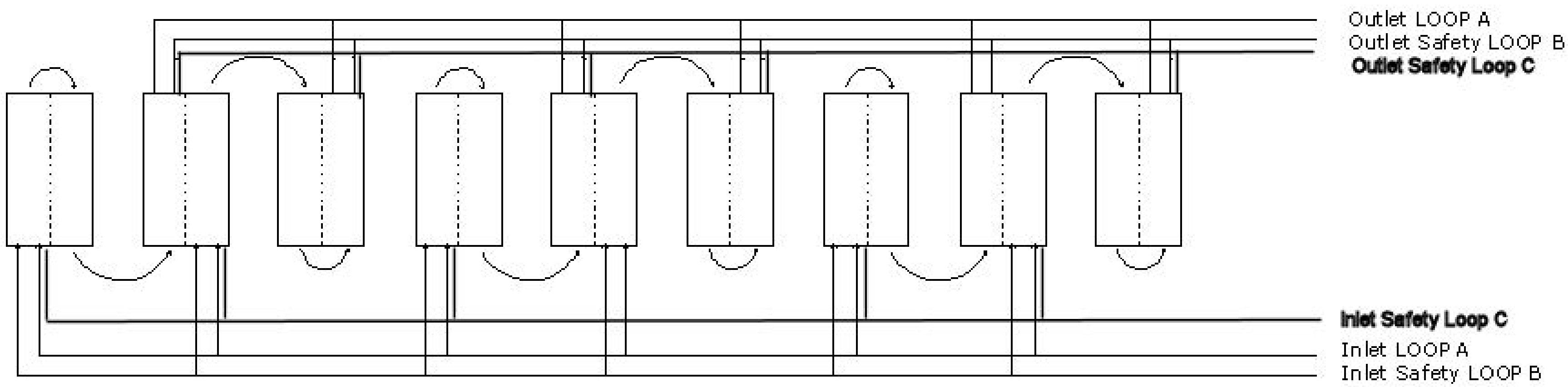
Alternative 1



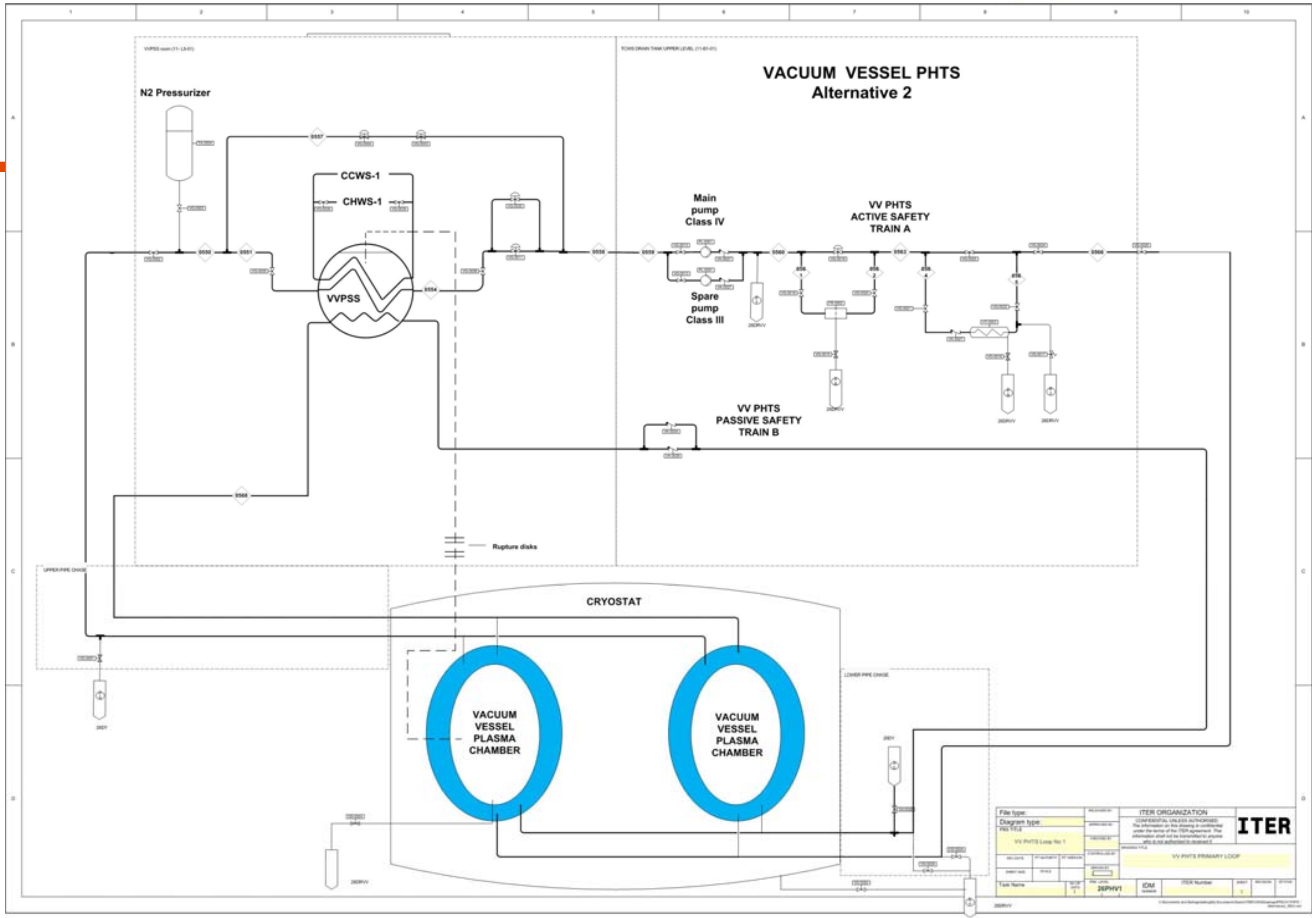
- 1 Primary FC cooling loop
- 2 NC safety loops
- Distribution header – lower pipe chase
- Collection header – upper pipe chase
- Inlet branches – bottom of VV (both primary and safety)
- Outlet branches – top of VV (both primary and safety)
- Safety pump parallel with primary pump
- 1 primary, 2 safety HXs in VVPSS tank

Alternative 1 Jumper System



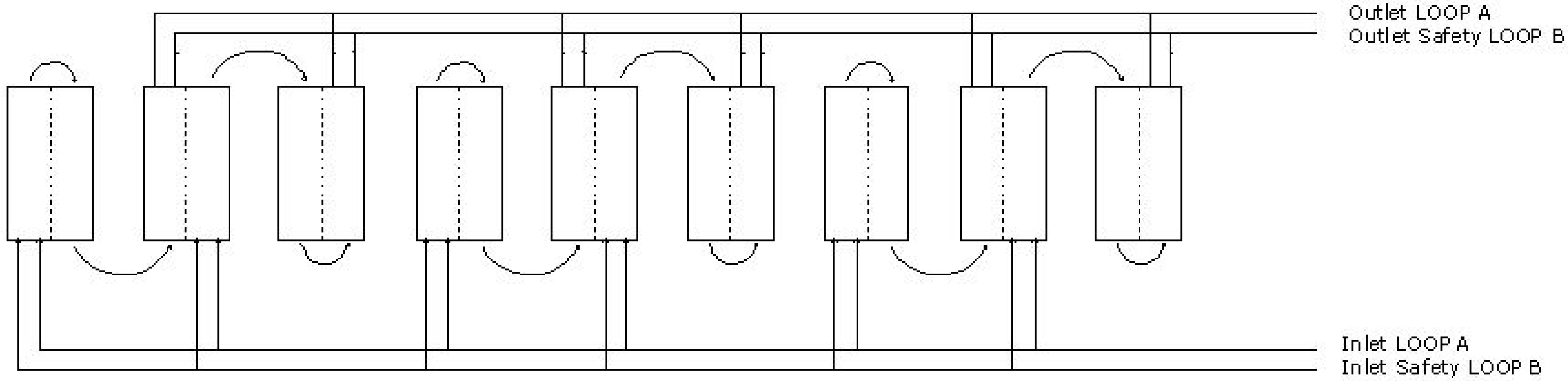
- Three 20° half-segments in series
- Primary and 2 safety loops in parallel
- 6 inlet branches – 6 outlet branches
- One top and one bottom jumper needed for each branch

Alternative 2



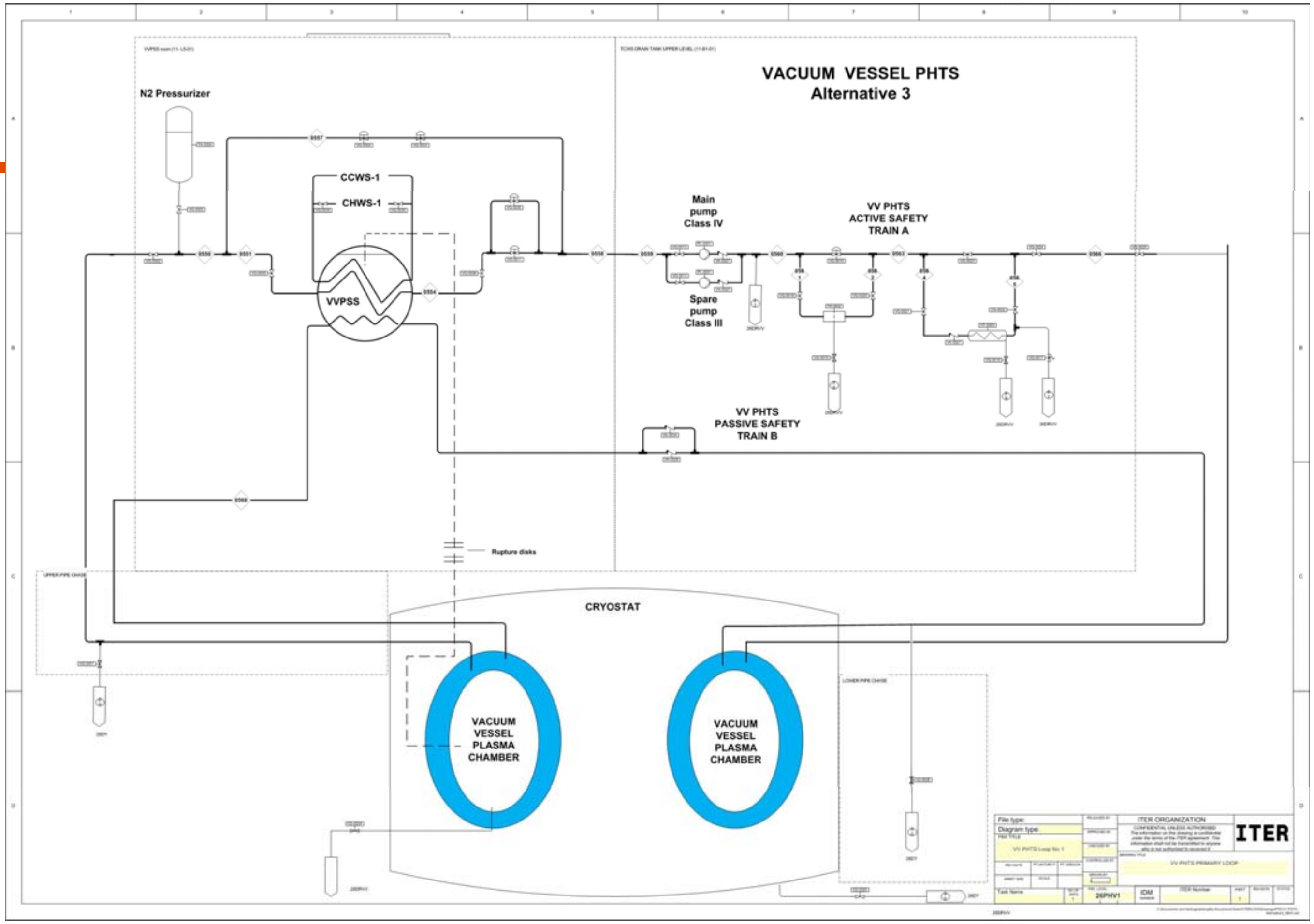
- 1 Primary FC cooling loop
- 1 NC safety loop
- Distribution header – lower pipe chase
- Collection header – upper pipe chase
- Inlet branches – bottom of VV (both primary and safety)
- Outlet branches – top of VV (both primary and safety)
- Safety pump parallel with primary pump
- 1 primary, 1 safety HX in VVPSS tank

Alternative 2 Jumper System



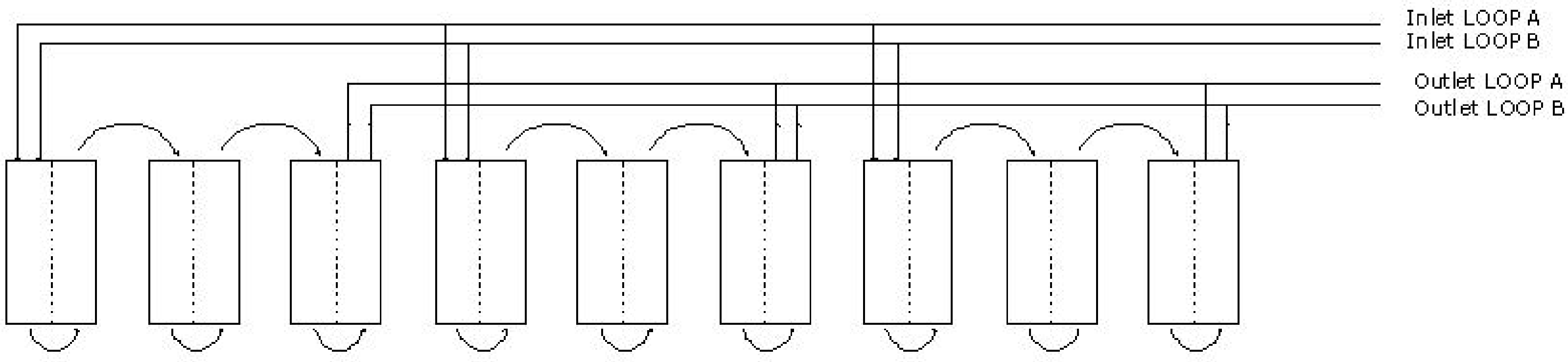
- Three 20^{o} half-segments in series
- Primary and 1 safety loops in parallel
- 6 inlet branches – 6 outlet branches
- One top and one bottom jumper needed for each branch

Alternative 3



- 1 Primary FC cooling loop
- 1 NC safety loop
- Distribution header – upper pipe chase
- Collection header – upper pipe chase
- Inlet branches – top of VV (both primary and safety)
- Outlet branches – top of VV (both primary and safety)
- Safety pump parallel with primary pump
- 1 primary, 1 safety HX in VVPSS tank

Alternative 3 Jumper System



- Six 20° half-segments in series
- Primary and 1 safety loops in parallel
- 3 inlet branches – 3 outlet branches
- Two top and three bottom jumpers needed for each branch

Discussion of Issues

(In no particular order)

Location of Primary and Safety Heat Exchange System

- Present HXs located on roof used for both primary cooling and safety cooling
  - Single confinement barrier
  - Subject to external events
- Solution
  - Move HX inside Tokamak building
- Issue
  - Location inside building
  - Configuration

Safety Classification of VV Cooling Water System

- Present function
  - Confinement of radioactive water
  - Provide passive cooling in loss of offsite power event
  - 2 independent loops used to provide redundancy
    - Present system does not really meet requirement for “independency” – piping for two systems are too close together
      - Common cause failure
      - Pipe whip from one could cause failure of other
- Safety group presently developing calculations to prove that VV water cooling is not required
  - Successful argument would eliminate safety classification for cooling

VV Pressure Drop —
Assuming Same Overall ΔT = 2^{o}C

- Existing VV
  - ΔP < 0.05 MPa
  - ΔT = 2^{o}C
  - Flow rate – 950 kg/s (2 loops)
  - Branch piping 18 in/18 out (100 mm)
- Alternative 1 & 2
  - Flow/20^o half-segment 18/6 =3 times higher
  - ΔP = 0.05 MPa X 3 X 3 X 3 = 0.05 X 27 = 1.35 MPa
- Alternative 3
  - Flow/20^o half-segment 18/3 = 6 times higher
  - ΔP = 0.05 MPa X 6 X 6 X 6 = 0.05 X 216 = 10.8 MPa
- ΔT must be permitted to increase (total loop flow decreased) if any of the alternatives are to be used

VV Pressure Drop —
Assuming Same Half-Segment Mass Flow

- Alternative 1 & 2
  - Mass flow through VV = 6/18 *950 kg/s = 317 kg/s
  - ΔT through VV = $2^{o}C \times 3 = 6^{o}C$
  - ΔP = 0.05 MPa X 3 = 0.15 MPa
- Alternative 3
  - Mass flow through VV = 3/18 *950 kg/s = 158 kg/s
  - ΔT through VV = $2^{o}C \times 6 = 12^{o}C$
  - ΔP = 0.05 MPa X 6 = 0.3 MPa

Coolant Loss in Case of Pipe Break

- Existing system
  - ½ VV coolant inventory lost
  - Water circulation in second ½ of VV
- Alternative 1 & 2
  - 1/3 of VV coolant inventory lost
  - No loop circulation
- Alternative 3
  - 0 VV coolant inventory lost
  - No loop circulation

Draining and Drying

- Existing system drains from bottom
- Alternatives 1 & 2
  - 3 segments jumpered in series
    - One can drain normally (gravity)
    - One can be drained by gas overpressure
    - The third must be drained by forced draining
- Alternative 3
  - 2 Segments jumpered in series
    - Both must be drained by forced draining
- Recommendation would be to include drains in lower jumpers for Alternatives

Natural Circulation Capability

- Existing system designed to perform under natural circulation conditions (safety)
  - Forced circulation is upward through VV – natural circulation same direction as forced circulation
- Alternatives 1 & 2
  - Inlet and outlet safety lines at bottom and top of VV respectively – NC possible
  - 3 half-segments jumpered in series
    - 2nd half-segment is in downflow
      - Flow direction is against gravity
      - Could lead to internal flow patterns under NC conditions
- Alternative 3
  - Inlet and out safety lines both at top of VV – no clear direction for NC
- If 40 kg/s is safety flow requirement, NC will not be able to achieve this value (12–15 kg/s appears to be max)
- Conclusion – Small safety rated forced circulation pump needed

In-Vessel Cooling

- Existing system – all half-segment flows in upward direction
- All alternatives – some half-segments in downflow
  - Against gravity
- Since flows are low in VV (large flow areas), buoyancy may be important even under forced convection conditions
- Re-evaluation of VV internal heat transfer may be required

Segment-to-Segment ΔP and ΔT

- Existing Segment-to-Segment ΔP and ΔT are 0
- In alternatives half-segment cooling is in series
  - Segment-to-Segment ΔP and ΔT > 0
  - If coolant temperature rise from inlet to outlet of VV is not changed
    - Alternatives 1 & 2
      - $\Delta P_s = 2 \times 3 \times 3 \times 0.05$ MPa = 0.9 MPa
      - $\Delta T_s = 2^oC/3 \times 2 = 1.33^oC$
    - Alternative 3
      - $\Delta P_s = 2 \times 6 \times 6 \times 0.05$ MPa = 3.6 MPa
      - $\Delta T_s = 2^oC/6 \times 2 = 0.67^oC$

Heat Exchanger Location Inside Tokamak Building

- PCR-190 shows HXs in VVPSS
  - VVPSS water can act as emergency heat sink
- VVPSS water
  - 4.2 kPa pressure
  - Only 2^{o}C of subcooling (28^{o}C)
- When removing decay heat
  - VVPSS water reaches saturation within ~ 8 hours
  - Boiling occurs beyond this point if VVPSS pressures are not allowed rise
  - If pressures are allowed to rise (i.e., isolate VVPSS), VVPSS pressures rise to ~8.4 kPa and 42^{o}C after 72 hours
- Since these conditions are not tenable from the standpoint of providing an effective relief path for the plasma chamber then the HXs need to be located outside the VVPSS

Jumpers and Branch Piping

- The existing design has no jumpers
- All Alternatives have jumpers
  - If no room exists to install lower jumpers, then:
    - Alternatives 1 & 2 are viable only if existing branch piping design is used: 18 inlet and 18 outlet
    - Alternative 3 would not be possible

Tables 1 & 2 Summarize this Information

Table 1. Comparison of two alternatives and existing design

Version	Main HX cooling	Number of forced circulation (FC) loops	Number of FC HX (location)	Major piping diameter	Mass flow in branch (kg/s)	VV pressure drop (MPa) {relative}	Segment-to-segment ΔT (2°C overall)	Segment-to-Segment ΔP (normal operation – same mass flow)
Existing	Air	2	2 (roof)	14”	950/18=53	0.05 {1}	0	0
Alternate 1	Water	1	1 (VVPSS)	20”	950/6=158	1.35 {27}	1.33	18 X existing segment ΔP
Alternate 2	Water	1	1 (VVPSS)	20”	950/6=158	1.35 {27}	1.33	18 X existing segment ΔP
Alternate 3	Water	1	1 (VVPSS)	20”	950/3=317	10.8 {216}	0.67	72 X existing segment ΔP

Version	VV pressure drop (MPa) assuming the same half-segment flow rate {relative}	ΔT (°C) (overall/segment-to-segment) (assuming the same half-segment flow rate)	Segment-to-Segment ΔP (MPa) (normal operation – same half-segment mass flow)	Number of emergency loops	Number of NC HX	Segment Jumpers needed (#)	How much coolant is lost in pipe break event?	Reevaluation of in vessel cooling required?
Existing	0.05 {1}	2/0	0	0	NC in FC piping	No	1/2	No
Alternate 1	0.15 {3}	6/4	0.1	2	2	Yes (12)	1/3	Yes
Alternate 2	0.15 {3}	6/4	0.1	1	1	Yes (12)	1/3	Yes
Alternate 3	0.3 {6}	12/4	0.1	1	1	Yes (15)	0	Yes

Tables 1 & 2 Summarize this Information (cont'd)

Table 1. Comparison of two alternatives and existing design (cont'd)

Version	Number of FC HX	Scaled branch piping dia.	# branch pipes required
Existing	2	1	18 in – 18 out
Alternate 1	1	√3	6 in – 6 out
Alternate 2	1	√3	6 in – 6 out
Alternate 3	1	√6	3 in – 3 out

Tables 1 & 2 Summarize this Information

Table 2. Compared to existing design

Version	NC performance	Distribution/collector reconfiguration	Normal pumping power requirements (same mass flow)	FC cooling capability (same mass flow)	Emergency cooling pump required	Branch piping complexity	Number of welds
Alternate 1	Worse	~same	> existing	More difficult	?	< existing	< existing
Alternate 2	Worse	~ same	> existing	More difficult	?	< existing	< existing
Alternate 3	Not possible	More difficult	>> existing	More difficult	yes	<< existing	<< existing

Version	Normal FC HX size (total area)	Draining	Cost
Alternate 1	< existing	Worse	?
Alternate 2	< existing	Worse	?
Alternate 3	< existing	Worse	?

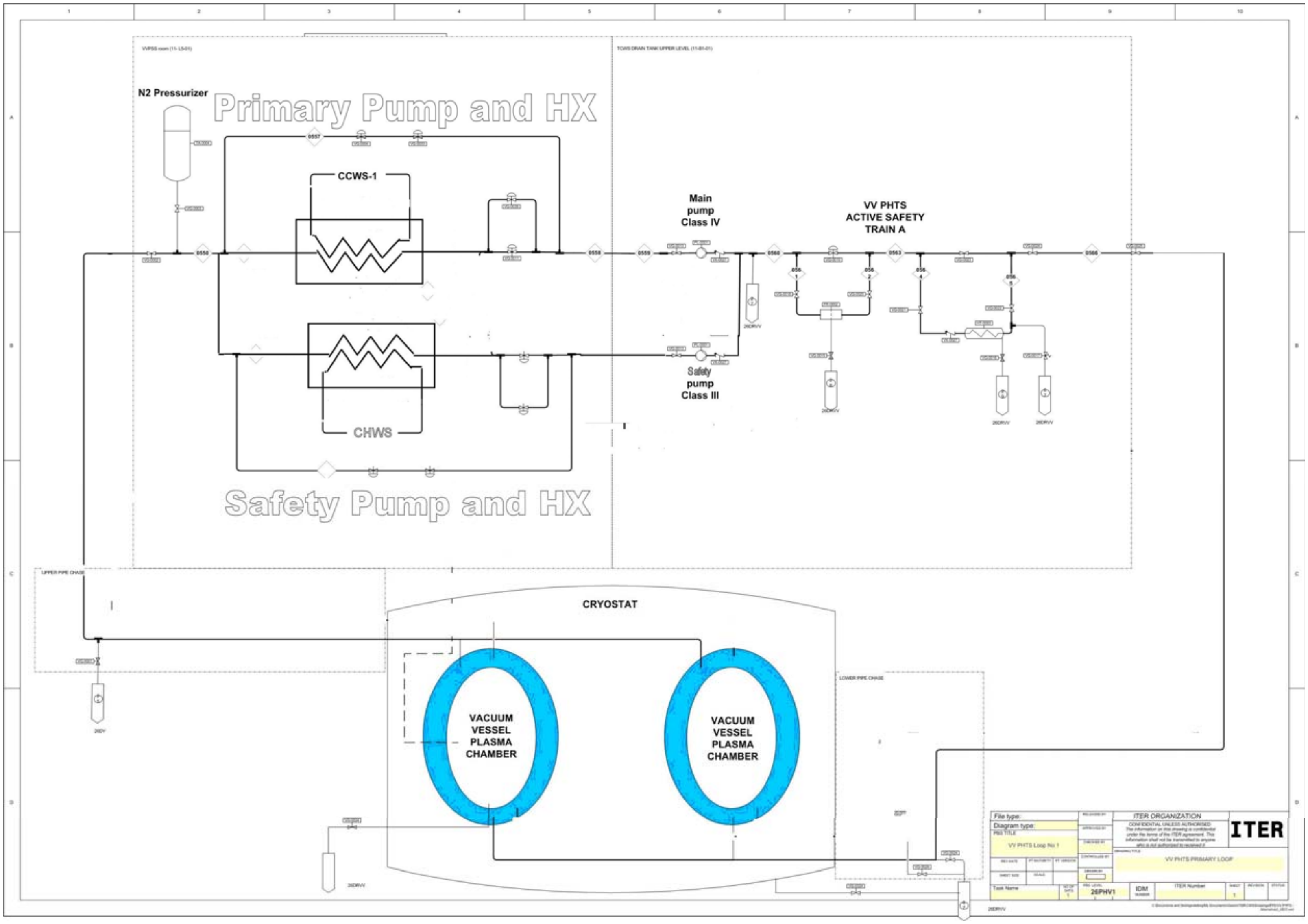
Conclusions

- Common cause failure arguments imply that multiple loops do not serve to add to the overall safety of the system
  - Alternatives 1 and 2 are essentially equivalent
- Calculations indicate that NC cooling does not meet the 40 kg/s flow requirement for safety cooling
  - A pumped safety system will be required to meet this criteria
    - HXs not required to be at a high elevation
  - A separate safety loop can be eliminated by maintaining the small pump in parallel to the main pump and including a heat exchanger in that bypass loop - both safety class
    - CHWS coolant to be used on the secondary side
- Both main and safety heat exchangers should be located outside the VVPSS system in order to avoid boiling or high pressures in the VVPSS tank
- Because of significant pressure drops introduced through the VV for all alternatives when a 2^{o}C temperature criteria is met, this requirement must be either relaxed or:
  - For Alternatives 1 & 2, the branch piping needs to revert to the present configuration 18 inlets and 18 outlets.
  - For Alternative 3, 9 inlets and 9 outlets would be preferred

Preferred Solution

- Alternative 2 as in PCR-190 with 4 changes
  - Elimination of the separate safety loop
  - Safety rated heat exchanger in series with the safety pump
  - Both safety and main heat exchangers outside the VVPSS
  - 18 inlet and 18 outlet branches – no jumpers

Proposed Configuration



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