ANALYSIS OF INTENTIONAL DEPRESSURIZATION DURING STATION BLACKOUT ACCIDENT IN A PRESSURIZED WATER REACTOR

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ABSTRACT

ANALYSIS OF INTENTIONAL DEPRESSURIZATION DURING STATION BLACKOUT ACCIDENT IN A PRESSURIZED WATER REACTOR. The intentional reactor coolant system depressurization strategy during a station blackout accident at four loops Pressurized Water Reactor has been analyzed using MELCOR 1.8.4 code. The first assumption was latched opening of pressurizer PORVs when the core exit temperature reached 922 K. The calculation result showed that the depressurization rate was insufficient. The system pressure was at 11 MPa when the reactor vessel lower head failed at 13,000 s. The second assumption was latched opening of PORVs and SRVs all together. The result predicted faster depressurization rate of about 0.15 MPa/s allowing the injection of water from accumulator at 12,045 s. The injected cool-borated water prevented core from severe damage, and until the end of calculation at 20,000 s. the reactor vessel was kept intact. Compared to the calculation result of TMLB' accident without intentional depressurization, it represented the delay of vessel failure more than 100 minutes.

Key words: Severe accident, Station Blackout, Accident Mitigation, PWR, Depressurization

INTRODUCTION

Since the containment building has a function as a last barrier, the containment building failure of a Pressurized Water Reactor (PWR) during a hypothetical severe accident will represent a major risk to the public health and safety due to the probability of radioactive release. One of the potential contributors to the early pressurization and failure of the containment is direct containment heating (DCH).

Direct containment heating is the result of a complex set of phenomena that may occur if the reactor pressure vessel (RPV) lower head is penetrated by molten core debris while the reactor coolant system (RCS) is at high pressure. Vessel penetration at high pressure can cause the molten core material to be ejected into the containment atmosphere at sufficiently high velocities that the core debris will be dispersed as small particles. Such kind of phenomenon was observed in the experimental study performed by Tarbell et al. [1]. Moreover, Frid [2], analyzed that a pressure difference of 1 MPa between RCS and the containment could produce a debris jet of about 15 m/s. Once core melt ejection begins, several processes may occur that can rapidly transfer a large amounts of energy to the containment atmosphere. If the amount of core material ejected is sufficiently large and the material is widely dispersed as fine fragments, the large energy release will cause a rapid pressurization to a level that will induced failure of containment.
An accident sequence initiating by a total station blackout (SBO) in a PWR could result in a High Pressure Melt Ejection (HPME). An example was shown by the result of SBO analysis of German PWR-1300 using Melt Core (MELCOR) code. This analysis predicted that during core melting the RCS pressure was at about 16 MPa [3]. Such a high pressure might result in a HPME if RPV lower head failure takes place. On the other hand, Probabilistic Safety Assessment (PSA) level I for PWRs had shown that an accident initiated from a total station blackout (namely TMLB'), is one of the dominant accidents leading to severe core damage [4].

As a strategy to prevent or mitigate HPME leading to DCH, the intentional RCS depressurization was proposed. Brownson et al. [5] had studied the RCS depressurization by latched opening of Power-Operated Relief Valves (PORVs) for four different types of US PWR Nuclear Power Plants (NPPs). The Reactor Excursion and Leak Analysis Program/Severe Core Damage Analysis Program (RELAP/SCDAP) computer code was used. The calculation results showed that in all cases, the intentional depressurization accelerated the RCS pressure decrease and it initiated accumulator injection. As consequence, the lower head failure was predicted to occur at about 500 minutes after SBO initiation. It was also observed that the timing of accumulator injection depended on the PORVs capability to depressurize. This study assumed the valves opening at the time the exit core temperature 922 K.

Chambers et al.[6] also studied the intentional RCS depressurization of Surry NPP using RELAP5/SCDAP. In this study, PORVs and RPV head vent were intentionally opened to depressurized RCS when the SG secondary side were dried. The calculations were not performed until the RPV lower head failure, but it could be shown that the accumulator injection occurred. On the other hand, it was observed that the failure of surge line prior to vessel failure from creep rupture was probable.

In the current study, the analyses of the intentional RCS depressurization as an accident management strategy of four loops PWR is performed using MELCOR 1.8.4 computer code. The emphasis of the current study is to assess the RCS depressurization characteristics. The depressurization was performed either by intentional latch opening PORVs or both PORVs and safety relief valves (SRVs) together. The last is aimed to conduct numerical simulation of the depressurization capability of design studied, although in the real plant SRVs could not intentionally be opened. As a reference calculation, the calculation of TMLB' without depressurization was first done [7]. The results of all runs and discussions are described in this paper.
CODE AND MODEL DESCRIPTIONS

The capability to depressurize a four-loop PWR using the pressurizer power operated relief valves (PORVs) is currently analyzed using MELCOR 1.8.4. The MELCOR 1.8.4 computer code is a light water reactor system transient code [8]. This code provides an integral calculations of the system thermal-hydraulic and core damage response. The core, primary system, secondary system, feedwater train, and system can be simulated. MELCOR either explicitly models or parametrically treats all key in-vessel and ex-vessel phenomena. Characteristic of severe accident in-vessel phenomena that are treated in MELCOR include the two-phase thermal-hydraulic response in the RCS, fuel rod heating, Zircaloy oxidation and hydrogen generation core degradation processes, debris bed behavior, and lower head response. In addition, fission product release, transport, deposition and re-vaporization are also treated.

A corresponding set of ex-vessel phenomena is also treated. In particular, MELCOR treats core/concrete interactions, containment and auxiliary building thermal-hydraulic response, containment heat structure response, hydrogen burning and detonation, aerosol behavior, and the impact of engineering safety features on thermal-hydraulics and radionuclide release and transport.

The CORE package of MELCOR is the module that treats the core degradation process. This package contains the models used for oxidation, hydrogen production, and cladding and lower head failures. There is no explicit model for cladding ballooning in MELCOR. Cladding rupture is modeled as occurring when either the cladding temperature exceeds a given threshold temperature or the cladding melts. The failure of core support plate and lower head are also modeled in parametrically, i.e. by a given threshold temperature and pressure.

A model of a four loops Westinghouse-designed PWR of 3025 MWth was used for the analyses. The model was originally prepared in JAERI. The improvements of the model were made for this study, especially for modeling SG secondary side and control functions of valve opening. The RCS, the steam generators, the containment building and the environment are modeled and are nodalized as shown in Figure 1. The four loops of RCS are modeled by two loops; one represents pressurizer attached loop (loop A) and the other represents lumped of three other loops (loop B). The model of the steam generator includes the tubes (control volume (CV) 210, 215, 260 and 265), downcomer (CV 309 and 339), riser (CV 310 and 340), main and auxiliary feedwater system (flow path (FL) 304, 306, 334 and 336), steam line (FL 326 and 356), main steam isolation valves, PORVs, and safety relief valves. The two pressurizer PORVs were modeled as a single valve connected to the top of pressurizer. The accumulators are both modeled in each loop (CV 235 and 285).
The reactor core nodalization, as a separate model from RCS model, consisted of 45 core cells divided in 15 axial levels and 3 rings as shown in Figure 2. The axial level: 1 through 3 modeled lower plenum, including the core support structure in level 4, while level 5 to 15 made up the active core region.

ASSUMPTIONS

The major assumptions for TMLB' calculation are as follows:

1. The total thermal power (fission and decay heat power) is 3025 MWth. As a default in MELCOR, it is assumed that the reactor was operated for 2 years full power operation before the accident;
2. Steady state is calculated for 50 s before initiation of station blackout;
3. At 0 s, total station blackout occurs;
4. Reactor scram occurs with the delay of 1 s;
5. The scram signal trip the primary coolant pump, close feed water valve and main steam isolation valve;
6. The auxiliary feed water pumps are unavailable;
7. The high pressure and low pressure injection systems are unavailable. The accumulator is set up to operate when primary system pressure at 4.42 MPa. Besides of above assumptions, several default parameters related to the core degradation are used, among others;
8. The cladding oxidation (and so, hydrogen production) is started when the cladding temperature reaches 1000 K;
9. The failure of cladding resulting into the gap release occurs at the cladding temperature 1173 K;
10. The tube guide penetrations failure is assumed when ever the temperature of the penetration reaches 1273.15 K.
11. The lower head failure allowing a debris ejection occurs when the temperature of bottom lower head node exceed failure temperature, and a total molten mass of 5000 kg or a melt fraction of 0.1 is necessary before debris ejection can begin (default of MELCOR 1.8.4).

Concerning timing of PORVs opening, the current calculation used the assumption proposed by [5], i.e. when ever the exit core temperature reached 922 K. At this temperature the quality of the PORVs discharge is higher [5].

RESULTS AND DISCUSSIONS

Results

The transient used in this analysis was the TMLB' sequence, which is a loss of both on- and off-site ac power, with early (immediate) failure of the steam-driven auxiliary feedwater pump. Then, the TMLB' calculation (named run 1) was performed and used as a calculation base.
The second calculation (named run 2) was done for TMLB' sequence with intentional RCS depressurization. The depressurization was done by latch opening of PORVs when the vapor core exit temperature at 922 K.

The third calculation (named run 3) was performed with assumption that in case of the PORVs depressurization capability was insufficient, then the safety relief valves (SRVs) were also opened intentionally together with PORVs. This assumption is to allow faster depressurization due to increasing flow area. However, it must be noted that in PWR design, studied only PORVs could be opened to intentional depressurization. So, this assumption must be considered as a numerical simulation breakthrough to overcome inadequacy of PORVs depressurization capability. In the view point of accident management, it could be considered as an investigation to develop accident management strategy alternatives. Such kind of investigation was also conducted by Kumamaru and Kukita [9], and Hidaka et al. [10].

Table 1 shows the timing key events predicted for each run. The calculation results of each run and discussions are described in detail below.

Run 1

The total loss of power during station blackout caused the primary coolant pumps coasted down, reactor scrammed and, the auxiliary feed water system was unavailable. The last led to secondary coolant inventory in SG's shell side boiled off. During the SG secondaries boil-off: the RCS pressure decreased because the heat sink was effective. Figure 3 shows the RCS pressure history. After scram, while pumps were coasting down, the pressure decreased following the decrease of coolant temperature. But, due to unavailability of feed water, SG shell side began to dry out at about 5000 sec, while the decay heat being transferred from the core. As a consequence of worse heat sink capability of secondary system, the temperature and the pressure of the primary system began to increase. The pressure reached quickly to the set point of PORVs, and PORVs started to open and close to maintain the primary system pressure.

On the other hand, the temperature increase caused the water level in the pressurizer increased. The water liquid vented out through PORVs when it reached the top of pressurizer. As a result of the water boil-off and water discharge from PORVs, the water level in reactor vessel decreased progressively as shown in Figure 4. At about 7980 s the water level reached the top of core.

The reactor core started to heat up when it uncovered. The upper part and inner ring of the core was heated first and faster. The temperature of the cladding increased without interruption. The oxidation of Zircaloy cladding started to occur just before the cladding failed, at 11,400 s. The hydrogen and heat generated caused the pressure rise momentarily as could be seen in Figure 3. When ever-the cladding failure temperature threshold was
exceeded, the gap release began to occur from the ring 1 at 11,492 s. Then, it was followed by the ring 2 and 3 at 11,612 s and 11,889 s, respectively.

When ever the melting temperature was exceeded, the core debris formed. The debris started to relocate downward progressively. Once reaching the core support plates, the support plates temperature increased and failed. The debris fell into the lower plenum and relocated at lower head vessel. The heat transferred from debris to vessel wall by conduction caused the lower head penetration to fail (at 15,449 s.) while the primary system pressure was still at PORVs set point. Following the vessel breakthrough, the coolant and the debris was discharged out the vessel. Then, the pressure dropped almost instantaneously.

Run 2

As in TMLB' sequence, because the RCS coolant inventory was continually being removed while PORVs cycled, the water level in the reactor vessel decreased. At 7980 s, the core became uncovered, and the fuel rod cladding in the upper regions of the core became steam cooled. However, the steam flow rate passing the cladding was inadequate to maintain an equilibrium temperature. When ever the fuel cladding temperature increase, the steam became superheated. At 11,180 s, the core exit steam temperature reached 922 K and the PORVs were latched open according to the intentional depressurization strategy.

After the PORVs were latched open, the RCS pressure began to decrease as shown in Figure 5. During the time required to reduce the RCS pressure, the core liquid level was continuing to decrease as shown in Figure 6. As a consequence, the temperature of the cladding increased. At about 12,600 s, the upper region of the innermost ring became debris. The relocation of the debris downward to the lower cell reached the core support plate. At 12,963 s, the core support plate failed allowing the debris to relocate into the vessel lower head. At about 13,000 s, the lower head penetration in ring 1 failed. The coolant was discharged through the breach. The RCS pressure dropped drastically from about 11 MPa to the ambient pressure as shown in Figure 5.

Run 3

Before valve latched opening, the sequence was identical with the calculation in run 2. At the time of PORVs and SRVs latched opening (11,180 s.), the pressure decreased quickly from PORVs set point to below the accumulator pressure set point, i.e. 4.2 MPa, with the rate of depressurization 0.15 MPa/s approximately as shown in Figure 7. Figure 8 shows the mass flow rate through SRVs. The flow was dominated by hot vapor flow. The total liquid mass discharged almost doubled than in run 2. Then, the depressurization was faster.
After accumulator injection, several small pressure peaks appeared which were due to steam generation in the core. The increase was small because both PORVs and SRVs were opened, so hot steam passed easily, and RCS was not pressurized. The injection of borated water from the accumulators occurred continuously until the borated water in accumulator tanks was depleted.

The injection of cold borated water from accumulator flooded the core. The liquid level in the core increased (as shown in Figure 9), and cooled the core. The fuel cladding temperature decreased except for the core uppermost region that continued to increase. Starting from about 12,000 s, the gap release was occurred. However, until the end of calculation (20,000 s.) no substantial core damage occurred, and the reactor vessel was still kept intact.

**Discussions**

From the above results, it is predicted that during TMLB', a vessel failure could occur at about 3.25 hr. after the TMLB' initiation. At the time of vessel failure, the coolant pressure was still at PORVs set point. So, HPME was likely happen. The overall sequence trends predicted in the current calculation are similar with the previous TMLB' studies [11].

On the other hand, MELCOR 1.8.4 could not calculate mechanical response to evaluate the pressure boundary integrity. But, according to the calculation result of the wall temperature, the integrity of RCS piping was apparently kept intact prior to the vessel failure. However, it must be noted that in this study, the hot leg counter current natural circulation (CCNC) was not modeled.

The result of run 2 showed that the intentional PORVs latched open during TMLB' was not able to mitigate or delay the severe core damage progression. The depressurization was not so fast to reached the accumulator set point prior to the reactor vessel failure. The pressure was still at about 11 MPa at the time of vessel failure due to relocation of the debris in lower plenum.

To evaluate the PWR's capability to depressurize. Brownson et al. [5] defines PORVs ratio which is the ratio of normalized PORV capacity to RCS volume given by:

\[
\text{PORV Ratio} = \frac{\text{GPORV}}{\text{V}_{\text{RCS}}}\text{study}/(\text{GPORV}/\text{V}_{\text{RCS}})\text{base} \quad \ldots \ldots \ldots \ldots \ldots (1)
\]

Where

- \(\text{G}_{\text{PORV}}\) = PORV mass flow rate of study and base PWRs
- \(\text{V}_{\text{RCS}}\) = RCS volume of study and base PWRs

Using the Surry NPP as the base plant. the PORV ratio of plant design studied is 0.78.
Still based on the results of Brownson et al. [5], the analysis of the SBO sequence for Sequoyah NPP (four loops PWR design), which has PORV ratio 0.75, showed that the depressurization could delay the accident progression. According to this, as the current plant design has greater PORVs ratio, so it could be expected that the depressurization would succeed to delay the core damage progression. But, the current calculation did not show that. The reasons for the discrepancies might be relied, among others, to the RCS nodalization. In Sequoyah reactor analysis, the one lumped loop model was used.

The other way to increase the depressurization capability is by assuming the opening of SRVs as well. The run 3 has shown that this strategy could allow the depressurization occurred rapidly, and the accumulator set point was reached only in 800 s (13.3 minutes) after opening the valves. The SRVs with about 2.3 times total flow area of PORVs discharged a bigger coolant mass flow rate from RCS to the containment. As the RCS depressurization was rapid, the injection of the cold water from accumulator tanks could take place before the core was severely damaged. And, it could cool the hot core structures.

Based on this analysis result, the increase of PORVs depressurization capability might be taken into account, for example by increasing the flow area or by adding the number of relief valves, in order to implement the proposed accident management strategy.

It is also interesting to note that from Figures 6 and 8 we could observe the swollen water level in the downcomer decreased to lower level rather than the water level in the core when the PORVs and SRVs were latched open. It might be due to lower pressure in the hot leg than in the cold leg side just after valves opening.

On the other hand, as a large amount of hot steam passed the pressurizer PORVs and SRVs, the wall temperature of the pressurizer surge line significantly increased. At 20,000 s, that temperature attained about 850K as shown in Figure 10. The temperature of the surge line might increase higher if CCNC is modeled in the calculation. If the pressurizer surge line rupture occurred due to high temperature, the pressure in RCS might decrease again and will reduce the risk of HPME. Note that there are two most probable ways of the RCS pressure boundary failure, i.e. the pressurizer surge line and SG U-tubes rupture. The SG U-tubes rupture represents a higher risk because it could result into the containment bypass, and the radionuclide release to the environment might occur. While, in the case of surge line failure, the radionuclide release would be still confined in the containment building.
CONCLUSIONS

The analysis of intentional RCS depressurization capability during a station blackout accident in PWR NPP was performed. For the reactor design studied, the intentional PORVs latched open was predicted to be insufficient to depressurize the RCS in order to allow the accumulator injection. The lower head vessel failed at about 13,000 s after the initiation of station blackout following debris relocation into lower plenum.

On the other hand, if the SRVs were assumed could be opened together with PORVs, the depressurization fate was sufficiently high, i.e. 0.15 MPa/s approximately, such that the accumulator pressure operation set point reached quickly. As a result, the hot core material could be cooled down, the severe core damage was limited on the upper part of the core, and the reactor vessel breach was delayed. The calculation result shows that until 20,000 s the lower head vessel was kept intact.

That result shows that the reactor design studied need a larger flow discharge area in order to the implementation of intentional RCS depressurization strategy could become effective.

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Table 1. Timing of Key Events.

<table>
<thead>
<tr>
<th>Events</th>
<th>Time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 1</td>
</tr>
<tr>
<td>Station blackout initiation</td>
<td>0</td>
</tr>
<tr>
<td>SG dried out</td>
<td>4981</td>
</tr>
<tr>
<td>RCS pressure at PORV set point</td>
<td>5340</td>
</tr>
<tr>
<td>Liquid at top of pressurizer</td>
<td>6360</td>
</tr>
<tr>
<td>Core coolant at saturation</td>
<td>7408</td>
</tr>
<tr>
<td>Start of core uncovery</td>
<td>7980</td>
</tr>
<tr>
<td>Core heatup</td>
<td>10,620</td>
</tr>
<tr>
<td>PORVs latched open</td>
<td>----</td>
</tr>
<tr>
<td>Start of Oxidation</td>
<td>11,400</td>
</tr>
<tr>
<td>Gap release</td>
<td></td>
</tr>
<tr>
<td>Ring 1</td>
<td>11,492</td>
</tr>
<tr>
<td>Ring 2</td>
<td>11,612</td>
</tr>
<tr>
<td>Ring 3</td>
<td>11,889</td>
</tr>
<tr>
<td>Core completely uncovered</td>
<td>13,023</td>
</tr>
<tr>
<td>Accumulators injection</td>
<td>----</td>
</tr>
<tr>
<td>Core Support Plate fails</td>
<td></td>
</tr>
<tr>
<td>Ring 1</td>
<td>15,823</td>
</tr>
<tr>
<td>Ring 2</td>
<td>13,550</td>
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<tr>
<td>Lower Head Penetration fails</td>
<td></td>
</tr>
<tr>
<td>Ring 1</td>
<td>15,449</td>
</tr>
<tr>
<td>Ring 2</td>
<td>13,603</td>
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<tr>
<td>Ring 3</td>
<td>13,634</td>
</tr>
<tr>
<td>Debris ejection</td>
<td>17,000</td>
</tr>
<tr>
<td>End of calculation</td>
<td>20,000</td>
</tr>
</tbody>
</table>

n.p. : not predicted until end of calculation
Figure 1. RCS nodalization

Figure 2. Core nodalization.
Figure 3. RCS pressure (Run 1).

Figure 4. Swollen water level in reactor vessel (Run 1).
Figure 5. RCS pressure (Run 2).

Figure 6. Swollen water level in reactor vessel (Run 2).
Figure 7. RCS pressure (Run 3).

Figure 8. Fluid mass flow discharged from SRV (Run 3).
Figure 9. Swollen water level in reactor vessel (Run 3).

Figure 10. The wall temperature of pressurizer surge line (Run 3).