Article

Numerical Simulation of an Out-Vessel Loss of Coolant from the Breeder Primary Loop Due to Large Rupture of Tubes in a Primary Heat Exchanger in the DEMO WCLL Concept

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Abstract: This work presents a thermohydraulic analysis of a postulated accident involving the rupture of the breeder primary cooling loop inside a heat exchanger (once through steam generator). After the detection of the loss of pressure inside the primary loop, a plasma shutdown is actuated with a consequent plasma disruption, isolation of the secondary loop, and shutoff of the pumps in the primary; no other safety counteractions are postulated. The objective of the work is to analyze the pressurization of the primary and secondary sides to show that the accidental overpressure in the two sides of the steam generators is safely accommodated. Furthermore, the effect of the plasma disruption on the FW, in terms of temperatures, should be analyzed. Lastly, the time transients of the pressures and temperatures in the HX and BB for a time span of up to 36 h should be obtained to assess the effect of the decay heat over a long period. A full nodalization of the OTSG was realized together with a simplified nodalization of the whole PHTS BB loop. The code utilized was MELCOR for fusion version 1.8.6. The accident was simulated by activating a flow path which directly connected one section of the primary with the parallel section of the secondary side. It is shown here that the pressures and the temperatures inside the whole PHTS system remain below the safety thresholds for the whole transient.

Keywords: WCLL-BB; MELCOR; PHTS; safety analysis; DEMO

1. Introduction

In the Roadmap to Fusion Electricity Horizon 2020, the European DEMOnstration Fusion Reactor (DEMO) is expected to be a nuclear fusion power plant with the aim of showing the feasibility of the production of electrical power through the conversion of around 2 GWth, generated continuously by the fusion reaction. The operational sequence is a pulsed operation, which consists of 11 pulses per day; each pulse comprises a burn time of 2 h (power pulse period; 100% of fusion power) and a dwell time of 10 min (1% of fusion power generated due to the decay heat) [1,2].

The work presented here aims to investigate the consequences of a loss of coolant accident in the primary heat transport system (PHTS) of the water-cooled lithium lead (WCLL) breeding blanket (BB) DEMO concept [2–4]. In particular, the objective of this work is the simulation of a rupture of pipes of the primary system into the PCS (power conversion system or secondary system) inside the once through steam generator (OTSG) which acts as interface between the two systems [5–7]. In normal operations, the energy transferred from the breeding zone (BZ) and from the first wall (FW) to PCS through steam generators is used to produce the main steam at condition suitable to feed the steam turbine.
The postulated accident foresees the rupture of the primary cooling loop inside the OTSG with a discharge of primary coolant in the secondary side.

In this work, a detailed nodalization of the primary and secondary system of the OTSG is presented together with a simplified nodalization of the whole BZ loop. A connection between the two sides of the OTSG is created in order to simulate the LOCA scenario, which comprises a mitigated plasma disruption, and the results of the consequent transients are analyzed and discussed.

The nodalization of the involved systems was created with MELCOR for fusion 1.8.6, and all the simulations were performed with the same code. The MELCOR code has been under development for fusion applications for many decades [8,9]. Chiefly because of its capabilities of assessing thermal–hydraulic transients of fusion reactor systems and the transport of radionuclides, MELCOR was chosen, together with other system thermal hydraulics codes, to be used to perform safety analyses for the ITER project and, consequently, for the DEMO project [10]. Especially in the last 10 years, MELCOR was widely used for accident analysis related to ITER reactor safety and in the preliminary design phase of the DEMO reactor ([11–17], among many others).

2. DEMO WCLL-BB PHTS System
2.1. General Parameters and Power Data

The thermodynamic cycle used as reference for the design of the WCLL BB PHTS DEMO reactor was mainly based on parameters similar to pressurized water reactors: the coolant was water at 15.5 MPa with inlet and outlet temperatures equal to 295 °C and 328 °C, respectively [3,7–9]. The main working parameters of the BB PHTS are given in Table 1, whilst the power parameters are reported in Table 2. Furthermore, Table 3 collects the mass flow rates of the FW and the BZ cooling systems. All the parameters and characteristics summarized here can be found in several technical and published studies [18].

| Description                          | Units | Parameters |
|--------------------------------------|-------|------------|
| Typology of coolant                 |       | Water      |
| Pressure                             | MPa   | 15.5       |
| Temperature range                    | °C    | 295–328    |
| Coolant density (-average)           | kg/m³ | 701.3      |
| Design pressure                      | MPa   | 17.8       |
| Design temperature                   | °C    | 345        |
| Total flow rate                      | kg/s  | 9936.0     |
| FW flow rate                         |       |            |
| Inboard (IB) blanket                 | kg/s  | 17.8       |
| Outboard (OB) blanket                | kg/s  | 35.5       |

Table 1. WCLL DCD BOP BB cooling system parameters [3].

| Description                          | Unit  | WCLL 2018 Design |
|--------------------------------------|-------|------------------|
| Total nuclear heating                | MW    | 1650.3           |
| Total FW Heat Flux                   | MW    | 272.7            |
| Neutron Wall Load                    | MW    | 167.0            |
| Total FW power                       | MW    | 439.8            |
| Total BZ power                       | MW    | 1483.2           |
| Total power                          | MW    | 1923.2           |

Table 2. DEMO and WCLL DCD BOP BB power balance [3].
Table 3. WCLL DCD BOP BB power and coolant flow rates (TD 295–328 °C) [3].

| Description          | Power (MW) | Mass Flow Rate (kg/s) |
|----------------------|------------|-----------------------|
|                      | Total      | FW        | BZ       | Total | FW       | BZ       |
| IB segment           | 12.780     | 3.449     | 9.331    | 66.0  | 17.8     | 48.2     |
| IB sector            | 25.560     | 6.898     | 18.662   | 132.0 | 35.6     | 96.4     |
| Total IB sectors (16)| 409.960    | 110.368   | 298.592  | 2112.0| 569.6    | 1542.4   |
| OB segment           | 31.545     | 6.867     | 24.678   | 163.0 | 35.5     | 127.5    |
| OB sector            | 94.635     | 20.601    | 74.034   | 489.0 | 106.5    | 382.5    |
| Total OB sectors (16)| 1514.160   | 329.616   | 1184.54  | 7824. | 1704.    | 6120.    |
| Total reactor        | 1923.120   | 439.984   | 1483.136 | 9936.0| 2273.6   | 7662.4   |

The WCLL DCD BOP BB PHTS constitutes two independent primary systems:
- The BZ primary system (BZ PHTS);
- The FW primary system (FW PHTS).

The main components of the WCLL BB PHTS are indicated in the 3D CAD model (see Figure 1). Table 4 reviews the system-relevant data [2,7,19,20]. Details of the system architecture can be found in [18].

During normal operations, in pulse time, BZ and FW PHTSs transfer power to the PCS, through two once through steam generators (OTSGs) per system (i.e., four SGs in total). The BZ PHTS power is 1483 MW, and the FW PHTS power is 439.8 MW. A total of six main coolant pumps (MCPs) are installed to allow the circulation of the primary coolant (four pumps for BZ PHTS and two for FW PHTS). Each PHTS is equipped with a pressurizer (PRZ).

Figure 1. Overview of the DEMO WCLL BB PHTS.
Table 4. System-relevant parameters.

| WCLL DCD BOP BB PHTS Design and Operating Parameters | BZ | FW |
|-----------------------------------------------------|----|----|
| **General**                                         |    |    |
| Thermal power (MW)                                  | 1483 | 439.8 |
| Operating pressure (MPa)                            | 15.5 | 15.5 |
| Reactor vessel inlet temperature (°C)               | 295 | 295 |
| Reactor vessel outlet temperature (°C)              | 328 | 328 |
| Overall volume (m³)                                 | ~563 | ~159 |
| Overall PHTS piping length (km)                     | ~3.2 | ~3.7 |
| Number of loops                                     | 2 | 2 |
| **Loop data**                                       |    |    |
| Piping length (km)                                  | ~1.25 | ~1.52 |
| Hot/cold manifolds per loop and size                | 8/8 | 8/8 |
| Hot/cold legs per loop and size                     | 1/2 | 1/1 |
| Hot/cold ring header per loop and size              | 1/2 | 1/1 |
| **Pump**                                            |    |    |
| Number of pumps per loop                            | 2 | 1 |
| Effective pump power to coolant (MW)                | 3.03 | 1.79 |
| **Pressurizer**                                     |    |    |
| Number of units                                     | 1 | 1 |
| Total volume (m³)                                   | 101.4 | 32.5 |
| Liquid volume (m³)                                  | 44.8 | 16.3 |
| **Heat Exchanger (Steam Generator)**                |    |    |
| Number of units                                     | 2 | 2 |
| Steam generator power (MWth/unit)                   | 742 | 219.9 |
| Type                                                | OTSG | OTSG |
| Heat transfer area (m²/unit)                         | 4903 | 1423 |
| Feedwater temperature (°C)                          | 238 | 238 |
| Exit steam pressure (MPa)                           | 6.4 | 6.4 |
| Steam flow per SG (kg/s)                            | 404 | 119.9 |
| Flow rate per SG (kg/s)                             | 3831.2 | 1136 |

2.2. BZ Once through Steam Generator

In the BZ Primary System, each OTSG removes 742 MWth of thermal power, with a mass flow rate of coolant equal to 3831.2 kg/s. On the secondary side, the water is assumed to be at a pressure of 6.4 MPa, and the feedwater coolant inlet temperature is expected to be at 238 °C. The feedwater flow rate is imposed at 404 kg/s, in order to produce the same amount of superheated steam at 299 °C. It is important to underline that the OTSG is still in a design phase [21,22]. A simplified scheme of a generic OTSG is shown in Figure 2 and the main characteristics are summarized in Table 5.

The selected OTSG is characterized by 7569 tubes, with a length of 12.987 m.
Figure 2. Conceptual scheme for once through steam generator [21].

Table 5. Main features of an OTSG.

| Feature                  | Value       |
|--------------------------|-------------|
| SG Power                 | MW<sub>th</sub>   | 742         |
| Primary side pressure    | MPa         | 15.5        |
| Primary side water T<sub>in</sub> | °C   | 328        |
| Primary side water T<sub>out</sub> | °C  | 295        |
| Secondary side pressure  | MPa         | 6.41        |
| Secondary side water T<sub>in</sub> | °C   | 238        |
| Secondary side water T<sub>out</sub> | °C  | 299        |
| No. of tubes             | --          | 7569        |
| Tube OD                  | mm          | 15.88       |
| Tube thickness           | mm          | 0.864       |
| Tube length              | m           | 12.987      |
| Tubesheet lattice        | --          | Square      |
| Tubesheet p/D            | --          | 1.28        |
| Heat transfer area       | m<sup>2</sup> | 4903      |
| V water tubes            | m<sup>3</sup> | 20         |
| D<sub>ext</sub> vessel   | m           | 2.9         |
2.3. BB and PHTS Integration

The WCLL DEMO 2018 blanket is composed of 16 sectors (22.5°) in the toroidal direction [4,23]. Each sector consists of three poloidal segments in the OB (outboard) blanket and two poloidal segments in the IB (inboard) blanket. The geometrical features and the inventory of the WCLL-BB are provided in Table 6.

The inner structure of each segment comprises a stack of about 100 toroidal–radial so-called breeding units (BUs). The BU is a sort of elementary cell repeated along the poloidal direction of each segment. It features the integrated FW–SW complex, the BZ, and the corresponding part of manifolds and BSS.

The coolant feeding pipes deliver cold water to FW and BZ systems, whilst the outlet pipes collect hot water and distribute it to the PHTS.

Considering the FW and BZ systems, the volume of water is estimated taking into account the BUs (assuming a rough value of 100 for each sector), the manifolds, and the feeding pipes. Furthermore, the velocities in the inlet feeding pipes and distributors were calculated assuming a density of 737.1 kg/m³ (15.5 MPa and 295 °C), while a density of 657.5 kg/m³ (15.5 MPa and 328 °C) was taken for the outlet pipes and collectors. The main geometrical data are provided in Table 6.

Table 6. WCLL BB In-Vessel inventory.

| Description                  | Pipe Size      | OD (mm) | Thick. (mm) | MF Total (kg/s) | v (m/s) | L (m) | L Tot (m) | V (m³) | H₂O Mass Inventory (kg) |
|------------------------------|----------------|---------|-------------|-----------------|---------|-------|----------|-------|------------------------|
| Inlet IB FW distributor      | DN-100         | 114.3   | 8.8         | 35.6            | 6.6     | 17.6  | 281.2    | 2.07  | 1522.21                |
| Inlet IB FW LIBS/RIBS        | DN-100         | 114.3   | 8.8         | 17.8            | 3.3     | 5.8   | 186.5    | 1.37  | 1009.43                |
| Outlet IB FW LIBS/RIBS       | DN-100         | 114.3   | 8.8         | 17.8            | 3.7     | 6.4   | 203.9    | 1.50  | 984.62                 |
| Outlet IB FW collector       | DN-100         | 114.3   | 8.8         | 35.6            | 7.4     | 17.6  | 281.2    | 2.07  | 1357.82                |
| Inlet IB BZ distributor      | DN-200         | 219.1   | 17.5        | 96.4            | 4.9     | 17.5  | 280.3    | 7.46  | 5500.35                |
| Inlet IB BZ LIBS/RIBS        | DN-150         | 168.3   | 12.7        | 48.2            | 4.1     | 4.0   | 128.1    | 2.05  | 1513.83                |
| Outlet IB BZ LIBS/RIBS       | DN-150         | 168.3   | 12.7        | 48.2            | 4.6     | 4.7   | 149.1    | 2.39  | 1572.12                |
| Outlet IB BZ collector       | DN-200         | 219.1   | 17.5        | 96.4            | 5.5     | 17.5  | 279.9    | 7.45  | 4989.97                |
| Inlet OB FW distributor      | DN-200         | 219.1   | 17.5        | 106.5           | 5.4     | 11.3  | 180.8    | 4.81  | 3548.13                |
| Inlet OB FW COBS             | DN-125         | 139.7   | 11.0        | 35.5            | 4.4     | 7.9   | 126.4    | 1.38  | 1013.89                |
| Inlet OB FW LOBS/ROBS        | DN-125         | 139.7   | 11.0        | 35.5            | 4.4     | 9.2   | 293.9    | 3.20  | 2357.06                |
| Outlet OB FW COBS            | DN-125         | 139.7   | 11.0        | 35.5            | 5.0     | 8.3   | 133.1    | 1.45  | 952.47                 |
| Outlet OB FW LOBS/ROBS       | DN-125         | 139.7   | 11.0        | 35.5            | 5.0     | 9.4   | 301.6    | 3.28  | 2157.42                |
| Inlet OB BZ distributor      | DN-350         | 355.6   | 28.0        | 382.4           | 7.4     | 10.6  | 170.3    | 12.00 | 8847.80                |
| Inlet OB BZ COBS             | DN-200         | 219.1   | 17.5        | 127.5           | 6.5     | 7.0   | 111.5    | 2.97  | 2187.86                |
| Inlet OB BZ LOBS/ROBS        | DN-200         | 219.1   | 17.5        | 127.5           | 6.5     | 7.4   | 236.1    | 6.29  | 4633.48                |
| Outlet OB BZ COBS            | DN-200         | 219.1   | 17.5        | 127.5           | 7.3     | 7.7   | 122.7    | 3.27  | 2147.62                |
| Outlet OB BZ LOBS/ROBS       | DN-200         | 219.1   | 17.5        | 127.5           | 7.3     | 8.4   | 267.9    | 7.13  | 4688.31                |
| Outlet OB BZ collector       | DN-350         | 355.6   | 28.0        | 382.4           | 8.2     | 11.0  | 176.3    | 12.43 | 8172.15                |
| **Total**                    |                |         |             |                 |         |       |          | 4094.1| 89.44                | 62,274.06 |

3. Postulated Accidental Scenario

In this section, the specifications of the accident—such as the event sequence and the main objectives—are reported and described in Tables 7–10.
Table 7. Accidental scenario general specifications.

| Parameter         | Specification                                                                                                                                 |
|-------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Name of event     | LBO3 out-vessel loss of coolant from the breeder primary loop due to large rupture of tubes in a primary HX in WCLL concept                    |
| Category          | Accident                                                                                                                                       |
| Objectives        | Show that accidental overpressure in the secondary loop of PHTS will be safely accommodated. Show that post-accident cooling of the decay heat removal system of the VV is sufficient to remove decay heat during the 32 h of the offsite loss of power. Show that radioactive releases, if any, are adequately confined. |
| Scope of analysis | Integrated breeder blanket PHTS thermohydraulic analysis. VV, VVPSS(W) pressure transient analysis if melting occurs due to mitigated plasma disruption. Analysis of ACPs and tritium transport in the containment volumes as a consequence of the plasma disruption, if melting occurs. |
| Acceptance criteria | Maximum Eurofer temperature < 550 °C  
Confinement integrity: BB module safety assessment pressure < 18 MPa  
Confinement integrity: VV safety assessment pressure < 200 kPa |

Table 8. Accidental scenario main events sequence.

| Parameter         | Specification                                                                                                                                 |
|-------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Definition of initiating event | Break in the primary cooling loop side (break size 0.0028 m², corresponding to the rupture of 9 tubes of the primary side) inside the HX toward the secondary side. |
| Possible transient sequence | Fusion power is terminated by loss of pressure (−20% of operating pressure) in the BB cooling loop inside the HX. The initiating event is followed by a fast plasma shutdown (FPS) actuated 3 s from the low signal, which leads to a mitigated plasma disruption for 5 ms.  
The disruption could cause failure of the FW cooling pipes in a BB module if temperature melting is reached in FW Eurofer. In such a case, the break flow area to be considered is reported in [SDL19], chapter 2.1.  
The VV decay heat removal cooling loops will cool down the in-vessel components post accident.  
Ingress of coolant and radioactive inventories (tritium, dust, and suspended products) will be mobilized.  
The rupture discs toward the VVPSS(W) open upon reaching the set VV pressure point.  
Mobilized radioactivity is transported into the VVPSS(W).  
After the coolant inventory is lost, the FW/breeder blanket modules will be cooled by steam convection and thermal conduction/radiation to the VV.  
The DV components are accounted for in this analysis as heat structures at the initial temperature and without cooling during the transient. |
| Aggravating failures | None. |
| Loss of power     | A loss of offsite power occurs at the same time of the plasma disruption. |

Table 9. Accidental scenario system assumptions.

| Parameter         | Specification                                                                                                                                 |
|-------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Process system assumptions | VV decay heat removal (DHR) will remove the decay heat. The temperature of the VV is maintained at 40 °C by DHR. |
| Safety systems assumptions | VV pressure limit is 0.2 MPa.  
VVPSS(W) rupture discs open upon reaching the VV pressure set point. |
| Source term       | Tritium, dust in the VV, ACP products in the PHTS, tritium and activated products in the breeder materials and/or purge gas. |
### Table 10. Expected results from the analysis of the accidental scenario.

| Parameter                  | Specification                                                                 |
|----------------------------|-------------------------------------------------------------------------------|
| **General**                | The output locations, parameters, and time trace should show the results of safety analyses to support objectives and purposes. The time span should cover until the transients are stabilized. |
| **FW temperature**         | Transient curve for FW and BB module temperature of the failed loop.          |
| **Confinement response**   | Pressures and atmosphere temperature in BB cooling loop, HX.                  |
| **Pressures and atmosphere temperature in VV and VVPSS(W) only in case of FW Eurofer structure melting.** |
| **Cooling system conditions** | Water break flow versus time in HX and in VV and VVPSS(W) only in case of FW Eurofer structure melting. Water inventory inside the affected FW/breeder blanket cooling system. |
| **Radioactive transport**  | Transient curves for tritium, dust, and sputtering concentration (airborne, deposited) in VVPSS(W) if FW structure melts. Bookkeeping of mobilized tritium, dust, and sputtering products if FW structure melts. |

### 4. Nodalization of the WCLL-PHTS

Figure 3 shows the whole nodalization of the BZ loop. Since the loop is symmetrical with respect to the two OTSGs, only half of the loop is represented, without losing consistency. All the geometrical characteristics of the components of the nodalization were retrieved from the references presented above and summarized in the previous sections of this document. A list of all the main characteristics can be found in Tables 7 and 8.

The whole nodalization can be roughly divided into two sections: the main one, more complex, which is the nodalization of the BZ OTSG, and the simpler one, which is the nodalization of the BB volumes; the two regions are highlighted in Figure 3, whilst a focus on the BZ OTSG is shown in Figure 4. The cold and hot rings provide a connection between the two regions. The pressurizer is directly connected to the hot ring.

The OTSG is partitioned in the primary and secondary side. Each side is divided into several control volumes (CVH in MELCOR), which correspond to the hemispherical top and bottom, as well as to the sections created by the support plates. The division into different sections is required to achieve a temperature gradient as close as possible to the actual one. All the control volumes are connected by flow paths (FL). CVH 10 and 11 (see Figure 4) are dummy volumes used only to impose the BCs to the secondary side at normal operations. The CHV and FL geometrical characteristics are summarized in Tables 11 and 12, respectively.

In normal conditions, the primary and secondary side are connected only by heat structures (HSs), which allows heat transfer between the volumes but do not permit any passage of fluids. Between the primary and secondary side, there are a total of 17 equal heat structures. Each HS has a cylindrical geometry divided into four nodes with a total thickness of 0.8 mm and a height of 0.7825 m, which corresponds to the height of the connected volumes. The multiplicity of the HS is equal to 7569, which means that the HS is equivalent to 7569 heat structures of the same type, for a total surface area of 4795 m$^2$. All HSs are made of stainless steel, and a convective condition is imposed on both sides of the HS.

The thermal power of the OTSG is simulated by means of two heat structures connected with the inboard and outboard sections of the BB regions. These two HSs provide 592 MW of thermal power to the outboard section (CVH 15) and 149 MW to the inboard section (CVH 14).

The accident is simulated by activating dummy flow paths which connect one volume of the primary side with the corresponding volume of the secondary side. The section area of this FL is equal to the rupture area (0.00312 m$^2$ for nine tubes on the OTSG primary side).
These FLs are located at different heights to allow sensitivity analysis on the location of the rupture.

### Table 11. CVH number and characteristics.

| Nodalization | Volume Water (m$^3$) | Height/Length (m) | Section (m$^2$) | Description          |
|--------------|----------------------|-------------------|-----------------|----------------------|
| Primary side |                      |                   |                 |                      |
| 1            | 3.22                 | 1.15              | 4.18            | Top hemisphere       |
| 2            | 0.72                 | 0.61              | 1.18            | Top tubesheet        |
| 31–46        | 15.36                | 0.7825            | 1.18            | Shroud tubes primary |
| 4            | 0.72                 | 0.61              | 1.18            | Bottom tubesheet     |
| 5            | 3.22                 | 1.15              | 4.18            | Bottom hemisphere    |
| Secondary side |                    |                   |                 |                      |
| 6            | 12.65                | 7.63              | 1.66            | Shell boiler         |
| 71–86        | 34.09                | 12.70             | 2.68            | Shroud secondary     |
| 8            | 1.81                 | 0.30              | 6.03            | Steam chamber        |
| 9            | 8.42                 | 5.08              | 1.66            | Shell SH             |
| Rings and BB |                      |                   |                 |                      |
| 12           | 36.04                | 146.5             | 0.246           | Hot ring             |
| 13           | 36.04                | 146.5             | 0.246           | Cold ring            |
| 16           | 7.73                 | 17.9              | 0.027           | Cold ring distributors IB |
| 18           | 14.67                | 13.1              | 0.07            | Cold ring distributors OB |
| 17           | 7.99                 | 18.5              | 0.027           | Hot ring collectors IB |
| 19           | 15.9                 | 14.2              | 0.07            | Hot ring collectors OB |
| 14           | 73.7                 | 14.7              | -               | BB inboard           |
| 15           | 121.616              | 12.3              | -               | BB outboard          |

### Table 12. FL number and characteristics.

| Nodalization FL | From CVH | To CVH | From Height (m) | To Height (m) | Section (m$^2$) | Hydraulic Diameter (m) | Length (m) |
|-----------------|----------|--------|-----------------|---------------|-----------------|------------------------|------------|
| Primary side    |          |        |                 |               |                 |                        |            |
| FL00100         | 12       | 1      | 4.25            | 16.5272       | 0.4117          | 0.724                  | 45         |
| FL00200         | 1        | 2      | 15.3732         | 15.3732       | 1.1818          | 1.2267                 | 0          |
| FL00300         | 2        | 31     | 14.7636         | 14.7636       | 1.1818          | 1.2267                 | 0          |
| FL03100 TO FL04600 | (31)   | (46)  | 13.9811          | 13.9491       | 1.1818          | 0.0141                 | 0.032      |
| FL00400         | 46       | 4      | 1.7636          | 1.7636        | 1.1818          | 1.2267                 | 0          |
| FL00500         | 4        | 5      | 1.154           | 1.154         | 1.1818          | 1.2267                 | 0          |
| Secondary side  |          |        |                 |               |                 |                        |            |
| FL00600         | 10       | 6      | 9               | 9             | 0.198639        | 0.0889                 | 0          |
| FL07100 TO FL08600 | (71) | (86)  | 13.9491          | 13.9811       | 0.89466         | 0.012636               | 0.032      |
| FL00700         | 6        | 71     | 2.2             | 2.2           | 4.330349        | 0.84579                | 0          |
| FL00800         | 86       | 8      | 14.4636         | 14.4636       | 2.6846          | 0.0279                 | 0          |
Table 12. Cont.

| Nodalization FL | From CVH | To CVH | From Height (m) | To Height (m) | Section (m²) | Hydraulic Diameter (m) | Length (m) |
|-----------------|----------|--------|-----------------|--------------|--------------|------------------------|------------|
| Rings and BB    |          |        |                 |              |              |                        |            |
| FL01200         | 5        | 13     | 0               | 2            | 0.246        | 0.56                   | 23         |
| FL01300         | 13       | 18     | 1.724           | 1.724        | 0.62         | 0.3                    | 10.6       |
| FL01400         | 18       | 15     | −7.746          | −7.746       | 0.564        | 0.1841                 | 10.6       |
| FL01500         | 15       | 19     | −7.746          | −7.746       | 0.564        | 0.1841                 | 10.6       |
| FL01600         | 19       | 12     | 3.784           | 3.784        | 0.62         | 0.3                    | 10.6       |
| FL01700         | 13       | 16     | 1.724           | 1.724        | 0.156        | 0.184                  | 17.5       |
| FL01800         | 16       | 14     | −4.446          | −4.446       | 0.255        | 0.1429                 | 4          |
| FL01900         | 14       | 17     | −4.446          | −4.446       | 0.255        | 0.1429                 | 4          |
| FL02000         | 17       | 12     | 3.784           | 3.784        | 0.156        | 0.184                  | 17.5       |
| Accident        |          |        |                 |              |              |                        |            |
| FL10101         | 33       | 84     | 12.7            | 12.7         | 0.0028       | 0.0141                 | 0          |
| FL10102         | 39       | 78     | 7.9             | 7.9          | 0.0028       | 0.0141                 | 0          |
| FL10103         | 45       | 72     | 2.2             | 2.2          | 0.0028       | 0.0141                 | 0          |

Figure 3. MELCOR nodalization of PHTS loop.
4.1. Boundary Conditions

In order to impose the required primary coolant mass flow rate of 3831.2 kg/s, a fluid velocity was imposed at FL12, since MELCOR does not allow to impose directly the mass flowrate. Furthermore, only for the initial steady condition, before the onset of the accident, the temperature on the bottom of the OTSG (CVH 5) was imposed to be 295 °C and the pressure was set at 15.5 MPa.

As mentioned in the previous section, two dummy CVHs (10 and 11) were used to impose the BCs at the secondary side. A pressure of 6.4 MPa and a feedwater coolant inlet temperature of 238 °C were imposed. The feedwater flow rate is kept at 404 kg/s by means of imposing an equivalent constant velocity FL, in order to produce the same amount of superheated steam at 299 °C.

The velocity (mass flow rate) imposed at FL12 was set to 0.0 at the FPS since the pumps were shut down due to the loss of offsite power. Furthermore, at the FPS, the FLs connecting the secondary side of the OTSG to the secondary loop are closed (thus acting as isolation valves), also interrupting the feed water flow in the secondary side. At the current stage, the design of the secondary loop is not completed.

4.2. Decay Heat

The decay heat was imposed using volumetric heat generation from heat structures connected with the outboard and inboard CVH. The total values and time trends, calculated using the most up-to-date volumetric nuclear heating data given in [24], are reported in Table 13.

**Figure 4.** Detail of BZ OTSG nodalization.
Table 13. Decay heat densities (MW/m\(^3\)) integrated into the WCLL full reactor [24].

| Name of Zone                              | Nuclear Heating | Cooling Time |
|-------------------------------------------|-----------------|--------------|
|                                           | MW/m\(^3\)      | s            |
| First wall (FW)                           |                 | 0 s          |
| W                                         | 2.18E+01        | 4.95E−01     |
| Eurofer                                   | 7.14E+00        | 1.76E-01     |
| Breeder module (BM)                       |                 | s            |
| BM caps and lateral walls                 | 1.81E+00        | 1.08E-02     |
| BM material mixture                       | 1.17E+00        | 1.23E-02     |
| BM backwall                               | 1.06E-01        | 1.50E-03     |
| BM back support/manifold                  | 5.64E-02        | 4.31E-04     |
| Sum (MW/m\(^3\))                         | 1.65E+03        | 2.21E+01     |

However, it is important to note that the values reported in [24] did refer to a different configuration of the WCLL, namely, the one which was composed of modules and, therefore, had a different material ratio; in this work, the total nuclear heating was recalculated scaling the values with an estimation of the total volume obtained from the most recent configuration of the inboard and outboard segments, and this may represent a source of error. Furthermore, it is difficult to estimate the role of the FW in cooling the decay heat of the breeding unit under this particular scenario, since—as shown in the results—the FW loop is not damaged by the plasma disruption, and it can be assumed still functional. As a first approach in this work, only the decay nuclear heating relative to the BM back wall and the manifolds is assumed to have an effect on the damaged BZ cooling loops.

5. Numerical Analyses

In the simulation, the system was initially left to run for 1000 s, to reach a stable steady state in operational conditions, and then the FL connecting the volumes involved in the rupture was opened. Three seconds after the low-pressure signal, i.e., when the pressure in the loop fell below 12.4 MPa, the FPS was activated; plasma disruption occurred, the pumps were stopped, and the secondary loop was isolated.

In total, three different cases were run, at three different rupture locations (top, middle, and bottom). Table 14 summarizes the different cases.

Table 14. Summary of simulation parameters.

| Rupture Location   | Number of Pipes | Rupture Size (m\(^3\)) | FL Involved |
|--------------------|-----------------|-------------------------|-------------|
| Case 1             | Top OTSG        | 9                       | 0.0028      | FL10101     |
| Case 2             | Middle OTSG     | 9                       | 0.0028      | FL10102     |
| Case 3             | Bottom OTSG     | 9                       | 0.0028      | FL10103     |

The event sequence of the accident is reported in Table 15.
Table 15. Event sequence.

| Event                      | Time (s) |
|----------------------------|----------|
| Steady state               | 0–1000   |
| Low-pressure signal        |          |
| Case 1                     | 1016.5   |
| Case 2                     | 1008.5   |
| Case 3                     | 1007.5   |
| FPS                        |          |
| Case 1                     | 1019.5   |
| Case 2                     | 1011.5   |
| Case 3                     | 1010.5   |
| End of the simulation      | 150,000  |

5.1. Pressure Evolution

Figures 5 and 6 show the pressure trend after the rupture, at different time scales. The pressure started decreasing and then showed a sharp peak when the low-pressure signal was reached. This was due to the rapid shutdown of the pump and the isolation of the loop. The same behavior was seen in all the cases, but it is worth noting that, for Case 1, the pressure drop was slower and the peak remained significantly lower than the other two cases. This was due to the different rupture conditions; in Case 1, the primary side discharged in a region of the secondary, which was filled with superheated vapor, whereas, in Cases 2 and 3, it was discharged in regions containing liquid water. Figure 7 shows the time trend of the vapor quality calculated in CVH 85 for Case 1.

Figures 8 and 9 show the pressure trend at the rupture locations of both the primary and the secondary side. In the secondary side of the OTSG, no pressure peaks were predicted, and the pressure increased to an equilibrium value by around 100 s in all the cases. Then, 200 s after the rupture, a steady state was reached, with the pressure lying between 12 and 13 MPa.

All pressures remained well below the threshold of 18 MPa, with the pressure peak for Cases 2 and 3 having a value of about 15 MPa, and that for Case 1 having a value of about 12.5 MPa.

Figure 5. Pressure trend after the rupture: primary side, 1000–1030 s.
Figure 6. Pressure trend after the rupture: primary side.

Figure 7. Vapor quality in volume 85 for Case 1.

Figure 8. Pressure trend after the rupture: primary and secondary sides, 1000–1200 s.

5.2. Temperature Evolution in the BB

Figures 10–12 show the time evolution of the temperature at the inlets and outlets of the BB, for the whole transient up to 36 h. Because of the effect of the decay heat, the temperatures did not reach a steady state, but tended to increase. The faster temperature increase after 104 s was due to the onset of weak natural circulation in the loop, with the water flow even changing direction several times in Cases 2 and 3, as shown in Figure 13. However, the increase could be considered slow throughout the whole transient, and all temperatures remained well below acceptable values.

As mentioned above, the difference between Case 1 and Cases 2 and 3 was due to a different height of the rupture in the primary side of OTSG for the three cases, with a jump of around 5 m between each case. The transient for Case 1 showed a different behavior from the very beginning, because, in this case, the primary discharged, through the rupture, into a region of the secondary which was filled with superheated vapor and not liquid water, as in Cases 2 and 3. This early difference consequently led to a radically different transient of the pressure and general behavior of the loop, compared with the other two cases.
5.2. Temperature Evolution in the BB

Figures 10–12 show the time evolution of the temperature at the inlets and outlets of the BB, for the whole transient up to 36 h. Because of the effect of the decay heat, the temperatures did not reach a steady state, but tended to increase. The faster temperature increase after $10^4$ s was due to the onset of weak natural circulation in the loop, with the water flow even changing direction several times in Cases 2 and 3, as shown in Figure 13. However, the increase could be considered slow throughout the whole transient, and all temperatures remained well below acceptable values.

As mentioned above, the difference between Case 1 and Cases 2 and 3 was due to a different height of the rupture in the primary side of OTSG for the three cases, with a jump of around 5 m between each case. The transient for Case 1 showed a different behavior from the very beginning, because, in this case, the primary discharged, through the rupture, into a region of the secondary which was filled with superheated vapor and not liquid water, as in Cases 2 and 3. This early difference consequently led to a radically different transient of the pressure and general behavior of the loop, compared with the other two cases.
Figure 10. Temperature evolution in the BB: Case 3.

Figure 11. Temperature evolution in the BB: Case 2.

Figure 12. Temperature evolution in the BB: Case 1.

Figure 13. Water mass flow rate in the loop: $10^4$–$10^5$ s.
6. Conclusions

This work presented a thermohydraulic analysis of a postulated accident involving the rupture of a breeder primary loop inside an HX (once through steam generator). After the detection of the loss of pressure inside the primary cooling loop, an FPS is actuated with a consequent plasma disruption, isolation of the secondary loop, and shutoff of the pumps in the primary; no other safety counteractions are postulated.

The objective of the work was to analyze the pressurization of the primary and secondary sides to show that the accidental overpressure in the two sides of the steam generators is safely accommodated. Furthermore, the effect of the plasma disruption on the FW, in terms of temperatures, should be analyzed. Lastly, the time transients of the pressures and temperatures in the HX and BB for a time span of up to 36 h should be obtained to assess the effect of the decay heat over a long period.

A full nodalization of the OTSG was realized together with a simplified nodalization of the whole PHTS BB loop. The code utilized was MELCOR for fusion version 1.8.6. The accident was simulated by activating a flow path which directly connected one section of the primary with the parallel section of the secondary side.

It was shown here that the pressures and the temperatures inside the whole PHTS system remained below the safety thresholds for the whole transient.

The only caveat of this analysis is due to the calculation of the effect of the decay heat, since the tables used for the estimation of this parameter referred to an old version of the WCLL-BB, as no other references are available on this issue.

It is believed that, for a fully comprehensive evaluation of the impact of the decay heat, a coupled calculation should be realized, connecting a nodalization of the FW PHTS loop and the PbLi loop with the nodalization of the BZ PHTS loop presented here.

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Abbreviations

| Abbreviation | Description                          |
|--------------|--------------------------------------|
| ACP          | Activate corrosion product           |
| BB           | Breeder blanket                      |
| BC           | Boundary condition                   |
| BOP          | Balance of plant                     |
| BSS          | Back supporting structure            |
| BZ           | Breeder zone                         |
| CAD          | Computer-aided design                |
| CVH          | Control volume hydrodynamics         |
| DHR          | Decay heat removal                   |
| DCD          | Direct coupling design               |
| DEMO         | DEMOnstration power plant            |
| FL           | Flow path                            |
| FPS          | Fast plasma shutdown                 |
FW  First wall  
HT package  Heat structure package  
IB  Inboard  
LOCA  Loss of coolant accident  
OB  Outboard  
OTSG  Once through steam generator  
PCS  Power conversion system  
PHTS  Primary heat transport system  
PbLi  Lead–lithium  
PRZ  Pressurizer  
VV  Vacuum vessel  
VVPS  Vacuum vessel pressure suppression system  
WCLL  Water-cooled lithium lead  
WPSAE  Work Package Safety and Environment

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