3.3 Cooling Water

3.3.1 Overview of the Cooling Water System

The cooling water system (CWS) consists of the tokamak cooling water system (TCWS), the component cooling water system (CCWS), the chilled water system (CHWS), and the heat rejection system (HRS).

The main drivers of the CWS design are cost reduction, segmentation and standardisation of the in-vessel components, facilitation of installation and maintenance, staged procurement, and acceptable impact on the building of pressure loading following an ex-vessel coolant leak.

The TCWS consists of the primary heat transfer systems (PHTSs) and their supporting systems, i.e. the chemical and volume control systems (CVCSs), the draining and refilling systems, and the drying system. The schematic flow diagram of the CWS is shown in Figure 3.3.1-1. The PHTSs are the:

a) vacuum vessel (VV) PHTS;
b) primary first wall/blanket (PFW/BLK) PHTS;
c) divertor/limiter (DIV/LIM) PHTS;
d) NB injector PHTS.

The systems a) – c) cool components inside the VV, and the vessel itself. The system d) (low and high voltage) serves the NB injectors installed at VV ports. The systems b) to d) are sometimes referred to as "in-vessel" PHTSs.

The schematic pipe routing of PHTSs is shown in Figure 3.3.1-2. The upper and lower pipe-chases are located above the upper port level and below the divertor port level respectively, and are interconnected by vertical shafts. Three pairs of inlet/outlet C-shaped manifolds of the PFW/BLK PHTS, two outlet C-shaped manifolds of the VV PHTS and inlet/outlet pipes for the NB cell are located in the upper pipe chase, and one pair of the inlet and outlet C-shaped manifolds of the DIV/LIM PHTS and two inlet C-shaped manifolds of the VV PHTS are located in the lower pipe chase. The east side of the upper pipe chase is integrated with the TCWS vault of the tokamak building, and it is vertically separated by a mezzanine floor.

The main loop components of the PHTSs, except for the VV PHTS, are sited in the upper area of the rectangular TCWS vault above the magnet and CVCS levels, and the components of the CVCSs are sited in the lower TCWS vault area at the magnet and CVCS level. The HRS pipes which serve PHTSs are routed below the mezzanine floor.

The closed volume formed by the pipe chases, vertical shafts, the NB cell, the TCWS vault, the TCWS vault extension, and the area for the CVCSs, constitutes a secondary confinement boundary for an ex-vessel coolant leak as shown in Figure 3.3.1-2.

The main components for the VV PHTS are located on the tokamak building roofs on the east and west sides, and at the divertor level in the drain tank area.

The components of the TCWS are based on fission power plant experience, and no difficulties are expected in their commercial availability. The same holds for the CCWS, the CHWS and the HRS. The layout of the TCWS components and the pipework is a standardised configuration for modularised installation and minimisation of impact by the magnetic field on the components. The layout agrees with the footprint allowed in the building design and with the safety strategy regarding the ability of the TCWS vault to withstand 0.2 MPa mixed steam/air peak overpressure following a large pipe break during operation.

From a cost and maintenance point of view, the number of PHTS loops should be reduced as much as possible. This also aids in minimising radiation exposure of maintenance workers, which is an ALARA requirement. However, a reduction in the number of loops increases the coolant inventory per loop and consequently also the peak pressure experienced in the containment vault during a postulated ex-vessel coolant leak. As a result, the pressure retention and leak tightness requirements, and hence the building costs, increase. The optimisation is therefore a trade off between these variables. The segmentation adopted is based on the premise that a containment volume with a pressure-bearing capacity of not exceeding 0.2 MPa would be feasible and cost effective. The full containment of the pressure has been adopted for postulated ex-vessel coolant leaks during plasma operation. This leads to three loops for the PFW/BLK PHTS and one for the DIV/LIM PHTS.

The peak pressures in the building vault have been estimated tentatively by simplified calculation and ~ the results showed that a large ex-vessel leak during plasma operation generates a peak pressure of ~ 0.17 MPa. Using more refined analysis with the MELCOR code, a peak pressure of 0.141 MPa was obtained. During baking, a peak pressure of 0.17 MPa would be obtained in the case of a small ex-vessel coolant leak (LBB case). However, the limit of 0.2 MPa would be exceeded in the case of a large leak. Therefore, for this event, the ITER strategy is based on the adoption of the LBB philosophy. Added to this, an engineered pressure relief system is provided that will open if the peak vault pressure exceeds 0.2 MPa and it will reseal at ~ 0.2 MPa under a hypothetical double-ended guillotine break during baking.

Tritium permeation into coolant loops is calculated to be very low. Latest test data and numerical calculations have given enhanced confidence that, in combination with an efficient coolant chemistry control and purification system, the concentration of activated corrosion products (ACPs) will be continuously kept at very low levels. The levels of tritium and ACPs in the coolant are monitored to ensure they are within safety limits, and the possibility of an additional communication with the detritiation system is allowed for in the design in case it is needed.

The CCWS removes heat from large process components which do not become activated. The CCWS transports heat from the components to the HRS, which is the ultimate heat sink. The system provides high quality cooling water where necessary for components with sensitive water chemistry needs. The maximum temperature of the CCWS feed water is basically 40°C. Loops in the CCWS for some of the power supply components, which require temperatures lower than 35°C, are served by the CHWS.

The CHWS services components and loops in the CCWS which require coolant temperatures lower than can be provided by the normal CCWS and HRS. The CHWS utilizes industrial chiller units to provide cooling water at 6°C with a return temperature of 12°C. The CHWS has separate loops for "safety-related" circuits (to the vault, hot cell and tritium plant) which may need to confine radioactivity.

The HRS is the final heat sink and uses cooling towers to reject heat to the environment. The HRS includes water circulation systems (WCSs) for the TCWS, the cryoplant warm compressors, the CCWS, and the CHWS. The safety-related CHWS circuits reject heat to separate dry cooling towers which form a separate part of the HRS.

The CCWS, the CHWS and WCSs in the HRS are zoned as shown in Figure 3.3.3-1, and the components for each zone are sited in the buildings in each zone and connected to pump stations outside the buildings. The pipework interconnecting the cooling tower, pump stations of WCSs and the buildings are routed inside service tunnels and trenches.

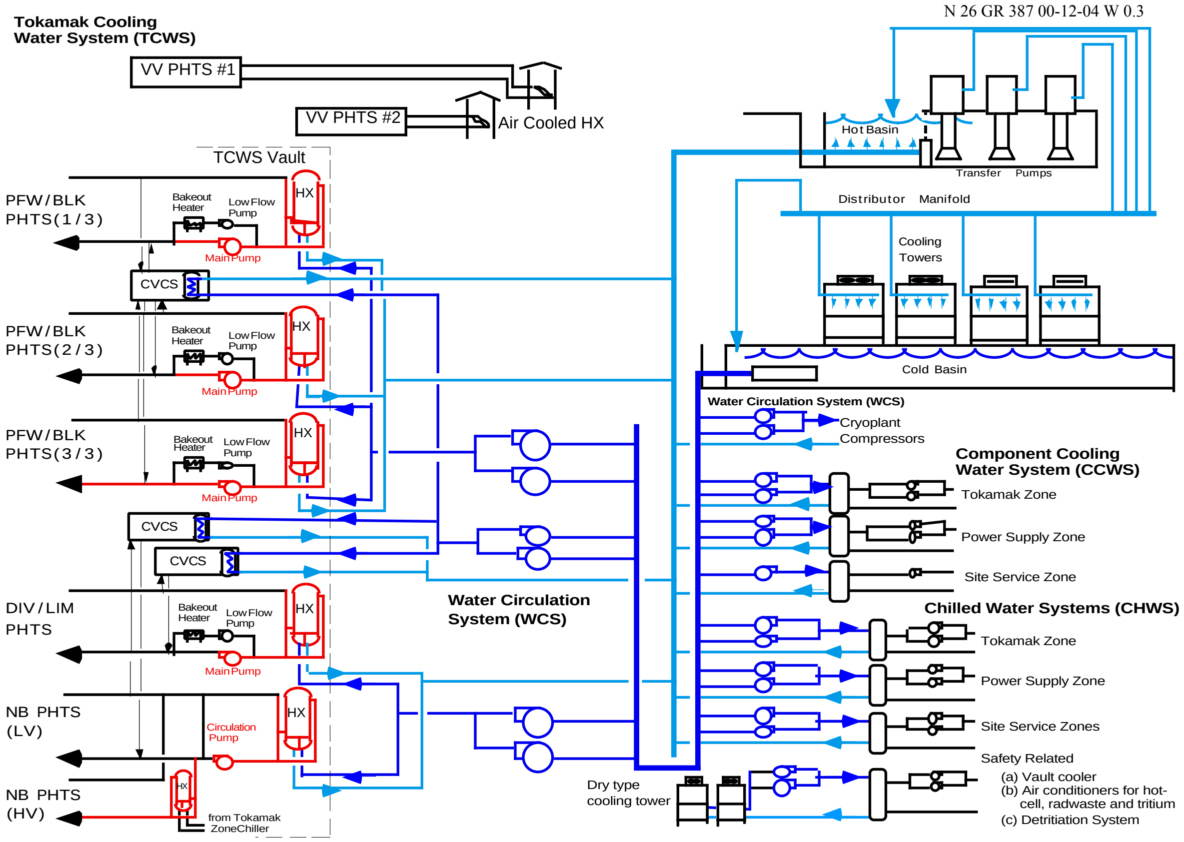

Figure 3.3.1-1 Schematic Flow Diagram of the Cooling Water System

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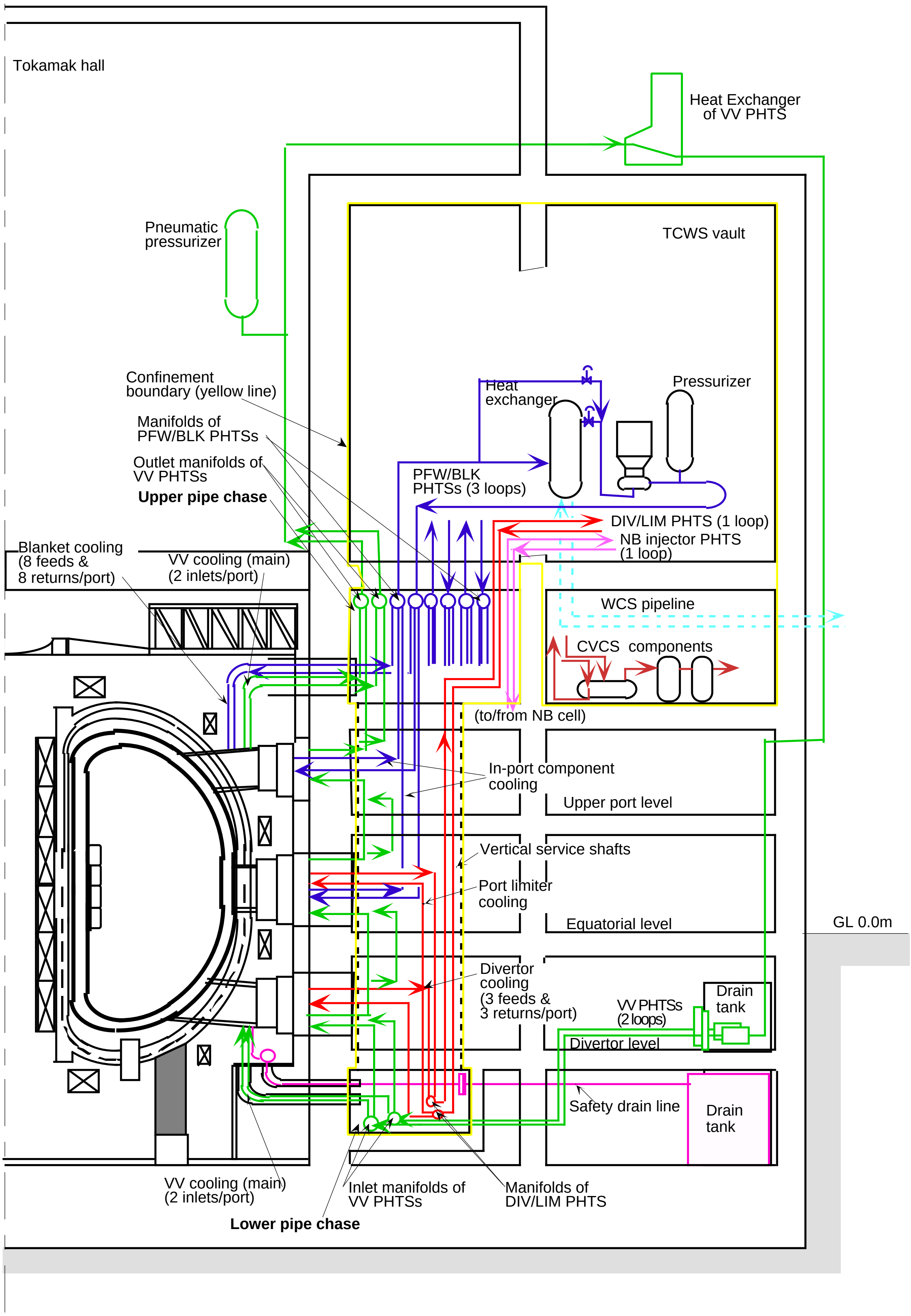

Figure 3.3.1-2 Concept of PHTS pipe routing

3.3.2 Functions of the Cooling Water System

The CWS has the following functions.

(1) TCWS

- remove the heat deposited in the in-vessel components and VV during a plasma pulse to the HRS by way of the WCSs, or directly to air;
- control the coolant temperature, flow rate and pressure for the in-vessel components and VV during normal operation as required;
- remove decay heat from the in-vessel components and the VV after plasma shutdown;
- provide the ability to bake the in-vessel components and the VV;
- provide safe confinement of the radioactive inventory of the coolant;
- confine radioactive materials from the tokamak following any failure of in-vessel component boundaries;
- measure the heat removed from the in-vessel components and VV to contribute to the determination of the overall fusion power balance;
- control the water chemistry in the in-vessel components and VV;
- allow in-vessel components to be isolated to facilitate leak localisation.

(2) CCWS

- remove the heat from components to the CHWS or to the HRS;
- control the coolant temperature, flow rate and pressure for the components as required;
- control the water chemistry in the components.

(3) CHWS

- provide low temperature coolant for the components;
- remove the heat from components to the HRS.

(4) HRS

- provide HRS coolant for the TCWS, CCWS and CHWS;
- remove the heat from the TCWS, CCWS and CHWS, and release it to the environment.

3.3.3 System Description

3.3.3.1 Tokamak Cooling Water System (TCWS)

3.3.3.1.1 PFW/BLK PHTS

The PFW/BLK PHTS is divided into 3 loops. Each of these loops supplies coolant to the blanket modules in three 40° sectors, three sectors apart. This cooling system also supplies coolant to the in-port components inside the equatorial and the upper ports.

All of the ~~16~~ 32 cooling water pipes from each adjacent pair of upper ports, 8 feeds and 8 returns for each upper port, that pass through the cryostat vacuum are integrated into one pipe bundle, and connected to the C shaped manifolds in the upper pipe chase. The pipe bundles at the cryostat penetration are contained within a guard pipe of approximately 1.4 m diameter that connects the cryostat and the biological shield wall.

The main data for the PFW/BLK PHTS are listed in Table 3.3.3-1 and a flow diagram for the PFW/BLK PHTS is shown in Figure 3.3.3-1. The loop is pressurised by a steam pressuriser connected to the cold leg. The heater is used to maintain coolant inlet temperature during baking.

Table 3.3.3-1 Main Data for the PFW/BLK PHTS

	Normal Operation	Baking
Thermal Power/Loop	230 MW	-
Coolant Inlet Temp.	100°C	240°C
Coolant Outlet Temp.	148°C	~240°C
Coolant Pressure at Inlet	3 MPa	4.4 MPa
In-Vessel Pressure Drop	1.0 MPa	~0.01 MPa
In-Vessel Water Holdup/Loop	~ 28 m^3	
Loop Number	3	
Flow Rate/Loop	1,130 kg /s	120 kg/s
Loop Pipe Inside Diameter(*1)	0.514 m	
Pressure Drop(*2)	2.0 MPa	0.1 MPa
Total Water Holdup/Loop	~ 130 m^3	
Pump - Pumping Power/Loop	Main pump 3,660 kW	Low flow pump 25 kW
Heat Exchanger - Exchange Heat - Heat Transfer Surface Area	234 MW 2,710 m^2 /unit	
Pressurizer Size	16.5 m^3	
Heater	~ 1,400 kW	

(*1) Coolant velocity = approx. 6 m/s
(*2) Total pressure drop including in-vessel components, heat exchanger and piping

The low flow pumps are also used for maintaining coolant circulation during long shutdown periods, for good chemistry control of the coolant throughout the loop. During loss of off-site power or loss of flow in category II events, the small pump units are automatically switched to class III power to remove decay heat for investment protection.

3.3.3.1.2 DIV/LIM PHTS

There is one DIV/LIM PHTS loop and it provides the primary coolant to 54 divertor cassettes as well as 2 port limiters. The main PHTS parameters are given in Table 3.3.3-2, and a flow diagram is shown in Figure 3.3.3-2. The loop layout, temperature control, and other characteristics are almost identical to that of the PFW/BLK PHTS loops.

The feed and return pipes to the divertor cassettes penetrate the cryostat inside the divertor ports, where they are routed, six per port, through the upper part of the ports. Outside the ports, the cooling pipes are individually routed from/to the C shaped manifolds in the lower pipe chase and finally to the TCWS vault via a vertical shaft.

Table 3.3.3-2 Main Data for the DIV/LIM PHTS

	Normal Operation	Baking
Thermal Power/Loop	202 MW (at flat-top)	-
Coolant Inlet Temp.	100°C	240°C
Coolant Outlet Temp.	150°C (for DIV) 128°C (for LIM)	~ 240°C (for DIV) ~ 240°C (for LIM)
Coolant Pressure	4.2 MPa	4.4 MPa
In-Vessel Pressure Drop	1.6 MPa	~ 0.02 MPa
In-Vessel Water Holdup/Loop	~ 23 m^3	
Loop Number	1	
Flow Rate/Loop	1,000 kg/s	100 kg/s
Loop Pipe Inside Diameter(*1)	0.514 m	
Pressure Drop(*2)	2.3 MPa	~ 0.1 MPa
Total Water Holdup/Loop	~ 145 m^3	
Pump - Pumping Power/Loop	Main pump 3,670 kW	Low flow pump 19 kW
Heat Exchanger - Exchange Heat - Heat Transfer Surface Area	206 MW 2,410 m^2 / loop	
Pressurizer Size	23.0 m^3	
Heater	1,600 kW	

(*1) Coolant velocity = approx. 6 m/s
(*2) Total pressure drop including in-vessel components, heat exchanger and piping

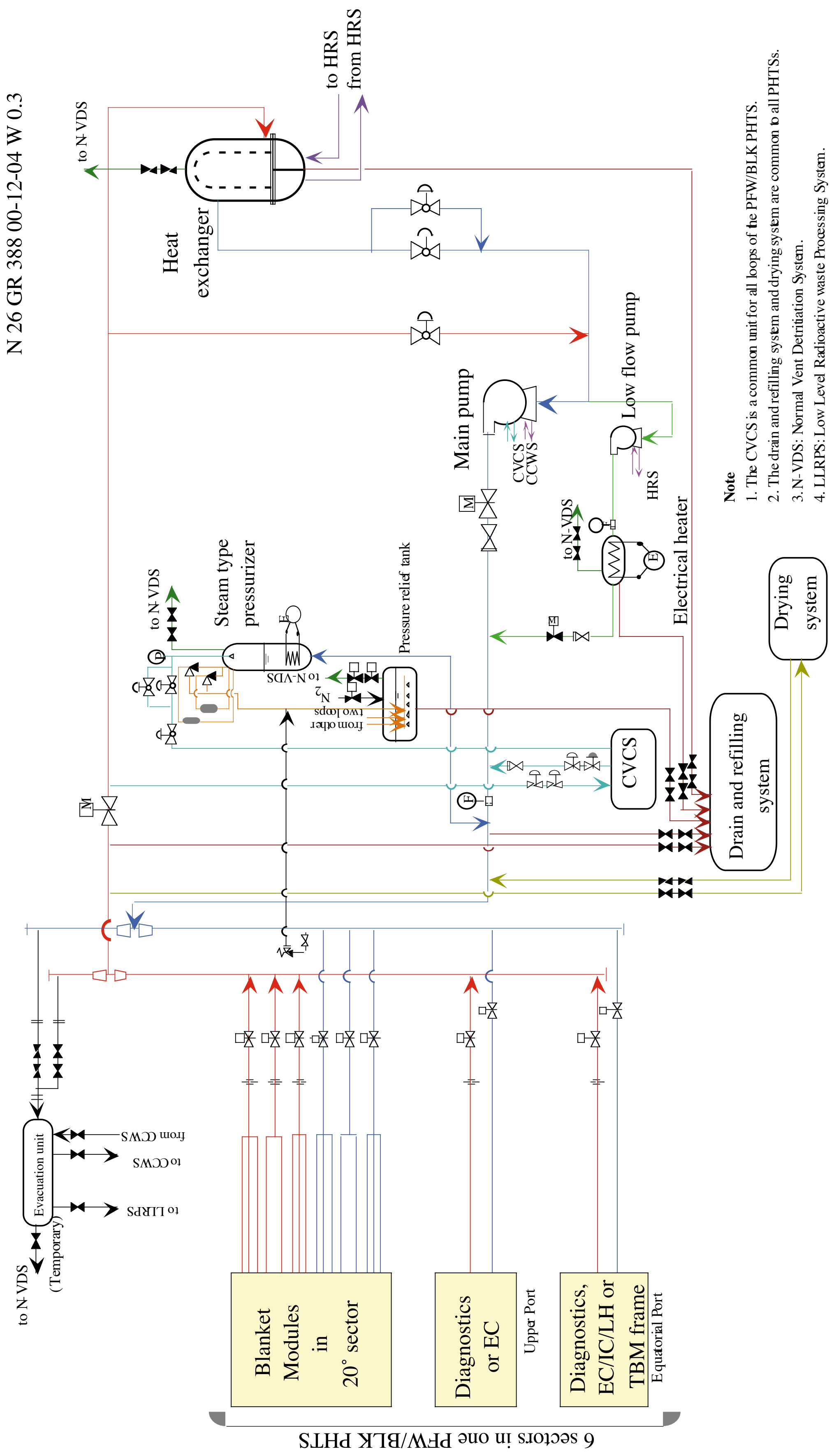

Figure 3.3.3-1 Flow Diagram of the PFW/BLK PHTS

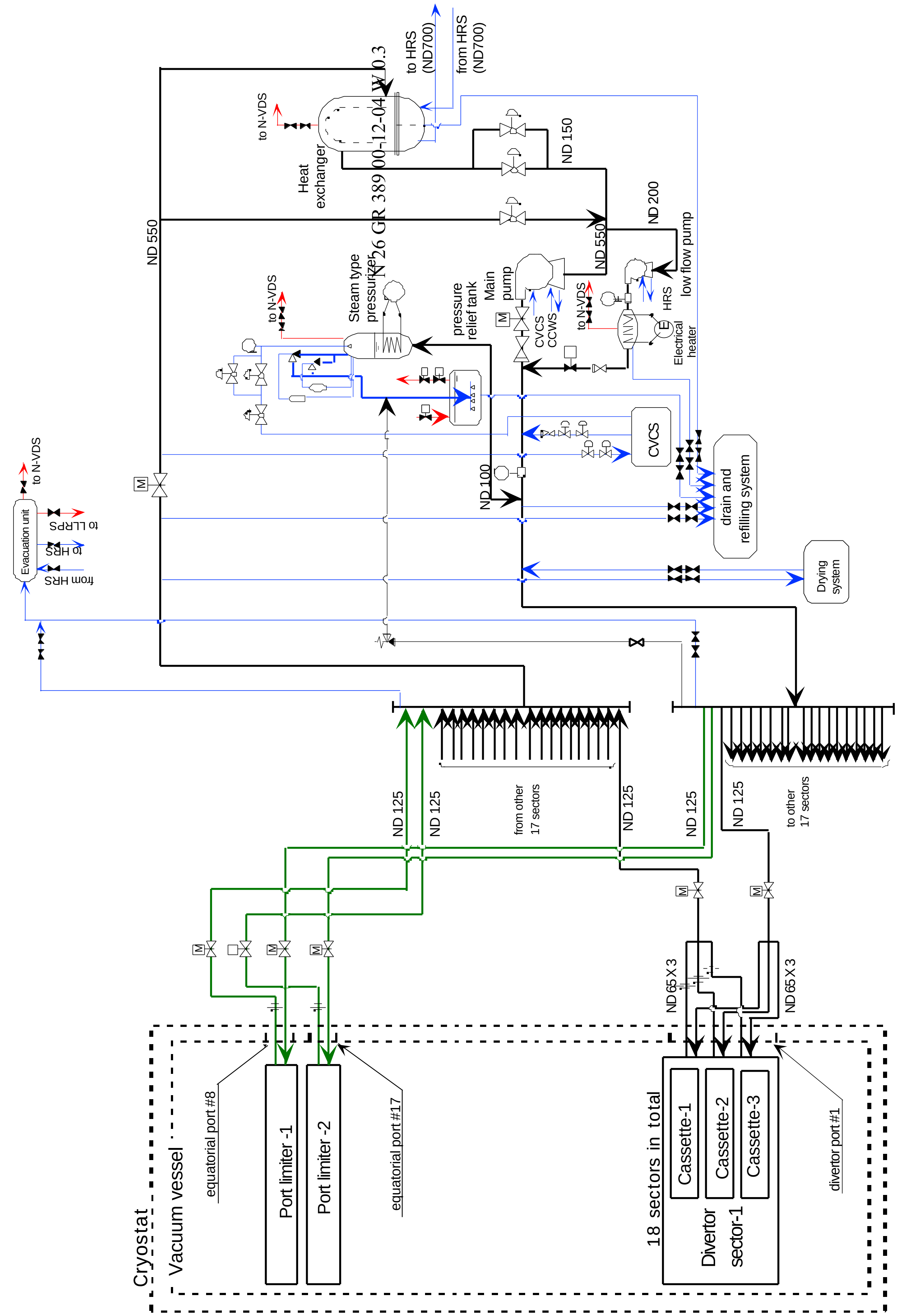

Figure 3.3.3-2 Flow Diagram of the DIV/LIM PHTS

3.3.3.1.3 VV PHTS

The VV PHTS has a safety role in that it provides the ultimate decay heat removal for all in-vessel components should the other PHTSs be unavailable. For this reason, the VV PHTS is required to have a passive heat removal capability, i.e. by means of natural convection.

The VV PHTS is divided into two loops, and each loop is connected to alternate halves of the 9 VV 40° sectors. This configuration confers redundancy in that decay heat can be adequately removed by one operational cooling loop in the event that the other becomes unavailable. Two inlet pipes (from different loops) penetrate the lower faces of each divertor port on either side of the port centreline, and the corresponding outlet pipes penetrate the top faces of the upper port in the same cooling path in 20° of the machine (10° of the machine either side of the ports). Two feeds per 20° sector from adjacent ports ensure that there are no stagnation zones in the flow fields of the inclined (upper and lower) ports. The cooling paths of pairs of feed and return pipes per 20° sector are connected alternately to the feed and return manifolds of the two VV PHTSs which are located in the lower and upper pipe chases, respectively. The main pipes are then routed through the upper pipe chase and tokamak hall to the top of the tokamak building where they connect with the air-cooled heat exchangers. In parallel with the main VV cooling lines, branch lines are connected in series to the VV closure plates at each divertor, equatorial, and upper ports of the sector. The main VV PHTS data are given in Table 3.3.3-3, and a flow diagram is shown in Figure 3.3.3-3. Each of the two loops is also designed to be able to remove the total heat load on the VV during off-normal conditions.

Table 3.3.3-3 Main Data for the VV PHTS

	Normal Operation	Baking
Thermal Power/Loop	5 MW	--
Coolant Inlet Temp.	100°C	200°C
Coolant Outlet Temp.	~ 103°C	~ 200°C
Inlet pressure	1.1 MPa	2.4 MPa
In-Vessel Pressure Drop	< 0.05 MPa	
In-Vessel Water Holdup/Loop	~ 110 m^3	
Loop Number	2	
Flow Rate/Loop	475 kg/s	
Loop Pipe Inside Diameter	0.33 m	
Pressure Drop	~ 0.6 MPa	
Total Water Holdup in a Loop	~ 160 m^3	~ 175 m^3
Main Pump - Pumping Power	1 / loop 450 kW	
Heat Exchanger - Heat Transfer Surface	3 / loop 1,591 m^2 /unit	
Heater - Size	1 / loop 1.7 MW	
Pressurizer (pneumatic type) - Size	1 / loop 30 m^3	

The VV PHTS does not have to have further confinement due to the low ACP and tritium level in the loops, thereby allowing the HXs and other loop components to be positioned outside the TCWS vault.

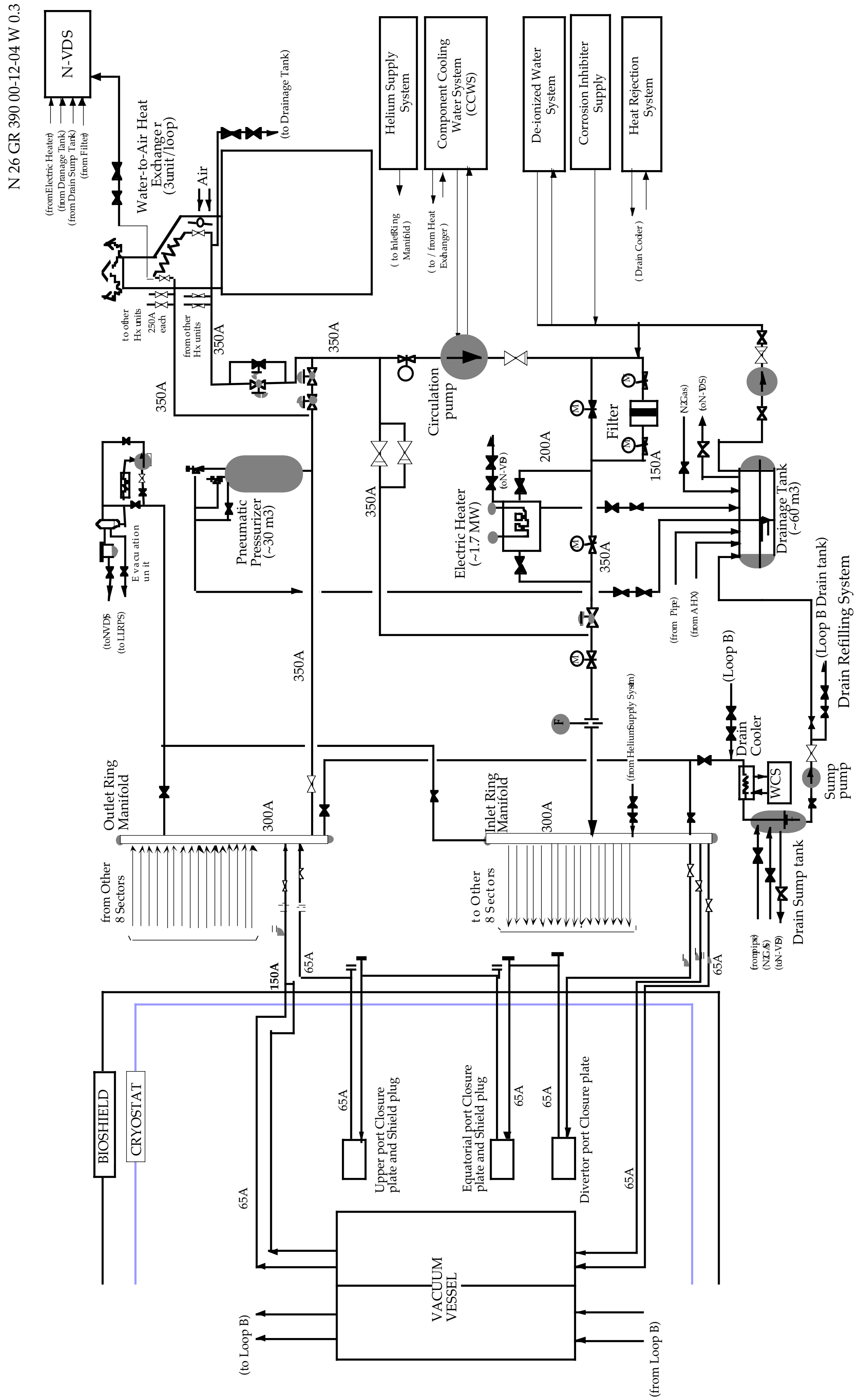

Figure 3.3.3-3 Flow Diagram of the VV PHTS

The main loop components except for the pneumatic pressurizer, i.e. pumps, filters and electrical heaters, are located in the gallery at the divertor level. Water-to-air HXs are located on the roof of the TCWS vault on the east (elevation + 34 m) and west (elevation + 31m) side of the tokamak hall and are enclosed with a chimney to enhance the natural convection of air.

The pneumatic pressurizer is located inside the tokamak hall and its volume is sufficient to accumulate the expansion volume from room temperature to baking temperature, and therefore no volume control system is needed.

Due to the relatively large thermal mass of the VV PHTS, the heat load during a plasma pulse is accumulated in the coolant and VV materials and released slowly, thereby smoothing the pulsed heat load. Numerical studies demonstrate that the same basic smoothing action occurs during 3,000 s non-inductive pulses, and confirm the feasibility of temperature control under these conditions. During normal plasma operation, forced circulation is used and the total flow is fed through the HX. The HX bypass is used only during the baking operation to control the VV inlet temperature at 200°C.

The valves in the main loop of the water-to-air HX line are the fail-open type. A non-return valve is provided in the bypass line for the main circulating pump, so that natural convection is ensured in case of pump trip.

3.3.3.1.4 NB injector PHTS

A single loop supplies coolant to both the low and high voltage components of the NB H&CD system, which are located in the NB cell at the equatorial port level. The main loop data are summarised in Table 3.3.3-4, and a flow diagram is shown in Figure 3.3.3-4.

Up to three NB injectors and one diagnostic NB system can be cooled by this PHTS.

Table 3.3.3-4 Main Data for the NB Injectors PHTS

	Low voltage components	**High voltage components** (ion source)	(other)
Thermal Power	86.9 MW	4.8 MW	10.5 MW
Coolant Inlet Temp.	75°C	20°C	55°C
Coolant Outlet Temp.	~110°C	40°C (3*)	95°C
Coolant Pressure	2.0 MPa	2.0 MPa	
In-Vessel Pressure Drop	1.0 MPa	0.9 MPa	
Loop Number	1		
Flow Rate	591.7 kg/s	48.8 kg/s	65.6 kg/s
Loop Pipe Inside Diameter (1*)	428.6 mm		
Pressure Drop (2*)	1.4 MPa		
Total Water Holdup	87 m^3		
Pumping Power	1.6 MW		
Pump Size (Vertical type)	5 m-D x 5.4 m-L		
Heat Exchanger - Exchange Heat - Heat Transfer Surface Area	Main heat exchanger 87.7 MW ~2,310 m^2	Chilled cooler 6.7 MW ~ 430 m^2	Pre-cooler 9.2 MW ~ 560 m^2
Pressuriser Size (Pneumatic type)	4.7 m^3		

(*1) Coolant velocity < 6 m/s
(*2) Total pressure drop including LV/HV components, Heat exchanger and piping
(*3) 40°C of the outlet temperature for the main components with 4.0 MW heat load

During operational periods, the inlet coolant temperature to the NB injector components must be maintained less than 80°C for the low voltage system and less than 20°C for the ion source and 60°C for the other components in the high voltage system despite the pulsed nature of plasma operation. However, there is no particular requirement for lower temperature limits and decay heat removal, such as for the other in-vessel PHTSs. Therefore, a HX bypass for temperature control and a low flow pump are not necessary, which simplifies the loop configuration.

A bypass line around the main pump and a stop valve with intermediate opening in this bypass line provide a trickle flow to the NB injectors during standby to reduce erosion of the Cu material in the NB injectors and to prevent freezing.

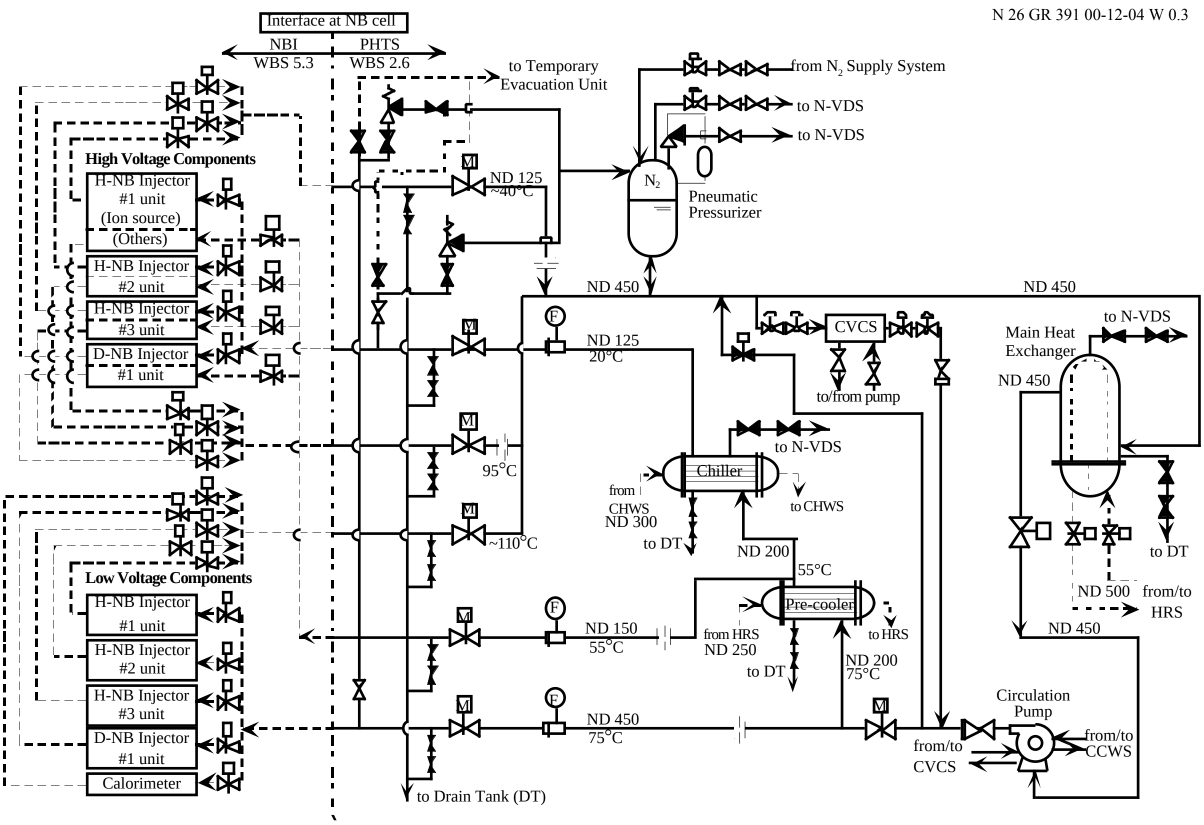

Figure 3.3.3-4 Flow Diagram of NB Injectors PHTS

3.3.3.1.5 Chemical and Volume Control Systems (CVCSs)

The CVCSs consist of three units for in-vessel PHTSs. These systems are installed in the TCWS vault below the mezzanine floor. A flow diagram of the CVCS for the PFW/BLK PHTS is shown in Figure 3.3.3-5, and the main data are summarised in Table 3.3.3-5.

The filtered stream is cooled in a recuperative HX to below ~100°C. Then it passes through a pressure reducer, where the coolant pressure is reduced from PHTS loop pressure to 0.5~1 MPa, being kept at this value in the remainder of the unit up to the re-injection pump. In a second HX called the letdown cooler, the temperature of the stream is reduced to ~50°C. At this temperature, the water is further purified in mixed ion-exchange resin beds.

After the resin bed, the stream is led to a volume control tank in which the hydrogen concentration is controlled. Via a high pressure re-injection pump, the coolant is re-pressurised and re-injected back into the loop, via the recuperative HX, or is pumped to a pressuriser or drain tank. A small bleed stream is also provided for the main pump shaft seal.

Table 3.3.3-5 Main data for the CVCS for PFW/BLK PHTS

Operational state or mode	Plasma Operation State	Baking	Decontamination Mode
Volumetric Flow Rate (at inlet)	45 m^3/h	45 m^3/h	90 m^3/h
Feed Coolant Temp.	148°C	240°C	100°C
Return Coolant Temp.	120°C	190°C	83°C
Feed Coolant Pressure	1.7 MPa	4.3 MPa	1.7 MPa
Return Coolant Pressure	3.4 MPa	4.6 MPa	3.4 MPa
Number of Inlet Filters in Service	1	1	2
Number of Resin Beds in Service	1	1	2
Number of Re-injection Pumps in Service	2	2	4
Loop Pipe Inside Diameter (1*)	78 mm		
Recuperative Heat Exchanger - Exchange Heat (Max) - Heat Transfer Surface Area	3 modules 6.5 MW 213 m^2		
Letdown Cooler - Exchange Heat (Max) - Heat transfer surface area	1 unit 2.6 MW 178 m^2		
Volume Control Tank	1 unit		
Inlet Filter	2 units		
Resin Bed	2 units		
Re-injection Pump - Pumping Power	4 units 70 kW		

(*1) Coolant velocity < 6 m/s

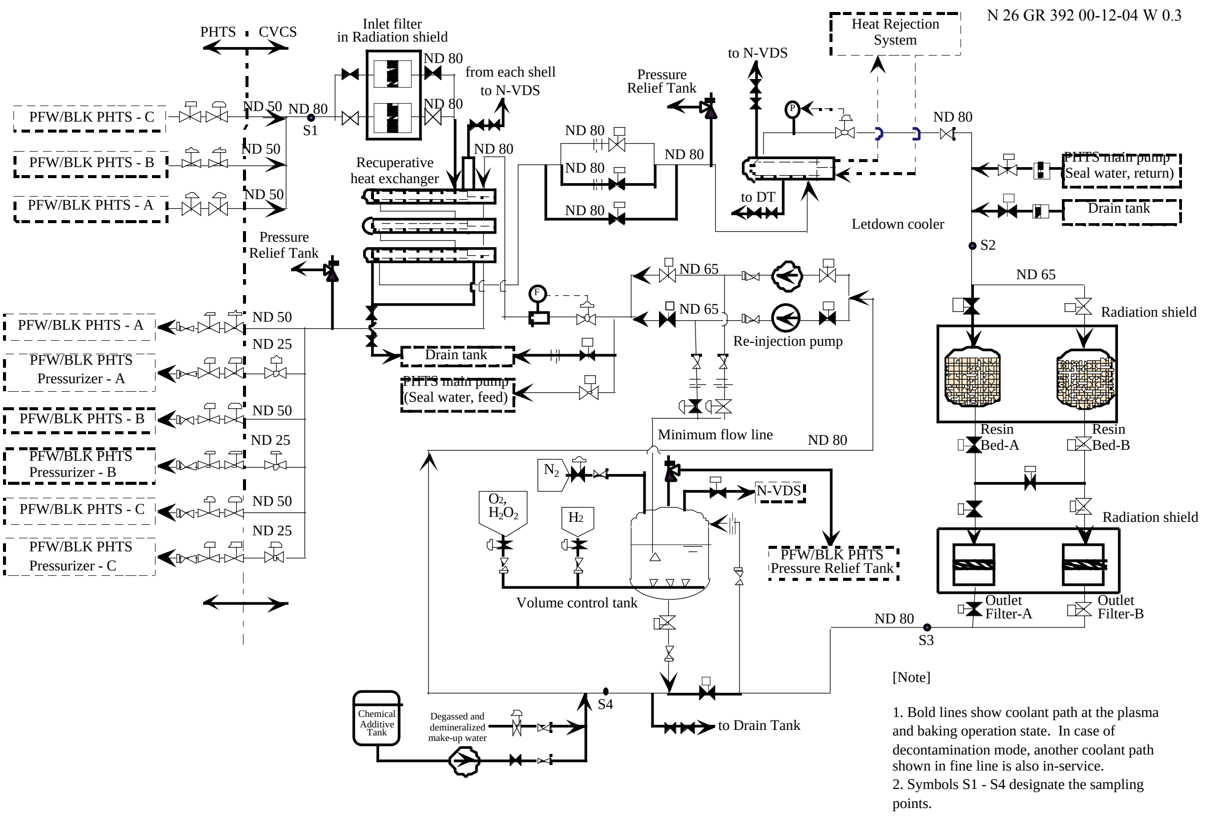

Figure 3.3.3-5 Flow Diagram of the CVCS for the PFW/BLK PHTS

Controlled oxidation is implemented to form a protective passivating oxide layer on the wetted surfaces after installation or maintenance, prior to plasma operation, in order to reduce the subsequent oxidation rate. Oxygen is added to the coolant to promote the formation of stable spinel-rich (mixed chromium/iron/nickel oxide) films.

During normal operation, the coolant chemistry will be controlled such that the further deposition of oxide layers on top of the stable spinel film is kept low. This is achieved by lowering the oxidation potential by adding and dissolving hydrogen in the coolant. Continuous circulation will be maintained through the filters and resin beds to remove suspended and dissolved compounds respectively in order to reduce the concentration of ACPs (activated corrosion products) in the coolant and keep the plate-out rates along the loop surfaces at an acceptably low level.

To lower the dose burden to maintenance workers, the ability to undertake an intensive campaign of ACP removal is foreseen. The flow rate through the CVCSs is in this case increased to approximately twice the normal processing rate and the chemistry is changed to remove deposited ACPs by dissolving oxygen and/or hydrogen peroxide in the coolant.

For the VV PHTS, a filter located on the divertor level of the tokamak building removes ACPs in the coolant, instead of the CVCS unit.

3.3.3.1.6 Draining and Refilling Systems

For maintenance and inspection operations, loops have to be drained partly or fully. Storage segmentation is based on avoiding the mixing of coolant at different contamination levels or chemistry requirements.

Some of the drain tanks are also used to receive the drain water from the VV via the emergency drainage lines during an in-vessel coolant leak. The assigned drain tanks, which have a total volume ~ 400 m^3, are maintained in a partially-evacuated condition, ~ 10 kPa, during operation, and they have a safety function.

To accommodate expelled coolant from the CVCSs, caused by expansion of the coolant during heating up from pulse operating temperature to baking temperature, separate drain tanks for volume control are required for the PFW/BLK and DIV/LIM PHTSs. The NB injector PHTS does not need a drain tank for volume control because there is no baking operation.

Refilling of the PHTSs loops is performed by the injection pumps through the CVCSs.

The draining and refilling systems, except that for the VV, are located in the drain tank area at the basemat level of the tokamak building. Valves, instrumentation and refilling pumps are also located in a room connected to the detritiation system. The draining and refilling system for the VV PHTS is located on the same floor but outside the room.

Table 3.3.3-6 shows the drain tank volumes of the draining and refilling system.

Table 3.3.3-6 Draining and Refilling System Tank Volumes

System	Number of drain tanks	Total internal volume (m^3)
PFW/BLK PHTS	2 (1)*	~ 500
DIV/LIM PHTS	2 (1)*	~ 200
VV PHTS	2	~ 120
NB injectors PHTS	2 (2)*	~ 120

* number of tanks in parentheses indicates those used for drainage following an in-vessel coolant leak

3.3.3.1.7 Drying System

After drainage, the residual water in the in-vessel components, the VV inter-wall space and the port closure plates must be dried to facilitate leak testing of the in-vessel components. The procedure is to blow out most of the residual water with nitrogen gas, from all modules that are open to the gas flow. Subsequently, hot nitrogen gas is introduced to evaporate and thereby remove the remaining liquid. It is intended that the system be used for both the blow-out and drying stages, in order to minimise the capital cost, and the capacity of the compressor and heat exchanger. Although two independent compressors for the blow-out and drying are designated because of the different working conditions (the compressor shaft powers required are ~500 kW for the blow-out and ~300 kW for the drying), the other components are used for both stages.

The design accounts for counter current flow limiting behaviour in the cooling paths and the flow area of the paths that have to be blown out concurrently. The limiting condition for the blow-out is 8 blanket modules to be blown concurrently: the residual water after the blow-out is evaluated as ~5% in this case. This evaluation has large uncertainty, depending on the configuration, and a confirmatory blow-out test will be needed, using the actual configuration.

The drying system data are given in Table 3.3.3-7. A simplified flow diagram of this system is shown in Figure 3.3.3-6.

The drying procedure can be roughly divided into two stages: a heat-up stage with the nitrogen at 150 - 200°C, 2.1 MPa, and a dry-out stage with the nitrogen at 150 - 200°C, 0.6 MPa. During the heat-up stage, the component and the residual water are heated to above 150°C. Then the gas pressure is reduced to ~0.5 MPa (i.e. saturation pressure at 150°C). The residual water is vaporised and extracted by the drying system.

This system has the capability to dry the blanket modules in two 20° sectors or the divertor cassettes in six 20° sectors in a single operation to a residual steam partial pressure of ~0.002 MPa (saturation pressure at 20°C). The estimated drying time, following the blow-out, is ~3 days for the blanket modules connected to one PFW/BLK loop and for all the divertor cassettes. The major components of the drying system are located in the TCWS vault cooler and dryer room in the tritium building.

At the price of reducing the number of components that can be blown out concurrently, the simplification of the common use of a single 300 kW compressor for all operations may be possible. Further development of the leak checking procedure detail is necessary before the requirements can be finalised.

Table 3.3.3-7 Main Data for the Drying System

	Blow-out mode	**Heat-up mode**	**Dry-out mode**
Fluid	Nitrogen	Nitrogen	Nitrogen + H_2O (steam)
Fluid Inlet Temp.	40°C	210°C	210°C
Fluid Outlet Temp.	40°C	160°C	160°C
Fluid Inlet Pressure	4.0 MPa	2.1 MPa	0.6 MPa
Number of loops	1		
Main piping size	ND 250		
Compressor - Compressor power	Magnetically floating bearing type ~500 kW, 1 unit	~300 kW, 1 unit	
Electrical Heater - Heater power	Shell and baffle type, 1 unit 690 kW		
Cooler Condenser #1 - Exchange heat	Cooled by HRS cooling water, 1 unit 370 kW		
Cooler Condenser #2 - Exchange heat	Cooled by chilled water, 1 unit 190 kW		
Drain Separator	Cyclone separator type, 1 unit		
Mist Separator	Vane separator type, 1 unit		
Filter	2 units, 3 μm (Mesh fineness)		

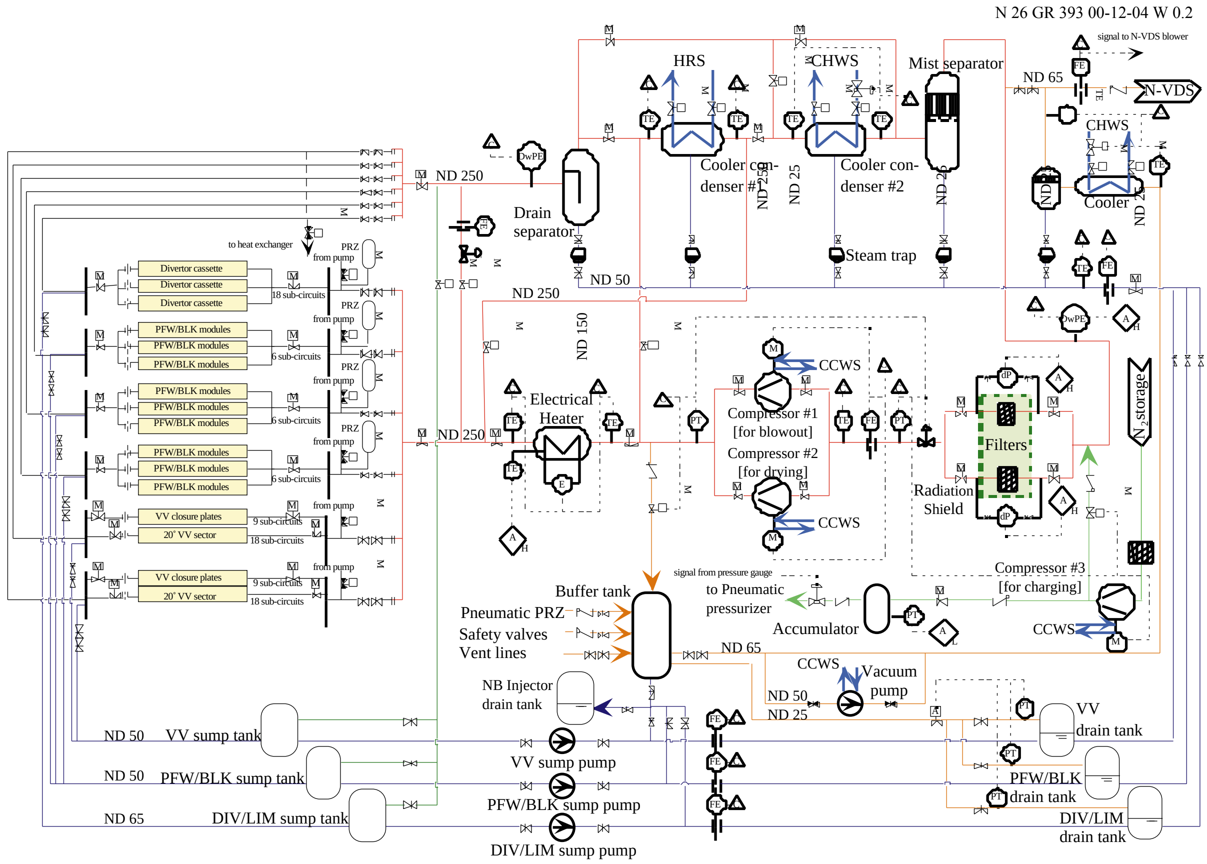

Figure 3.3.3-6 Flow Diagram of the Drying System

3.3.3.2 Component Cooling Water System (CCWS)

The CCWS provides demineralised cooling water flow at a specified quality to components and systems, and transfers heat to the circulating water via intermediate HXs. The total heat rejected through the CCWS is ~ 120 MW when operating at full capacity.

The heat loads of clients, and the flow rate and temperature condition in each CCWS, are summarised in Table 3.3.3-8. The schematic flow diagram is shown in Figure 3.3.3-7. The intermediate HXs are of the plate type.

The CCWS is partitioned into three zones.

(i) Tokamak zone

This serves pumps inside the tokamak building, NB active compensation/correction coils, and the RF heating components inside the assembly building. As the power supply components for the RF H&CD require an inlet temperature less than 35°C, the corresponding CCWS sub-loop (CCW-1C) is interfaced with a CHWS.

The inlet and outlet temperatures in Table 3.3.3-8 are those under the most adverse conditions. As a lower inlet temperature is acceptable, no temperature control is foreseen. The loop (CCW-1C) for the power supply components has a bypass line on the intermediate HX to avoid the component temperature becoming lower than the dew point.

(ii) Power Supply zone

This serves power supply components, and the loops are located in the magnet power supply switching network building. The CCWS for some power supply components requires an inlet temperature of less than 35°C, and the corresponding CCWS sub-loop (CCW-2B) is interfaced with the CHWS. Two sub-loops have demineralisers to maintain the required electric conductivity of the coolant.

(iii) Site services zone

This serves components in the site services building, the control building, the laboratories and offices.

Table 3.3.3-8 Heat Loads and Flow Rates for the CCWS

System (Loop)	Clients		Heat Load of Clients		Flow Rate		Inlet/Outlet Temp. (°C)	
	Name	Location	MW	Sum.	(kg/s)	Sum.	In	Out
CCWS in tokamak zone [Loop CCW-1A]	PHTSs pumps	Tokamak building	1.8	3.3	85.3	94.3	40	45
	NB ACCC*	NB cell	1.5		9.0		40	80
CCWS in tokamak zone [Loop CCW-1B]	IC H&CD components	Assembly hall	21.6	81.6	172.1	650.1	40	70
	EC H&CD gyrotron	Assembly hall	60.0		478.0			
CCWS in tokamak zone [Loop CCW-1C]	IC H&CD power supply	Assembly hall	1.92	5.9	222.2	322.2	30	34.4
	EC H&CD power supply	Assembly hall	4		100.0			
CCWS in power supply zone [Loop CCW-2A]	Reactors	Power supply zone	5.84	18.8	94.4	228.1	40	59.7
	Busbars	Power supply zone	10.11		111.4			
	Switching network and fast discharge	Power supply zone	2.83		22.2			
CCWS in power supply zone [Loop CCW-2B]	RPCs** + coil converters	Power supply zone	5.73	9.2	291.7	475.0	30	34.6
	NB injector power supply	Power supply zone	3.45		183.3			
CCWS in site services zone [Loop CCW-3]	Component in building	Site service zone	0.6	0.6	28.7	28.7	40	45

* Active Compensation/ Correction Coils ** Reactive Power Compensating Units

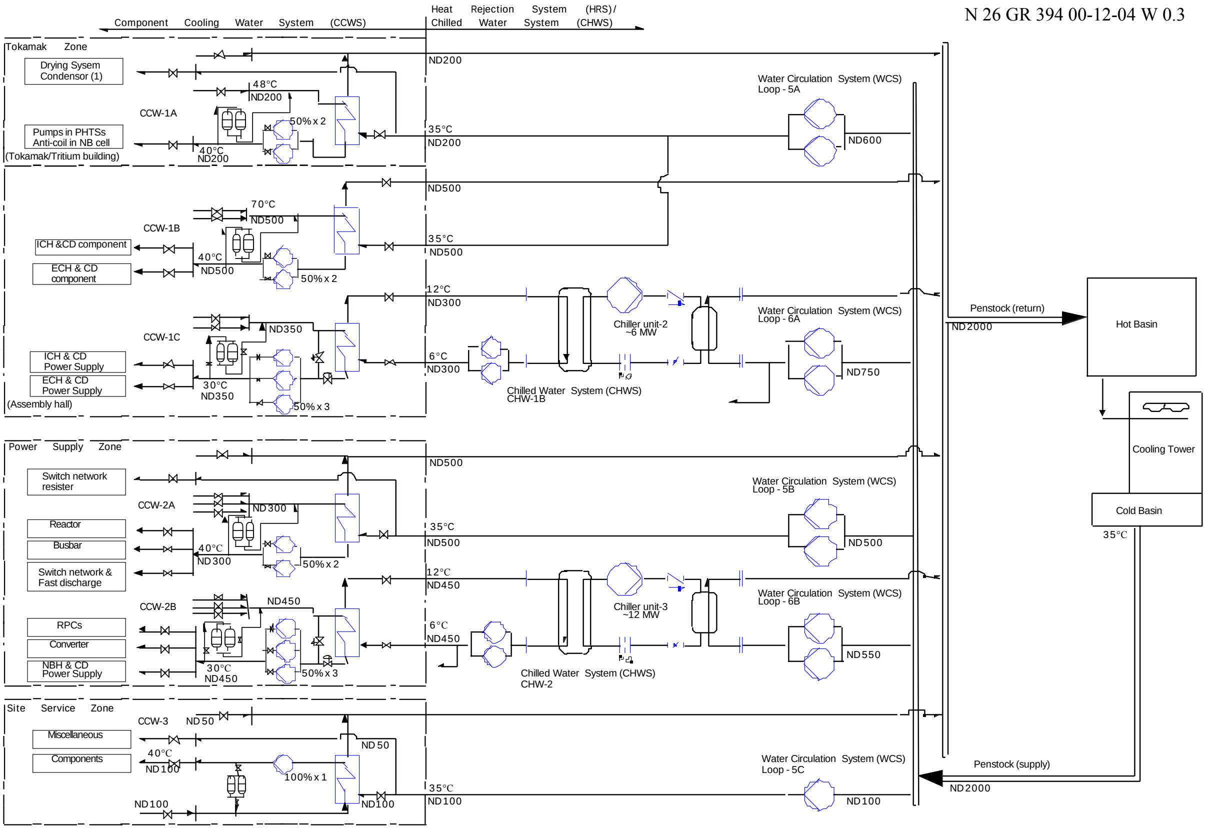

Figure 3.3.3-7 Schematic Flow Diagram of the CCWS

3.3.3.3 Chilled Water System (CHWS)

The CHWS provides a flow of chilled water (~ 6°C) to those plant systems which require low temperature, such as HVAC, and CCWS for the power supply components. The total heat rejected through the CHWS is ~ 41 MW when operated at full capacity. There are two CHWS loops for the tokamak zone, one for the power supply zone and one for the site services zone. In addition, two independent “safety-related” loops of the CHWS are installed in the tokamak zone. The heat load for the safety-related CHWS is ~4 MW, and full redundancy appropriate to its safety importance classification (SIC) is provided.

The heat loads required by the clients, and the flow rates and temperature conditions in each CHWS are summarised in Table 3.3.3-9. The system configuration is shown in Figure 3.3.3-8.

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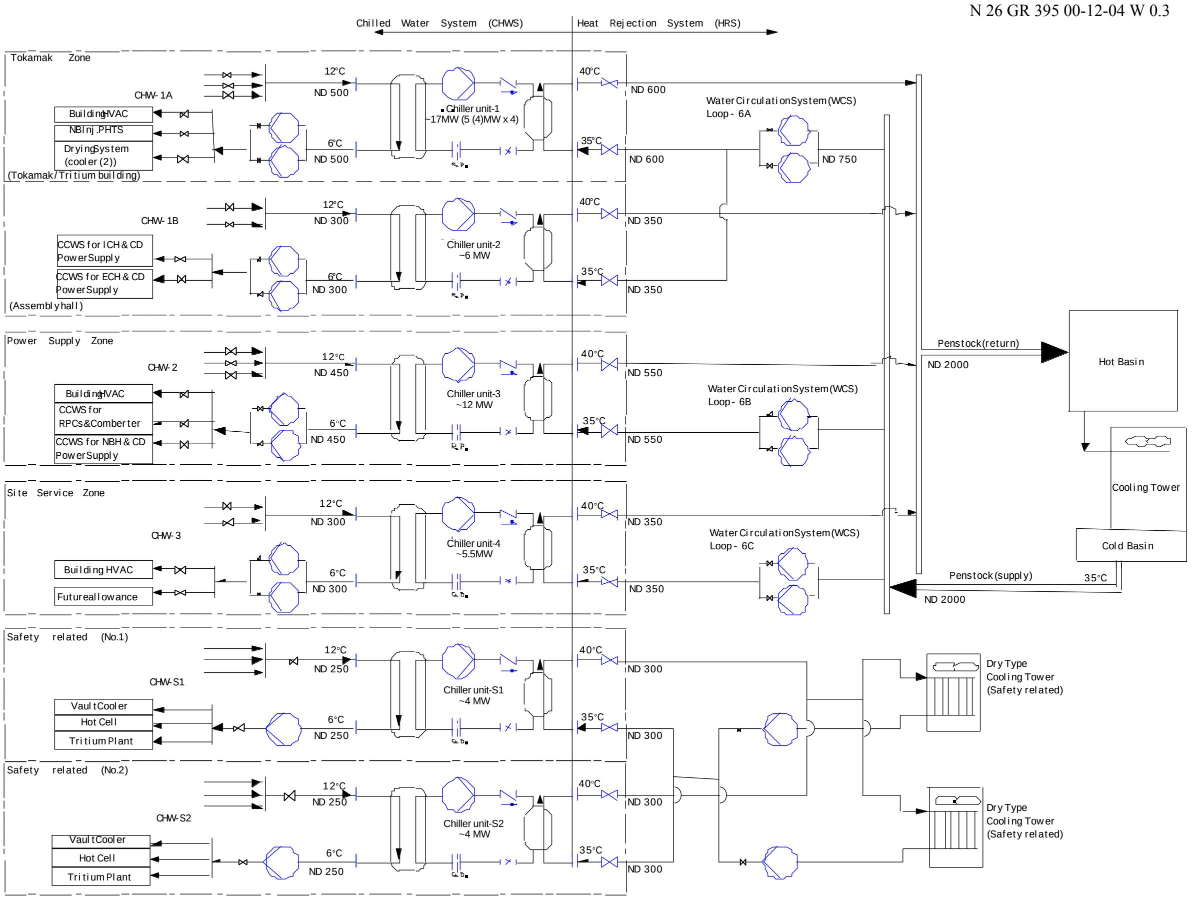

Figure 3.3.3-8 Schematic Flow Diagram of the Chilled Water System (CHWS)

Table 3.3.3-9 Heat Loads, Temperatures and Flow Rates for the CHWS

System (Loop)	Clients		Heat Load of Clients		Flow Rate		Inlet/Outlet Temp. (°C)	
	Name	Location	MW	Sum.	(kg/s)	Sum.	In	Out
CHWS in tokamak zone [Loop CHW-1A]	Tokamak building HVAC	Tritium building	9.3	17.0	370.4	675.2	6	12
	Radwaste/ personnel building HVAC	Radwaste building	0.75		29.9			
	NB injector chilled HX (for HV)	Tritium building	6.7		266.9			
	Drying system: condenser #2	Tritium building	0.2		8.0			
CHWS in tokamak zone [Loop CHW-1B]	CCWS for ICH&CD power supply	Assembly hall	1.9	5.9	76.5	235.8	6	12
	CCWS for ECH&CD power supply	Assembly hall	4		159.3			
CHWS in power supply zone [Loop CHW-2]	Buildings HVAC	Power supply zone	2.9	12.1	115.5	481.2	6	12
	CCWS for RPCs* + coil converters	Power supply zone	5.73		228.3			
	CCWS for NB injectors power supply	Power supply zone	3.45		137.4			
CHWS in site services zone [Loop CHW-3]	Buildings HVAC	Site services zone	5	5.5	199.2	219.1	6	12
	Future allowance load	Site services zone	0.5		19.9			
Safety-related CHWS [Loop CHW-S1]	TCWS vault cooler	Tritium building	1.1	4.0	43.8	159.3	6	12
	Hot cell HVAC	Hot cell building	0.9		35.9			
	Tritium plant	Tritium plant building	2		79.7			
Safety-related CHWS [Loop CHW-S2]	TCWS vault cooler	Tritium building	1.1	4.0	43.8	159.3	6	12
	Air conditioning in hot cell	Hot cell building	0.9		35.9			
	Tritium plant	Tritium plant building	2		79.7			

* Reactive Power Compensating Unit

3.3.3.4 Heat Rejection System (HRS)

The HRS provides the final heat sink and rejects all heat loads in the ITER plant. It consists of water circulation systems (WCSs) and the cooling tower system (CTS). Water is provided at a maximum temperature of 35°C and returned at a maximum temperature of 75°C.

The WCSs provide pipeline connections for cooling water feed and return streams from the HXs of all heat transfer systems to the heat sink, i.e. the CTS. The WCSs interface with the CTS at the collecting hot basin and the distribution cold basin. The HRS has 3 loops for the TCWS, one for the cryoplant warm compressors, 3 loops for the CCWS and 3 loops for the CHWS. Water is circulated from a cold penstock, through pumps situated in pump stations which are located just outside the clients' buildings. The heat loads, temperatures and flow rates in the WCSs are summarised in Table 3.3.3-10.

The design of the circulating pump motors allows polarity changeover to enable the main pumps to change to low pump speeds during low flow operation (including the case of loss of site power) for the WCSs serving the PHTSs. This enables the elimination of separate low flow pumps and associated piping and valves. In the event of a single main pump trip, the remaining pump will supply sufficient flow to maintain the return temperature to less than 90°C, and thus prevent boiling.

The design of the CTS, including the basins, is based on a cost optimisation between cooling tower heat rejection capacity and temperature levelling capacity in the hot basin. The capacity of the cooling tower units is based on the most thermally adverse burn (3,000 s of burn with 350 MW of fusion power, see 3.3.4.4). Based on ITER site reference conditions, the system is envisioned to consist of 8 cooling cells and 4 fans. The volume of the hot basin is 12,000 m^3 and the cold basin 20,000 m^3.

Additionally, a dedicated dry type CTS with a capacity of ~ 5 MW is adopted for the safety-related CHWS. The heat loads and flow rates in the safety-related HRS are shown in Table 3.3.3-11. This system is connected to class III power during off-normal conditions.

Table 3.3.3-10 WCS Heat Loads and Flows (non-safety related)

System name	Clients		Design heat Load in HRS		Flow Rate		Inlet/Outlet Temp. (°C)	
	Name	Location	MW	Sum.	kg/s	Sum.	In	Out
Primary first wall and blanket WCS [Loop 1]	PFW/BLK heat exchanger #1	TCWS vault	234	702	1,400	4,195	35	75
	PFW/BLK heat exchanger #2	TCWS vault	234		1,400		35	75
	PFW/BLK heat exchanger #3	TCWS vault	234		1,400		35	75
Divertor and limiter & neutral beam injectors WCS [Loop 2]	DIV/LIM heat exchanger	TCWS vault	206	303	1,230	1,980	35	75
	NB injector heat exchanger	TCWS vault	88.0		600		35	70
	Pre-cooler for NB injector (HV)	TCWS vault	9.2		147		35	70
CVCS WCS [Loop-3]	PFW/BLK CVCS-1	TCWS vault	3.5	11.2	55.8	118	35	50
	DIV/LIM CVCS-1	TCWS vault	1.4		22.3		35	50
	NB injectors CVCS-1	TCWS vault	0.3		4.0		35	50
	Test blanket modules PHTSs	TCWS vault	6.0		35.8		35	75
Cryoplant compressor WCS [Loop 4]	Cryoplant compressor	Cryoplant building	25	25	854	854	35	42

Table 3.3.3-10 WCS Heat Loads and Flows (non-safety related) (cont'd)

System name	Clients		Design heat Load in HRS		Flow Rate		Inlet/Outlet Temp. (°C)	
	Name	Location	MW	Sum.	kg/s	Sum.	In	Out
Component cooling water system(1) [Loop 5A]	PHTS pumps	Tokamak zone	1.8	85.7	85	755	35	40
	NB ACCC**	Tokamak zone	1.5		9		35	75
	IC H&CD (components outside VV)	Tokamak zone	21.7		173		35	65
	EC H&CD gyrotron	Tokamak zone	60.2		480		35	65
	Drying system: Condenser #1	Tokamak zone	0.5		8		35	50
Component cooling water system(2) [Loop 5B]	Reactors	Power supply zone	5.89	24.6	201	684	35	42
	Busbars	Power supply zone	10.3		352		35	42
	Switching network and fast discharge	Power supply zone	2.88		98		35	42
	Switching network resisters	Power supply zone	5.50		33		35	75
Component cooling water system(3) [Loop 5C]	Components in building	Site services zone	0.6	1.2	21	26.2	35	42
	Miscellaneous in building	Site services zone	0.6		6		35	60
Chilled water system(1) [Loop 6A]	Tokamak buildings HVAC	Tritium building	11.6	28.6	556	1,368	35	40
	Radwaste/ personnel building HVAC	Tritium building or Radwaste building	0.94		45		35	40
	NB injectors chiller (for HV)	Tritium building	8.4		400		35	40
	IC H&CD power supply	Assembly hall	2.40		115		35	40
	EC H&CD power supply	Assembly hall	5.00		239		35	40
	Drying system: Condenser #2	Tritium building	0.25		12		35	40
Chilled water system(2) [Loop 6B]	Buildings HVAC	Power supply zone	3.63	15.1	174	722	35	40
	RPCs*** + coil converters	Power supply zone	7.16		342		35	40
	NB injectors power supply	Power supply zone	4.31		206		35	40
Chilled water system(3) [Loop 6C]	Buildings HVAC	Site services zone	6.25	6.9	299	329	35	40
	Future allowance load	Site services zone	0.63		30		35	40
HRS TOTAL	-	-	-	1,205*	-	11,030	-	-

* Total capacity in clients. Maximum heat load for CTS is ~ 1,120 MW
** Active Compensation/Correction Coils
*** Reactive Power Compensating Units

Table 3.3.3-11 WCS Heat Loads and Flows (safety-related)

System name	Clients		Design Heat Load in HRS		Flow Rate		Inlet/Outlet Temp. (°C)	
	Name	Location	MW	Sum.	kg/s	Sum.	In	Out
Safety-related [Loop 7]	TCWS vault cooler	Tritium building	1.4	5.0	67	239	35	40
	Hot cell HVAC	Hot cell building	1.1		53		35	40
	Tritium plant	Tritium building	2.5		120		3	40.

3.3.4 System Performance Analysis Summary

3.3.4.1 Stress in PHTS piping

A complex pipe network is laid out inside the TCWS vault and the upper and lower pipe chases. Thermal and seismic stress analyses have been performed confirming the design feasibility.

(1) The piping stress in the in-vessel PHTSs are below the allowable values for both of ASME III class 2 and ANSI-ASME B.31.3 codes.
(2) The piping stresses in the VV PHTS are below the allowable values for MITI Bulletin 501 and JEAG-4601 code (similar to the ASME III code).

As a result, the PHTS layout has been confirmed to be satisfactory for the stress.

3.3.4.2 Temperature, Pressure and Flow Rate Control in PHTSs

Due to the pulsed nature of machine operation the coolant temperatures, pressures and flow rates have to be controlled within certain ranges. These ranges are determined by a number of limiting parameters including nominal coolant inlet temperature, pressure and flow conditions that guarantee a safe margin from critical heat flux at any location inside the components, as well as avoiding excessive thermal stresses in the in-vessel and ex-vessel loop components.

(i) In-vessel Component PHTSs

Temperature control in the PFW/BLK and DIV/LIM PHTSs is achieved by controlled bypassing of the HX. During a plasma pulse, the coolant exit temperature follows the power deposition profiles of the in-vessel components, delayed by the thermal capacity of the components subject to transient temperature conditions. During fusion burn, therefore, up to the full primary coolant flow may be routed through the HX, thereby raising its temperature while the component inlet temperature is controlled at 100°C within a control band. During dwell, the inlet temperature to the in-vessel components has to be maintained at nominally 100°C. This requires full bypassing of the HX, except for any small heat load due to decay heat and pumping power. Temperature changes in the coolant lead to concomitant volume changes which are accommodated by the pressuriser. Pressure changes in the steam pressurisers corresponding to water insurge or outsurge resulting from thermal expansion or contraction of the loop water, are controlled by the use of cool water spray or heaters in the pressuriser.

A thermohydraulic analysis has been performed using the ATHENA code, and the results show that the fluctuations in temperature and pressure during the burn are within +8/-0°C and ± 0.2 MPa, respectively The analytical results for the PFW/BLK PHTS are shown in Figure 3.3.4-1. The fluctuation is within the acceptable band, and this indicates acceptable controllability of the systems.

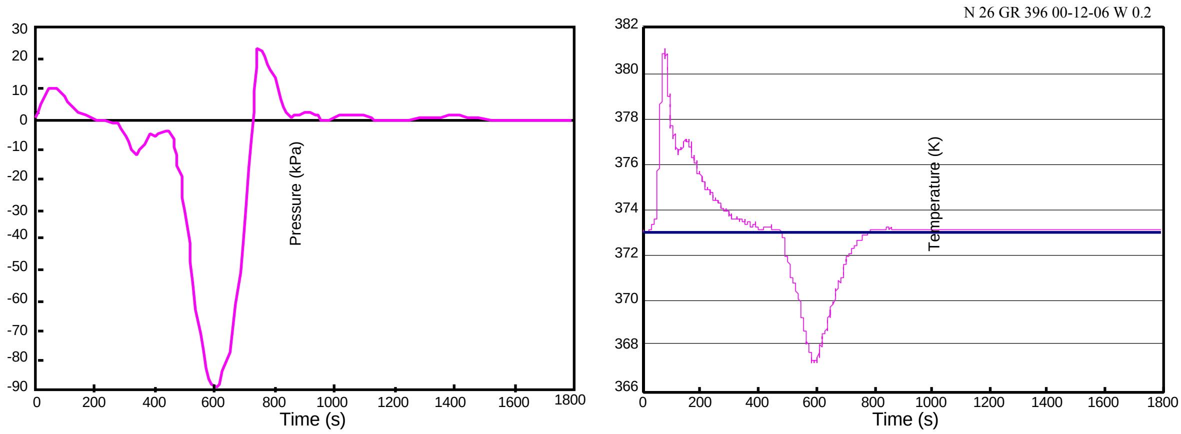

Figure 3.3.4-1 Trends of Pressure and Temperature in the PFW/BLK PHTS (100% power pulse)

The heat load of ITER is expected to cover a very wide range (i.e., zero to full power) and to change between zero power and full power in a short time (i.e. about 50 s at fusion start-up). This operating condition is quite different from that for conventional large heat transfer systems. Parametric thermohydraulic analyses are ongoing using the ATHENA code, and the preliminary results show that fluctuations in temperature and pressure during the burn cycle are within acceptable limits.

The total flow rate must be maintained within an acceptable range during normal operation. Deviation of flow rate caused by a change of flow resistance around the HX and its bypass line, as a result of the operation of control valves, is maintained within the allowable range by adoption of an appropriate control logic for the independent, cage-type, control valves.

(ii) VV PHTS

Temperature control in the VV PHTS is achieved by air-flow control in the air chimney which surrounds the air-cooled HXs. The control variable is the inlet air damper opening, with a feedback signal derived from the HX outlet temperature excursion from the setpoint. The HX bypass is used only during the baking operation to preclude heat rejection through the HXs.

Numerical studies predict a ~ 500 s delay for temperature perturbations, corresponding to a long coolant transit time through the VV cooling path, and a high degree of levelling of the pulsed heat load, on account of the large thermal mass of the VV thermally coupled materials. To reach a quasi-steady temperature condition in the VV structure requires 3 reference plasma pulses due to the large thermal mass of the VV. The VV inlet temperature during the second pulse increases because the heat transferred from the VV is larger than the HX capacity. The temperature in the VV, however, reaches the maximum in the third pulse, and it fluctuates corresponding to the heat balance in the loop. As shown in Figure 3.3.4-2, the temperature fluctuation at the VV inlet is within +2.7/-0.2°C.

For a 3,600 s pulse with 500 MW of fusion power, a more conservative condition than the current design reference, the inlet temperature increases continuously because of a lack in the heat release capability of the HX. The maximum temperature increase during the burn duration is ~ 7 °C, and this is within the control band.

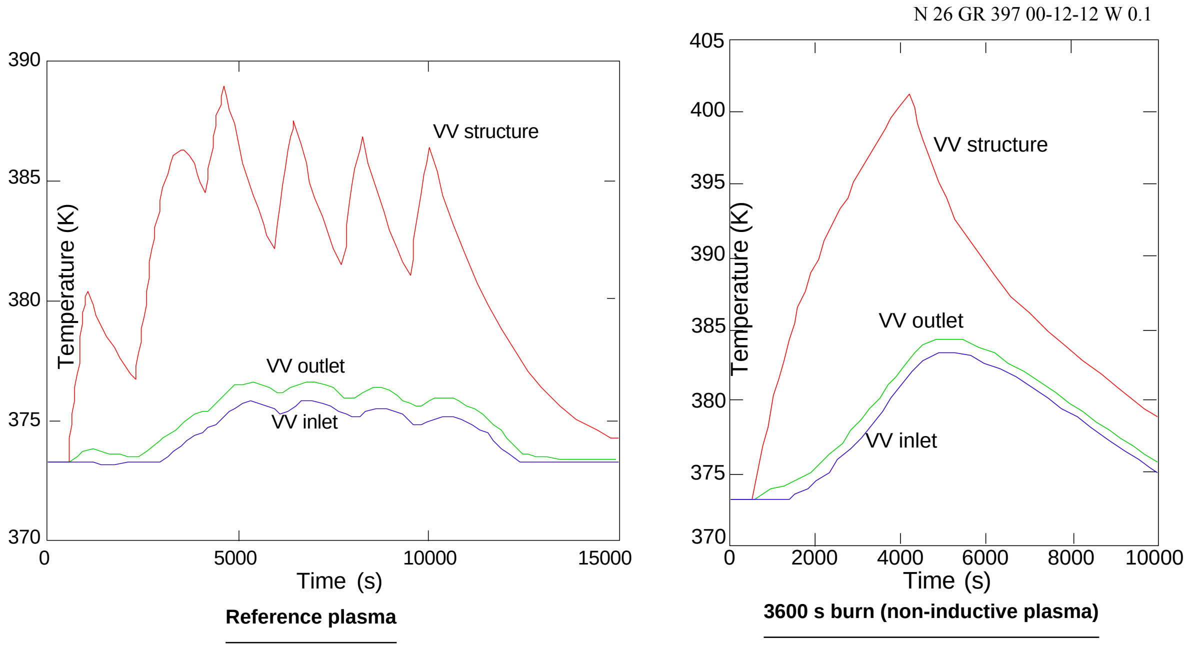

Figure 3.3.4-2 Trends of Temperature in the VV PHTS under Reference Plasma and Long Burn Conditions

Pressure regulation is achieved by either supplying nitrogen gas to, or abstracting it from, the pneumatic pressuriser. Pressure regulation is needed during normal operation, particularly during the operation mode change between pulsed and baking. However, pressure regulation is not needed during off-normal conditions.

3.3.4.3 Decay Heat Removal

Decay heat removal is performed by the heat transfer loops, i.e., the complete "train" formed by the PHTSs and the HRS, or directly to the environment (for the VV PHTS). Since the amount of decay heat to be removed is only a small fraction of the nuclear heat load during a plasma pulse, most PHTSs loops employ a low flow pump of approximately 10% of full flow throughput, to remove decay heat from the in-vessel components. These pumps are connected to class III power to protect investment in case of a loss of site power or a loss of flow during a category II event. Since loss of coolant flow in the HRS leads to the loss of the heat sink, one pump in the WCSs for the PFW/BLK and DIV/LIM PHTSs is also connected to class III power (non-safety), utilising polarity changeover type pumps to minimise the class III power requirement.

The role of the VV PHTS as the safety system for decay heat removal, in the event that all other systems fail, is to be able to remove decay heat in a passive mode, i.e. by natural convection. To fulfil this role, two fully independent loops are employed, each loop being capable of safely removing the entire decay heat, acting alone. This capability has been confirmed by numerical studies. It has also been confirmed by numerical studies that the coolant temperature during the winter season (-15°C outside air temperature) is above 0°C for at least 6 days after event initiation. Therefore, the anti-freeze system is not safety importance classified.

3.3.4.4 Operation under 3,000 s Pulse Conditions

The PHTSs are designed for the maximum heat load, and they impose no limitation on longer pulse duration. On the other hand, the HRS has been designed for 3,000 s pulse length operation with 350 MW fusion power.

The hot basin size and the cooling tower capacity in the HRS depend on the temperature levelling (mixing) efficiency in the hot basin. Mixing within the basin is promoted by injecting the inlet hot water into the basin through a spatially distributed injection system, and by turbulent convection. The mixing behaviour has been analysed using the FLUENT code, and an almost simultaneous, complete mixing is predicted.

The numerical studies indicate that the maximum basin temperature increases as the basin volume decreases, and that higher basin temperatures require a higher cooling tower (CT) capacity (number of CT cells). The limiting condition for the cold basin (CT outlet) temperature is 35°C, which is the maximum temperature condition for the client systems such as the PHTSs. The most thermally adverse design condition is that for the 3,000 s pulse length operation with 350 MW of fusion power. Under this condition, the numerical study predicts that a cold basin volume of 12,000 m^3 is required, and this is adopted as the reference volume.

The maximum temperature for a CT is ~ 48°C under the reference plasma conditions, and the corresponding required number of CT cells is ~ 6. The maximum value of the CT inlet temperature during a 3,000 s burn is predicted to be ~ 54°C, so 2 additional CT cells are required to maintain the maximum CT outlet temperature below 35°C. Therefore, 8 CT cells are specified as the reference design. However, installation of the additional 2 CT cells can be deferred until the 3,000 s burn operation is initiated. The ability of the supply water subcooling to compensate for evaporation from the free surface of the CT is not significant, because the evaporation is less than 4 % of the circulation flow rate.

One way to attain a longer burn duration is to prescribe less adverse atmospheric conditions. The CT performance under lower atmospheric (air) temperature conditions has been investigated numerically. The required atmospheric temperature to cool the water to 35°C decreases as the CT inlet temperature increases. The maximum CT inlet temperature is 55°C, and under this condition, an atmospheric temperature of 27.8°C is required to cool the cold basin water to 35°C. For atmospheric temperatures below 27.8°C, the numerical studies indicate that the cold basin temperature does not exceed 35°C, and under these conditions, there is no limitation on the operation duration without two additional CT cells.

3.3.4.5 Operating Duration under Higher Power Plasma

The allowable operating duration of the TCWS under a higher fusion power (~ 700 MW) has been investigated numerically. The blanket PHTS is taken as the study case. The integrity of the in-vessel components under higher power conditions is outside the scope of this study.

The coolant temperature in the blanket modules responds to an increased heat load with a time delay, and this coolant temperature propagates through the cooling loop at the flow velocity. The overall heat transfer rate in the HX increases in correspondence with the primary coolant temperature rise, and the temperature in the cold leg depends on the overall heat transfer rate in the HX.

The temperature trends at each location, the hot leg, the HX inlet, the main pump inlet, and the cold leg have been investigated using a simplified numerical model.

The allowable burn duration with a fusion power 40% greater than the reference value is ~ 60 s, due to the limitation of the blanket inlet temperature needed to keep sufficient thermal margin inside the blanket modules. This is the only factor from the heat transfer system side limiting the duration of high-beta plasma operation. Other aspects related to the higher temperature conditions do not generate additional constraints.

A countermeasure to prolong the allowable duration is to set a lower inlet temperature for the blanket modules in advance of the expected ~ 40% higher fusion power, and to set a lower HRS temperature for the HX to keep the requisite heat transfer capacity in the HX. In this case, the cold leg temperature during the first pass will be lower than the upper limit of the blanket module inlet temperature, and longer operation will be possible.

The thermal hydraulic behaviour under various temperature conditions has been investigated. These temperature conditions are compatible with the heat transfer capacity of the HRS, with the logarithmic mean temperature difference between the shell and tube sides in the HX remaining virtually the same across the range of temperature conditions. Therefore, the same temperature conditions can be maintained as during normal conditions.

Although the HX heat transfer capacity is increased corresponding to increases in the HX inlet temperature and the logarithmic mean temperature difference, the heat transfer capacity cannot match the thermal load with a ~ 40% higher fusion power. This means that the allowable duration cannot be extended without a bound under the conditions that have been investigated. The attainable duration, however, is extended under lower temperature conditions. The allowable duration under various conditions is summarized in Table 3.3.4-1.

Table 3.3.4-1 Allowable Operation Durations under Various Conditions

Condition	Case-1*	Case-2*
100°C (Blanket inlet) 35°C (HX inlet of HRS)	~ 60 s	~ 60 s
90°C (Blanket inlet) 25°C (HX inlet of HRS)	~ 160 s	~ 180 s
85°C (Blanket inlet) 20°C (HX inlet of HRS)	~ 260 s	~ 360 s

Case-1: with fouling and 5 % HX plugging,
Case-2: with fouling and no plugging

Fatigue of the tube sheet in the HX would be larger under lower temperature conditions because of the relatively high temperature difference between the shell and tube sides. Therefore, fatigue analysis is required in the detailed design phase if lower temperature operation is selected as one of the operation conditions.

3.3.5 Assessment of the Design

The cooling water system and its functions required to accomplish the ITER mission have been defined and the basic system design has been completed. The design operating conditions of critical components has been established. The cost reduction, segmentation of the in-vessel components, standardisation of components, feasibility of the installation and maintenance, staged installation, and acceptable impact for the building design due to peak pressures under ex-vessel coolant leaks, are the main drivers in these designs. These drivers lead to the number of loops and the layout adopted.

It has also been confirmed that the systems as designed satisfy the requirements on temperature and pressure control in the PHTSs, passive decay heat removal capability in the VV PHTS, and operational capability for 400 s pulses under reference plasma conditions and 3,000 s burn in non-inductive operation. The operable duration under 40% higher fusion power will be between 60 s and 360 s depending on the season (ambient atmospheric conditions) and inlet temperature pre-cooling.

In addition to site-specific design, further activity is desirable in the following areas to improve plant performance, to support an operating license application, and to optimise the system design:

(1) demonstration and measurement of data validating the natural convection characteristics of VV PHTS;
(2) plant operation/control system design (including plant shutdown sequence after off-normal events);
1) optimisation of layout considering facilitation of installation and maintenance, particularly for the upper pipe chase (including the pipe freeze method for leak localisation);
2) clarification of requirements for drying such as the maximum number of in-vessel components to be dried concurrently, and drying duration;

3) clarification of counter current flow limiting correlation for the blanket module and divertor cassette configuration, and optimisation of the system to blow-out the residual water after gravity drainage.