AUDIT REPORT

JUSTIFICATION OF COLD LEG BREAK

FIBROUS DEBRIS LIMIT DEFINED IN WCAP-17788-P

PRESSURIZED WATER REACTOR OWNERS GROUP

1. Scope and Purpose

By letter dated July 17, 2015, the Pressurized Water Reactor Owners Group (PWROG) submitted topical report (TR) WCAP-17788-P, "Comprehensive Analysis and Test Program for GSI-191 [Generic Safety Issue-191] Closure (PA-SEE-1090)" (Agencywide Documents Access and Management System (ADAMS) Accession No. ML15210A668), to the U.S. Nuclear Regulatory Commission (NRC) for review and approval. The TR is an approach to define an in-vessel fibrous debris limit and provides a means for increasing the approved fibrous debris limit used by licensees to resolve GSI-191.

Further justification for the fibrous debris limit in the cold leg break (CLB) methodology is required for the NRC staff to complete a safety evaluation (SE) of TR WCAP-17788-P. The PWROG intended to submit this supplemental information in support of WCAP-17788-P by November 30, 2015 (ADAMS Accession No. ML15245A649). The NRC staff conducted a regulatory audit on October 5, 2015, at the Westinghouse Electric Company office in Rockville, MD. This audit allowed NRC staff to review the details of the supplemental information to gain confidence that it will include the required justification to complete a SE. It also increased NRC staff knowledge on the subject to provide technical support to the PWROG during an upcoming Advisor Committee on Reactor Safeguards sub-committee meeting.

Specific topics discussed during the audit included:

- Description of large CLB loss-of-coolant accident (LOCA) scenario
- Overview of CLB methodology
- Identification of supporting technical bases
- Discussion of dominant physical phenomena
- Experimental evidence to support **[ ]** fiber limit
  - Fiber accumulation in low head/lower plenum region
  - Subscale alternate flow path testing
  - 3x3 rod bundle testing
  - Brine testing
- Analytical evidence to support **[ ]** limit
  - SKBOR sensitivities with various core inlet blockage scenarios
  - Other analytical evidence

The members of the Office of Nuclear Reactor Regulation (NRR) and PWROG employees present during the audit is included below.

Enclosure

NRC Audit Team:

- Ashley Smith, Technical Reviewer, Safety Issues Resolution Branch, NRR
- Steve Smith, Technical Reviewer, Safety Issues Resolution Branch, NRR
- Andrea Russell, Technical Reviewer, Safety Issues Resolution Branch, NRR
- Victor Cusumano, Chief, Safety Issues Resolution Branch, NRR
- Vesselin Palazov, Contractor, Information Systems Laboratories
- Caroline Tilton, Technical Reviewer, Technical Specifications Branch, NRR
- Jonathan Rowley, Project Manager, Licensing Processes Branch, NRR

PWROG Staff:

- Tim Croyle, Manager SEEI, Westinghouse Electric Company (Westinghouse)
- Jeff Brown, PWROG GSI-191 Team Lead, Arizona Public Service
- James Spring, Senior Engineer, Westinghouse
- Gordon Wissinger, Consulting Engineer, AREVA Inc. (AREVA)
- Kurt Flaig, PWROG GSI-191 Team, Dominion Power

2. Documents Audited

During the audit, the PWROG presented details of the following:

- CLB Evaluation Method (Volume 3 of WCAP-17788-P)
- Results of laboratory tests performed to support the CLB fibrous debris limit in the TR
    - Lower plenum debris accumulation study
    - Subscale alternate flow path tests
    - 3x3 rod bundle tests
    - Subscale brine test
- Results of sensitivity studies performed to support the CLB fibrous debris limit in the TR along with a description of key analytical assumptions
    - WCOBRA/TRAC thermal hydraulic studies
    - Studies using SKBOR

Given the expeditious audit request by the NRC staff, the materials presented were both preliminary and proprietary. Therefore, they are not be included with this audit report. The supplemental information provided by PWROG per the August 31, 2015, letter (ADAMS Accession No. ML15245A649) will include final results of the audit presentations.

3. Audit Activities and Observations

3.1 Description of Large CLB LOCA Scenario

The PWROG presented an overview of a large-break LOCA in the cold leg and the associated response in the reactor coolant system. Refer to Section 3.2 of Volume 3 of WCAP-17788-P for a detailed description.

3.2 Overview of CLB Methodology

The PWROG provided the NRC staff an overview of the CLB methodology in Volume 3 of WCAP-17788-P. As described in the submittal a major conservatism is that 100 percent of the debris that reaches the inner vessel remains there. That is, all debris is either caught at the core inlet, remains suspended in the liquid phase within the core region, or captures locally around spacer grids. No credit is taken for debris settling below the core region, debris collection in other regions of the inner reactor vessel, or penetration through the core region. The CLB methodology calculates the amount of fiber delivered to the core entrance between the initiation of sump recirculation and hot leg switchover using plant-specific values. The calculation ends when boric acid precipitation actions are taken (i.e., hot leg switchover) or when there is no more debris left in the recirculation sump.

3.3 Identification of Supporting Technical Bases

Currently, the PWROG plans to submit a revised version of Section 7 of Volume 1 of WCAP-17788-P describing CLBs. The supplemental information will also include a summary report of results for the 3x3 rod bundle tests, subscale brine tests, and thermal hydraulic cases using WCOBRA/TRAC.

3.4 Discussion of Dominant Physical Phenomena

Dominant physical phenomena are evaluated using phenomena identification and ranking tables (PIRTs). For the CLB methodology, two PIRTs were used. The first is the PIRT submitted as Volume 2 of WCAP-17788-P and the second is found in WCAP-17047-NP, which was submitted for information as part of the boric acid precipitation program. Both PIRTs have similar thermal hydraulic and debris transport sections used to identify dominant physical phenomena.

3.5 Experimental Evidence to Support **[ ]** Limit

The PWROG presented results of four different experiments to justify the CLB fibrous debris limits:

1. Lower plenum debris accumulation study
2. Subscale alternate flow path tests
3. 3x3 rod bundle tests
4. Subscale brine tests

Details of each experiment are discussed in the Sections 3.5.1 - 3.5.4.

3.5.1 Lower Plenum Debris Accumulation Study

This study was completed at the Applied Research Laboratory at The Pennsylvania State University. The testing was completed for an advanced plant design to observe debris collection at low pressure regions in the reactor vessel. It was noted that the plant design for this testing has one lower core support plate where current operating plant designs can have three or four similar plates below the core region (e.g., lower core plate, lower support plate, and diffuser plate(s)). The testing introduced batches of 50 grams of Nukon fiber (equating to more than **[ ]**) with flows between 3.6 and 10 gallons per minute (gpm).

Pictures of the debris settling on and around the lower core support plant and skirt region were presented to the NRC staff. It was seen that fiber settled in the low pressure regions and formed a visible layer of fiber on the lower core support plate. This shows that assuming all debris reaches the core is conservative. The amount of fiber that collected was not quantified and the capture efficiency was not recorded.

The PWROG presented the results of this study to show the ability of debris to settle in low pressure regions of the reactor vessel. The PWROG does not plan to credit the settling phenomena shown by these tests in WCAP-17788-P.

3.5.2 Subscale Alternate Flow Path Tests

The PWROG performed tests to determine if alternate flow paths in the core could be blocked by debris. A plate with a 0.75 inch perforated hole was subject to fiber and particulate at different flow rates. The fiber additions discussed during the audit were:

- Fiber only at about 0.75 gpm
- Fiber and particulate (particulate to fiber (p:f) ratio of 1:1) at about 2 gpm
- Fiber only at about 4 gpm

The total amount of debris added was 37.5 grams equating to 12.5 g/FA for each of the additions above.

A video of the test was viewed during the audit. No blockage of the alternate flow path was seen. The different flow rates did not have any visual effect on the test result. The change in pressure drop/resistance through the plate as a result of the fiber additions was negligible.

Like the lower plenum debris accumulation study discussed in Section 3.5.1, the results of this test will not be used by the PWROG to quantify fibrous debris limits for CLB in WCAP-17788-P.

3.5.3 3x3 Rod Bundle Tests

The PWROG presented test results of a 3x3 rod bundle test. The test was conducted in 2008 as part of the boric acid precipitation program to understand the impact heat transfer had on the mixing volume and the physical characteristics of the mixture. The results of these tests were previously submitted to the NRC staff for information in WCAP-17360-P.

The test rig consisted of a 3x3 array of heater rods. There is a downcomer available for flow to reach the fuel array, but, since the intent of the test was to understand the impact of heat transfer of mixing, a pump was not used to introduce a flow rate. The flow rate equaled the boil off rate from the heated rods. One hundred fifty g/FA of debris was added at a p:f ratio of 1:1.

Boric acid precipitation was visually observed on unheated surfaces of the test. There was no debris accumulation observed at the core inlet, but debris did settle along the bottom of the test rig and p-grid. The NRC staff expressed concerns regarding scaling in these tests.

The results of this test are currently being used in Volume 1 of WCAP-17788-P to justify the hot leg break in-core limit. The supplemental information to be submitted by the PWROG will include concise information as to why the results of this test apply under CLB conditions and how they can be used to justify the CLB limit in WCAP-17788-P.

3.5.4 Subscale Brine Tests

The last experiment presented by the PWROG was the subscale brine test. This test intended to show that a density gradient exists between the core and lower plenum under prototypical CLB conditions that will allow communication between the core and lower plenum. The NRC staff had the opportunity to witness one of these tests in February 2015. The trip report can be found at ADAMS Accession No. ML15083A511.

In support of the test specification for the proposed brine subscale adiabatic test loop, the PWROG referred to the work by J. Tuunanen, H. Tuomisto, P. Raussi, "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, Volume 148, Pages 217-231, 1994. The study describes two experimental apparatuses that were built and used in boron mixing tests performed at the Imatran Voima Oy (IVO) Hydraulic Laboratory in Finland. Each apparatus included a test section connected to a lower plenum simulator. The test section of both apparatuses simulated the lower part of a VVER-440 reactor fuel bundle and the core inlet nozzles. In the first test apparatus, the lower plenum simulator was represented by a 15 centimeter (cm) outer diameter tube. In the second apparatus, a lower plenum simulator with a height of 50 cm and a rectangular cross sectional area measuring 70 cm by 15 cm and having the same volume as the lower plenum of the first test apparatus was used. Brine was injected into the top of the test section and fresh water through the lower plenum simulator into the bottom of the test section and concentration measurements taken at various locations across the test sections and lower plena.

A similar concept was used by the PWROG in specifying and performing the subscale brine experiments. The devised test apparatus was based on an existing one previously used for head loss testing. It was noted that the PWROG test loop was resembling more closely the IVO test apparatus, which had its lower plenum represented by a pipe (one-dimensional) instead of a rectangular chamber (two-dimensional). The PWROG explained that the scaling of the tests was based on dimensionless groups represented by the Grashof (Gr) and Froude (Fr) numbers and presented formulations for both dimensionless groups. In addition, the Richardson number was also mentioned as relevant without providing specific additional information. The PWROG noted that the devised test loop was more closely resembling the IVO test apparatus, which had its lower plenum represented by a pipe (one-dimensional) instead of a rectangular chamber (two-dimensional).

The test uses a brine solution instead of a boric acid solution prototypic in a plant. It was noted by the PWROG that the viscosity of the brine solution is much greater than that of boric acid. Due to this, the Gr number was evaluated for each solution. The difference in viscosity has negligible effect on the Gr number, therefore, a brine solution was used for the tests.

Shakedown tests of the facility were run with debris additions ranging from **[ ]** and a flow rate up to 0.75 gpm. Pressure drop was less than 0.1 pounds per square inch differential during these tests. Results of the shakedown tests showed the weight percent of potassium bromide decreased as inlet flow increased. These results were expected and testing continued.

As the test results were shown to the audit team, the PWROG noted two items about the results. First, probe drift was experienced in some test results towards the end of testing. A pre- and post-calibration was applied to the results to account for uncertainty due to probe drift. Second, some results show erroneous flow rates where the flow rates recorded were higher than the capability of the pumps. This was attributed to problems with the flow meter. The PWROG determined that the flow measurement inaccuracies were caused by bubbles in the flow meter. The flow measurement inaccuracies were very large and likely not attainable with the installed pumps. It is unlikely that the flow rates changed because they were maintained by positive displacement pumps whose speeds were maintained on program. The PWROG substituted flow data from tests with the same flow profile to allow the results to be assessed meaningfully.

A case was run without any fiber addition. The results of this test were compared to the Epstein model prediction. The results compared fairly well verifying the adequacy of the test loop.

Afterward, a set of cases was run to determine repeatability of the test loop. For these tests, **[ ]** of fiber and brine was injected into the test loop and t = 0. These cases showed the test loop produced repeatable results.

Additional cases were run to understand the effect of delaying brine injection with respect to the timing of debris addition. The brine injection was delayed 1200 seconds (20 minutes) and compared to the results of injecting brine at t = 0. The results of delayed brine injection showed comparable boric acid buildup and breakthrough of the debris bed. The main driver of debris bed breakthrough is flow rate. Overall, delaying brine injection does not significantly change the resulting amount of boric acid buildup within the core region.

Another set of cases were run to determine the effect of particulates. Particulates caused a disruption in the debris bed to occur sooner than with fiber alone. The remaining cases were run without particulates to be conservative.

Ultimately, the effect of fiber on communication with the lower plenum was studied. The PWROG postulated that if there was breakthrough of the fiber bed before the solubility limit of boric acid was reached, communication between the core and the lower plenum regions would be established. Debris loads of **[ ]** were tested for both Westinghouse and AREVA fuel assembly designs using an unbuffered brine solution. For the first six or so tests the flow rate started at 0.8 gpm and was reduced, following a decay heat curve, to 0.5 gpm where it was held constant for the remainder of the test. For the remaining tests, the flow rate was started at 0.8 gpm and decreased continually for the entire test duration. It really depends on how long the test was conducted but in most cases the ending flow rate for these tests was between 0.5 and 0.25 gpm. The tests were run at atmospheric pressure. Results of these tests are in the table below.

Vendor	Debris Load **[**		
Westinghouse			
AREVA			**]***

* PWROG noted that using a buffered solution will increase the solubility limit by ~5 percent so that there would be enough margin for the AREVA tests to pass at **[ ]**. Also, crediting containment accident pressure would have a similar effect on the solubility limit in solutions at saturation temperature as it increases with increasing pressure.

3.6 Analytical Evidence to Support **[ ]** Limit

The PWROG summarized thermal hydraulic analysis completed to support the CLB limit. Two codes were used for this analysis: SKBOR and WCOBRA/TRAC.

3.6.1 SKBOR Studies

The PWROG boric acid precipitation evaluation model, SKBOR, was described to the NRC staff. SKBOR is used by Westinghouse to assess hot leg switchover timing during CLB analyses. An overview of the equations that create the main framework of the code were presented. The code uses a mass balance to determine the mass of boric acid and water in the core and sump as a function of time. Basically, the mass of boric acid in the sump is decreasing over time as the mass of boric acid in the core is increasing as a function of time.

Recently, SKBOR was updated to include 50 percent of the lower plenum volume as part of the core volume. The same fluid conditions are assumed to be present within the lower plenum and core in these calculations.

Even though SKBOR seems like a simplistic set of mass balance equations, Westinghouse maintains the necessary quality control process for the code since it is used for licensing basis applications. Results of the code have been validated against BACCHUS test results and Westinghouse may validate results of the code against PKL tests in the future, provided the PKL results are made available.

3.6.2 Other Analytical Evidence

Results of thermal hydraulic analyses using WCOBRA/TRAC were presented during the audit. These analyses were completed to support the long term core cooling conclusions in WCAP-16793-P-A. These sensitivity studies intended to illustrate the flow dynamics that could be experienced at the core inlet during a CLB LOCA. The WCOBRA/TRAC evaluations simulated the effects of debris buildup at the core inlet by ramping-up the dimensionless friction factor (CD) at the core inlet to a large number, resulting in a reduction of flow. After the core inlet resistance ramped up to its maximum value of about CD = 10^9 (which essentially eliminates all flow through the path), the simulations were run out to 40 minutes to show that the flow rate supplied to the core would be sufficient to remove decay heat and maintain a coolable core geometry with 99.4 percent of the core inlet area blocked.

4. Closing Briefing

Throughout the audit, the PWROG presented evidence to support the CLB limit of **[ ]** as defined in WCAP-17788-P. The NRC staff better understands this evidence and will consider it going forward with the TR review.

The PWROG intends to use results from the 3x3 rod bundle test and WCOBRA/TRAC analytical work to support that debris **[ ]** for CLB cases. The PWROG intends to use results from the brine tests to support **[ ]**.

Based on the audit, the NRC staff understands that the information used from the 3x3 rod bundle test, brine test, and WCOBRA/TRAC will be either referenced or included in the supplemental information provided pursuant to the August 31, 2015, letter.

Overall, the audit was effective and the objectives defined in the audit plan were accomplished. The information and knowledge obtained will assist in review of the TR.