PWROG
PWR Owners Group

GSI-191 Path Forward In-vessel Effects

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Agenda

- Background
- Overview
- Test Facility Evaluation
- Repeatability Evaluation
- Test Plan
- Alternate Flowpath Methodology

Background

- GL 2004-02 issued to identify and request utilities to address the affect of debris from the sump on long-term core cooling (LTCC).
- Industry guidance for in-vessel effects: WCAP-16793-NP
  - Demonstrate there is reasonable assurance the LTCC requirements of 10 CFR 50.46 are satisfied in the event debris and chemical products in the recirculating coolant are delivered from the containment sump to the core.
  - Applicable to fleet of PWRs, regardless of design.

Background

- WCAP-16793-NP combined the debris limits defined by fuel assembly (FA) testing with analysis and evaluation to demonstrate adequate heat-removal capability for all plant scenarios including:
  - Blockage at the core inlet
  - Collection of debris at spacer grids
  - Deposition of fiber and chemical precipitates on fuel rods
- The assurance of LTCC demonstrated in WCAP-16793-NP Rev 1 is applicable to the fleet of PWRs, regardless of design

Show: REASONABLE ASSURANCE of LTCC

$T_{clad} \leq 800$ F

(1) Sufficient flow enters core to remove DH and make up for fluid that is lost to boiling:

$dP_{available} > dP_{debris}$

- FA Testing
- W/CT Analysis

(2) Local buildup of debris at spacer grids does not impede core cooling

- FA Testing
- ANSYS Analysis

(3) Deposition on fuel rods does not impede core cooling

- LOCADM
- Hand Calculations
- ANSYS Analysis

$t \leq 50$ mils

(1) Deposition by impurities (debris and/or chemicals)

- LOCADM

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Blockage at the Core Inlet

- Adequate flow to remove decay heat will continue to reach the core even with debris buildup at the inlet. Supported by:
  - FA testing demonstrating that the head available to drive flow into the core is greater than the head loss at the inlet due to a debris buildup

$$\Delta P_{available} > \Delta P_{debris}$$

    - $\Delta P_{available}$ is a plant-specific value. PWROG is providing a tool for utilities to determine their actual $\Delta P_{available}$
    - ΔP_{debris} is determined by testing.
  - W/CT
    - Provided insight into core flow patterns considering significant blockage at the core inlet
    - Demonstrated that sufficient liquid could enter the core to remove decay heat should an extensive blockage occur
- Details in Sections 3 and 9 of WCAP-16793-NP, Rev 1.

Show: REASONABLE ASSURANCE of LTCC

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Blockage at Spacer Grids

- Decay heat will continue to be removed even with debris collection at FA spacer grids. Supported by:
  - FA Testing
    - At debris limits, flow will continue through blockage.
  - ANSYS Analysis
    - Finite element analysis demonstrated 50 mils of buildup does not impede core cooling.
- Details in Section 4 of WCAP-16793-NP, Rev 1.

Show: REASONABLE ASSURANCE of LTCC

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- FA Testing
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(2) Local buildup of debris at spacer grids does not impede core cooling

- FA Testing
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- Hand Calculations
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$t \leq 50$ mils

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- LOCADM

Deposition on Fuel Rods

- Decay heat will continue to be removed even with debris and chemical deposition on fuel rods. Supported with:
  - LOCADM
    - Plant-specific calculation.
  - Hand Calculations
    - Maximum surface temperature with 50 mils of deposition plus scale and oxide layers is less than 800 F.
  - ANSYS Analysis
    - Finite element analysis demonstrated 50 mils of buildup does not impede core cooling.
- Details in Sections 5, 6, and 7 of WCAP-16793-NP, Rev 1.

Show: REASONABLE ASSURANCE of LTCC

$T_{clad} \leq 800$ F

(1) Sufficient flow enters core to remove DH and make up for fluid that is lost to boiling:

$dP_{available} > dP_{debris}$

- FA Testing
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(2) Local buildup of debris at spacer grids does not impede core cooling

- FA Testing
- ANSYS Analysis

(3) Deposition on fuel rods does not impede core cooling

- LOCADM
- Hand Calculations
- ANSYS Analysis

$t \leq 50$ mils

(1) Deposition by impurities (debris and/or chemicals)

- LOCADM

Deposition on Fuel Rods

- Deposition by impurities (debris and/or chemicals) cannot exceed a buildup of 50 mils. Supported with:
  - LOCADM
    - Plant-specific evaluation.
    - Includes "bump-up factor" to account for fiber adherence.
- Details in Section 7 of WCAP-16793-NP, Rev 1.

Conclusion

- WCAP-16793-NP Rev 1 combined the debris limits defined by fuel assembly (FA) testing with analysis and evaluation to demonstrate adequate heat-removal capability for all plant scenarios including:
  - Blockage at the inlet
  - Collection of debris at spacer grids
  - Deposition of fiber and chemical precipitates on fuel rods
- The assurance of LTCC demonstrated in WCAP-16793-NP Rev 1 is applicable to the fleet of PWRs, regardless of design

FA Test Conservatisms

- Debris introduction sequence – particulate, fiber, chemical precipitates
  - Fiber & Particulate alone well within limits
- Uniform flow
- Constant, high flow rate
  - ~15x greater than the core boiloff rate
- Recirculation for multiple opportunities to capture debris
- No boron
- No buffer
- Boiling neglected
- Low temperature (70 F)
- Bypass flow paths neglected

Overview

- Westinghouse and AREVA conducted FA testing at separate facilities:
  - AREVA tested at Continuum Dynamics, Inc. (CDI)
  - Westinghouse tested at the Westinghouse Research and Technology Unit (RTU)
- Proposed path forward is designed to resolve facility questions by quantifying several of the conservatisms in the test process that do not model prototypic conditions.
- Recent testing has disclosed that there are differences in the behavior of debris collection on Westinghouse and AREVA fuel assemblies at different particulate to fiber (p:f) ratios.
- These behavioral differences are small in comparison to the conservatisms inherent in the fuel assembly tests.
- Conservatisms inherent in the FA testing show a single fiber load can be defined for both Westinghouse- and AREVA-fueled plants.
  - Proposed testing will be performed at one facility with one FA.

Overview

- The following slides summarize:
  - The suitability of testing at a single facility,
  - The repeatability of the test process and results,
  - The planned test parameters, and
  - Analytical methodology on alternate flow paths that can be used to further demonstrate reasonable assurance of LTCC.
    - This methodology augments the existing defense in depth analyses supporting the conservative nature of the FA test program
      - WC/T, ANSYS, Hand Calculations

Suitability of Testing at a Single Test Facility

Test Facility Evaluation

- Westinghouse and AREVA conducted the FA testing for the PWROG at separate test facilities.
  - To ensure consistency between facilities, Westinghouse and AREVA worked together to develop a common test protocol to be followed by each test site.
  - This conservative protocol was shared with NRC staff during development.
- Both test facilities used a representative FA design consistent with FA designs currently employed in operating PWRs.
  - The flow rates, temperature and testing methods were selected to bound conditions expected following a postulated LOCA.
  - The test method involved adding various amounts of debris materials to the test loop and measuring the pressure drop across the test assembly in order to define a debris limit that would guarantee LTCC.
  - Debris loads included fibers, particulates, and chemical precipitates that may form in the containment water pool.

Test Facility Evaluation

- During FA testing, PWROG discovered the impact of particulate-to-fiber (p:f) ratio on results.
  - Tests at the limiting hot-leg break p:f ratios resulted in different fiber limits for AREVA and Westinghouse.
- NRC staff asked the PWROG to address differences between limits by conducting a cross-test. The results of this test would identify what (if any) influence facility differences had on the results.
- PWROG agreed to test the AREVA FA at the Westinghouse facility:
  - Prior to testing AREVA FA, Westinghouse was tasked with repeating two PWROG tests.
    - These tests resulted in higher dP values than the original tests.
    - Root Cause Investigation (RCI) conducted by Westinghouse to identify cause.
  - AREVA performed a repeat of an earlier test (conducted at CDI) at Westinghouse RTU.
    - Differences in debris bed formation were observed.
    - The rate of increase in dP with fiber addition was much higher at RTU than CDI.
    - Final dP with only particulate and fiber was within ± 25% of dP value collected at CDI.

Test Facility Evaluation

- As a result of the RCI, Westinghouse conducted additional FA testing.
  - Due to the new data from the Westinghouse test loop at low p:f ratios, the Westinghouse and AREVA results at these conditions have been re-evaluated.
  - This re-evaluation supports the conclusion that the differences in test facilities are small relative to the conservatisms in the test procedure; therefore testing can be performed at either facility.
  - Up-coming slides will support these statements.
- Additional testing will be conducted at a single test facility to quantify several conservatisms inherent in the testing and define a single bounding fiber limit for the operating fleet.

Test Facility Evaluation

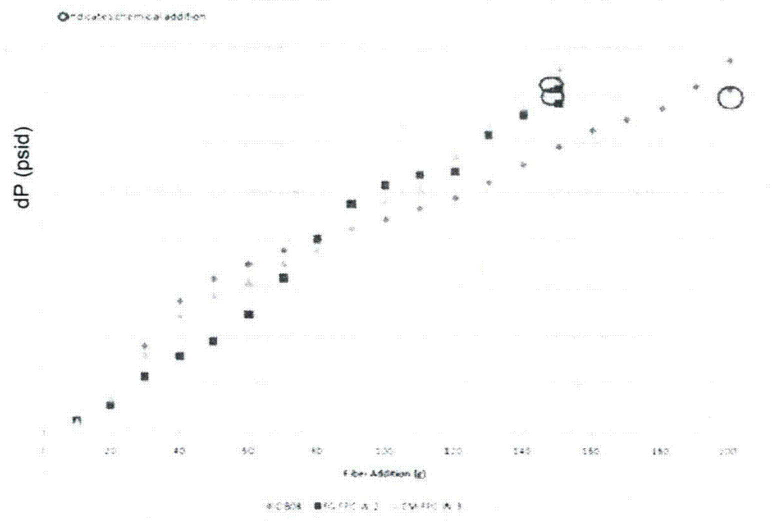
- The following slides provide the information necessary to demonstrate that testing at one facility is both bounding and applicable to the entire operating fleet:
  - Comparison of High Particulate Data (p:f >10:1)
  - Comparison of Low Particulate Data (p:f <10:1)
  - Cross Test Results
  - Demonstrate Applicability of Results from One Facility to Entire Fleet

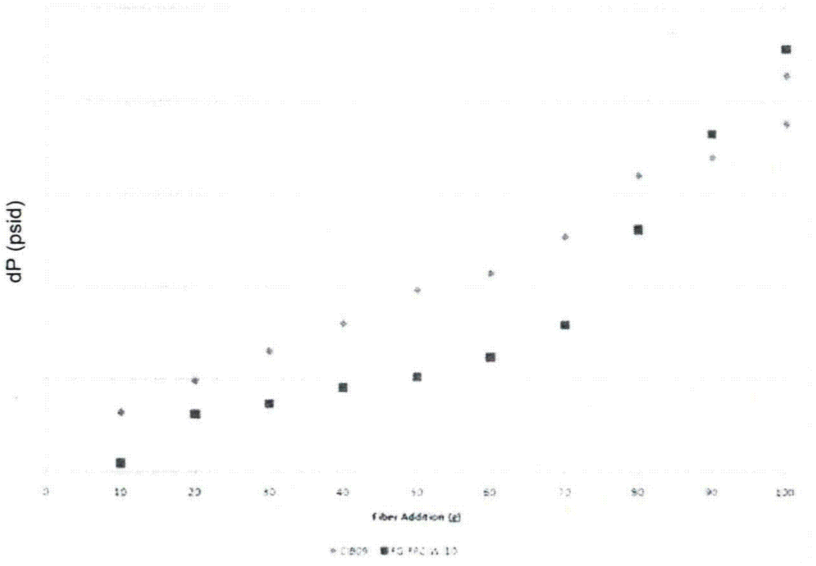
Test Facility Evaluation

- Comparison of High Particulate Data
  - Test results show good agreement regardless of test site or FA type.
  - Test results show good agreement at both hot-leg and cold-leg break conditions.
- Based on industry data: the majority of plants are operating at debris loads in excess of the limiting p:f ratio. At these conditions, facility differences do not exist.

Test Facility Evaluation

- **Comparison of High Particulate Data**





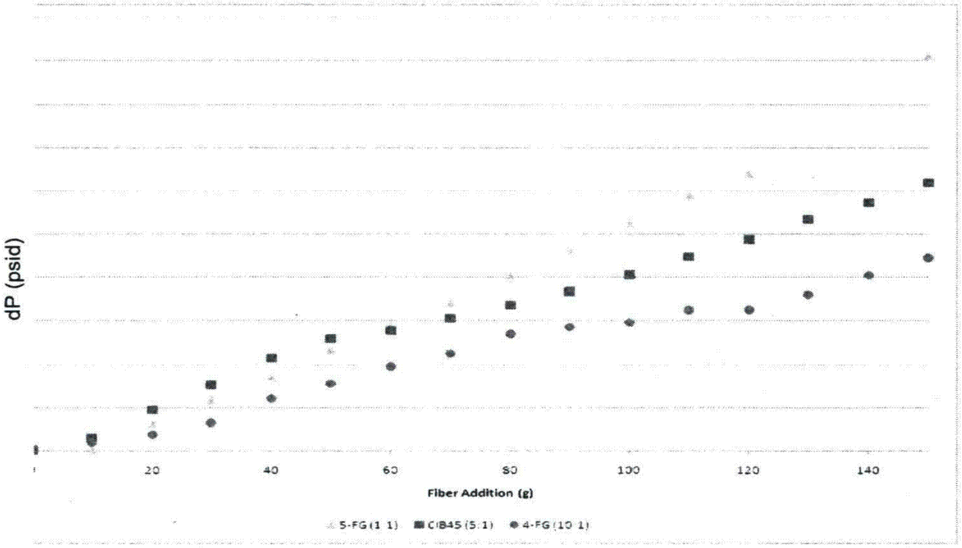
- Westinghouse and AREVA **Hot-Leg Break** Data at High P:F Ratios
- Westinghouse and AREVA **Cold-Leg Break** Data at High P:F Ratios

Test Facility Evaluation

- Comparison of Low Particulate Data
  - Data collected from tests conducted with AREVA and Westinghouse FAs at hot-leg break conditions and low p:f ratios resulted in a different fiber load criterion. It was initially concluded that the FA design caused different behaviors at low p:f ratios.
  - AREVA and Westinghouse tests conducted with similar low p:f debris loads at hot-leg break conditions have been re-evaluated.
  - Based on a comparison of these data, test results from the Westinghouse FA reasonably represent test results from the AREVA FA and vice versa.

Test Facility Evaluation

- **Comparison of Low Particulate Data**



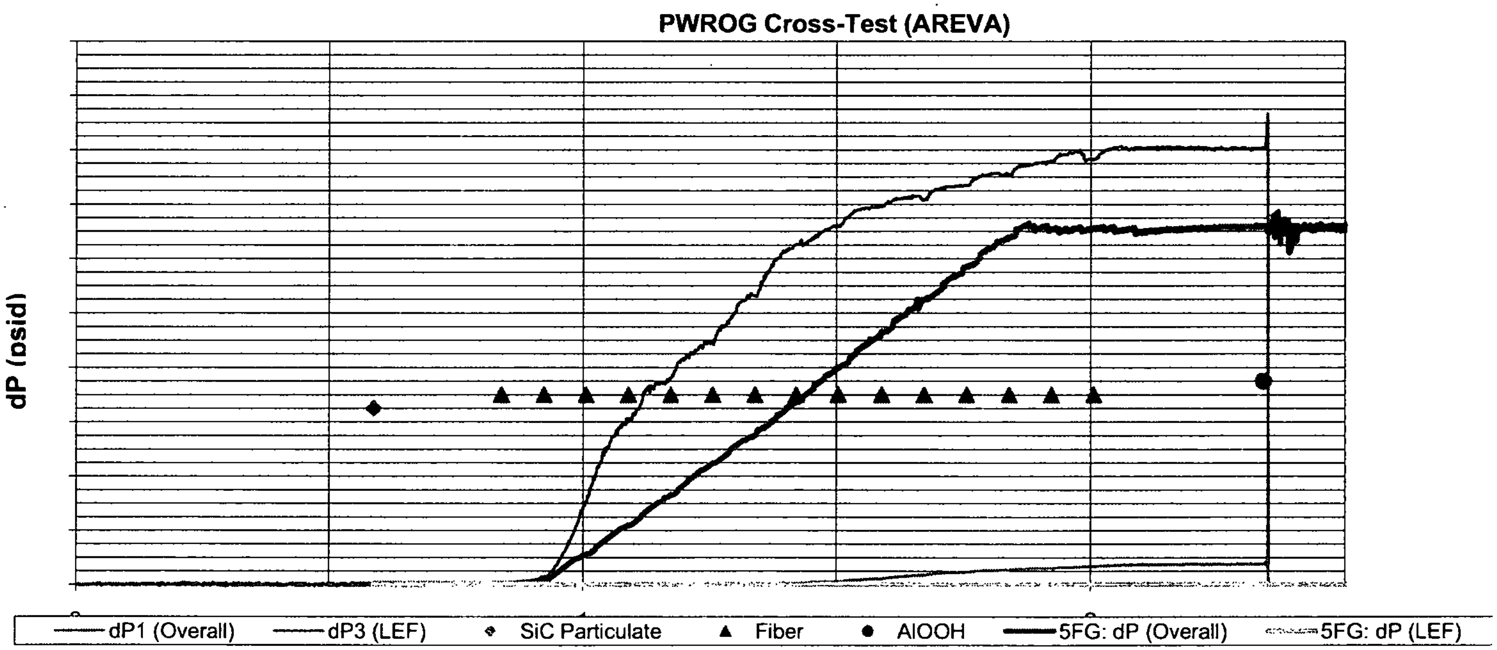
  - The data from the Westinghouse conducted test at a p:f equal to 5:1 is between the AREVA tests conducted at p:f ratios equal to 1:1 and 10:1, as expected.

Test Facility Evaluation

- Cross Test
  - Disparity of 10x fiber tolerance between Westinghouse and AREVA raised questions on test facilities and prompted cross testing.
  - Both AREVA and Westinghouse had previously conducted tests with 150 grams of fiber at a hot-leg break conditions and a p:f ratio equal to 1:1 in their respective test facilities.

Test Facility Evaluation

- Cross Test Results with the AREVA FA showed:
  - The rate of dP increase and the distribution of debris differed between facilities.
  - The maximum dP due to debris and the final dP results were consistent – regardless of test facility.
  - The FA test program is designed to define the maximum dP due to debris.

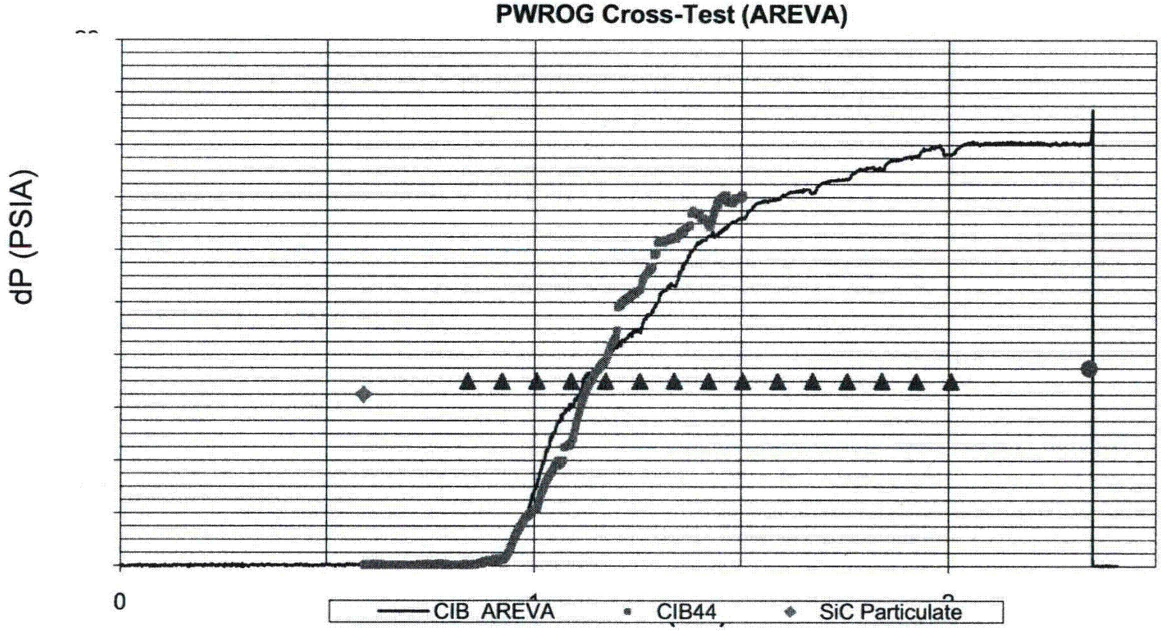


Test Facility Evaluation

- Root Cause Investigation (RCI)
  - Westinghouse benchmark tests at RTU prior to cross test indicated larger variability than expected.
  - RCI performed to identify most likely reasons for this variability.
  - When key causes were addressed with follow up testing, variability RTU results significantly reduced.
    - Fiber tolerances more consistent with AREVA
  - Based on these results it is concluded that facility differences are minimal in comparison to testing conservatisms

Test Facility Evaluation

- **Cross Test Results**
  - The 150g 1:1 p:f ratio baseline test conducted with the Westinghouse FA (CIB44) is compared to the cross-test results



  - This demonstrates that similar dP values were repeated at the Westinghouse test loop even with differing FAs

Test Facility Evaluation

- Applicability of AREVA FA test results (at CDI) to the entire fleet:
  - Currently, the fiber tolerance defined by testing to date for AREVA-fueled plants is less than the fiber tolerance defined for Westinghouse-fueled plants.
  - Testing at CDI with the AREVA FA will define a single fiber limit that is applicable to both Westinghouse- and AREVA-fueled utilities.
  - All results obtained from the conservatisms testing of the AREVA FA at CDI will therefore be bounding for the entire fleet.

Test Facility Conclusions

- Conservatism testing will be conducted at CDI with the AREVA FA and the results will be applicable to the entire operating PWR fleet for the following reasons:
  - At high p:f ratios (>10:1), results are consistent between facilities.
  - At low p:f ratios (<10:1), results are consistent between facilities.
  - Testing at CDI resulted in the definition of a lower fiber limit.
  - Further testing at CDI will provide the best opportunity for quantification of conservatisms.

Test Plan

Test Plan

- The testing will be conducted at CDI at hot-leg break conditions with the AREVA FA and will incorporate/quantify the combined effects of:
  - Higher temperatures
  - Boron and buffering agents
  - Rate of chemical introduction and solubility
  - Boiling

- NOTE: The test parameters listed in the following slides are still preliminary.

Test Plan: Effect of Increased Temperature

- Over the first 30 days following a LOCA the sump temperature is likely to range from ~250°F to 130°F
- *Previous test conditions:*
  - Although the post-LOCA sump temperature will remain above 130°F, FA testing was performed at ambient conditions (~70°F).
  - This temperature was chosen to maximize the water viscosity and promote higher head losses through the debris beds.

Test Plan: Effect of Increased Temperature (cont.)

- *Proposed change to test conditions:*
  - Will test with mixing tank coolant = 120°F.
    - Temperature is representative of minimum sump temperature that will be experienced after a LOCA.
  - Darcy's Law explains behavior:

$$\frac{\Delta P}{\omega} = \frac{L\mu}{\kappa}$$

where:

ΔP = pressure drop across bed
ω = flow velocity (ft/s)
L = length of porous bed (ft)
μ = dynamic viscosity (lbf=sec/in^2)
κ = permeability (ft^2)

- Increased temperature results in decrease in viscosity.
- As viscosity decreases, pressure drop decreases

Test Plan: Boron

- Boron used by all plants (achieves shutdown margin)
- *Previous test conditions:*
  - Boron was not included in previous testing.
- *Proposed change to test conditions:*
  - Boron concentration of mixing tank will be set between 800 and1200 ppm Boron.
  - Value representative of minimum sump Boron concentration of operating fleet.
  - This will make the test coolant prototypic of post-accident conditions.

Test Plan: Buffer

- Buffering used by all plants (neutralize sump pH)
- *Previous test conditions:*
  - Buffer was not included in previous testing.
- *Proposed change to test conditions:*
  - Sodium tetraborate (NaTB) will be used as the representative buffer. (Next slides discuss this selection.)
  - Only enough NaTB to maintain a pH of 7 in the mixing tank will be used. This is conservative as the neutral pH will mitigate any chemical surrogate solubility concerns.

Test Plan: Buffer – Selection of NaTB

- Research conducted to evaluate properties of buffered and un-buffered boric acid solutions under conditions simulating that experienced during the LTCC phase following a LOCA. Research is summarized here:

Coolant	Density (lbm/ft^3)	Viscosity (lbm/ft-s)	Surface Tension (lbf/ft)
Pure Water	61.2	2.83E-04	0.0045
NaOH	61.3	3.04E-04	0.0044
TSP	61.7	3.05E-04	0.0043
NaTB	61.5	3.10E-04	0.0040

- As previously stated, as demonstrated by Darcy's Law, an increase in viscosity results in an increase in head loss.
  - NaTB has the highest viscosity of all buffers. Therefore, testing with this buffer will bound all buffers.

Test Plan: Effect of Buffer & Boron on Chemical Surrogate

- AlOOH will continue to represent all chemical precipitate products.
- Aluminum solubility decreases in a boron-free environment.
  - Mitigating action: Bounding amounts of chemical surrogate will be added to mixing tank to ensure solubility limit is exceeded and chemical surrogate can effectively plug debris bed.
- Research has demonstrated efficiency of surrogate on plugging debris bed is less at elevated pH values.
  - Mitigating action: Only enough buffer will be added to mixing tank to maintain pH of 7 to avoid chemical solubility issues.

Test Plan: Rate of Chemical Introduction and Solubility

- Chemical products form slowly in the post-LOCA sump pool
- *Previous test conditions:*
  - This behavior was not modeled in the PWROG FA test program.
  - Chemical surrogate was added to the loop in excess of production rate and expected concentration resulting in a conservative increase in head loss.

Test Plan: Rate of Chemical Introduction and Solubility (cont.)

- *Proposed change to test conditions:*
  - Expected chemical precipitate production rate of the utilities will be evaluated.
    - The quantity of chemicals used will bound all plants.
  - Chemical surrogate will be introduced at a rate that is two times greater than that of the worst case fleet scenario.
  - Chemical concentration in the mixing tank will be measured.
  - Full chemical load of previous tests will be added to test to ensure maximum dP is recorded with fiber load.

Test Plan: Boiling

- For the most limiting blockage, the flow to the core may be just enough to remove core decay heat, at which point boiling will commence.
- Boiling in a hot-leg break provides a greater core void fraction than used to calculate the available driving head.
- Boiling at any debris blockage will disrupt the blockage.
- Disruption of the debris blockage will result in a lower overall core dP.
- *Previous test conditions:*
  - Boiling was not modeled in the PWROG FA test program.
  - Testing was performed at ambient conditions at a constant flow rate assuming a water solid core.

Test Plan: Boiling (cont.)

- *Proposed change to test conditions:*
  - If the dP exceeds the acceptable limits, the test will then transition to simulate coolant spilling over the steam generator tubes with an immediately decrease in flow rate.
  - Introduce nitrogen into the loop to simulate boiling in the upper part of the assembly.

Test Plan: Summary

- Testing will be conducted at CDI with AREVA FA to quantify select conservatisms of the initial test program.
- The new fiber limit will be applicable to both Westinghouse- and AREVA-fueled plants.

Variable	**Planned Test Parameter***
Flow (gpm)	44.7
Final P:F Ratio	1:1
Particulate = silicon carbide	TBD g
Fiber = Nukon®	TBD g
Chemical = AlOOH	830 g
Temperature	120°F
Boron	800 – 1200 ppm
Buffer = NaTB	Equal to amount required to maintain mixing tank pH of 7
* Preliminary values	

Alternate Flow Path