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Thermal Hydraulic Transient Analysis of ITER Chilled Water System: Decay Heat Exchanger Leak

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Abstract. Chilled Water System (CHWS-1) is an ITER safety cooling system comprised of two independent and segregated trains (CHWS-1A and CHWS-1B), which provide cooling water to components located in Tokamak and Hot Cell Complexes.

VV-PHTS is the only component that, during water baking mode, operates at high pressure than CHWS-1. In case of leaks, it represents a risk in terms of over pressurization and contamination of the CHWS-1 (due to tritiated water and activated corrosion products (ACPs)). Therefore, this paper postulates CHWS-1 leak events at one interface: Vacuum Vessel Primary Heat Transfer System. (VV-PHTS).

Three scenarios have been analysed: an incident event (heat exchanger pipe leakage) and two accident events (heat exchanger tube break and multiple tubes break).

A simplified RELAP5-3D model of CHWS-1B was developed to perform thermal hydraulic transient analysis as well as to define and size system operation and control.

A postulated accident management strategy is included while also defining CHWS-1 instrumentation and control (I&C), which play a relevant role in event detection and mitigation procedures.

The simulation results are studied to analyse and verify the system behavior as well as the required actions to reach and maintain a safe state after the given events.

With respect to the events studied, this paper reports and confirms the system design to properly and safely bring CHWS-1B to a shutdown, as per corresponding ITER project requirements.

This operating scenario has been studied for academic purposes; it is not related to the actual CHWS-1B design. During VV-PHTS baking mode, decay HX is not foreseen to be operative. In order to avoid affecting the redundancy of the system, this study supports this decision.

Keywords: Safety Important, RELAP5-3D, Thermal-Hydraulic Transient Analysis, Instrumentation & Control, Accident Management Strategy, ITER.

ACRONYMS

ACP: Activated Corrosion Product

CHWS: Chilled Water System

CILD: Client Decay HX Isolation on Leak & Pipe Break (LOCA) Detection

DM: Demineralized Water

DS: Detritiation Systems

DTR: Drain Tank Room

FP: Fail in Position

HX: Heat Exchanger

HLA: High Level Alarm

HPA: High Pressure Alarm

I&C: Instrumentation and Control

LAC: Local Air Cooler

LLA: Low Level Alarm

LOOP: Loss of Off-Site Power

LPA: Low Pressure Alarm

NBCP: Nuclear Building Confinement Protection

PIC: Protection Important Components

PRV: Pressure Relief Valve

PZR: Pressurizer

SIC: Safety-Important Component

TBM: Test Blanket Module

TDJ: Time-Dependent Junction

TDV: Time Dependent Volume

VHLA: Very High Level Alarm

VLLA: Very Low Level Alarm

VV PHTS: Vacuum Vessel Primary Heat Transfer System

VVPSS: Vacuum Vessel Pressure Suppression System

1. Introduction

ITER represents a critical step in the development of fusion energy, by providing an integrated demonstration of the physics and technology required for a fusion power plant.

The success of ITER highly depends on the effective removal of exceeding heat from the in-vessel components and the vacuum vessel during all stages of Tokamak operation, along with cooling the supporting systems. This objective will be accomplished by the Cooling Water System (CWS) [2].

The overall Cooling Water System (CWS) of ITER machine is divided into the following subsystems: Tokamak Cooling Water System, the Heat Rejection System (HRS) and the Secondary Cooling Water System [1].

The Secondary Cooling Water System is composed of the Component Cooling Water System, the conventional Chilled Water System (CHWS-H2) and the Safety Chilled Water System (CHWS-1).

CHWS-1 is a Safety Important System which operation is needed for the proper functioning of Protection/Safety Important Activities (PIA) & Components (PIC/SIC) (e.g. the decay heat removal from Plasma Facing Components and Vacuum Vessel).

Therefore, the CHWS-1 safety Instrumentation and Control (I&C) plays an important aspect of its relevant design. It is needed to monitor and detect any potential accidental scenarios that could imply tritium and Activated Corrosion Product (ACP) water contamination from the clients to the CHWS-1 circuits.

For this reason, in the present paper postulated incident and accident events (not related to the actual CHWS-1B design) that could cause the contamination of the CHWS-1 water, were investigated.

Decay heat exchanger tubes leakages and ruptures were studied in order to analyse the event evolution, define required measures to isolate the affected zone and estimate the amount of contamination in the system. It should be noted that this event type alone would not jeopardize CHWS-1 functioning.

The simulation is performed by means of RELAP5-3D version 4.4.2 code and the main results obtained are presented and briefly discussed [7].

2. CHWS-1 DESCRIPTION

CHWS-1 design considers two independent and segregated subsystems, CHWS-1A and CHWS-1B. Their primary function is to provide 6°C cooling water to safety-relevant redundant components in Tokamak and Hot Cell Complexes of ITER. Namely, it represents the secondary side of heat exchangers found in ITER Detritiation System (DS), Local Air Coolers (LACs), Vacuum Vessel Primary Heat Transfer System (VV-PHTS), Vacuum Vessel Pressure Suppression System (VVPSS), Test Blanket Module (TBM) Helium Coolant System and Hot Cell furnaces [3].

The system is sized for a temperature difference of 6° (6°C supply, 12°C return) while its operating pressure regime is 0.13 - 1.3 MPa.

With regards to cooling capacity, CHWS-1A and CHWS-1B can remove 1.81 MW and 2.39 MW, respectively, with a total flowrate of 72.25 kg/s and 95.44 kg/s.

CHWS-1 shall provide secondary nuclear confinement in the event of VV-PHTS heat exchange leak and meets ITER Safety-Important Component (SIC) requirements [1].

The system has to maintain coolant temperature, pressure, flow rate and water chemistry to ensure that component temperature and thermal margins are maintained during all the operations.

It also provides:

- Drain and refill capability (maintenance).
- Sampling capability for tritium and Activated Corrosion Products (ACPs).

The heat absorbed by CHWS-1 is transferred directly to the environment via air-cooled chillers.

Each subsystem consists of three air-cooled chillers and three horizontal centrifugal pumps (2W + 1S configuration), a pressurizer (PZR), a chemical dosing unit, valves, together with a dedicated piping distribution as well as instrumentation for monitoring and operational purposes, as shown in Figure 1.

Both CHWS-1 trains operate in parallel, using two pumps (each train).

The independence of these systems is also guaranteed by the physical separation of piping and equipment. Their physical separation aims to minimize the effect of system shut down in case of any foreseeable event. In addition, simultaneous failure of both trains is not envisaged.

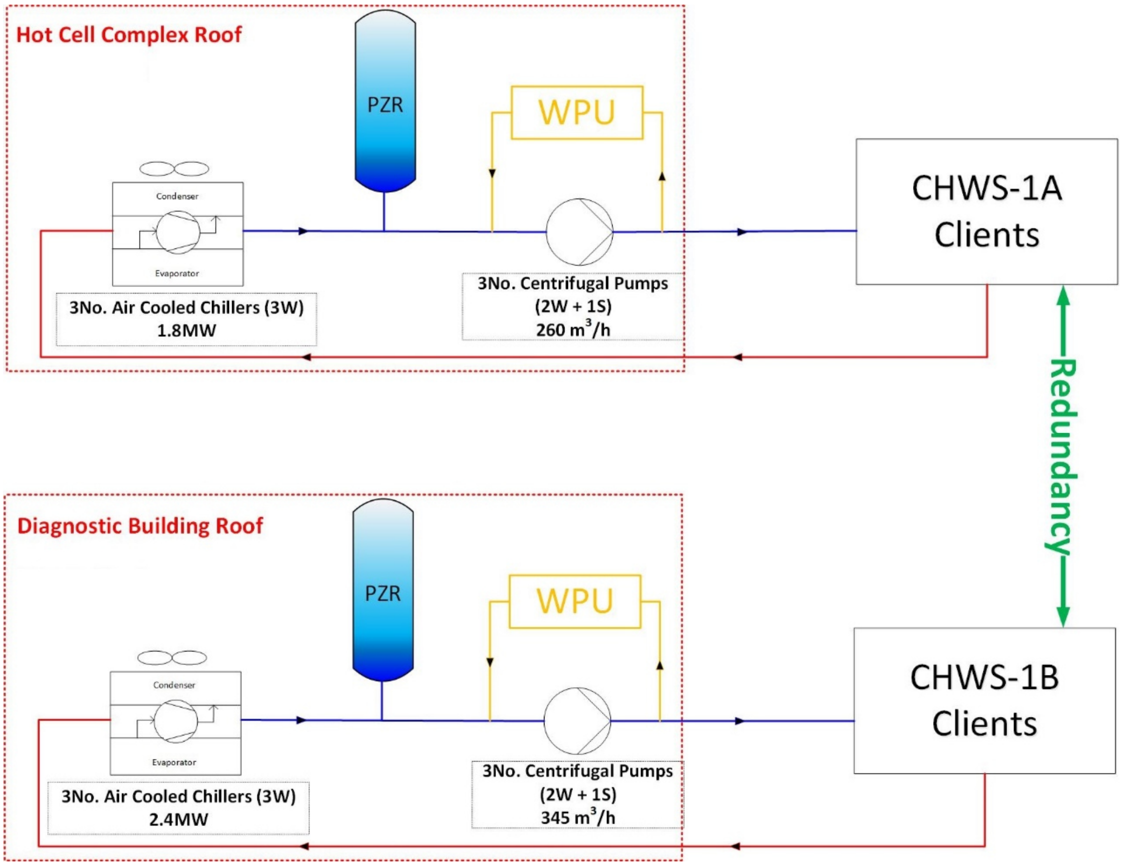

Figure 1: Basic configuration of CHWS-1

Pneumatic operated isolation valves are provided in order to isolate the system during accident scenarios, which could jeopardize Tokamak nuclear confinement barrier or render the system inoperative (Protection Important Components (PIC) valves).

CHWS-1 is a safety-important system and it is therefore designed to withstand all conditions resulting from any design-basis situations (normal operations or incidental/accidental situations) during and after which the system shall continue accomplishing its functions.

Piping that penetrates a last confinement barrier is designed to ensure that the confinement function is maintained during and after a design-basis event, including a seismic event.

Vacuum Vessel Primary Heat Transfer System (VV-PHTS) is the only component that is fed exclusively by CHWS-1B. The system needs to provide decay heat removal operations to this component only during Plasma Operation in case of Loss of off-site power (LOOP).
When VV-PHTS operates in water baking mode, the HX primary side is isolated from the rest of VVPHTS system. In the secondary side, the chilled water is deviated through a bypass line that is used when Class IV power is available.

The aim is to analyse the system behavior if it is requested to provide decay heat removal operation during water baking mode. Consequently, in case of necessity, there could be the possibility to accelerate the reduction of temperature in the VV-PHTS due to the intervention of CHWS-1B.

VV-PHTS baking mode operating pressure is higher than the one on CHWS-1 side. If VV-PHTS Decay HX is exposed to this high operating pressure, water may leak into CHWS-1B. VV-PHTS Decay HX leak into CHWS-1B has the added concern of contamination in terms of tritiated water and activated corrosion products (ACPs) [4].

3. Analysed Events

This paper describes the study of postulated events (incident and accident) that could cause tritium contamination of CHWS-1 [4] [5].
The analysed cases are used in order to test the safety function of the system, verifying its capability of accident mitigation and confinement barrier, so that no environmental contamination could occur as a consequence of these scenarios.

Tritium contamination of CHWS-1 water may occur only via components, served by the system, by means of leakage through the corresponding heat exchangers. It is assumed that a leak to CHWS-1 system can occur when VV-PHTS Decay HX primary side operating pressure is higher than the one measured on its secondary side (CHWS-1 side).

VV-PHTS is the only component, served by CHWS-1, that operates at higher pressure.

The analysis considers as Reference Event a water leakage from the VV-PHTS (primary side) to the CHWS-1B (secondary side). This event could happen exclusively during water baking thermal hydraulic conditions on VV-PHTS side because it is the only operating mode in which the pressure in the heat exchanger primary side is higher than secondary side.

In water baking operation, the heat exchanger pressure is 2 MPa on the primary side and 0.8 MPa on the secondary side (Table 1).

The maximum tritium concentration in VV-PHTS cooling water is 0.21 mg/m^3 (76 GBq/m^3), including measurement uncertainties [4]. While the maximum activity concentration due to ACPs is 66.5 MBq/ m^3 [6].

Table 1: Operating Conditions of VV-PHTS Decay Heat Exchanger

	Primary Side		Secondary Side	
Temperature [°C]	195	176	6	12
Pressure [MPa]	2	1.98	0.8	0.75
Mass flow [kg/s]	23.9		20	

In this paper, the following scenarios have been studied:

- Incident event: heat exchanger leakage.
- Accident event: heat exchanger tube rupture.
- Accident event: multiple heat exchanger tubes rupture.

The aim of incident analysis is to calculate the maximum allowed leakage through the decay heat exchanger, verify that no significant radiation deposit in the system results from the event and no serious consequential failures are expected (according to the limitation shown in Section 3.1).

While the accident scenarios, due to heat exchanger tubes rupture, are studied in order to analyse the system behavior and estimate the impact of the event in term of contamination.

3.1. Tritium and Activated Corrosion Product (ACP) Limitations

A drain line is provided in the CHWS-1 system to command, by operator action, the discharge of contaminated water. The drain line is further connected to the plant waste disposal system.

ITER suspicious effluents are sent to ITER Radwaste Treatment & Storage System and, afterwards, to the CEA/Cadarache Centre facilities for processing before release into the environment.

The maximum allowed level of activity contamination must be 74 MBq/m^3 for tritium releases and 74 kBq/m^3 for ACPs, according to ITER and CEA limitations ([8] and [9]). In order to guarantee CHWS-1B capability of quickly draining and refilling water, this limitation cannot be exceeded.

4. CHWS-1B RELAP5-3D Model

Referring to the system configuration described in Section **Errore. L'origine riferimento non è stata trovata.** and shown in Figure 2, a full model of the CHWS-1B has been prepared to perform the transient calculations.

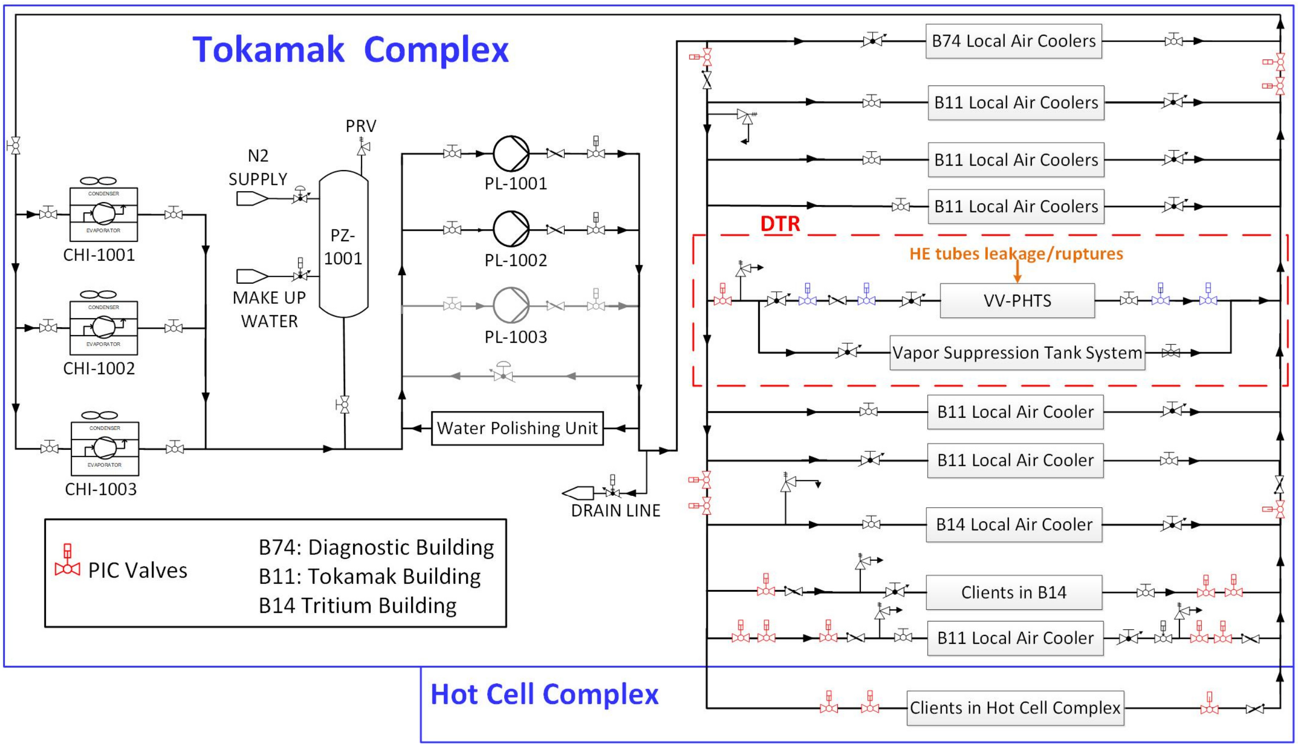

Figure 2: CHWS-1B Layout

4.1. Assumptions

To develop the CHWS-1B model, the following assumptions were considered:

- The model includes two operating pumps modelled as "Bingham Pump" and implemented with a logic trip based on the indication shown in Section 5. The presence of the stand-by pump is excluded from this analysis.
- Pump by-pass line has been modelled to maintain the proper flow to each component served by CHWS-1B. Online flow meter is provided on the pump common discharge header and it is used to regulate the FCV located in the bypass line. Associated logic has been implemented in the motor valve.
- Three air-cooled chillers have been modelled following a simplified approach: Their geometry has been selected in order to keep the total CHWS-1B water inventory. Heat structures have been implemented with a constant power boundary commanded by a trip logic in order to keep the water temperature at 6°C. A second trip has been set in order to interrupt chiller operation followed by a pump stop.
- A gas-PZR (N_2) has been modelled as a vertical cylinder. Pressure and water level are maintained by a demineralized water (DM) make-up line, N_2 supply line and a pressure relief valve.
  The N_2 supply and DM make-up lines are both modelled with a time-dependent volume (TDV) and a motor valve [12]. Corresponding valve trip logic is set according to Sections 5.2 and 5.3.
- Each component fed by the system in the Tokamak Complex has been modelled individually, except for three interfaces in the Tritium Building (B14), which are located considerably far away from the Reference Event location. For this reason, they have been collapsed into one equivalent component [10].
- As Hot Cell Complex building design is in the conceptual phase, its contribution to the overall CHWS-1 has been included as a *lump* component, following a conservative approach.
- Each component cooled by CHWS-1B, except VV-PHTS, has been modelled with a pipe segment and a heat structure [[13],[14]]. The geometry has been defined in order to respect the water inventory for each unit, while its associated heat structure has been set with a constant power condition. The heat transfer of these components is not stopped during all the simulation. This represents a conservative approach for the analysis of the transient since, in real conditions, heat transfer will be reduced as chilled water flow is interrupted.

- The primary side of the VV-PHTS Heat Exchanger is modelled in two different ways based on the analysed scenario:
  - When the incident scenario of the heat-exchanger leakage is performed, the HX primary side is modelled with a pipe segment connected upstream to a time dependent volume (TDV) and a time-dependent junction (TDJ) while it is connected downstream to a second TDV.
  - For the tubes rupture accidental events, the primary side is modelled with two parallel pipes instead of one. One pipe segment is sized in order to represent the HX tubes that remain intact during the event (P-5 in Figure 3), while the other line (P-6 and P-8 in Figure 3) is sized according to the number of broken tubes and consequently connected to the primary side in order to simulate the guillotine breaks (V-13 and V-14 in Figure 3)

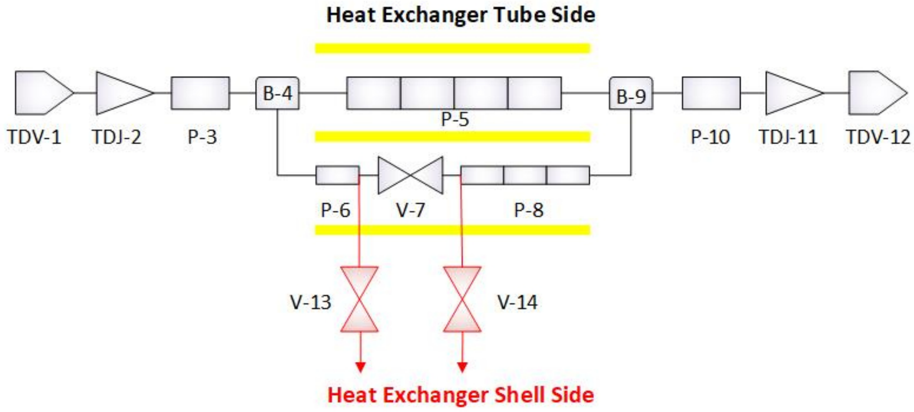

Figure 3: VV-PHTS Primary Side (during accidental scenarios)

While the secondary side of the HX is modelled as a single pipe segment connected to the CHWS-1 piping.

- CHWS-1 Protection Important Components (PICs) Valves are included in the model (marked in red in Figure 2).
- PIC valves and DTR isolation valves (marked in blue in Figure 2) have been modelled as motor valves with a closure time of 10 s and 5 s, respectively. These assumptions have been taken in order to intervene promptly during accident cases but also avoiding potential water hammer events [3]. The open/closure trip of these valves has been fixed according to Section 5.
- Several pressure relief valves have been located throughout the system. These valves are modelled as servo valves and they intervene in case of over pressurization events in order to not exceed the design pressure in the system (2.1 MPa). [11].
- Throughout this study, I&C response time of 5 s has been considered and implemented for all the CHWS-1B instrumentation.

5. Instrumentation and Control

CHWS-1 design considers the presence of required I&C for key components and at specific locations to fulfil conventional and safety functions.

Corresponding Instrumentation and Control (I&C) is implemented in the RELAP5-3D model to guarantee the system proper operation and protection.

5.1. Temperature Measurement

CHWS-1 temperature is monitored at specific locations to guarantee cooling function:

- At Chillers inlet and outlet lines, to ensure the temperature water within the operating range.
- At outlet line of each component cooled by CHWS-1, in order to verify that 12°C will not be exceeded.
- For each pump, as part of pump protection, to control the bearing temperature and the chilled water circulation pump motor winding temperature.

5.2. Pressure Measurement

Pressure in the system is an essential parameter that needs to be observed and monitored. Therefore, several pressure instruments are installed at the following location:

- Pressurizer. Readings taken are used for the pressure control.

  Two pressure alarms are set (Table 2): High Pressure Alarm (HPA) and Low Pressure Alarm. (LPA).

  In the case of PZR pressure reaching LPA, the valve in the nitrogen supply line opens.
  If PZR pressure exceeds HPA, the Safety PRV opens automatically, releasing excess pressure into the atmosphere.

  If the pressure in the pressurizer reaches LPA, the pump's trip and the consequently shut down of the system are commanded.

Table 2: Pressure Alarms in the PZR

$P_{pre\text{-}charge}$ during normal operation	0.22 MPa
LPA	0.17 MPa
HPA	0.27 MPa

- At the discharge line of the pumps to monitor their performance.
- At the inlet and outlet line of each Chiller.
- At VVPHTS supply and return lines, as shown in Figure 4 and listed in Table 3.

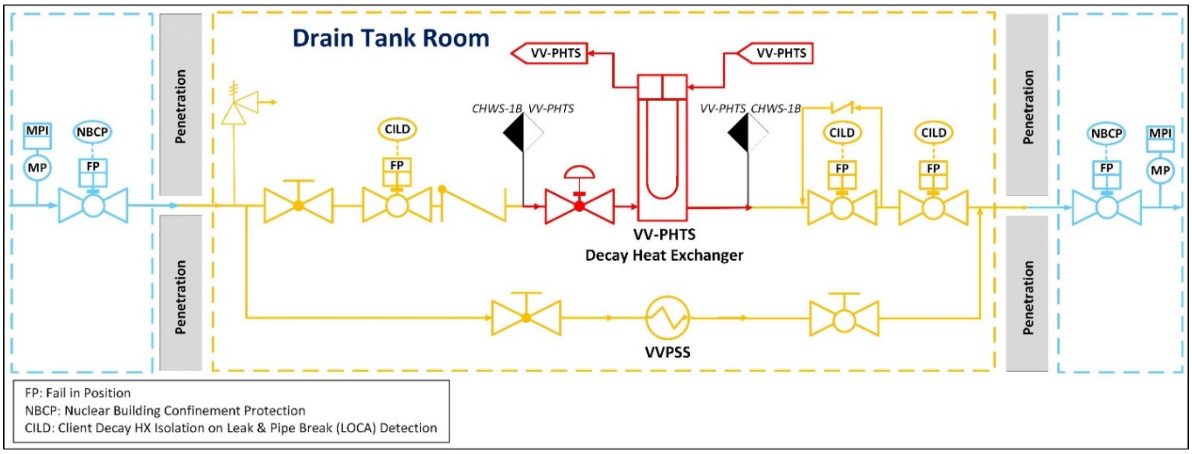

Figure 4: CHWS-1B line in the Drain Tank Room

When the measured pressure reaches the low-pressure setpoint (50% less than the pressure during normal operation), this means that a potential pipe break is causing a depressurization, so a signal is sent to command the closure of the PIC valves, to trip the pumps and to stop the system.
A high-pressure set point is also fixed (150% higher than the pressure during normal operation). This value is still lower than the system's design pressure and is used to detect an overpressure event in the DTR.

Table 3: Pressure Instrumentation in DTR

P during normal operation	1 MPa
LP setpoint	0.5 MPa
VLP setpoint	0.1 MPa
HP setpoint	1.5 MPa

- Pressure instrumentation is provided at the supply and return lines of some relevant components cooled by CHWS-1: VVPSS, DS and TBM.

If the measured pressure decreases until the limit of 0.1 MPa, the pumps' trip and the closure of the PIC valves are commanded.

5.3. Level Measurement

This instrumentation is used to measure, regulate and maintain the required water level in the pressurizer.

Pressurizer level control considers four alarms: Very High Level Alarm (VHLA), High Level Alarm (HLA) Low Level Alarm (LLA) and Very Low Level Alarm (VLLA) (as shown in Figure 5 and listed in Table 4) [15].

Table 4: Alarms in the Pressurizer

VLLA	0.25 m
LLA	0.4 m
HLA	0.7 m
VHLA	1.3 m
Total Height	2.00 m
Water Level during normal operation	0.57 m

When PZR level reaches LLA, make-up line feeds PZR with demineralized water. The valve remains open until the water attains the normal operating level.
When PZR level reaches HLA, a signal is sent to close the valve in DTR and isolate the potential accident.
The VLLA and VHLA command the trip of the pumps and the closure of the PIC valves in order to avoid jeopardizing the system.

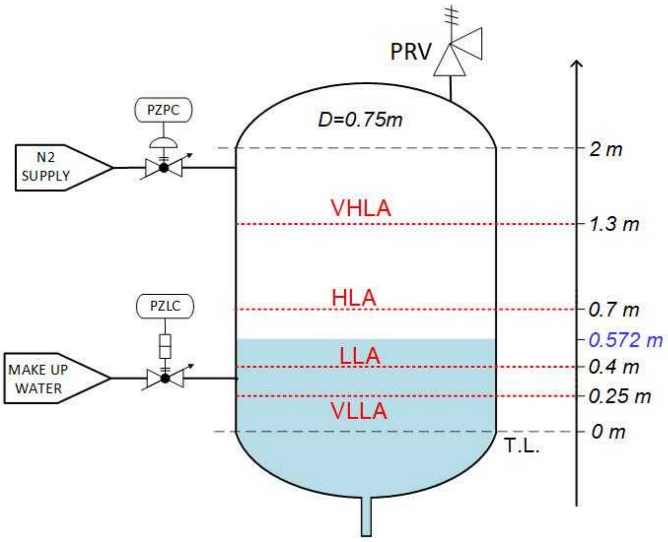

Figure 5: Level Control in the PZR

5.1. Flow Measurement

It is important to maintain the predefined water flow through each component fed by CHWS-1 to guarantee proper heat rejection. For this reason, a flow element, transmitter and indicator are provided on the pump common discharge header. This flow instrumentation is used to regulate the valve in the pump bypass line and maintain a constant flow in the system.

6. Analysis of the incident and accident scenarios

After having defined the CHWS-1B design, steady-state and transient analysis have been performed in incidental and accidental conditions.

All the analysed events consist in a water leakage from the VV-PHTS (primary side) to the CHWS-1B (secondary side).

During all the RELAP5 cases, in the first 100 s, a transient simulation has been performed in order to reproduce the start-up of the system. Then, the system reaches and operates in steady-state conditions for 100 s.

At 200 s from the start of the simulation, the incident/accident happens.

The results obtained from these numerical simulations allow to assess the capability of the system to respond to adverse conditions, verify the required time of intervention and evaluate the event mitigation.

6.1. Heat Exchanger Leakage

The incident case due to a small leakage has been analysed.
The cause of this leakage might be a small crack in the heat exchanger tubes and it represents, in practical terms, a difficult scenario to detect.

The size of this postulated small crack is defined so that the maximum leak rate in the heat exchanger does not cause CHWS-1B to exceed the contamination limit of 74 MBq/m^3 (see Section 3.1) and guarantee the CHWS-1 operation for 32 h. The 32 h value was selected as representative of a long duration loss of off-site power.

Indeed, the leakage rate was calculated considering the maximum contaminated activity in VV-PHTS water (76 GBq/m^3) and the total CHWS-1B water inventory of 57 m^3:

$$Q_{\text{leakage,MAX}} = \frac{(74\ \text{MBq/m}^3)\ \cdot\ 57\ \text{m}^3}{32\text{h}\ \cdot\ (76010\,\text{MBq/m}^3)} = 1.66\ \text{E}^{-03} = 1.66\ \text{l/h}$$

The RELAP5 simulation was performed for over 32 h in order to test the safety of the system and verify how it intervenes in order to not exceed the contamination level in the water.

It is crucial to be able to promptly discover the incident and isolate the affected zone; in order to mitigate the water contamination due to this event, the two CHWS-1B valves located on inlet and outlet lines of the VV-PHTS decay heat exchanger need to be closed. These valves are provided with fail in position type actuator.

The level of water in the PZR gradually increases until it reaches the HLA. At this point, a signal commands the closure of the isolation valves in the DTR (Figure 6).

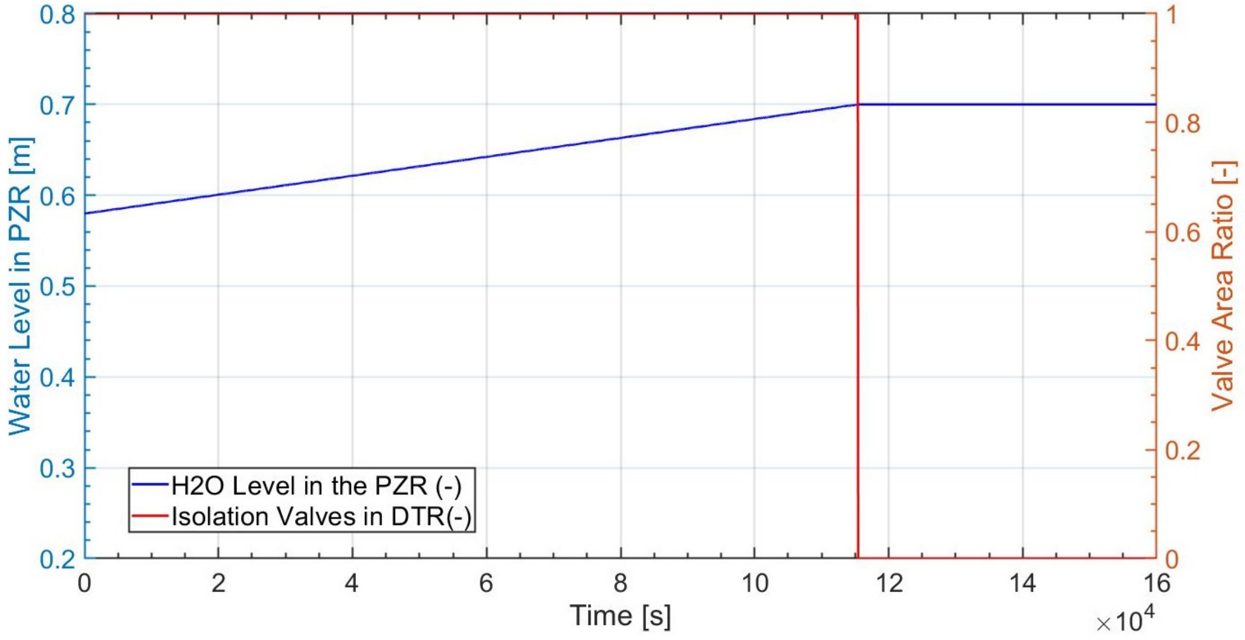

Figure 6: Level of water in the PZR vs time (incident analysis)

According to Section 4.1, the VV-PHTS is isolated 10 s after HLA is triggered (5 s have been considered for the I&C response time and further 5 s for the closure of the valves).

After the isolation of the affected CHWS-1B lines, the instrumentation located in the discharge line of the pumps detects a flow variation and commands the opening of the valve in the bypass line; in this way, the system can continue its operation, guaranteeing the required mass flow to the remain components fed by CHWS-1B.

In Figure 7, the trend of the mass flow through the bypass line has been shown.

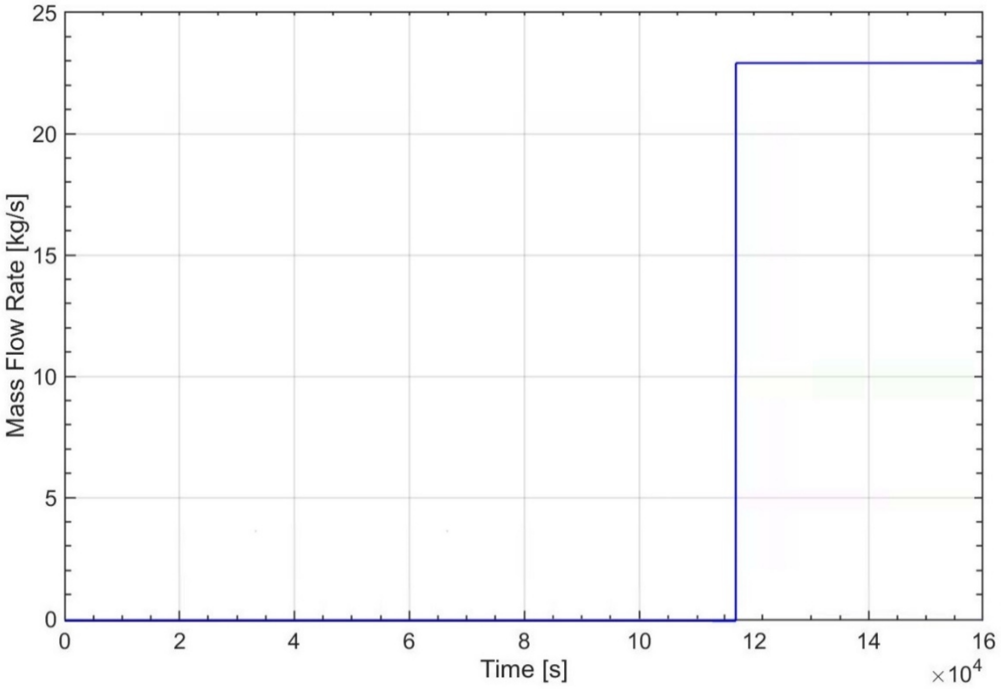

Figure 7: Mass flow through the pumps bypass line (incident analysis)

The total amount of water that flows from VV-PHTS into CHWS-1 during the RELAP5 simulation is 46.17 kg (Figure 8). In order to be conservative, this water has been considered with the maximum tritium concentration of 76 GBq/ m^3 and maximum ACPs concentration of 66.5 MBq/ m^3.

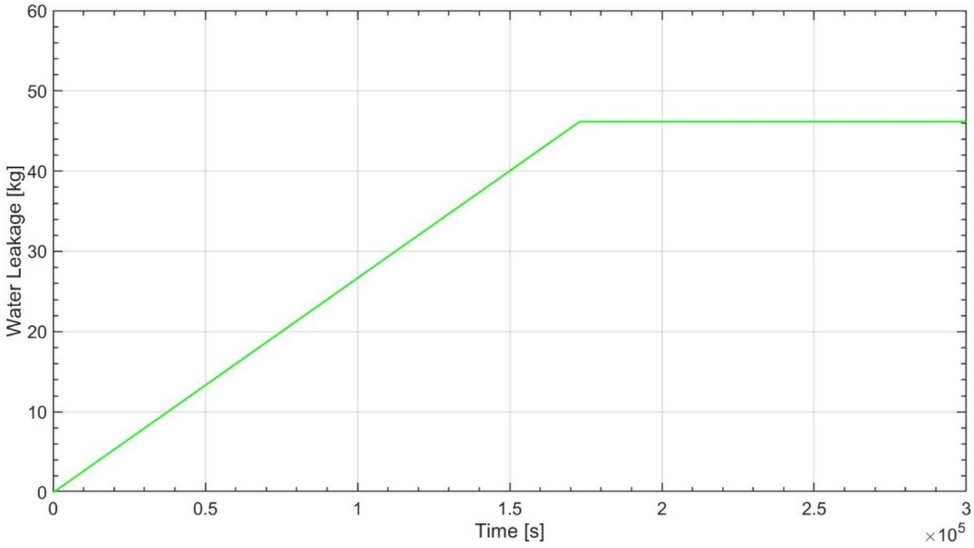

Figure 8: Amount of water leaked from VV-PHTS to CHWS-1(incident analysis)

The leak flow into the secondary loop is an input parameter in order to calculate the level of contamination in the system due to this event. It is assumed that tritium and ACPs, leaked into the HX secondary side, are confined within the secondary loop, which is considered to be intact.
Activation products and tritium will not be released into the atmosphere.

The total inventory of the CHWS-1B corresponds to 57 m^3 and, consequently, the level of contamination due to this event has been calculated and shown in Table 5.

$$C_{T,CHWS-1B} = \frac{C_{T,VV-PHTS} \cdot \rho \cdot Q_{leak}}{Q_{tot,CHWS-1B}} = \frac{76\ GBq/m^3 \cdot\ 46.17\ kg}{57m^3 \cdot 10^3\ kg/m^3} = 61.6\ \ MBq/m^3$$

$$C_{ACPs,CHWS-1B} = \frac{C_{ACPs,VV-PHTS} \cdot \rho \cdot Q_{leak}}{Q_{tot,CHWS-1B}} = \frac{66.5\ MBq/m^3 \cdot\ 46.17\ kg}{57m^3 \cdot 10^3\ kg/m^3} = 53.9 \cdot 10^{-3}\ \ MBq/m^3$$

Where:

$C_{T,CHWS\text{-}1B}$ and $C_{ACPs,CHWS\text{-}1B}$ are, respectively, the tritium and ACP activity concentrations in the system after the incidental event.

$C_{T,VV\text{-}PHTS}$ and $C_{ACPs,CHWS\text{-}1B}$, respectively, the maximum tritium and ACP activity concentrations in VV-PHTS.

Q_{leak} is the total amount of water that flows from VV-PHTS into CHWS-1.

$Q_{tot,CHES\text{-}1B}$ is the total inventory of CHWS-1B.

Table 5: Contamination due to leakage of VV-PHTS heat exchanger

	CHWS-1B Contamination Level	Contamination Limitation [6]
Tritium Concentration [MBq/m^3]	61.6	74
ACPs Concentration [MBq/m^3]	$53.9 \cdot 10^{-3}$	$74 \cdot 10^{-3}$

Both tritium and ACPs concentrations result below the limitations.

Moreover, a sampling connection is provided in the CHWS-1B system and periodic sampling may be taken for water quality analysis.

At this point, the drain line may be opened in order to discharge the contaminated water. While the PZR make-up line may refill the system with clean demineralized water.

6.1. Heat Exchanger Tubes Break

HE tube ruptures have been analysed as accidental cases in order to investigate the system behavior and to guarantee a proper detection and mitigation of these events.

The VV-PHTS decay heat exchanger is a “Shell and Tube, 1 shell pass and 2 tube passes” and the guillotine break of a tube has been performed.
Afterwards, the simultaneous failure of 5 tubes (10% of the HX total tubes) has been studied to test the robustness of the analysis with respect to multiple failures.

The transient analysis has been performed starting from steady-state and it lasted 1200 s in order to be able to analyse the event fully.

All the events cause a rapid increase of CHWS-1B pressure in the DTR that is detected by the instrumentation located in that zone (see Section 5.2).

Consequently, the closure of the PIC valves and the trip of the pumps are commanded and in 15 s (5 s is due to the I&C timing and 10 s is the valves closure time), the system stops operating.

In the meantime, the accident will cause an increase of water in the pressurizer and the HLA will command the closure of the isolation valve in the DTR.

Figure 9 shows water level trend in the PZR during a guillotine break and the state of the valves that determine the isolation of the system.

In Figure 10, it is shown the amount of contaminated water that flows in CHWS-1B during the accident scenarios.

No action from the primary side has been considered.

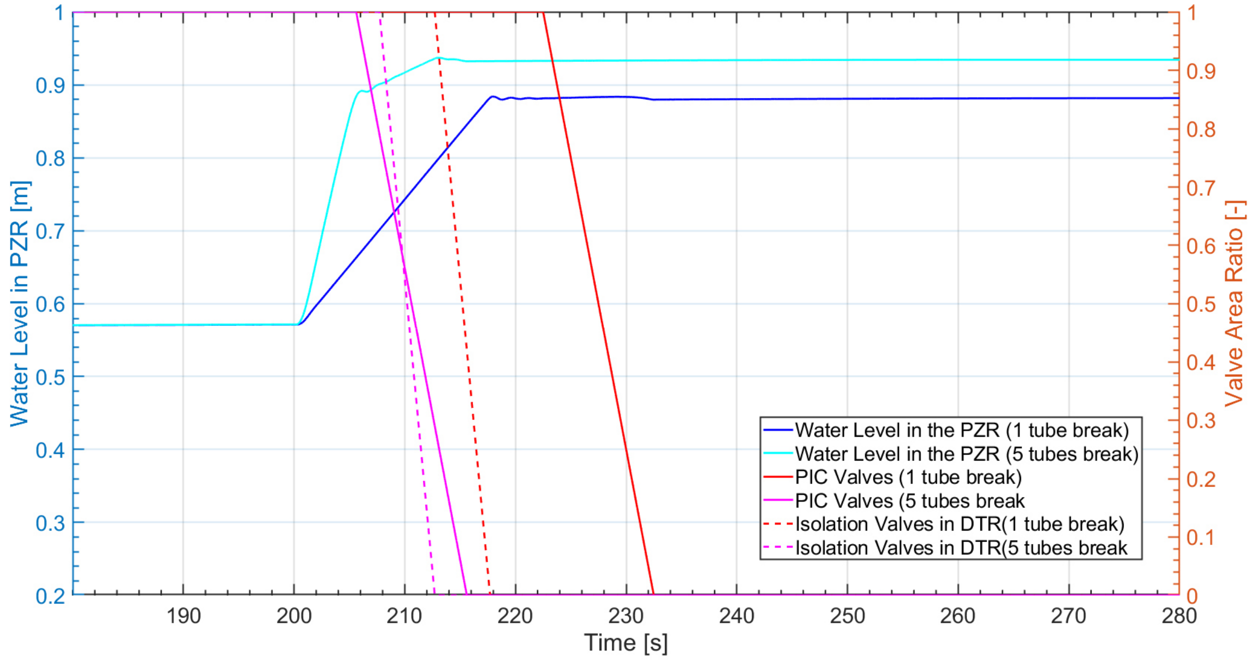

Figure 9: Level of water in the PZR and PIC valves state vs time

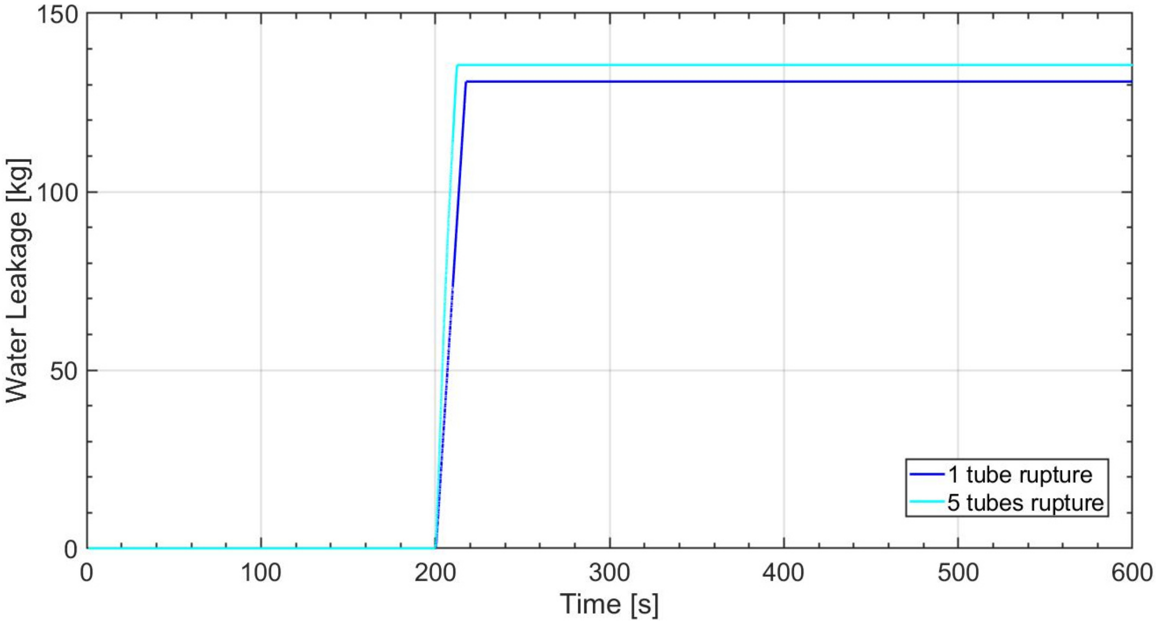

Figure 10: Amount of water through VV-PHTS heat exchanger

The high pressure setpoint of the I&C and the closure time of the valves have also been selected to avoid a peak of pressure during the accident that will exceed the CHWS-1B design pressure, eventually jeopardising the system.

These accidents cause the over pressurization of the system. The radioactive contamination exceeds the limitations provided in Section 3.1 (as shown in Table 6).

$$C_{T,CHWS-1B} = \frac{C_{T,VV-PHTS} \cdot \rho \cdot Q_{5-\text{tube break}}}{Q_{tot,CHWS-1B}} = \frac{76\ \text{GBq/m}^3 \cdot\ 135.5\ \text{kg}}{57\text{m}^3 \cdot 10^3\ \text{kg/m}^3} = 61.6\ \text{MBq/m}^3$$

$$C_{ACPs,CHWS-1B} = \frac{C_{ACPs,VV-PHTS} \cdot \rho \cdot Q_{5-tube\ break}}{Q_{tot,CHWS-1B}} = \frac{66.5\ MBq/m^3 \cdot\ 135.5\ kg}{57m^3 \cdot 10^3\ kg/m^3} = 53.9 \cdot 10^{-3}\ \ MBq/m^3$$

Where:

$C_{T,CHWS-1B}$ and $C_{ACPs,CHWS-1B}$ are, respectively, the tritium and ACP activity concentrations in the system after the accidental event.

$C_{T,VV-PHTS}$ and $C_{ACPs,CHWS-1B}$, respectively, the maximum tritium and ACP activity concentrations in VV-PHTS.

$Q_{5-tube\ break}$ is the total amount of water that flows from VV-PHTS into CHWS-1.

$Q_{tot,CHES-1B}$ is the total inventory of CHWS-1B.

Table 6: Contamination due to VV-PHTS heat exchanger tubes rupture

	CHWS-1B Contamination Level (1-tube break)	CHWS-1B Contamination Level (5-tube break)	Contamination Limitation [6]
Tritium Concentration [MBq/m^3]	174.48	180.67	74
ACPs Concentration [MBq/m^3]	$15.26\cdot10^{-2}$	$15.81\cdot10^{-2}$	$74\ \cdot10^{-3}$

The system cannot continue to guarantee its function of water regulation by refilling and draining lines (see Section **Errore. L'origine riferimento non è stata trovata.**). CHWS-1B shutdown is executed.

After the closure of the PIC valves, the pressure and the temperature in the system increase due to the power provided by the heat exchangers at the system interfaces.
As mentioned in Section 4.1, in order to be conservative, the components fed by the CHWS-1B have been modelled with constant power. For this reason, after the closure of the PIC valves, temperature and pressure in the system will increase more than in real conditions.

Pressure relief valves (shown in Figure 2 and described in Section 6) intervene in order to counteract the pressure increase and not exceed the system design pressure.

Nevertheless, after 15 min, the pressure conditions in the system are still under control (Figure 11).

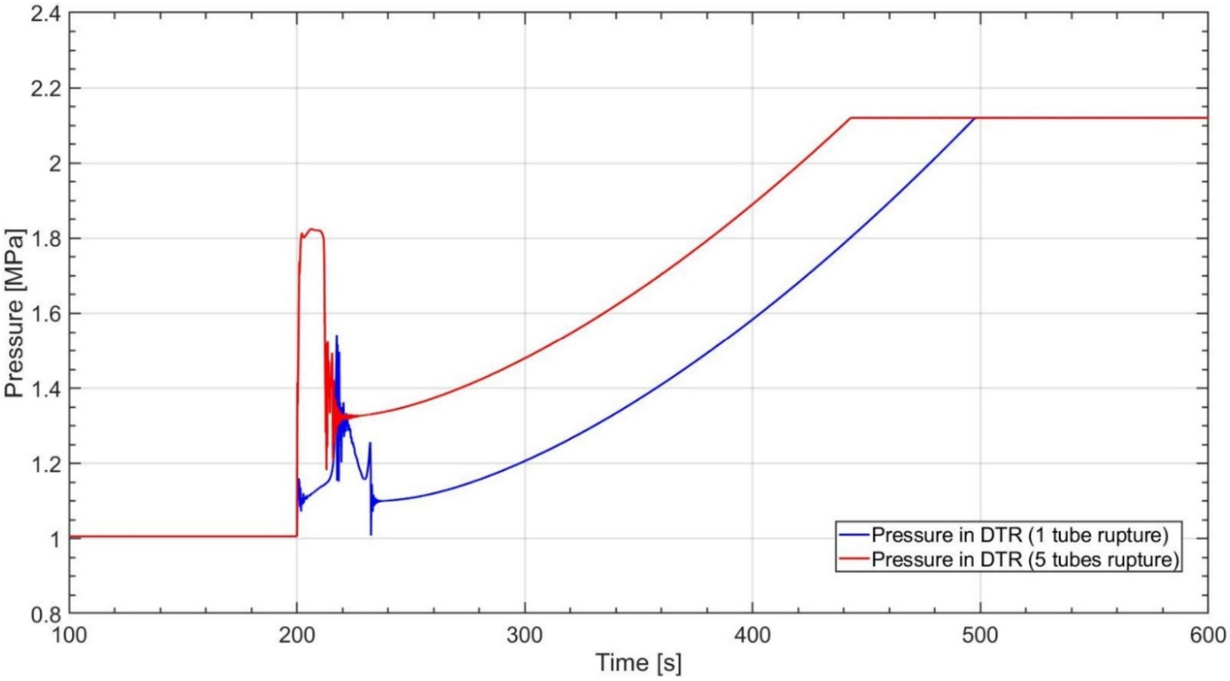

Figure 11: Measured pressure in the DTR inlet line

Meanwhile, CHWS-1 cooling operation is still provided by the CHWS-1A. After the complete mitigation of the accident, the CHWS-1B system could be gradually restarted and returned to normal operating conditions, keeping the damaged zone (DTR) isolated.

7. Conclusion

The activity discussed in this paper is aimed at analysing the CHWS-1 behaviour in case of postulated incidental/accidental scenarios. System code RELAP5/Mod3.3 was used, for which a preliminary model of the CHWS-1B systems was prepared.

Three scenarios have been studied: an incident event (heat exchanger pipe leakage) and two accident events (heat exchanger tube break and multiple tubes break). They have been selected to evaluate the system response and calculate the level of contamination caused by VV water flowing into CHWS-1B.

A sensitivity analysis was carried out and the different cases were evaluated on the basis of main parameters (mass flow, pressure, temperature). During the analysed scenarios, the simulation outcome shows that the system is able to detect and mitigate the incident/accident efficiently.

Despite the considered events have been studied exclusively for academic purposes, the analysis is useful if VV-PHTS temperature reduction is increased by CHWS-1B early intervention. This study may also be used to optimize CHWS-1 design and operating modes.

The results show that for incidental and accidental events including water contamination as well as pressure and temperature transients, there is no risk of system failure and environmental hazard.

During the analysed incident, the heat exchanger leakage is promptly detected and the affected line isolated. The level of tritium is maintained below the required limitation of 74 MBq/m^3 while the system can quickly drain the contaminated water.

More severe leakages, due to a single or multiple tube rupture in the heat exchanger, cause an over pressurization of the system and the contaminated water in CHWS-1B rapidly exceeds the tritium limitations. The accident management strategy guarantees the efficient shutdown of the CHWS-1B without affecting the integrity of the system; it can assure the possibility to restart the system afterwards. Meanwhile, the cooling operation of the system is accomplished by CHWS-1A.

In conclusion, the performed activity highlights that the system is able to mitigate all analysed incidental/accidental scenarios effectively. Nevertheless, the shutdown of the system must be executed in order to avoid exposing other components, served by CHWS-1B, to contamination risk.

As the current CHWS-1B design eliminates the chance of these events to ever occur, this study provides supporting evidence that it is a valid operating choice. Meanwhile, this investigation provides supporting evidence if CHWS-1 were to provide cooling capacity during VV baking mode.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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