LOCA Analysis and Development of a Simple Computer Code for Refill-Phase Analysis

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Abstract

The loss of coolant accident based on a double-ended cold leg break is analyzed with the discharge coefficient (Ca) of 0.4. This analysis covers the whole transient period from the start of depressurization to the complete refilling of the core by using RELAP4/MOD6-EM and RELAP4/MOD6-HOT CHANNEL for the system thermal-hydraulics and the fuel performance during the blowdown phase respectively, and RELAP4/MOD6-FLOOD and TOODEE2 during the refool phase.

A simple analytical method has been developed to account for the lower plenum filling by approximating steam-water countercurrent flows and superheated wall effects at the downcomer during the refill period. Based on the informations-at the time of EOB (end-of-bypass), the refill duration time and the initial reflooding temperature were estimated and compared with the results from the RELAP4/MOD6, resulting in a good agreement.

In addition, some parametric studies on the EOB were performed. The form loss coefficient between upper head and upper downcomer was found to be sensitive to the occurrence of the spurious EOB. Appropriate form loss coefficients should be taken into account to avoid the flow oscillations at the downcomer. The analyses with the six and three volume core nodalizations, respectively, show much similar trends in the system thermal-hydraulic performance, but the former case is recommended to obtain good results.

요 약

原子爐 冷却 系統의 配管 破裂에 随幾乎 冷却材 喪失 事故를 방출계수 0.4에 대하여 分析하였다.
이 分析은 原子爐 冷却系統의 配管 破裂에 의하여 發生된 減壓부터 減壓까지의 全過程 故障을
包含한다. 系統 熱水力과 核燃料 性能 評価를 위하여 BLOWDOWN 原則에서는 RELAP4/MOD6-EM

코드와 RELAP4/MOD6-HOT CHANNEL 코드를 사용하였으며 REFLOOD 단계에서는 RELAP4/MOD6-FLOOD 코드와 TOODEE2 코드를 응용 사용하였다.

LOWER PLENUM 充填式 고려하기 위하여 DOWNCOMER에서 충분히 유의하게 열전달과 토수의 영역을 귍似하며 그 영역의 모델이 개발되었다. 이는 EOB 발생 시의 영향을 고려하여 EOB 발생 후 초기의 동역 분석한 결과가 보였다. RELAP4/MOD6에 의해 분석 결과의 비교하여 적합한 一致를 보였다.

또한, EOB 발생에 영향을 미치는系統変數의 연구가 진행되었다. DOWCOMER와 UPPER HEAD 사이의 摩擦损失이 EOB 발생에 대한 영향을 이었다. 적절한 摩擦损失系數의 選擇를 통한 EOB 발생을 防止할 수 있었다. 傾斜 nodalization이 적합한 場面과 境面인 境面의 分析 결과가 系統熱力學의 領域에서 근似한 결과를 나타내지만, 좋은 결과를 얻어하려면 境面의 境面가 要求된다.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$f$</td>
<td>liquid</td>
</tr>
<tr>
<td>$g$</td>
<td>gas</td>
</tr>
<tr>
<td>$h$</td>
<td>nitrogen</td>
</tr>
<tr>
<td>$o$</td>
<td>gas</td>
</tr>
<tr>
<td>$s$</td>
<td>steam</td>
</tr>
<tr>
<td>$i$</td>
<td>inlet</td>
</tr>
<tr>
<td>$o$</td>
<td>initial</td>
</tr>
<tr>
<td>$LP$</td>
<td>lower plenum</td>
</tr>
<tr>
<td>$out$</td>
<td>outlet</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure</td>
</tr>
<tr>
<td>$RF$</td>
<td>reflooding</td>
</tr>
<tr>
<td>$S$</td>
<td>steam</td>
</tr>
<tr>
<td>$w$</td>
<td>wall</td>
</tr>
<tr>
<td>$ws$</td>
<td>wall structure</td>
</tr>
</tbody>
</table>

**Subscripts**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>coolant</td>
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</table>
steam generators are promptly isolated on the secondary side by closing the turbine steam supply valves and the feedwater valves.

The reactor during LOCA suffers from blowdown, refill, and reflood phases in sequence. In the generic model, the RELAP4-EM1 blowdown calculation is continued after end-of-bypass (EOB), through the refill period, to the bottom of core recovery (BOCREC).

RELAP4-EM is used to describe the thermal-hydraulic behavior during the blowdown phase, and thus the fluid conditions obtained from the calculation are used as boundary conditions of RELAP4-EM HOT CHANNEL14 calculation. The RELAP4-EM HOT CHANNEL model is used to determine the first peak cladding temperature that occurs during the blowdown phase, and to establish the temperature profile and the extent of the metal-water reaction. The thermal-hydraulic calculation using RELAP4-FLOOD19 begins after refill. After RELAP4-FLOOD calculation, the time-dependent fluid boundary condition in TOODEE22 are taken from the results, and thus TOODEE2 is used to determined both the peak cladding temperature and the extent of metal-water reaction during the reflood period.30 These concepts can be schematically depicted in Figure 1.

The determination of end-of-bypass plays an important role in the LOCA analysis since it provides the time for core-water subtraction and the application of adiabatic assumption for fuel rod heat-up, both of which are used in the LOCA analysis for the most conservatism. However, the RELAP4-EM may produce, due to some inherent numerical instability, spurious spikes in downcomer flowrates causing earlier occurrence of EOB which is phenomenologically inconsistent. In order to prevent the spurious flow spikes, special considerations must be taken into account. In this analysis, parametric studies by altering the form loss coefficient and the core pressure drop settings were carried out in order to obtain phenomenologically consistent EOB time.

In the refill phase, the primary purpose of continuing the blowdown calculation is to determine the accumulator injection flow rates, and to initialize RELAP4-FLOOD. However, RELAP4-EM needs a tremendous running time just for calculations of the refill duration time and the initial reflooding temperature. Furthermore, it is quite suspect whether RELAP4-EM deals well with the thermal-hydraulic phenomena occurred during the refill period. Then, a simple analytical approach is here considered to develop a computer code for the refill-phase analysis. The model accounts for the lower plenum filling by approximating steam-water countercurrent flows and superheated wall effects at the downcomer, during the refill period based on the informations at the time of the EOB.

II. Evaluation of end of Bypass

Here the spurious EOB is studied to figure out what caused the phenomenon. In addition, some sensitivity studies are performed and recommendation values are presented to avoid the spurious EOB. The important parameters taken into account in this study are form loss coefficient and core pressure drop settings.

2.1 Effect of Form Loss Coefficient

Some potential problems which could encoun-
Fig. 2. Volume Nodalization of Vessel

In case of zero resistance, the superheated vapor flow into the upper downcomer from the upper head can not be neglected. Thus a significant amount of superheated vapor in the upper head flows through the junction into the downcomer during the blowdown, and the cushion effect of the superheated vapor in the core diminishes, and flow oscillations can occur in the core inlet flow. The effects of the oscillations are propagated through the system and spurious flow spikes in the downcomer may prematurely signal end of bypass.

2.2 Effect of Core Pressure Drop Setting

In the core modeling, the frictional pressure drop of active core is 22.8 ± 4.6 psi. We should provide the pressure at the center of volume 2 and 30 (or 29) as shown in Figures 2–3. This value corresponds to the frictional pressure drop of the active core plus the gravitational pressure drops between the volume 2 and volume 30. EOB is very sensitive to the pressure drop setting between volume 2 and volume 30. In general, pressure drop is directly related to the friction factor. From the above core pressure, the uncertainty of pressure drop is ± 4.6 psi and this corresponds to ± 3.5 of friction factor. In addition, the gravitational pressure drop in the volume 2 and volume 30 are 1.594 psi and 0.560 psi, respectively, as shown in Table 1. These correspond to about 1.5 and 0.5 of friction factor, respectively. The pressure drop between volume 2 and volume 30 is 26.255 psi for the former case, which does not include gravitational pressure drop, and 28.38 psi for the latter case.

Fig. 3. Gravitational Heads through Various Volumes
Table 1. Gravitational Pressure Drops of Each Volume

<table>
<thead>
<tr>
<th>Volume</th>
<th>Density (lbm/sec)</th>
<th>A Half of the Volume Height (ft)</th>
<th>Gravitational Pressure Drop (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>42.3</td>
<td>10.85</td>
<td>1.594</td>
</tr>
<tr>
<td>30</td>
<td>42.3</td>
<td>3.2389</td>
<td>0.56</td>
</tr>
<tr>
<td>29</td>
<td>42.3</td>
<td>8.32</td>
<td>1.366</td>
</tr>
</tbody>
</table>

Table 2. Summary of Results of the End-of-Bypass Evaluation

<table>
<thead>
<tr>
<th>Case</th>
<th>Index in Fig. 2</th>
<th>K and I of J54</th>
<th>Pressure Drop (psi)</th>
<th>System Pressure</th>
<th>EOB (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>K=1.223, I=10</td>
<td>26.25</td>
<td>145.0</td>
<td>14.78</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>K=4.0, I=50.0</td>
<td>26.25</td>
<td>74.0</td>
<td>17.16</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>K=4.0, I=50.0</td>
<td>28.38</td>
<td>30.0</td>
<td>17.72</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>K=1.223, I=10</td>
<td>26.25</td>
<td>150.0</td>
<td>14.56</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>K=4.0, I=50.0</td>
<td>29.25</td>
<td>15.2</td>
<td>20.2</td>
</tr>
</tbody>
</table>

Fig. 4. Downcomer Flow Rate

which includes gravitational pressure drop.

As can be seen above, the uncertainty of core pressure drop is considerably great, so that friction factor contains considerable uncertainty. Therefore, it is desired to establish reasonable core pressure drop settings in order to avoid spurious EOB. The effect of pressure settings on the EOB is shown in Table 2 and Figure 4.

III. Refill Methodology

In order to provide a more continuous ECCS analyses, the capability to perform lower plenum refilling subsequent to a LOCA blowdown has been added to RELAP4-EM. In the generic model, the RELAP4-EM blowdown calculation is continued after end-of-bypass, through the refill period, until BOCREC. The primary purpose of continuing the blowdown calculation through refill is to determine the variable accumulator injection flow rates, and to initialize RELAP4-FLOOD. But, because of the tremendous RELAP4-EM running time, the continuation of RELAP4-EM for detailed calculation through refill is doubtful to calculate just two outputs of refill duration time and initial reflooding temperature. The capability of RELAP4-EM to calculate thermal-hydraulic variables during the refill period is also questionable, since the flow situation is quite complicated due to the presence of two-phase flow throughout the whole system, and the induced unreasonable oscillation may lead to unexpected results. Thus, a simple analytical method is developed to simulate the lower plenum filling by approximating countercurrent flow and superheated wall effects during the refill period.

3.1 Refill Duration Time

The refill calculation starts with known initial conditions, such as, accumulator water available, accumulator gas pressure, RCS back pressure (containment pressure) and volume of water needed to complete the filling of lower plenum, which can be obtained from RELAP4-EM and CONTEMPT-LT. In addition, the accumulator line flow resistance and area, total accumulator tank volume and SI flowrate should be specified.
The accumulator and safety injection (SI) water from the broken loop is assumed to completely spill through the break for cold leg breaks. For the remaining accumulator, the flow rate is calculated using a momentum equation across the accumulator line. It is further assumed that all of the accumulator water that does not spill to the break flows into the downcomer. During refill, the RCS back pressure is taken to be the containment pressure, and is calculated continuously by CONTEST-LT. The accumulator pressure is updated at each time step using isentropic expansion considerations for the nitrogen gas. The SI flow is assumed to be constant. The total water flow from the accumulator and SI is added to the lower plenum. The volume of water injected into the lower plenum is integrated over time and, when injection water equals the lower plenum volume, recovery is said to occur and reflood calculations are initiated.

The refill period starts when the injection water reaches the lower plenum. This time delay is given as an input to the FILL code, which will be described later.

If the incompressible and irrotational state is assumed, the governing and constitutive equations will be given as:

Momentum equation:

\[ \frac{L}{A} \frac{dW}{dt} = P_{\text{out}} - P_{\text{in}} + \rho_g \cdot g \cdot (Z_{\text{out}} - Z_{\text{in}}) \]

\[ + \frac{KW^2}{2rA^2} \]

Mass conservation for the nitrogen gas:

\[ V_{\text{gas}}(t) = V_{\text{gas}}(t_0) + \int_{t_0}^{t} W(t) / \rho dt \]

State equation for the nitrogen gas:

\[ P_{\text{gas}}(t) V_{\text{gas}}(t)^{1.4} = P_{\text{gas}}(t_0) V_{\text{gas}}(t_0)^{1.4} \]

Total time delay

= Time delay due to hydrodynamic effect + gravity falling time (1.1 sec) + delay time due to thermal effect (2.3 sec)

The last two time delays chosen above are obtained from CREARE experiments and also the sum is similar to that of EXXON analysis.

3.2 Initial Reflooding Temperature

The initial reflooding temperature of the average rod in the hot assembly for RELAP4-FLOOD is calculated using TOODEE2 for the hot assembly power of interest (adiabatic process). And the initial temperatures of the RELAP4-FLOOD heat conductors are conservatively taken as their respective temperature at end-of-bypass. In addition, two options are for determining the subcooling of core inlet water. The first option assumes that the inlet water temperature is constant at 150°F (RESSAR & WRENFLOOD).

The second is a core inlet temperature which is calculated by the energy balance equation. The model consists of two reference elements which represent lower plenum and the downcomer annulus. For the purpose of this calculation, the downcomer is assumed to suffer from annular until the coolant temperature of the downcomer outlet is less than the saturation temperature. The duration time is calculated to be 3.2 sec. After that free convective heat transfer is assumed because the falling velocity is sufficiently low, i.e., less than 1 m/sec. And then the perfect mixing is assumed in the lower plenum. The total available metal metal sensible energy is the sum of the heat from the reactor vessel shell and the heat from the reactor vessel internal structures. We assume the steady state heat transfer during refill period. Then, the energy balance equations are given:

\[ Q_w = h A (T_w - T_C) \] for wall surface,

\[ Q_C = C_p W (T_{\text{out}} - T_{\text{in}}) \] for coolant,

\[ Q_{WS} = \rho C_p V [T_w(t) - T_w(t_0)] \] for wall structure,

where the heat transfer coefficient for the liquid film is obtained from Dittus-Boelter correlation:

\[ h = 0.023 \frac{k}{d} \left[ \frac{\rho V_d}{\mu} \right] \times \frac{Pr^{0.4}}{d} \]

and the hydraulic diameter for the annular flow
is given\(^9\),
\[
d = 4\delta
\]
\[
\delta/\left(\frac{1.5}{g^* \sin \theta}\right)^{1/3} = 0.375 \left(\frac{(\rho \cdot u \cdot \delta)}{\mu}\right)^{0.562}
\]

For the free convective heat transfer, empirical correlations can be obtained as follows. Over the years, it has been found that average free convective heat transfer coefficients can be represented in the following functional form for a variety of circumstances:

\[Nu = C(Gr \cdot Pr)^{m}\]

\[C = 0.21 \quad \text{and} \quad m = 2/5\] is used for the vertical surfaces.\(^{10}\)

At last, the temperature rise in the tower plenum, \(\Delta T_{LP}\), due to vessel wall heating is calculated by assuming perfect mixing and using the free convective heat transfer coefficient mentioned above.

Averaged coolant temperature of lower plenum at BOCREC time is obtained from weighting by injection flowrate,

\[T = \frac{WTdt}{\int W dt}\]

Then, the initial reflooding temperature can be obtained as follow;

\[T_{ref} = T + \Delta T_{LP}\]

3.3. Development of FILL code

The refill analysis for KNU-1 and KNU-5 & 6 was performed with the FILL code which was programmed with models mentioned above. The FILL code is composed of a main program and subprograms called ACCU, SAT and SUB.

In The FILL code, volume and pressure are calculated for the nitrogen gas using the mass conservation and the state equation. Mass flow rate is also computed from momentum equation by assuming the loop pressure during the refill period. The subprogram ACCU, where the Euler-Gauss predictor-corrector method is utilized as a computational method, is used to solve the momentum equation in an accumulator.

If the injection water into the downcomer is

\[\text{Fig. 5. Flow Chart of Fill Code}\]

\[\text{Fig. 6. Accumulator Flow for KNU-1}\]

equal to lower plenum mass, BOCREC is assumed to occur.

Then, the temperature of the heat conductors and coolant are computed using the result of
Table 3. Results of Refill Calculation

<table>
<thead>
<tr>
<th></th>
<th>Time (sec)</th>
<th>Refill Duration (sec)</th>
<th>Temperature Increase (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EOB</td>
<td>BOCREC</td>
<td></td>
</tr>
<tr>
<td>KNU 1</td>
<td>FSAR</td>
<td>19.8</td>
<td>33.4</td>
</tr>
<tr>
<td></td>
<td>Model</td>
<td>17.75</td>
<td>32.5</td>
</tr>
<tr>
<td>KNU 5 &amp; 6</td>
<td>FSAR</td>
<td>29.8</td>
<td>43.1</td>
</tr>
<tr>
<td></td>
<td>RELAP</td>
<td>26.8</td>
<td>44.2</td>
</tr>
<tr>
<td></td>
<td>Model</td>
<td>26.8</td>
<td>43.1</td>
</tr>
</tbody>
</table>

Fig. 7. Accumulator Flow Rate for KNU-5 & 6

The results show good agreements with those from RELAP/MOD6, as shown in Figures 6~7 and Table 3.

IV. Conclusion

Some parametric studies on the end-of-bypass were carried out in order to obtain phenomenologically consistent EOB time, and then recommendation values were presented. The occurrence of the spurious end-of-bypass were found to be sensitive to the form loss coefficient in the junction between the upper head and the upper downcomer volumes, and to the core pressure drop settings. By altering form loss coefficient and core pressure drop settings, spurious end-of-bypass could be avoided.

During the refill period, the FILL code for the refill time and the initial reflooding temperature has been developed for the sake of saving computation time. It accounts for lower plenum filling by approximating steam-water countercurrent flows and superheated wall effects at the downcomer. The results were compared with those from the RELAP4/MOD6 analysis, and showed good agreements in refill duration time and initial reflooding temperature.

References