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Attention: J. S. Wermiel, Chief
Reactor Systems Branch
Office of Nuclear Reactor Regulation

Our ref: LTR-NRC-02-67

December 18, 2002

Subject: Submittal of Addendum 3 to WCAP-10266-P-A, Rev. 2 (Proprietary) and WCAP-11524-A, Rev. 2, (Non-Proprietary), "Incorporation of the LOCBART Transient Extension Method into the 1981 Westinghouse Large Break LOCA Evaluation Model with BASH (BASH-EM)"

References:
1. Letter from S. Dembek (NRC) to H. Sepp (Westinghouse), "Potential Non-Conservative Modeling of Downcomer Boiling in the Approved Westinghouse 1981 Evaluation Model Using BASH", March 27, 2002.
2. Letter from H. Sepp (Westinghouse) to G. Shukla (NRC), "Follow-up to July 11, 2002 Meeting Regarding Treatment of Downcomer Boiling in BASH-EM", LTR-NRC-02-38, August 1, 2002.
3. Letter from J. Galembush (Westinghouse) to S. Bloom (NRC), "Proprietary Presentation Material from August 11, 2000 Meeting to Discuss Downcomer Boiling", LTR-NRC-00-5979, September 7, 2000.

Dear Mr. Wermiel:

Enclosed are copies of the Proprietary and Non-Proprietary versions of the Westinghouse document "Incorporation of the LOCBART Transient Extension Method into the 1981 Westinghouse Large Break LOCA Evaluation Model with BASH (BASH-EM)", Addendum 3 to WCAP-10266-P-A, Rev. 2 (Proprietary) and WCAP-11524-A, Rev. 2 (Non-Proprietary). The document is being submitted for NRC review and approval, in accordance with Reference 1.

Formal assessments pursuant to 10 CFR 50.46 have been completed for the plants within Westinghouse BASH-EM analysis cognizance, as committed in Reference 2, and are being communicated to licensees in parallel with this submittal. There were no violations of the 10 CFR 50.46 acceptance criteria, and therefore no reporting pursuant to 10 CFR 21 is required.

This submittal contains Westinghouse proprietary information consisting of trade secrets, commercial information, or financial information which we consider privileged or confidential pursuant to 10 CFR 9.17(a)(4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure. Accordingly, correspondence with respect to this letter should reference the Application for Withholding and accompanying Affidavit (AW-00-1422) that were provided in Reference 3.

This material is for your internal use only and may be used solely for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Commission, the Office of Nuclear Reactor Regulation, the Office of Nuclear Regulatory Research, and the necessary subcontractors that have signed a proprietary non-disclosure agreement with Westinghouse without the expressed prior written approval of Westinghouse.

Correspondence with respect to any Application for Withholding should reference AW-00-1422 and should be addressed to H. A. Sepp, Manager of Regulatory and Licensing Engineering, Westinghouse Electric Company, P. O. Box 355, Pittsburgh, Pennsylvania, 15230-0355.

Very truly yours,

H. A. Sepp, Manager
Regulatory and Licensing Engineering

Attachments

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Westinghouse Proprietary Class 3

WCAP-11524-A, Revision 2
Addendum 3

December 2002

Incorporation of the LOCBART Transient Extension Method into the 1981 Westinghouse Large Break LOCA Evaluation Model with BASH (BASH-EM)

Westinghouse

WESTINGHOUSE PROPRIETARY CLASS 3

WCAP-11524-A, Revision 2
Addendum 3

Incorporation of the LOCBART Transient Extension Method into the 1981 Westinghouse Large Break LOCA Evaluation Model with BASH (BASH-EM)

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December 2002

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EXECUTIVE SUMMARY

This report describes the incorporation of the LOCBART transient extension method into the 1981 Westinghouse Large Break LOCA Evaluation Model with BASH (BASH Evaluation Model, or BASH-EM). This method was developed to extend BASH-EM transients beyond the point at which downcomer boiling occurs in BASH, by correlating the boiling-induced reduction in downcomer driving head to a corresponding reduction in the core inlet flooding rate. This approach is used to ensure adequate termination of the fuel rod cladding temperature and oxidation transients, as required to demonstrate compliance with the acceptance criteria of 10 CFR 50.46.

ACKNOWLEDGEMENTS

The author would like to acknowledge Dawn Crytzer, Aaron Everhard, Cesare Frepoli, Mitch Nissley, Sharen Saunders, and Mike Young for their contributions to this effort.

1 INTRODUCTION

The 1981 Westinghouse Large Break LOCA Evaluation Model with BASH (BASH Evaluation Model, or BASH-EM) is used to perform large break LOCA simulations in accordance with the requirements of 10 CFR 50 Appendix K. Westinghouse has developed a method to extend BASH-EM transients beyond the point at which downcomer boiling is predicted to occur in BASH, by correlating the boiling-induced reduction in downcomer driving head to a corresponding reduction in the core inlet flooding rate. This approach, which is referred to as the LOCBART transient extension method, is used to ensure adequate termination of the fuel rod cladding temperature and oxidation transients, as required to demonstrate compliance with the acceptance criteria of 10 CFR 50.46.

This report describes the incorporation of the LOCBART transient extension method into the BASH Evaluation Model. Section 2 provides a brief description of the main computer codes that comprise the BASH Evaluation Model. Section 3 describes the LOCBART transient extension method, including the procedure used to calculate the core inlet flooding rate after downcomer boiling. Section 4 describes the model validation, including comparisons against experimental data. Section 5 explains how the BASH Evaluation Model complies with the sections of 10 CFR 50 Appendix K cited in the USNRC letter of 27 March 2002 [Reference 1-1], both prior to downcomer boiling and during the transient extension.

This report has been prepared as an addendum to WCAP-11524-A, Revision 2 [Reference 1-2], in which the BASH Evaluation Model was originally approved for licensing applications by a USNRC SER of 13 November 1986. Addendum 1 was approved by a USNRC SER of 15 September 1987 [Reference 1-3], and Addendum 2 was approved by a USNRC SER of 20 January 1988 [Reference 1-4], so the present report is denoted as Addendum 3 to WCAP-11524-A, Revision 2.

1.1 REFERENCES FOR SECTION 1

1-1. Letter from S. Dembek (USNRC) to H. Sepp (Westinghouse), "Potential Non-Conservative Modeling of Downcomer Boiling in the Approved Westinghouse 1981 Evaluation Model Using BASH", March 27, 2002.

1-2. WCAP-11524-A, Revision 2, "The 1981 Version of the Westinghouse ECCS Evaluation Model Using the BASH Code", March 1987.

1-3. WCAP-11524-A, Revision 2, Addendum 1, "The 1981 Version of the Westinghouse ECCS Evaluation Model Using the BASH Code; Addendum 1: Power Shape Sensitivity Studies", December 1987.

1-4. WCAP-11524-A, Revision 2, Addendum 2, "The 1981 Version of the Westinghouse ECCS Evaluation Model Using the BASH Code; Addendum 2: BASH Methodology Improvements and Reliability Enhancements", May 1988.

2 OVERVIEW OF BASH EVALUATION MODEL

This section provides a brief description of the main computer codes that comprise the BASH Evaluation Model.

The SATAN-VI code [Reference 2-1] is used to compute the blowdown thermal-hydraulic portion of the large break LOCA transient. The transient behavior of the system is determined from the governing conservation equations of mass, energy, and momentum, applied to an interconnected system of control volumes and flow paths. A constitutive drift flux model allows for relative motion between the liquid and vapor phases, with a flooding model used to limit the drift velocity during counter-current flow situations. The core is modeled using a hot channel and an average channel, with radial flow paths used to simulate crossflow between the channels. Fluid conditions in the hot channel are transferred to LOCBART, and define the thermal-hydraulic boundary conditions during the blowdown phase of the transient.

The BASH code [Reference 2-2] is used to compute the refill and reflood thermal-hydraulic portions of the large break LOCA transient. The refill module of BASH contains the thermal-hydraulic models that describe the transport of water from the ECCS injection points to the reactor vessel lower plenum. The reflood module of BASH contains the thermal-hydraulic models that compute the integrated system response during reflood, including the core pressure, core inlet flooding rate, and core inlet enthalpy which are supplied to LOCBART as boundary conditions during this phase of the transient. The minimum containment pressure transient is computed using the interactive COCO module [Reference 2-3] for dry containment plants, or the stand-alone LOTIC2 code [Reference 2-4] for ice condenser containment plants, and defines the system pressure boundary condition for the refill and reflood thermal-hydraulic calculations.

The SMUUTH code [Reference 2-2] is used to smooth the core inlet flooding rate and enthalpy during reflood. The smoothing procedure yields a core inlet flooding rate that is piece-wise constant over three segments, and was designed to reduce the reflood oscillations predicted by BASH while preserving the net mass flow into the core.

The LOCBART code [Reference 2-2] is used to compute the cladding temperature and oxidation transients for the highest-powered fuel rod in the core. LOCBART analyzes the blowdown, refill, and reflood phases of the large break LOCA transient and provides a mechanistic treatment of core heat transfer during reflood, which represents a significant improvement relative to prior application of the FLECHT correlation. The mechanistic models calculate the heat transfer coefficients appropriate to the flow and heat transfer regimes that develop axially in the hot channel, with a detailed spacer grid heat transfer model used to account for the effects of local flow acceleration and improved interfacial heat transfer.

2.1 REFERENCES FOR SECTION 2

2-1. WCAP-8302, "SATAN VI Program: Comprehensive Space-Time Dependent Analysis of Loss-of-Coolant", June 1974. (Approved in Reference 2-5.)

2-2. WCAP-10266-P-A, Revision 2, "The 1981 Version of the Westinghouse ECCS Evaluation Model Using the BASH Code", March 1987.

2-3. WCAP-8327, "Containment Pressure Analysis Code (COCO)", July 1974. (Approved in Reference 2-5.)

2-4. WCAP-8354-P-A, Supplement 1, "Long Term Ice Condenser Containment Code - LOTIC Code", April 1976.

2-5. WCAP-8471-P-A, "The Westinghouse ECCS Evaluation Model: Supplementary Information", April 1975.

3 DESCRIPTION OF LOCBART TRANSIENT EXTENSION METHOD

To ensure adequate termination of BASH-EM transients, a method has been developed to extend the LOCBART calculation beyond the point at which downcomer boiling is predicted to occur in BASH. This approach is based on a method developed by MPR [Reference 3-1] and uses a void fraction correlation proposed by Sudo [Reference 3-2] to estimate the average void fraction in the downcomer during boiling, which is then converted to an equivalent void height. The corresponding reduction in downcomer driving head is used to calculate a reduction in the core inlet flooding rate, which is conservatively assumed to remain constant and is used to extend the LOCBART calculation. [

]$^{(a,c)}$

The following procedure is used to compute the flooding rate after downcomer boiling:

1. [

   ]$^{(a,c)}$

2. [

   ]$^{(a,c)}$

3. *Evaluate fluid saturation properties.* The following fluid saturation properties are evaluated based on [
   ]$^{(a,c)}$:

   h_{fg} = heat of vaporization (BTU/lbm)

   ρ_f = saturated liquid density (lbm/ft^3)

   ρ_g = saturated vapor density (lbm/ft^3)

   μ_f = saturated liquid viscosity (lbm/s-ft)

   μ_g = saturated vapor viscosity (lbm/s-ft)

   σ = surface tension (lbf/ft)

4. [

   ]$^{(a,c)}$

[

]$^{(a,c)}$

5. *Compute the void fraction (α) using the Sudo correlation.* Per Reference 3-2, this correlation assumes the following basic form:

$$\alpha = \frac{Y}{AX^m}$$

where:

Regime	A	m
X ≤ .0005	.00523	-.704
.0005 < X ≤ .004	.093	-.325
X > .004	.54	0

and where:

$$X = \left(\frac{\mu_g j_g}{\sigma g_c}\right)\frac{\left(\frac{\mu_f}{\mu_g}\right)^{.82}}{\left(\frac{\rho_f}{\rho_g}\right)^{.2}} \qquad Y = \frac{\left(\frac{\sigma g_c}{\rho_f g D^2}\right)^{.064}}{\left(\frac{\mu_f}{\mu_g}\right)^{.125}}$$

and where: D = tube diameter (ft)

g = 32.2 ft/s^2

g_c = 32.2 ft-lbm/lbf-s^2

[

]$^{(a,c)}$

6. [

]$^{(a,c)}$

[

]^(a,c)

7. [

]^(a,c)

3.1 REFERENCES FOR SECTION 3

3-1. "Summary of Results from the UPTF Downcomer Separate Effects Tests, Comparison to Previous Scaled Tests, and Application to U.S. Pressurized Water Reactors", MPR-1163, July 1990.

3-2. Sudo, Y., "Estimation of Average Void Fraction in Vertical Two-Phase Flow Channel Under Low Liquid Velocity", Journal of Nuclear Science and Technology, 17(1), pp. 1-15, January 1980.

3-3. Sudo, Y., and Akimoto, H., "Downcomer Effective Water Head During Reflood in Postulated PWR LOCA", Journal of Nuclear Science and Technology, 19(1), pp. 34-45, January 1982.

4 MODEL VALIDATION

4.1 DISCUSSION OF SUDO CORRELATION

As discussed in Section 3, the Sudo Correlation [Reference 4-1] assumes the following basic form:

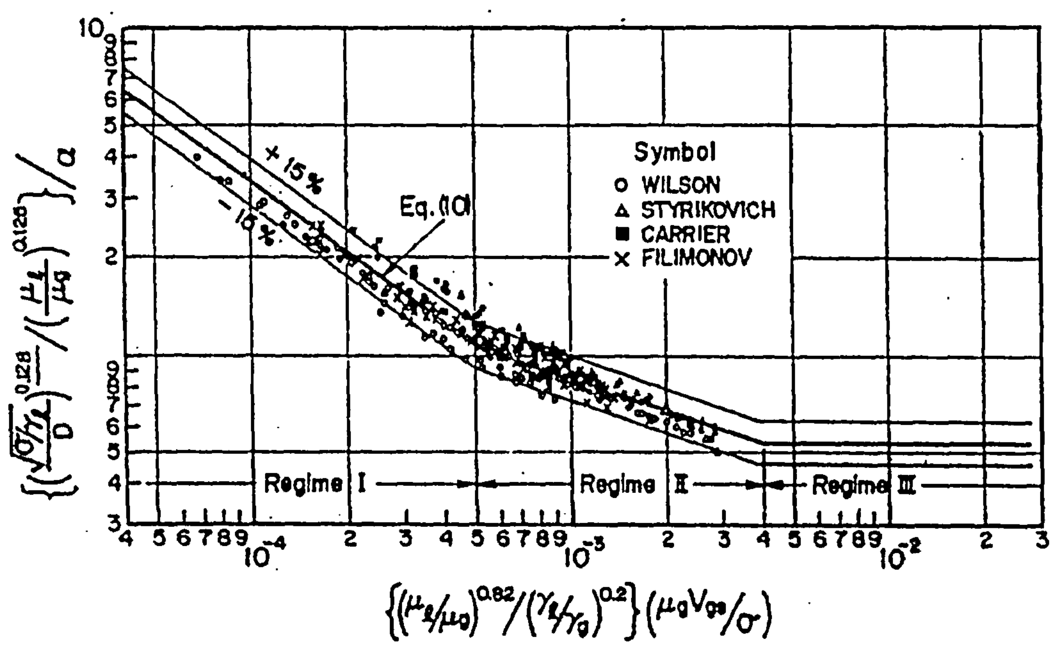
$$\alpha = \frac{Y}{AX^m}$$

where X is proportional to j_g, Y is proportional to $D^{-0.128}$, and the effect of pressure is reflected through the saturation properties ρ_f, ρ_g, μ_f, μ_g, and σ. The coefficient A and exponent m are evaluated as a function of X, and the tabulated values in Section 3 correspond to the bubbly/bubbly-slug, fully-developed slug, and annular flow regimes. [

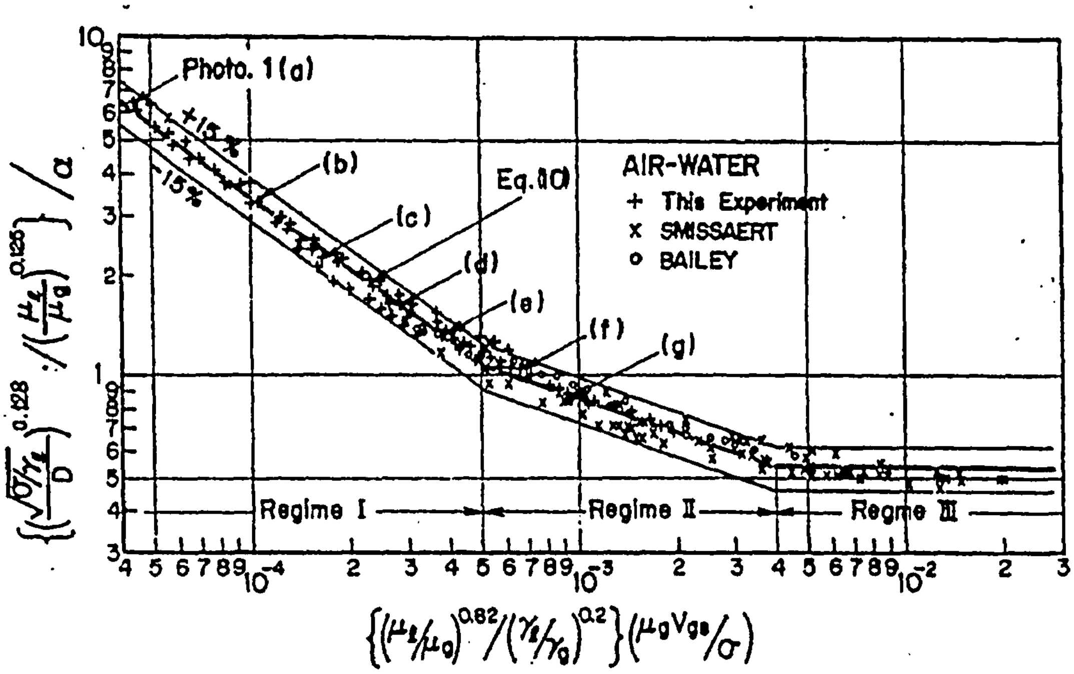
]$^{(a,c)}$

The Sudo Correlation was developed using data from both steam-water and air-water systems. The steam-water data span tube diameters from 2.5 to 19 inches, pressures from 90 to 1630 psia, and superficial liquid velocities from 0 to 12 inches per second. The air-water data span tube diameters from 2.1 to 6 inches, with a pressure of 14.7 psia and a superficial liquid velocity near zero. These conditions span the range of interest for PWR reflood calculations [

]$^{(a,c)}$, indicating that the Sudo Correlation database is consistent with the intended application. Figure 4-1 [Reference 4-1] compares the Sudo Correlation to the experimental data upon which it was based. As shown in Figure 4-1, the error band on the correlation is about ±15%, indicating that the functional form proposed by the author produces an accurate calculation of the void fraction under a fairly wide range of conditions.



(a) Steam-water system



The alphabets (a)~(g) correspond to Photo. 1(a)~(g).

(b) Air-water system

Figure 4-1: Comparison of Sudo Correlation to Basis Data

4.2 VALIDATION AGAINST EXPERIMENTAL DATA

Reference 4-2 describes separate effects tests performed by the Japan Atomic Energy Research Institute (JAERI) to investigate the effect of downcomer steam generation on the effective driving head for core reflooding. The experiments were conducted in a full scale, rectangular downcomer simulator under atmospheric pressure, with heated walls to simulate the metal heat release that occurs during a PWR large break LOCA reflood transient. Section 4.2.1 describes the test facility and experimental procedure, and Section 4.2.2 describes the application of the LOCBART transient extension method to predict experimental results from the JAERI facility.

4.2.1 Facility Description and Experimental Procedure

Figure 4-2 [Reference 4-2] provides a schematic of the test facility. The downcomer simulator consisted of two heated carbon steel plates of thickness 50 mm, arranged in parallel to create a rectangular flow channel of height 6.5 m, width 1 m, and gap 0.2 m. The inner surfaces were lined with stainless steel of thickness 6 mm, which prevented corrosion of the carbon steel plates and simulated the cladding in a PWR reactor vessel. Water was supplied to the downcomer simulator through two injection lines: one at the bottom, which simulated the rapid filling of the downcomer during accumulator injection, and one at the top, which simulated the lower flow rates typical of pumped ECC delivery. A water extraction line was provided at the bottom of the downcomer simulator, and was used in some experiments to simulate the loss of downcomer inventory due to the core reflooding process.

As shown in Figures 4-3 and 4-4 [Reference 4-3], 25 sets of thermocouples and 15 differential pressure transducers were placed at various elevations along the downcomer walls. Each set of thermocouples consisted of three thermocouples located at 0, 8, and 51 mm from the inner wall surface, and measurements of the temperature distribution in the downcomer walls were used to calculate the local heat flux by the method of inverse heat conduction. The indication from differential pressure transducer DP1 was used to determine the collapsed liquid level, which provides a measure of the reduction in driving head due to downcomer boiling and entrainment.

Measurements of temperatures and pressure differences began after the downcomer walls and injection fluid were heated to the desired temperature. The wall temperature was between 200 and 300°C for all tests except one, which is representative of the average vessel metal temperature at the beginning of a simulated PWR reflood transient. The injection temperature was between 96 and 100°C, which is at or near saturation at the system pressure of about 1 atmosphere. This is representative of the temperature of liquid entering the downcomer during a simulated PWR reflood transient after the accumulators have emptied, when most or all of the ECC subcooling is removed due to condensation of steam in the cold legs.

Water was provided to the downcomer simulator by one of two injection modes: mode "A", which used the bottom injection port for a rapid initial filling, or mode "B", which used the top injection port for a gradual initial filling. In both modes, the top injection port was used after the initial filling, with excess water removed through an overflow line. Injection mode "A" is of primary interest for simulated PWR reflood transients, which are characterized by a rapid initial filling rate from the beginning of reflood until the accumulators are empty.

In some experiments, the water extraction line was used to investigate the effect of a small, downward liquid velocity on the effective downcomer head. Per Reference 4-2, "The results show no significant effect of extracted water velocity on effective water head in the range of 0 to 2 cm/s downward."

Figure 4-5 [Reference 4-3] shows the differential pressure measurements from a sample experiment (Run No. 115) using injection mode "A". As shown in Table 1 of Reference 4-2, this experiment had an initial wall temperature of 250°C, an extracted water velocity of 0 cm/s, an injected water temperature of 98°C, and a gap width of 200 mm. Water reached the heated section of the downcomer simulator at about 13 seconds, and the differential pressures (collapsed liquid level) increased rapidly during the initial filling. The collapsed liquid level reached a maximum about 25 seconds into reflood (i.e., about 38 seconds into the experiment), around which time injection was transferred from the bottom to the top of the downcomer simulator. The collapsed liquid level began to decrease as voids started to accumulate in the heated region, reaching a minimum about 75 seconds into reflood, then began to increase as the wall heat addition continued to decrease. A quasi-equilibrium condition was reached about 140 seconds into reflood, after which the collapsed liquid level remained relatively constant for the remainder of the simulation.

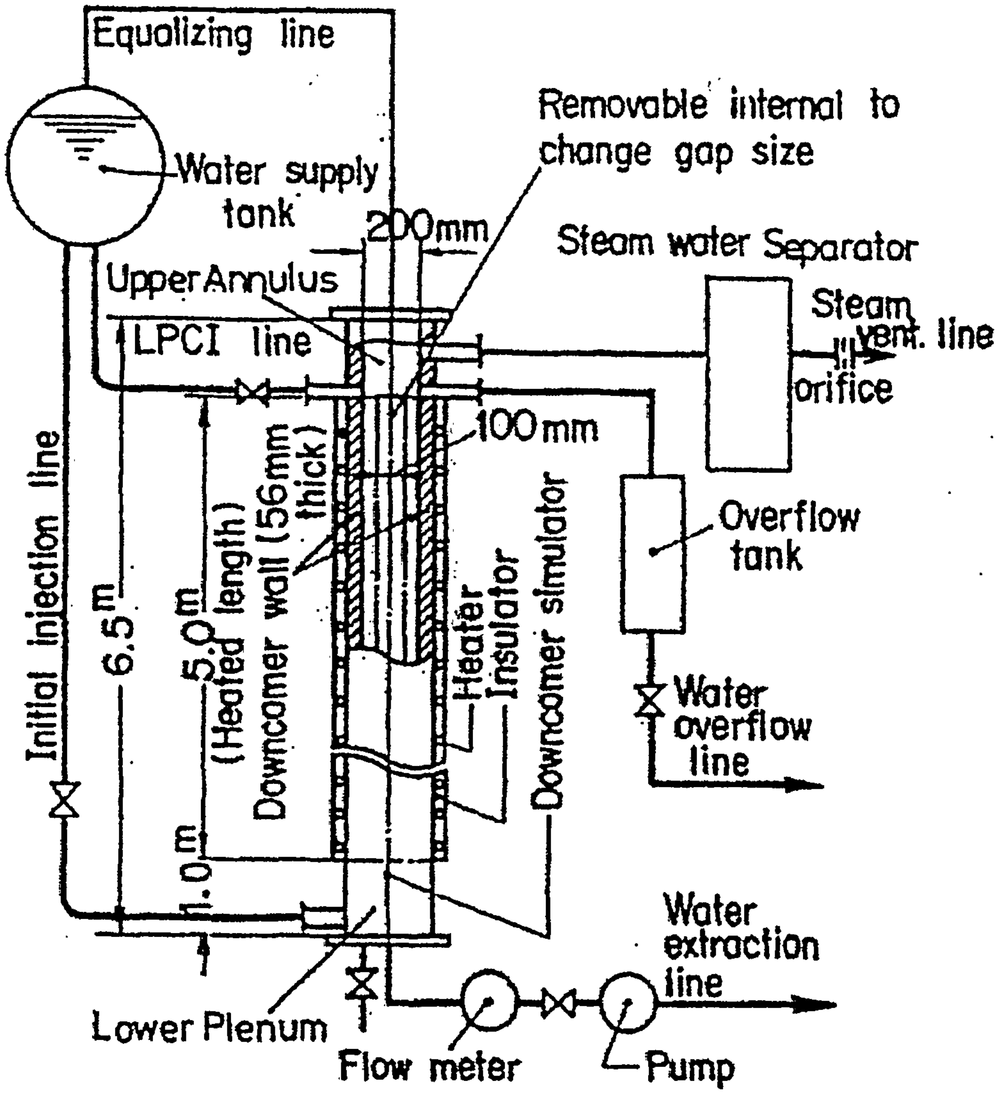


Fig. 1 Schematic of test apparatus

Figure 4-2: Schematic of JAERI Facility

(g)

Figure 4-3: Location of Thermocouples in JAERI Facility

(g)

Figure 4-4: Location of Differential Pressure Transducers in JAERI Facility

(g)

Figure 4-5: Differential Pressure Measurements from JAERI Run No. 115

4.2.2 Application of LOCBART Transient Extension Method to JAERI Tests

In order to demonstrate that the LOCBART transient extension method is capable of predicting the reduction in downcomer driving head due to boiling and entrainment, calculations were completed at various times for Run No. 115 from the JAERI facility. As discussed in Section 4.2.1, this experiment used injection mode "A", an initial wall temperature of 250°C, and a gap width of 200 mm, which are representative of typical PWR reflood simulations, and an injected water temperature of 98°C, which is representative of the temperature of water reaching the downcomer in a typical PWR reflood simulation after the accumulators have emptied. As discussed in Section 4.2.1, the extracted water velocity was found to have little effect on the downcomer collapsed liquid level, and the value of 0 cm/s for Run No. 115 is considered adequate for the present purposes.

Calculations were performed at 15, 50, and 100 seconds (after injection water reached the heated section), corresponding to the points A, B, and C (respectively) from Figure 9(a) of Reference 4-2; 75 seconds, corresponding to a local minimum in the downcomer collapsed liquid level; and, 200 seconds, corresponding to the quasi-equilibrium period at the end of the simulation. [

](a,c) The collapsed liquid level was calculated based on the lower 4.645 m of the heated region, corresponding to the span of differential pressure transducer DP1. As shown in Table 4-1, the calculations indicate that the collapsed liquid level is generally over-predicted [

](a,c)

Table 4-1: Collapsed Liquid Level Predictions for JAERI Run No. 115

[

](a,c)

As discussed in Reference 4-2, direct application of the Sudo Correlation showed good agreement against experimental results when the effective water head was changing slowly, but indicated that further development would be required to capture transient effects when the effective water head was changing rapidly. For example, the Sudo Correlation does not reflect the additional steam generation that occurs during periods of depressurization as the saturation temperature is reduced, and will therefore tend to under-predict the void fraction and over-predict the collapsed liquid level under these conditions. [

](a,c)

[

]^(a,c)

(a,c)

Figure 4-6: Axial Void Fraction Profile for JAERI Run No. 115

4.3 ASSESSMENT OF LATERAL ENTRAINMENT EFFECTS

While the effects of vertical entrainment due to steam escaping from the downcomer are captured through use of the Sudo Correlation, the effects of lateral entrainment due to steam flowing through the cold legs also need to be considered. [

](a,c)

4.4 TREATMENT OF OTHER BASH-CALCULATED PARAMETERS AFTER DOWNCOMER BOILING

[

](a,c)

(a,c)

Figure 4-7: Effect of Pressure on Flooding Rate After Downcomer Boiling

(a,c)

Figure 4-8: Effect of Core Collapsed Liquid Level on Flooding Rate After Downcomer Boiling

4.5 REFERENCES FOR SECTION 4

4-1. Sudo, Y., "Estimation of Average Void Fraction in Vertical Two-Phase Flow Channel Under Low Liquid Velocity", Journal of Nuclear Science and Technology, 17(1), pp. 1-15, January 1980.

4-2. Sudo, Y., and Akimoto, H., "Downcomer Effective Water Head During Reflood in Postulated PWR LOCA", Journal of Nuclear Science and Technology, 19(1), pp. 34-45, January 1982.

4-3. Sudo, Y., and Murao, Y., "Experiment of the Downcomer Effective Water Head During a Reflood Phase of PWR LOCA", JAERI-M 7978, October 1978.

4-4. NUREG/IA-0127, GRS-101, MPR-1346, "Reactor Safety Issues Resolved by the 2D/3D Program", July 1993.

4-5. WCAP-9561-P-A, "BART-A1: A Computer Code for the Best Estimate Analysis of Reflood Transients", March 1984.

5 APPENDIX K COMPLIANCE

The USNRC letter of 27 March 2002 [Reference 5-1] required Westinghouse to demonstrate how BASH-EM and the LOCBART transient extension method comply with various requirements of 10 CFR 50 Appendix K. Corresponding information was presented to the USNRC staff on 11 July 2002, and is summarized in Sections 5.1 to 5.7. In each section, the USNRC statement from Reference 5-1 is shown in italicized text, followed by the Westinghouse response.

5.1 SECTION I.A.6 - REACTOR INTERNALS HEAT TRANSFER

10 CFR Part 50, Appendix K, Section I.A.6 requires that heat transfer from the reactor vessel walls and non-fuel internal hardware be taken into account. W must demonstrate how this is accomplished in the 1981 EM using BASH and with the LOCBART extension method after the onset of downcomer boiling.

In the BASH code, fluid nodes simulate mass and energy storage in a fluid volume; metal nodes simulate energy storage in a metal volume; flow links simulate mass, energy, and momentum transfer between fluid nodes; and, heat links simulate energy transfer between metal and fluid nodes. For most of the metal structures in the reactor coolant system, energy transfer between the metal and fluid has little effect on the system thermal-hydraulic transient, and a single metal node temperature is calculated using the slab heat transfer model described in Section 3.13 of Reference 5-2. For the lower plenum and downcomer, an accurate simulation requires the resolution of internal temperature gradients, and a metal node temperature profile is calculated using the more detailed model described in Section 3.14 of Reference 5-2. This model uses an implicit finite-difference solution scheme; considers plate, cylindrical, or spherical geometry; and, allows modeling of composite structures, thereby providing a reasonably accurate calculation of the internal temperature profile.

The metal-to-fluid heat transfer calculations utilize the heat link models described in Section 3.20 of Reference 5-2, with appropriate consideration of the metal node type (i.e., slab or detailed) as described therein. These models consider subcooled, saturated, and superheated fluid, and maximize the metal-to-fluid energy transfer by using the maximum heat flux from possible heat transfer regimes. Figure 5-1 shows the heat transfer regime selection logic for subcooled fluid, which is applied to the downcomer in PWR calculations. The heat transfer regimes considered for this fluid state include natural convection, forced convection, nucleate boiling, transition boiling, and film boiling, with departure from nucleate boiling evaluated using the MacBeth critical heat flux correlation. Figure 5-2 shows the downcomer metal-to-fluid heat flow rate for a sample BASH PWR calculation. Subcooled transition boiling exists very early in reflood, followed by subcooled nucleate boiling until the bulk downcomer fluid reaches saturation.

As discussed in Section 3, the LOCBART transient extension method uses the downcomer metal-to-fluid heat flow rate at the onset of downcomer boiling to calculate the reduction in the core inlet flooding rate. This treatment is appropriate early in reflood, since the transition between subcooled and saturated nucleate boiling would produce a minimal effect on the metal-to-fluid heat flow rate, and is conservative later in reflood, since no credit is taken for further removal of wall energy which would eventually terminate boiling and restore driving head for core reflooding.

(a,c)

Figure 5-1: BASH Heat Transfer Regime Selection Logic for Subcooled Fluid

(a,c)

Figure 5-2: Downcomer Metal-to-Fluid Heat Flow from Sample BASH Calculation

5.2 SECTION I.D.3 - CALCULATION OF REFLOOD RATE

10 CFR Part 50, Appendix K, Section I.D.3 requires that "The refilling of the reactor vessel and the time and rate of reflooding of the core be calculated by an acceptable model that takes into consideration the thermal and hydraulic characteristics of the core and of the reactor system ... The effects on reflooding rate of the compressed gas in the accumulator which is discharged following accumulator water discharge shall also be taken into account." W must demonstrate how this is accomplished in the 1981 EM using BASH and with the LOCBART extension method after the onset of downcomer boiling.

Section I.D.3 of 10 CFR 50 Appendix K pertains to the calculation of the reflood rate, and identifies three considerations (locked rotor assumption, carryover fraction, and accumulator nitrogen discharge) that must be specifically addressed.

Locked Rotor Assumption
In BASH, the reactor coolant pump is modeled as resistance in the cold leg, based on a locked rotor assumption. This yields the maximum resistance through the pump, which was shown in a prior Evaluation Model study [Reference 5-3] to reduce the flooding rate and increase the peak cladding temperature. There is no change in the locked rotor assumption after the onset of downcomer boiling.

Carryover Fraction
In Reference 5-2, the comparisons of BASH against experimental data were made directly against the measured flooding rate and integral flooding rate, in addition to the total carryover fraction. The former quantities are more easily defined for gravity reflood simulations, and more directly influence the peak cladding temperature since the flooding rate is supplied to LOCBART as a boundary condition. These comparisons showed that BASH provides a reasonable to conservative prediction of the carryover fraction, and conservatively predicts the flooding rate and integral flooding rate. The flooding rate is reduced after the onset of downcomer boiling to account for the loss of driving head between the downcomer and core, in the manner described in Section 3.

Accumulator Nitrogen Discharge
As discussed in Appendix F of Reference 5-2, a prior Evaluation Model study [Reference 5-4] showed that accumulator nitrogen discharge pressurizes the downcomer and increases the flooding rate. This behavior is supported by experimental results (e.g., LOFT), and was used to conclude that accumulator nitrogen discharge could be conservatively neglected in BASH. (Note that accumulator nitrogen discharge is modeled in the minimum containment pressure calculations, but produces a minimal effect on the flooding rate.) As discussed in Reference 5-5, Semiscale tests indicated a long-term increase in system pressure due to accumulator nitrogen discharge. This would produce an increase in the flooding rate, which is conservatively neglected, and a decrease in pumped injection flow, which is a very small effect over the pressure range of interest and is also neglected. There is no change to the treatment of accumulator nitrogen discharge after downcomer boiling.

5.3 SECTION I.D.4 - STEAM INTERACTION WITH EMERGENCY CORE COOLING WATER

10 CFR Part 50, Appendix K, Section I.D.4 requires that "The thermal-hydraulic interaction between steam and all emergency core cooling water shall be taken into account in calculating the core reflooding rate..." W must demonstrate how this is accomplished in the 1981 EM using BASH and with the LOCBART extension method after the onset of downcomer boiling.

As discussed in Section 11.0 of Reference 5-2, BASH assumes equilibrium behavior in the cold legs. This assumption maximizes the condensation of steam flowing from the intact cold legs to the downcomer, which minimizes the pressurization of the downcomer due to steam flowing through the broken nozzle and reduces the flooding rate. This assumption also minimizes the subcooling of the ECC fluid entering the downcomer, which reduces the time required for the downcomer to reach saturation and leads to an earlier reduction of the flooding rate using the LOCBART transient extension method.

As discussed in Section 11.0 of Reference 5-2, an additional pressure drop is applied in the cold legs to account for pressure oscillations during accumulator injection. As discussed in Section 2.2.1 of Reference 5-4, this pressure drop bounds steam/water mixing data for injection angles of 90° (1.8 psi) and 45° (0.6 psi), and was approved for licensing application as being sufficiently conservative. In a BASH Evaluation Model calculation, the accumulators are predicted to empty well before the onset of downcomer boiling, and this requirement is not pertinent to the LOCBART transient extension method.

During the LOCBART transient extension, the effects of downcomer boiling and entrainment are considered in the calculation of the reduced flooding rate. Vertical entrainment effects due to steam escaping from the downcomer are reflected through use of the Sudo void fraction correlation, the application of which is described in Section 3. As discussed in Section 4.3, lateral entrainment effects due to steam flowing through the intact cold legs are [

]$^{(a,c)}$

5.4 SECTION I.D.5 - REFILL AND REFLOOD HEAT TRANSFER

10 CFR Part 50, Appendix K, Section I.D.5 requires that (a) for reflood rates of one inch per second or higher, reflood heat transfer coefficients shall be based on applicable experimental data for unblocked cores including FLECHT results, and (b) during refill and during reflood when reflood rates are less than one inch per second, heat transfer calculations shall be based on the assumption that cooling is only by steam, and shall take into account any flow blockage calculated to occur as a result of cladding swelling or rupture as such blockage might affect both local steam flow and heat transfer. W must demonstrate how this is accomplished in the 1981 EM using BASH and with the LOCBART extension method after the onset of downcomer boiling.

Compliance of BASH-EM with Section I.D.5 of 10 CFR 50 Appendix K was originally demonstrated in Section 11.0 of Reference 5-2, and is supplemented by the validation of the LOCBART reflood heat transfer models as described in Reference 5-6. When the flooding rate is less than or equal to 1 inch per second, direct heat transfer to liquid is ignored, and assembly blockage is modeled if the hot assembly average rod has been predicted to burst. There is no change to the basic modeling of reflood heat transfer during the LOCBART transient extension, though it is noted that heat transfer from the rods to the coolant is generally degraded when the flooding rate is reduced. Refer to Section 5.5 for a sensitivity study demonstrating the effect of reducing the flooding rate on the cladding temperature and oxidation after the onset of downcomer boiling.

Except for rod-to-rod radiation, LOCBART assumes an adiabatic heatup during the refill phase of the transient. This assumption, combined with the substantial delay that is predicted to occur between the end of bypass and the beginning of reflood, produces a severe cladding temperature excursion that has been estimated in Reference 5-7 as a source of about 100 K (180°F) conservatism in Appendix K Evaluation Models.

In LOCBART, assembly blockage is modeled as a reduction in mass velocity in the vicinity of the burst, with no direct credit taken for the beneficial effects of flow acceleration, turbulence intensification, and droplet atomization that have been observed experimentally (e.g., Reference 5-8). With this formulation, assembly blockage leads to a local reduction in cladding-to-fluid heat transfer and a corresponding local increase in cladding temperatures, which is conservative relative to experimental results and can represent a substantial conservatism in the analysis when the peak cladding temperature occurs late in reflood. Figure 5-3 illustrates the effect on cladding temperature and oxidation for a LOCBART calculation with a late-reflood peak cladding temperature, and [

]$^{(a,c)}$

Reference 5-6 describes the validation of the LOCBART reflood heat transfer models against FLECHT, FLECHT SEASET, and G2 experiments. For the simple egg-crate grids used in the FLECHT experiments, LOCBART was shown to predict peak cladding temperatures near the mean of the data, with a slightly conservative capture fraction. For the production-type mixing vane grids used in the G2 experiments, LOCBART was shown to predict peak cladding temperatures that bound nearly all of the data. This difference in behavior was attributed to the inability of the LOCBART spacer grid heat transfer models to fully capture the heat transfer benefit of the mixing vanes, and can represent a substantial conservatism in the analysis when the peak cladding temperature occurs late in reflood.

(a,c)

Figure 5-3: Effect of Assembly Blockage on Peak Cladding Temperature and Maximum Local Oxidation

5.5 SECTION II.2 - SOLUTION CONVERGENCE

10 CFR Part 50, Appendix K, Section II.2 requires that for each computer program, solution convergence be demonstrated by studies of system modeling or noding and calculational time steps. This requirement is not satisfied because the BASH code fails when downcomer boiling is predicted to occur. W should discuss how and why the BASH code fails, and demonstrate why the 1981 BASH-EM solution converges under these conditions and is acceptable for the entire duration of its expected calculational period (entire duration of the refill and reflood portions of the transient).

[

](a,c)

For BASH, solution convergence is demonstrated in Section 11.0 of Reference 5-2. For LOCBART, solution convergence is based primarily on the axial node spacing and time step selection. The axial node spacing is determined by the maximum allowable value from Reference 5-10 (6"), the value required to adequately resolve the axial blockage profile (3"), and the minimum value implied by Section I.A.5 of 10 CFR 50 Appendix K (3"). The time step size during reflood is calculated internally using appropriate selection criteria, with a maximum value of [ ](a,c) and a minimum value of [ ](a,c) for standard PWR calculations. Figure 5-5 shows the effect of reducing the maximum allowable value on cladding temperature and oxidation for a sample LOCBART calculation, and indicates a minimal effect on results for this case.

Figures 5-6 and 5-7 show the effect of varying the flooding rate after downcomer boiling on peak cladding temperature and maximum local oxidation for a sample LOCBART calculation. [

]$^{(a,c)}$ These calculations show that the peak cladding temperature and maximum local oxidation increase with decreasing flooding rate after downcomer boiling, which is consistent with the expected result.

(a,c)

Figure 5-4: Sample Calculations of Void Fraction Using Homogeneous Equilibrium Assumption

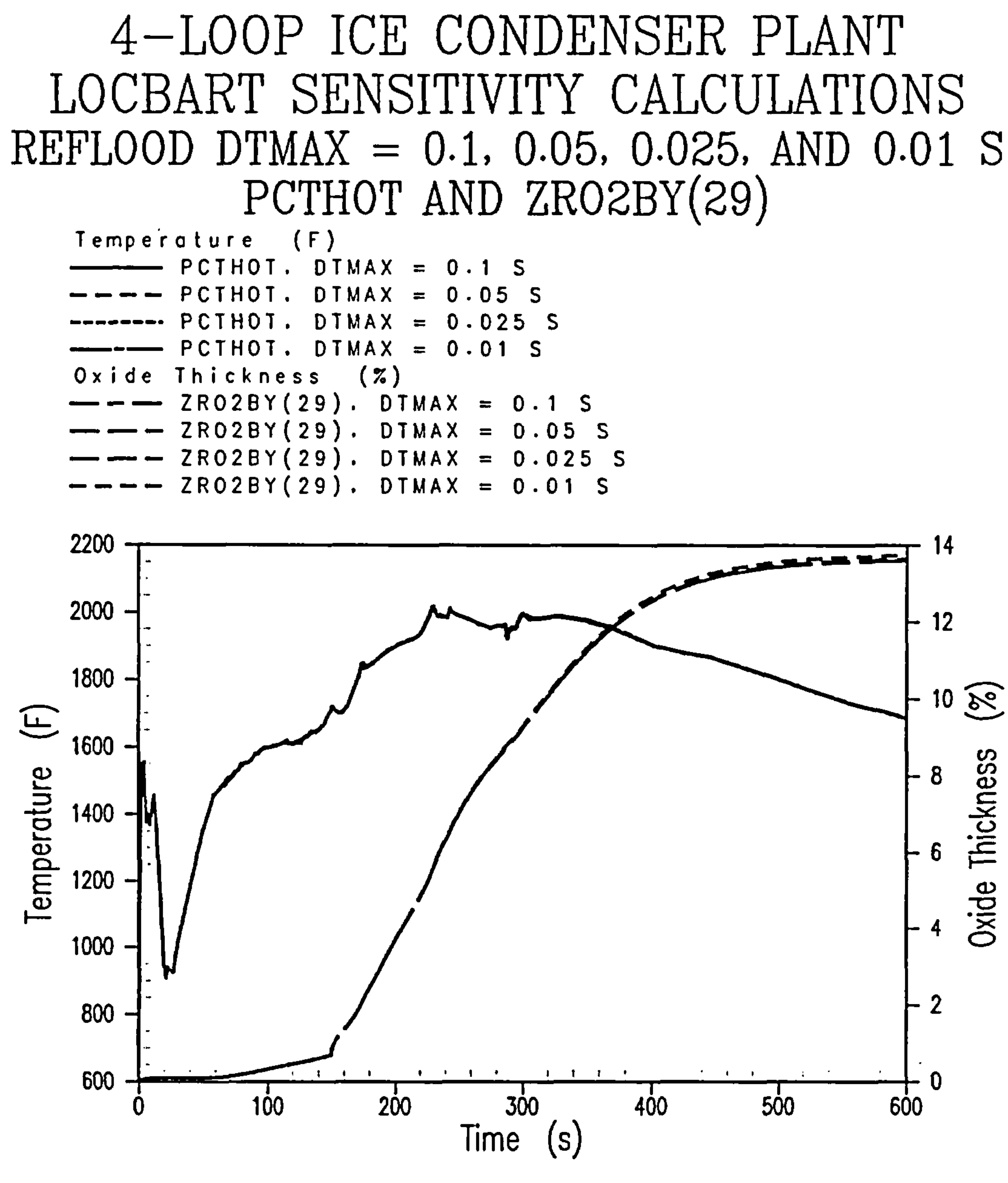


Figure 5-5: Effect of Maximum Reflood Time Step Size on Peak Cladding Temperature and Maximum Local Oxidation

(a,c)

Figure 5-6: Effect of $(V_{IN})_4$ / $(V_{IN})_3$ on Peak Cladding Temperature

(a,c)

Figure 5-7: Effect of $(V_{IN})_4$ / $(V_{IN})_3$ on Maximum Local Oxidation

5.6 SECTION II.3 - SENSITIVITY STUDIES

10 CFR Part 50, Appendix K, Section II.3 requires that sensitivity studies be performed to evaluate the effect on results of "phenomena assumed in the calculation to predominate". W originally assumed that downcomer boiling would not occur, and therefore sensitivity studies of this phenomenon were not performed. Based on current knowledge of downcomer boiling and its impacts on peak clad temperature (PCT), the staff requires that sensitivity studies be performed.

Sensitivity calculations were completed to demonstrate the effect of system pressure and core collapsed liquid level on the flooding rate after downcomer boiling, and the results are presented in Section 4.4. Sensitivity calculations were also completed to demonstrate the effect of assembly blockage, maximum reflood time step size, and flooding rate after downcomer boiling on peak cladding temperature and maximum local oxidation, and the results are presented in Sections 5.4 and 5.5. This section describes additional sensitivity calculations that were completed to demonstrate the effect of pumped ECC flows and downcomer metal heat release on peak cladding temperature and maximum local oxidation. This section also presents sensitivity calculations that compare the peak cladding temperature predicted using BASH-EM to the 50th and 95th percentile peak cladding temperatures predicted using the 1996 Westinghouse Best Estimate LOCA Evaluation Model with WCOBRA/TRAC (BELOCA), which demonstrate the substantial conservatism that is predicted using the Appendix K methodology.

Pumped ECC Flows

The Safety Evaluation Report to Reference 5-2 requires consideration of both minimum and maximum pumped ECC flows. A sensitivity calculation was completed for a 4-loop ice condenser plant using maximum pumped ECC flows in BASH, to demonstrate how this change affects the calculated results when downcomer boiling is considered in the analysis. The minimum containment pressure transient was reduced by [

]$^{(a,c)}$ for the maximum ECC flow case, which is representative of the sensitivity of LOTIC2 to this change.

Figure 5-8 compares the downcomer liquid temperature and containment pressure for the BASH calculations modeling minimum (min SI) and maximum (max SI) pumped ECC flows. The downcomer temperature is reduced for the max SI case, which more than offsets the small decrease in saturation temperature due to reduced containment pressure, and produces a substantial delay in downcomer boiling. [

]$^{(a,c)}$

Downcomer Metal Heat Release

A sensitivity calculation was also completed in which the downcomer heat links in BASH were turned off just prior to downcomer boiling. As shown in Figure 5-11, this causes the downcomer liquid temperature to remain just below saturation, and allows the BASH calculation to be extended significantly beyond the point at which downcomer boiling would otherwise be encountered. Figure 5-12 compares the downcomer liquid level (ZDC), core collapsed liquid level (ZM), and quench front elevation (ZQ) and indicates no apparent difficulty in either case, indicating that BASH is capable of extended simulations when downcomer boiling does not occur. [

]$^{(a,c)}$ Figure 5-14 compares the peak cladding temperature and maximum local oxidation and indicates a fairly substantial reduction in both parameters during the transient extension, which is consistent with the expected result given [ ]$^{(a,c)}$

BASH-EM vs. BELOCA

BASH-EM calculations were completed for two plants that are now licensed with the 1996 Westinghouse Best Estimate LOCA Evaluation Model (BELOCA). Plant "A" is a 3-loop Westinghouse plant with a dry atmospheric containment design, and plant "B" is a 4-loop Westinghouse plant with an ice condenser containment design. These calculations used the standard BASH-EM methodology to the extent possible, with inputs selected based on the BELOCA analysis values where appropriate. This approach allows a reasonably direct comparison of the BASH-EM peak cladding temperature to the BELOCA 50th and 95th percentile peak cladding temperatures, and provides a measure of the substantial conservatism that is generally believed to exist in Appendix K Evaluation Models.

[

]$^{(a,c)}$

(a,c)

Figure 5-8: Downcomer Liquid Temperature and Containment Pressure for Min SI vs. Max SI Sensitivity Calculation

(a,c)

Figure 5-9: Integral Flooding Rates for Min SI vs. Max SI Sensitivity Calculation

(a,c)

Figure 5-10: Peak Cladding Temperature and Maximum Local Oxidation for Min SI vs. Max SI Sensitivity Calculation

(a,c)

Figure 5-11: Downcomer Liquid Temperature for Downcomer Metal Heat Release Sensitivity Calculation

(a,c)

Figure 5-12: Vessel Levels for Downcomer Metal Heat Release Sensitivity Calculation

(a,c)

Figure 5-13: Integral Flooding Rates for Downcomer Metal Heat Release Sensitivity Calculation

(a,c)

Figure 5-14: Peak Cladding Temperature and Maximum Local Oxidation for Downcomer Metal Heat Release Sensitivity Calculation

(a,c)

Figure 5-15: BASH-EM and BELOCA Peak Cladding Temperatures for Plant "A"

(a,c)

Figure 5-16: BASH-EM and BELOCA Peak Cladding Temperatures for Plant "B"

5.7 SECTION II.4 - COMPARISON TO APPLICABLE EXPERIMENTAL DATA

10 CFR Part 50, Appendix K, Section II.4 requires that to the extent practicable, predictions of the evaluation model, or portions thereof, shall be compared with applicable experimental information. W should provide a comparison of the LOCBART extension method to appropriate experimental data. The comparison should include appropriate scaling considerations.

The validation of the LOCBART transient extension method against applicable, full-scale experimental data is described in Section 4.

5.8 REFERENCES FOR SECTION 5

5-1. Letter from S. Dembek (USNRC) to H. Sepp (Westinghouse), "Potential Non-Conservative Modeling of Downcomer Boiling in the Approved Westinghouse 1981 Evaluation Model Using BASH", March 27, 2002.

5-2. WCAP-10266-P-A, Revision 2, "The 1981 Version of the Westinghouse ECCS Evaluation Model Using the BASH Code", March 1987.

5-3. WCAP-8170, "Calculational Model for Core Reflooding After a Loss of Coolant Accident (WREFLOOD Code)", June 1974.

5-4. WCAP-8471-P-A, "The Westinghouse ECCS Evaluation Model: Supplementary Information", April 1975.

5-5. NUREG/CR-4945, EGG-2509, "Summary of the Semiscale Program (1965-1986)", July 1987.

5-6. WCAP-10484-P-A, Addendum 1, "Spacer Grid Heat Transfer Effects During Reflood", September 1993.

5-7. NUREG/IA-0127, GRS-101, MPR-1346, "Reactor Safety Issues Resolved by the 2D/3D Program", July 1993.

5-8. Erbacher, F. J., "Cladding Tube Deformation and Core Emergency Cooling in a Loss of Coolant Accident of a Pressurized Water Reactor", Nuclear Engineering and Design 103, pp. 55-64, 1987.

5-9. WCAP-12945-P-A Volume I (Revision 2) and Volumes II-V (Revision 1), "Westinghouse Code Qualification for Best Estimate Loss of Coolant Accident Analysis", March 1998.

5-10. WCAP-9561-P-A, "BART-A1: A Computer Code for the Best Estimate Analysis of Reflood Transients", March 1984.

5-11. WCAP-14404, "Methodology for Incorporating Hot Leg Nozzle Gaps into BASH", August 1995.

6 CONCLUSIONS

This report has described the incorporation of the LOCBART transient extension method into the BASH Evaluation Model (BASH-EM). Compliance of BASH-EM with the aspects of 10 CFR 50 Appendix K cited in the USNRC letter of 27 March 2002 [Reference 6-1] was demonstrated prior to downcomer boiling, and is not adversely affected thereafter by the use of the LOCBART transient extension method. Application to a full-scale separate effects test showed that the downcomer collapsed liquid level was well predicted under conditions representative of the intended application, indicating that the method can reasonably be applied to ensure adequate termination of the fuel rod cladding temperature and oxidation transients. [

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6.1 REFERENCES FOR SECTION 6

6-1. Letter from S. Dembek (USNRC) to H. Sepp (Westinghouse), "Potential Non-Conservative Modeling of Downcomer Boiling in the Approved Westinghouse 1981 Evaluation Model Using BASH", March 27, 2002.