DETAILED EVALUATION OF THE IN-VESSEL SEVERE ACCIDENT MANAGEMENT STRATEGY FOR SBLOCA USING SCDAP/RELAP5

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As part of an evaluation for an in-vessel severe accident management strategy, a coolant injection into the reactor vessel under depressurization of the reactor coolant system (RCS) has been evaluated in detail using the SCDAP/RELAP5 computer code. A high-pressure sequence of a small break loss of coolant accident (SBLOCA) has been analyzed in the Optimized Power Reactor (OPR) 1000. The SCDAP/RELAP5 results have shown that safety injection timing and capacity with RCS depressurization timing and capacity are very effective on the reactor vessel failure during a severe accident. Only one train operation of the high pressure safety injection (HPSI) for 30,000 seconds with RCS depressurization prevents failure of the reactor vessel. In this case, the operation of only the low pressure safety injection (LPSI) without a HPSI does not prevent failure of the reactor vessel.

KEYWORDS : Severe Accident, Accident Management Strategy, RCS Depressurization, Coolant Injection, In-Vessel

1. INTRODUCTION

Coolant injection into the reactor vessel under depressurization of the reactor coolant system (RCS) is a very important strategy to prevent failure of the reactor vessel during severe accidents. This can be achieved by the operation of the safety injection system with RCS depressurization. The positive effects of this strategy are that it reduces the temperature of the core and prevents failure of the reactor vessel. The negative effect of this strategy is enhanced hydrogen generation. As this strategy has positive and negative points, a detailed evaluation is necessary before it can be applied to an actual nuclear power plant.

In the evaluation of a severe accident management strategy, a detailed analysis of the operator action timing and capacity using a best estimate computer code is very important to set up the operator action procedure during such accidents. Many studies involving the use of best estimate computer codes have been conducted to investigate melt progression [1-4]. However, few detailed evaluations of in-vessel severe accident management strategies have been performed using best estimate computer codes. For this reason, coolant injection into the reactor vessel with depressurization of the RCS to prevent a reactor vessel failure in the Optimized Power Reactor (OPR) 1000 has been evaluated by using the SCDAP/RELAP5/MOD3 computer code [5].

The OPR 1000, a pressurized water reactor (PWR), was developed by incorporating the latest technologies and experiences in construction and operation gained from previous nuclear power plants, including the EPRI advanced light water reactor (ALWR) requirements. The design features of the OPR1000 are a two-loop RCS design and a 1,000 MW_e power level. In the OPR1000, eight condenser dump valves (CDV) and four atmospheric dump valves (ADV) for secondary depressurization are installed in the main steam line. Two safety depressurization system (SDS) valves for direct RCS depressurization are installed at the top of the pressurizer. Two high and two low safety injection pumps are connected to four cold legs. In the SAMG of the OPR1000, the entry condition exists when the core exit temperature reaches 650 °C. For the in-vessel strategies in the SAMG for the OPR1000, a coolant injection into the steam generator, depressurization of the RCS to 2.9 MPa, and a coolant injection into the RCS are used.

In this study, a high pressure sequence of a small break loss of coolant accident (SBLOCA) without safety injection (SI) was selected as an initial event, as this sequence is the main severe accident of the OPR1000. According to the Level I probabilistic safety assessment (PSA) results [6] for the OPR1000, dominant severe accident sequences are a SBLOCA without SI, a station blackout (SBO), a steam generator tube rupture, a total loss of feed water (LOFW), a medium break LOCA without SI, and a large break LOCA without SI, with some lesser accidents. There is no operator action in the severe accident management process of the SBO sequence, as power is unavailable during these events. A steam generator tube rupture sequence is very similar to a SBLOCA. It is not necessary to depressurize the RCS for the medium and large break LOCAs because these are low RCS pressure sequences. A total LOFW sequence had already been evaluated in detail using the SCDAP/RELAP5 computer code [7]. For this reason, a SBLOCA without SI has been evaluated in detail.

In this study, RCS depressurization consists of direct RCS depressurization using a pressurizer safety depressurization valve and indirect RCS depressurization using a secondary feed and bleed operation. A safety injection is three trains of high-pressure safety injection (HPSI) and a low-pressure safety injection (LPSI) without the broken RCS loop. Sensitivity studies of the coolant injection timing and capacity under RCS depressurization have been performed to determine the proper operator action for this sequence.

2. SCDAP/RELAP5 CODE DESCRIPTION AND INPUT MODEL

The SCDAP/RELAP5 computer code, which represents a merging of the RELAP5/MOD3 [8] and severe core damage analysis package (SCDAP) models [9], is designed to calculate the severe accident situations of the overall RCS thermal-hydraulic response, core damage progression, reactor vessel heat-up and damage, and fission product release and transport. The code was developed at the Idaho National Engineering and Environmental Laboratory (INEEL) under the sponsorship of the U.S. Nuclear Regulatory Commission (USNRC). The RELAP5 models calculate the overall RCS thermal-hydraulics, control system interactions, reactor kinetics, and the transport of noncondensable gases. A model is also included in RELAP5 to calculate the flow losses in porous debris. The SCDAP model calculates the heat-up and damage progression in the core structures and the lower head of the reactor vessel. Treatment of the core in SCDAP models includes a fuel rod heat-up, ballooning and rupture, fission product release, rapid oxidation, zircaloy melting, UO_2 dissolution, ZrO_2 breach, flow and freezing of the molten fuel and cladding, and debris formation and its behavior. The COUPLE model

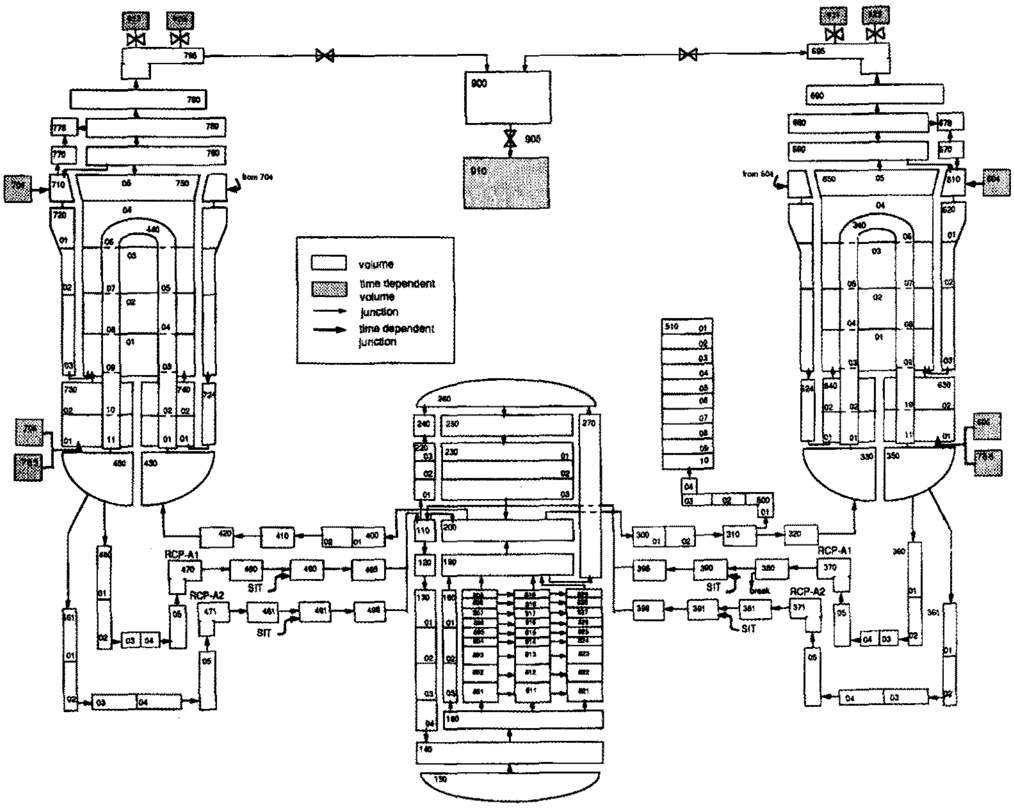

Fig. 1. SCDAP/RELAP5 Input Model for the OPR1000

[10] of the SCDAP/RELAP5 calculates the heat-up of the debris and surrounding structures in the reactor lower head vessel after a core slumping to the lower head occurs.

Fig. 1 shows the SCDAP/RELAP5 input model for the OPR1000. The input model for the SCDAP/RELAP5 calculation of the OPR1000 is a combination of the RELAP5, SCDAP, and COUPLE input models. The heat structures for the fuel rods and the lower part of the reactor vessel in the RELAP5 input model were replaced by SCDAP and COUPLE input models, respectively. In the RELAP5 models, the reactor vessel, two hot legs, two steam generators, four reactor coolant pumps (RCP), four cold legs, and two feed and steam lines were modeled. The reactor core was simulated as three channels to evaluate its thermal-hydraulic behavior in detail, and each channel was composed of ten axial volumes. A surge line and a pressurizer were attached to one of the hot legs in the primary coolant loop. Four safety injection tanks (SITs) were connected to the cold legs. One safety depressurization system (SDS) valve for the direct depressurization of the RCS was connected to the top of the pressurizer. Three safety injection lines of the HPSI and the LPSI without a broken RCS loop were connected to the cold legs, one to each leg.

The secondary side of the steam generator consisted of a cylindrical shell, a downcomer through which the main feedwater was supplied, a separator, and a steam dome. The main feedwater system was modeled as time-dependent volumes to simulate normal operation. The main steam safety valves and a main steam isolation valve were also modeled for a steady state simulation of the OPR1000. The turbine was modeled as a time-dependent volume. As a secondary feed system in the transient, the auxiliary feedwater system was modeled. Eight CDVs and four ADVs for the depressurization of the steam generator were modeled in the main steam line.

In the SCDAP input model, the component numbers of the fuel and the control rods were 3 and 3, respectively, in this study. The axial node numbers for the fuel and control rods were 10 for each component in order to simulate the ballooning and relocation after a rupture of the fuel cladding accurately. The radial node numbers of the fuel and the control rods were 6 and 2, respectively. In the COUPLE input, the lower part of the reactor vessel was divided into 234 nodes and 204 elements. The potential for creep rupture was evaluated the steam generator tubes, surge line, hot legs, and the reactor vessel. For the RELAP5, the SCDAP, and the COUPLE input data of the reactor vessel, the specifications outlined in the safety analysis report of the OPR1000 were primarily utilized.

3. RESULTS AND DISCUSSION

The base case of the SBLOCA was initiated by introducing a 0.034 m diameter hole in the cold leg. There was no RCS depressurization and no safety injection into the RCS in the base case. The reactor and the RCPs were assumed to be tripped upon accident initiation. The secondary side of the steam generator was fed by auxiliary feedwater pumps. The RCS water inventory rapidly decreased and boiling started in the core because the safety injection pumps were not actuated. The fuel began to heat up when the core uncovered. Oxidation of the fuel cladding began when the cladding surface temperature reached 1,000 K. The fuel cladding failed due to sausage-type ballooning. When the cladding surface temperature reached 1,700 K, the oxidation rate of the zircaloy was accelerated as steam was supplied from the bottom of the reactor vessel. This resulted in a rapid increase of the cladding surface temperature. At a cladding surface temperature of nearly 2,500 K, the zircaloy inside the

Table 1. Significant Events in the Case of One CDV Opening

Case	SIT Actuation Time / LPSI Actuation Time (sec)	First Relocation Time to the LP (sec)	Large Relocation Time to the LP (sec)	RV Failure Time (sec)	RCS Pressure at RV Failure (MPa)
Base	n/a - n/a	6,222	6,222	6,330	6.72
CDV1-6 min	5,328 - n/a	32,244	33,800	34,030	3.34
CDV1-6 min, SDS1-32500	5,328 - n/a	32,814	32,814	33,095	2.25
CDV1-6 min, LPSI3	5,328 - 7,832	38,531	39,967	40,200	3.30
CDV1-1 min, LPSI3	5,032 - 6,078	47,928	47,928	49,235	2.37
CDV1-6 min, HPSI1-30000	5,328 - 30,000 (HPSI)	Fuel Melting Time = 30,359 seconds, No RV Failure			

Table 2. Effects of the Primary and Secondary Depressurization on Significant Events

Case	SIT Actuation Time, LPSI Actuation Time (sec)	First Relocation Time to the LP (sec)	Large Relocation Time to the LP (sec)	RV Failure Time (sec)	RCS Pressure at RV Failure (MPa)
Base	n/a - n/a	6,222	6,222	6,330	6.72
CDV1-6 min	5,328 - n/a	32,244	33,800	34,030	3.34
CDV1-6 min, LPSI3	5,328 - 7,832	38,531	39.966.5	40,200	3.30
CDV1-6 min, SDS1-32500	5,328 - n/a	32,814	32.814	33,095	2.25
CDV1-6 min, LPSI1, SDS1-32500	5,328 - 7,832	No Fuel Melting & RV Failure			

oxide shell began to liquefy and the outer portion of the fuel pellets was dissolved. The relatively thin ZrO_2 shell ruptured at approximately 2,700 K because the shell strength decreased with the increase in temperature. The bottom of the core dried out because a hot mixture of the liquefied fuel and cladding had relocated downward. Debris formed at the bottom of the fuel rods, where the liquefied mixture had resolidified. The melting temperature of the zirconium dioxide was 2,960 K, and that of the uranium dioxide was 3,120 K in these calculations. Flow blockage in the lower part of the core region occurred due to the melting of the fuel and the formation of cohesive debris. The molten core material relocated to the lower plenum of the reactor vessel. Finally, the reactor vessel failed by creep due to a relocated melt thermal attack.

Table 1 shows the SCDAP/RELAP5 predictions on the timing of significant events for the SBLOCA in the case of one CDV opening for the RCS depressurization. In the table, CDV1-6 min indicates that one condenser dump valve for the indirect RCS depressurization opens 6 minutes after the implementation of the SAMG, when the core exit temperature reaches 650 °C. This time is equivalent to 4,966 seconds after the transient is initiated. SDS1-32500 indicates that one SDS valve for the direct RCS depressurization opens 32,500 seconds after the transient is initiated. LPSI3 and HPSI1 represent the three train injections of the LPSI and one train injection of the HPSI, and LP and RV are the lower plenum and the reactor, respectively. The actuation pressures of the HPSI and the LPSI are 13.2 MPa and 1.45 MPa, respectively.

As shown in Table 1, only 1 CDV opening 6 minutes after the implementation of the SAMG can depressurize the RCS, which results in a delay of the reactor vessel failure time of approximately 462 minutes. However, this can not depressurize the RCS to 2.9 MPa, which is the RCS depressurization target in the SAMG of the OPR1000. Despite the fact that the entire secondary bleed system of 8 CDVs and 4 ADVs was opened 6 minutes after the SAMG was implemented, the RCS pressure did not decrease to 2.9 MPa. For this reason, greater RCS depressurization is necessary for the SBLOCA without SI. When the operator opened one SDS valve 32,500 seconds after the transient was initiated, the RCS pressure was less than 2.9 MPa upon reactor vessel failure for the SBLOCA with a secondary feed and bleed operation. Additional evaluation results pertaining to RCS depressurization in the OPR1000 can be found in the literature [11]. Only one train operation of the HPSI at 30,000 seconds with RCS depressurization using one CDV valve 6 minutes after implementation of the SAMG prevents a reactor vessel failure in spite of the fuel melting at 30,359 seconds after the transient is initiated. In this case, only the LPSI operation does not prevent reactor vessel failure. In addition, only the LPSI operation at the earlier depressurization time 1 minute after implementation of the SAMG does not prevent reactor vessel failure.

Table 2 shows the effect of a primary and a secondary depressurization on significant events for the SBLOCA. Only one train operation of the LPSI with RCS depressurization using one CDV valve 6 minutes after implementation of the SAMG and one SDS valve opening at 32,500 seconds prevents a reactor vessel failure for the SBLOCA in the OPR1000. Table 3 shows the effect of the HPSI actuation time and capacity on significant events for the SBLOCA. One train operation of the HPSI at 30,696 seconds with RCS depressurization using one CDV valve 6 minutes after implementation of the SAMG prevents a reactor vessel failure in spite of the fuel melting 30,410 seconds after the transient is initiated. However, 31,296 seconds is too late for one train operation time of the HPSI for the prevention of a reactor vessel failure in the SBLOCA of the OPR1000. Three train operations of the HPSI at 30,000 seconds with RCS depressurization prevents the fuel from melting and prevents a reactor vessel failure. Three train operations of the HPSI at 31,296 seconds prevents a reactor vessel failure in spite of the fuel melting at 30,397 seconds, but 31,996 seconds is too

Table 3. Effect of the HPSI Actuation Time and Capacity on Significant Events

Case	SIT Actuation Time, HPSI Actuation Time (sec)	First Relocation Time to the LP (sec)	Large Relocation to the LP (sec)	RV Failure Time (sec)	RCS Pressure at RV Failure (MPa)
Base	n/a - n/a	6,222	6,222	6,330	6.72
CDV1-6 min, LPSI3	5,328 - n/a	38,531	39.967	40,200	3.30
CDV1-6 min, HPSI1-30000 sec	5,328 - 30,000	Fuel Melting Time = 30,359 seconds, No RV Failure			
CDV1-6 min, HPSI1-30696 sec	5,328 - 30,696	Fuel Melting Time = 30,410 seconds, No RV Failure			
CDV1-6 min, HPSI1-31296 sec	5,328 - 31,296	32,454	32,454	32,610	7.56
CDV1-6 min, HPSI3-30000 sec	5,328 - 30,000	No Fuel Melting, No RV Failure			
CDV1-6 min, HPSI3-31296 sec	5,328 - 31,296	Fuel Melting Time = 30,397 seconds, No RV Failure			
CDV1-6 min, HPSI3-31996 sec	5,328 - 31,996	33,177	33,177	33,330	5.38

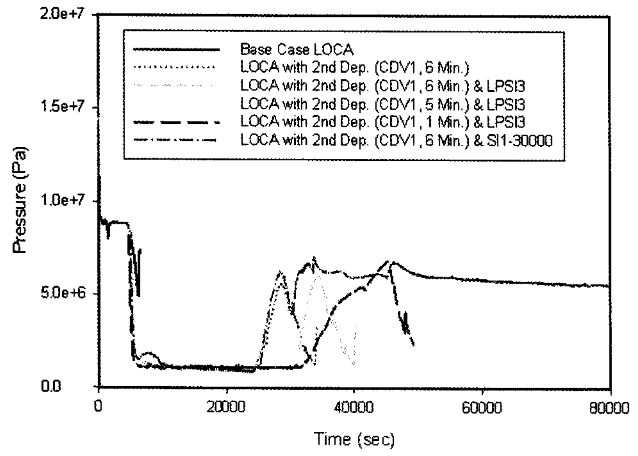

Fig. 2. Pressurizer Pressure with One CDV Opening

late for the prevention of a reactor vessel failure.

Fig. 2 shows the pressurizer pressure during the SBLOCA in the case of one CDV opening for the RCS depressurization. In this Figure, SI denotes the actuation of the HPSI. After the LOCA occurred at 0 seconds, the pressurizer pressure rapidly decreased to the saturation pressure corresponding to the hot leg temperature at the beginning of the transient. As the coolant began to boil, the expansion of the coolant caused by boiling was able to offset the break flow, and the pressurizer pressure was maintained at the saturation pressure. When the operator opened one CDV for RCS depressurization, the pressurizer pressure rapidly decreased. The steady decrease in the pressurizer pressure stopped after the SITs began a coolant injection into the RCS. When the injected water entered the core, it boiled and thus raised the pressurizer pressure. This increase of the pressurizer pressure was stopped by no coolant injection from the SITs, and the pressure decreased again. When the pressure was low enough, the coolant was injected again. This cycling of SITs actuation led to a slow reduction in the RCS pressure. With no safety injection, when the molten core material relocated to the lower plenum, the pressurizer pressure increased on account of the boiling of the coolant in the lower plenum. Actuation of the safety injection stopped the decrease of the pressurizer pressure by the boiling of the injected water.

The collapsed water levels of the core region in the case of one CDV opening for the RCS depressurization are shown in Fig. 3. Due to the loss of the RCS coolant inventory through the break, the collapsed water level decreased to the bottom position of the fuel rod and the reactor core was dried up when complete core uncovery occurred. When the SITs were actuated by RCS depressurization, the core water level increased. The cycling of SITs actuation resulted

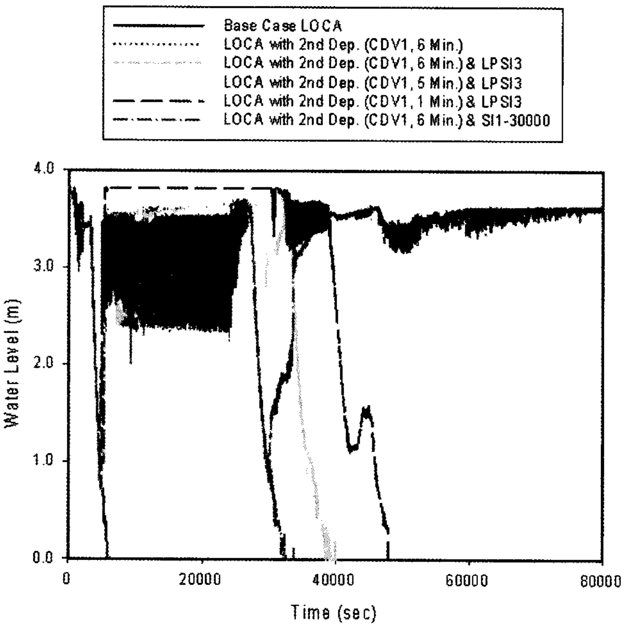

Fig. 3. Collapsed Water Level of the Core with One CDV Opening

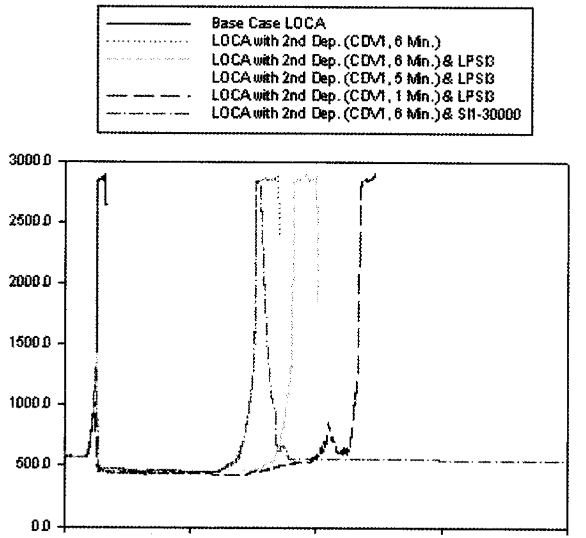

Fig. 4. Maximum Cladding Surface Temperature with One CDV Opening

in a cycling of the core water level. When the SIT actuation process was finished, this decreased rapidly. The collapsed water level increased again to the top or the middle of the core region by the actuation of the safety injection.

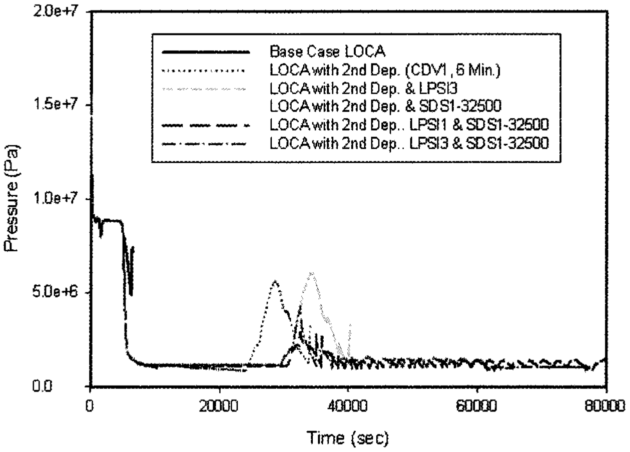

Fig. 5. Effects of the Primary and Secondary Depressurization on the Pressurizer Pressure

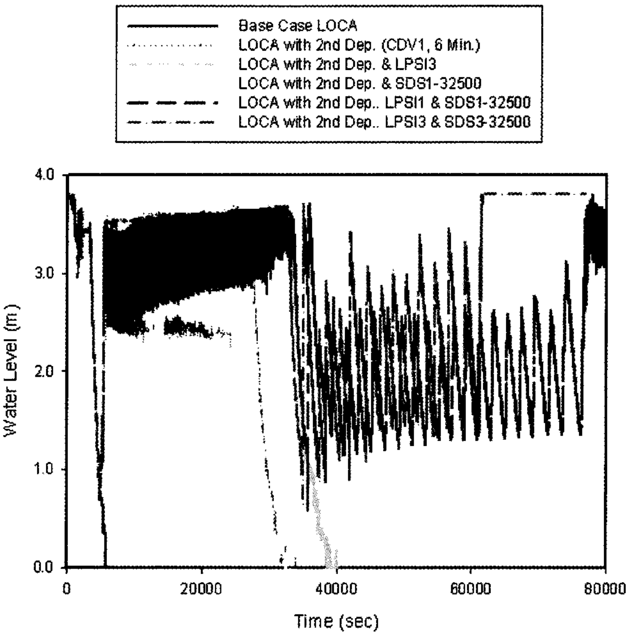

Fig. 6. Effects of the Primary and Secondary Depressurization on the Collapsed Water Level in the Core

Fig. 4 shows the maximum fuel cladding surface temperatures for the SBLOCA in the case of one CDV opening for RCS depressurization. The fuel cladding surface temperature is slightly higher than the surrounding coolant temperature until the coolant in the core volume corresponding to each fuel rod is vaporized. The fuel cladding surface temperature at the top of the fuel rods rose when a core uncovery event occurred at the top of the core. When the fuel cladding temperature increased to 1,000 K, fuel cladding oxidation began. Following this time, the fuel cladding temperature increased abruptly due to the generation of heat associated with the actions

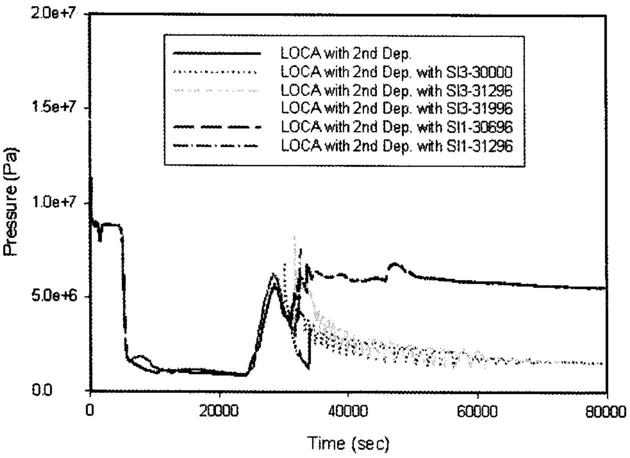

Fig. 7. Effect of the HPSI Actuation Time and Capacity on the Pressurizer Pressure

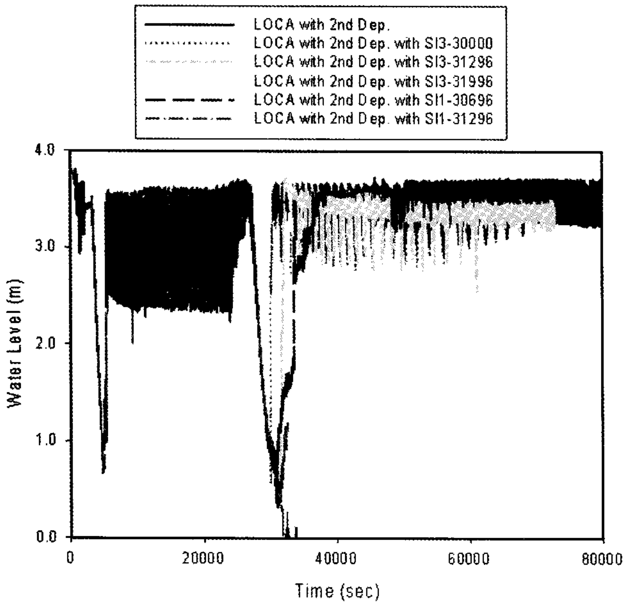

Fig. 8. Effect of the HPSI Actuation Time and Capacity on the Collapsed Water Level in the Core

of cladding oxidation. Effective actuation of the SITs by RCS depressurization caused a delay of the rapid increase of the maximum cladding temperature. When the low pressure safety injection was actuated, the maximum cladding surface temperatures did not decrease to the saturation temperature. However, actuation of the high pressure safety injection at 30,000 seconds led to a decrease of the maximum cladding surface temperatures to the saturation temperature.

Figs. 5 and 6 show the effects of primary and secondary depressurization on the pressurizer pressure and the collapsed core water level during a SBLOCA with a subsequent safety injection. When the operator opened one safety depressurization valve for direct RCS depressurization, the pressurizer pressure decreased. The actuation of the LPSI led to an increase of the collapsed water level to the top or the middle of the core region. The pressurizer pressure and the core collapsed water level after the actuation of the LPSI showed oscillatory characteristics. Figs. 7 and 8 show the effect of the HPSI actuation time and capacity on the pressurizer pressure and the collapsed core water level during the SBLOCA with a subsequent safety injection. When the HPSI was actuated, the pressurizer pressure did not decrease due to the boiling of the injected water. The actuation of the HPSI led to an increase of the collapsed water level to the top or the middle of the core region.

4. CONCLUSIONS

A coolant injection into the reactor vessel with depressurization of the RCS to prevent reactor vessel failure has been evaluated using the SCDAP/RELAP5 computer code during a SBLOCA in the OPR1000. The SCDAP/RELAP5 results have shown that only one train operation of the HPSI at 30,000 seconds with RCS depressurization prevents failure of the reactor vessel. In this case, only the LPSI operation does not prevent a reactor vessel failure. Only the LPSI operation with RCS depressurization and one SDS valve opening at 32,500 seconds prevents a reactor vessel failure. One train operation of the HPSI at 30,696 seconds with RCS depressurization prevents a failure of the reactor vessel in spite of fuel melting at 30,410 seconds, but 31,296 seconds is too late to prevent this. Three train operations of the HPSI at 30,000 seconds with RCS depressurization prevents the fuel from melting and prevents a reactor vessel failure. Three train operations of the HPSI at 31,296 seconds prevents a reactor vessel failure in spite of the fuel melting at 30,397 seconds, but 31,996 seconds is too late. It is concluded that safety injection timing and capacity with RCS depressurization timing and capacity are very effective against reactor vessel failures. The present results can be used for SAMG development studies for the OPR1000.

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