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Revision 0

July 2009

Small Scale Un-buffered and Buffered Boric Acid Nucleate Boiling Heat Transfer Tests with a Single Fuel Rod in a Vertical Channel

Westinghouse

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Revision 0

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Kansai Electric Co., LTD	Mihama 1, 2 & 3, Ohi 1, 2, 3 & 4, Takahama 1, 2, 3 &4 (W & MHI)	X	
Korea Hydro & Nuclear Power Corp.	Kori 1, 2, 3 & 4 Yonggwang 1 & 2 (W)	X	
Korea Hydro & Nuclear Power Corp.	Yonggwang 3, 4, 5 & 6 Ulchin 3, 4 , 5 & 6 (CE)	X	
Kyushu	Genkai 1, 2, 3 & 4, Sendai 1 & 2 (MHI)	X	
Nuklearna Electrarna KRSKO	Krsko (W)	X	
Nordostschweizerische Kraftwerke AG (NOK)	Beznau 1 & 2 (W)	X	
Ringhals AB	Ringhals 2, 3 & 4 (W)	X	
Shikoku	Ikata 1, 2 & 3 (MHI)	X	
Spanish Utilities	Asco 1 & 2, Vandellos 2, Almaraz 1 & 2 (W)	X	
Taiwan Power Co.	Maanshan 1 & 2 (W)	X	
Electricite de France	54 Units	X	

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LIST OF ACRONYMS AND ABBREVIATIONS

B&W	Babcock and Wilcox
CCFL	Counter Current Flow Limitation
CE	Combustion Engineering
DC	Direct Current
ECCS	Emergency Core Cooling System
LOCA	Loss of Coolant Accident
LTC	Long Term Cooling
MUT	Make-Up Tank
NRC	Nuclear Regulatory Commission
PIRT	Phenomena Identification and Ranking Table
PWR	Pressurized Water Reactor
PWROG	Pressurized Water Reactor Owners Group
SI	Safety Injection
STD	Science and Technology Department
W	Westinghouse
WCAP	Westinghouse Technical Report Number Preface (formerly Westinghouse Commercial Atomic Power)

EXECUTIVE SUMMARY

Following a LOCA in a PWR, the RCS begins to depressurize and, for all but the smallest breaks, significant boiling occurs in the core. The ECCS injects borated water into the reactor vessel to keep the core fuel temperatures at acceptably low levels. All three US PWR nuclear plant designs (Westinghouse, CE, and B&W, advanced plant designs excluded) have ECCS features that, with or without operator action, initiate a core dilution mechanism to prevent the core region boric acid concentration from reaching the precipitation point. The three US PWR designs have different ECCS designs, different procedures for preventing boric acid precipitation, and different methodologies for evaluating the potential for boric acid precipitation. The NRC staff has often cited the disparity of methods and assumptions used to address long term cooling boric acid control across the US PWR fleet, and the NRC has requested that the industry develop conformity in this area. In response, the PWROG funded a program to develop a LOCA boric acid precipitation control analytical approach, applicable to all PWR designs that would be acceptable to the NRC staff. An early objective in this program was to develop a Phenomena Identification and Ranking Table (PIRT) that would provide guidance as to what phenomena the methodology needed to address and how sophisticated of a methodology was needed. While developing the PIRT, it became apparent that there is a relatively low state-of-knowledge regarding the properties of un-buffered and buffered boric acid solutions in the areas of the convective boiling heat transfer, surface tension, and viscosity. Since any new LOCA boric acid precipitation evaluation methodology must consider relevant phenomena, the PWROG boric acid precipitation control program funded tests to investigate the heat transfer behavior of buffered and un-buffered boric acid solutions under conditions simulating that expected during the long term cooling phase following a LOCA. The results of these tests are summarized in this report.

Section 1 provides an introduction including background, motivation for performing the tests, the test objectives and a discussion of the PIRT high ranked phenomena. Sections 2 through Section 4 provide the details of each of the series of tests. Section 5 summarizes the results for evaporation rates and thermal data. Section 6 presents conclusions and recommendations.

1 INTRODUCTION

1.1 BACKGROUND

All three US PWR nuclear plant designs (W, CE, and B&W) use boron coolant to control core reactivity and are subject to concerns regarding potential boric acid precipitation in the core for scenarios that preclude direct safety injection flow through the core for extended periods following a Loss of Coolant Accident (LOCA). All three plant designs have ECCS features that, with appropriate operator action, initiate a flow through the core to prevent the core region boric acid concentration from reaching the boric acid precipitation point. Up to this point in time, simple models using conservative boundary conditions have been used to demonstrate adequate boric acid dilution. These simplified methods are used to determine the time at which appropriate operator action must be taken to initiate an active boron dilution flow path. All three US PWR designs have different ECCS designs, different procedures for preventing boric acid precipitation, and different methodologies for evaluating the potential for boric acid precipitation. Nevertheless, there are common approaches, assumptions and simplifications that have been used in virtually all PWR calculations that address the potential for boric acid precipitation. Recent Extended Power Uprate Programs have provided the opportunity for the NRC to challenge some of these common approaches, assumptions and simplifications with regards to regulatory compliance and technical justification.

In August of 2005, shortly after the Waterford Extended Power Uprate was approved, the NRC staff made known to the industry an extensive list of NRC questions related to the potential for boric acid precipitation after a LOCA event. In response to these questions and the NRC's concerns regarding the methodologies used by industry to analyze the potential for boric acid precipitation, the PWROG funded a long-term program to develop a LOCA boric acid precipitation control analytical approach, applicable to all PWR designs that would be acceptable to the NRC staff. Phase 1 of the long term program is to establish evaluation model scenarios, assumptions and acceptance criteria that would be acceptable to the NRC. The initial task of Phase 1 was to develop a Phenomena Identification and Ranking Table (PIRT) that would provide guidance as to what phenomena the methodology needed to address and how sophisticated of a methodology was needed (Reference 4). In the series of PIRT expert panel sessions that followed, it became clear that there is a relatively low state-of-knowledge in the area of the physical properties of un-buffered and buffered boric acid solutions that would be typical of those found in a PWR containment sump after a LOCA. A follow-up study of LOCA coolant chemistry and possible post LOCA chemical reactions provided insights on how different chemistries might affect long term cooling (LTC) of the reactor core (Reference 5). The study concluded that a variety of different coolant chemistries could exist after a LOCA. For plants which add sodium hydroxide for pH control, the coolant would contain a variety of dissolved species which may behave quite differently than simple boric acid solutions. Such solutions, depending on pH, would tend to precipitate sodium borates rather than boric acid and would do so at different concentration levels. Likewise, plants adding trisodium phosphate or sodium tetraborate would also have different properties than boric acid solutions. The presence of pH control agents will affect not only precipitation from solution, but also other properties such as convective boiling heat transfer, surface tension, and viscosity. Changes in these properties may in turn affect heat transfer. Since the codes currently used for predicting post LOCA boric acid precipitation and heat transfer consider only water and boric acid solutions, it was decided that heated rod testing should be performed to make sure that the pH control agents did not unfavorably alter the heat transfer. Since the boiling and heat transfer characteristics of concentrated sump solutions had ramifications beyond the

PWROG boric acid precipitation program, Westinghouse internally funded an initial Round 1 of tests to investigate buffered boric acid with sodium hydroxide (to form a sodium borate solution) at intermediate and low levels of pH.

The results of the initial round of tests indicated that a second series of tests, Round 2, were warranted. The Round 2 tests, again funded by Westinghouse, investigated buffered boric acid with sodium hydroxide (sodium borate) at high levels of pH, buffered boric acid with tri-sodium phosphate, and boric acid without buffering agents. After the second round of tests, it was determined that concentrated sodium borate solutions were [

]^{c}

After the Round 2 tests, it became apparent that buffered boric acid boiling tests could provide valuable support for justifying a new boric acid precipitation analysis methodology. For example, knowledge obtained from the tests would increase the state-of-knowledge of medium and high ranked mixing phenomena identified in the PIRT for boric acid and buffered boric acid solutions. The results could also be used to address potential NRC concerns over the ability of a concentrated sump solution to remove decay heat without a significant clad heat up. Finally, the tests could provide insights for subsequent small scale mixing tests and provide data to support assumptions regarding the potential for precipitation in the boiling region for buffered boric acid solutions. With this perspective, the PWROG approved a revision to PA-ASC-0264 that funded a third round of tests and the documentation of all three rounds of tests in a formal report. This report would then be available to all PWROG members participating in project PA-ASC-0264. One objective of Round 3 of testing was to confirm previous observations with an improved apparatus that is more prototypic of the post-LOCA core boiling conditions.

1.2 MOTIVATION

Heated beaker tests were performed with buffered boric acid solutions such as sodium borate.
[

]^{c}

It is known that boiling point elevation may occur with addition of any solute to a solvent. The presence of solute, especially if it is a less volatile solute, will reduce the ability of solvent molecules at the surface of liquid-vapor interface to escape (overcome intermolecular bonds) and increase the vapor pressure. Due to the intermolecular bonds, a higher vapor pressure is needed to reach boiling point. This can be improved via agitation (such as via turbulence imparting additional energy to liquid molecules to overcome intermolecular bonds) and/or more effective nucleation near liquid-vapor interface.

Solubility curves for buffered boric acid solutions suggest the possibility of a lower limit at a higher pH. If the turbulent bubble behavior is reduced, boiling heat transfer from the fuel rod due to turbulent bubble behavior could be reduced at higher concentrations of solution. This is due to the degraded circulation to bring liquid in contact with rod surface.

Solubility characteristics above N/B = 0.5 cannot be extrapolated from the data available in open literature. Figure 1.2-1 depicts saturation lines for various forms of sodium borate (Reference 8).

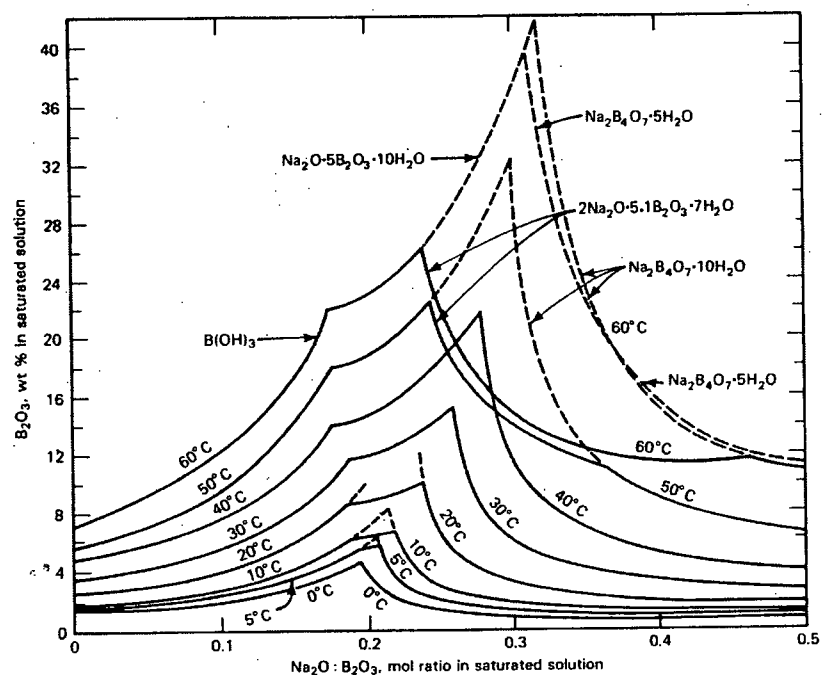

Figure 1.2-1 Sodium Borate Saturation Limits

Information from open literature (Reference 1) supports the ability of chemical solutions such as sodium borate to provide boiling heat transfer comparable to water. However, no such data has been found demonstrating the performance of chemical solutions in boiling channel geometry at various combinations of pH and boric acid concentrations. To further elaborate, no such data exists pertaining to the precipitation and/or deposition of the solute in such solutions expected during post-LOCA conditions in a nuclear reactor core.

1.3 OBJECTIVES

The primary objective of the nucleate boiling heat transfer tests was to determine the ability of sump chemical solutions to provide adequate boiling heat transfer from a simulated fuel rod without irreversible precipitation or irreversible deposition in a boiling channel configuration. A secondary objective was to assess fuel cladding integrity within the concentrated sump chemical solutions and any deposits which might form.

The tests were broken into three rounds of experiments as described below.

Round 1

The objective of Round 1 of testing was to investigate boric acid buffered with sodium hydroxide (sodium borate) at intermediate and low levels of pH.

Round 2

The objective of Round 2 of testing was to investigate boric acid buffered with sodium hydroxide (sodium borate) at high levels of pH, boric acid buffered with tri-sodium phosphate, and boric acid without buffering agents. The test article was also modified to eliminate [ ]^{c} that occurred during Round 1 of the tests.

Round 3

The objective of Round 3 of testing was to investigate the boric acid buffered with sodium tetraborate and confirm previous observations by performing a repeat test with boric acid buffered with sodium hydroxide. The test article was also modified to better represent the liquid volume of a core sub-channel region and to extend the two-phase regime (bubbly and churn) to include the slug flow regime.

1.4 HIGH RANKED PIRT ITEMS

During the PIRT process, phenomena are ranked for importance through the various periods identified for the transient and the state of knowledge is assessed based upon the diverse experience of the PIRT review team. For specific phenomena to receive a ranking of HIGH it must be considered crucial to obtain the correct or conservative predication of the transient during the particular period being investigated relative to the other phenomena in question. PIRT items that received the ranking of HIGH are of the greatest interest. A summary of the PIRT items that received the ranking of HIGH are listed in Table 1.4-1 (Reference 4).

Table 1.4-1 High Ranked PIRT Items

	Phenomena
1.	Decay Heat Level
2.	Boiling Heat Transfer Regime (Nucleate, Transition, or Film Boiling)
3.	Boiling Channel Hydraulic Geometry
4.	Sub-cooling of Fluid entering Boiling Channel
5.	Two-phase Flow Regime (bubbly, slug, etc.) including Bubble Size/Motion
6.	Nucleation Characteristics of Boiling Surface (zircaloy tube)
7.	Precipitation in Boiling Regime a. Impact of chemical solution solubility b. Impact of chemical solute transport/mixing (concentration distribution)
8.	Deposition of solute material on heated surfaces above two-phase mixture level a. Impact of surface temperature on evaporation of solvent (i.e., water) b. Impact of solute concentration in liquid phase c. Impact of liquid entrainment or transport of liquid phase onto heated surfaces

Table 1.4-1 High Ranked PIRT Items (cont.)	
	Phenomena
9.	Nucleation characteristics of chemical solution a. Impact of dissolved gases in chemical solution b. Impact of nucleation particles from sump in chemical solution
10.	Surface wetting characteristics of chemical solution
11.	Chemical solution thermo-fluid properties (latent heat of vaporization, surface tension, etc.) a. Impact of chemical solution pH b. Impact of chemical solution concentration c. Impact of system pressure

2 ROUND 1 TESTS

The test apparatus used in Round 1 testing is described in Section 2.1. Several key geometrical and thermal hydraulic parameters are specifically noted as their orientation and design was modified as the tests progressed. Section 2.2 focuses on key observations that were made pertaining to flow regime, bubble nucleation points, bubble size, precipitation, and heat transfer characteristics. Section 2.3 outlines distortions that had significant impact on the results obtained. These distortions were taken into careful consideration when implementing modifications as the test progressed to help acquire more accurate and precise data.

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2.1 ROUND 1 BOILING CHANNEL TEST FACILITY

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Figure 2.1-1 Photograph of Round 1 Boiling Channel Test Article

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Figure 2.1-2 Schematic of Round 1 Boiling Channel Test Article

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Figure 2.1-3 Example Fuel Channel Configuration (Combustion Engineering Assembly with 0.440 inch diameter Rods)

2.2 ROUND 1 OBSERVATIONS

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Figure 2.2-1 Round 1: Nucleate Boiling, Water, 3% Decay Heat

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Figure 2.2-2 Round 1: Nucleate Boiling, Sodium Borate (Na/B = 0.3), 3% Decay Heat, End of Test

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Figure 2.2-3 Round 1: Nucleate Boiling, Sodium Borate (Na/B = 0.3), 1.5% Decay Heat, End of Test

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Figure 2.2-4 Round 1: Two-Phase Flow Regime, Water, 3% Decay Heat

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Figure 2.2-5 Round 1: Two-Phase Flow Regime, Sodium Borate (Na/B = 0.1), 3% Decay Heat, Start of Test

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Figure 2.2-6 Round 1: Two-Phase Flow Regime, Sodium Borate (Na/B = 0.3), 3% Decay Heat, End of Test

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Figure 2.2-7 Round 1: Froth Region, Water, 3% Decay Heat

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Figure 2.2-8 Round 1: Froth Region, Sodium Borate (Na/B = 0.1), 3% Decay Heat, Start of Test

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Figure 2.2-9 Round 1: Froth Region, Sodium Borate (Na/B = 0.3), 3% Decay Heat, End of Test

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Figure 2.2-10 Round 1: Fuel Rod Deposition, Sodium Borate (Na/B = 0.3), Zero Power

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Figure 2.2-11 Round 1: Fuel Rod Deposition, Sodium Borate (Na/B = 0.3), Zero Power, Partially Flooded

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Figure 2.2-12 Round 1: Fuel Rod Deposition, Sodium Borate (Na/B = 0.3), Power Increased to Induce Convection Flow to Accelerate Dissolution

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Figure 2.2-13 Round 1: Deposit in Lower Plenum for Sodium Borate (Na/B = 0.1) at End of Test. Deposit Marked with Arrow

2.3 ROUND 1 DISTORTIONS

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Figure 2.3.1-1 Round 2: Distortions, Water, 3% Decay Heat

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Figure 2.3.1-2 Round 2: Distortions, Sodium Borate (Na/B = 0.3), 3% Decay Heat, End of Test

3 ROUND 2 TESTS

3.1 BOILING CHANNEL TEST FACILITY MODIFICATIONS

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3.2 SOLUTIONS TESTED DURING ROUND 2 BOILING CHANNEL TESTS

The following solutions were tested during Round 2.

- Water (for reference purposes)
- Un-buffered Boric Acid (2 Runs)
- Boric Acid + Sodium Hydroxide (NaOH) with Na/B molar ratio = 0.7 (2 Runs)
- Boric Acid + Trisodium Phosphate ($Na_3PO_4 \cdot 12H_2O$), pH 7
- Boric Acid + Sodium Tetraborate ($Na_2B_4O_7 \cdot 10H_2O$)

The concentrations from the above solutions are given in Table 3.2-1 (Reference 6). Since three different cartridge heaters were used, each with slightly different thermocouple positions, three different water reference runs were made, one with each heater. This allowed more precise comparisons to be made between the heat transfer properties of water and the highly concentrated solutions.

It should be noted that Boric Acid + Sodium Tetraborate test and the repeat Boric Acid + NaOH with Na/B molar ratio = 0.7 were classified as Round 3 tests in the test plan in reference to the chronological sequence in which they were performed. In this report, they have been reported as Round 2 due to similarity in objective with the earlier tests. The following are the distinguishing characteristics between the 3 types of tests:

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Table 3.2-1 Round 2 Tests with Starting Chemical Concentrations in Grams per Kilogram Solution c

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Figure 3.2-1 Round 2 Test Article

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Figure 3.2-2 Round 2: Nucleate Boiling, Water, 3% Decay Heat

Figure 3.2-3 Round 2: Nucleate Boiling, Un-buffered Boric Acid, 3%Decay Heat

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Figure 3.2-4 Round 2: Nucleate Boiling, Boric Acid + NaOH, Na/B = 0.7, 3% Decay Heat

Figure 3.2-5 Round 2: Nucleate Boiling, Boric Acid + TSP, 3% Decay Heat

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Figure 3.2-6 Round 2: Nucleate Boiling, Boric Acid + NaTB. 3% Decay Heat

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Figure 3.2-7 Round 2: Boric Acid + TSP, 3% Decay Heat. 15 msec between frames.

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Figure 3.2-8 Round 2: Two-Phase Flow, Water, 3% Decay Heat

Figure 3.2-9 Round 2: Two-Phase Flow, Boric Acid buffered w/Sodium Hydroxide (Sodium Borate pH~10), 3% Decay Heat

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Figure 3.2-10 Round 2: Two-Phase Flow, Un-buffered Boric Acid, 3% Decay Heat

Figure 3.2-11 Round 2: Nucleate Boiling, Boric Acid + TSP 3% Decay Heat

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Figure 3.2-12 Round 2: Nucleate Boiling, Boric Acid + NaTB. 3% Decay Heat

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Figure 3.2-13 Round 2: Boric Acid + TSP, 3% Decay Heat. 10 msec between frames.

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Figure 3.2-14 Round 2: Froth Region, Water, 3% Decay Heat

Figure 3.2-15 Round 2: Froth Region, Boric Acid buffered w/Sodium Hydroxide (Sodium Borate pH~10), 3% Decay Heat

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Figure 3.2-16 Round 2: Froth Region, Boric Acid buffered w/Tri-Sodium Phosphate, 3% Decay Heat

Figure 3.2-17 Round 2: Froth Region, Boric Acid w/NaTB, 3% Decay Heat

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Figure 3.2-18 Round 2: Froth Region, Un-buffered Boric Acid, 3% Decay Heat

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Figure 3.2-19 Round 2: TSP Buffered Boric Acid

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Figure 3.2-20 Round 2: Fuel Rod Deposition, Boric Acid Buffered w/Tri-Sodium Phosphate

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Figure 3.2-21 Round 2: Fuel Rod Deposition, Un-buffered Boric Acid

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Figure 3.2-22 Round 2: Moisture Separator Deposition, Boric Acid Buffered w/Tri-Sodium Phosphate

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Figure 3.2-23 Round 2: Deposition of boric acid in lower plenum region, Boric Acid Test 1.

Table 3.2-2 Round 2 Boric Acid Concentrations – First Boric Acid Test

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Figure 3.2-24 Round 2: Deposition of Boric Acid in Lower Plenum Region, Boric Acid Test 2

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Figure 3.2-25 Round 2: Deposition of Boric Acid in Lower Plenum Region, Boric Acid Test 2

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Figure 3.2-26 Round 2: Deposition of Boric Acid in Lower Plenum Region at End of Test 2 After Cooling

Table 3.2-3 Round 2 Boric Acid Concentrations – Second Boric Acid Test c

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Figure 3.2-27 Round 2: Deposition of Boric Acid in Lower Plenum Region at End of Test after Cooling

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Figure 3.2-28 Round 2: Deposition of Sodium Borate after Loss of Coolant Flow at End of Na/B = 0.7 Test (L09)

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Figure 3.2-29 Round 2: Rod Appearance after Deposit Removal at End of Na/B = 0.7 test (L09)

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Figure 3.2-30 Round 2: Rod Appearance after Deposit Removal at End of Na/B = 0.7 test (L09) – Close-up.

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Figure 3.2-31 Round 2: Temperatures in Upper Region of Apparatus during Na/B = 0.7 test (L09)

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Figure 3.2-32 Round 2: Temperatures at Vessel Bottom During Na/B = 0.7 test (L09)

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Table 3.2-4 Round 2 Concentrations Measured for Tests L10 and L12

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3.3 ROUND 2 DISTORTIONS

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4 ROUND 3 TESTS

4.1 TESTS L11, L12, AND L13 WITH IMPROVED DOWNCOMER

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Table 4.1-1 Round 3 Improved Down Comer Tests c

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Figure 4.1-1 Round 3: Schematic of Channel Used for Tests L11 through L16

4.2 SMALL CHANNEL TESTS

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Table 4.2-1 Round 3 Small Channel Tests c

4.3 TESTS L14, L15 AND L16 WITH A 1.25-INCH SQUARE CHANNEL

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Figure 4.3-1 Round 3: Detail of Channel Used for Tests L14, L15, and L16

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Figure 4.3-2 Round 3: Bubbly flow during Test L16 (H_3BO_3/TSP). 500 Watts, 25 Inch Elevation

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Figure 4.3-3 Round 3: Bubbly Flow During Test L16 (H_3BO_3/TSP). 560 Watts, Channel Top

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Figure 4.3-4 Round 3: Boiling Curve for Test L14 (Water) compared to Test L15 (H_3BO_3/NaOH)

4.4 TESTS L14B AND L15B WITH A 0.5 X 0.5 INCH SQUARE CHANNEL

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Figure 4.4-1 Round 3: Detail of Channel with Inlet/Outlet Restriction Used for Test L14B and L15B

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Figure 4.4-2 Round 3: Formation of Large Bubble at 560 W in Test L14B (Water)

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Figure 4.4-3 Round 3: Boiling Curve for Test L14B (Water)

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Figure 4.4-4 Round 3: Cladding Temperature for Test L15B (H3BO3/NaOH) at 559.3 Watts

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Figure 4.4-5 Round 3: Boiling Curve for Test L14B (Water) compared to Test L15B (H_3BO_3/NaOH) in 0.5 x 0.5 inch Square Channel

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5 ROUND 1 AND 2 EVAPORATION RATES AND THERMAL DATA

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5.1 ROUND 1 ROD TEMPERATURES AND EVAPORATION RATES

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Figure 5.1-1 Round 1: Simulated Fuel Rod Temperature Comparison for Water vs. Boric Acid Buffered with Sodium Hydroxide

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Figure 5.1-2 Round 1: Channel Fluid Temperature Comparison for Water vs. Boric Acid Buffered with Sodium Hydroxide

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Figure 5.1-3 Round 1: Make-Up Tank Normalized Fluid Mass Comparison for Water vs. Boric Acid Buffered with Sodium Hydroxide

5.2 ROUND 2 ROD TEMPERATURES AND EVAPORATION RATES

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Figure 5.2-1 Round 2: Simulated Fuel Rod Temperature Comparison of Water vs. Un-buffered Boric Acid

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Figure 5.2-2 Round 2: Simulated Fuel Rod Temperature Comparison for Water vs. Boric Acid Buffered with Tri-sodium Phosphate

Figure 5.2-3 Round 2: Simulated Fuel Rod Temperature Comparison of Water vs. Boric Acid and Boric Acid Buffered with Sodium Hydroxide

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Figure 5.2-4 Round 2: Channel Fluid Temperature Comparison for Water vs. Un-buffered and Buffered Boric Acid

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Figure 5.2-5 Round 2: Lower Plenum Temperature vs. Bulk Coolant Temperature for Boric Acid (L08)

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Figure 5.2-6 Round 2: Make-Up Tank Normalize Fluid Mass Comparison for Water vs. Un-buffered and Buffered Boric Acid

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Figure 5.2-7 Round 2: Make-Up Tank Normalized Fluid Mass Comparison for Water vs. Boric Acid Buffered with Sodium Tetraborate

6 CONCLUSIONS AND RECOMMENDATIONS

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APPENDIX A
ISSUES NOT ADDRESSED IN BOILING CHANNEL TESTS

The boiling channel tests with boric acid and buffered boric acid solutions did not address several different known scenarios of interest. It is recommended that future tests be conducted to investigate the following scenarios/phenomena:

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