Fusion Engineering and Design, 165 (2021) 112244, https://doi.org/10.1016/j.fusengdes.2021.112244

Thermal Hydraulic Transient Analysis of ITER Safety-Relevant Secondary Cooling Water System

Lavinia Vicini[a,b], Nicolás Schiliuk[a], Eugenio Coscarelli[a], Giovanni Dell'Orco[a], Vincenzo Narcisi[b], Gianfranco Caruso[b]

[a] *ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, St. Paul-lez-Durance Cedex 13067, France*

[b] *Sapienza, University of Rome, Department of Astronautical, Electrical and Energy Engineering (DIAEE), Corso Vittorio Emanuele II, 244, 00186, Rome, Italy*

The design of the Chilled Water System (CHWS-1) of ITER (Nuclear Facility INB-174) considers two independent and segregated subsystems, CHWS-1 A & B, which provide cooling water to safety-relevant components in Tokamak and Hot Cell Complexes.

CHWS-1 is a Safety Important System needed for the proper functioning of Protection/Safety Important Activities & Components and therefore Single Failure Criterion is included in its design, while physical separation between its trains is maintained as much as possible.

However, both CHWS-1 trains are located in the Tokamak Complex Drain Tank Room (DTR) and thus, measures are taken in order to protect them from common causes of failure (i.e. Fire or High Energy Line Break).

A failure of a given train in the DTR is investigated in order to analyse the consequences and take required additional measures so as to guarantee full safety cooling to CHWS-1 components outside DTR.

A RELAP5 model of CHWS-1B is developed and a pipe break inside the DTR modelled, to perform thermal hydraulic transient analyses of this event.

From the results, the transient evolution of the main thermal hydraulic parameters is determined and the required times of intervention evaluated in order to restore the cooling function of the affected CHWS-1 train for its remaining components. Thus, an accident management strategy is included in the analysis effort as well as a definition of CHWS-1 instrumentation and control fulfilling a relevant role in the event detection and mitigation. This paper summarizes the results of this activity.

Keywords: Safety Important, RELAP5, Pipe Break, Thermal-hydraulic transient analysis, Instrumentation & Control, Accident management strategy.

ABREVIATIONS

CHWS: Chilled Water System

DM: Demineralized Water

DTR: Drain Tank Room

HCC: Hard Core Component

HLA: High Level Alarm

HPA: High Pressure Alarm

LPA: Low Pressure Alarm

I&C: Instrumentation and Control

LAC: Local Air Cooler

LLA: Low Level Alarm

PRV: Pressure Relief Valve

PZR: Pressurizer

TBM: Test Blanket Module

TDJ: Time-Dependent Junction

TDV: Time-Volume Junction

VHLA: Very High Level Alarm

VLLA: Very Low Level Alarm

VV PHTS: Vacuum Vessel Primary Heat Transfer 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. For this reason, safety system design, like Chilled Water System (CHWS-1), would represent a challenge of great importance.

The ITER Secondary Cooling Water System is composed of the Component Cooling Water System, the conventional Chilled Water System and the Safety Chilled Water System. CHWS-1 design considers two independent and segregated subsystems, trains A & B, which provide cooling water to safety-relevant redundant components in Tokamak and Hot Cell Complexes of the ITER plant: Detritiation Systems, Local Air Coolers of the Hot Cell Complex and Tokamak Complex, Vacuum Vessel Primary Heat Transfer System (VV PHTS) and Test Blanket Module Helium Coolant System.

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

During operating states, both systems are capable to work in parallel, using two pumps (each train); the operating regime is 6-12°C (supply/return).

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

Moreover, probability of radioactive contamination in CHWS-1 is very low. Contamination of the CHWS-1 water, due to tritium and activated corrosion products, can happen only due to VV PHTS heat exchanger leak into CHWS-1, thus it is not foreseen to occur during normal operation.

Pneumatic operated isolation valves are provided in order to isolate the system during accident scenarios, which could jeopardize Tokamak last confinement barrier (Hard Core Component valves).

Tokamak Complex Drain Tank Room (DTR) represents critical zone for CHWS-1 because both the trains are placed there and in addition, a cooling pipe defined as high-energy line is located in their vicinity.

This study aims to investigate a postulated CHWS-1B pipe break in DTR, in order to analyse the event evolution and define required measures to isolate the affected CHWS-1B zone. In addition, it is also put forward the possibility to timely re-start the affected train and thus guarantee full safety cooling to CHWS-1 components outside DTR.

This event will not jeopardize the safety function of the CHWS-1; its functions can be fulfilled with just one train working due to the redundancy of the clients fed by both the systems.

The simulations performed by means of RELAP5 mod3.3 code and the main results obtained are presented and briefly discussed.

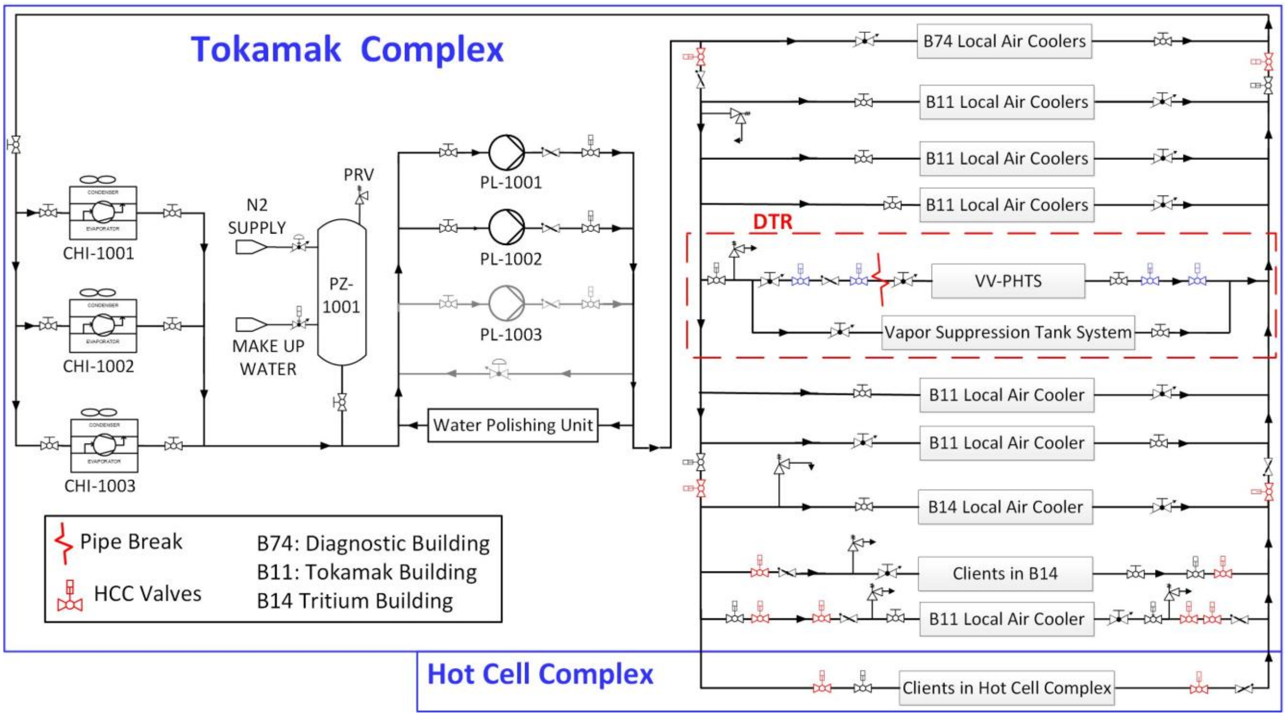

Figure 1: General layout of CHWS-1B

2. CHWS-1B RELAP5 MODEL

The system configuration that has been considered for the RELAP5 analysis is shown in Figure 1.

2.1. Assumptions

In order 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 of Chapter 2.2. The presence of the stand-by pump is excluded from this analysis.
- Three air-cooled chillers have been modelled with a simplified approach. Their geometry has been selected in order to keep the water inventory of the components. 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 stop the chiller operation when the pumps trip occurs.
- A gas-PZR (N_2) has been modelled as a vertical cylinder. Pressure and water level are maintained by a DM make-up line, a N_2 supply line and a pressure relief valve.
  The make-up and supply lines are both modelled with a time-dependent volume (TDV) and a motor valve commanded by corresponding trips set according to Chapter 2.2.
- 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 accident

location. For this reason, they have been collapsed into one equivalent component [1].

- The system design in the Hot Cell Complex is still ongoing and thus its contribution to the overall CHWS-1 is included as a *lump* component.
- Each component fed by CHWS-1B, except for the VV-PHTS, has been modelled with a pipe segment and a heat structure. The geometry has been developed in order to respect the inventory of water of each unit and the heat structure has been set with a constant power condition This still 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 VV-PHTS model includes the shell side of the Heat Exchanger and a pipe segment connected upstream to a TDV and a time-dependent junction (TDJ) while downstream to a second TDV.
- CHWS-1 Hard Core Components (HCCs) Valves are included in the model (marked in red in Figure 1).
- HCC valves and DTR isolation valves (marked in blue in Figure 1) have been modelled as motor valves with a closure time of 10 seconds and 5 seconds, respectively. These assumptions have been done in order to intervene promptly during accident cases but also avoiding potential water hammer events.
- In order to avoid vacuum formation, cavitation due to depressurization and potential water hammer consequence (due to water column separation phenomena), as a preliminary approach four Air Vacuum Breaker Valves have been located in the system [3].

2.2. Instrumentation and Control

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

Pressurizer level and pressure controls consider four level alarms (VHLA, HLA, LLA and VLLA) and two pressure alarms (HPA and LPA) (Table 1).

Table 1: Alarms in the Pressurizer

VLLA	0.25 m
LLA	0.4 m
HLA	0.7 m
VHLA	1.3 m
Cylinder Total Height	2.00 m
Water Level during normal operation	0.58 m
$P_{pre\text{-}charge}$ during normal operation	2.2 bar
LPA	1.7 bar
HPA	2.7 bar

When PZR level is below LLA, make-up line feeds PZR with demineralized water. The valve remains open until the water attains normal operating level (0.55 m).

In the case of PZR high pressure reaching HPA, the Pressure Relief Valve (PRV) in the nitrogen supply line opens. If PZR pressure exceeds HPA, the PZR Safety PRV opens automatically, releasing excess pressure into the atmosphere [2].

Pressure transmitters are installed in numerous locations through the CHWS-1 piping network. Associated I&C is considered so that when the measured pressure reaches the first pressure setpoint (50% less than the pressure during normal operation), a signal will command the closure of the isolation valves in the DTR in order to isolate the potential break. If the pressure reaches a second setpoint (1 bar) this means that the break could be located in other areas of the system or that the break in the DTR had caused a too fast depressurization so a second command will be sent to close the HCC valves and stop the system.

HCC valves command is also triggered due to PZR VLLA as well as PZR LPA.

Meanwhile, during the accident scenario, the trip of the pump is commanded when any of the following conditions occur:

- Water level in the pressurizer reaches VLLA or HLA.
- Pressure in the pressurizer reaches LPA
- Pump suction pressure goes under the low limit of 1 bar.

Finally, if the pressure in the system increases, reaching the system design pressure (21 bar), several pressure relief valves, located throughout the system (Figure 1) intervene in order to avoid system over pressurization.

3. ANALYSIS OF THE ACCIDENT SCENARIO

After having defined the system design, the CHWS-1 Model has been implemented to perform thermal transient simulations in accidental conditions. The results obtained from this numerical simulation allow to assess the capability of the system to respond to adverse conditions, verify the required time of intervention and evaluate the event mitigation.

Several pipe break scenarios have been performed, ranging from small to very large breaks (10% pipe area break to double-ended guillotine break).

The accumulated water leaked through the break is shown in Figure 2. The total inventory of the system corresponds to 40000 kg.

The simulation has been run for 1000 seconds in order to study the response of the system. This running time has been chosen so that the complete transient is captured.

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

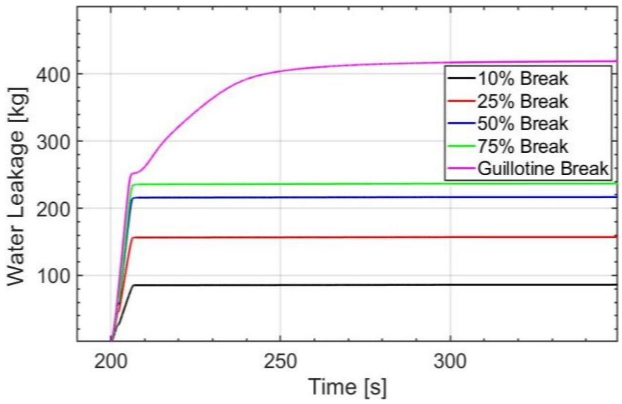

Figure 2: Amount of water through the pipe break

At 200 seconds, the pipe break happens. For all the cases shown, one second after the pipe break, the pressure transmitter located upstream of the pumps already records the anomaly; the measured pressure reaches the first pressure setpoint and the signal to close the isolation valves in the DTR is sent. Meantime, in the PZR, the level of water decreases and reaches the LLA, and thus the make-up valve is commanded to open in order to provide demineralized water.

During all the cases presented, the pressure decrease occurs rapidly, compared to the closure time of the isolation valves; subsequently, the pressure measured by the instrumentation reaches 1 bar and thus the HCC valves are commanded to close, and consequently the pumps and chillers are tripped. Figure 3 shows the trend of the water level in the PZR during a guillotine break and the state of the valves that determine the isolation and refilling of the system. This trend is maintained, also during the other accident scenarios. The intervention times remain unchanged while the PZR level variation is less accentuated according to the size of the break

After 225 s the curves stabilize and remain constant.

Although the water level in the pressurizer become stable, the flow rate of water lost by CHWS-1B, during the guillotine break accident, continues to slowly increase up to approximately 300 seconds (as shown in Figure 2). This happens because the water inside the isolated section of the CHWS-1 piping, located in the DTR, will flow through the pipe break even after the closure of the isolation valves.

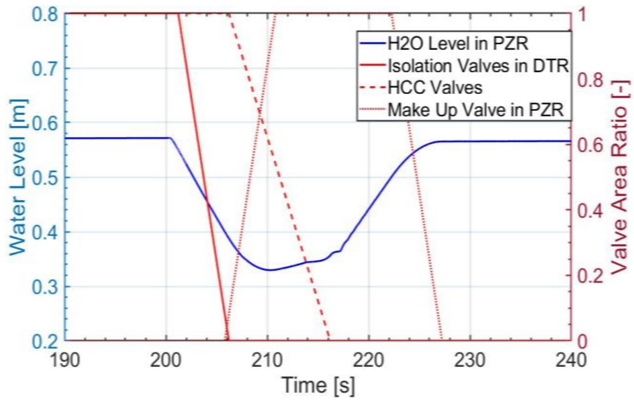

Figure 3: Level of water in the PZR vs time

After the closure of the HCC valves, the pressure and the temperature in the system increases due to the power provided by the Heat Exchangers at the system interfaces. During these simulations, the components fed by the CHWS-1B have constant power so, even after the closure of the valves, the temperature and pressure increases more than in real conditions. Nevertheless, after a consistent amount of time from the start of the accident (800 seconds), the pressure conditions in the system are still under control.

Meanwhile, CHWS-1 cooling operation are still provided by the CHWS-1A.

When the accident is completely mitigated, the static pressure in the CHWS-1B needs to be restored and the system could be gradually restarted and returned to normal operating conditions, keeping the DTR isolated.

4. CONCLUSIONS

The study reports the results of a transient analysis of the CHWS-1B, under accidental conditions (Pipe break in DTR). CHWS-1 is a safety-important system, designed to withstand all loads and conditions resulting from any design basis situations, normal or accidental, and to continue fulfilling its safety functions.

During all the transient cases that have been analysed, the accident management strategy guarantees efficient detection and mitigation.

In fact, after the isolation and the shutdown of the system, it is possible to maintain a stable condition for a consistent amount of time without affecting the integrity of the system.

Further studies are envisaged in order to assess post-event situation and to identify the required operations to restore the operating function of the system.

DISCLAIMER

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

REFERENCES

[1] Engineering Thermofluids, Thermodynamics, Fluid Mechanics, and Heat Transfer", Mahmoud Massoud,

Springer 2005
[2] API 520 Part I - Sizing, Selection, and Installation of Pressure-relieving Devices Part I—Sizing and Selection
[3] Air Valves: Air-Release, Air/Vacuum & Combination; American Water Works Association; Second Edition.
[4] RELAP5/MOD3.3 CODE MANUAL; January 2002; Information Systems Laboratories, Inc.; Rockville, Maryland; Idaho Falls, Idaho
[5] Technical Standard “Flow of Fluids Trough Valves, Fittings, and Pipe Technical Paper ;No. 410M”; Crane, 2013 Edition
[6] ASTM A672/A672M – 09, “Standard Specification for Electric-Fusion-Welded Steel Pipe for High-Pressure Service at Moderate Temperatures”
[7] ASTM A312/A312M – 12a, “Standard Specification for Seamless and Welded Austenitic Stainless Steel Pipes”