Analysis of the Consequences in the Loss-of-Coolant Accident in
Wendelstein 7-X Experimental Nuclear Fusion Facility

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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. Starting 2007, Lithuanian energy institute (LEI) is a member of European Fusion Development Agreement (EFDA) organization. LEI is cooperating with Max Planck Institute for Plasma Physics (IPP, Germany) in the frames of EFDA project by performing safety analysis of fusion device W7-X. Wendelstein 7-X (W7-X) is an experimental stellarator facility currently being built in Greifswald, Germany, which shall demonstrate that in the future energy could be produced in such type of fusion reactors. In this paper the safety analysis of 40 mm inner diameter coolant pipe rupture in cooling circuit and discharge of steam–water mixture through the leak into plasma vessel during the W7-X no-plasma “baking” operation mode is presented. For the analysis the model of W7-X cooling system (pumps, valves, pipes, hydro-accumulators, and heat exchangers) and plasma vessel was developed by employing system thermal-hydraulic state-of-the-art RELAP5 Mod3.3 code. This paper demonstrated that the developed RELAP5 model enables to analyze the processes in divertor cooling system and plasma vessel. The results of analysis demonstrated that the proposed burst disk, connecting the plasma vessel with torus hall, opens and pressure inside plasma vessel does not exceed the limiting 110 kPa absolute pressure. Thus, the plasma vessel remains intact after loss-of-coolant accident during no-plasma operation of Wendelstein 7-X experimental nuclear fusion facility.

1. Introduction

Today, about 80% of all energy produced comes from the fossil fuel (oil, carbon, and natural gas). European scientists are developing environmentally friendly, safe, and renewable energy technologies. Nuclear fusion is one of them. Nuclear fusion reactors promise high power energy sources, which have low impact on environment, are safe and have virtually unlimited fuel resources. This technology is not limited to heat and electricity generation, it also could be used for hydrogen production, which would lead to further development of the “hydrogen economy”.

European nuclear fusion research program allows using common European research and their development resources in all important research areas. The co-operation of European researches is directed in the operation of the Joint European Torus (JET) program and in the execution of the European Fusion Development Agreement (EFDA) technological program, which is devoted to the ITER project, and also encompasses promising DEMO research. European fusion research and development program, based on EURATOM contract, is being coordinated and carried out by the European Commission. Lithuanian energy institute (LEI) in the frames of EFDA program is cooperating with Max Planck Institute for Plasma Physics (IPP, Germany) by performing safety analysis of Wendelstein 7-X Experimental Nuclear Fusion Facility W7-X.
The stellarator W7-X is presently under construction at the Max-Planck-Institut für Plasmaphysik, Greifswald, Germany [1]. The superconducting magnet system enables continuous operation, limited by the cooling water system whose capacity to remove the plasma heat load onto the wall components is designed for 30 minutes full power operation.

In this paper the consequences of the Loss-of-Coolant Accident (LOCA) in the cooling system of W7-X facility are analysed. The ingress of water during the W7-X no-plasma “baking” operation mode into the plasma vessel represents one of the critical failure events, since primary and secondary steam production leads to a rapid increase of the inner pressure in the vacuum (plasma) vessel. A rupture of the 40 mm target module cooling pipe could lead to the loss of vacuum condition up to an overpressure in the plasma vessel, damage of in-vessel components (for example: the bellows of the ports) [2, 3]. The pressure behaviour in the plasma vessel depends on the amount of discharged water through the leak. Thus, the processes both in the target modules cooling system and plasma vessel should be modelled. It should be noted that during “baking” operation mode no plasma in the plasma vessel exists, i.e. no special models for plasma simulation are required. The analysis was performed by employing the computer models, based on thermal hydraulic system code RELAP5. The results of the presented studies are used to optimize the design of the coolant circuits of W7-X, which is now under construction, and to define protection measures and instructions in order to ensure safe operation.

2. Modelling of W7-X target modules cooling system

The main parameters of W7-X are: average major radius 5.5 m, average plasma radius 0.53 m, total weight 725 t (see FIG. 1). Wendelstein7-X facility is composed of 2×5 so-called divertor units located in the plasma vessel with the bean-shaped cross section. 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 at elevation about +3.5 m. The connections to the lower ports are at -3.5 m. Each divertor unit is assembled from 12 separate horizontal and vertical target modules (see FIG. 2) capable to remove maximum 10 MW/m² convective stationary power load [2].

FIG. 1. Fragment of W7-X torus [1].
The W7-X facility target modules cooling system consists of two coolant circuits: The Main Cooling Circuit (MCC) and the so-called “baking” circuit. The MCC is used for cooling of the target modules when the W7-X facility under normal operation. Before plasma operation, the target modules and other in-vessel components must be heated up in order to ‘clean’ the surfaces by thermal desorption and the subsequent pumping out of the released volatile molecules. The “baking” circuit is mainly used for this purpose. Both MCC and “baking” circuits are connected together and supply water to the same target modules. During operation of W7-X in the “baking” mode, the heat, necessary for target modules heating is generated in electrical heater. There is only one pump for all target modules loops in the “baking” operation mode. For the “cooling” operation mode there are other pumps available in the MCC, but here for the defined analysis not of concern. To maintain constant pressure in “baking” circuit, the pressurizer pressurized by nitrogen is used. The components heater, pump, nitrogen pressurizer are located at elevation -8.1 m. The automatic valves at the module manifolds are at elevation ~0 m. The height of the pressurizer is 2.85 m (2.10 m for the cylindrical part), the diameter is 1.25 m the total volume = 2.5 m$^3$. The volume ratio nitrogen/water is about 0.5. The nitrogen pressure in the pressurizer is controlled between 0.9 – 1.1 MPa [3]. According the drawings presented by facility developers, the volume of water in two divertor units with 12 target modules each is approximately 0.457 m$^3$, thus, the total volume of water in all 2×5 divertor modules is 0.457 × 5 = 2.28 m$^3$. The water is provided to the upper and lower target modules in each divertor unit through lower and upper ports. A simplified scheme of the circuits is shown in FIG. 3.

The amount of water in the all pipelines, connecting the target modules with the both MCC and the “baking” circuits is 1.66 m$^3$. The largest amount of water is used in the MCC – 63.1 m$^3$, while the amount of water in “baking” circuit is very small – 1.06 m$^3$.

The maximum water temperature is 160°C, the water pressure is about 1.0 MPa under the W7-X “baking” operation mode. 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 modules during “baking” operation mode is about 1 m/s [3].

The designed working pressure in the plasma vessel is about $10^{-2}$ Pa (deep vacuum) and pressure increase can lead to the break of plasma vessel and damage of in-vessel components and diagnostics devices as well as bellows of the ports. A rupture of the 40 mm diameter target module pipe near the port flange of the outer vessel, right at a place at the inner surface of the target module, during plasma vessel “baking” operation mode was selected for the analysis. The response of “baking” circuit and the evaluation of the amount of discharged water in the plasma vessel are presented in the following sections.

**FIG. 2.** W7-X top view and scheme of single divertor unit with horizontal (1h-9h) and vertical (1v-3v) target modules [1]
The analysis of accident with water ingress to the plasma vessel was performed using thermal-hydraulic state-of-the-art RELAP5 Mod3.3 code. RELAP5 [4] is a “best estimate” system code for the analysis of all transients and postulated accidents in light water reactor systems, including both large and small-break loss-of-coolant accidents as well as the full range of operational transients. Because the W7-X facility divertor cooling system is filled by water (coolant accepted in RELAP5 code) and can be described by mentioned RELAP5 components (pumps, valves, pipes, heat structures, etc.), it was decided to develop the model of main cooling circuit and “baking” circuits for RELAP5 code.

For the modelling of the selected accident (40 mm target module pipe rupture) in “baking” operation mode it is sufficient to develop a detailed model of the “baking” circuit. However both MCC and “baking” circuit are connected together (see FIG. 3). Thus, it was decided to develop a detailed model of both connected circuits. The measurements (pipe lengths, elevations, pump parameters, heater power and valves parameters) and the configuration of pipes (necessary for evaluation of form loss coefficients) were taken from the drawings provided by the W7-X design office.

The W7-X cooling system supplies 10 divertor units. The divertors can be grouped into two groups – upper and lower divertor units. One single upper divertor unit, connected with lower divertor unit creates one torus segment. Thus, each torus segment is composed of 18 horizontal (9 upper and 9 lower) target modules and 2x3 vertical target modules. In the developed RELAP5 nodalisation, four torus segments are modelled as equivalents (with the corresponding water volume and hydraulic resistance). One single torus segment is modelled in more extended format. In this torus segment, the upper and lower, horizontal and vertical target modules were modelled separately. From horizontal target modules two single target modules were selected: one in upper and one in lower position. These elements of single target modules allow to model rupture of single target module.

The complicated three-dimensional geometry of the Plasma Vessel (PV) volume in the stellarator (see FIG. 1 and FIG. 2) in the developed model is simplified to the geometry of horizontal cylinder. The ends of the cylinder are open and joined together, simulating closed circle of torus geometry (see FIG. 4). The whole volume (108 m$^3$) of the plasma vessel was modelled using one element “pipe 199”. The inner surface area (215.3 m$^2$) and wall thickness (0.019 m) of vessels’ structures in the model correspond to the available design data [3, 5]. One additional small volume (0.026 m$^3$) – element “196” models the volume into which the water is released from the ruptured pipe. It is defined for the aims of simulation – it helps to
more realistically model the stem – water mixture flowing from the ruptured pipe into the volume on the back side of divertor. The plasma vessel is connected to the Torus hall by pipe with burst disk. This disk is simulated using valve “217”, which is closed at the beginning and opens if pressure difference in plasma vessel and torus hall exceeds 10 kPa. The flow area of this valve (when it is open) is equal to the area of the burst disk (0.049 m²). Such safety measure is planned to be implemented in W7-X to prevent overpressure of plasma vessel. The torus hall is simulated in RELAP5 model using time dependent volume “218” with atmospheric pressure. Due to limitation of RELAP5 code it was assumed that the pressure in plasma vessel is equal to 1000 Pa – lowest possible pressure used in RELAP5 computer code. In FIG.4 the main cooling circuit inlet valve is marked as E2, the outlet valve – E2’, the “baking” circuit inlet automatic valve – E3, outlet valve at the “baking” circuit – E3’. The check valve at the outlet from torus segment targets is marked as E1’. The analogical valves are installed in each torus segments. At “baking” operation mode the MCC inlet valves are closed and baking” circuit inlet automatic valves – opened. In the case of pressure increase in the plasma vessel (it indicates the access of water through rupture in cooling circuit) the automatic valves are closing, reducing the discharge of water.

![FIG. 4. Nodalization scheme of stellarator with rupture in 40 mm diameter feeder pipe.](image)

### 3. Analysis of double-ended guillotine rupture of 40 mm pipe in upper target module

It was assumed during the modelling that rupture occurs in the 40 mm diameter feeder pipe, connecting single upper horizontal target module (see FIG. 4). The following assumptions are used:

- Double ended guillotine rupture occurs at time moment \( t = 0 \) s. Break fully opens within 0.01 s.

- To reduce the discharge of water the automatic valves on the inlets to each torus segments (valve E3 in FIG. 4) are closing. Signal for automatic actuation of valves is generated when pressure in plasma vessel reaches 2000 Pa. The calculations (see below) show that pressure reaches 2000 Pa in plasma vessel 0.14 s after the rupture occurred.
Delay between parameter reaches the set-point and signal generation – 0.5 s. Delay between signal generation and start of valve actuation – 1 s. Time to full closure of automatic valve on target module inlets – 5 s. Thus, 6.64 s after the rupture the torus segment inlet automatic valves are fully closed.

- Another measure to reduce the discharge of water from rupture to plasma vessel – automatic trip of pump in “baking” circuit. It was assumed that signal for automatic pump trip is the same as for closure of automatic valve – when pressure in plasma vessel reaches 2000 Pa (0.14 s). Delay between parameter reaches the set-point and pump trip – 1 s. Thus, trip of pump in “baking” circuit begins 1.14 s after the rupture.

- When the pressure in plasma vessel exceeds 110 kPa (absolute pressure), the burst disk opens and steam from PV is discharged to the torus hall.

The discharge of coolant through the rupture is presented in FIG. 5. The figure shows that the water flow in the “baking” circuit stops after the closure of automatic valves. After the close of the inlet automatic valve the discharge of coolant through the rupture slightly decreases but the water from other target modules in this torus segment is discharged until the pressure in piping decreases down to the pressure in plasma vessel.

![FIG. 5. Water flow rate through the pump and discharge of coolant through the rupture.](image)

The pump trip occurs 1.14 s after the rupture, thus leads to pressure decease at pump outlet (see FIG. 6). After the automatic valves at inlets of torus segments start closure, pressure in the “baking” circuit starts increasing. This is because inertia of pump impeller – after the pump trip the impeller is still rotating for about 1.5 minutes. The water is supplied into pipelines that cause the pressure increase in system upstream the valves. After the automatic valves are fully closed, the pressure in pump header starts to decrease slowly. This is because after automatic valves closure the water is discharged only from the affected torus segment. The pressure in affected torus segment slowly decreases, when pressure in other (intact) torus segments remains nominal (see FIG. 6), because closed automatic valves isolated them. The information about the emptying of target modules in the affected torus segment is presented in FIG. 7. In this figure the decrease of water volume in targets is presented. As it is shown in FIG. 7, because of small water inflow from the lower targets, the affected target will be completely empty after 90 s; intact vertical target module — 43 s after the break, while two-third of water remains in the intact lower target modules in time interval t = 20 – 90 s after the break. 150 s after the break, due to inflow from other targets and pipes, the lower target modules will be full of water, it is presented in FIG. 7.
After pipe rupture takes place, the steam – water mixture from the broken pipe is discharged into plasma vessel through the small volume. This volume models the volume formed with plasma vessel wall and target wall. Initially the conditions in the small volume are the same as in PV (air at vacuum condition). After the rupture, due to injection of coolant, the pressure in small volume and inside PV starts to rise (see FIG. 8). Pressure differences inside the different elements and nodes in plasma vessel are insignificant, because whole volume of the PV is open for mass transfer and coolant release from the ruptured pipe is small enough. When the absolute pressure in plasma vessel reaches 110 kPa (42 s after the initiation of break), burst disk opens. Opening of the burst disk is followed by the discharge of steam from PV to the torus hall, and the pressure decrease in the vessel. The mass flow rate of steam through the burst disk is presented in FIG. 9. Burst disk opens (at time moment t = 42 s) while the release of coolant from the ruptured pipe is still taking place. Mass flow rate through the burst disk reaches its biggest value (almost 2 kg/s) just after it has opened. However this initial flow rapidly decreases to zero at t = 100 s. At time interval 110 – 150 s the small negative flow rate through the burst disk is observed (see FIG. 9). This little negative flow of air from the burst disk to the torus hall (the suction of air into PV) is because of water condensation process in PV.

The analyses of behaviour of temperatures during the accident is not presented, because temperature changes in W7-X device is not so important for safety reasons as pressure increase in plasma vessel. On the other hand, due to high inertia of massive steel constructions, the temperature change within short analyzed time period is insignificant. Obtained results
show that the flow area of the burst disk (0.049 m²) is sufficient to prevent pressure inside the plasma vessel exceeding 110 kPa in the case of simulated accident. The behaviour of pressure inside plasma vessel, calculated using RELAP5 code, is very similar to the calculations performed using COCOSYS code [6].

4. Conclusions

The analysis of accident with water ingress into the plasma vessel in Wendelstein nuclear fusion device W7-X was performed. The rupture of the 40 mm target module cooling pipe was selected as one of the critical failure events with loss of coolant, since primary and secondary steam production leads to a rapid increase of the inner pressure in the vacuum (plasma) vessel. To reach this goal the model of W7-X divertors, main cooling and “baking” circuits and the plasma vessel were developed using thermal-hydraulic state-of-the-art RELAP5 Mod3.3 code. The performed analysis of rupture of 40 mm diameter pipe in the single upper horizontal target module demonstrate that the area of burst disk is sufficient to prevent pressure inside the plasma vessel exceeding 110 kPa in the case of simulated accident. The prepared models will be used for further analyses of other accidents to prove the safety of W7-X fusion facility.

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6. References