Enclosure 2

MFN 09-740

Paper and Presentation, "ESBWR Chimney Flow Regimes"

Public Version

GE Hitachi Nuclear Energy

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ESBWR Chimney Flow Regimes

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This is a non-proprietary version of the ESBWR Chimney flow Regimes, which has the proprietary information removed. Portions of the document that have been removed are indicated by open and closed double square brackets as show here [[ ]].

IMPORTANT NOTICE REGARDING CONTENTS OF THIS REPORT

Please Read Carefully

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ESBWR Chimney Flow Regimes

(Author: Bharat Shiralkar)

Summary

A review of analytical models and data leads to the conclusion that the flow in the ESBWR chimney is in the churn-turbulent flow regime at rated power. If a transition did occur to annular flow, it would be at a high void fraction to an annular flow with a large fraction of entrained droplets. The transition would be mild, without a significant change in the radial void profile. The flow and neutron noise levels are evaluated to be acceptably small.

Theoretical Basis

Classical slug flow which bridges the entire cross section of the pipe does not occur in large pipes at high pressure. Kataoka and Ishii [2] provide a relation for the critical hydraulic diameter, above which slugs cannot exist due to Taylor instability.

$$D_h^* = \frac{D_h}{\sqrt{\sigma / g\Delta\rho}} \geq 40 \quad \text{.......(1)}$$

At ESBWR operating pressures around 70 bars, this corresponds to a critical hydraulic diameter of 6.4 cm.

Hence, the two-phase flow transitions from a bubbly flow to a churn-turbulent flow regime. This transition occurs at a void fraction of about 0.3 due to interference between adjacent bubbles [3, 8]. Bubbles agglomerate and break up due to interactions between neighboring bubbles. Some investigators have proposed further subdivisions within the churn turbulent flow regime such as churn-bubbly at lower void fractions and churn-froth at the upper end of void fractions.

The transition from churn-turbulent flow to annular flow is hypothesized to occur when the vapor velocity is high enough to entrain liquid into the gas flow. Because the transition is from churn-turbulent flow, rather than from slug flow, the annular regime will be one with a large amount of dispersed droplets entrained in the flow. This transition should be relatively mild as it occurs at high void fractions, and without a dramatic change in the radial liquid distribution.
Wallis [1] correlated the critical gas velocity for the annular transition as:

$$j_g^* = 0.4 + 0.6 * j_f^* \quad \text{.......(2)}$$

where

$$j_g^* = \frac{j_g\sqrt{\rho_g}}{\sqrt{gD(\rho_f - \rho_g)}}, \; j_f^* = \frac{j_f\sqrt{\rho_f}}{\sqrt{gD(\rho_f - \rho_g)}}$$

Mishima and Ishii [referenced in 8] have proposed an alternate correlation for the transition:

$$j_g^+ = N_{\mu f}^{-0.2} \quad \text{...(3)}$$

where

$$j_g^+ = \frac{j_g \rho_g^{1/2}}{(\sigma g \Delta\rho)^{1/4}}, \quad N_{\mu f} = \mu_f / \left(\rho_f \sigma \sqrt{\sigma / g\Delta\rho}\right)^{1/2}$$

Equation 3 has only a weak dependence on the viscosity number, $N_{\mu f}$. The transition value of j_g^+ varies from 4.21 to 4.37 over the range of pressures from 1 bar to 70 bar. At 70 bar, the critical superficial vapor velocity (j_g) is calculated to be 2.4 m/s.

Both Equations (2) and (3) have limitations. The Wallis correlation is based on air-water data from small tubes (1 inch diameter). For large tubes, the parameter j_g^+, in which the length scale is the Taylor wavelength, seems more appropriate than j_g^*, which is based on the pipe diameter. The Mishima-Ishii correlation is based on j_g^+, but is independent of the liquid flow rate. This can result in the prediction of an annular flow transition at unrealistically low void fractions (~ 0.3) when the liquid velocities are significant.

TRACG uses a different approach to calculating the transition to annular flow, as discussed in Section 5.1.1 of [4]. The transition is calculated on the basis that the average vapor velocities in churn-turbulent flow and annular flow are equal at the transition void fraction. This leads to the relation:

$$C_{0,bc} j + \overline{v_{gj,bc}} = C_{0,a} j + \overline{v_{gj,a}} \quad \text{...(4)}$$

where the distribution parameters (C_0) and void weighted drift velocities (v_{gj}) are calculated using the relationships in bubbly-churn (*bc*) and annular (*a*) flow regimes at the transition void fraction.

<u>Experimental Data</u>

Void fraction measurements and flow regime identification observations have been made in References 4, 5, 7 and 8. A comparison of the test parameters is shown in Table 1.

All sets of data show a transition from bubbly flow to a churn-turbulent flow regime. This transition takes place at a void fraction between 0.2 and 0.38, with 0.3 the commonly accepted value. There is no slug flow regime. The data in Reference [8] identify an intermediate large cap bubble flow regime before the flow transitions to a fully churn-turbulent flow regime at a void fraction of 0.5. This cap bubble regime could be specific to the low-pressure air-water test.

Only the Ontario Hydro data [4] had a high enough vapor velocity to produce annular flow. The flow regime transitions were deduced from plots of the standard deviation of the void fraction fluctuations. Data from 5 gamma densitometer beams as well as from density head fluctuations were analyzed. [[

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Though the void fractions in the Purdue [8] and Omebere-Iyari [7] tests were as high as 0.83, the flow remained in the churn-turbulent regime. For these tests, the vapor velocity was lower than the Mishima-Ishii criterion (Equation 3).

ESBWR Chimney Operating Range

At rated power, the conditions in the central and peripheral chimney partition regions are shown in Table 2. Both regions are calculated to be in the churn-turbulent flow regime by TRACG. If the Wallis criterion [1] is applied, the critical vapor velocity for annular flow is of the order of 5.41 m/s. This is almost twice the actual vapor velocity in the central chimney. Hence, a churn-turbulent flow regime would be predicted. The Mishima-Ishii criterion [3] predicts a critical vapor velocity of 2.4 m/s relative to the velocity of [[ ]] in the central chimney. Hence, a transition to annular flow would be calculated. The most credible evidence comes from the Ontario Hydro tests, where the critical velocity was found to be of the order of 5 to 5.5 m/s. In the tests, the void fraction under these conditions was lower, around 0.7 relative to [[ ]] in the central chimney. The vapor velocity is expected to be the more dominant parameter determining the transition to annular flow than the void fraction. The central chimney region most likely remains in the churn-turbulent regime at rated power.

It should also be noted that the transition to annular flow occurs from churn-turbulent flow at high void fractions, not from slug flow. The flow transitions to an annular flow with a substantial fraction of dispersed droplets. Hence, the liquid distributions in the two regimes will be similar; the transition will be mild. There is no bi-stable behavior that causes jumps between dramatically different flow characteristics. Figure 10 of [9] shows the radial void distributions measured in the Ontario Hydro tests as the average void fraction increased from low values to above 0.8. The void distributions are well behaved, without large changes as the flow regime transitions from churn-turbulent to annular flow with entrainment.

Flow Noise in Churn-Turbulent Flow

The Dodewaard plant [13] had a chimney configuration similar to the ESBWR, though with a smaller chimney cell (0.254 m vs. 0.610 m), and flow from four bundles and the associated bypass region feeding the chimney cell (Table 2). The operating pressure of 75.5 bar was similar to ESBWR. The plant operated with a typical average chimney void fraction of 0.49 and chimney mass fluxes of the order of 384 kg/m^2-s, (as obtained from Reference 6). At these conditions, a churn turbulent flow regime would be expected in the chimney (void fraction greater than 0.3 and less than that for transition to annular flow). Flow noise typical of the churn turbulent flow regime must have been present in the chimney during Dodewaard operation. The plant operated for 28 years without any reported instances of excessive noise in the core resulting from unsteady phenomena in the chimney. APRM noise was acceptably low, Reference [14], and there were no issues with the neutron noise level.

In the Ontario Hydro tests [4, 9], the loop was drained into a storage tank, and the loop void fraction increased and the mass flux decreased from 3500 to 600 kg/m^2-s. At a void fraction of 0.7, the mass flux ranged from 1000 to 1500 kg/m^2-s. The Ontario Hydro test data show some noise in the void fraction data at these conditions. There was a high frequency component at about 3 Hz and a low frequency component of about 0.15 Hz. The amplitude of the noise was of the order of 5 % (1 σ) [9].

This was the basis for the inputs to the TRACG study reported in [10]. Oscillations imposed on the chimney void faction (5%) showed acceptable results for neutron flux noise.

References:

1. G. B. Wallis, *One-dimensional Two-phase Flow*, p. 347, McGraw Hill, 1969.
2. I. Kataoka and M. Ishii, *Drift flux model for large diameter pipe and new correlation for pool void fraction*, Int. J. Heat Mass Transfer, Vol. 30, N0.9, pp. 1927-1939, 1987.
3. *TRACG Model Description,* NEDE-32176P, Rev. 4, January 2008. (Proprietary)
4. Joint Study *Report: Analysis and Evaluation on the Two-Phase Flow in a Large Diameter Piping*, Proprietary Report by JAPC, GE, Ontario Hydro Technologies and University of Toronto, 1996. (Proprietary)
5. Dubrovskii, I. S., *Hydrodynamics of Adiabatic Two-Phase Flow in Large Core Risers,* Teploenergetika, 21 (2), pp. 31-35, 1974.
6. *TRACG Qualification for SBWR*, NEDC-32725P, Vol. 2, Table 6.1-1, 6.1-3.
7. Omebere-Iyari, N.K., et al., 2008. *The characteristics of gas/liquid flow in large risers and high pressures*. Int. J. Multiphase Flow 34 (5), 461–476.
8. J.P. Schlegel, P. Sawant, S. Paranjape, B. Ozar, T. Hibiki and M. Ishii, *Void fraction and flow regime in adiabatic upward two-phase flow in large diameter vertical pipes*, Nuclear Engineering and Design, In Press, Corrected Proof, Available online 11 September 2009.
9. H. A. Hassanein, et al, *Steam-Water Two-Phase Flow in Large Diameter Vertical Piping at High Pressures and Temperatures,* Volume 1, Part B, Proceedings of ICONE-4, New Orleans, 1996.
10. MFN- 08-715 – Response to RAI 21.6-114 (Proprietary)
11. DCD Table 4.4-6: 26A6642AP Revision 6 August 2009
12. NEDC-32725P Volume 2, September 1997, Sections 6.1 and 6.2 (Proprietary)
13. Oosterkamp, W.J. 1987 Reactor physics at the Dodewaard BWR - KEMA Scientific & Technical Reports 5 (9): 219-257. ISSN 0167-8590; ISBN 90-353-0056-4.
14. T.H.J.J Van Der Hagen, *Stability Monitoring of a Natural-Circulation-Cooled Boiling Water Reactor*, 1989, KEMA, ISBN 90-353-1017-9, SISO 644.5 UDC 621.039(043.3).

Table 1: Large Pipe Data

Reference	Geometry Dia x Height, (m)	Pressure (bar)	Void fraction range	j_g (m/s)	j_f (m/s)	j_g+	Flow regimes*	Transition to C-T	Transition to dispersed annular
Ontario Hydro [4]	Pipe 0.51 x 12.4	64	0–0.83	0.1-7.6	0.4-3.5	0.17-12.8	B, C-T, A	α=0.3	j_g=5-5.5m/s; α>0.70
Dubrovskii [5]	Riser 0.6 x 3	30–100**	0-0.54	0.08-0.65	0.18-0.32	0.15-1.18	B, C-T	---	N/A
Omebere - Iyari [7]	Pipe, 0.194 x 9	46	0-0.77	0.1-1.48	0.01-0.65	0.13-1.95	B, C-T	α=0.38-0.68	N/A
Schlegel [8]	Pipe, 0.15 x 4.4	1 (air-water)	0.02-0.83	0.1-5.1	0.01-2	0.02-1.07	B, C-T	α=0.2-0.3	N/A

* Bubbly (B), Churn-Turbulent (C-T), and Annular (A)
** Data shown in paper are at 100 bars

Table 2: Plant Chimney Conditions at Rated Power

Plant	Geometry: Hydraulic Diameter x Height (m)	Pressure (bar)	Void Fraction	j_g (m/s)	j_f (m/s)	j_g+	Flow Regime
ESBWR Central Chimney	0.61 x 6.61 Ref. [10], [11]	[[					Likely Churn-Turbulent
ESBWR Peripheral Chimney	0.61 x 6.61 Ref. [10], [11]					]]	Likely Churn-Turbulent
Dodewaard	0.254 x 3 Ref. [12], [13]	75.5	0.49	0.79	0.66	1.53	Likely Churn-Turbulent

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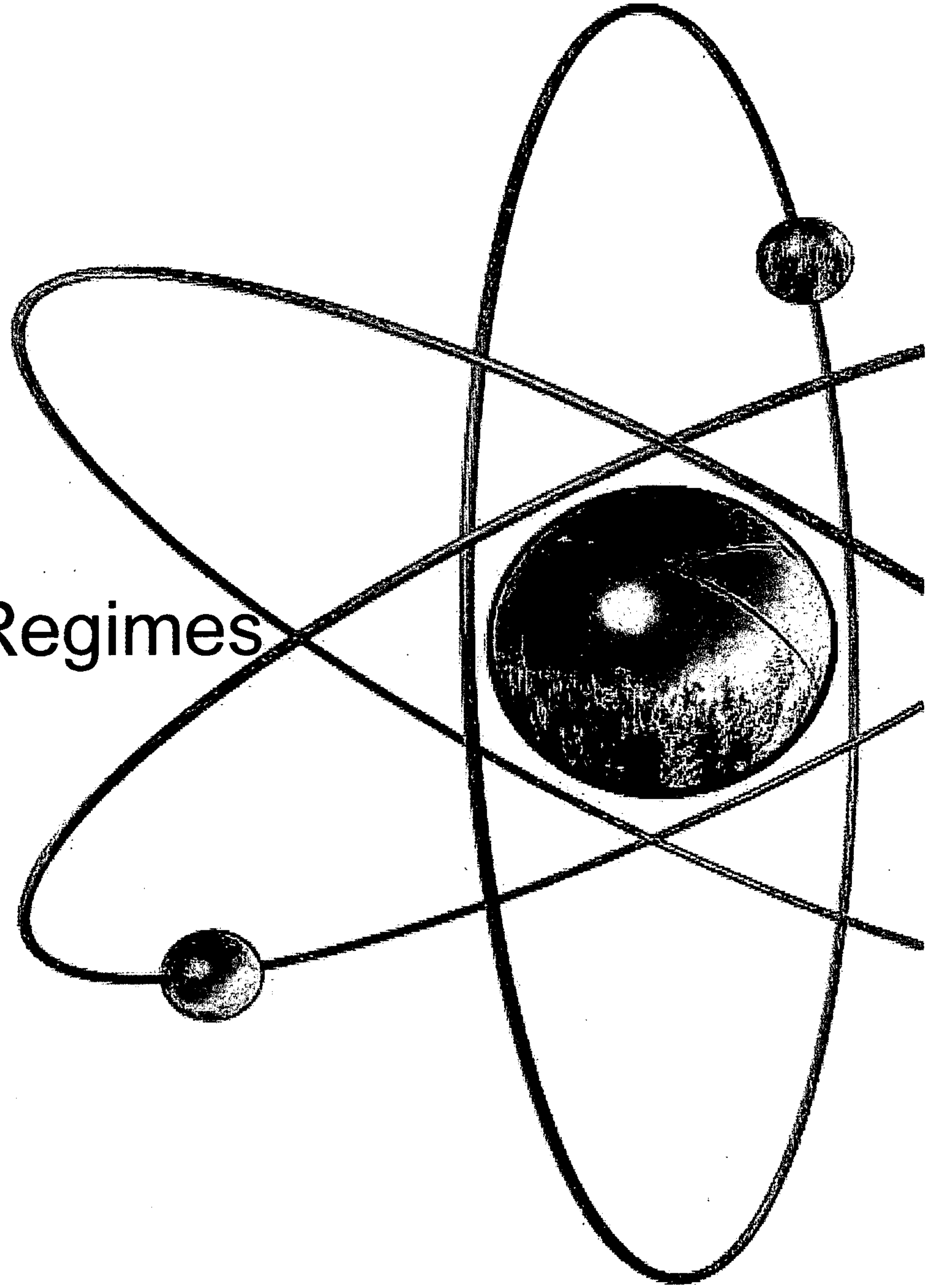
ESBWR Chimney Flow Regimes



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ESBWR Chimney Flow Regimes

- ESBWR chimney void fraction
  - At natural circulation, the highest power/flow ratio and therefore also the highest void fraction will exist at rated power.
  - Minor variations will exist due to power shape and core inlet subcooling
- ESBWR chimney hydraulic conditions at rated power

		j_g (m/s)	j_f (m/s)	α	
Central Region	[[				]]
Peripheral Region	[[				]]

- TRACG calculates steady flow with no indication of oscillations/noise

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TRACG ESBWR Chimney Flow Regimes

- TRACG calculates churn turbulent (C-T) in ESBWR chimney
  - Slug flow cannot exist in the chimney

    Kataoka and Ishii determined the maximum diameter beyond which slugs cannot exist based on Taylor instability

    $$\frac{D_h}{\sqrt{\frac{\sigma}{g\Delta\rho}}} > 40$$

    For ESBWR operating conditions this criterion is satisfied for D > 0.06 m
  - Transition to dispersed annular flow happens at high void fraction

    TRACG uses a correlation similar to the Wallis correlation and calculates the transition from churn turbulent to annular flow as the condition where the vapor velocities are equal for the two correlations

    For ESBWR operating conditions this criterion is satisfied for $\alpha \approx 0.86$
  - At the transition, TRACG calculates transition to dispersed droplet flow

    TRACG uses Mishima's and Ishii's correlation for the entrainment fraction for dispersed annular flow

    For ESBWR operating conditions this correlation gives an entrainment fraction $E \approx 1.0$

Data and TRACG Qualification

- TRACG qualified for two-phase flow predictions for large hydraulic diameters.

  Ontario Hydro test

	Hydraulic Diameter	Height
	m	m
Ontario Hydro Test	0.51	12.4
ESBWR	0.61	6.61

Similar range for key parameters.

Difference well within capability of correlations.

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Comparison of TRACG/OHT Void Fraction During the Time Periods of Varying Mass Flow Rate (280°C/6.4 MPa)

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Figure 3.1-47. Comparison of TRACG and Time-Averaged Data for Average Void Fraction at Nominal Temperature of 280°C

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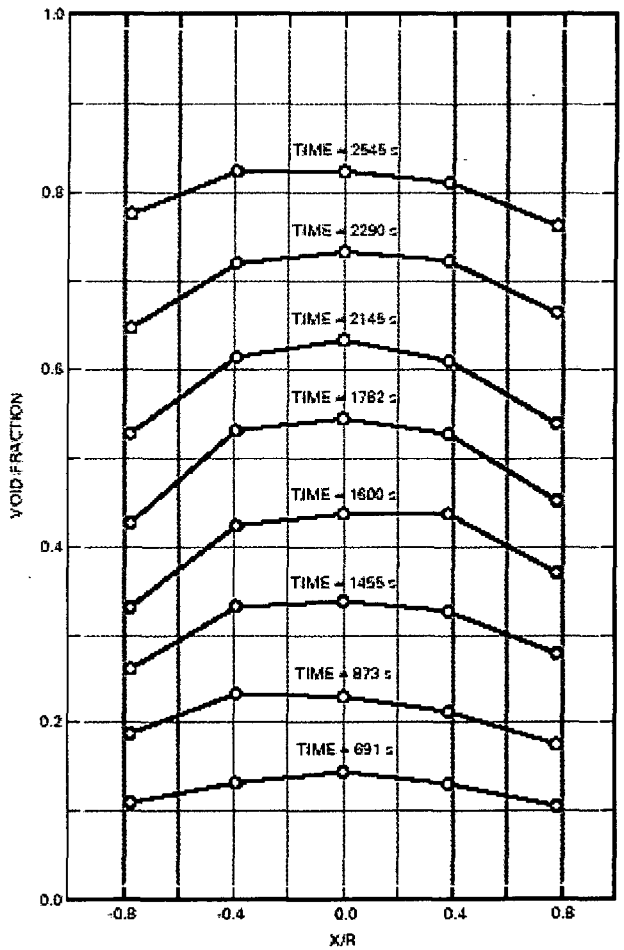
Data and TRACG Qualification



NOTE: TIME-AVERAGED DATA WAS USED FOR PLOTTING THIS GRAPH.
ORIGINAL DATA WAS AVERAGED OVER 36 SECONDS.

Figure 3.1-42. Radial Void Fraction Distribution at Nominal Temperature of 280°C

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Figure 3.1-46. Local Void Fluctuations at ~2500 s at Nominal Temperature of 280° C

- No indication of flow instability in these tests
  - Indications of transition to dispersed annular flow observed for $j_g \approx 5 - 5.5$ m/s
    This is approximately twice the ESBWR chimney flow at rated conditions.
- Minor fluctuations in void fraction observed, mostly at low void fractions
- These observations supported by other data and plant experience

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Other Data and Plant Experience

Large pipe data

Reference	Geometry Dia x Height, (m)	Pressure (bar)	Void fraction range	j_g (m/s)	j_f (m/s)	j_g^+	Flow regimes*	Transition to C-T	Transition to dispersed annular
Ontario Hydro [4]	Pipe 0.51 x 12.4	64	0–0.83	0.1-7.6	0.4-3.5	0.17-12.8	B, C-T, A	α=0.3	j_g=5-5.5m/s; α>0.70
Dubrovskii [5]	Riser 0.6 x 3	30–100**	0-0.54	0.08-0.38	0.18-0.29	0.21-0.97	B, C-T	---	N/A
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* Bubbly (B), Churn-Turbulent (C-T), and Annular (A)

** Data shown in paper are at 100 bars

Plant data

Plant	Geometry: Hydraulic Diameter x Height (m)	Pressure (bar)	Void Fraction	j_g (m/s)	j_f (m/s)	j_g^+	Flow Regime
ESBWR Central Chimney	0.61 x 6.61 Ref. [10], [11]	[[				]]	Likely Churn-Turbulent
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Dodewaard	0.254 x 3 Ref. [12], [13]	75.5	0.49	0.79	0.66	1.53	Likely Churn-Turbulent

The references in these tables are from the document: "ESBWR Chimney Flow Regimes" by B. Shiralkar

Other Data and Plant Experience

Neutron Noise

- Plant Data
  - Dodewaard
    - Chimney in churn-turbulent flow
    - APRM noise was acceptably low

- TRACG calculations
  - Perturbations to chimney void fraction
  - Magnitude based on Ontario Hydro noise data
  - Acceptable noise in neutron flux

Sensitivity to Chimney Void fraction Noise

- Impact of noise evaluated by perturbing chimney void fraction
  - RAI 21.6-114
  - Noise level chosen based on Ontario Hydro data
  - Insignificant impact on core power - <1%

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ESBWR Chimney Flow Regimes

- TRACG calculates churn-turbulent flow in ESBWR chimney
  - Transition to dispersed droplet flow for high void fractions
  - Flat cross sectional void profile and minimal variation in local densities

  - TRACG calculations supported by data and plant experience

- Impact of chimney void fraction oscillations simulated by TRACG with insignificant impact on core performance.

  - Chimney void fraction oscillations do not adversely impact ESBWR operation.

Enclosure 3

MFN 09-740

Affidavit

Larry J. Tucker

December 2, 2009

GE- Hitachi Nuclear Energy Americas, LLC

AFFIDAVIT

I, Larry J. Tucker, state as follows:

(1) I am the Manager, ESBWR Engineering, GE Hitachi Nuclear Energy Americas LLC ("GEH"), and have been delegated the function of reviewing the information described in paragraph (2) which is sought to be withheld, and have been authorized to apply for its withholding.

(2) The information to be discussed and sought to be withheld is delineated in the letter from Mr. Richard E. Kingston to U.S. Nuclear Regulatory Commission, entitled *'Transmittal of Paper and Presentation, "ESBWR Chimney Flow Regimes,"'* dated December 2, 2009. The information in Enclosure 1, which is entitled *'MFN 09-740 Paper and Presentation, "ESBWR Chimney Flow Regimes" – GEH Proprietary Information'* contains proprietary information, and is identified by [[dotted underline inside double square brackets{3}]]. Figures and other large objects are identified with double square brackets before and after the object. In each case, the superscript notation {3} refers to Paragraph (3) of this affidavit, which provides the basis for the proprietary determination.

(3) In making this application for withholding of proprietary information of which it is the owner or licensee, GEH relies upon the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC Sec. 552(b)(4), and the Trade Secrets Act, 18 USC Sec. 1905, and NRC regulations 10 CFR 9.17(a)(4), and 2.390(a)(4) for "trade secrets" (Exemption 4). The material for which exemption from disclosure is here sought also qualify under the narrower definition of "trade secret", within the meanings assigned to those terms for purposes of FOIA Exemption 4 in, respectively, Critical Mass Energy Project v. Nuclear Regulatory Commission, 975F2d871 (DC Cir. 1992), and Public Citizen Health Research Group v. FDA, 704F2d1280 (DC Cir. 1983).

(4) Some examples of categories of information which fit into the definition of proprietary information are:

a. Information that discloses a process, method, or apparatus, including supporting data and analyses, where prevention of its use by GEH's competitors without license from GEH constitutes a competitive economic advantage over other companies;

b. Information which, if used by a competitor, would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product;

c. Information which reveals aspects of past, present, or future GEH customer-funded development plans and programs, resulting in potential products to GEH;

d. Information which discloses patentable subject matter for which it may be desirable to obtain patent protection.

The information sought to be withheld is considered to be proprietary for the reasons set forth in paragraphs (4)a. and (4)b. above.

(5) To address 10 CFR 2.390(b)(4), the information sought to be withheld is being submitted to NRC in confidence. The information is of a sort customarily held in confidence by GEH, and is in fact so held. The information sought to be withheld has, to the best of my knowledge and belief, consistently been held in confidence by GEH, no public disclosure has been made, and it is not available in public sources. All disclosures to third parties, including any required transmittals to NRC, have been made, or must be made, pursuant to regulatory provisions or proprietary agreements which provide for maintenance of the information in confidence. Its initial designation as proprietary information, and the subsequent steps taken to prevent its unauthorized disclosure, are as set forth in paragraphs (6) and (7) following.

(6) Initial approval of proprietary treatment of a document is made by the manager of the originating component, the person most likely to be acquainted with the value and sensitivity of the information in relation to industry knowledge, or subject to the terms under which it was licensed to GEH. Access to such documents within GEH is limited on a "need to know" basis.

(7) The procedure for approval of external release of such a document typically requires review by the staff manager, project manager, principal scientist, or other equivalent authority for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside GEH are limited to regulatory bodies, customers, and potential customers, and their agents, suppliers, and licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or proprietary agreements.

(8) The information identified in paragraph (2) above is classified as proprietary because it contains computer code analysis inputs and assumptions used by GEH for analyzed transients using the TRACG computer model. Development of these inputs and assumptions and the TRACG computer code was achieved at a significant cost to GEH, and is considered a major GEH asset.

(9) Public disclosure of the information sought to be withheld is likely to cause substantial harm to GEH's competitive position and foreclose or reduce the availability of profit-making opportunities. The information is part of GEH's comprehensive BWR safety and technology base, and its commercial value extends beyond the original development cost. The value of the technology base goes beyond the extensive physical database and analytical methodology and

includes development of the expertise to determine and apply the appropriate evaluation process. In addition, the technology base includes the value derived from providing analyses done with NRC-approved methods.

The research, development, engineering, analytical and NRC review costs comprise a substantial investment of time and money by GEH.

The precise value of the expertise to devise an evaluation process and apply the correct analytical methodology is difficult to quantify, but it clearly is substantial.

GEH's competitive advantage will be lost if its competitors are able to use the results of the GEH experience to normalize or verify their own process or if they are able to claim an equivalent understanding by demonstrating that they can arrive at the same or similar conclusions.

The value of this information to GEH would be lost if the information were disclosed to the public. Making such information available to competitors without their having been required to undertake a similar expenditure of resources would unfairly provide competitors with a windfall, and deprive GEH of the opportunity to exercise its competitive advantage to seek an adequate return on its large investment in developing and obtaining these very valuable analytical tools.

I declare under penalty of perjury that the foregoing affidavit and the matters stated therein are true and correct to the best of my knowledge, information, and belief.

Executed on this 2nd day of December 2009.

Larry J. Tucker

Larry J. Tucker
GE-Hitachi Nuclear Energy Americas LLC