RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

APR1400 Design Certification

Korea Electric Power Corporation / Korea Hydro & Nuclear Power Co., LTD

Docket No. 52-046

RAI No.:	**399-8510**
SRP Section:	**15.06.05 – Loss of Coolant Accidents Resulting From Spectrum of Postulated Piping Breaks Within the Reactor Coolant Pressure Boundary**
Application Section:	**15.06.05**
Date of RAI Issue:	**02/03/2016**

Question No. 15.06.05-9

Regulatory Basis:

Title 10 of the Code of Federal Regulations, Part 50.46 requires an analysis of ECCS performance following loss of coolant accidents. The calculational framework used for the evaluation of the ECCS system in terms of core short term behavior and long term cooling performance are referred to as an evaluation model. It includes one or more computer programs, the mathematical models used, the assumptions and correlations included in the program, the procedure for selecting and treating the program input and output information, the specification of those portions of the analysis not included in computer programs, the values of parameters, and all other information necessary to specify the calculational procedure.

The evaluation model used by the applicant must comply with the acceptance criteria for ECCS given in 10 CFR 50.46. The following questions pertain to the RELAP5/MOD3.3 and CONTEMP4/MOD5 programs which comprise the APR1400 Evaluation Model:

1. The version of RELAP5/MOD3.3 used in these analyses has known errors in the Groeneveld (1986) tables implementation. These errors were corrected in RELAP5/MOD3.3 Patch04 in October, 2010. Additionally, the Groeneveld (2006) tables were updated in a later RELAP5/MOD3.3 version (incremental version3.3kg).

   If the applicant has not corrected these errors in the version used to perform the analyses in DCD Section 15.6.5, provide an assessment of the effect of these errors. Note that because these results will be used in a CSAU/BEPU analysis, it is not sufficient to determine if the results are conservative. As a minimum, the effect of the errors should affect the uncertainty in the analysis results.

2. When using the coupled codes RELAP5 and CONTEMPT with a one-to-one time step correspondence, it is correct to use fluid, vapor and non-condensable flows as calculated by each code. However, if either of the codes uses more than one time step to reach the next coupling time, it is necessary to provide the integral of some properties over the coupling time interval (fluid enthalpy, vapor enthalpy, fluid mass flow, vapor mass flow and air mass flow) not just the last times step values. If this is not done, these properties are not conserved.

   Explain how the passed quantities are defined to ensure conservation of mass and energy.

3. In the LBLOCA Topical Report, it is stated that the break flow is underpredicted for the LOBI experiments. There are multiple critical flow models in RELAP5/MOD3.3 for subcooled and saturated critical flow. Please specify which correlation was used in each flow regime. For example, was the Henry-Fauske (recommended) or the default Ransom-Trapp model used? What discharge factors were used in the chosen model and how were they determined?

4. It is well known that RELAP5 convects an incorrect amount of energy into the downstream volume connected to a junction. There is a junction flag (the e flag) that can be used to correct this. This is only an issue at the breaks where the pressure change across the junction is large.

   Provide justification that break flow is correctly treated in this regard. Otherwise, containment pressures will be too low.

5. Due to the location of the break and the location of the pressurizer, there will be times during the transient that flow and thermal conditions from each loop will be different. Assuming that the inlet plenum nodalization in the full plant model is the same as that used in the topical report, the inlet plenum is modeled as a single volume. This implies that there is complete mixing of the flows from each loop and that the core inlet conditions are therefore uniform across the core.

   Please justify that the use of a single volume, hence uniform inlet conditions, is based on some experimental data or explain if loop-to-loop mixing is accounted for using some other model?

6. The modeling of the reactor vessel in the downcomer region and the thermal shield on the other side of the downcomer are critical to the prediction of downcomer filling during the refill and reflood phases. Since rapid temperature transients caused by fluid heating (or cooling) the walls initially only affects the surface of the metal and does not involve all of the metal mass. It is crucial to choose a “good” mesh spacing to capture accurately these effects. There are modeling guidelines based on the component Biot Number in the RELAP5-3D manuals to provide help on the development of an accurate mesh spacing.

Please provide a discussion of the adequacy of the mesh size selected for the analyses.

7. For the LOBI experiments discussed in the LBLOCA Methodology Topical Report, late in the transient, the RELAP5 based Engineering Model predicts 150K superheat in both hot legs and the intact loop cold leg. This seems to be unrealistically high.

   Is the same level of vapor superheat seen in the full plant model? If so, are there modeling adjustments that can be made to reflect more closely the experimental data? How was this uncertainty handled in the final evaluation?

8. In the early reflood phase, there are series of cyclic events that involve steam binding caused by reverse heat transfer in the steam generation. Subsequent lower reflood rates in the core are followed by increased steam generation in the core. Through this cyclical process, the core is eventually reflooded. The cyclical behavior involves a number of complex and interrelated processes. Has the ability of RELAP5/MOD3.3 to model these types of phenomena been demonstrated through comparisons to test data or other methods?

9. In the analysis of the LOFT test in the LBLOCA topical report the applicant notes: “For all calculations, this accumulated liquid in the core is larger than the amount obtained by subtracting the expelled liquid amount out of the downcomer from the delivered liquid amount to the downcomer. This implies that a portion of the liquid in the downcomer is carried to the core by the core up-flow behavior.” RELAP5 has a tendency to accumulate “mass error” particularly in two-phase regions. When the mass error is large relative to the change in mass of interest, it often masks the actual behavior of the system. The mass error can usually be reduced by using smaller time steps and/or renodalizing the region where the mass error is occurring.

   Provide justification that the mass error for full plant evaluation as well as the LOFT test results ensure that the conclusions remain correct and that mass error is not influencing the conclusions.

10. During the early reflood phase, it is stated that the entrained liquid travels to the upper plenum where it is de-entrained and accumulates in the upper plenum where it subsequently flows down through the lower power (cooler) assemblies. This sets up a three-dimensional flow pattern (essentially a Natural Circulation flow path up the hot assemblies and down the cooler assemblies).

    Since RELAP5/MOD3.3 is a set of one-dimensional models, how is the model constructed to capture these three-dimensional phenomena and how is the model qualified/validated?

Response

1)

Groeneveld CHF lookup table of RELAP5/MOD3.3 has errors reported as follows.

Related sub-routine: chftab.ff

Description: In April 2010, an IRUG member reported an error in the RELAP5-3D implementation of the Groeneveld critical heat flux (CHF) look up table after comparing the coding in subroutine CHFTAB to the 1986 paper. A subsequent, more detailed review by RELAP5-3D developers revealed 41 errors or inconsistencies, some of which were minor (e.q., difference in the last digit due to round off for interpolated values), and some of which were significant. These errors affect all RELAP5 versions since and including RELAP5/MOD3 version 3.0 and all RELAP5-3D versions.

Development code version: 3.3in

Complete date: 25, August, 2010

Based on the above code modification information, CHF lookup table data file (chftab.ff) of RELAP5/MOD3.3/K is changed to the modified CHF lookup table data file (RELAP5/MOD3.3 Patch 4).

Figure 1-1 and Figure 1-2 show code accuracy results for RELAP5/MOD3.3/K (topical report code) and modified CHF lookup table data of RELAP5/MOD3.3/K (modified code) against THTF, LOFT and LOBI test data. Figure 1-1 shows calculation results using the topical report code, but it differs from Figure 4-7 of the topical report because Figure 4-7 of the topical report contains an error. Figure 4-7 will be replaced with Figure 1-1 of this response. Comparison results of the code accuracy show that the effect of the error modification on the Groeneveld lookup table data is evaluated within [ ]TS.

Figure 1-3 and Figure 1-4 show plant SRS calculation results for the topical report code and the modified code. Overall quench times for both results are similar and the third highest (95/95 confidence level) PCT values are the same as [ ]TS.

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Figure 1-1. Code Accuracy of RELAP5/MOD3.3/K for Blowdown Phase

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Figure 1-2. Code Accuracy of Modified RELAP5/MOD3.3/K for Blowdown Phase

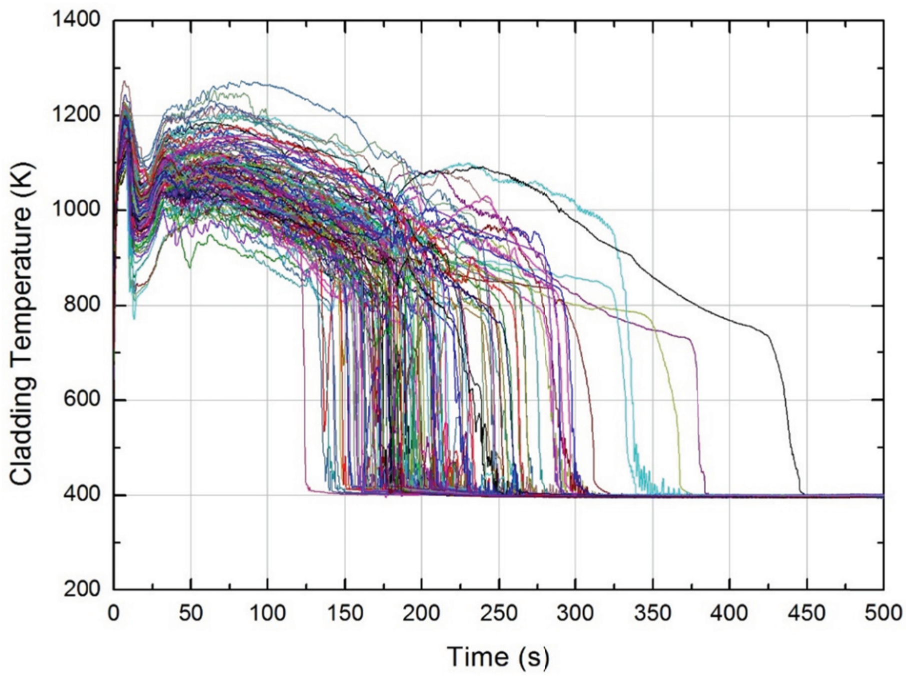

Figure 1-3. SRS Calculation Results of RELAP5/MOD3.3/K

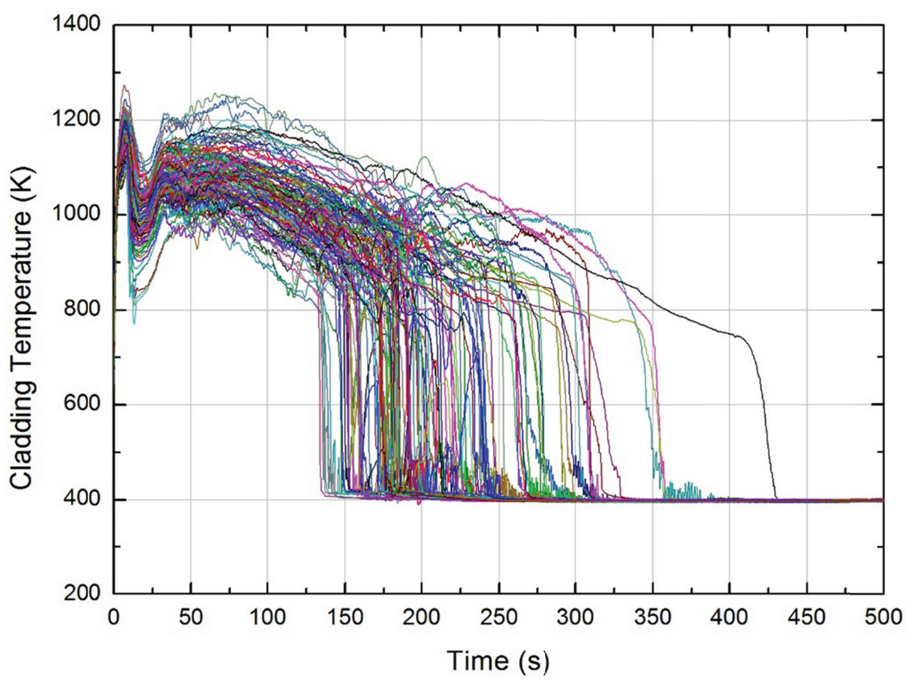

Figure 1-4. SRS Calculation Results for of Modified RELAP5/MOD3.3/K

2)

[ ]TS.
RELAP5 calculates total released mass and energy data for liquid, vapor and non-condensable gas through the breaks [ ]TS. Then, the CONTEMPT code calculates containment pressure [ ]TS. After the loading of CONTEMPT, RELAP5 and CONTEMPT exchange mass, energy, and pressure data for every calculation time step of RELAP5.

3)

As described in Section 4.2.2.7.1 of the topical report, Ransom-Trapp critical flow model is used in CAREM, and discharge coefficients for subcooled single-phase and two-phase were obtained based on the code assessment against MARVIKEN tests. The results of the assessment show that the Ransom-Trapp critical flow model [ ]TS for the subcooled single-phase critical flow and [ ]TS for the two-phase critical flow. Therefore, discharge coefficients for subcooled single-phase and two-phase were determined as [ ]TS respectively to match the calculated results with experimental data.

4)

A sensitivity study of the e-flag option in the junction at the break was performed for the plant base case to evaluate the effect of the e-flag junction. Figure 4-1 shows the containment pressure with activated e-flag option and de-activated e-flag option, respectively. Containment pressures for those two cases do not have significant differences. Discharged mass with de-activated e-flag option is larger than that with activated e-flag option at 500 sec, by 0.2 %, as shown in Figure 4-2, thus it can be considered negligible. Therefore, it is confirmed that the e-flag option does not have a significant effect on the calculation for the amount energy of the downstream volume.

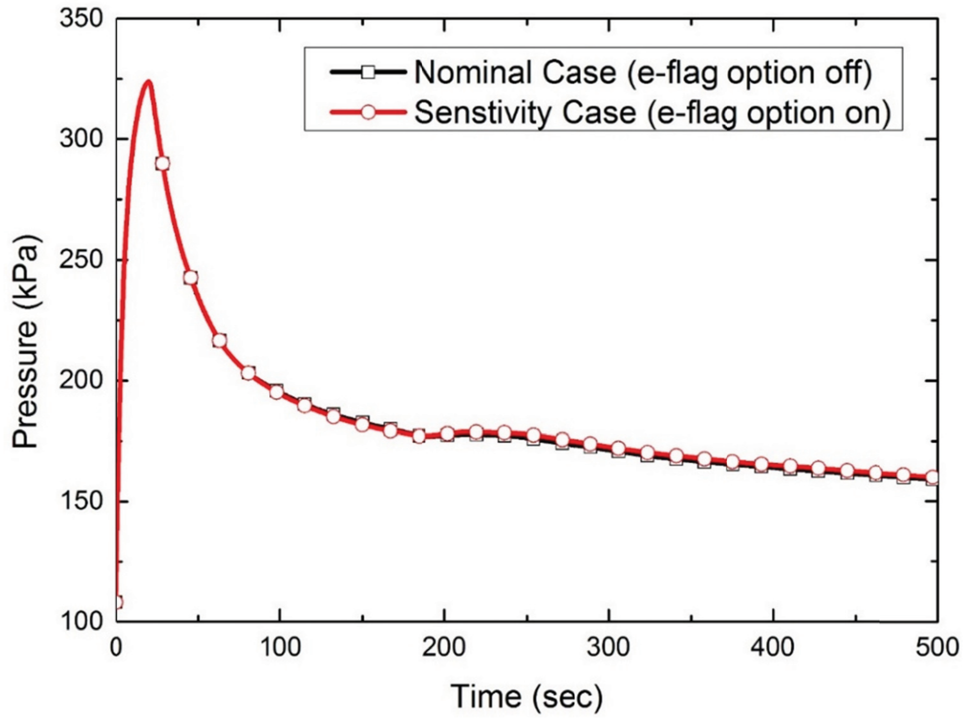

Figure 4-1. Containment Pressure

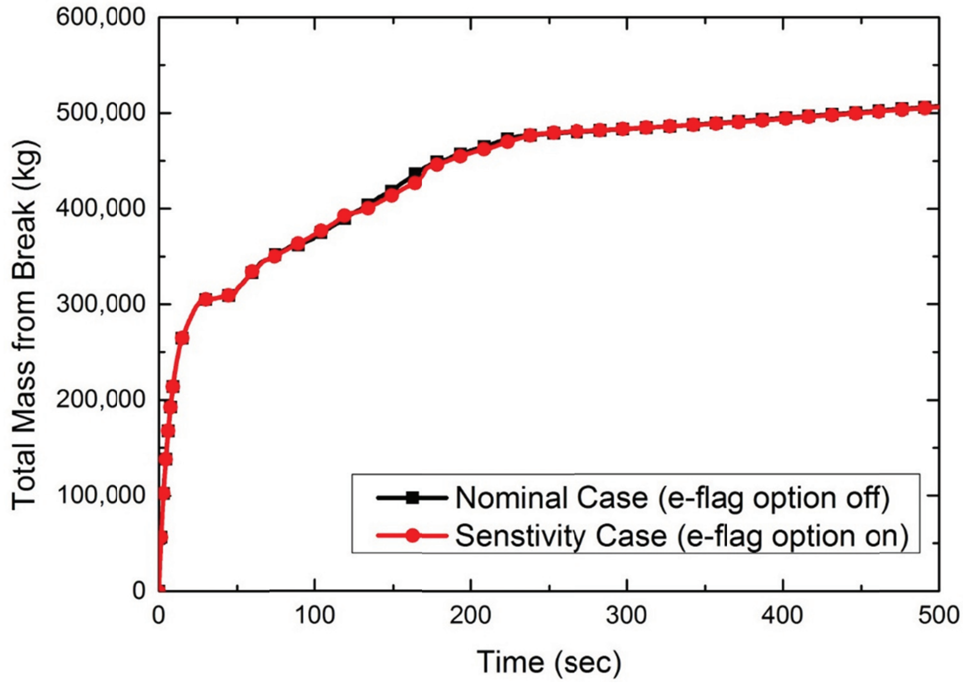

Figure 4-2. Discharged Mass from the Break

5)

The flow path of the coolant in the reactor vessel is shown in Figure 5-1. The flow rate between inlet plenum and each loop in the APR1400 plant is almost uniform because the coolant from the each loop flows through the flow skirt and lower support plate holes.

The flow skirt is a cylindrical structure with a number of holes as shown in Figure 5-2. This structure enhances the occurrence of mixing in the lower plenum, thus it uniformly distributes the inlet flow. The coolant from the flow skirt flows into the core through the lower support structure. The lower support structure is composed of the cylinder, support beam and bottom plate, as presented in Figure 5-3; the bottom plate has holes for flow distribution.

Therefore, even though non-uniform flow from the downcomer [ ]TS enters into the lower plenum, the flow is redistributed uniformly and then the uniform flow enters into the core because of the complex structures such as flow skirt and lower support structure. Based on this, the inlet plenum of the APR1400 plant is modeled [ ]TS.

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Figure 5-1. Flow Path of the Coolant in the Reactor Vessel

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Figure 5-2. Flow Skirt of APR1400

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Figure 5-3. Lower Support Structure and In-Core Instrumentation Nozzle Assembly

6)

The downcomer wall of the APR1400 plant is composed of [ ]TS. In CAREM, in order to model the downcomer wall, [ ]TS presented in Figure 6-1. The RELAP5-3D code manual in Reference [6-1] requires that a mesh point be placed at the interface between two heat structure compositions. Thus, as shown in Figure 6-1, [ ]TS.

The performance of different mesh layout strategies is a strong function of the Biot number. The Biot number represents the ratio of convective and conductive heat transfer and is given by:

$$\mathrm{Bi} = \frac{hL}{k}$$

Where h is the convective heat transfer coefficient, L is the thickness of the wall, and k is the thermal conductivity of the wall material. The Biot number has a significant effect on the mesh size, and the line in Figure 6-2 shows the recommended maximum relative surface node size (β_{max}). The equation for the recommended maximum surface node size is given by:

$$\frac{1}{\beta_{max}} = 0.338Bi + 5.2$$

In the calculation for the APR1400 plant, the current mesh interval size is allowable since the surface node ($\beta = \frac{1}{2}\delta_1/L$, $\frac{1}{2}\delta_1$ is one half of the first mesh interval size, L is the wall thickness) is always lower than β_{max} during the transient as illustrated in Figure 6-3.

In Reference [6-1], in order to perform the accurate calculation of the temperature gradients, the use of the graduated or spatially variable mesh point intervals with smaller mesh point intervals near the surface in contact with the fluid is recommended. The current nodalization of the APR1400 plant is shown in Figure 6-1, and the sensitivity study for analysis of the mesh layout strategies was performed. The nodalization of the downcomer wall used in the sensitivity study is shown in Figure 6-4.

Through the sensitivity study for mesh size of the downcomer wall, it is confirmed that the current noding transfers more heat to the fluid than the variable mesh (Figure 6-5). However, the differences are not significant. And, more heat transferred to the fluid is conservative from the viewpoint of downcomer boiling. Consequently, the current nodalization for the downcomer wall of the APR 1400 plant as shown in Figure 6-1 is used for the LBLOCA analysis.

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Figure 6-1. Heat Structure Mesh Point for Downcomer Wall of APR1400 Plant

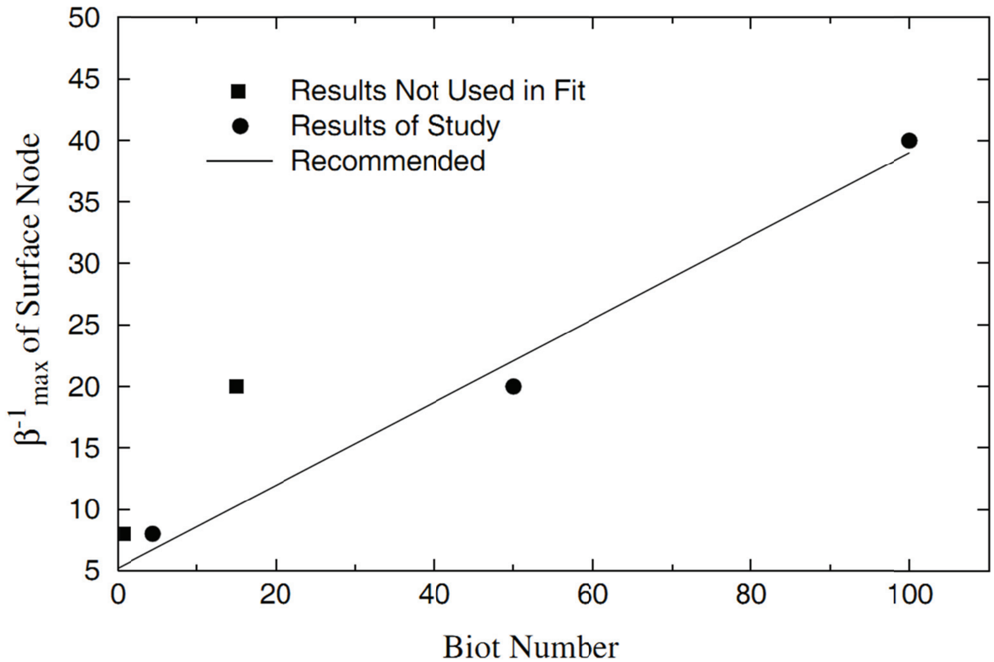

Figure 6-2. Effect of Biot Number on Suggested Surface Node Size

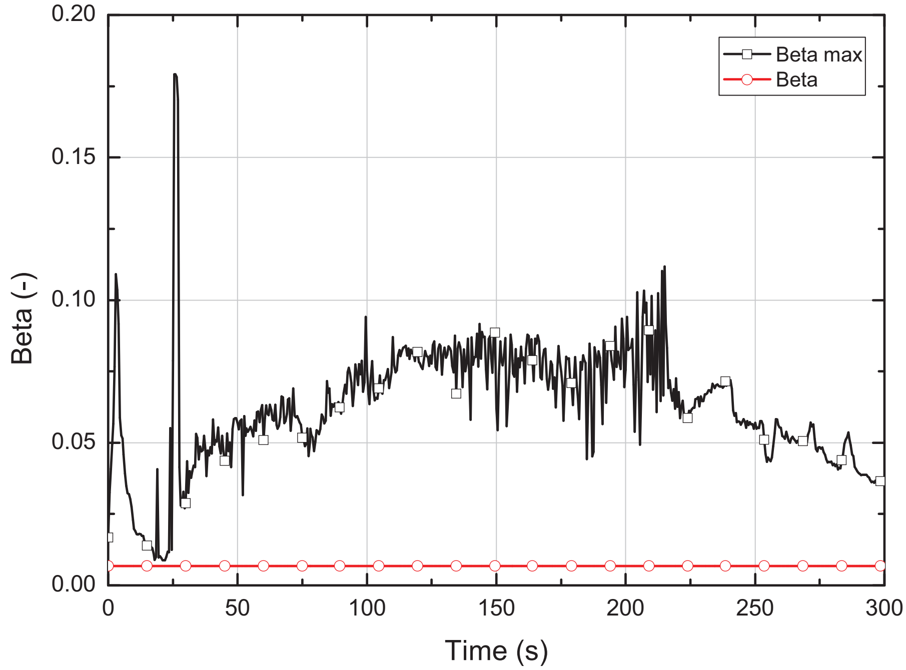

Figure 6-3. Maximum Acceptable Surface Node Size for APR1400 Plant Calculation

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Figure 6-4. Nodalization Strategies of Downcomer Wall

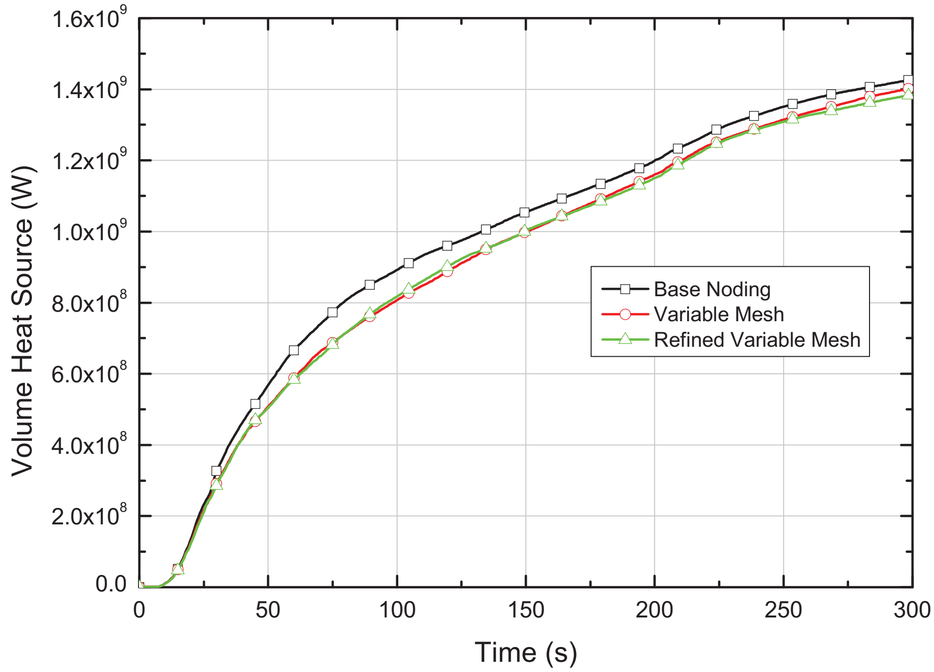

Figure 6-5. Total Volume Heat Source from the Downcomer Wall to the Fluid

Reference

[6-1] "RELAP5-3D Code manual Volume V: User's Guidelines," INEEL-EXT-98-008347, INEEL, July 2002.

7)

Figure 7-1 and Figure 7-2 show the calculation results of the intact loop hot and cold leg fluid temperatures for the APR1400, respectively. The reflood period initiates about 30 sec after the break, and superheated vapor comes out from the core, and superheated vapor comes out until 70 sec. However, the temperature difference between the liquid and vapor phases in Figure 7-1 is smaller than the 150 K observed in the LOBI assessment results, and the vapor temperature eventually drops to a liquid temperature at about 70 sec after the break because the core water level is increased. The cold leg fluid temperatures also show similar behavior, but the temperature difference is bigger than that of the hot leg because of the reverse heat transfer phenomenon in the steam generator.

The LOBI A1-66 test was designed to investigate the thermal hydraulic behavior of the system during the blowdown and refill periods, and the core inlet safety injection flow rate is not enough to cause entrainment of droplets to the hot leg. It makes superheated vapor in the hot leg. Superheated vapor continuously flows in from the core, whereas inflow of liquid phase is almost zero at about 30 sec after the break as shown in Figure 7-3. At this time the code calculates the liquid temperature as saturation temperature and vapor temperature as superheated temperature, all of which is coming from the core. For the cold leg in the LOBI assessment results, the temperature difference of liquid and vapor phases increases at 18 sec after the break because the safety injection from the SIT starts at this time. The liquid temperature drops below the saturation temperature because of the low temperature of the SIT injection water, whereas the vapor temperature maintains saturation temperature.

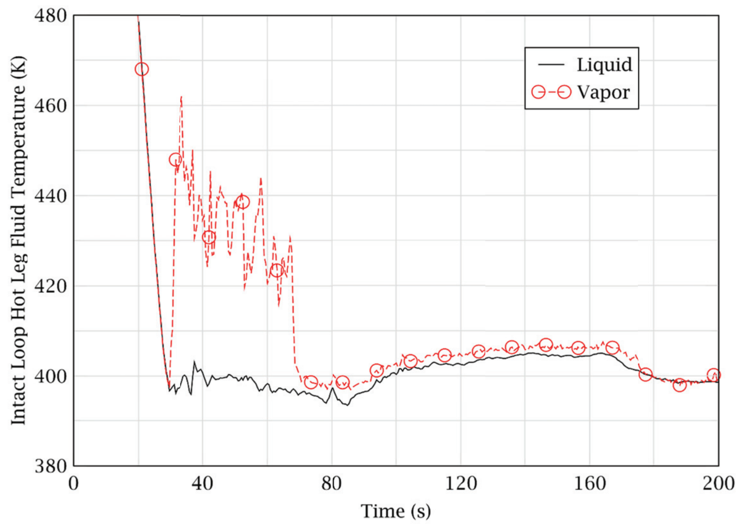

Figure 7-1. Calculation Result of Intact Hot Leg Fluid Temperature for APR1400

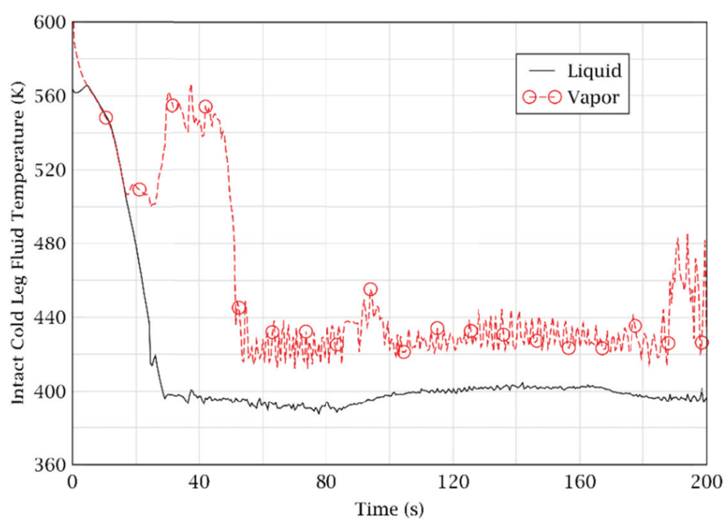

Figure 7-2. Calculation Result of Intact Cold Leg Fluid Temperature for APR1400

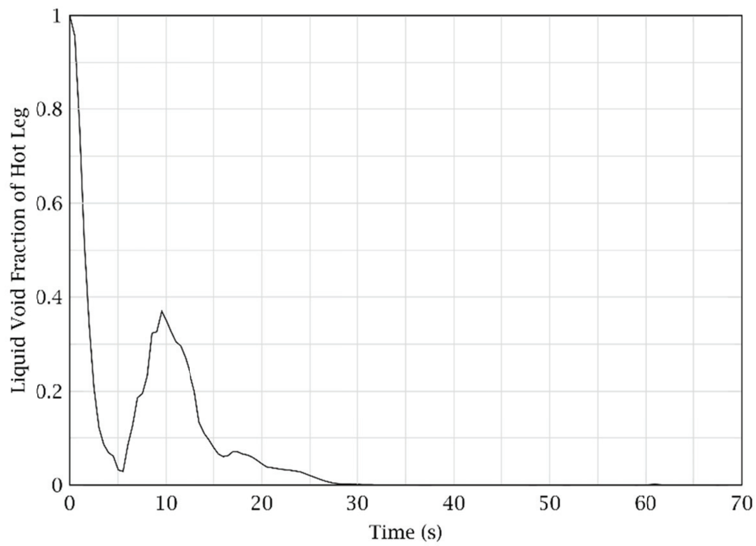

Figure 7-3. Calculation Results of Hot Leg Liquid Fraction for LOBI A1-66

8)

Code capability for the reflood phenomena was evaluated and described in Appendix C, D, and E of the topical report. The ATLAS test is used to confirm the code capability for the cyclic behavior.

The ATLAS test facility was designed to investigate thermal hydraulic behaviors of the APR1400. Therefore, the ATLAS test data and assessment results are determined to analyze the cyclic behavior of the core.

As shown in Figure 3-19 and Figure 3-20 of Appendix E, resorting to only collapsed water level data in the core and downcomer is [

]TS. Therefore, the pressure difference between upper head and downcomer is investigated directly.

Figure 8-1 and Figure 8-2 show test and code calculated data on the pressure difference between the upper head and downcomer for ATLAS test 15. In test 15, [

]TS. This pressure difference behavior is observed several times in Figure 8-1.

To confirm the code predictability for the cyclical behavior described above, it needs to be confirmed whether the code can predict the pressure difference behavior. Figure 8-2 shows the code predicted result of the pressure difference between the upper head and downcomer. [

]TS.

Consequently, it is concluded based on the code assessment results of the ATLAS test that RELAP5/MOD3.3/K have the capability to predict cyclical behavior in the core and downcomer.

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Figure 8-1. Pressure Difference between Upper Head and Downcomer for ATLAS Test 15

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Figure 8-2. Code Predicted Pressure Difference between Upper Head and Downcomer for ATLAS Test 15

9)

In the RELAP5 code, two types of mass errors are computed as described in Reference [9-1]. If either ε_m or ε_{rms} is larger than 8 x 10^{-3}, the time step is repeated with one half of the time step size. The maximum of ε_m or ε_{rms} for all volumes can be found in minor edit (ERRMAX, current estimate of the truncation mass error fraction). The mass error fraction for the APR1400 plant and the LOFT test calculation are shown in Figure 9-1. As shown in Figure 9-1, the mass error is always lower than 8 x 10^{-3} during the transient.

Figure 9-2 and Figure 9-3 show the mass errors in all systems for the APR1400 plant and the LOFT test calculation. The total system masses at the start of each calculation are about [ ]TS respectively, and the total system masses at the end of each calculation are about [ ]TS respectively. The mass error for the APR1400 plant and the LOFT test are represented in Figure 9-4 and Figure 9-5. Since the mass error for the plant and the LOFT test calculation (300 kg and 1.5 kg respectively) are very low compared with total system mass, the effect on the calculation result is negligible.

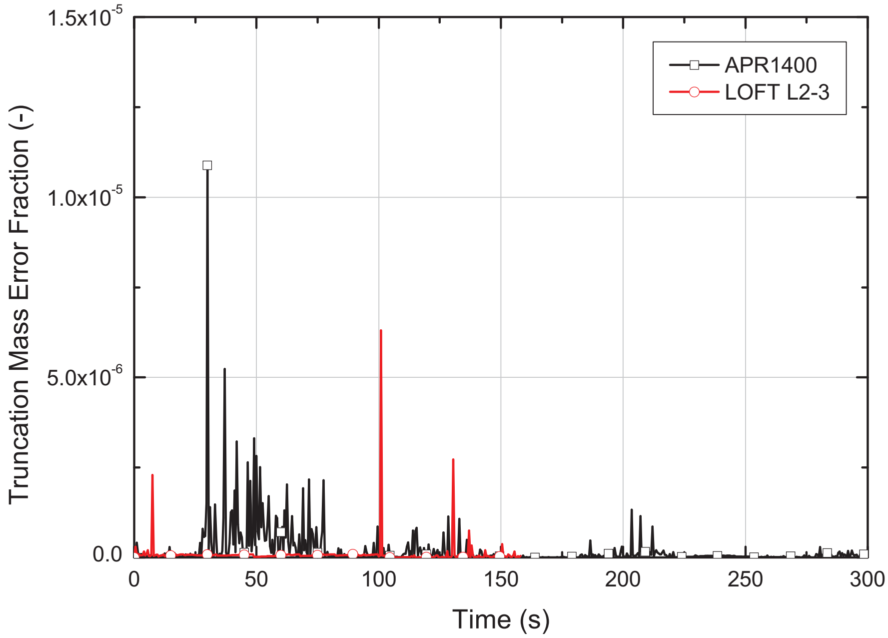

Figure 9-1. Truncation Mass Error Fraction for APR1400 Plant and LOFT L2-3 Test

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Figure 9-2. Total Mass in All the Systems of APR1400

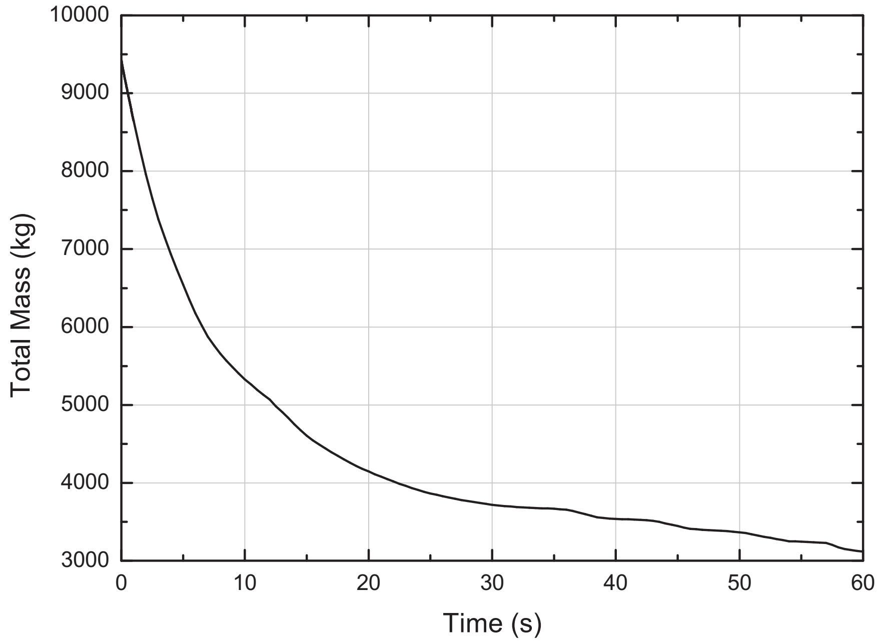

Figure 9-3. Total Mass in All the Systems of LOFT L2-3 test

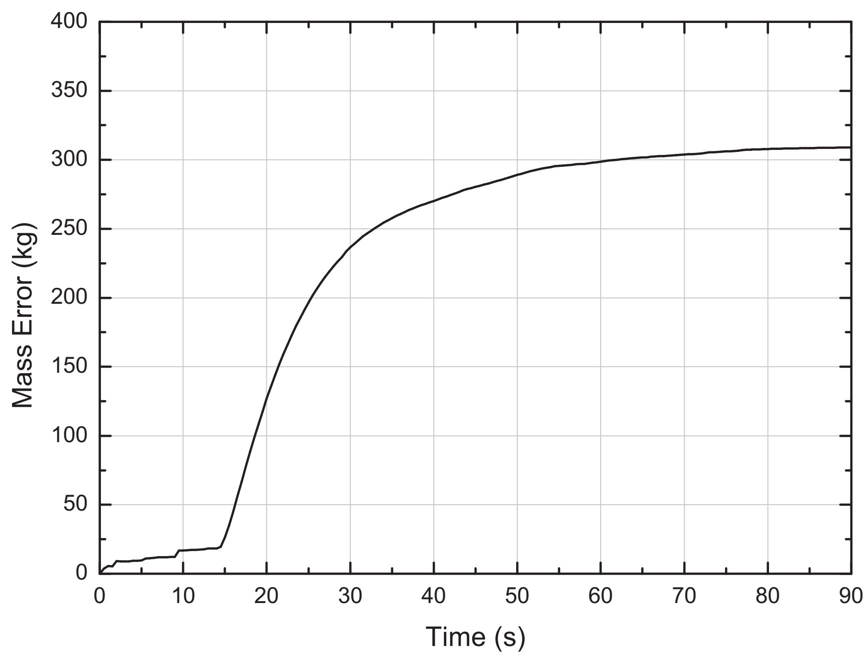

Figure 9-4. Mass Error in All the Systems of APR1400

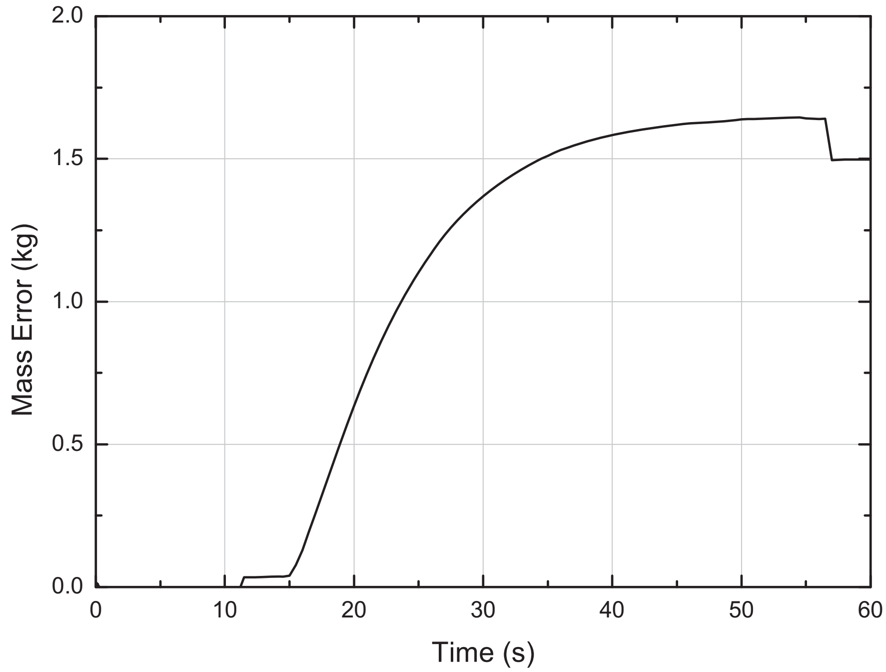

Figure 9-5. Mass Error in All the Systems of LOFT L2-3

Reference

[9-1] "RELAP5/MOD3.3 Code Manual Volume 1: Code Structure, System Models, and Solution Methods," NUREG/CR-5535, Information Systems Laboratories, March 2003.

10)

Predictability and conservatism of [ ]TS were assessed against various SETs and IETs and the assessment results are described in Appendix C, D, and E of the topical report. Therefore, it can be concluded that the applicability of [ ]TS was confirmed.

As to the multi-dimensional flow in the core, [ ]TS. However, the current core nodalization is applicable for the APR1400 because [ ]TS.

In general, experiments on CCFL are well correlated with the Kutateladze number as shown in Figure 10-1. Most important thing to check is the limiting gas velocity, $v_{s,Limit}$, above which no liquid fall back is possible.

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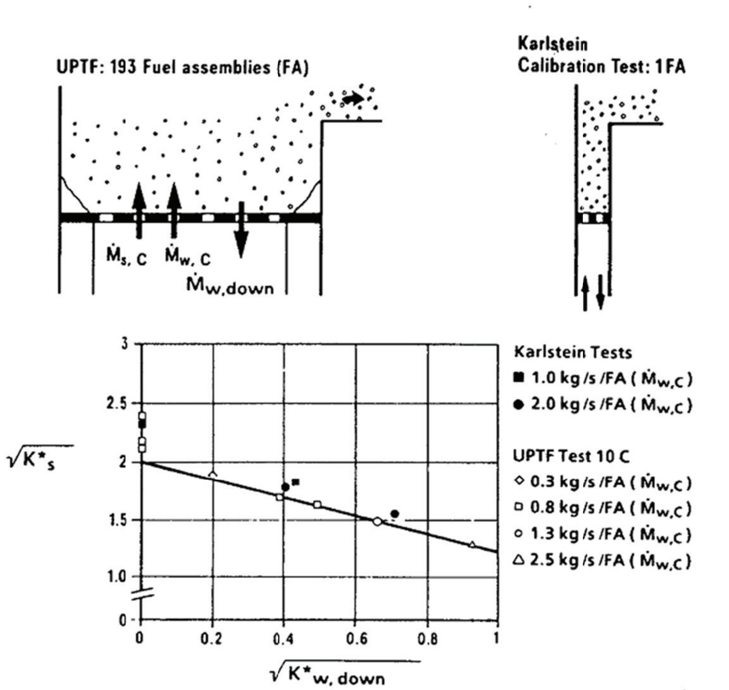
]TS

Consequently, chances of such liquid fall back causing multi-dimensional thermal hydraulic behavior are [

]TS thermal hydraulic behavior for the APR1400 LBLOCA analysis.



COUNTERCURRENT FLOW OF SATURATED STEAM AND WATER AT THE TIE PLATE

FIGURE 4.4-1

Figure 10-1. Figure 4.4-1 of the reference [10-1]

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Figure 10-2. Steam Velocity at Tie-Plate

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Figure 10-3. Steam and Liquid Flow Rate through the Tie Plate

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Figure 10-4. Core Nodalization to Capture Multi-Dimensional Flow

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Figure 10-5. Quadratic View of Core Fuel Assemblies

TS

Figure 10-6. Collapsed Water Levels of Upper Plenum Volumes

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Figure 10-7. Accumulated Liquid Mass Flow Rate from Low Power Channel and Average Channel to Upper Plenum

Reference

[10-1] “2D/3D Program Work Summary Report,” NUREG/IA-0126, GRS-100, MPR-1345, 1993.

Impact on DCD

There is no impact on the DCD.

Impact on PRA

There is no impact on the PRA.

Impact on Technical Specifications

There is no impact on the Technical Specifications.

Impact on Technical/Topical/Environmental Reports

Topical report (APR1400-F-A-TR-12004) will be revised as attached markup.

There is no impact on Technical or Environment Report.

RAI 399-8510 – Question 15.06.05-9

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Attachment (1/2)

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Figure 4-7 Code Accuracy during Blowdown Phase

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Figure 4-7 Code Accuracy during Blowdown Phase