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.:	**398-8457**
SRP Section:	**15.06.05 – Loss of Coolant Accidents Resulting From Spectrum of Postulated Piping Breaks Within the Reactor Coolant Pressure Boundary**
Application Section:	**15.6.5.2, 15.6.5.3**
Date of RAI Issue:	**02/03/2016**

Question No. 15.06.05-5

1. Section 2 of the Long-Term Cooling (LTC) technical report indicates that the procedure to distinguish a large break from a small break is based on whether the pressure is above or below 450 psia at approximately 8 hours after initiation of the event. The implicit assumption is that the primary system is refilled and that the operators can switch to shutdown cooling (SDC). How is it determined that there are no voids trapped in the primary system that could impede operation of the SDC? Could the Safety Injection Tanks (SITs) have injected noncondensable gas that is trapped in the system? What is the basis for increasing the pressure from the lower value in CENPD-154?

2. The analysis does not appear to account for reduced injection flow during the switchover to hot leg injection at 3 hours (Section 3.5.4). Is there a reduced flow during this transition period and how is it addressed in the calculation?

3. As shown in Figure 2-1, between 2 and 3 hours, the switch is made to align SI flow to the hot legs and the DVI nozzles. This is apparently done regardless of the break size. How is it assured that most or all of the SI flow does not go to a break located in the loop between the DVI and hot leg injection points, stagnating the core flow and resulting in a heatup and continued buildup of the boron concentration in the core?

4. The number of axial nodes in the heated core region is less than that for other plants that use variations of the interim methodology. Ten nodes are used in the core region. However, the subscript Z_{20} in Equation 1 indicates that CEFLASH-4AS (the reference for this equation) uses 20 nodes in the core region. Twenty nodes is closer to the number used in other applications of the interim methodology. How was the use of only 10 nodes justified as a sufficient number to yield a conservative void fraction at each node?

5. To make an understandable licensing record, all of the variables in equations 1 through

13 must be clearly defined in a nomenclature list. Provide this list, and also explain the relationship between the nomenclature in the technical report and that in Section II D of CEFLASH-4AS topical report that is cited as the source of the phase separation model.

6. In Section 2.3, it is noted that the “small and large break LOCA bring for distinctly different responses in the long-term cooling plan”. It appears that the analysis addresses the small breaks, e.g., CELDA calculates the long-term depressurization and refill of the RCS for small breaks and determines whether the refilling of RCS is achieved for small breaks. The CELDA analysis is initialized from the CEFLASH-4AS analysis that is performed for the early part of accident. CEFLASH-4AS is a SBLOCA code. If CELDA is used for large breaks, how is it initialized?

   The discussion of how the computer codes are used for the LTC analysis appears to address only the small breaks. Further information is needed on how the large breaks are addressed. For example how is it determined that “*The LTC analysis also determines that the large-break procedures can flush the core for break sizes down to 0.004 ft$_2$*." Please identify any computer codes in addition to the BORON code that are used for the LBLOCA analysis and provide information on their approval status.

7. Early in a LBLOCA, the steam upflow from the core may entrain the hot leg injection flow and prevent the hot leg injection from flushing the high boron concentration coolant from the core. How does the analysis account for this possibility? Provide justification for any CCFL correlation used for this application.

8. In Section 3.5.2, it is stated that the BORON code has been modified due to the difference between the RWT and the IRWST. Although the equations in the BORON code documentation are not numbered, please identify which equations were modified and the extent of the modifications.

9. It is mentioned that for C-E plants when the RWT is emptied, ECC injection is switched to the sump. Is the BORON code modification simply to continue injection from the IRWST with no switch to the sump? The BORON code also includes injection from a boric acid storage tank (BAST). How is this injection path addressed for AP1400?

10. The documentation for the BORON code makes a statement to the effect that “for core flush conditions an evaluation of the code equations indicates that a time step interval of one hour or less gives conservative results.” Provide justification that the BORON code analysis has reached a converged solution.

11. The solubility limit of 29.3 wt % is greater than that at 212 F, the saturation temperature of pure water at 14.7 psia. According to Table 3-6, the solubility limit used in the analysis is based on a temperature of 217.9 F, presumably the boiling temperature of the boric acid solution at 14.7 psia. Were the liquid density used to calculate the wt % of boron and the water properties used to calculate the boiloff rate based on this same temperature?

12. Figure 4-2 shows that the “Pressure after Refill” as a function of break size settles out to approximately 80 psia for breaks between 0.04 and 0.07 ft2. What physical phenomenon is causing the pressure to remain constant for this wide range of break sizes?

13. Figure 4-3 shows the buildup of boric acid concentration which depends on the boiloff rate and appears to be independent of break size? For smaller breaks where natural circulation is mixing the coolant, the switch to hot leg injection could possibly hinder the natural circulation by introducing cold liquid into the hot side of the natural circulation loop. How does the approach used address this possibility?

14. In the CENPD-254 methodology, the maximum break size for the small break analysis is determined by the auxiliary feedwater capacity. There is no mention of auxiliary feedwater capacity in the technical report. How was the upper limit size determined for the small break?

15. Assumption 2d. states “RCS cooldown begins at 2 hours post-LOCA.” How is this assumption used in the analysis? Tables 3-2 and 3-5 show values starting at 1 hour. Tables 3-3 and 3-4 show values beginning at 0.0083 hours. In section 3.5.3 decay heat is calculated at one hour.

16. In calculating the boiloff rates at various times, was only the decay heat varied? Was a pressure of 14.7 psi used for all pressure dependent calculations? If not, what pressure was used?

Response

1\.
The throttling procedure has been specified so that voiding will not occur. At 8 hours after the LOCA, the hot leg temperature will have been reduced to the shutdown cooling entry temperature of 380 °F by use of the steam generator atmospheric dump valves. The SI pumps are then throttled to bring RCS pressure to the shutdown cooling entry pressure of 400 psia. Since the saturation temperature corresponding to 400 psia is 444 °F, there will be 64 °F of subcooling in the hot leg and no voids will exist. Also, the operator isolates or vents the SITs to avoid injecting a large quantity of noncondensible gas into the RCS.

The overlap RCS pressure for the large break and small break analysis is from 92 psia to 1042 pisa. A decision point pressure of 450 psia is chosen within this range. The 450 psia decision point pressure allows sufficient margin for the instrument error.

2.
The injection flow is not considered to decrease during the switchover to hot leg injection. Instead, the injection flow is assumed conservatively. The flushing flow rate is calculated by hot side SI injection flow and core boil off rate as shown in Fig.1. Even though 2 SI pumps actuate during the switch over period, it is assumed that 4/10 of the total flow from a single SI pump enters the reactor vessel from the hot leg and all of the decay heat from the core boils off liquid. At 3 hours, core flushing flow is decreased to 23 gpm. After 3 hours, as the core boil off rate has decreased, the core flushing flow has increased. The flushing flow rate is used to compute the boric acid concentration in the core.

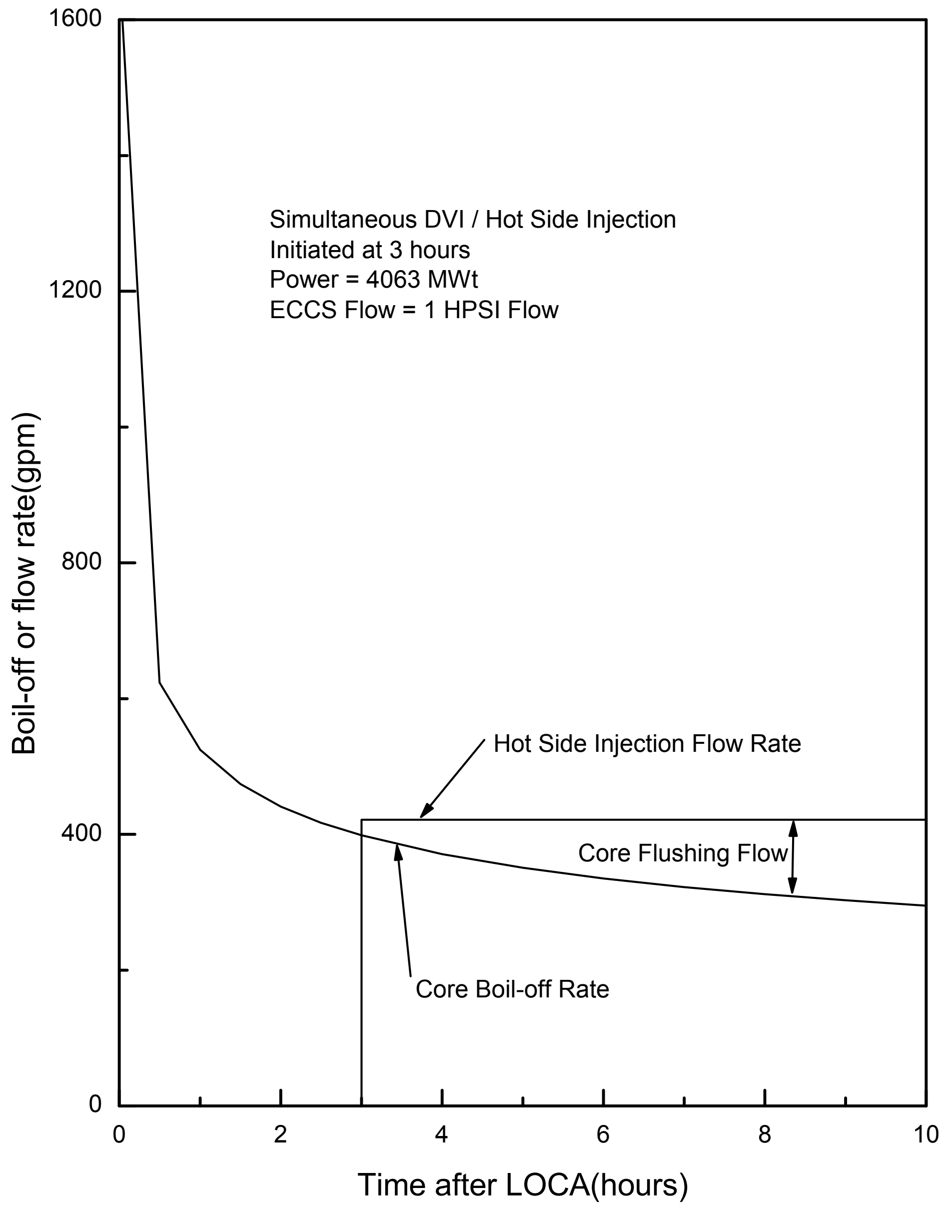

Figure 1 Core flush by hot side injection

3.
The Korea Atomic Energy Research Institute (KAERI) conducted the ECC bypass tests using the MIDAS facility to study the ECC bypass phenomena, which can occur in the direct vessel injection (DVI) system. According to the MIDAS test, bypass flow occurs at the break location mainly during the reflood phase. The considerable amount of steam generated in the core during this period causes the bypass flow to go out through the cold leg break [APR1400-F-A-TR-12004, Appendix F].

We assumed the failure of one of the two emergency diesel generators so that 2 SI pumps actuate during the transient. After 3 hours, the operator manipulates 2 SI pumps for simultaneous hot leg and direct vessel injection. Then SI flow to the DVI lines may spill out of the break. In contrast, hot leg injection flow is assured that most of the SI flow does go to core,and ECC bypass does not occur due to the small amount of steam generated in the core. Furthermore, in the analysis, only one SI pump is assumed to be active in the code calculation for conservatism.

4.
Ten nodes are used in the Interim methodology. The average void fraction of 10 nodes is similar to the average void fraction of 20 nodes as shown in the tables below. Furthermore, we calculate the mixing volume using the top of core region, which is a more conservative assumption than average void fraction of the core region.

Table 1 Void fraction of 10 nodes (Top of region Vs. Average of region)

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Table 2 Void fraction of 20 nodes (Average of region)

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Table 3 Calculation Results of Mixing Volume using the Interim Methodology

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5.

The nomenclature list is provided below for the technical report. Also, a table for explaining the relationship between the nomenclature and the CEFLASH-4AS topical report is provided in Table 1. The first column is the equations 1 through 13 and explanations described in technical report, and the second column is for the CEFLASH-4AS topical report. And, the equations are added to the third column in Table 1 because the formations of main equations in the technical report are from CENPD-254-P-A.

NOMENCLATURE LIST

V_D	drift velocity
N	region index
α(Z)	the void fraction as a function of axial position
ρ_v	vapor density
A_N	cross-sectional area of region N
$\dot{P}_N$	the bubble production rate
W_N	the in-flow bubbles from the lower sub-region
h_{lv}	latent heat of vaporization
$\dot{W}_{\text{flashing}}$	the linear flashing steam rate
$Z_{2ø}$	two-phase mixture height
$M_{\text{GB,SS}}^{N}$	the steady state bubble mass of region N
Z_N	either the height of region N or the two-phase mixture height in region N.
Q	the total energy deposition rate for region N
α_A	void fraction in the lower plenum
α_B	void fraction in the core region
α_C	void fraction in the outlet plenum

Table 1 Relationship between the nomenclature and CEFLASH-4AS topical report

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Non-Proprietary

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6.
The largest break size in the CELDA calculation is 0.5 ft^2 that is the SBLOCA region. Therefore, the CELDA code is initialized using the CEFLASH-4AS conditions. The CELDA code is not used for large breaks, so we don't initialize this code using the large break conditions.

The BORON code is used to compute the boric acid concentration in the core, and covers large breaks down to 0.004 ft^2. The double ended cold leg break size, however, is considered to calculate boric acid concentration. Other break sizes are not considered for the calculation; because the double ended cold leg break size is the limiting break for long term boric acid accumulation due to the addition of the largest amount of coolant with high boron concentration to the inner vessel from SITs and SI Pumps.

The methodology and input for the BORON calculation in CENPD-254 is modified to reflect the following. The major differences between modifications (interim methodology) and CENPD-254 is describes as follows.

- Void Effect – The mixing volume and the void fraction is taken into account when computing the boric acid concentration.
- Time-varying Mixing Volume –The variation in the mixing region while considering the pressure drop in the loop is considered.
- Decay Heat – Appendix K decay heat model with multiplier 1.2 for all times has to be used.

The modified BORON code was applied to PSAR for construction permit of Shinhanul 3&4 in Korea. Now, this code is under review by Korean regulatory body.

7.

Injection of SI flow to the hot leg cannot be assured of flushing the reactor vessel until the hot leg steam flow drops below the minimum velocity which can entrain the injected water. Thus, the switch to simultaneous DVI/hot leg injection of the SI flow should not be performed until the steam flow in the hot legs drops below the entrainment velocity.

The steam flow in the hot legs is determined based on the following assumptions:

(1) All of the decay heat in the core is used to generate steam.
(2) The total generated steam flow is split equally between the two hot legs.
(3) The flows in the core and the hot legs is saturated at 14.7 psia.

The critical flow rate below which the steam flow will not entrain liquid in the hot leg is determined using an equation formulated by Wallis.

When entrainment is 0 %, dimensionless gas velocity, π_2, in the equation below, is conservatively used are 1.3E-04 (actual value in the correlation is 2.46E-04).

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Therefore, steam velocities below 81.95 [ft/sec] will not entrain the injection water in the hot legs. The steam generation rate required to achieve a hot leg steam velocity of 81.95 [ft/sec] is

$M_{steam} = Q_g \times \rho_g \times A_{Hotleg} \times 2$(# of Hot leg)
$= 81.95 \times 1/26.792 \times 9.621 \times 2 = 58.86$ [lbm/sec]

The time at which the steam generation rate in the core drops below the value related to no entrainment is determined by the decay heat model from the following equation.

$M_{steam} = Q_{core} * f_{decay\ heat} / h_{fg}$ [lbm/sec]

The decay heat fraction is determined using the decay heat model of the BORON computer code described in CENPD-254-P-A. And is provided below.

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Where,

f_d = normalized decay heat fraction including 1.1 conservative multiplier

T = time (seconds)

Consistent with NRC imposed restrictions on the acceptability of the boric acid precipitation methodology, a decay heat multiplier of 1.2 is applied as shown below:

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The time dependent steam generation rate and decay heat fraction are calculated and summarized in the Table 3 below.

Table 3. Time vs. Steam generation rate

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Based on Table 7, the corresponding time for when the steam flow will not entrain liquid in the hot leg is 7180 sec. [Approximately 2 hours] Therefore, the switch over time of 3 hours is acceptable because there will be no potential of liquid entrainment in the hot leg at that time.

8.
In the original CE plants, 90% of RWT volume is used as ECC water. Because the suction from RWT is stopped due to RAS (Recirculation Actuation Signal) when the RWT level drops to less than 10% of the RWT level. However, there is no interruption of suction from IRWST in the APR1400 design. Thus, the coefficient related to RWT volume is modified from 0.9 to 1.0 in the BORON code. When the BORON code was applied to APR1400, which has IRWST, the BORON code was modified for the equations of boric acid in sump and sump water mass. The modified equations and nomenclature are provided below.

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NOMENCLATURE of variables in equations

VSUMP	lbm of solution in SUMP
VRCS	lbm of solution in RCS
VRWT	lbm of solution in RWT
VBAST	lbm of solution in BAST
VSIT	lbm of solution in SIT
BSUMP	boric acid wt% in SUMP
BRCS	boric acid wt% in RCS
BRWT	boric acid wt% in RWT
BBAST	boric acid wt% in BAST
BSIT	boric acid wt% in SIT

Decay heat energy

Decay heat energy was assumed to be zero from 0 to 10 seconds because there is a small mixing volume in the core due to the blowdown phase of large break event. Therefore the boil-off rate by decay heat is zero during this period.

Modification of Injection path

The injection path is modified for IRWST in APR1400. And it is described in Question 9.

9.

Injection paths addressed in the BORON code are summarized in Table 4.

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Table 4. Time vs. Injection Path

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10.
Figure 2 shows boric acid concentrations according to time step intervals. It is calculated by the original BORON code with core flush condition at 3.0 hours. As shown in Figure 2, the calculation of boric acid concentrations corresponding to time step intervals less than one hour have converged(solid lines), while the time step intervals that are larger than one hour have not (dotted lines). Therefore, the time step interval of less than one hour is acceptable for analyzing the BORON code.

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Figure 2 Boric acid concentration for Time step interval

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11.
The boiling temperature of the boric acid solution at 14.7 psia is 217.9 °F. For this temperature the fractional weight of the boric acid in solution is 29.3 wt%. The temperature condition of 217.9 °F is used only for the solubility limit calculation.

The solubility limit condition (217.9 °F and 14.7 psia) is not used for the boiloff rate calculation. In the boiloff rate calculation, we use the saturation temperature (212 °F) at 14.7 psia.

Boron source density is used for the calculation of boron solution volume. The large volume of boron solution is conservative, since it results in a large amount of boric acid injected into the RCS. Therefore, we use the saturation temperature (212 °F) at 14.7 psia because lower density causes a large volume of boron solution than higher density.

12.
RCS pressures for breaks larger than $0.04ft^2$ are the same at 8 hours as shown in Figure 3 (See the dotted lines). The RCS does not fill fully at 8 hours for breaks larger than $0.04ft^2$. Thus, the RCS pressure does not increase until the RCS fills fully even though SI pumps are injected. These phenomena can be observed by inner vessel water level as shown in Figure 4 (See the dotted lines). The Inner vessel water levels for breaks larger than $0.04ft^2$ have not reached the top of the pressurizer within 8 hours. So the RCS pressure for these breaks maintains approximately the same value of 80 psia.

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Figure 3 Pressure of RCS spectrum

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Figure 4 Inner vessel collapsed level spectrum

13.

The double ended cold leg break size is the limiting break for long term boric acid accumulation in the inner vessel region, because the largest amount of coolant with high boron concentration is added to the inner vessel from SITs and SI pumps. Therefore, only the double ended cold leg break size is considered to calculate boric acid concentration by the BORON code. Thus, the boric acid concentration for the double ended cold leg break size is depicted in Figure5.

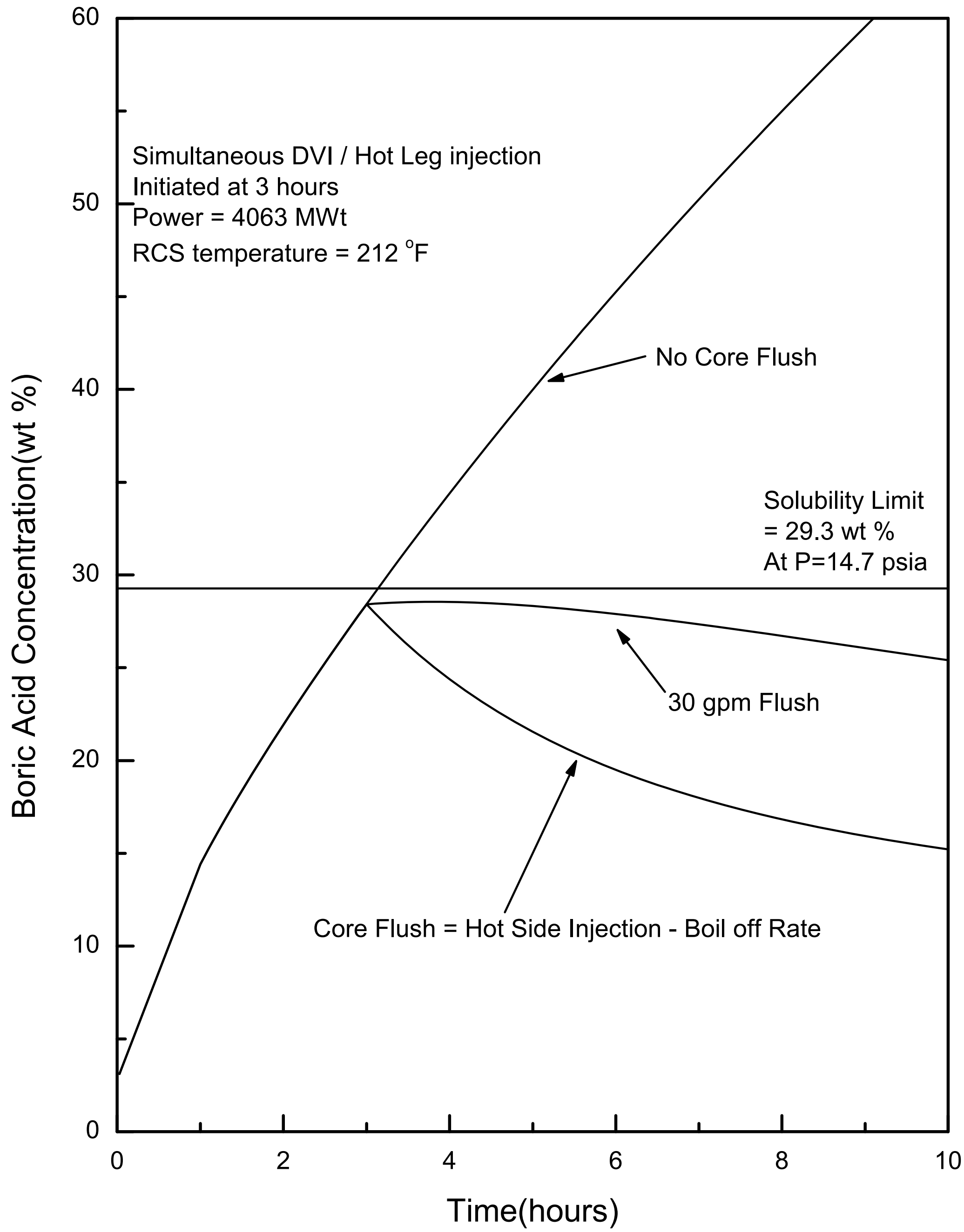

Figure 5. Inner Vessel Boric Acid Concentration vs. Time

The mixing volume for computing the boric acid concentration is changed to include the additional volume from the top of the core to the top of the hot leg piping at the RV outlet nozzles. If the water level in the inner vessel is higher than the top of hot leg, boron precipitation is not a concern. Natural circulation is not considered in the BORON code because natural circulation begins when injected water refills to the top of the steam generators, in the case of smaller break sizes.
Even though the switch to hot leg injection could possibly hinder the natural circulation by cold water; boron precipitation does not occur around the top of the core. Thus natural circulation is not addressed in the BORON code.

14.
The decision time at which the operator decide whether to use the large break procedure or the small break procedure in order to continue the cooldown of the RCS. This time (8hr) is determined between the earliest time at which the SDC entry conditions can be achieved, and the latest time for which auxiliary feedwater can be assured to be available.

In order for the SDC system to be used to remove heat from the RCS, there must be sufficient liquid in the hot leg from which it takes suction. If RCS is refilled before the decision point time, the break case is assured of having sufficient coolant in the RCS to use the SDC system. Thus, the decision time determines the upper limit size of small break for which the SDC system can be used. This break size is 0.04 ft^2 as is shown in Figure 6 below.

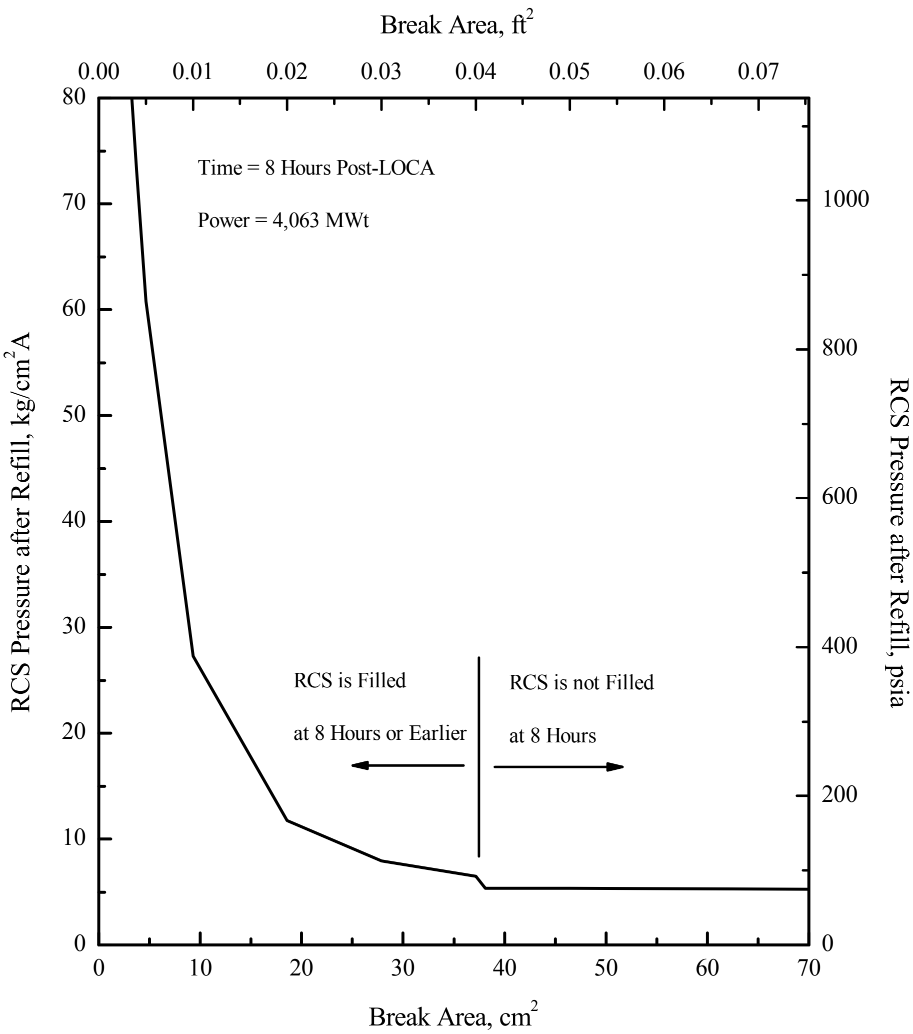

Figure 6. RCS Pressure after Refill vs. Break Area

The NATFLOW code is used to calculate the SDC entry time and the CEPAC code is used to calculate the exhausting time of auxiliary feedwater. Finally, the refill time of RCS is calculated by CELDA code.

15.
In the CENPD-254 methodology, the secondary temperature is calculated by the CEPAC code and provides the secondary temperature as a function of time that is input to the NATFLOW and CELDA code. The assumption 2d is used in the CEPAC code analysis for secondary cooling. This assumption means secondary system cooling start at 2 hours.

Table 3-2, 3-3 and 3-5 in TeR contain boiloff rate and void fraction of 1, 2 and 3 hours for time varying mixing volumes.
Table 3-4 and section 3.5.3 in TeR show 1 hour boilloff rate and time dependent boilloff rate, which is used for core flush flow.

16.
In calculating the boiloff rates at various times, the decay heat is the only dependent variable of time. The pressure of 14.7 psi is used for all pressure dependent calculations for conservatism.

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

Technical report (APR1400-F-A-NR-14003) 3.5.5 will be revised as indicated in the attached markup.

fraction of each core region was calculated by using the equations below and the results are shown in Table 3-2 and Table 3-3. In this report, the average void fraction shown in Table 3-3 was used to calculate the mixing volume.

The mixing volume used in the interim methodology was calculated by applying the CEFLASH-4AS phase separation model to this region, using the following equation:

The variables in equations 1 through13 were defined in Table 3.8.

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Equation 1

where, $\dot{P}_N$ = bubble production rate = $\left(\frac{Q}{h_{fg}} + \dot{W}_{flashing}\right) 1/Z_N$ → h_{lv}

W_N = flow bubbles from the lower sub-region

V_D = drift velocity = $3.0EXP^{-0.75\frac{P}{1000.0}}$

$$\alpha(Z) = \frac{\dot{P}_N(Z_{20}-Z_N)+W_N}{\dot{P}(Z_{20}-Z_N)+V_D\rho_V A_N+W_N}$$ → $$\alpha(Z) = \frac{\dot{P}_N(Z_{2\emptyset}-Z_N)+W_N}{\dot{P}(Z_{2\emptyset}-Z_N)+V_D\rho_v A_N+W_N}$$ Equation 2

α_B and α_C can be obtained from Equation 1,

$$M_{GB,SS}^{N} = \rho_v A_N \int_{Z_1}^{Z_{2\emptyset}} \alpha(Z)dZ = \int_{Z_1}^{Z_{2\emptyset}} \frac{\dot{P}_N Z_N + W_N}{\dot{P}_N Z_N + (V_D\rho_v A_N) + W_N} dz$$

$$\alpha_B = \rho_g A_N \int_{Z_1}^{Z_{20}} \alpha(Z)dZ = \int_{Z_1}^{Z_{20}} \frac{\dot{P}_N Z_N+W_N}{\dot{P}_N Z_N+(V_D\rho_g A_N)+W_N} dz$$ Equation 3

$$= \rho_g A_N[Z_N - \frac{V_D\rho_g A_N}{\dot{P}_N}\ln\left(\frac{\dot{P}Z_N+V_D\rho_g A_N+W_N}{V_D\rho_g A_N+W_N}\right)]$$ Equation 4

$$= \rho_v A_N[Z_N - \frac{V_D\rho_v A_N}{\dot{P}_N}\ln\left(\frac{\dot{P}Z_N+V_D\rho_v A_N+W_N}{V_D\rho_v A_N+W_N}\right)]$$

and, Equation 4 is divided by $\rho_g A_N Z_N$ → $\rho_V A_N Z_N$

$$\alpha_B = 1 - \frac{k}{\dot{P}_N Z_N}\ln\left(\frac{\dot{P}Z_N+k+W_N}{k+W_N}\right).$$ Equation 5

If we assume the condition is subcooled, $W_N = 0,\ W_{flashing} = 0$

$$\alpha_B = 1 - \frac{k}{\dot{P}_N Z_N}\ln\left(\frac{\dot{P}Z_N+k}{k}\right)$$ Equation 6

$$\therefore \alpha_B = 1 - \frac{k}{\dot{m}} \ln\left(\frac{\dot{m}+k}{k}\right)$$ Equation 7

where, $k = V_D \rho_g A_N$ → $V_D \rho_V A_N$

$$\dot{P}_N = \left(\frac{Q}{h_{hg}} + \dot{W}_{flashing}\right) {}^{1}/_{Z_N} \gg \dot{P}_N Z_N = \frac{Q}{h_{fg}} = \dot{m}$$

h_{hg} → h_{lv}; h_{fg} → h_{lv}

$$\frac{V_D}{1-\alpha_C} \rho_f A_C \alpha_C = \dot{P}_N Z_N + W_N$$ → $$\frac{V_D}{1-\alpha_C} \rho_V A_C \alpha_C = \dot{P}_N Z_N + W_N$$ Equation 8

$$\frac{k\alpha_C}{1-\alpha_C} = \dot{m}$$ Equation 9

$$\therefore \alpha_C = \frac{\dot{m}}{k+\dot{m}}.$$ Equation 10

The summarized results of the void fraction (α) are:

$$\alpha_A = 0$$ Equation 11

$$\alpha_B = 1 - \frac{k}{\dot{m}(t)} \ln \frac{\dot{m}(t)+k}{k}$$ Equation 12

$$\alpha_C = \frac{\dot{m}(t)}{k+\dot{m}(t)}.$$ Equation 13

The variables used in the above equations are summarized in Table 3-1 and, the values for the time-dependent-boil-off rate are calculated in Table 3-4. In this report, we assumed a core of ten regions. The mixture height vs. time and the core and upper plenum void distributions at three time points of time are shown in Table 3-2 and Table 3-3, respectively.

The final mixing volume, based on a void fraction that corresponds to the above three points of time, is shown in Table 3-5. Void fraction α_C was calculated considering the core-area to outlet-plenum ratio. The result of α_C is shown in Table 3-3.

Table 3-8 NOMENCLATURE LIST

V_D	drift velocity
N	region index
$\alpha(Z)$	the void fraction as a function of axial position
ρ_v	vapor density
A_N	cross-sectional area of region N
$\dot{P}_N$	the bubble production rate
W_N	the in-flow bubbles from the lower sub-region
h_{lv}	latent heat of vaporization
$\dot{W}_{flashing}$	the linear flashing steam rate
$Z_{2ø}$	two-phase mixture height
$M_{GB,SS}^{N}$	the steady state bubble mass of region N
Z_N	either the height of region N or the two-phase mixture height in region N.
Q	the total energy deposition rate for region N
α_A	void fraction in the lower plenum
α_B	void fraction in the core region
α_C	void fraction in the outlet plenum

Table 3-8 is added