Post-LOCA Long Term Cooling Evaluation Model

Revision 1

Non-Proprietary

March 2017

REVISION HISTORY

Revision	Date	Page	Description
0	September 2014	All	First Issue
1	March 2017	All	Revised to reflect RAI-8457

ABSTRACT

This report is to establish adequacy of the LTC (long-term cooling) of the reactor vessel following the LOCA (loss of coolant accident) for the APR1400 design. This report provides the overview of the applicable methodology and the description of specific assumptions incorporated into the codes used to analyze the LTC (long-term cooling), as well as a discussion of the bases for applying these codes and methods to the APR1400 design. The validation of principle models of these codes is presented through comparisons with computer codes that have been approved by the USNRC. The following codes are used in the LTC analysis:

The CEPAC (Reference 1) computer program is used to calculate the secondary system temperature, the NATFLOW (Reference 1) computer program is used to calculate the RCS (reactor coolant system), core and loop natural circulation flow rates and temperatures after RCS has refilled for small breaks, and the CELDA (Reference 1) computer program is used to calculate the long-term depressurization and refill of the RCS for small breaks. Boric acid concentration in the core is calculated by using the BORON (Reference 1) computer program.

This report also provides history of changes in methodology for LTC analysis. For the calculation of boric acid concentration, the new mixing volume assumption based on the Westinghouse LTC analysis of Waterford 3 (Reference 2) is used.

Based on the results of this analysis, it is concluded that the APR1400 SIS (safety injection system) satisfies all of 10 CFR 50.46 (Reference 3) acceptance criteria for LTC.

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ACRONYMS AND ABBREVIATIONS

CE	Combustion Engineering
CFR	Code of Federal Regulation
DVI	direct-vessel injection
ECCS	emergency core cooling system
FAP	fuel alignment plate
HF	Henry-Fauske
IRWST	in-containment refueling water storage tank
LOCA	loss of coolant accident
LTC	long-term cooling
NPP	nuclear power plant
PWR	pressurized water reactor
RCS	reactor coolant system
RWT	refueling water tank
SBLOCA	small break LOCA
SCS	shutdown cooling system
SDC	shutdown cooling
SG	steam generator
SI	safety injection
SIS	safety injection system
USNRC	U.S. Nuclear Regulatory Commission

1 INTRODUCTION

The post-LOCA long-term cooling is defined as beginning at the time that the core is reflooded and ending when the plant is secured. During the long-term, operator action is needed to assure that core cooling is maintained until the plant can be brought to a cold shutdown condition. The LTC (long-term cooling) plan culminates in a secured plant with a minimum number of decisions and actions on the part of plant operators.

The purpose of this technical report is to present the LTC computer codes and methodologies for the analysis of LTC events in the APR1400 design control document (Reference 4) Chapter 15, except for the dose evaluation. The LTC methodology used for the APR1400 design is very similar to the conventional LTC methodology (Reference 1) used for currently operating U.S. Combustion Engineering (CE)-fleet PWRs (Pressurized Water Reactors).

In Chapter 2, the basic LTC plan for the APR1400 design is described. The details of analytical approach and changes in methodology are described in Chapter 3. Through the results of LTC analysis in Chapter 4, it is confirmed that the LTC methodology is applicable in the APR1400 design successfully.

2 BASIC LONG-TERM COOLING PLAN

2.1 Functional Requirement

The basic function of long-term cooling plan is to maintain the core at safe temperature levels while avoiding the precipitation of boric acid in the RCS.

2.2 Operational Sequence

The LTC plan makes provision for maintaining core cooling and boric acid flushing by simultaneous hot-leg and DVI (direct-vessel injection) line injection for large break LOCA, for initiating shutdown cooling, if the break is small enough to assure successful operation of SCS. The knowledge of pressurizer pressure gives an idea to the plant operator for decision of the procedure.

Figure 2-1 show the basic sequence of events and timing of operator actions in the long-term cooling plan, as applied to the APR1400 design.

Major assumptions on operator actions in CENPD-254 (Reference 1) methodology are as follows:

- At one hour after LOCA, the operator has started operation of the steam generator cooldown.

- At two hours after LOCA, the operator has started operation of hot-leg and DVI line injection simultaneously.

- At eight hours after LOCA, if the RCS pressure remains above 450 psia, the reactor coolant system has been filled with liquid water.

2.3 Basis of Plan

The LTC plan is based on the following reasoning.

1) Small and large break LOCA bring for distinctly different responses in the long-term cooling plan.

2) It is possible to determine from the pressurizer pressure whether the break is large or small.

The simultaneous hot-leg and DVI line injection from the SI (safety injection) pumps is prescribed by the LTC plan following any LOCA. This simultaneous injection prevents boric acid precipitation for an extensive range of large and intermediate sized breaks in either hot-leg or DVI line. For extremely small breaks, where reactor coolant system pressure remains high, the simultaneous injection flow is too small to provide effective flushing of the boric acid however, with extremely small breaks the system refills and the boric acid concentration remains low due to its dispersal throughout the RCS by natural circulation. As indicated in Figure 2-2, there is a range of break sizes where boric acid precipitation is prevented by either flushing by SI pump injection or by dispersal by natural circulation.

In addition to boric acid precipitation, the cooling of the RCS must be considered. The SI pump injection is capable of adequate cooling of the RCS for all but the smallest breaks. For the smallest breaks, the steam generators are initially employed to cool the RCS, with subsequent activation of the SCS (shutdown cooling system). There is a range of break sizes for which the SI pump injection alone can cool the RCS after the initial period of steam generator heat removal, but which also yields system conditions such that eventual successful entry into shutdown cooling is assured. Therefore, there is an overlap in which either of the two different core cooling modes is satisfactory as shown in figure 2-2.

2.4 Emergency Core Cooling System Alignments

The different alignments of the ECCS (emergency core cooling system) used in the LTC plan are as follows:

- Initial recirculation mode

The injection by SI pumps from the IRWST (in-containment refueling water storage tank) has been secured.

- Simultaneous injection mode

One or one half of the SI pump flow has been realigned to the RCS hot-legs. The LTC plan calls for a shift to this mode at about two hours after any LOCA.

- Shutdown cooling mode

A small break is indicated by reactor coolant system pressure above 450 psia, at about eight hours after the LOCA. In this case, the reactor coolant system is entirely refilled. The SI pumps maintain the system pressure, and the RCS liquid level is sufficient for entry into SDC mode. The reactor coolant system temperature is then checked to assure that steam generator cooling has reduced it to the shutdown cooling entry value. Then, the SI pumps are realigned to discharge entirely into the DVI line; then they are throttled to reduce the RCS pressure to the SDC entry value. The shift is then made to the SDC mode.

LOCA : Loss of Coolant Accident
SG : Steam Generator
SIT : Safety Injection Tank
SI : Safety Injection
OSP : Off Site Power
P : Primary Pressure
AFAS : Auxiliary Feedwater Actuation Signal
SCS : Shutdown Cooling System
SIAS : Safety Injection Actuation Signal
t : Time after LOCA, hrs

Note :

The values for pressure shown are those indicated by the instrumentation. They account for Instrumentation uncertainty.

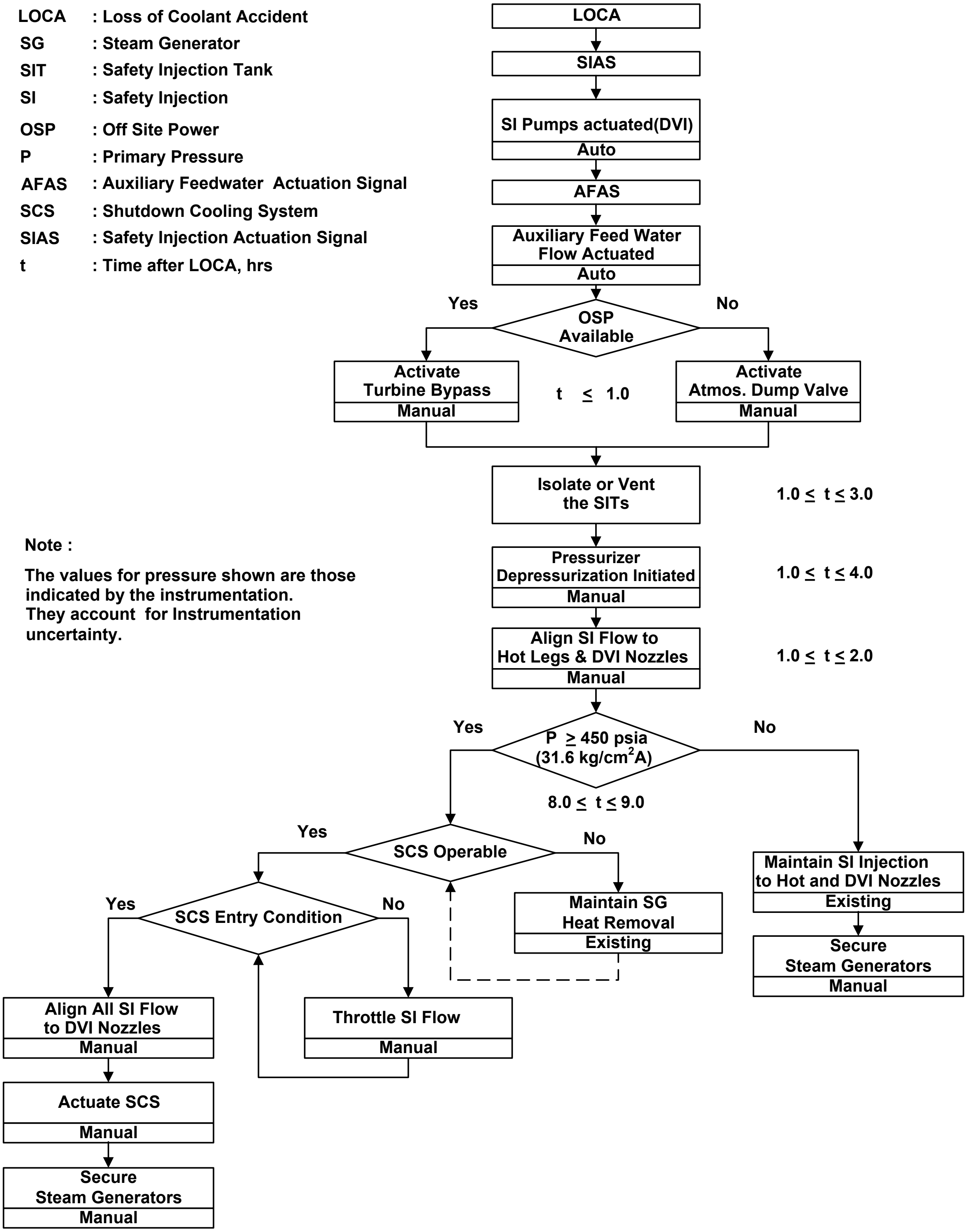


Figure 2-1 Long Term Cooling Plan

Simultaneous Hot Leg/DVI Nozzles Injection Cools Core and Flushes Boric Acid from Vessel. (break areas from 3.7 (0.004) up to 464.5 (0.500) and larger)

Refill of RCS Disperses Boric Acid throughout System and SGs are able to cool RCS to SDC Entry Temperature. (break areas from 34.4 (0.037) down to 2.8 (0.003) and smaller)

Break Area cm^2 (ft^2)	RCS Pressure at 8 Hours kg/cm^2A (psia)
464.5 (0.500)	2.8 (38)
92.9 (0.100)	5.3 (75)
46.5 (0.050)	5.3 (76)
37.2 (0.040)	5.3 (76)
35.3 (0.038)	5.3 (76)
34.4 (0.037)	6.0 (86)
27.9 (0.030)	7.6 (108)
18.6 (0.020)	11.3 (161)
9.3 (0.010)	25.9 (368)
4.6 (0.005)	57.4 (816)
3.7 (0.004)	69.6 (990)
2.8 (0.003)	83.2 (1184)

Figure 2-2 Overlap Range of Cold-Leg Break Area

3 ANALYTICAL APPROACH

3.1 General Description

The basic objective of the LTC analysis is to demonstrate the long-term coolability of core. The analysis procedures account for single-failures to assure that the performance objectives are consistent with this assumption.

It is important to recognize the difference in behavior between large and small break LOCAs in long-term cooling. The difference is that the RCS will remain at high pressure for small breaks and the injection flow rate will be too low for effective cooling; thus, small breaks require the SGs to cool the RCS until SDC can be initiated. In contrast, large breaks are adequately cooled by the injection flow because this flow is large due to the low RCS pressure. However, large breaks must utilize simultaneous hot-leg and DVI line injection to flush boric acid from the vessel. Thus, the LTC large-break and small-break analyses are different from each other.

Another issue to be considered is the effect of break location. For any large hot-leg break, the short-term ECCS injection flow through DVI lines will fill the annulus and provide the elevation head necessary to force flow through the core and out of the hot-leg break. Liquid flow which is in excess of the core boil-off will provide a substantial flushing flow through the core, and it will decrease and maintain the core boric acid concentration similar to that of the low levels at initial IRWST.

For large cold-leg breaks, however, boric acid concentrates in the core as long as the cold-leg injection is continued. If it is determined that the break occurred in the cold-leg (and hot-leg injection is possible.), the ECCS injection flow would be switched to hot-leg injection only. When sufficient elevation head builds up on the hot-leg, the core flushing flow will move down through the core and up through the annulus to the break.

In case of slot break at top of the cold-leg, the margin will be reduced because loop-seal refilling will increase the pressure drop of core-to-break steam flow. However, water in the cold-leg can be credited. Therefore, the margin will be increased because crediting water in the cold-leg will increase the hydrostatic head of the downcomer. The additional pressure drop will be covered by this margin. Therefore, long-term loop-seal refilling with a slot break at the cold-leg does not significantly affect the boric acid precipitation analysis.

Since the break location may not be easily determined, the long-term ECCS alignment should be able to cope with breaks in other locations. This ability is achieved by converting from short-term ECCS injection of cold-leg to long-term injection of simultaneous DVI and hot-leg. The intact side of RCS will build up the elevation head necessary to transfer flow through the core and out of the break. The cold-leg injection flow will continue through the cold-leg ECCS injection nozzles while the hot-leg injection point will be through the hot-leg suction lines of shutdown cooling system.

3.2 LTC Boric Acid Precipitation Analysis

The LTC analysis boric acid precipitation (Reference 1) is chiefly concerned with control of the boric acid concentration. The timely initiation of simultaneous DVI line and hot-leg SI pump injection enables the intact side of the vessel to accumulate liquid elevation head. Once sufficient head has been established, a flushing flow of liquid through the core and out through the break will be provided thereby cooling the core and removing boric acid.

3.3 LTC Cooldown Analysis

The post-LOCA procedures (Reference 1) for LTC cooldown is similar to those used during a normal cooldown to a cold shutdown condition. Long-term cooling of the core can be performed by the SDC

system since the RCS will be refilled by the SDC system where the simultaneous DVI and hot-leg injection is unable to cool and flush the core.

3.4 Codes Used in the LTC Analysis

The LTC calculations are performed by using the LTC codes, which is described down below.

The CELDA (Reference 1) is used to describe the long-term primary system depressurization process and to determine whether the refilling of RCS is achieved for small breaks. The analysis is initialized from the CEFLASH-4AS analysis that is performed for the early part of accident. The steam generator secondary temperature as a function of time is input from the CEPAC analysis.

The NATFLOW (Reference 1) calculates the natural circulation flow rates in the core, and primary system pressure and temperature that occur in the absence of a primary system break. The code is run in an iterative sequence with the CEPAC code which provides the secondary system temperature as a function of time.

The BORON (Reference 1) is used to compute the boric acid concentration in the core and determines if the core flow is sufficient to prevent the solubility limit of boric acid from being exceeded.

The CEPAC (Reference 1) models the steam generators, including the operation of steam generator atmospheric dump valves, and provides the secondary system temperature as a function of time is used for input of the NATFLOW and CELDA codes. NATFLOW and CELDA codes do not contain independent steam generator models.

3.5 Changes in Methodology

The following sections of this report describe the method of analysis and the method of updated licensing basis of boric acid precipitation analysis.

3.5.1 Interim Approach Used at Waterford 3

Some non-conservatism has been identified in the previous methodology (Reference 1), and as a result, in 2005, the USNRC suspended approval of CENPD-254 (Reference 5), which is the old LTC methodology for CE-designed nuclear power plants. The major issues related to the suspension are described as follows:

Void effect: The mixing volume must be justified and the void fraction must be taken into account when computing the boric acid concentration.

Time-varying mixing volume: The analysis to determine boric acid concentration needs to account for the variation in the mixing region while considering the pressure drop in loop.

Decay heat: The decay heat model in appendix K with a multiplier of 1.2 has to be used at all times.

Boric acid solubility limit: The solubility limit must be justified.

The ’interim approach’ is to reflect resolutions of four issues above to CENPD-254, and the methodology applying such interim approach is the ‘interim methodology’. The updated analysis for the APR1400 design utilized the post-LOCA LTC methodology with the interim approach. The two items described below in more detail are related to void effect and time-varying mixing volume issues.

(1) The liquid volume in the core and upper plenum mixing volumes (based on the void fraction) was calculated by applying the CEFLASH-4AS (Reference 6) phase-separation model to this region. The

phase-separation model used in CEFLASH-4AS was originally approved by USNRC for computing the mixture level in the core following all SBLOCAs. This model was shown to accurately predict the void fraction and, hence, the two-phase level in regions experiencing high rates of heat addition following SBLOCAs.

(2) The mixing volume was increased to include 50 percent of the reactor vessel lower plenum. The BACCHUS test (Mitsubishi Heavy Industries) (Reference 7) employed to simulate post-LOCA boric acid mixing in the lower plenum, and in the core of a Westinghouse and CE-designed PWR, was cited as justification for expanding the mixing volume to include a portion of lower plenum. The tests showed that the entire lower plenum volume contributed mixing, and thus only 50 percent of this volume to be credited is conservative.

3.5.2 Modification of the BORON Code for Application of IRWST

The APR1400 design adopts IRWST instead of the refueling water tank (RWT) used in previous CE-type plants. In CE-type plants, ECC is injected from the RWT for a certain amount of time and is changed to the sump when the RWT is emptied. In the APR1400 design, however, ECC is injected from IRWST from the beginning. Therefore, the BORON code for APR1400 was modified to model the IRWST.

3.5.3 Steam Flow Rate Calculation Using the Decay Heat Model (ANS 1971)

The decay heat fraction (DHF) at one hour post-LOCA is determined by using the BORON computer code decay heat model described in CENPD-254-P-A, which is reproduced below.

| | TS

where

DECAY = normalized decay heat fraction including 1.1 conservative multiplier

T = time (seconds).

When using a time of 1 hour or 3600 seconds, the DHF is:

TS

DECAY = | | = 0.016143

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

Decay Heat Fraction (including 1.2 decay heat multiplier)

= 0.016143 * 1.2 / 1.1

= 0.01761

The core power level, including power measurement uncertainty, is 4063 MWt. Therefore, using the above data, the core water boil-off rate (WBO) at 1 hour post-LOCA is equal to the core power times the decay heat fraction divided by the heat of vaporization, as shown below:

WBO = 4063 MWt * 948.04 Btu/sec-MWt * 0.01761 / (1150.28 − 180.18) Btu/lbm

WBO = 69.95 lbm/sec

3.5.4 Core Flush Flow

Core flush begins two hours after the ECCS is realigned according to the LTC plan for DVI line/hot-leg at two hours post LOCA. The core flushing flow is 1 SI pump flow or 1/2 SI pump flow for both cold-leg break and DVI line break. This report used 1/2 SI pump flow for the core flushing flow, for conservatism. The core flushing flow obtained is thus shown below.

$W_{flush} = 1/2\ W_{SI} - W_{boiloff}$

where, W_{flush} = core flush flow rate

W_{SI} = SI injection flow rate into the reactor vessel

$W_{boiloff}$ = water boiled off rate in the reactor vessel

The BORON code is applied to calculate the boric acid concentration of double-ended guillotine breaks. Thus, the RCS pressure is reduced to the containment pressure. However, 0.45 W_{SI} was used instead of 1/2 W_{SI} for analytical flexibility.

$W_{flush} = 0.45\ W_{SI} - W_{boiloff}$

3.5.5 Calculation Method and Result for the Mixing Volume

The major variables for calculation of the mixing volume are shown in Table 3-1. Figure 3-1 shows the mixing volume change from CENPD-254 to interim. Each part of the mixing volume is shown in Figure 3-2. The atmospheric conditions (14.7 psia, 212 °F) assumed for LTC analysis were used to perform the following calculations.

A flat axial power shape was selected as a reasonably conservative representation of the axial power distribution. Therefore, in this report multiple core regions were included, as shown in Table 3-2. The void 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 through 13 were defined in Table 3-8.:

TS

Equation 1

where, $\dot{P}_N$ = bubble production rate = TS

W_N = flow bubbles from the lower sub-region

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

TS

Equation 2

α_B and α_C can be obtained from Equation 1,

TS

Equation 3

Equation 4

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

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

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

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

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

where, $k = V_D \rho_V A_N$

TS

$\gg \dot{P}_N Z_N = \frac{Q}{h_{lv}} = \dot{m}$

$$\frac{V_D}{1-\alpha_C}\rho_V A_C \alpha_C = \dot{P}_N Z_N + W_N$$ 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.

3.6 Major Assumptions and General System Parameters

The major assumptions used in performing the LTC analysis are as follows:

a. No offsite power is available.

b. The worst single failure is the loss of two SI pump trains with additional conservativeness. This results in the following:

1) Two SIPs are operable.

2) One motor-driven auxiliary feedwater pump is operable.

c. One atmospheric dump valve on each SG is available to cool down the RCS.

d. RCS cooldown begins at 2 hours post-LOCA.

e. The SITs are vented or isolated before establishing shutdown cooling conditions for the small-break LTC procedure.

f. The pressurizer is depressurized to establish shutdown cooling conditions for the small-break LTC procedure.

g. RCS cooldown is terminated when the hot leg temperature is below the maximum shutdown cooling entry temperature including instrument uncertainty.

h. Pump flow rates and initial water source inventories used in the large-break LOCA boric acid precipitation analysis are selected to maximize the boric acid concentration in the core.

i. The solubility limit (29.3 wt %) (Reference 8) at the boiling temperature of boric acid at 1.03 kg/cm^{2}A is conservatively assumed as shown in Table 3-6. The real pressure is higher than 1.03 kg/cm^{2}A considering the downcomer head and RCS flow resistance. Therefore, it is conservative limit.

Significant core and system parameters used in the post-LOCA long-term cooling analysis are presented in Table 3-7.

Table 3-1 Major Variables for Calculation of the Mixing Volume

	Value	Reference
Power (Q)	4063 MWt	3983*1.02
Enthalpy (h_{fg})	970.05 Btu/lb	14.7 psia
A_{core}	[	]
$A_{Outlet\ Plenum}$		
ρ_g	0.03732 lb/ft^3	14.7 psia
V_D	2.967 ft/sec	$3.0EXP^{-0.75\frac{14.7}{1000.0}}$
K=(V_D* ρ_g *A_{core})	[	]

TS

TS

s

Table 3-2 Calculation of α_B (Top of the Core Region)

Mixing Volume Region	Height, ft	Calculated Boil-off rate for each Region, lbm/sec			Void Fractions		
		1 hour	2 hours	3 hours	α_B (at 1 hour)	α_B (at 2 hours)	α_B (at 3 hours)
1	1.25						
2	1.25						
3	1.25						
4	1.25						
5	1.25						
6	1.25						
7	1.25						
8	1.25						
9	1.25						
10	1.25						

TS

Table 3-3 Calculation of α_C at each Time

Time (hours)	α_C
0.0083	
0.56	
1.0	
1.39	
1.5	
2.0	
2.78	
3.0	
4.0	
5.0	
8.0	
13.0	

TS

Table 3-4 Calculation of the Boil-off Rate

Time (hours)	Decay Heat	$\dot{m}$ (lbm/sec)
0.0083	0.058345	231.74
0.56	0.020358	80.86
1.0	0.017611	69.95
1.39	0.016219	64.42
1.5	0.015913	63.20
2.0	0.014809	58.82
2.78	0.013638	54.17
3.0	0.013381	53.15
4.0	0.012453	49.46
5.0	0.011777	46.78
8.0	0.010471	41.59
13.0	0.009274	36.84
24.0	0.007956	31.60

Table 3-5 Calculation Results of Mixing Volume Using the Interim Methodology

Region		Volume (ft^3)	Void Fraction	Final Volume (ft^3)	**TS**
Lower Plenum (A)	Bottom inactive core (top of lower support structure to bottom of active core)				Crediting 50% participation of the lower plenum volume is conservative relative to the BACCHUS test results.
	Flow skirt to top of lower support structure				Only liquid
Core (B)	Core, guide tube, core shroud				The void fraction in the core is calculated using the CEFLASH-4AS phase separation model.
Outlet Plenum (C)	Bottom of FAP to bottom of hot-leg				The liquid volume in the outlet plenum is calculated by applying the core-to-outlet plenum area ratio to the core exit void fraction
	Top inactive core (top of active core to bottom of FAP)				
Total Volume, ft^3					

Table 3-6 Solubility Limit of Boric Acid Solution

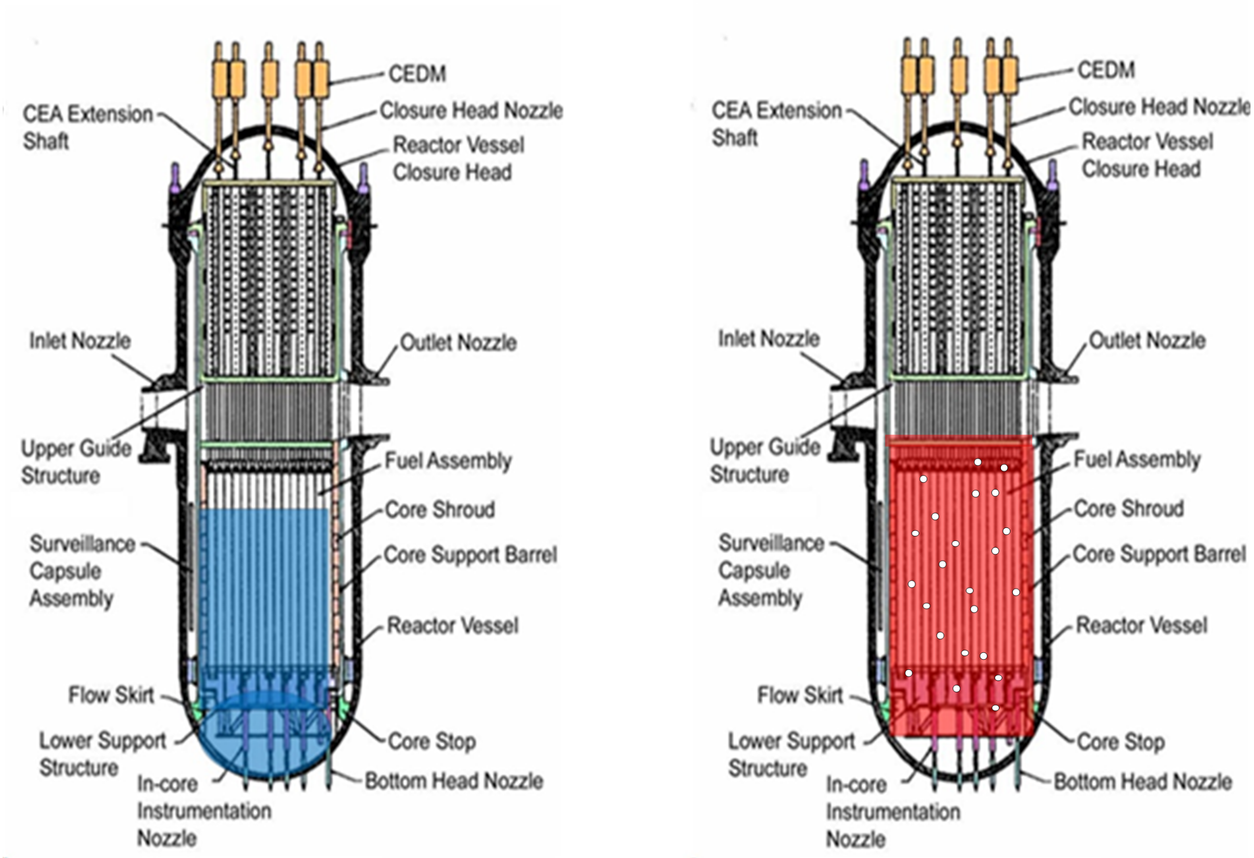
Temperature, °F	Temperature, °C	Pressure, (psia) /atm	Solubility, wt%
32	0.0	14.7 / 1.0	2.70
50	10.0	14.7 / 1.0	3.51
68	20.0	14.7 / 1.0	4.65
86	30.0	14.7 / 1.0	6.34
104	40.0	14.7 / 1.0	8.17
122	50.0	14.7 / 1.0	10.23
140	60.0	14.7 / 1.0	12.97
158	70.0	14.7 / 1.0	15.75
176	80.0	14.7 / 1.0	19.06
194	90.0	14.7 / 1.0	23.27
212	100.0	14.7 / 1.0	27.53
217.9	103.3	14.7 / 1.0	29.27

Table 3-7 General System Parameters and Initial Conditions

<table>
<tr><th colspan="2">Quantity</th><th>Value</th></tr>
<tr><td colspan="2">Reactor Power Level (102 % of Nominal), MWt</td><td>4,062.66</td></tr>
<tr><td colspan="2">SCS Entry Temperature, °C (°F)</td><td>193 (380)</td></tr>
<tr><td colspan="2">SCS Entry Pressure, kg/cm^{2}A (psia)</td><td>28.1 (400)</td></tr>
<tr><td colspan="2">Atmospheric Dump Valve Capacity, per Valve at 70.3 kg/cm^{2}A (1,000 psia), kg/hr (lbm/hr)</td><td>430,900 (950,000) (min)</td></tr>
<tr><td colspan="2">Auxiliary Feedwater Storage Tank Capacity, per tank, L (gal)</td><td>1,870,000 (494,000) (min)</td></tr>
<tr><td rowspan="3">Boric Acid Concentration, wt% (ppm)</td><td>RCS</td><td>0.94 (1,650) (max)</td></tr>
<tr><td>IRWST</td><td>2.52 (4,400) (max)</td></tr>
<tr><td>SIT</td><td>2.52 (4,400) (max)</td></tr>
</table>

Table 3-8 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
$\dot{W}_{flashing}$	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



CENPD-254-P-A Interim

Figure 3-1 Mixing Volume Change

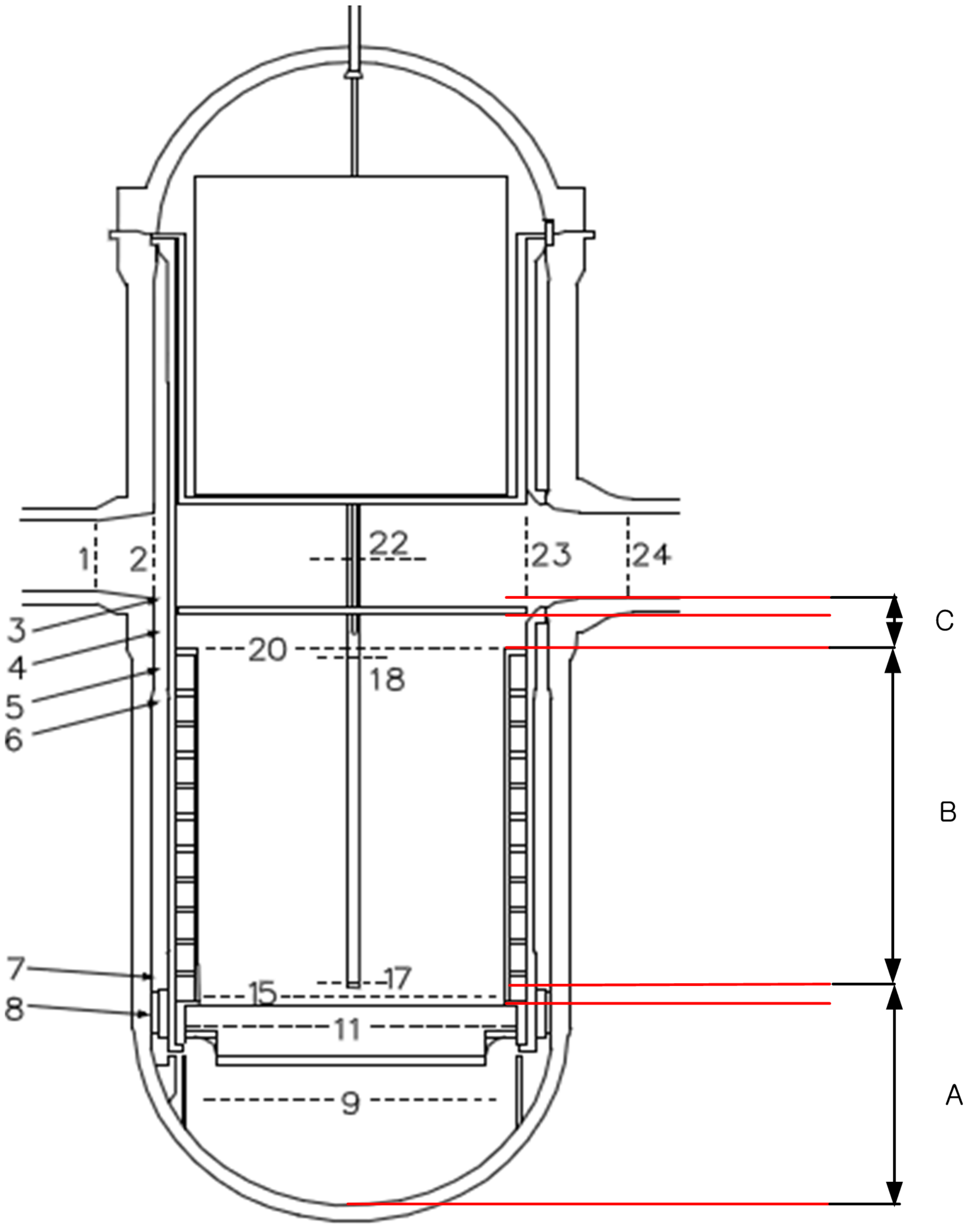


Figure 3-2 The Mixing Volume Calculated by Interim Methodology

4 RESULTS OF LTC ANALYSIS

The objective of this technical report is to describe improvements arising from changes in the methodology and the LTC codes. For the analysis of LTC, the new mixing-volume-calculation and cooldown methodology is the same as that used for the Westinghouse LTC analysis of Waterford 3 (Reference 2) at extended power uprate.

The LTC analysis predicts that the RCS will be refilled at various times depending on break sizes, as shown in Figure 4-1. As shown in the figure, for a break size as large as 0.037 ft^2, the RCS is refilled within eight hours. In addition, the LTC analysis determines that the time over 14 hours is required to exhaust all auxiliary feedwater during cooldown of the RCS. Therefore, to allow a sufficient margin of time to avoid exhaustion of auxiliary feedwater, a period of eight to nine hours is selected for the operator to decide whether the small break LTC procedure is appropriate. These results demonstrate that SCS can be used for breaks as large as 0.037 ft^2 for long-term cooling and flushing of the core. The LTC analysis also determines that the large-break procedures can flush the core for break sizes down to 0.004 ft^2.

The operator chooses the appropriate procedure based upon the RCS pressure indicated at between eight and nine hours. Figure 4-2 presents the RCS pressure at eight hours for a wide range of break sizes. A decision point pressure of 450 psia is chosen. 450 psia decision point allows sufficient margin of $\pm$300 psia more conservative than an instrument error. The reasonable assurance is provided for the operator to select the proper procedure for any break size.

The BORON code calculates the transient boric acid concentration in the RCS. The results are shown in Figure 4-3. As shown in the figure, flushing flow of 30 gpm can prevent the boric acid precipitation. The designed hot leg injection is 455.85 gpm. The boil-off rate is 441.00 gpm at the time of simultaneous injection and the flushing flow is 14.85 gpm. Thus it can be concluded that the sufficient amount of margin exists in the core flush flow. Moreover, as shown in Figure 4-4, the interim methodology is more conservative than the traditional CENPD-254 methodology from the perspective of boron precipitation time.

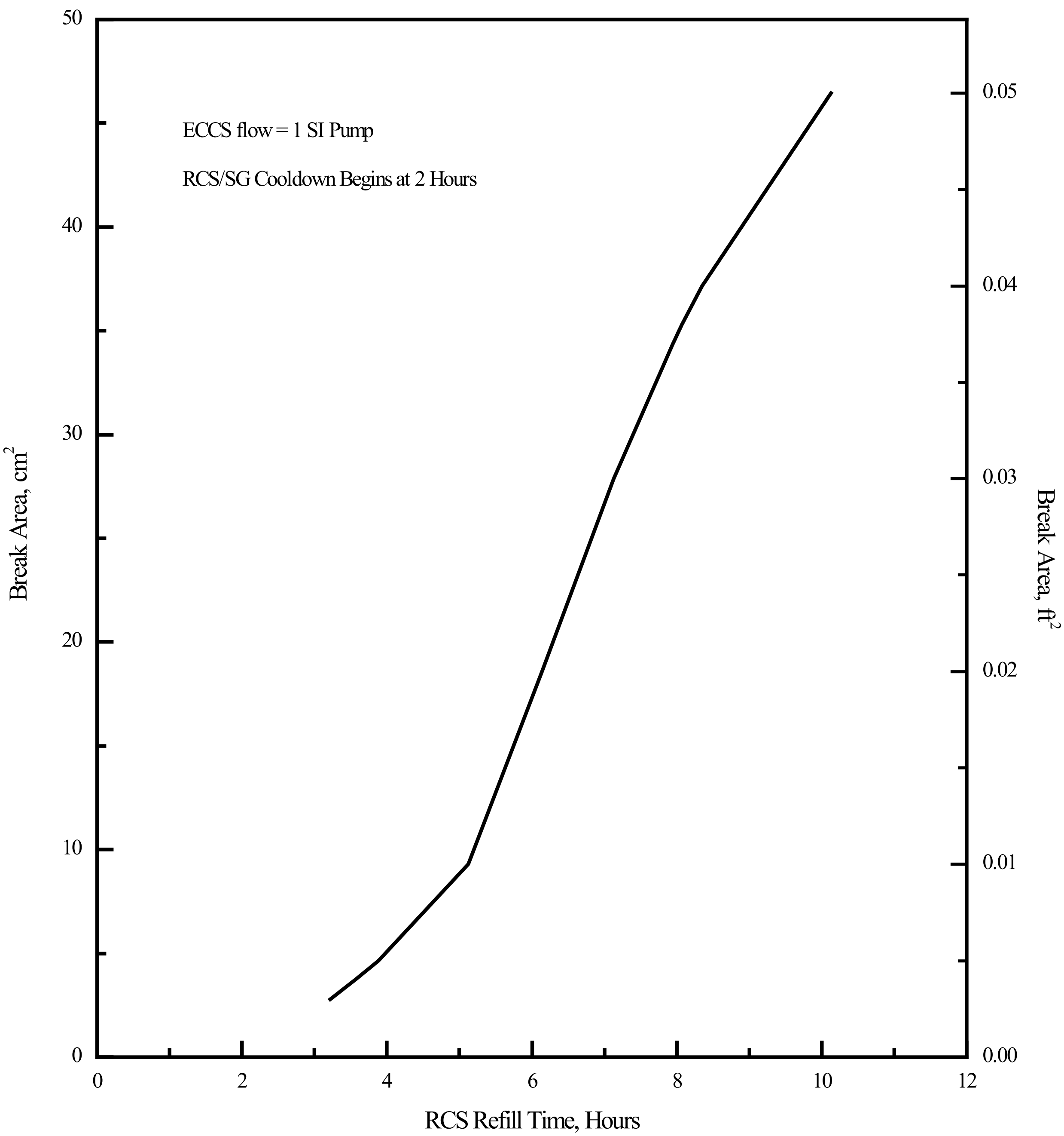


Figure 4-1 RCS Refill Time vs. Break Area

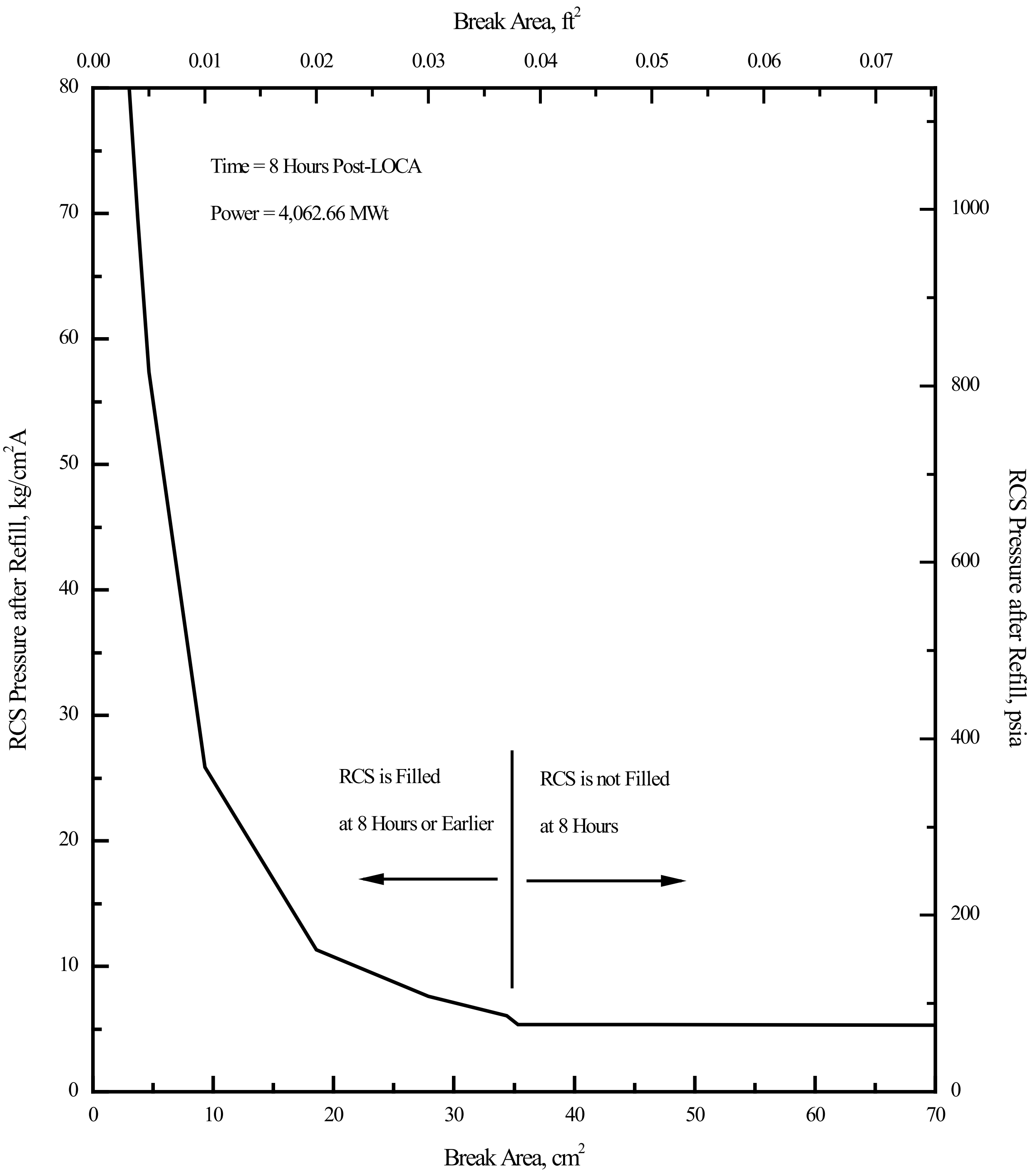


Figure 4-2 RCS Pressure after Refill vs. Break Area

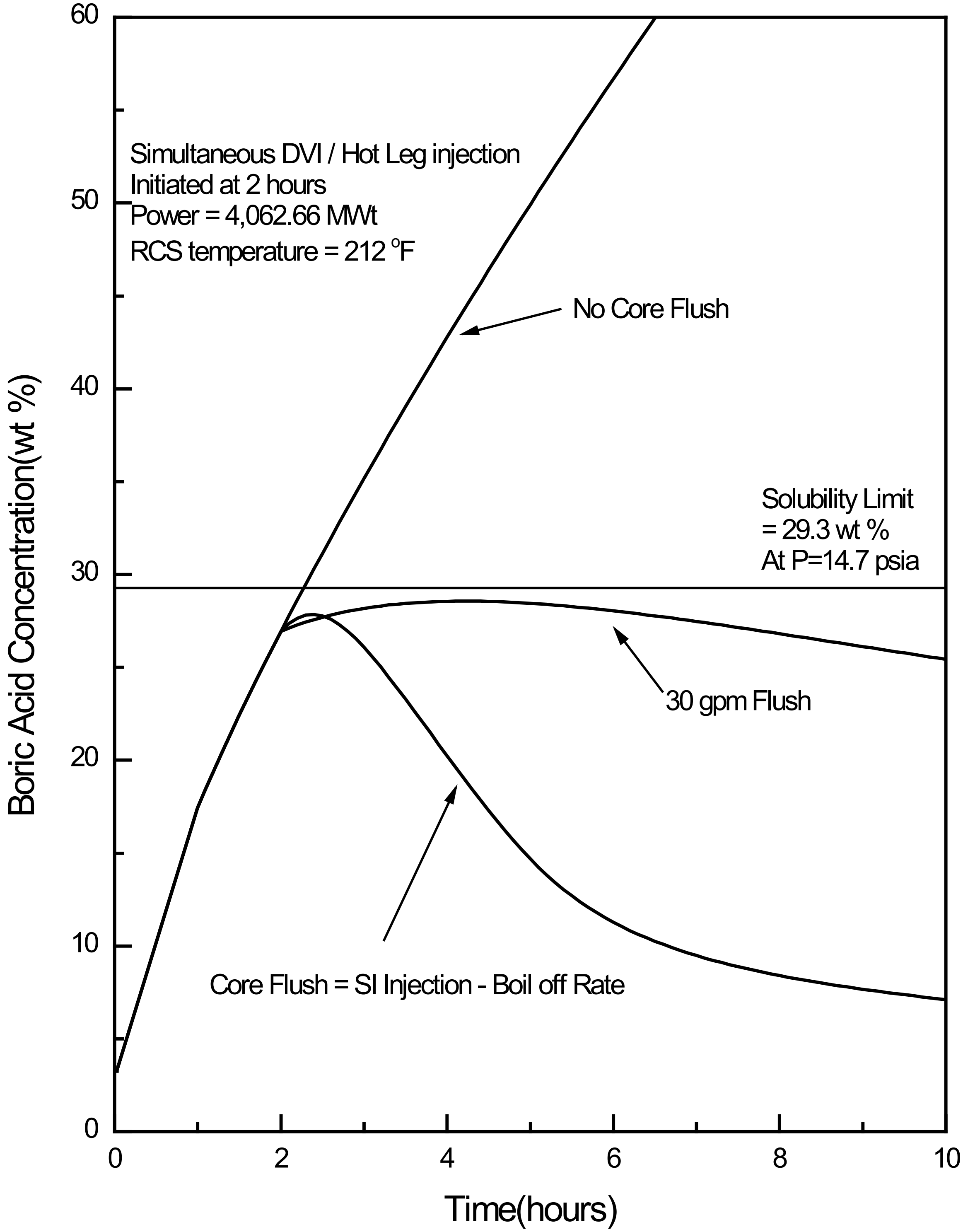


Figure 4-3 Inner Vessel Boric Acid Concentration vs. Time

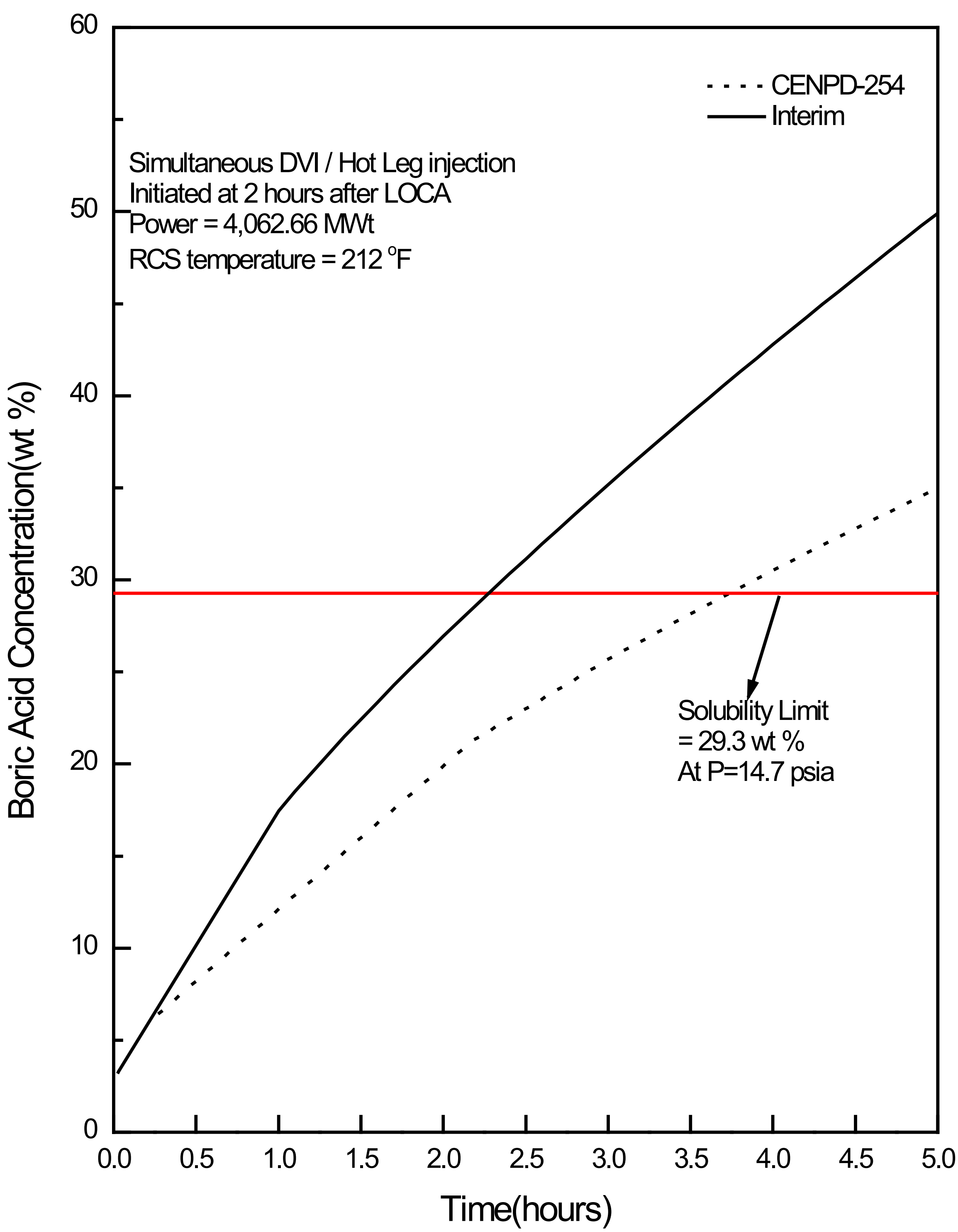


Figure 4-4 BORON Calculated Results of Mixing Volume Change

5 CONCLUSIONS

On the basis of the information in this technical report, the mixing volume is evaluated by applying interim methodology. Boric acid precipitation does not occur when simultaneous injection is started two hours after the accident. It is concluded that the existing codes and methodologies are appropriate for the APR1400 LTC analyses. In addition, it is concluded that the information provided in this technical report supports its purpose to provide key technical information related to the computer codes, methods, and models applicable to the regulatory requirements.

6 REFERENCES

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