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LOCA plus Loss of One Emergency Core Cooling System Simulated by RELAP5/MOD3.3 Patch 05

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ABSTRACT

The second generation reactors were designed and built to withstand without loss to the structures, systems, and components necessary to ensure public health and safety during design basis accidents (DBAs). In the transient and accident analysis the effects of single active failures and operator errors were considered. There are also accident sequences that are possible but were judged to be too unlikely and therefore were not fully considered in the design process of second generation reactors. In that sense, they were considered beyond the scope of design basis accidents that a nuclear facility must be designed and built to withstand. They were called beyond design basis accidents (BDBA).

After Fukushima Dai-ichi in the Europe the design extension conditions (DEC) were introduced as preferred method for giving due consideration to the complex sequences and severe accidents without including them in the design basis conditions. In the study, the analysis was performed to see if the selected plant design of two loop pressurized water reactor can prevent spectrum of loss of coolant accidents (LOCAs) together with the complete loss of one emergency core cooling function (e.g. high pressure safety injection or low pressure safety injection). The analysed break spectrum ranged from 1.27 cm to 30.48 cm. For each break size two simulations were performed, one without high pressure injection system (HPIS) and one without low pressure injection system (LPIS), with other safety systems available. For calculations the latest RELAP5/MOD3.3 Patch 5 has been used and the RELAP5 input model of two-loop pressurized water reactor. Besides this for smaller breaks ranging from 1.27 cm to 5.08 cm leading to core heatup (being DEC as new equipment is needed) accident management strategies to depressurize the primary system in order to enable injection of accumulators and LPIS have been also studied.

The results show that accident management strategies are successful. However, the control of DEC needs to be achieved primarily by safety features for DEC and not only by accident management measures that are using equipment designed for other purposes. Therefore, it can be concluded that safety injection pump with sufficient pressure capability should be introduced to prevent smaller break LOCAs in case the HPIS is lost or safety injection pump with lower pressure capability and depressurization system.

1 INTRODUCTION

The term "design extension conditions" has been introduced to define some selected accident sequences due to multiple failures by the European Utility Requirements document [1]. The design extension conditions were introduced as preferred method for giving due consideration to the complex sequences and severe accidents at the design stage of the reactors of third generation without including them in the design basis conditions. The Western European Nuclear Regulators Association (WENRA) recommended a “design extension” analysis in 2007 [2] and they proposed a list of events to be analysed at minimum. After Fukushima Dai-ichi accident also the International Atomic Energy Agency (IAEA) published standard introducing the term design extension conditions (DEC) [3], which was prepared prior to the Fukushima Dai-ichi accident. WENRA reference levels (RLs) from 2014 [4] also introduced DEC term.

The lessons learned from the Fukushima Dai-ichi accident have led to the reinforcement of some requirements in IAEA SSR-2/1 and revision 1 of IAEA SSR-2/1 has been released in 2016 [6], redefining that the DEC comprise of "postulated accident conditions" (before "accident conditions"). WENRA did not follow the newest IAEA definition of DEC in spite of the fact that modification is significant.

Slovenia implemented WENRA reference levels issue F requirements into its Rules on radiation and nuclear safety factors [7]. The DEC A shall cover: a) events occurring during the defined operational states of the plant; b) events resulting from internal or external hazards; and c) common cause failures. In the presented analysis two such common cause DEC A scenarios were simulated, loss of coolant accident (LOCA) in cold leg together with complete loss of high pressure injection system (HPIS) and LOCA with complete loss of low pressure injection system (LPIS). This is also in line with IAEA TECDOC-1791 document [8] and WENRA guidance document [5] for issue F.

The analysis presented will show if the plant design can prevent above LOCA scenarios with existing safety systems or not (in this case additional DEC safety features are needed). Following document [8], the control of DECs is expected to be achieved primarily by features implemented in the design (safety features for DECs) and not only by accident management measures that are using equipment designed for other purposes. This means that in principle a DEC is such if its consideration in the design leads to the need of additional equipment or to an upgraded classification of lower class equipment to mitigate the DEC.

2 LOCA SCENARIO, RELAP5 INPUT MODEL AND SIMULATED CASES DESCRIPTION

In the following LOCA scenario, RELAP5 input model and simulated LOCA break cases are described.

2.1 LOCA Scenario Description

In the LOCAs simulated in a two-loop pressurized water reactor (PWR), from the emergency core cooling systems (ECCSs) two accumulators were assumed available and either the high pressure or the low pressure emergency core cooling system (each consisting of two trains). The initiating event is opening of the valve simulating the break in the cold leg with reactor operating at 100% power. The reactor trip on (compensated) low pressurizer pressure (12.99 MPa) further causes the turbine trip. The safety injection (SI) signal is generated on the low-low pressurizer pressure signal at 12.27 MPa. On SI signal either high pressure injection system (HPIS) or low pressure injection system (LPIS) and motor driven (MD) pumps of auxiliary feedwater (AFW) system are actuated. The HPIS started to inject, when pressure is lower than 15.14 MPa. When pressure drops below 4.96 MPa, both accumulators start to inject. Larger is the break size, faster is the accumulator discharge. When pressure drops below 1.13 MPa, the LPIS start to inject. In the case of smaller breaks, the high primary pressure can prevent accumulators and LPIS to inject.

2.2 RELAP5 Input Model Description

For calculations the latest RELAP5/MOD3.3 Patch 5 [9] has been used and the RELAP5 input model of two-loop pressurized water reactor (PWR), used also in study [10]. A two loop PWR reactor power is 1994 MW and thermal power 2000 MW. The base model consists of 469 control volumes, 497 junctions and 378 heat structures with 2107 radial mesh points. In terms of SNAP this gives 304 hydraulic components and 108 heat structures. Hydraulic components in SNAP consist of both volumes and junctions, where pipe with more volumes is counted as one component. Each heat structure in SNAP connected to pipe is also counted as one component and not as many heat structures as pipe has volumes like it is counted in the RELAP5 output file. This explains the difference in the number of heat structures in Figure 1 and that reported in RELAP5 output file.

Modeling of the primary side includes the reactor pressure vessel (RPV), both loops (LOOP 1 and 2), the pressurizer (PRZ) vessel, pressurizer surge line (SL), pressurizer spray lines and valves, two pressurizer power operated relief valves (PORVs) and two pressurizer safety valves, chemical and volume control system (CVCS) charging and letdown flow, and reactor coolant pump (RCP) seal flow. Emergency core cooling system (ECCS) piping includes high pressure safety injection (HPSI) pumps, accumulators (ACCs), and low pressure safety injection (LPSI) pumps. The secondary side consists of the SG secondary side, main steam line, main steam isolation valves (MSIVs), SG relief and safety valves, and main feedwater (MFW) piping. The turbine valve is modeled by the corresponding logic. The turbine is represented by time dependent volume. The MFW and AFW (auxiliary feedwater) pumps are modeled as time dependent junctions.

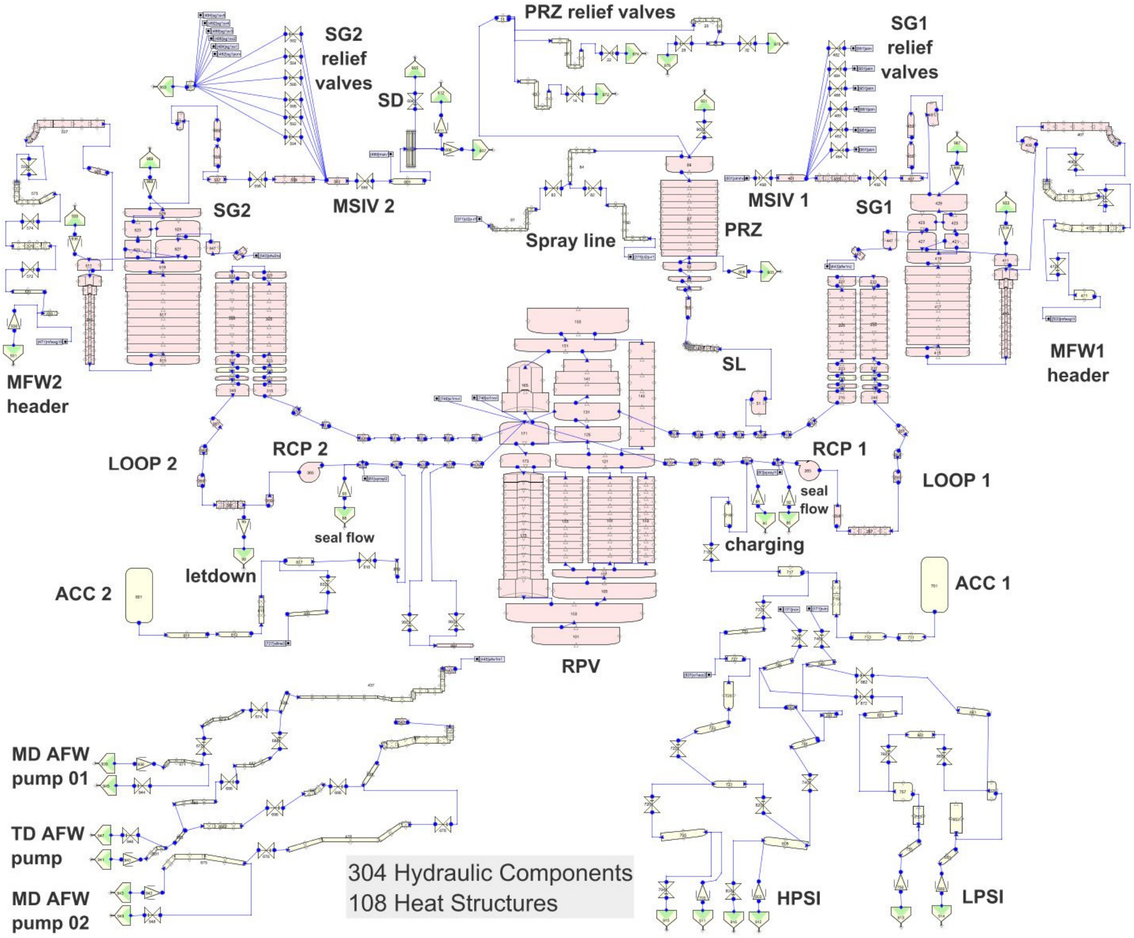

Figure 1: RELAP5 Two-loop PWR Hydraulic Components View

2.3 Simulated LOCA Break Cases

The break sizes simulated were 1.27 cm, 2.54 cm, 5.08 cm, 7.62 cm, 10.16 cm, 15.24 cm, 20.32 cm and 30.48 cm equivalent diameter cold leg breaks. For each break size two simulations were performed, one without HPIS and one without LPIS, with other systems available as can be seen from Table 1. In all simulations default values for break flows were used for Ransom Trapp critical flow model.

Table 1: LOCA Scenario Cases without One ECCS (HPIS or LPIS)

Break size diameter	Case without HPIS ('noHP')	Case without LPIS ('noLP')
1.27 cm (0.5 inch)	sb0.5_noHP	sb0.5_noLP
2.54 cm (1 inch)	sb1_noHP	sb1_noLP
5.08 cm (2 inch)	sb2_noHP	sb2_noLP
7.62 cm (3 inch)	sb3_noHP	sb3_noLP
10.16 cm (4 inch)	sb4_noHP	sb4_noLP
15.24 cm (6 inch)	sb6_noHP	sb6_noLP
20.32 cm (8 inch)	sb8_noHP	sb8_noLP
30.48 cm (12 inch)	sb12_noHP	sb12_noLP

In addition to the LOCA scenarios (i.e. DEC), which could not be mitigated, scenarios with accident management (AM) measures were also simulated, shown in Table 2. First AM strategy (AM1) was to depressurize the reactor coolant system RCS through the secondary side, using steam generator (SG) PORVs to depressurize SGs to 1.2 MPa. Second AM strategy (AM2) was to depressurize the RCS through the secondary side, using SG PORVs to depressurize SGs to 0.7 MPa.

Table 2: LOCA Scenario Cases without HPIS and Using Accident Management Strategies

Break size diameter	Accident management (AM) measures	Scenario label
1.27 cm (0.5 inch)	AM1: using SG PORVs to depressurize SGs to 1.2 MPa	sb0.5_noHPdsg12
2.54 cm (1 inch)	AM1: using SG PORVs to depressurize SGs to 1.2 MPa	sb1_noHPdsg12
5.08 cm (2 inch)	AM1: using SG PORVs to depressurize SGs to 1.2 MPa	sb2_noHPdsg12
1.27 cm (0.5 inch)	AM2: using SG PORVs to depressurize SGs to 0.7 MPa	sb0.5_noHPdsg7
2.54 cm (1 inch)	AM2: using SG PORVs to depressurize SGs to 0.7 MPa	sb1_noHPdsg7
5.08 cm (2 inch)	AM2: using SG PORVs to depressurize SGs to 0.7 MPa	Sb2_noHPdsg7

3 RESULTS

3.1 Results of LOCA Break Size Spectrum without HPIS

The results for simulations of LOCA spectrum ranging from 1.27 cm to 30.48 cm with assumed loss of HPIS are shown in Figure 2. The simulations were performed for 24 h (86400 s), if simulation was not terminated before due to core heatup. It is shown that in the case of loss of HPIS the breaks smaller than 5.08 cm are small enough that the primary pressure is not depressurized below accumulator and LPIS injection setpoint. This leads to the core uncovery and finally heatup of average fuel rod cladding above 1100 K. This means that smaller break LOCAs are DEC for selected PWR. In case of 5.08 cm and 7.62 cm break sizes the primary system pressure dropped below the injection setpoints but core heatup is not prevented. For break sizes equal or larger than 10.16 cm it was shown that cooling through the break is sufficient and primary pressure drops sufficiently to enable LPIS injection in the long term. LPIS has sufficient injection capacity to cool the reactor in the long term. This is in accordance with the results obtained from BETHSY 9.1b experiment [11], in which 5.08 cm break on the cold leg together with a complete failure of the HPIS leads to core heatup before performing depressurization of the primary side through the secondary side.

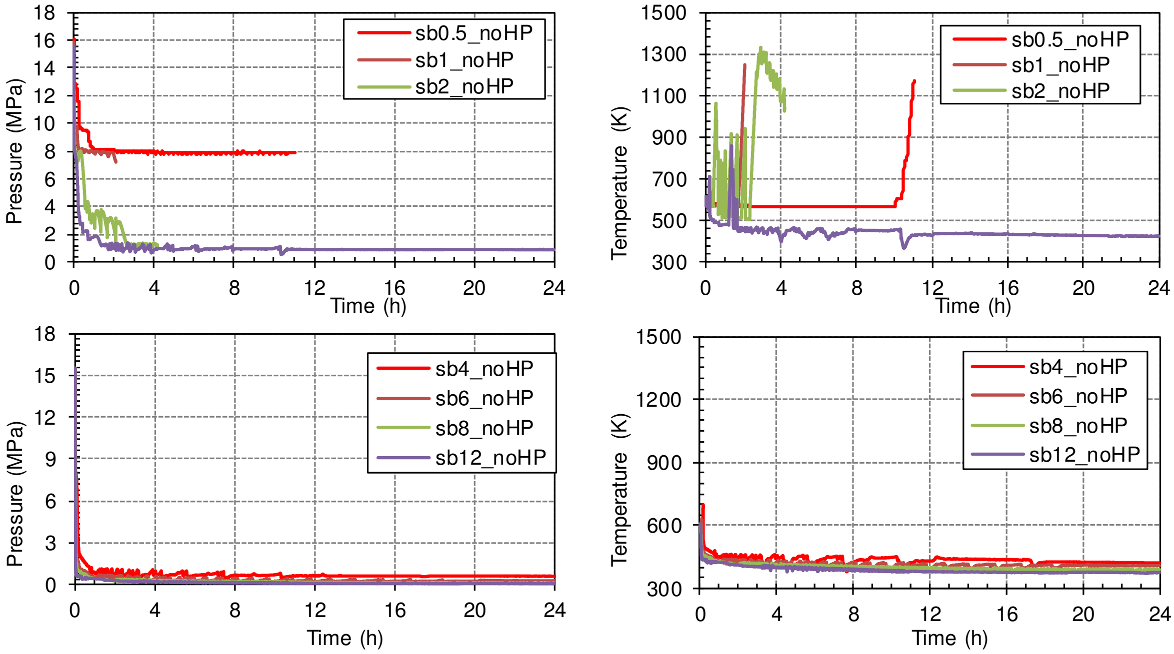

Figure 2: Pressure (left) and average fuel rod cladding temperature (right) for LOCA Break Size Spectrum without HPIS (top - 1.27 cm to 7.62 cm; bottom - 10.16 cm to 30.48 cm)

3.2 Results of LOCA Break Size Spectrum without LPIS

The results for simulations of LOCA spectrum ranging from 1.27 cm to 30.48 cm with assumed loss of LPIS are shown in Figure 3. The simulation time was 24 h (86400 s). It is shown that in the case of loss of LPIS the HPIS has sufficient injection capacity in the long term for all simulated break sizes for the selected PWR.

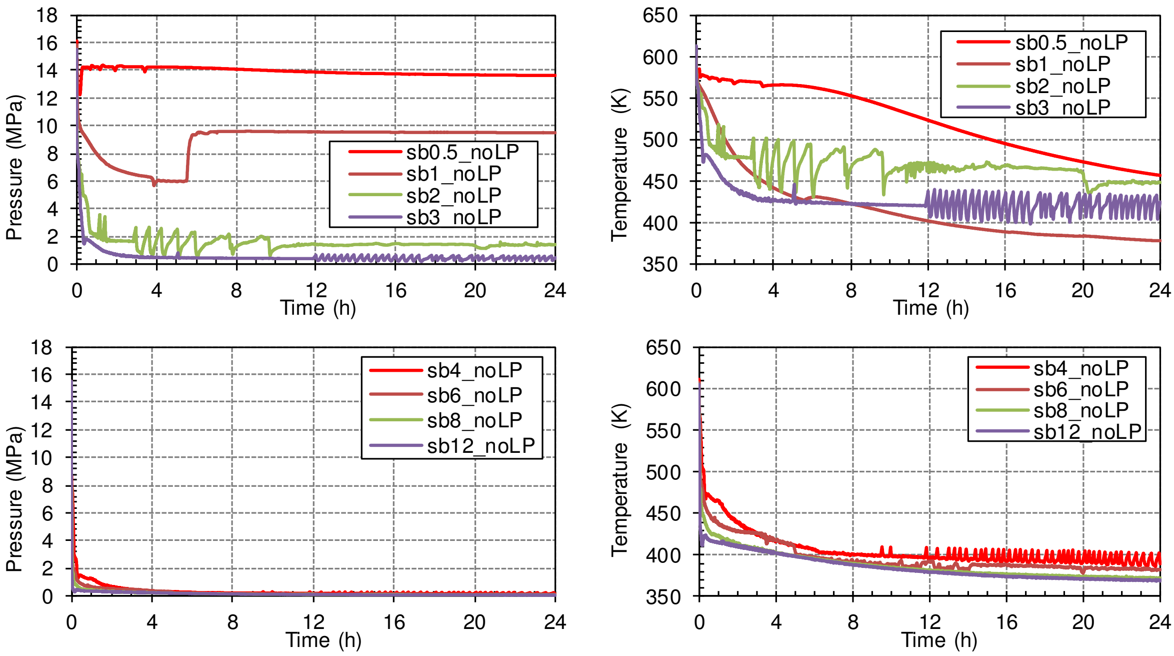

Figure 3: Pressure (left) and average fuel rod cladding temperature (right) for LOCA Break Size Spectrum without LPIS (top - 1.27 cm to 7.62 cm; bottom - 10.16 cm to 30.48 cm)

The HPIS system has capability to inject at high pressure, therefore in the case of 1.27 cm and 2.54 cm breaks the pressure is maintained and cooling through the break is sufficient. For break sizes from 5.08 cm to 10.16 cm the initial cooling of the core is faster, but after two to three hours the cooling rate is decreased. In case of breaks equal or larger than 10.16 cm it can be seen that larger is the break size the faster is the initial cooling through the break. Also, injection capacity of HPIS pumps is sufficient to prevent any core heatup and establish long term core cooling.

3.3 Results of LOCA Break Size Spectrum 1.27 cm to 5.08 cm without HPIS and Using AM Strategy

In section 3.1 it was shown that the primary system was not sufficiently depressurized to enable LPIS injection. Therefore, AM strategy reducing the primary pressure through the secondary side depressurization has been assumed in the simulations. The simulation time was 24 h (86400 s). The results are shown in Figures 4 and 5. As can be seen from Figure 4 the AM1 strategy with depressurization to 1.2 MPa has been successful only for 1.27 cm break size LOCA in preventing the core heatup. The main reason is that the primary system inventory leak is small enough not to uncover core and the break flow is smaller due to the depressurization. However, pressure drop it is not sufficient to enable LPIS injection in the first hours. On the other hand, the AM2 strategy with depressurization to 0.7 MPa has been successful for breaks 1.27 cm and 2.54 cm, while in the case of 5.08 cm break size LOCA only short term initial peak in cladding temperature occurred for around 2 minutes exceeding 1000 K and peak value approximately 1050 K. The larger depressurization of primary system contributes both to smaller break flow and LPIS injection on the other hand (see Figure 5). The capacity of LPIS is sufficient to cover the core and fill the primary system.

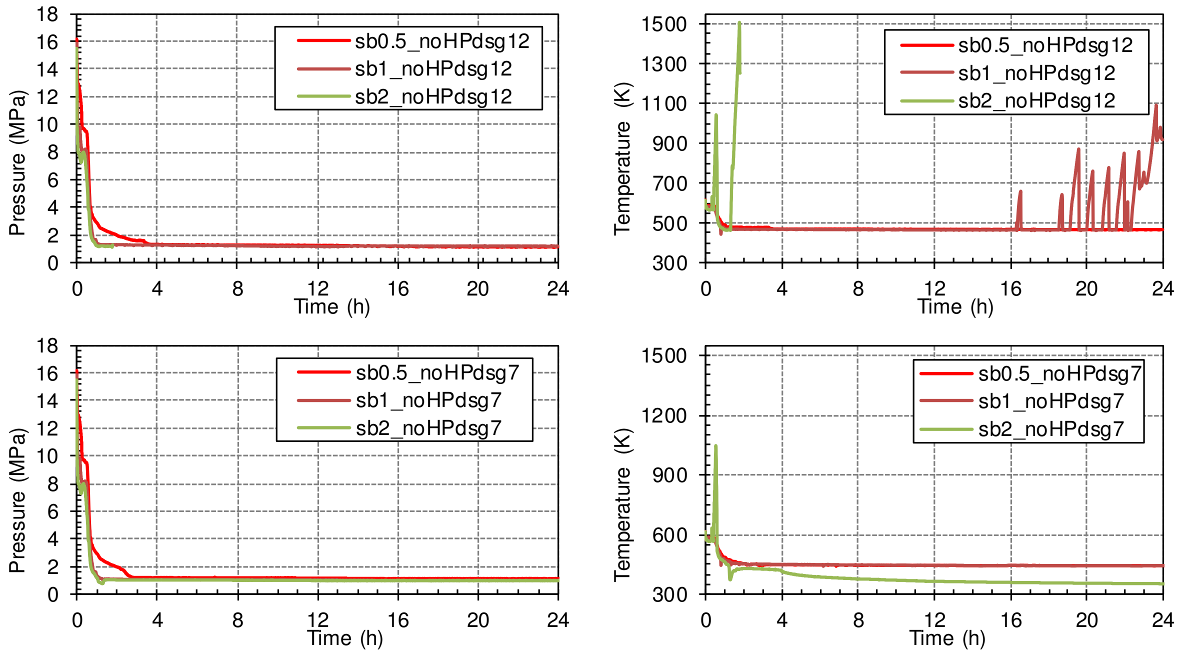

Figure 4: Pressure (left) and average fuel rod cladding temperature (right) for LOCA Break Sizes 1.27 cm to 5.08 cm without HPIS and using accident management strategy (top – depressurization to 1.2 MPa; bottom - depressurization to 0.7 MPa)

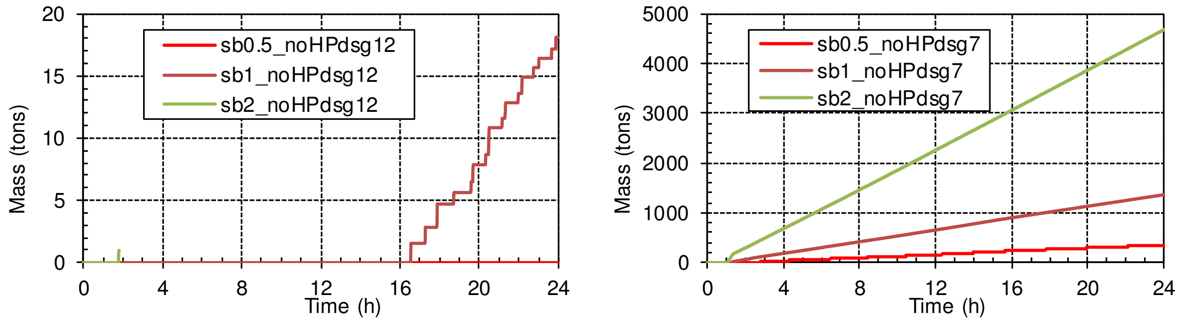

Figure 5: Injected LPIS mass for AM1 (left) and AM2 (right) for LOCA Break Sizes 1.27 cm to 5.08 cm without HPIS and using accident management strategy

The obtained calculated results agree with the experimental findings. For example, cold leg break tests have been conducted at the large scale test facility (LSTF) for five break areas 0.5%, 1%, 2.5%, 5% and 10% of the scaled cold leg flow area, with totally failed HPIS [12]. Test data of LSTF and model calculations showed that intentional primary system depressurization with the use of the pressurizer (PRZ) PORVs is effective for break areas of approximately 0.5% or less, is unnecessary for breaks of approximately 5% or more, and might be insufficient for intermediate break areas to maintain adequate core cooling. It was also shown that there might be possibility of core dryout after accumulator injection and before LPIS injection for break areas less than approximately 2.5%.

On LSTF the secondary side depressurization procedure was simulated in a 0.5% cold-leg break LOCA experiment with total failure of the HPI and auxiliary feedwater (AFW) systems [13]. In the experiment, the primary-side pressure closely followed the secondary side depressurization that was initiated by opening the atmospheric relief valves on the broken-loop SG, and dropped to the accumulator injection pressure before the core became severely overheated.

4 CONCLUSIONS

The RELAP5/MOD3.3 Patch05 computer code calculations of loss of coolant accident (LOCA) without high pressure injection system (HPIS) and LOCA without low pressure injection system (LPIS) for a spectrum of break sizes ranging from 1.27 cm (0.5 inch) to 30.48 cm (12 inch) have been performed. When HPIS is not available, depressurization of the primary side through the secondary side can be used in case of smaller breaks to mitigate the consequences. For larger breaks, the pressure drop is faster and LPIS maintained the core inventory. When LPIS is not available, the HPIS has sufficient capacity for safety injection in case of simulated LOCA break spectrum. It was shown that accident management strategy using steam generator power operated relief valves to depressurize the primary system below LPIS injection setpoint are sufficient to mitigate smaller size LOCA without HPIS operable. However, the control of design extension conditions (DEC) is expected to be achieved primarily by features implemented in the design (safety features for DECs) and not only by accident management measures that are using equipment designed for other purposes. This means that in principle a DEC is such if its consideration in the design leads to the need of additional equipment or to an upgraded classification of lower class equipment to mitigate the DEC. Therefore, it can be concluded that safety injection pump with sufficient pressure capability should be introduced to prevent smaller break LOCAs in case the HPIS is lost or safety injection pump with lower pressure capability and depressurization system.

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