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Frontier between medium and large break loss-of-coolant accidents of pressurized water reactor

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ABSTRACT

In order to provide the probabilistic safety assessment with more realistic condition to calculate the frequency of the initiating event, a study on the frontier between medium-break and large-break loss-of-coolant accidents has been performed by using best-estimate thermal-hydraulic code, TRACE. A methodology based on the combination of the essential safety features and system parameter has been applied to the Zion nuclear power plant to evaluate the validity of the frontier utilized for the probabilistic safety assessment. The peak cladding temperature has been chosen as a relevant system parameter that represents the system behavior during the transient. The results showed that the frontier should be extended from 6 to 10 in based on the required safety functions and system response.

Keywords: Loss-of-coolant accident; Frontier; Probabilistic safety assessment; Initiating event

1. Introduction

The probabilistic safety assessment (PSA) allows the considerations of a broader set of potential challenges and gives the priority of the sequences based on the significance of the risk. Therefore, the application of the PSA has been on the increase in many industries including the nuclear. Especially, the regulatory activities in the nuclear field have adopted the methodology of the PSA, named risk-informed regulation, to extend the traditional deterministic safety analysis methodology. The introduction of the PSA into the regulatory activities are expected to cover larger accident scenarios than the traditional safety analysis based on the design basis accidents (DBAs) and to result in more realistic safety analysis based on the significance of the sequence. The risk-informed evaluation of the acceptance criteria for the emergency core cooling system (ECCS) in 10 CFR 50.46 can be a typical example of such activities to combine the probabilistic and deterministic approaches in the safety analysis [1].

The evaluation of the ECCS performance during a loss-of-coolant accident (LOCA) is one of the most important analyses to demonstrate the safety of a nuclear reactor system. Because a LOCA is defined as a postulated accident that results from the loss of coolant at a rate in excess of the capability of the reactor coolant makeup system, in general, the size of a LOCA has very wide range from 0.5 in equivalent diameter to the diameter of the largest pipe in the reactor coolant system (RCS) [2]. In deterministic approach, an analysis of the double-ended guillotine break is performed as an analysis of a DBA to show the safety of the reactor system during a large break LOCA (LBLOCA). An analysis of a small break LOCA (SBLOCA) is also conducted for the ECCS evaluation, but the break spectrum for the SBLOCA depends on the plant design and the analysis methodology that are varied plant by plant.

In the context of the risk-informed regulation, according to the break size, the LOCA of interest can be classified into three groups: SBLOCA, medium break LOCA (MBLOCA), and LBLOCA. Defining the frontiers between LOCAs is one of the most important tasks to evaluate the risk and the significance because it determines the frequency of the initiating event and, as a result, affects the estimation of the core damage frequency (CDF). The criteria to define the frontier have been suggested from the beginning of the application of the

PSA. The historical definition of the LOCA size categories was made during the WASH-1400 evaluation [3]. In the report, the LOCA initiating events are classified into six groups:

- large pipe breaks (6 in to approximately 3 ft equivalent diameter),
- small to intermediate pipe breaks (2–6 in equivalent diameter),
- small pipe breaks (0.5–2 in equivalent diameter),
- large disruptive reactor vessel rupture,
- gross steam generator ruptures, and
- ruptures between systems that interface with the RCS.

In the classification, it is remarkable that the frontiers among SBLOCA, MBLOCA, and LBLOCA are 2 and 6 in equivalent diameters. This definition has been used in many probabilistic safety studies [4–6]. However, the detailed technical background of the frontiers was not included in the report. In addition, the standard in terms of the equivalent break diameter is insufficient to be used generally because the critical break size can vary according to the plant configuration. Therefore, additional consideration has been introduced to reflect the system behavior and required system operability to the classification of the LOCA. In NUREG/CR-4550, in addition to the break size, the following generic definitions for an MBLOCA and an LBLOCA were accepted for the assessment:

- *MBLOCA*: A break that does not depressurize the reactor quickly enough for the low-pressure systems to automatically inject and provide sufficient core cooling to prevent core damage. However, the loss from the break is such that high capacity systems (i.e., 1,500–5,000 gpm) are needed to make up the inventory depletion.
- *LBLOCA*: A break that depressurizes the reactor to the point where the low-pressure systems can inject automatically providing sufficient core cooling to prevent core damage.
- Additional consideration defined by flow rate has been employed in other analyses to estimate the LOCA frequencies [7,8].

However, the development of the criteria including the system behavior is still required because the present criteria are not applicable to all nuclear power plants (NPPs). The parameter related to the plant behavior during a LOCA should be included in order to take into account the characteristics of each NPP.

In this study, the frontier between an MBLOCA and an LBLOCA was examined for the Zion NPP [9]. The calculations based on the required safety functions for each LOCA have been performed in order to determine the frontier. Because the behavior of the maximum peak cladding temperature (PCT) is one of the most important parameters during the LOCA, the maximum PCT during the transient was selected as a system parameter reflecting the effect of the system characteristics on the frontier.

2. Thermal-hydraulic model

2.1. Thermal-hydraulic code

The thermal-hydraulic system code used for this study is TRACE (TRAC/RELAP Advanced Computational Engine) V5.0 RC3 [10]. The TRACE is the latest best-estimate system codes developed by the U.S. Nuclear Regulatory Commission for analyzing steady-state and transient neutronic/thermal-hydraulic behavior of light-water reactors. The code is a product of a consolidation of the capabilities of the main system codes of the U.S. Nuclear Regulatory Commission, such as TRAC-PF1, TRAC-BF1, RELAP-5, and RAMONA.

TRACE includes the models of multidimensional two-phase flow, nonequilibrium thermodynamics, generalized heat transfer, reflood, level tracking, and reactor kinetics. A two-fluid model is used to evaluate the gas–liquid flow. A mass conservation equation and an additional transport equation are included to describe the no condensable gas and the dissolved solute in the liquid phase, respectively. In order to describe the transfer of mass, momentum, and energy between phases and the interaction of phases with the structure, flow-regime-dependent constitutive equations are included because interactions strongly depend on the flow characteristics.

The finite volume method has been adopted to solve the partial difference equations for two-phase flow and heat transfer. A multi-step time-differencing procedure and semi-implicit time-differencing method are available to discretize the fluid dynamic equations for the one-dimensional and three-dimensional components. By default, a multi-step time-differencing procedure is applied because it allows the material Courant limit condition to be exceeded and results in larger time step for faster running during slower transient. The heat transfer makes use of a semi-implicit time-differencing method. A system of coupled nonlinear equations for hydrodynamic phenomena is solved by the Newton–Raphson iteration scheme and the resulting linearized equations are solved by direct matrix inversion.

2.2. Nodalization

The Zion Unit 1 is a pressurized water reactor with a 3,250 MWth power designed by Westinghouse Electric, Co. LLC, Cranberry Township, PA, USA [9]. The primary system consists of four loops, and each loop includes a *U*-tube steam generator (SG), a reactor coolant pump, a hot leg, and a cold leg. The safety injection (SI) system is composed of the high-pressure injection system (HPIS), the low-pressure injection system (LPIS), and an accumulator in each cold leg. The HPIS consists of two medium-head injection pumps and two charging pumps, while two residual heat removal pumps are employed for the LPIS.

The nodalization for the calculation with TRACE has been developed on the basis of an available TRACE nodalization generated within the framework of Phase IV of the Best Estimate Methods for Uncertainty and Sensitivity Evaluation program [11]. As shown in Fig. 1, a reactor pressure vessel (RPV) and four separated loops are described in the nodalization. The thermal-hydraulic model for TRACE employs 112 hydraulic components, 85 heat structures, and 396 control systems. The RPV has been modeled by using a three-dimensional vessel component that consists of 4 azimuthal sections, 6 radial rings, and 27 axial levels, as shown in Fig. 2. The active core has been described by using 4 radial rings and 18 axial levels. 5 power groups and 20 heat structures are used to describe the heat generation from the active core [12].

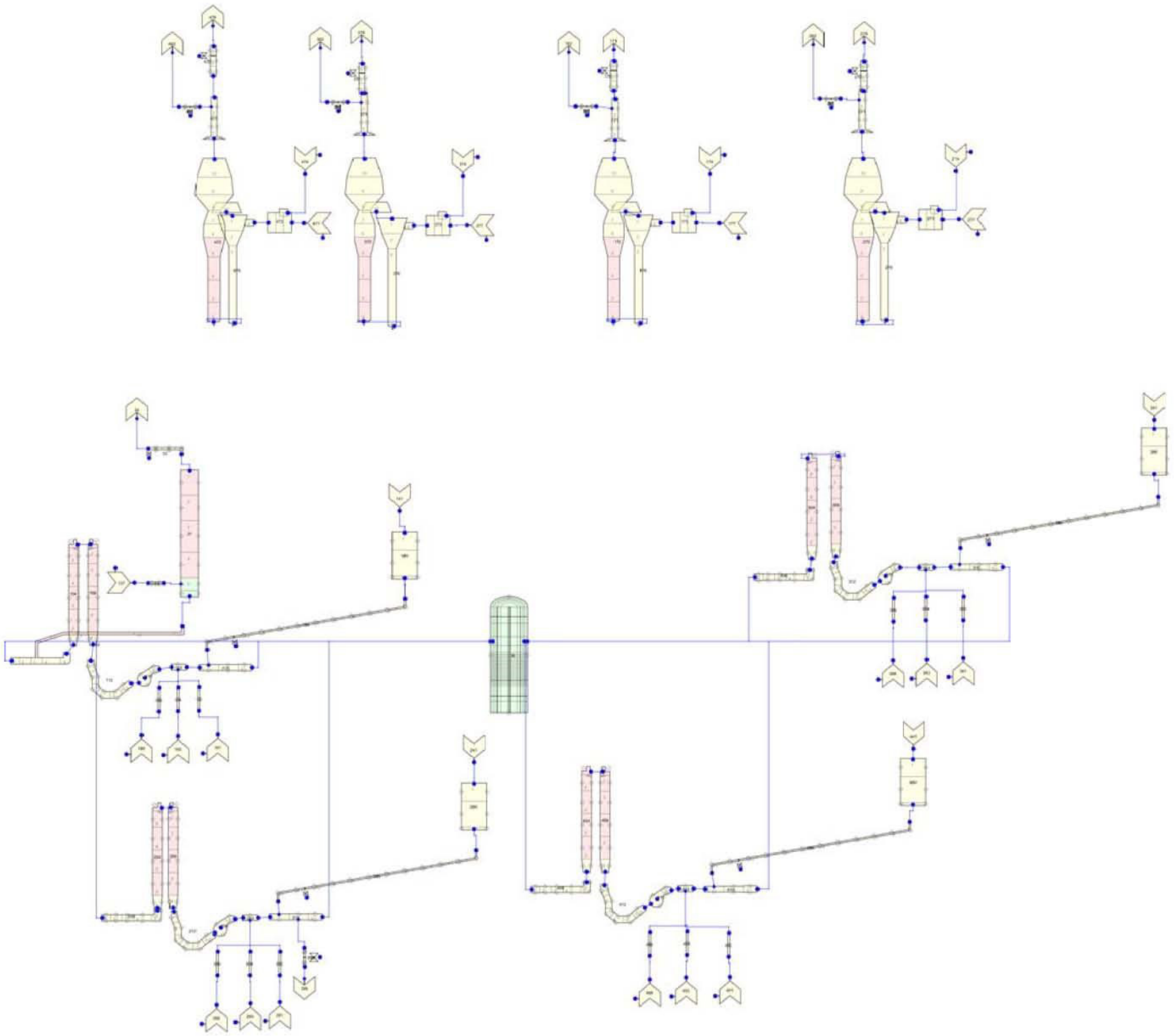

Fig. 1. Nodalization of Zion nuclear power plant.

The SG is modeled by using several pipe and tee components that represent the inner structures of the SG such as *U*-tube, downcomer, riser, steam dome, and steam separator [13]. A feedwater line and an auxiliary feedwater line are connected to each SG in order to provide water to the SG in normal and emergency operation modes, respectively. A steam line connected to each SG has two valves that are a relief valve and a steam isolation valve. During the accident, the steam isolation valve will be close so that the SG will be isolated.

Each loop includes injection lines for a medium-head injection, a charging, and a low-head injection. Usually, the charging pump does not work as a part of the SI system. However, the Zion NPP employs two charging pumps for SI system, and they inject the water to the primary system during the emergency as high-head injection pumps. As a passive safety feature, an accumulator pressurized by nitrogen is attached to each cold leg and a check valve is used to isolate the accumulator during normal operation. The break is located at one of the cold legs and connected to the break component which reveals the containment with atmospheric pressure [14]. The break size is ranged from 3 to 8 in and 8 to 16 in with the increment of 1 and 2 in, respectively.

2.3. Initial and boundary conditions

The initial conditions, which are listed in Table 1, have been determined on the basis of the final safety analysis report of the Zion NPP [9]. The pressures of the primary and secondary systems are 15.5 and 4.83 MPa, respectively. The temperature rise through the core is 34.7 K when the flow rate in the RCS is 17,400 kg/s.

Because the necessity of the HPIS is one of the parameters that characterize the frontier between an MBLOCA and an LBLOCA, the calculation was performed with and without the HPIS. When the HPIS works, one charging pump is

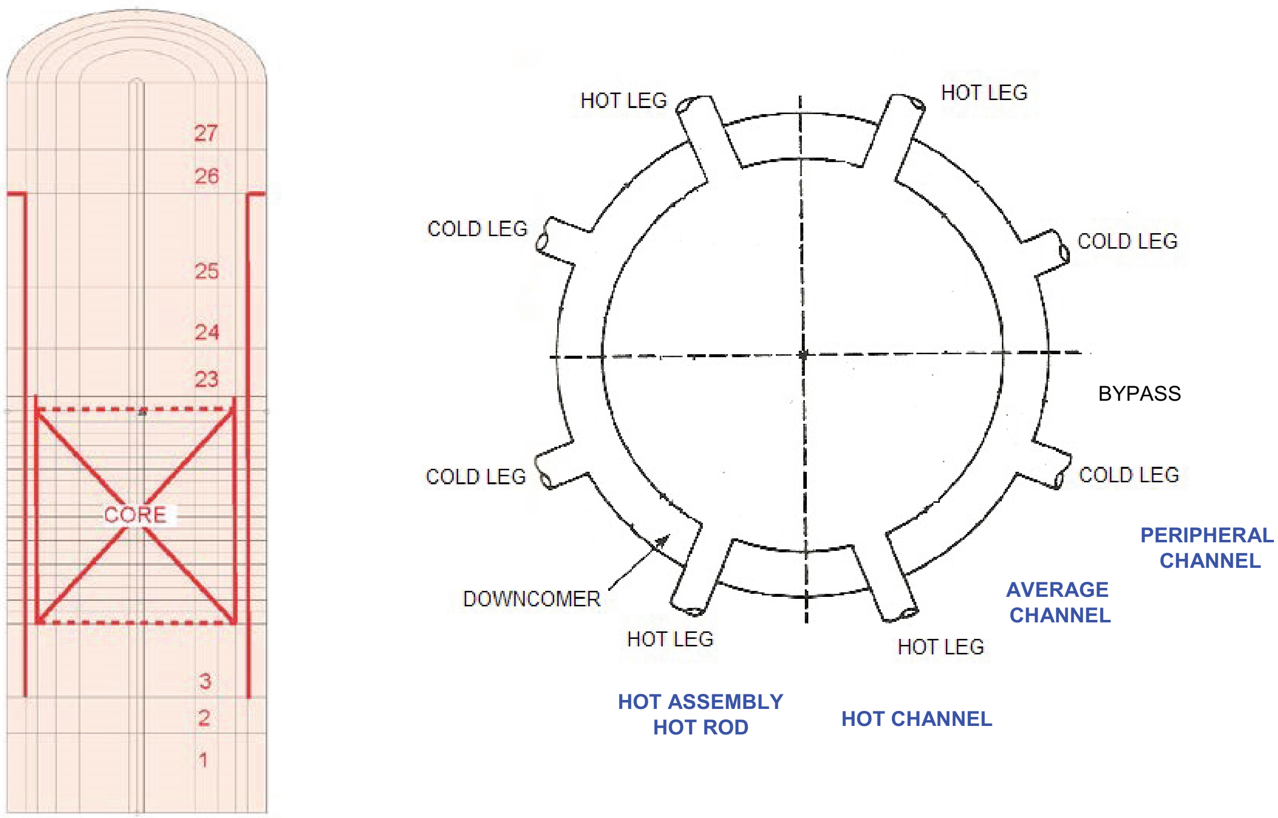

Fig. 2. 3-D nodalization for RPV.

Table 1
Initial conditions

Parameters	Nominal
Power (MWth)	3,250
Reactor pressure (MPa)	15.5
Cold leg temperature (K)	553.0
Hot leg temperature (K)	587.7
Feedwater flow (kg/s)	1,761.5
Feedwater temperature (K)	493.5
SG pressure (MPa)	4.83
Pressurizer level (m)	8.8

considered to be available because the purpose of the calculation is to find the necessity of the HPIS out. In addition, at the frontier between an MBLOCA and an LBLOCA, it is expected that the primary pressure will decrease quickly due to the large break size. Therefore, the fact that the charging pump has less flow rate than the medium-head injection pump at low pressure as shown in Fig. 3 can support the decision to make use of a charging pump for the HPIS. The LPIS is available for all calculations because it should be operable during later phase of the accident in an MBLOCA and the successful heat removal by the LPIS is a requirement of a LBLOCA.

The cooling of the primary system by the secondary system is not considered during the transient based on the functional requirement of an MBLOCA and an LBLOCA, which does not require additional cooling using the secondary

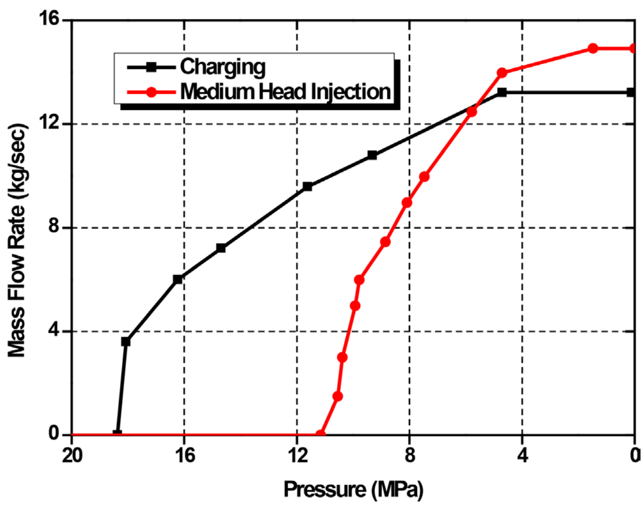

Fig. 3. Characteristics of charging and medium-head injection pumps.

system. Therefore, once the secondary system is isolated by the reactor trip signal, it will remain isolated during the transient [15]. In case of the MBLOCA with small break size, due to the small break flow, the pressure of the primary system decreases slowly and the primary system will remain in high temperature. In this case, the heat will be transferred from the primary system to the secondary system for a relatively long time and it will results in the increase of the pressure of the SG. In order to prevent over-pressurization of the SG, the relief valve and the auxiliary feedwater system will operate to dump the steam to the atmosphere and to maintain the SG level, respectively.

3. Results and discussion

3.1. Result of the calculations with HPIS

Fig. 4 shows the time trace of the PCT during the transient. The maximum PCT increases as the break size increases up to 6 in. However, it is found that the PCT does not increase in cases with break sizes of 3 and 4 in. It means that the break sizes are sufficiently small so that the accident can be mitigated by using the HPIS without the increase of the PCT more than the initial temperature. In the meantime, the break sizes are large enough to decrease the primary pressure to the pressure at which the sufficient high-pressure injection can be provided by a charging pump.

In the case of the 5 in break, the PCT begins to increase more than the initial temperature around 6,000 s later than the break initiation. As shown in Fig. 5, the flow through the break is greater than one injected from the HPIS so that the

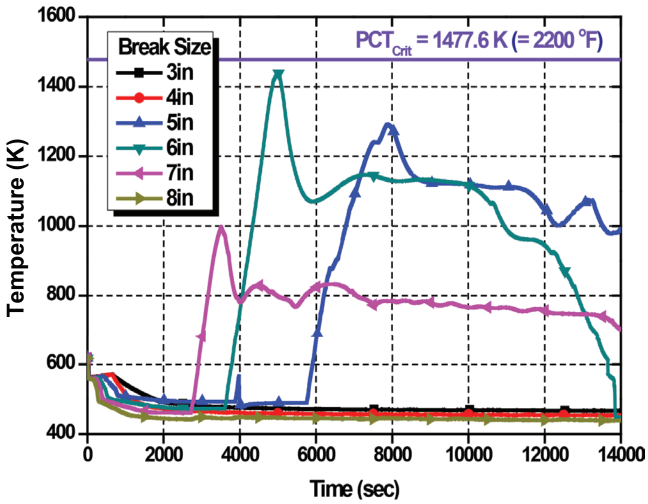

Fig. 4. Time trace of maximum PCT (with HPI).

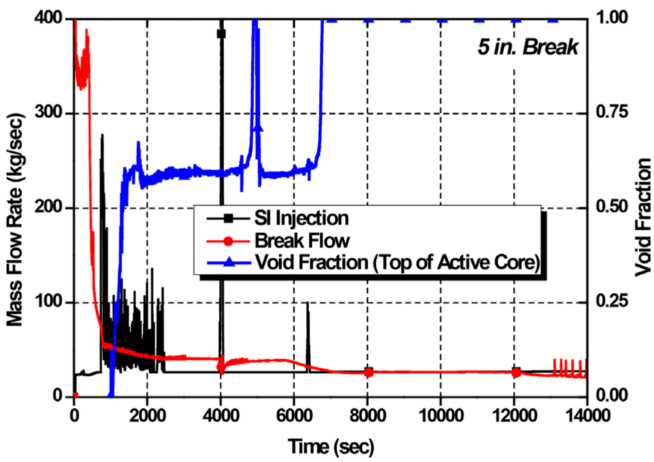

Fig. 5. Parameters related to the RPV inventory (5 in break with HPI).

PCT begins to increase as soon as the top of the active core is uncovered [16]. However, the reactor core cools down continuously as the level of the RPV is maintained by the equilibrium between the flow from the HPIS and through the break. The case with a break of 6 in shows the similar but faster transient compared with 5 in break, as shown in Fig. 6. The bigger break size results in the faster heat-up and cool-down. The highest maximum PCT among all cases is 1,437.8 K by 6 in break that is quite close to the acceptance limit of 1,477.6 K based on the specification in 10 CFR 50.46. It means that 6 in break cannot be successful without the HPIS and additional high-pressure injection pumps are required to mitigate the accident with sufficient PCT margin. Because the minimum specification for success of a MBLOCA is the success of two-out-of-four pumps in the HPIS, the highest maximum PCT in the actual safety analysis of an MBLOCA is expected to be sufficiently lower than this calculation result.

The decrease of the maximum PCT is presented in the cases with the break larger than 6 in. The result shows that the maximum PCT becomes less than the initial temperature again from the 8 in break. It is also found that the maximum PCTs of the cases with the break more than 8 in are still less than the initial temperature even though no HPIS is implemented, which will be explained later. Therefore, it can be concluded from the results that the HPIS is required, at least, up to 6 in break and the necessity of the HPIS should be evaluated by the calculations without the HPIS.

3.2. Results of the calculations without HPIS

A series of calculations without HPIS has been conducted to figure out the necessity of the HPIS. The calculation has been conducted for a range of 6–16 in and the same initial and boundary conditions except for the conditions for the HPIS have been implemented.

In Fig. 7, the time trace of the maximum PCT of the cases with break size of 6, 7, and 8 in is presented. As expected from the results described in the previous section, the maximum PCT of 6 in break increases as soon as the top of the active core is uncovered, and the highest maximum PCT is more than the acceptance limit. This result reveals that the HPIS is essential to mitigate the LOCA of 6 in break without causing the core damage. The result of 7 in break shows similar but faster transient compared with 6 in break due to

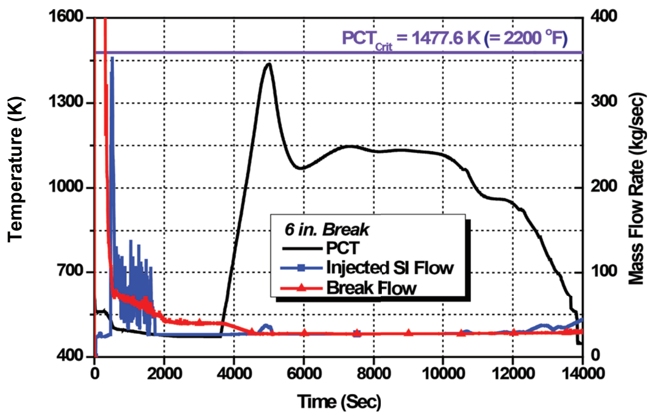

Fig. 6. Time trace of maximum PCT (6 in break with HPI).

larger break size. Therefore, it can be concluded that 6 and 7 in breaks should be definitely included in the range of the MBLOCA.

The result of 8 in break shows similar transient with 6 or 7 in breaks in the beginning. The maximum PCT increases rapidly as soon as the top of the active core is uncovered and the time of the PCT increase is earlier than smaller break due to the faster decrease of the water level in the RPV. Because of relatively large break, the pressure of the primary system decreases fast enough to provide sufficient SI before the maximum PCT reaches to the acceptance limit. Therefore, the maximum PCT starts to decrease at around 2,000 s from the break initiation. Although the highest maximum PCT does not exceed the acceptance limit, it is not reasonable to include 8 in break into the spectrum of an LBLOCA. The highest maximum PCT of this case has only small margin of 165.2 K to the acceptance limit. Therefore, it is expected that the 95/95 PCT (the highest maximum PCT with a probability of 95% and a confidence level of 95%) will be greater than the acceptance limit when an uncertainty analysis is conducted. In addition, it can be addressed that the case with 8 in break is a case on the way to the frontier between MBLOCA and LBLOCA because this case shows slower transient than other cases with bigger break and the maximum PCT does not increase in the case with 10 in break as shown in Fig. 8. Therefore, it is concluded that the case with 8 in break should be included in the spectrum of an MBLOCA.

Fig. 9 shows the time trace of the maximum PCT for larger breaks than 8 in. As mentioned above, it is found that the maximum PCT does not increase more than the initial temperature in the case of 10 in break. However, the break larger than 10 in results in the increase of the maximum PCT more than initial temperature. In addition, the time of the PCT increase and the peak of the maximum PCT become faster and higher, respectively, as the break size gets larger. Based on the behavior of the maximum PCT, it is concluded that the cases with the break sizes larger than 10 in results in different behavior from the 10 in break, so that 10 in break can be a turnover point in the viewpoint of the maximum PCT.

3.3. Frontier between MBLOCA and LBLOCA

Fig. 10 presents the highest maximum PCT according to the break size. The highest maximum PCTs in the MBLOCA and LBLOCA regions are calculated with and without HPI operation, respectively. From the plot, it is found that the highest maximum PCT begins to increase, as the break size gets bigger. The peak presents at the break size of 6 in and then the temperature starts to decrease.

The highest maximum PCT does not exceed the initial temperature of the system when the break sizes of 8 and 10 in

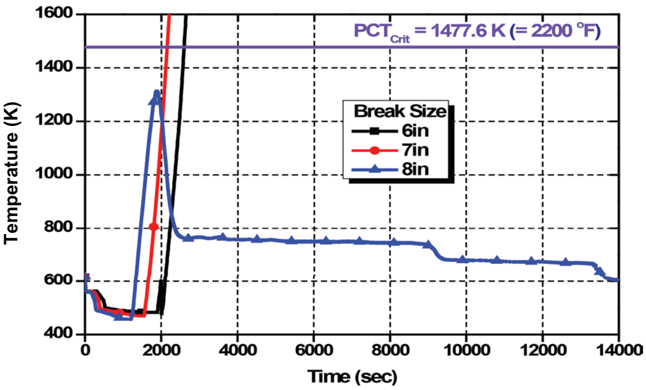

Fig. 7. Time traces of maximum PCTs for 6, 7 and 8 in breaks without HPI.

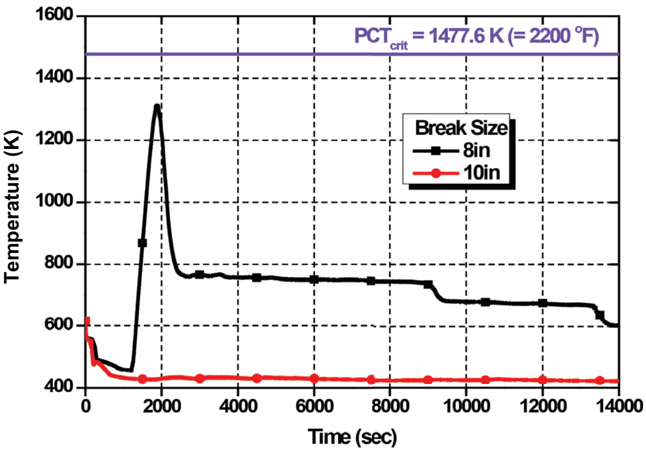

Fig. 8. Comparison of maximum PCTs between 8 and 10 in breaks.

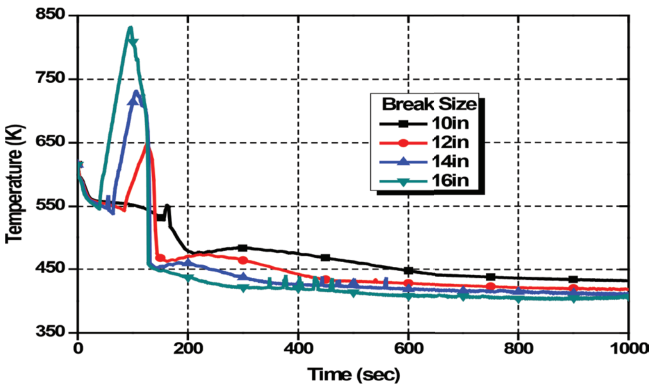

Fig. 9. Time trace of PCTs for bigger breaks without HPI.

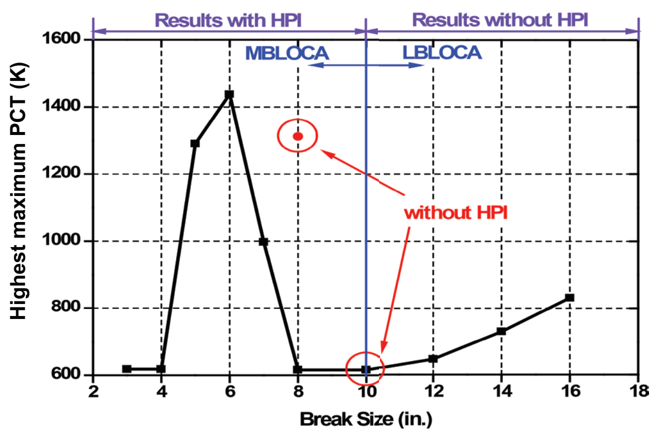

Fig. 10. Behavior of highest maximum PCT according to the break size.

are considered. However, when the HPIS does not operate, the 8 in break results in very high temperature that has only small margin to the acceptance criteria [17]. As mentioned in previous section, it reveals that the HPIS is still required for 8 in break. Therefore, from the PCT point of view, it is concluded that the availability of the HPIS has nothing to do with the consequence when the break size is larger than 10 in. Based on the result, it is obvious that 10 in break is a turnover point since the highest maximum PCT begins to increase from 12 in break and keeps increasing, as the break size gets bigger. Considering observations, it can be concluded that 10 in break should be the frontier between an MBLOCA and an LBLOCA of the Zion NPP.

4. Conclusion

In this study, a methodology to determine the frontier between MBLOCA and LBLOCA has been suggested on the basis of the PCT behavior and required safety functions come from the conventional PSA approach. The methodology has been demonstrated with an application to the Zion NPP. The relevant calculation was done by using the best-estimate thermal-hydraulics code, TRACE.

From the results, it was found that the frontier between an MBLOCA and an LBLOCA should be changed from 6 to 10 in based on the required safety function and the system response. It will result in the change of the initiating event frequencies of an MBLOCA and an LBLOCA and, therefore, the CDF of each event should be revised.

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