DCP_NRC_002796
February 26, 2010

ENCLOSURE 26

APP-GW-GLR-111 Non-Proprietary

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1.0 INTRODUCTION

Assurance of long-term cooling (LTC) of the fuel elements comprising the core of a nuclear reactor is a regulatory requirement that must be met in order to license a light water reactor (LWR). In the most simplistic sense, LTC refers to the removal of the heat generated by the long-lived radioactive decay of the fission products and actinides generated during the normal operation of a nuclear reactor. The passive core cooling system (PXS) serves this function following a postulated loss-of-coolant-accident (LOCA).

During a LOCA, the PXS design utilizes automatic depressurization (ADS) valves connected to the hot legs (HL) to reduce the reactor coolant system (RCS) pressure in a controlled fashion to allow continued injection of water into the RCS. Figure 2-1 shows the HL ADS flow path. Once open, this flow path vents considerable quantities of water as well as steam from the RCS. The water that leaves through these valves carries boron and other chemicals out of the RCS which automatically limits the buildup of these chemicals in the core. For AP1000, the maximum concentration of boron in the core has been determined to be less than 7400 ppm boron. The solubility temperature of boron at this concentration is only 50 °F and as a result there is no concern with precipitation in the lower plenum during LTC following a LOCA.

This report will investigate the potential for chemicals plating out on the fuel rod surface areas and inhibiting heat transfer during LTC following a LOCA. The two most prevalent chemicals in the post LOCA containment water are considered in this investigation. These chemicals are boric acid (BA, H_3BO_3) dissolved in the water contained in the in-containment refueling water storage tank, core make-up tank, and accumulators; and trisodium phosphate dodecahydrate (TSP, $Na_3PO_4 \cdot 12H_2O$) contained in sump baskets (as crystals) used to neutralize the boric acid in order to mitigate corrosion and promote iodine retention post accident.

The evaluation of the potential for plate-out of unbuffered boric acid (BA) or buffered boric acid (BA+TSP), collectively referred to as the solute, will consider information resources such as phenomena identification and ranking tables (PIRT), Westinghouse bench-scale tests, open literature, and other docketed sources.

2.0 PHENOMENA IDENTIFICATION AND RANKING

A phenomena identification and ranking table (PIRT) was developed with figures of merit related to unbuffered/buffered boric acid transport, mixing, and precipitation modes in Reference 1 (WCAP-17047-NP). Although the PIRT was primarily developed for the current operating fleet of pressurized water reactors (PWRs), the phenomena and their ranking for the region of interest, the core, are equally valid for the AP1000 design. During the PIRT process, phenomena are ranked for importance and the state of knowledge is assessed based upon the diverse experience of the PIRT review team. The PIRT review team consists not only of subject matter experts from within the sponsoring organization but also of industry/academic experts external to the sponsoring organization. The external experts who comprise the PIRT review team represent the chemical, mechanical, and nuclear engineering disciplines:

- Dr. Ali Borhan, Professor of Chemical Engineering, The Pennsylvania State University
- Dr. John M. Cimbala, Professor of Mechanical Engineering, The Pennsylvania State University
- Dr. Lawrence E. Hochreiter, Professor of Mechanical and Nuclear Engineering, The Pennsylvania State University

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 2-1. Figure 2-1 depicts the expected solute concentration distribution in the reactor vessel. In the discussion of experiments, features of the test facilities are related back to the high ranked PIRT items in Table 2-1.

3.0 REVIEW OF AVAILABLE EXPERIMENTAL DATA

3.1 Westinghouse Single Rod Bench-Scale Experiment

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3.2 Review of Rod Bundle Test Facilities

Tests have been conducted in rod bundle facilities to study the potential for solute precipitation. These facilities are REWET-II, VEERA (References 2 and 3), and a full-height slab core facility (Reference 4). Notable features of these facilities are:

REWET-II (Figure 3.2-1 (A))

- Power to coolant volume ratio preserved
- Rod bundle geometry (19, 8-foot, 0.360-inch diameter heater rods)

VEERA (Figure 3.2-1 (B))

- Rod bundle geometry (1 full fuel assembly)
- Accurate simulation of core outlet structures

Modified VEERA (Figure 3.2-1 (C))

- Rod bundle geometry (1 full fuel assembly)
- Accurate simulation of core inlet and outlet structures (PIRT Item 7)

Slab Core Facility (Figure 3.2-2)

- Full height radial slab
- Full length heater rods
- Core inlet/outlet and upper/lower plenum structures accurately simulated (PIRT Item 7)

The scale and geometry of the test facility had a significant impact on the boric acid concentration distribution in the facilities listed above (PIRT Items 4 and 5). In the small-scale REWET-II facility, concentration gradients were observed, not only between regions, but also within regions. As the scale was increased in the VEERA and Slab Core facilities, mixing within regions such as the core was more complete and gradients were nearly eliminated in all but the single-phase regions (PIRT Item 10b). Also, as the scale increased and became more multi-dimensional, transport of solute between regions such as from the core to the lower plenum became more evident. The REWET-II facility showed limited transport from the core to lower plenum regions; whereas, the VEERA and Slab Core facilities clearly showed transport from the core to lower plenum once a threshold concentration/temperature difference was achieved.

In all of the test facilities, precipitation was not observed in the heated core region unless the two-phase mixture level was maintained within the heated section of the core region. The mixture level for the AP1000 during LTC always remains well above the decay heat region of the fuel rods. The mixture level is high enough that sufficient entrainment exits the HL ADS path to limit the maximum boron concentration to 7400 ppm. This same phenomenon was observed in the REWET-II when entrained droplets were allowed to escape the system as would occur for the AP1000 design (PIRT Item 3b).

Precipitation was observed to occur in the core outlet plenum and/or the reactor vessel lower plenum when the solute concentration reached the regional saturation limit that is primarily determined by the temperature of the region. Precipitation in the either the outlet or lower plenums occurred in the test facilities when the concentration reached the saturation limit for those regions. The maximum concentration expected in the AP1000 is 7400 ppm boron which corresponds to the saturation limit at 60 °F which is well below the minimum temperatures expected in the AP1000 outlet and lower plenums during LTC.

4.0 CONCLUSIONS

The [ ]^{a,c} does not fully address all the flow regimes found in a typical PWR core region during post-LOCA conditions. However, additional PWR heated rod testing in the presence of boric acid solution with decay heat level heat input and low pressure is available, has been reviewed, and can be applied to AP1000. Additional heated rod testing includes rod-bundle (VEERA/REWET Tests) geometries and multi-rod full-height slab core geometry. These tests generally show the following precipitation behavior in the heated rod region:

- No bulk precipitation in the heated rod region.
- No local precipitation observed in the non-boiling region of the heated rods.
- Some local precipitation may be observed in the boiling region near the two-phase mixture level for a core uncovery situation. The boric acid precipitation form is usually amorphous however and can be re-dissolved in the presence of continuous liquid phase which restores rod heat transfer and pressure drop characteristics.

The more prototypic geometries of the multi-rod and rod bundle tests displayed precipitation behavior in the heated rod region that was consistent with the [ ]^{a,c} for un-buffered boric and boric acid buffered with trisodium phosphate. [ ]^{a,c} showed that solute deposition on the heated rods could only be achieved by deliberately reducing the two-phase mixture level into the heated region. Deposition was not observed on the heated rods when they were covered by either a single or two-phase mixture at decay heat power levels.

Deposition of boric acid or boric acid buffered with trisodium phosphate is not expected to occur during post-LOCA conditions in the AP1000 since the heated core region has been shown to always be covered by a two-phase mixture (Reference 5).

5.0 REFERENCES

1. "Phenomena Identification and Ranking Tables (PIRT) for Un-Buffered/Buffered Boric Acid Mixing/Transport and Precipitation Modes in a Reactor Vessel During Post-LOCA Conditions," WCAP-17047-NP, ADAMS Accession Number ML09010338, May 2009.

2. Tuunanen, J. et al., "Experimental and Analytical Studies of Boric Acid Concentrations in a VVER-440 Reactor during the Long-Term Cooling Period of Loss of Coolant Accidents," Nuclear Engineering and Design, 1994.

3. Tuunanen, J., et al., "Long-Term Emergency Cooling Experiments with Aqueous Boric Acid Solution with the REWET-II and VEERA Facilities," Proc. Int. ENS/ANS Conf. on Thermal Reactor Safety, Vol. 4, Avignon, 1988.

4. W3FI-2005-0007, "Supplement to Amendment Request NPF-38-249, Extended Power Uprate, Waterford Steam Electric Station, Unit 3," ADAMS Accession Number ML050400463, February 2005.

5. "Impact on AP1000 Post-LOCA Long-Term Cooling of Postulated Containment Sump Debris," APP-PXS-GLR-001 Revision 4, February 2010.

Table 2-1 High Ranked PIRT Items for Boiling/Non-Boiling Regions of Core
Phenomena
1. Decay heat level
2. Boiling heat transfer regime (Nucleate, Transition, or Film Boiling)
3. Two-phase flow regime (bubbly, slug, etc.) a. Impact of bubble size/motion b. Impact of two-phase mixture level swell
4. Natural circulation transport due to "chimney effect"
5. Natural convection transport due to density instability analogous to Rayleigh-Bénard convection
6. Turbulent transport (dispersion) of solute
7. Core region hydraulic geometry
8. Sub-cooling of fluid entering core region
9. Nucleation characteristics of boiling surface (zircaloy tube)
10. Precipitation in boiling regime a. Impact of chemical solution solubility b. Impact of chemical solute transport/mixing (concentration distribution)
11. 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
12. Nucleation characteristics of chemical solution a. Impact of dissolved gases in chemical solution b. Impact of nucleation particles from sump in chemical solution
13. Surface wetting characteristics of chemical solution
14. 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

Table 3.1-1 AP1000 and Single Rod Test Range of Conditions

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a,c

Figure 2-1: Expected Solute Concentration Distribution during Post-LOCA Conditions

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Figure 3.1-1 Single Rod Test Article

a,c

Figure 3.1-2 Heater Rod Surface at 4, 11, 18, and 27-inch Elevations

a,c

Figure 3.1-3 Deposit Re-dissolution during Flood-up Following Uncovery (23-inch Elevation)*

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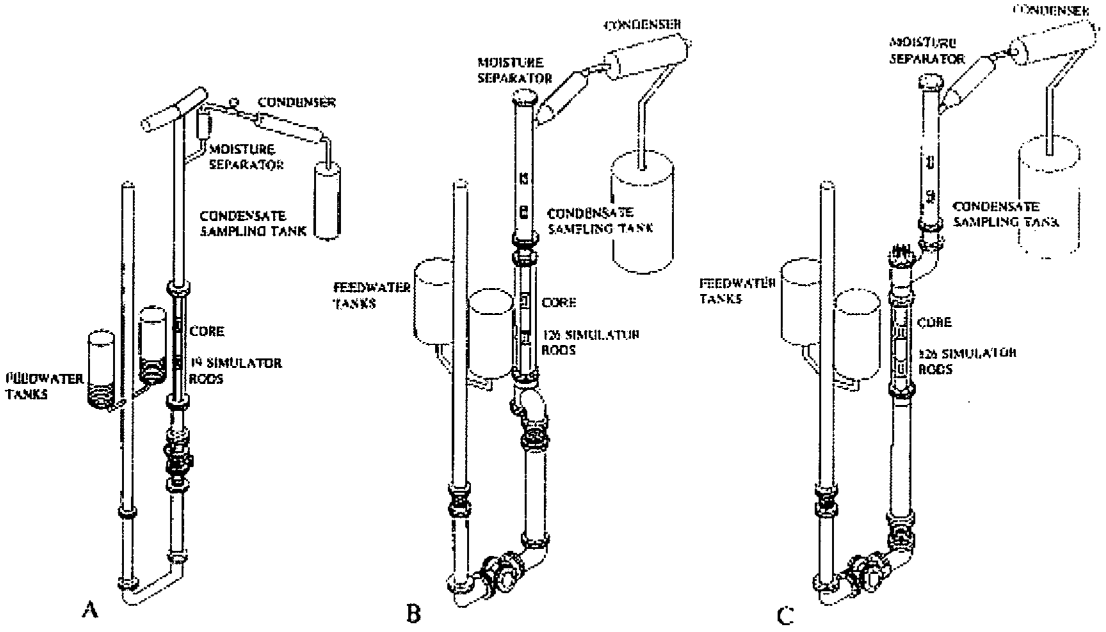

Figure 3.2-1 Diagram of REWET-II (A), VEERA (B), and Modified VEERA (C) Test Facilities

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Figure 3.2-2 Slab Core Test Facility