The Integral Analysis of 40 mm Diameter Pipe Rupture in Cooling System of Fusion Facility W7-X with ASTEC Code

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ABSTRACT

Fusion is the energy production technology, which could potentially solve problems with growing energy demand of population in the future. Wendelstein 7-X (W7-X) is an experimental facility of stellarator type, which is currently being built at the Max-Planck-Institute for Plasmaphysics located in Greifswald, Germany. W7-X shall demonstrate that in future the energy could be produced in such type of fusion reactors. The safety analysis is required before the operation of the facility could be started. Rupture of 40 mm diameter pipe, which is connected to the target to ensure heat removal from the vacuum vessel in case of no-plasma operation mode “baking” is one of the design basis accidents. During “baking” mode the vacuum vessel structures are heated to the temperatures required for plasma ignition. This accident was selected for the detailed analysis using integral code ASTEC, which is developed by IRSN (France) and GRS mbH (Germany).

This paper presents the integral analysis of W7-X response to a selected accident scenario. The model of the main cooling circuit and “baking” circuit was developed for CESAR module and the model of vacuum vessel – for CPA module of ASTEC code. There were analysed two cases: 1) rupture of a pipe connected to the upper target and 2) rupture of a pipe connected to the lower target. The results of analysis showed that in both cases the water is almost completely released from the targets into the plasma vessel. In both cases the pressure rapid increase in the plasma vessel and in 22 s the pressure increases to the set point of safety valve opening, which prevents further rise of pressure.

1 INTRODUCTION

Fusion power is the power generated by nuclear fusion reactions, i.e. two light atomic nuclei fuse together to form a heavier, more stable nucleus releasing the binding energy [1]. At present, several experimental fusion reactors are under construction, among them ITER, which is built in France, KSTAR in South Korea, Wendelstein 7-X (W7-X) in Germany. W7-X is a stellarator, which shall demonstrate that in the future energy could be produced in such type of fusion reactors. It is presently under construction at the Max-Planck-Institute for Plasmaphysics located in Greifswald, Germany. The superconducting magnet system enables continuous operation, limited only by the plasma exhaust cooling water system whose capacity is designed for 30 minutes full power operation.

Prior to start of the facility operation its safety has to be demonstrated by performance of the safety analysis. The ingress of water during the W7-X no-plasma operation modes “Baking” and “Hot Liner” into the plasma vessel represents one of the most critical failure
events, since primary and secondary steam production leads to a rapid increase of the inner pressure in the vessel. It should be noted that in “baking” mode no plasma in the plasma vessel exists, i.e. no special models for plasma simulation are required. Such event could lead to loss of vacuum condition up to overpressure in the plasma vessel, damage of in-vessel components and diagnostics as well as bellows of the ports. Therefore increase of pressure in excess of 1.1 bar must be avoided by means of active (safety valves) and passive safety devices (burst disk, mass loaded disk).

This paper presents the analysis of loss-of-coolant accident (LOCA) in W7-X facility. This paper also includes short description of ASTEC code, which was selected for the analysis of the event, and the description of W7-X cooling system.

2 W7-X TARGET MODULES COOLING SYSTEM

The plasma vessel in W7-X facility is composed of five modules, which are divided each into two sectors to allow threading of the innermost coils during assembly (see Figure 1). The vessel components consist of the target plates, baffles, panels and heat shields, control coils, cryo-pumps, port protection and special port liners and the complex system of cooling water supply lines [3]. Each divertor unit is assembled from 12 separate horizontal and vertical targets (see Figure 2). Figure 2 shows model of one divertor target module with a total plasma facing surface of ~2 m². Most part of the target can withstand heat loads of up to 10 MW/m² and the middle part of the horizontal target plate has to withstand power loads only up to 1 MW/m².

Figure 1: Fragment of W7-X torus

W7-X facility target cooling system consists of two circuits. One of these is called the Main Cooling Circuit (MCC) and another one the “Baking” circuit. MCC is used for cooling of targets when W7-X facility is on normal operation. Before normal operation and ignition of plasma the targets and other components must be warmed up. “Baking” circuit mainly is used for this purpose. Both MCC and “Baking” circuits are interconnected and supply water to the same targets. In “Baking” mode all target inlet valves of MCC are closed, but connection with “Baking” circuit still exist through bypass.

The zero point for the W7-X elevation is in the centre of the torus. The highest point (pipes to the upper ports of the outer vessel) is about +3.5 m. The connections to the lower ports are at -3.5 m. The Heater, Pump, Pressuriser are located at -8.1 m. The automatic valves at the module manifolds are at ~0 m. The height of the pressuriser is 2850 mm (2100 mm for the cylindrical part), and the diameter is 1250 mm, leading to total volume of 2500 l. Volume ratio of nitrogen and water is ~0.5. The nitrogen pressure in the pressuriser is controlled.
between 9-11 bar leading to 10 bar static pressure [1]. The power of the heater is 180 kW. The heater is a simple cylinder of diameter 270 mm and length 1950 mm in horizontal position.

Figure 2: W7-X divertor target module with horizontal and vertical targets

The electrical heater wires are just inside the vessel and here is no inner pipe system inside the heater. There is only one pump for all target loops in the operation mode “Baking”. For the MCC there are other pumps available, but here for the defined analysis not of concern.

In “baking” mode the maximum water temperature is 160 °C, the water pressure is about 1.0 MPa. The corresponding mass flow of water in the “Baking” circuit is 177 m$^3$/h (44.6 kg/s), the flow velocity through the cooling tubes of the target elements is \( \approx 1 \) m/s [1].

This analysis assumes a rupture of the 40 mm diameter target module pipe near the flange of the outer vessel, right at the place of the inner surface of the torus, during the vessel “Baking” operation mode. It was qualified as the leading to the one of the most severe consequents [3].

3 MODELS OF MAIN COOLING CIRCUIT AND “BAKING” CIRCUIT AND PLASMA VESSEL FOR ASTEC

The analysis of LOCA in W7-X was performed using code ASTEC (Accident Source Term Evaluation Code). ASTEC is an integral code for Light Water Reactors source term severe accident calculation, from the initiating event until radioactive release out of the containment [4]. The main physical phenomena are validated in 20 applications on experiments (validation test-cases), in 26 operationality test-cases and in 16 plant application test-cases. The reactor Cooling system for a 2” cold leg break phenomena was validated in BETHSY 9.1 b test. Now the integral code ASTEC is used for the modelling of the ITER (International Thermonuclear Experimental Reactor) as well. ASTEC code consists of several modules, which are developed for the analysis of separate tasks. In this analysis there were used two modules CESAR and CPA.

CESAR module simulates the whole front-end phase in the vessel (with a simplified core modelling) and in the loops, and then, after the beginning of core degradation phase, two-phase thermal-hydraulics in the loops and in the vessel upper plenum only. The models are based on a thermal-hydraulics simulator code, the physical models of which were derived from the reference thermal-hydraulics code CATHARE [4]. Two phases are considered: water and gas (steam + 1 non-condensable gas). The system is made of 5 scalars mass and energy conservation equations associated with 5 state variables.

CPA module is used for simulation of thermal-hydraulics and aerosol behaviour in containment. Lumped-parameter approach (volumes represented by nodes connected by junctions) in simple or multi-compartment containments (tunnels, pit, dome…) with possible leakages to the environment or to normal buildings, with more or less large openings to the environment [4].
The other modules DIVA, ELSA, SOPH AerO S, RUPUICUV, MEDI CI S and IODE are not relevant for the selected accident scenario simulation in the fusion type facility.

For the modelling of selected accident (40 mm target pipe rupture) in “Baking” operation mode it is enough to develop detail model of “Baking” circuit. Thus, it was decided to develop detailed model of both connected circuits (see Figure 3). The geometric characteristics (pipe lengths, elevations, pump parameters, heater power and valves parameters) and configuration of pipes (it is necessary for evaluation of form loss coefficients) were taken from W7-X facility design.

![Figure 3: Nodalisation scheme of W7-X cooling system](image)

The simplified scheme for modelling of targets (nodalisation scheme) was developed (see Figure 4). As it is seen from presented scheme, four target modules are modelled as simplified one equivalent element: “F5-F5’”, “G5-G5’”, “H5-H5’”, “J5-J5’”.

![Figure 4: Modelling of targets (nodalisation scheme)](image)

One of target modules is modelled in more extended format: the two single targets were selected (one in upper and one in lower position). These upper and lower single elements allows to model rupture of single target feeder pipe. The Target Module “E5-E5” is modelled in more detailed manner (see Figure 6). The pipe elements “136”, “137”, “139” and “140” are used for modelling of upper and bottom horizontal Targets. Six vertical Targets are modelled by employing “138” pipe element. Element “146” is identical to “130”, element “139” – to “136” and element “140” – to “137”. For modelling of double ended guillotine break the ASTEC/CESAR connection module BREAK is used. Element “199” models the plasma vessel with pressure equal 0.01 bar.

The pump in the model was described by a pressure difference as a function of the flow rate. Pump model STRU PUMP available in the ASTEC code is used. For the modelling of the pressuriser a special type of node “swollen water level” was used. The valves from MCC...
and “Baking” circuit on inlet and outlet were modelled using ASTEC/CESAR module STRU SYSTEMS/VALVE. The non-return valves were modelled by a difference of the proportionality coefficients used in the calculation of the local pressure loss for reverse flows. The heater was modelled by the heat structure with defined initial temperature and the heat source of 180 kW.

![Figure 5: Cross-section of the developed nodalisation scheme of the vacuum vessel for one module (black – nodalisation nodes, green – atmospheric junctions)](image)

Device is composed out of five parts with similar configurations, called modules. Each module of the vacuum vessel is subdivided into nine virtual control nodes (zones) in the scheme (Figure 5), four in the central part of the scheme cross-section (nodes C**), four in the outer part (nodes O**) and one in the bottom part (node BOT), in which released water is collected. Figure 5 shows cross-section of one module nodalisation scheme. All five modules are simulated in the analysis.

All adjacent zones of one module are connected by atmospheric junctions. Areas of these junctions and their lengths are calculated from the cylinder geometry. Corresponding zones of the adjacent modules (e.g., CBL zones of the first and second modules) except BOT zones also are connected by atmospheric junctions, properties of which are calculated from the geometry of cylinder.

INJ zone is the zone into which the water release from the ruptured pipe is simulated. It is defined for the aims of simulation – it helps to more realistically model the water flowing from the ruptured pipe to the wall of the vacuum vessel. INJ zone is present only in one module. Geometric parameters of this zone were selected according to port data and the initial thermodynamic parameters are the same is in the whole vacuum vessel. Two zones not presented in the Figure 5 were also simulated – torus hall and environment.

The former is a 16800 m$^3$ volume hall in which stellarator torus is situated. Conditions in the hall were selected according to planned normal operation of W7-X device. OTL node of the vacuum vessel third module and torus hall node are separated by the simulated burst disk. Burst disk is simulated by defining an atmospheric junction, which is closed at the beginning and opens if pressure difference between the zones it connects reaches indicated value (direction considered). Area of this junction was set equal to the area of the burst disk.

**4 RESULTS OF ANALYSIS**

This section presents the results of analyses of 40 mm pipe rupture, connecting single upper or lower horizontal target. Double ended guillotine rupture of 40 mm pipe in “Baking” mode was modelled with the integral code ASTEC. Before accident the water temperature in the “Baking” circuit is 433.16 K (160 °C) and density – 907 kg/m$^3$. The water flow rate through “Baking” circuit is 177 m$^3$/h (44.6 kg/s). The pressure in plasma vessel is 1000 Pa. Valves from the main cooling circuit to targets are closed on inlet and outlet. Valves from the “Baking” circuit are open on inlet and outlet.
In this paper there are analysed the following scenarios:

1. Double ended guillotine rupture of DN40 pipe in the upper target.
2. Double ended guillotine rupture of DN40 pipe in lower target.

In the model it was assumed that the rupture occurs in the module E5-E5’ (see Figure 6). The rupture occurs in DN40 feeder pipe, connecting single upper horizontal target (element “136” in Figure 6) and another scenarios, the break occurs in lower DN40mm horizontal target. The boundary conditions are the same in both cases (see Table 1).

Table 1 The following events were assumed to occur:

<table>
<thead>
<tr>
<th>Event</th>
<th>Time (s)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>T = 0.0 s</td>
<td>Double ended guillotine break of DN40 (inner diameter 0.0443 m) occurs.</td>
</tr>
<tr>
<td>2.</td>
<td>T = 1.14 s</td>
<td>Trip of pump on “Baking” circuit</td>
</tr>
<tr>
<td>3.</td>
<td>T = 1.64 s</td>
<td>Closure of valves on Target inlets begins.</td>
</tr>
<tr>
<td>4.</td>
<td>T = 6.64 s</td>
<td>Valves on Target inlets are fully closed.</td>
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</tbody>
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From the comparison of the pressure in lower and upper affected targets (see Figure 7 (b)) we can see, that in firsts seconds after accident in lower affected target the pressure is slightly higher, because the position of the break is lower, which causes slightly larger discharge of coolant through the ruptured pipe. (see Figure 7).

The discharge of the coolant through the ruptured pipe and pump flow rate are presented in Figure 8. The water flow in the cooling system stops when the automatic valves are closed. After closure of the inlet automatic valves, the discharge of coolant slightly
decreases, but the water from other targets in this module is discharged until pressure in the affected targets decreases down to the pressure in the plasma vessel.

Figure 8: Comparison of upper and lower target break scenarios. Water flow rate through the pump and discharge of coolant through the upper and lower targets breaks

Since the inlet automatic valves are closed, the water is discharged only from the affected module. The process of emptying of the targets in affected target module can be understood from Figure 9. This figure shows the behaviour of void fraction in the targets is presented 0 - means pure water, 1 – pure steam. The affected target “1TH – upper” and other targets will be empty after approximately 43 s, but small amount of water (2 kg) remains in the lower targets.

Figure 9: Void fraction in the affected target module

The pump trip appears in 1.14 s after the rupture and leads to pressure decrease in the pump outlet (see Figure 10). The pressure in other modules drops down to ~ 0.6 MPa and remains constant, because the automatic valves have isolated them.
5 CONCLUSIONS

The models of target cooling system in W7-X facility were developed by ASTEC code. In this paper 2 scenarios of double ended guillotine break of DN40mm pipe in upper and lower targets inlet are presented.

1. Amount of water discharged through the break is slightly larger in case of the double ended guillotine break of the pipe in the lower target, comparing to the upper target break case.

2. Obtained results showed that the planned area of the burst disk should be sufficient to prevent pressure inside the vacuum vessel exceeding 1.1 bar in the case of simulated accident.

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REFERENCES


