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Realistic Large Break Loss of Coolant Accident Mass and Energy Release and Containment Pressure and Temperature Analyses

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Abstract

To investigate the realistic behavior of mass and energy release and resultant containment response during large break Loss of Coolant Accident (LOCA), analyses are performed for Yonggwang (YGN) 3&4 nuclear power plants by using a merged version of RELAP5/CONTEMPT4 computer code. Comparative analyses by using conservative design computer codes are also performed. The break types analyzed are the double-ended guillotine breaks at the cold leg and hot leg. The design analysis resulted in containment peak pressure during post-blowdown phase for the cold leg break. However, the RELAP5/CONTEMPT4 analyses show that the containment pressure has a peak during blowdown phase, thereafter it decreases monotonously without the second post-blowdown peak. For the hot leg break, revised design analysis shows much lower pressure than that reported in YGN 3&4 final safety analysis report. The RELAP5/CONTEMPT4 analysis shows similar trend and confirmed that the bypass flow through the broken loop steam generator during post-blowdown is negligibly small compared to that of cold leg break. The low pressure and temperature predicted by realistic analysis presented in this paper suggest that the design analysis methodology contains substantial margin and it can be improved to provide benefit in investment protection, such as, relaxing plant technical specifications and reducing containment design pressure.

1. Introduction

In the containment design basis event of large break loss-of-coolant accident (LOCA), mass and energy are released from the postulated pipe break to the containment. The release phases encompass blowdown, refill, reflood, and post-reflood. During the blowdown phase, most of the primary coolant in the reactor coolant system (RCS) is discharged to the containment. Major energy sources consist of the primary coolant, sensible heat of RCS metal, and core stored energy. During the post-blowdown period, major sources of energy are steam generator (SG) secondary, decay heat and stored energy in the RCS metal. The SG heat removal during post-blowdown phase has different characteristics depending on break locations. For cold leg breaks the steam and entrained liquid carried out of the core pass through SG, where the entrained water is evaporated and could be superheated to the temperature of SG secondary fluid. Therefore, in the conservative licensing analysis the containment is repressurized during post-blowdown phase due to this reverse heat transfer. While for hot leg breaks since the broken leg provides a direct path, majority of the fluid from the core is directly discharged to the containment without passing through SG. Therefore, in the case of hot leg break quantitative analysis for the post-blowdown phase has not been performed in the safety analysis for the post-blowdown phase has not been performed in the safety analysis report of System 80 type plants [1]. USNRC Standard Review Plan (SRP) [2] also does not require quantitative analysis for the post-blowdown phase of hot leg break. It was a general trend for the System 80 type plants that the containment peak pressure during post-blowdown phase of the cold leg break was higher than the blowdown peak pressure of the hot leg break. The cold leg break case was a limiting design basis event for the determination of containment design pressure.

is very close to that of System80 plants. Therefore, YGN 3&4 plants are expected to show similar mass and energy release behavior as that of System 80. However, the containment pressure for the hot leg break was shown much higher than those of cold leg break in the YGN 3&4 Final Safety Analysis Report (FSAR)[4]. Differently from System80 plants the peak pressure during the blowdown phase for the hot leg break was very close to the post-blowdown peak pressure of the cold leg break and therefore it was required to perform analysis for the post-blowdown phase of the hot leg break. However, since design computer code for the analysis of post-blowdown phase of the hot leg break was not available, a very simple conservative analytical method was employed to calculate the mass and energy release rates. This is quite contradictory from previous trends. Therefore, it became very important to deeply investigate the realistic behavior of LOCA containment mass and energy releases.

Since experimental data for the double-ended hot leg break focused on mass and energy release behavior is rare, it is beneficial to rely on the state-of-the-art thermal-hydraulic computer code to understand realistic behavior of hot leg break. In this paper, analyses for mass and energy release and resultant containment responses are performed by using a merged version of RELAP5/CONTEMPT4[5]. Conservative analyses by using design computer codes are also performed for comparison purpose.

2. Analysis Method

The licensing computer codes for use in the mass and energy release analyses for the containment design for YGN 3&4 FSAR are CEFLASH-4A[6], FLOOD-3[7] for blowdown and post-blowdown period, respectively. The containment pressure and temperature responses are calculated by CONTEMPT-LT[8] code. Since FLOOD-3 computer code is not applicable to the analysis of hot leg break post-blowdown phase, KAERI recently developed COMET[9,10] computer code, which has capability to analyze both cold leg and hot leg breaks. Cold leg break model of COMET is essentially the same as that of FLOOD-3. Hot leg break model is introduced additionally and couple of deficiencies in FLOOD-3 have been improved in the COMET. The algorithm employed in the COMET for the reflood phase is same for cold leg break and hot leg break and it consists of two steps. Firstly, core inlet mass flow rate and the mass fraction leaving the top of active core is calculated. This hydraulic model calculates core flooding rate and carry-over rate fraction (CRF). Then, core exit conditions due to heat transfer in the core is calculated based on the energy balance. Also heat transfer from the SG secondary side to the primary is calculated. The detailed discussion on the mathematical models and input descriptions are described in references 9 and 10.

KAERI has also developed the RELAP5/CONTEMPT4 code, a merged version of RELAP5/MOD3.1 and CONTEMPT4/MOD5[11]. RELAP5/MOD3.1 and CONTEMPT4/MOD5 are explicitly coupled by using the concept of inter-process control so that code modifications might be minimized and the inherent features of each code might not be degraded. The merged version is capable of considering the mutual effects of RCS and containment. The CONTEMPT4/MOD5 is a multi-compartment and multi-junction containment analysis code and its numerical solution scheme is basically explicit. Since the numerical solution procedures of two codes are different each other, external coupling is made instead of close internal coupling. The verification and validation of RELAP5/CONTEMPT4 are discussed in reference 5. The merged version has been used in KAERI for the development of realistic evaluation methodology for emergency core cooling (ECC) system performances for large break LOCA.

The containment back-pressure does not affect the mass release rates to containment during blowdown phase, because the break flow is critical flow. However, during post-blowdown phase, the break flow rates depend on containment back-pressure. Thus it is desirable to simulate the simultaneous responses of both RCS and containment during post-blowdown phase for the realistic evaluation of containment performance. But the design analysis method requires iterative computer runs to get consistent boundary conditions between computer codes. The use of merged version eliminates the inconsistency of models.

The plant design data for the representation of the RCS and containment are taken from the YGN 3&4 FSAR. Plant nodalization schemes for the RCS representation for CEFLASH-4A and RELAP5/CONTEMPT4 analyses are shown in Figures 1 and 2. As discussed above design analysis employs COMET computer code for the analysis of post-blowdown period different from YGN 3&4 FSAR. The hydraulic networks employed in the COMET analyses are shown in Figures 3 and 4 for hot leg break and cold leg break respectively. On the other hand, RELAP5/CONTEMPT4 can be used throughout blowdown and post-blowdown phases.

Table 1 shows major plant parameters used in the design analysis and RELAP5/CONTEMPT4 analysis. Most of the plant parameters and initial conditions used for the RELAP5/CONTEMPT4 analysis are at nominal values except core power and ECC system performance data. Core power level of 102% and 1973 ANS decay heat including 20% uncertainty are used. The capacity of ECC system such as safety injection tank (SIT) and safety injection pump (SIP) is maximized considering design uncertainties.

Table 1. Major Plant Parameters

Parameter	Design analysis	RELAP5/CONTEMPT4 analysis
core power (MWt)	2871	2871
RCS pressure (MPa)	16.03	15.51
core flow rate (kg/s)	14106.4	14848.8
cold leg temp. (K)	573.2	569
SG pressure (MPa)	7.38	7.37
SG level (m)	11.87	12.11
SIAS* set point (MPa)	12.89	12.89
containment vol.(m^3)	77220.5	77220.5
spray flow rate (kg/sec)	218.34	218.34
spray delay time (sec)	93	93

* SIAS means safety injection actuation signal

As for the containment analysis, Tagami and Uchida correlations are selected for the condensation heat transfer during blowdown and post-blowdown period, respectively. These correlations have been used in the conservative containment analysis for the design purpose. One train of spray system is assumed unavailable and maximum delay time for the spray is assumed. Since the main purpose of the present study is to identify the differences in mass and energy release behavior predicted by design analysis and RELAP5/CONTEMPT4 analysis, major assumptions and models for containment analyses are taken as same. Therefore, input for CONTEMPT4 portion of RELAP5/CONTEMPT4 and CONTEMPT-LT are adjusted to result in same pressure and temperature with same mass and energy release input data.

3. Analysis Results

3.1. Blowdown Phase

Double-ended guillotine breaks are assumed. The

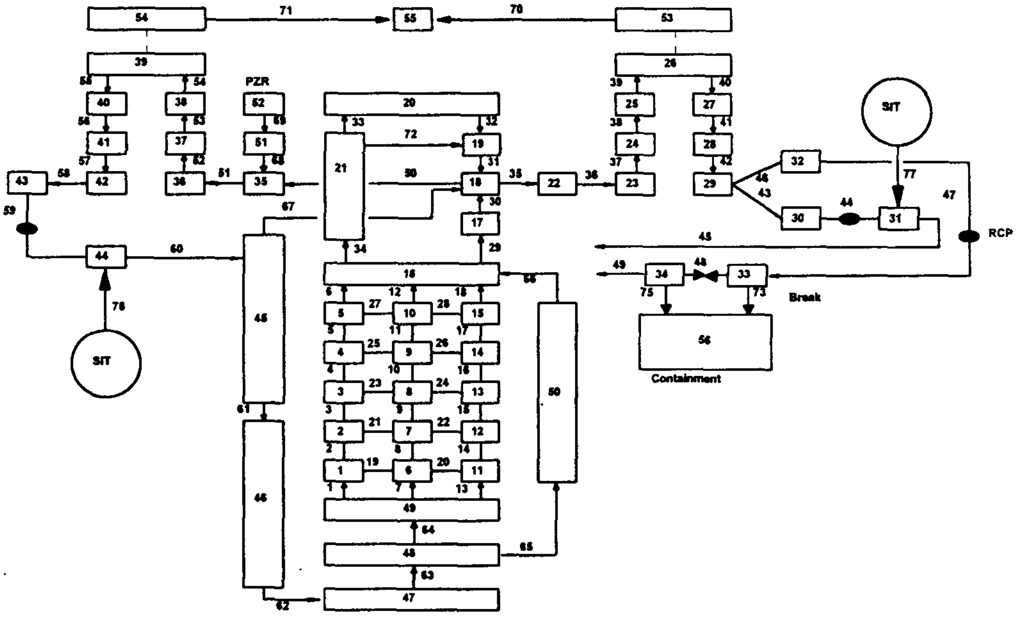

Fig. 1. CEFLASH-4A Plant Nodalization

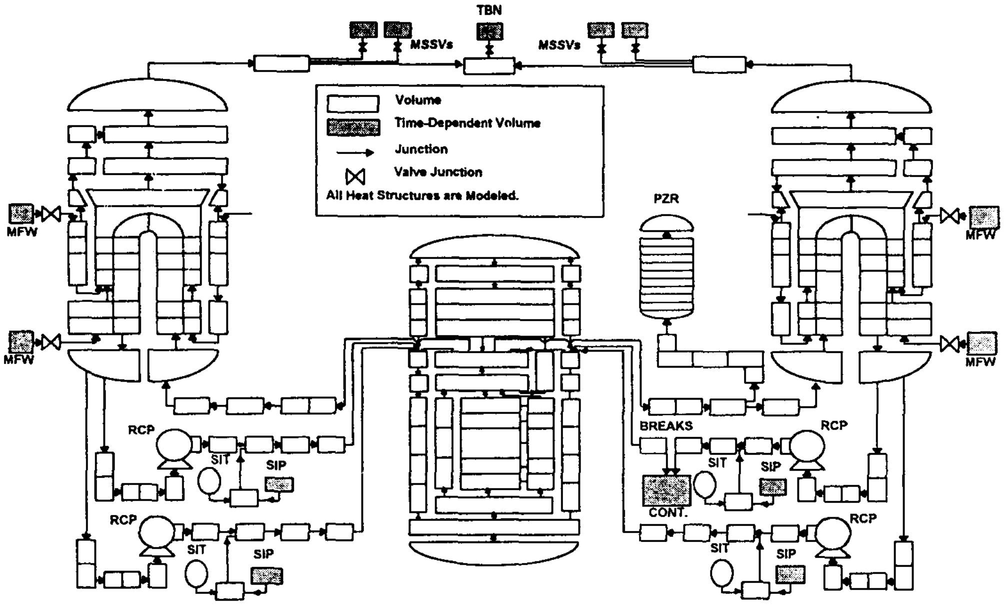

Fig. 2. RELAP5/MOD3 Plant Nodalization

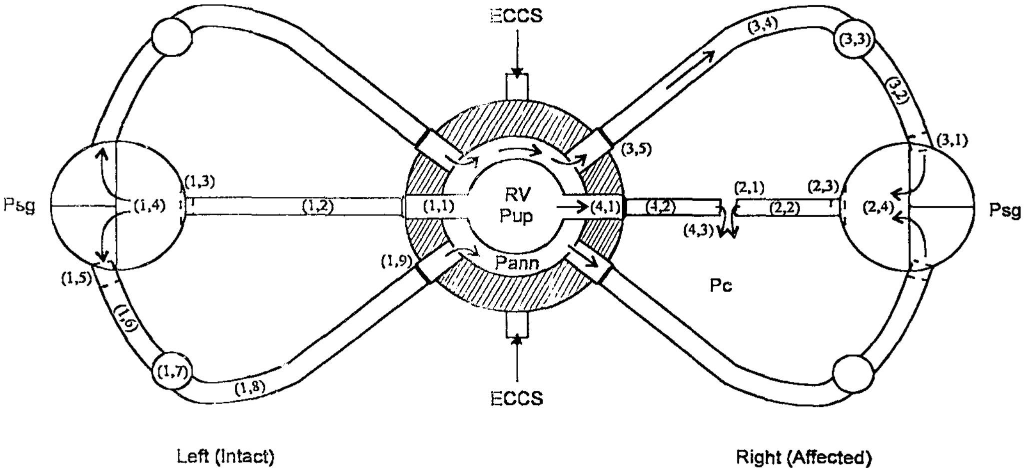

Fig. 3. Hydraulic Network Model for Hot Leg

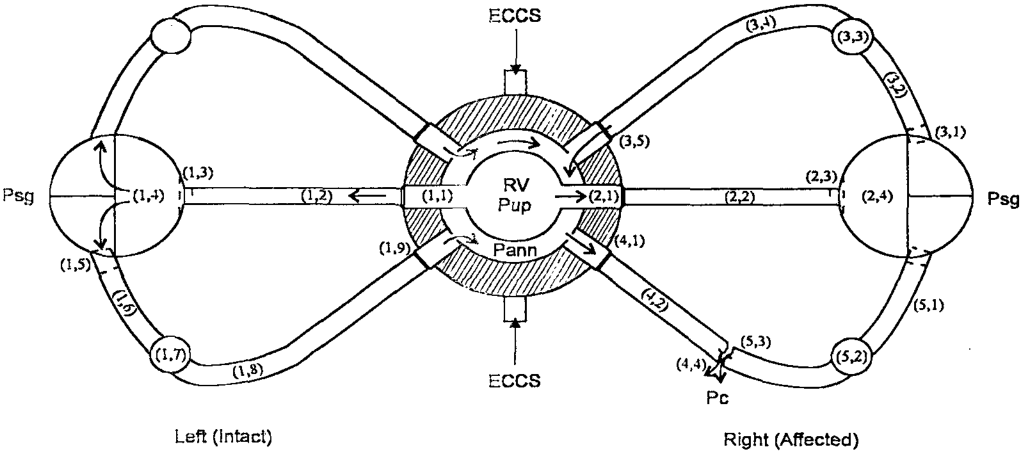

Fig. 4. Hydraulic Network Model for Cold Leg

break areas are 0.456 m^2 and 0.894 m^2 for discharge and hot leg break, respectively. Figure 5 shows the comparison of transient RCS pressure during blowdown predicted by RELAP5/CONTEMPT4 and CEFLASH4A. DL and HL represent the discharge leg and hot leg cases, respectively. It is shown that two predictions are generally in the same trend. The RELAP5/CONTEMPT4 analysis shows smooth pressure transient until the end of blowdown (EOB) which is defined as the time when RCS reaches an equilibrium condition with the containment. Also the EOB clearly appears in the RELAP5/CONTEMPT4 result in contrast to the ambiguity in the CEFLASH-4A. The end point of CEFLASH-4A predictions in Figure 5 represents assumed EOB time for the design analysis. Determination of clear EOB is

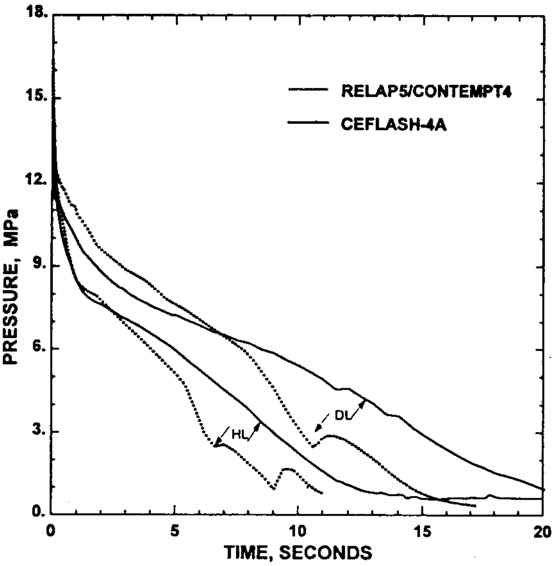

Fig. 5. RCS Pressures

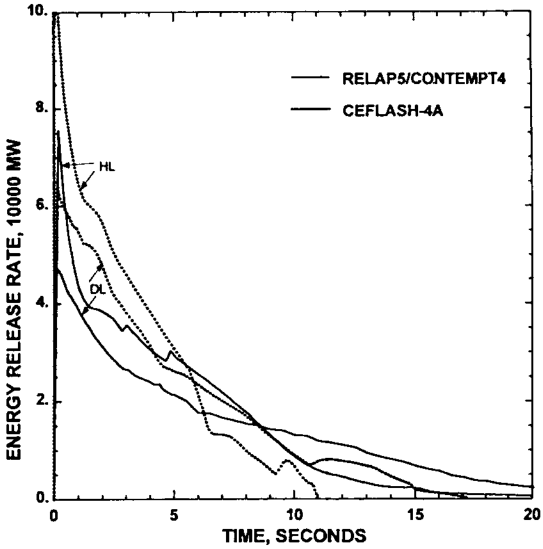

Fig. 6. Energy Release Rates

important in the design analysis, since the thermal hydraulic conditions at EOB are transferred to the post-blowdown analysis code, such as FLOOD-3 or COMET. Therefore, the EOB should be carefully determined that conservatism be maintained during the switch-over of computer codes in the design analysis. However, the EOB does not have such a significance in the RELAP5/CONTEMPT4 analysis, since RELAP5/CONTEMPT4 can simulate entire phase of LOCA.

Figure 6 shows the energy flow rates discharged to containment during blowdown phase. The hot leg break case results in much energy flow into containment during blowdown in a short period due to bigger break size, which will result in higher blowdown peak containment pressure. It is also shown that CEFLASH-4A analysis results in much greater energy release than RELAP5/CONTEMPT4 analysis. The deviations between RELAP5/CONTEMPT4 and design analysis are due to conservative initial conditions and assumptions, especially the increased RCS fluid volume by 3.5 percent to account for uncertainties employed in the CEFLASH-4A design analysis. Also, DNB time is arbitrary extended until the core becomes voided by steam to obtain a conservatively high energy release rate from the core in the CEFLASH-4A analysis. During blowdown, the energy release calculated by design analysis method is 10 percent higher than the RELAP5/CONTEMPT4 calculation for discharge leg break.

3.2. Post-Blowdown Phase

Different from YGN 3&4 FSAR, COMET computer code is employed in this paper to analyze mass and energy release during post-blowdown phases including reflood and post-reflood. It is to be noted that COMET code model is essentially same as that of FLOOD-3 for cold leg break and FLOOD-3 does not provide hot leg break model. The detailed verification and validation of the COMET computer code are provided in the references 9 and 10. For licensing analysis after EOB, the refill phase is eliminated by making the conservative assumption that the bottom of the core recovery occurs immediately after EOB. The results of the COMET analysis and those of RELAP5/CONTEMPT4 are compared herein.

Since the steam fraction of break flow essentially

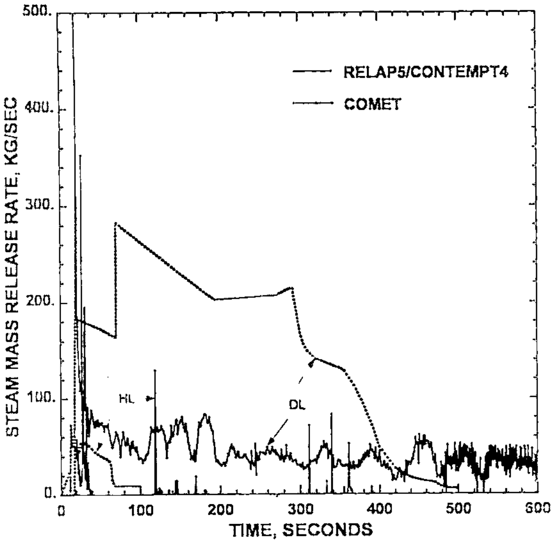

Fig. 7. Steam Mass Release Rates

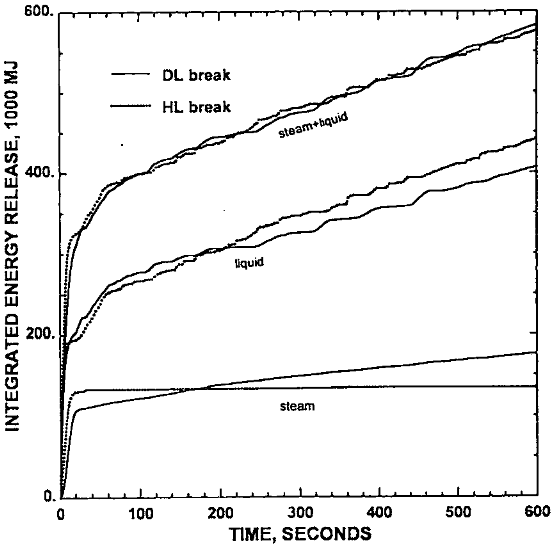

Fig. 8. Integrated Energy Release

pressurizes containment atmosphere, the steam flow rates are compared in Figure 7 for DL and HL. The integrated steam flow and total flow for DL and HL calculated by RELAP5/CONTEMPT4 are shown in Figure 8. The steam flow can be determined from the junction void fraction and total flow rate. As shown in Figure 7, COMET steam flows are much higher than those of RELAP5/CONTEMPT4 analyses due to conservative models and assumptions. Since the SG secondary side is a major energy source transferred to containment during the post-blowdown period, the significant deviation in steam flow rates shown in Figure 7 is due to conservative SG heat transfer model. In COMET calculation, constant heat transfer coefficients of 57000 w/m^2-K and 13000 w/m^2-K are used for nucleate boiling on the tube side and condensation on the SG secondary side, respectively. These constants are maximum values for the corresponding heat transfer regimes, which remains constant throughout the entire transient. However, according to RELAP5/CONTEMPT4 calculation, heat transfer from the SG is not high enough to evaporate all the entrained liquid leaving the core. Much higher CRF value employed in the COMET calculation is also the reason for the difference. The CRF model in COMET is based on the simple and conservative approach of NUREG-0800 SRP. On the other hand, RELAP5/CONTEMPT4 model is a mechanistic one.

Steam which flows through the intact loop SG encounters the injected ECC water in the cold legs. Based upon steam/water mixing test data[12], a thermal equilibrium approach is applicable such that the amount of water available is sufficient to condense this steam flow during the safety injection tank (SIT) injection phase. In COMET analysis 42 percent of total steam flow is assumed to be condensed during SIT injection phase. The abruptly reduced steam flow rates in early transient due to this condensation effect are shown in Figure 7. However since the steam release rates predicted by RELAP5/COMTEMPT4 are much lower than those predicted by COMET, the condensation credit of 42 percent is proved to be a conservative estimate.

For hot leg break, since the flow resistance from the core to the break location is very small, core flooding rate is relatively high and the majority of the fluid leaving the core is vented directly to the con-

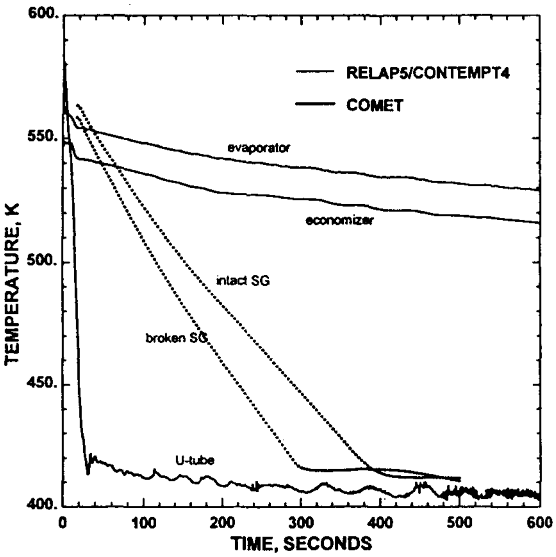

Fig. 9. SG Temperatures for DL Break

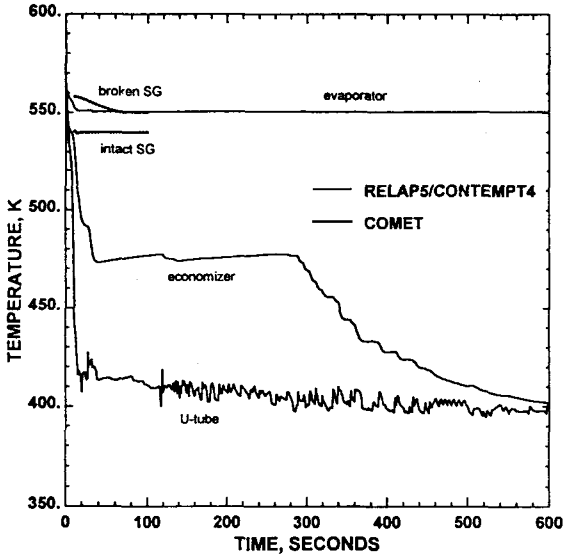

Fig. 10. SG Temperatures for HL Break

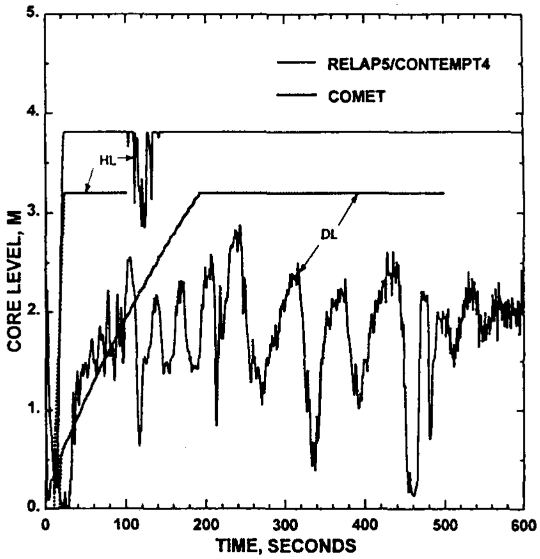

Fig. 11. Core Level

tainment through the broken hot leg. In RELAP5/CONTEMPT4 calculation, it is found that the bypass flow through the broken loop SG is established as intermittent spikes and its amount is negligible, while the break flow from the RV side after EOB is pure liquid as shown in Figure 8. In the case of COMET analysis a little steam flow is predicted during 100 seconds which is much bigger than that of RELAP5/CONTEMPT4 analysis but much less than that of cold leg break. It demonstrates that the hot leg break model embodied in the COMET computer code is very conservative.

The transient SG secondary water temperatures are presented in Figure 9 and Figure 10 for discharge and hot leg break, respectively. As shown in the figures the temperatures in the SG nodes for discharge leg break gradually decrease, while for hot leg break only economizer temperature decreases. It demonstrates that the injected ECC water reaches just up to the economizer region. The temperature of U-tube remains almost constant, which is saturation temperature corresponding to containment pressure. The temperatures predicted by COMET rapidly reach an equilibrium condition due to high heat transfer, which is consistent with the mass and energy release rate behavior discussed above.

Figure 11 shows the collapsed water level in the active core. Since the flooding rate varies in proportion to the square root of the loop resistance, the reflood period for hot leg break is very short (about 10 seconds) compared to that of cold leg break. For hot leg break once the core is filled with the ECC

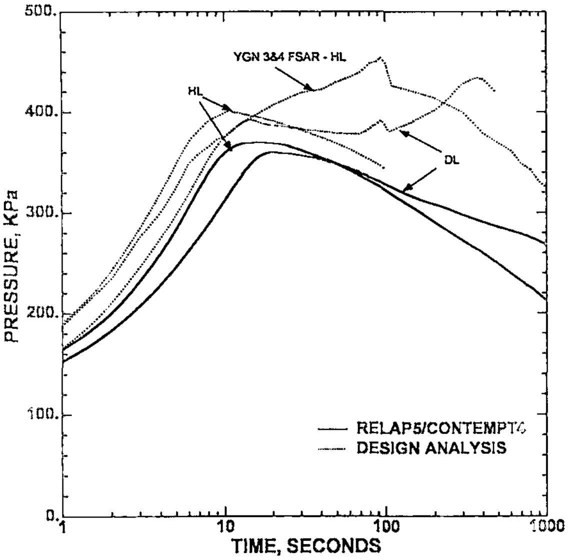

Fig. 12. Containment Pressures

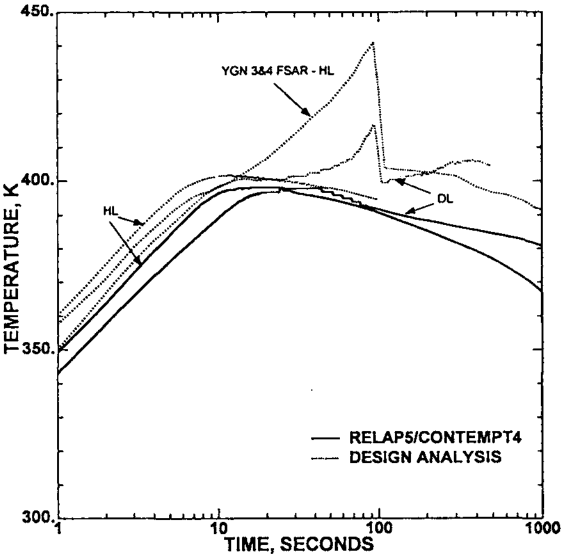

Fig. 13. Containment Temperatures

water, the thermodynamic state of the average core becomes subcooled and core water level is sustained during the remaining period of the transient. The core level in COMET results is maintained at 3.2 m because the CRF is conservatively assumed to be 1.0 after core level reaches 0.61 m (2 ft) below top of active core. The general trend is quite similar to that of RELAP5/CONTEMPT4.

Figure 12 and Figure 13 show the containment pressure and temperature transients for the hot leg break and discharge leg break analyzed by RELAP5/CONTEMPT4 analysis and design analysis. For the hot leg break the YGN 3&4 FSAR pressure and temperature are also compared.

Regarding the containment model, RELAP5/CONTEMPT4 analysis is using CONTEMPT4 portion and design analysis is using CONTEMPT-LT. However, the inputs for both computer codes were adjusted to results in essentially the same pressure and temperature transients with same mass and energy release input. As the coolant exits the rupture, a fraction of it flashes into steam due to the pressure and temperature differences between the RCS and containment. Temperature flashing model, where break flow is splitted into steam and liquid components based on the containment atmosphere temperature, was selected for both calculations.

As shown in Figure 12 the containment pressure predicted by RELAP5/CONTEMPT4 analysis reaches peak near the EOB, and thereafter it decreases monotonously for both discharge and hot leg breaks. For the cold leg break the post-blowdown peak is not predicted in the RELAP5/CONTEMPT4 analysis, while it appears in the conservative design analysis. This significant difference is due to the over-conservative assumption and models embedded in the design analysis methodology. As shown in Figure 7, since the mass and energy release rate predicted by RELAP5/CONTEMPT4 is one third of that calculated by design analysis, it is wise to remove over-conservatism employed design analysis to optimize the plant design parameters.

In the case of hot leg break the pressure response predicted by revised design analysis and RELAP5/CONTEMPT4 analysis is very different from that reported in the YGN 3&4 FSAR. As compared in Figure 12 the present analyses result in containment peak pressure during blowdown and the containment is not pressurized after EOB, while the YGN 3&4 FSAR reported that the containment pressure continuously increases until 90 seconds well after EOB. As discussed above since is no physical mechanism for rapidly releasing the SG energy to the containment after EOB for the hot leg break, it can be said that the YGN 3&4 FSAR methodology for the hot leg break is unnecessarily conservative. The trends of containment temperatures in Figure 13 for cold leg break and hot leg break are similar to those of pressure.

The realistic LOCA mass and energy release and containment analyses presented in this paper indicate that there are substantial margin in the current design analysis as clearly shown in Figures 12 and 13. The low pressure and temperature predicted by realistic analysis suggests that the containment design pressure and Equipment Environment Qualification curve used in the current design contains substantial margin and it can be improved to provide benefit in investment protection, such as, relaxing plant technical specifications and reducing containment design pressure.

4. Conclusions

The postulated double-ended breaks at the discharge leg and hot leg for the YGN 3&4 plants are analyzed in a realistic manner with respect to containment mass and energy release. The analysis employs a merged version of RELAP5/CONTEMPT4. Conservative design analyses are also performed for comparison purpose. The containment peak pressure predicted in the present analysis is much lower than that of the design analysis. For discharge leg break, the predicted containment pressure reaches a peak near the EOB, thereafter it decreases monotonously without the second reflood peak. It is also found that after the EOB of hot leg break, the bypass flow through broken leg SG is negligibly small and the flow from RV side is almost liquid so that the containment could not be pressurized after the EOB. The results of present indicate that the design analysis methodology contains substantial margin and it can be improved to provide benefit in investment protection, such as, relaxing plant technical specifications and reducing containment design pressure.

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