WCAP-16793-NP, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid"

December 17, 2009

Agenda

- Background
- FA Testing
  - Overview
  - Microtherm
  - CL Breaks
  - HL Breaks
- Conclusions & Acceptance Criteria

Background/Overview

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)
- Utility responses to GL must include:
  - Basis for concluding that that adequate ECCS flow is available for long-term core cooling in spite of blockage at flow restrictions downstream of the screens (i.e. downstream effects)
  - Description of modifications, if needed, to provide for adequate ECCS flow
- Industry guidance for fuel effects
  - WCAP-16793-NP

Background - WCAP-16793-NP Basis

- Demonstrate that there is reasonable assurance long-term core cooling requirements of 10 CFR 50.46 are satisfied with debris and chemical products in the recirculating coolant delivered from the containment sump to the core
- Draw from and address:
  - The design of the PWR from all US vendors,
  - The design of the open-lattice fuel from all US vendors,
  - The design and tested performance of replacement containment sump screens from all US vendors, and tested performance of materials inside containment
- Applicable to the fleet of PWRs, regardless of the design (B&W, CE, or Westinghouse)

Background

- It is the combination of debris limits defined by fuel assembly (FA) testing with the evaluations presented in WCAP-16793-NP that demonstrate adequate heat-removal capability for all plant scenarios:
  - Blockage at the inlet
  - Collection of debris at spacer grids
  - Deposition of fiber and chemical precipitates on fuel rods

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 with:
  - Demonstrate 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
    - Provides insight into core flow patterns even with a significant blockage at the core inlet
    - Demonstrate that sufficient liquid could enter the core to remove core decay heat should an extensive blockage occur
- Details in Sections 3 and 9 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

Blockage at Spacer Grids

- Decay heat will continue to be removed even with debris collection at FA spacer grids. Supported with:
  - 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

T_{clad} ≤ 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 ≤ 50 mils

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

- 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
- 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

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.

WCAP-16793-NP, Rev. 1

- In April 2009, WCAP-16793-NP, Revision 1 was published.
- Document provided detail discussions of the previously discussed topics with the intent of demonstrating reasonable assurance of LTCC in the event of a LOCA.
- Revision 1 included FA test results and proposed debris limits. References:
  - AREVA – 51-9102685-000
  - Westinghouse – WCAP-17057-P, Rev. 0

Request for Additional Information

- Upon review of WCAP-16793-NP, Rev. 1 and supporting FA test reports, the staff requested additional information (RAI).
- 43 RAIs submitted.
  - 27 draft responses submitted and accepted
  - Remaining 16 require additional test data
- The RAIs that require testing can be categorized as follows:
  - Microtherm
  - Cold-Leg Break Data
  - Hot-Leg Break Data

Request for Additional Information

- The following slides discuss:
  - Comparison of AREVA & Westinghouse test results
  - Overview of FA test & debris bed formation
  - RAIs: Microtherm
  - RAIs: Cold-Leg Break
  - RAIs: Hot-Leg Break

Fuel Assembly Testing: Comparison of AREVA & Westinghouse Test Results

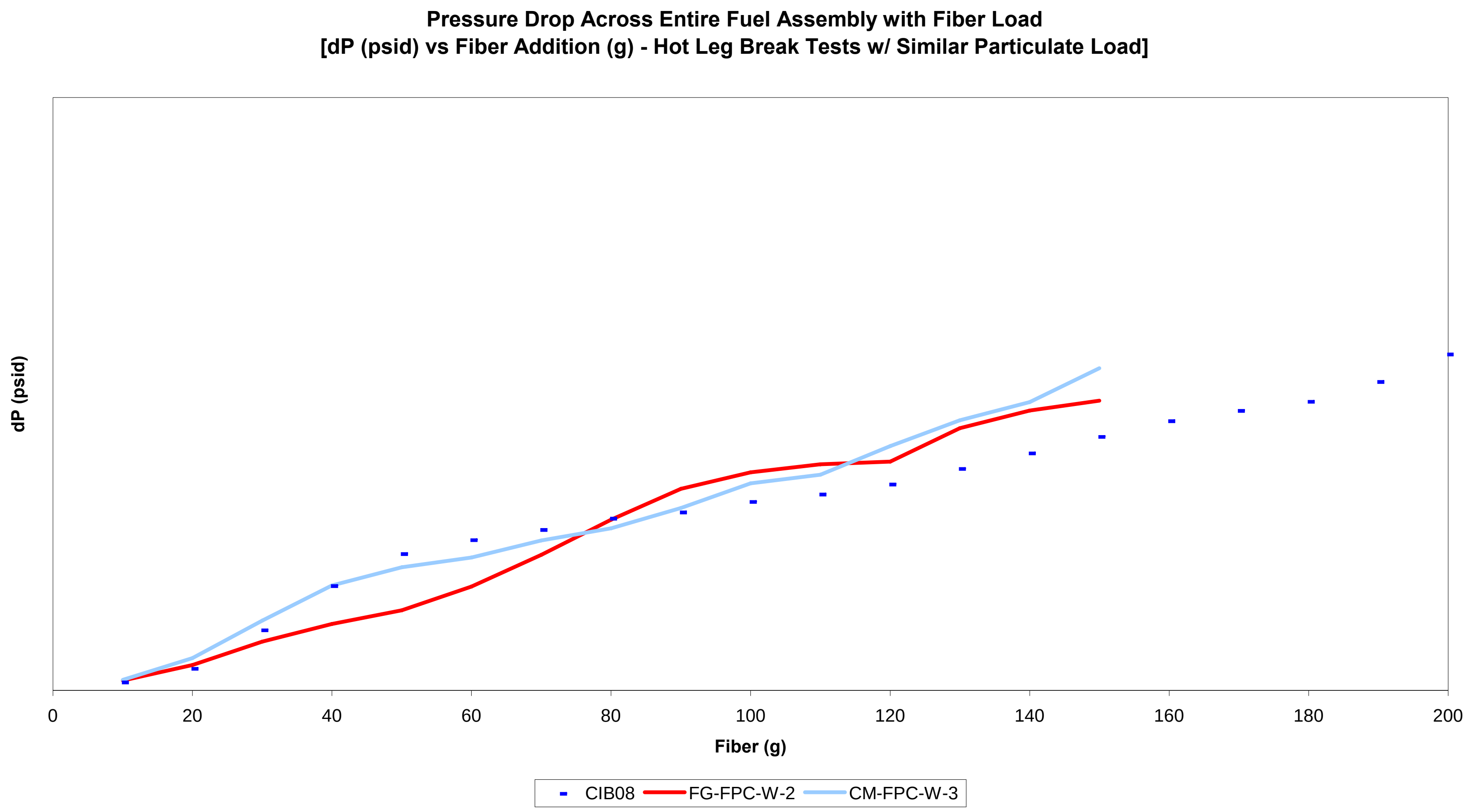
FA Testing

- Westinghouse and AREVA conducted FA tests at independent facilities.
- Comparison of test results from high particulate tests showed similar trends.

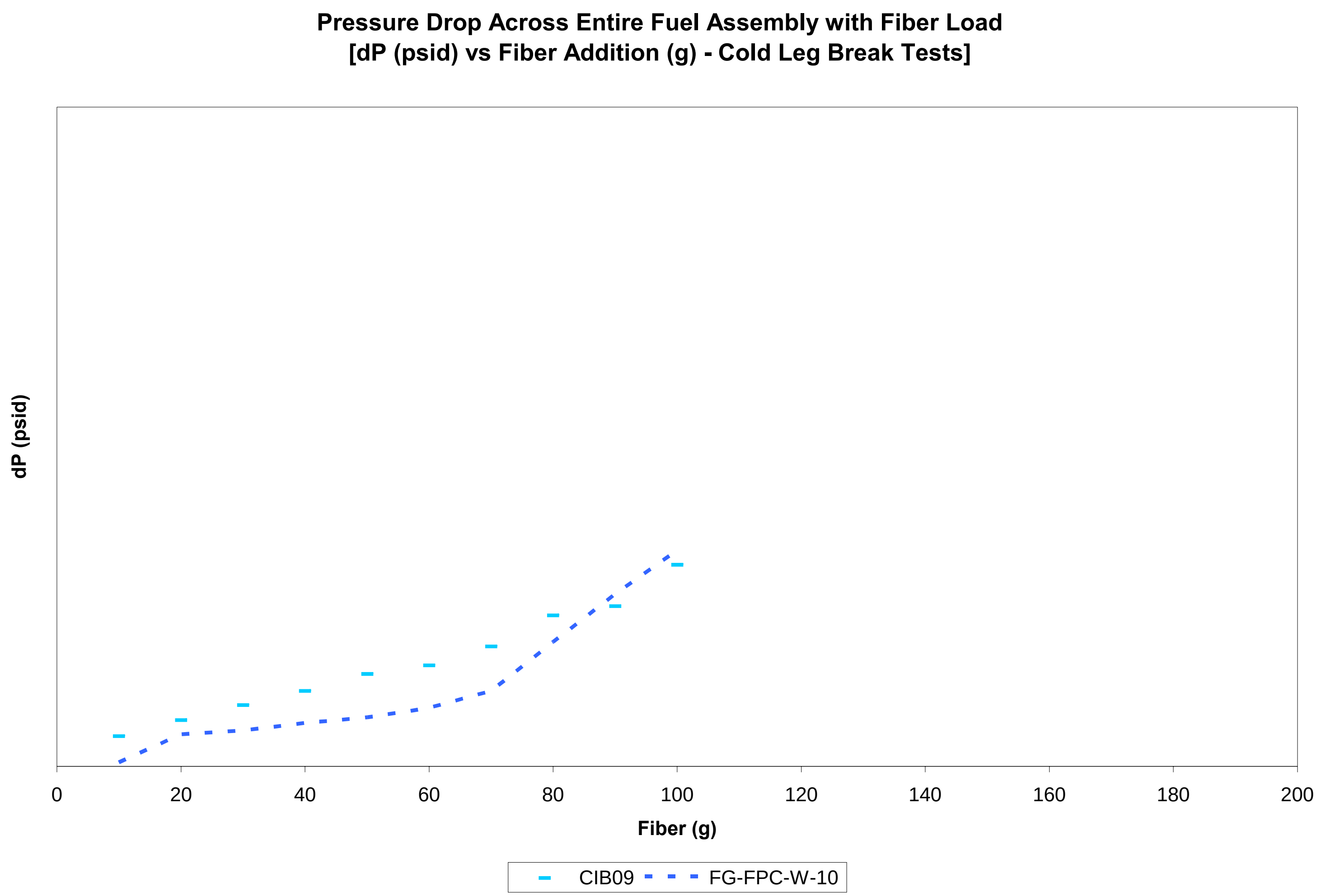
W & A Test Parameters

Test No.	Flow Rate (gpm)	Nukon (g)	Particulate (lbm)	AlOOH (g)
CIB08	44.7	200	29	4180
FG-FPC-W-2	44.7	150	29	4540
CM-FPC-W-3	44.7	150	29	4540
CIB09	3.0	100	29	4536
FG-FPC-W-10	3.0	100	29	4540

W & A Comparison: Hot-Leg Data



W & A Comparison: Cold-Leg Data



FA Testing

- The test results are comparable for both AREVA and Westinghouse fuel.
- Therefore, testing at either facility is acceptable to answer RAIs.
- Additional comparisons from low particulate tests will be included in the final RAI submittal.

Fuel Assembly Testing: Overview

FA Testing Overview

- Debris can build up at the core inlet
- In order to determine if sufficient flow will reach the core to remove core decay heat through a potential inlet blockage, it must be demonstrated that the head available to drive flow into the core is greater than the head loss at the inlet due to a possible 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.

Pressure Drop from Debris

- The head loss through a possible debris buildup at the core inlet is a function of the amount and type of debris that reaches the RCS

$$\Delta P_{debris} = f(\text{debris type, debris amount})$$

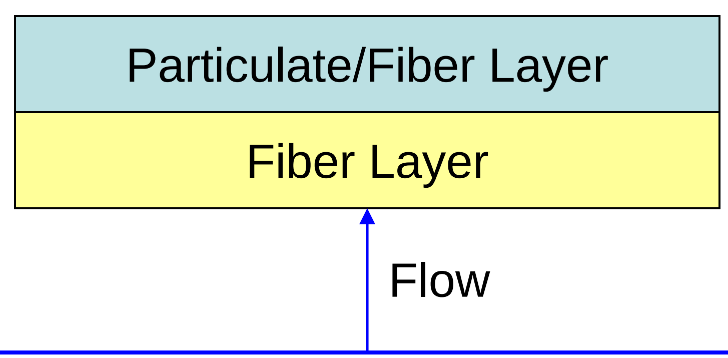
- Multiple combinations of debris can reach the RCS.
  - The amount and combinations at any given time are related to the plant design and timing of the arrival of the various debris
  - A 30-day debris load is tested in order to produce a bounding limit

Pressure Drop from Debris

- A fiber bed must be present to collect the particulates at the core entrance
  - Otherwise, the particulates will simply pass through and no blockage will occur
- The presence of fiber is the limiting variable.
- However, amount of particulate influences resulting ΔP.

Formation of Debris Bed

- Fiber by itself is fairly porous, even with very small fibers.
- The particulates can fill the small gaps among the fibers and decrease the porosity of the bed.
  - Testing was conducted with 10μm silicon carbide particles.
  - Small particles are conservative to test with as they fill the interstitial gaps and result in the lowest porosity.
- In general terms, the debris bed formation observed in these tests can be described by this figure:



Thickness of Debris Layers

- If no particulate is present, then the debris bed will be made up entirely of the fiber layer.
- If particulates are present in abundance (high particulate-to-fiber ratio (p:f)), then the debris bed will be fully saturated with particulates. In this instance, the addition of chemical has little to no impact on the total head loss.
- In the event of low p:f cases, the number of particulates is not great enough to fully saturate the fiber. In this instance, the addition of chemical will impact the total head loss.

Fuel Assembly Testing: Microtherm

Microtherm Data

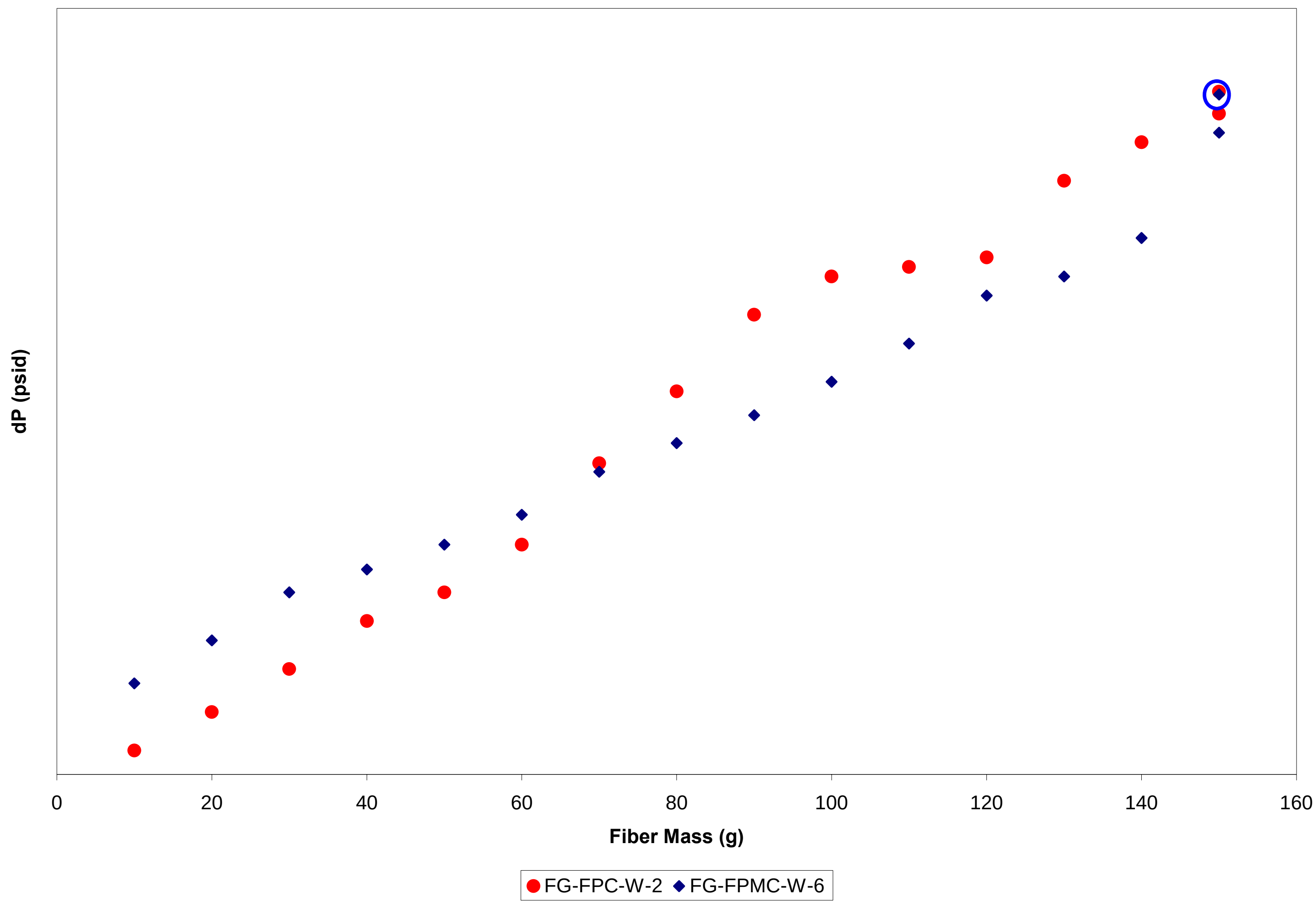
- Original Microtherm data set consisted of two tests: one from AREVA and one from Westinghouse. This data generated three questions:
    1. The order of Microtherm introduction
    2. The presence of cal-sil in the Westinghouse test
    3. Validity of test results for all break scenarios
- Data will be used to address following RAIs:
    - WCAP-16793-NP, Rev. 1: 16
    - WCAP-1705-P, Rev. 0: 1, 7
    - 51-9102685-000: 6

Microtherm – Hot-Leg Data

- The original AREVA data is used to evaluate the behavior of microporous material at hot leg conditions.
- The test parameters are provided here and the test results are provided on the next slide.

Test	Flow Rate (gpm)	Particulate (g)	Fiber (g)	Chemical (g)	Microporous (g)
FG-FPC-W-2	44.7	13,154	150	4540	0
FG-FPMC-W-6	44.7	13,154	150	4540	544

Hot-Leg Data with Microtherm



Microtherm – Hot-Leg Data

- The test with Microtherm and silicon carbide provided similar results as a test with only silicon carbide.
- Conclusion: Microtherm behaves like a particulate.

Microtherm – Cold-Leg Data

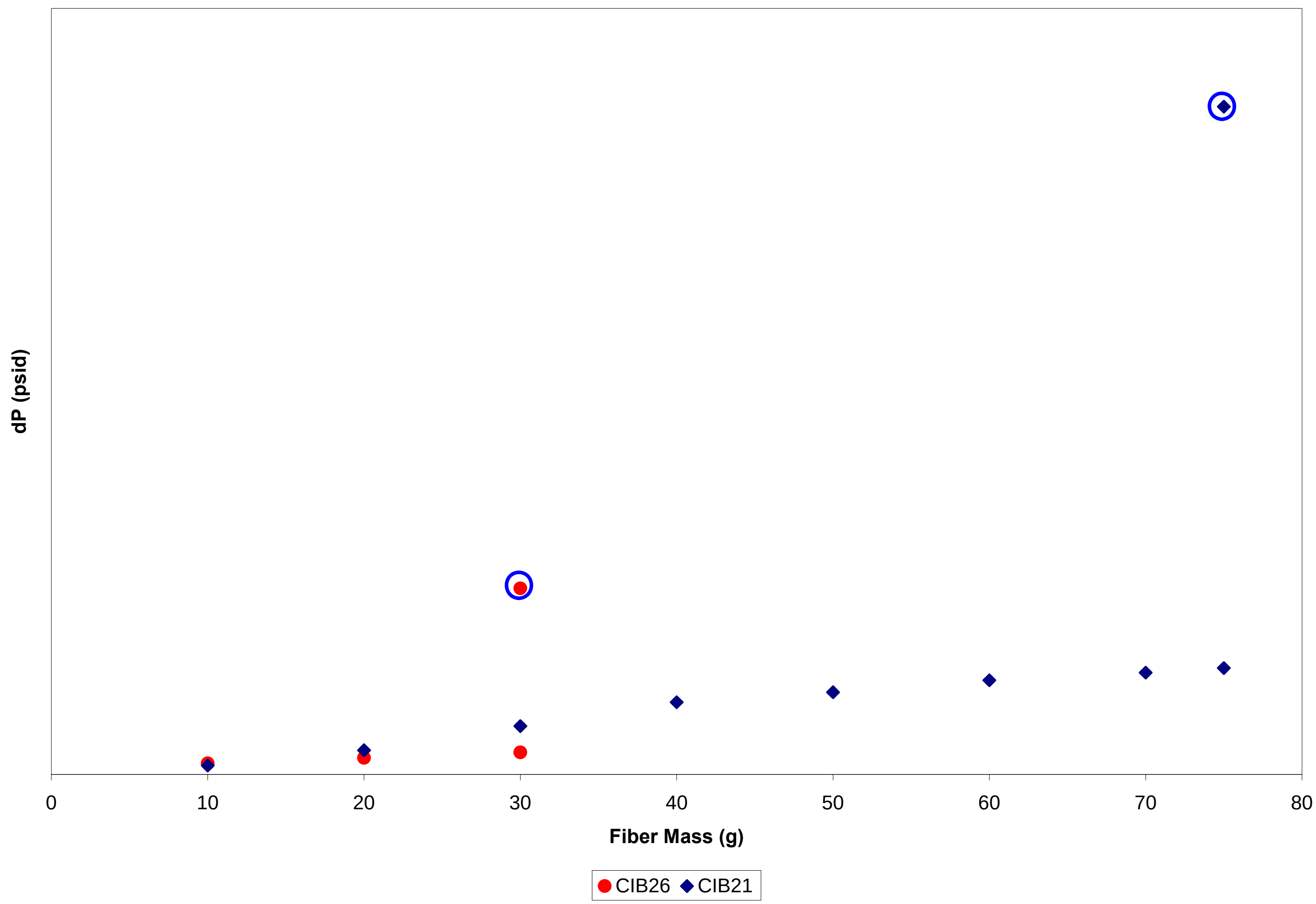
- Additional test was run to further investigate:
  - Cold-leg break scenario
  - Introduction sequence
  - Behavior of Microtherm is like that of a particulate
- CIB26 conducted with:
  - Only Microtherm as particulate
  - Cold-leg break flow rate
  - All Microtherm introduced at beginning

Microtherm – Cold-Leg Data

Test	Flow Rate (gpm)	Particulate (g)	Fiber (g)	Chemical (g)	Microporous (g)
CIB21	3	363	75	415.6	0
CIB26	3	0	30	415.6	30

- Microtherm and SiC have the same particle size.
- A comparison of SiC to Microtherm must be made between a SiC test that has the same number of particulates (and volume).
  - $\rho_{microtherm}$ = 2,199 g/ft^3
  - ρ_{SiC} = 28,260 g/ft^3
  - $\rho_{SiC}/\rho_{microtherm}$ = 12.9
- The amount of SiC in CIB21 is 12x greater than the amount of Microtherm used in CIB26. Therefore these tests were conducted with approximately the same number of particles and can be compared.

Microtherm – Cold-Leg Data



Microtherm – Cold-Leg Data

- As illustrated in the previous figure, the dP with fiber addition is essentially the same for CIB21 and CIB26. The presence of Microtherm does not impact the head loss.
- The dP after chemical addition is not compared because CIB21 was conducted with a larger fiber mass than CIB26. However, both CIB21 and CIB26 realized a significant increase in head loss upon the addition of chemical.
- Conclusion: Microtherm behaves like a particulate.

RAI Status

- The tests conducted at both hot- and cold-leg break flow rates produce dPs that are the same as tests conducted with only SiC.
- Therefore, **microporous insulation is a particulate and does not require a separate debris load criteria**.
- This conclusion addresses the following RAI topics:
  1. The order of Microtherm introduction
  2. The presence of cal-sil in the Westinghouse test
  3. Validity of test results for all break scenarios

Path to Closure

- One additional test will be conducted to provide additional information:
  - Cold leg break flow (3.0 gpm)
  - 18 grams of fiber
  - 15:1 particulate-to-fiber ratio
    - 135 g SiC
    - 135 g Microtherm

Fuel Assembly Testing: Cold-Leg Break

Cold-Leg Break RAIs

- Original cold-leg data set consisted of two tests: one from AREVA and one from Westinghouse. This data generated three questions:
  1. Justify the basis for changing the acceptance criteria to only the dP at the core inlet.
  2. Justify cold-leg break has been fully evaluated & debris load acceptance criteria is valid for a cold-leg break.
  3. Evaluate the effect of low particulate.
     - Will also be used to address chemical effect questions.

Cold-Leg Break RAIs

- Data will be used to address following RAIs:
  - WCAP-16793-NP, Rev. 1: 15, 18
  - WCAP-1705-P, Rev. 0: 2, 3, 4, 5 & 8
  - 51-9102685-000: 4 & 6

Cold-Leg Break Acceptance Criteria

- The original AREVA and Westinghouse test reports each contained one CL test.
- The head loss acceptance criteria did not account for any head loss accumulated at the spacer grids.
- The tests conducted to answer the RAIs used the dP over the entire FA as the head loss acceptance criteria.

Cold-Leg Break Evaluation

- In order to justify the CL has been fully evaluated and the debris load acceptance criteria is valid, the following sensitivities were evaluated:
  - Particulate-to-fiber ratio study at various fiber loads
  - Particulate-to-fiber ratio study at fiber acceptance criteria load

Cold-Leg Data

Test	Particulate (g)	Fiber (g)	Chemical (g)	(p:f)	Max dP before Chem (psid)	Max dP after Chem (psid)
FG-FPC-W-10	13,154	100	4,540	132		
CIB09	13,154	100	4,536	132		
CIB21	363	75	416	4.84		
CIB22	0	75	416	0		
CIB23	75	75	416	1		
CIB24	630	30	416	21		
CIB25	600	20	416	30		
CIB29	90	18	416	5		
CIB30	270	18	416	15		
CIB31	540	18	416	30		
CIB32	810	18	416	45	**Limiting Case**	
CIB33	1080	18	416	60		

The tests highlighted in yellow will be used to define the acceptance criteria.

Cold-Leg Break Acceptance Criteria

- **Fiber $\leq$ 18 g per FA**
  - The plant-specific flow split will be used to translate this value into the equivalent RCS fiber load.
    - Flow split is the ratio of boiloff rate to the total ECCS flow.
  - The flow split is a plant-specific value. The PWROG is providing a tool for utilities to determine their actual flow split.
- **$\Delta P_{available} \geq 1.7$ psid**
  - The $\Delta P_{available}$ is a plant-specific value. The PWROG is providing a tool for utilities to determine $\Delta P_{available}$.

- If plants are unable to demonstrate acceptability, they can pursue plant-specific evaluations.
- All particulate and chemical loads are bounded by the fiber limit.

Conservatisms

- 1.2 times ANS 71 decay heat with actinides is used to determine boiloff rate.
- Tested at 3 gpm/FA which is higher than expected boiloff rate @ 20 minutes.
- Tested at constant flow rate
  - With time, flow rate will decrease with decay heat.
  - As flow decreases, ΔP_{debris} decreases.
- $\Delta P_{available}$ will be calculated with conservative conditions
  - Core void fraction
  - Liquid density
  - Pressure drop through loops

RAI Status

Q: Justify the basis for changing the acceptance criteria to only the dP at the core inlet.

A: For all additional tests, AC was based on dP over entire FA.

Q: Justify cold-leg break has been fully evaluated & debris load acceptance criteria is valid for a cold-leg break.

A: 12 tests conducted to fully evaluate CL

Q: Evaluate the effect of low particulate.

A: Low particulate does impact head loss. Therefore, p:f study conducted at 18 grams of fiber.

Fuel Assembly Testing:
Hot-Leg Break

Hot-Leg Break RAIs

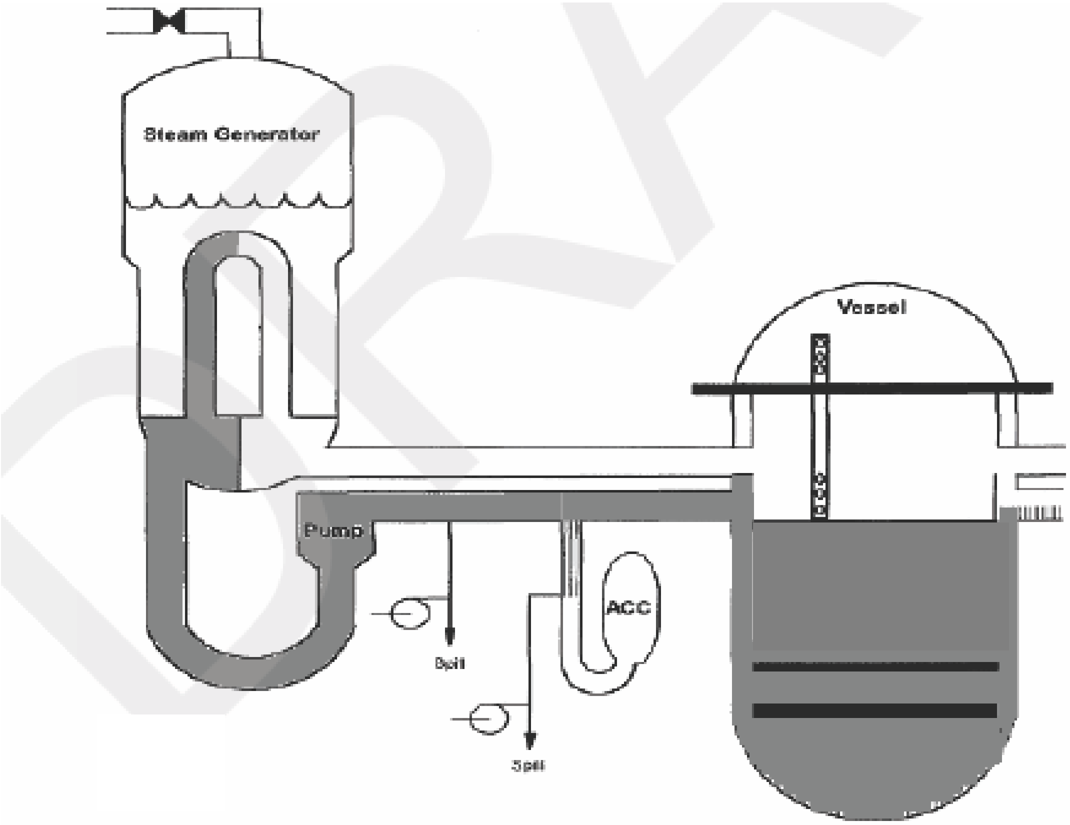
- Original hot-leg data set consisted of many tests from AREVA and Westinghouse. This data generated one important question:
  1. Evaluate the effect of low particulate.

- Data will be used to address following RAIs:
  – WCAP-1705-P, Rev. 0: 3 & 4
  – 51-9102685-000: 4

Description of $\Delta P_{available}$

- ECCS must pass through core to exit break.
- Driving force is manometric balance between the liquid in the downcomer and the core.
- As debris bed builds in the core, the liquid level will begin to build in the cold-legs and flow will spill back through the reactor coolant pumps into the pump suction piping, SG inlet plenum and SG tubes.
- As level begins to rise in the SG tubes, the elevation head to drive the flow through the core increases.
- Driving head reaches its peak right before the flow begins to spill over the shortest SG tubes (W & CE) or reaches HL spillover elevation (B&W).

Liquid Level with Presence of Debris



FA Test ΔP_{debris} Limit

- FA tests are designed to define debris limits such that spillover will not occur.
- Pressure drop caused by debris will be limited to the available driving head defined by the liquid level at or just below the spillover elevation with all of the flow still going though the core.

Hot-Leg Break Data

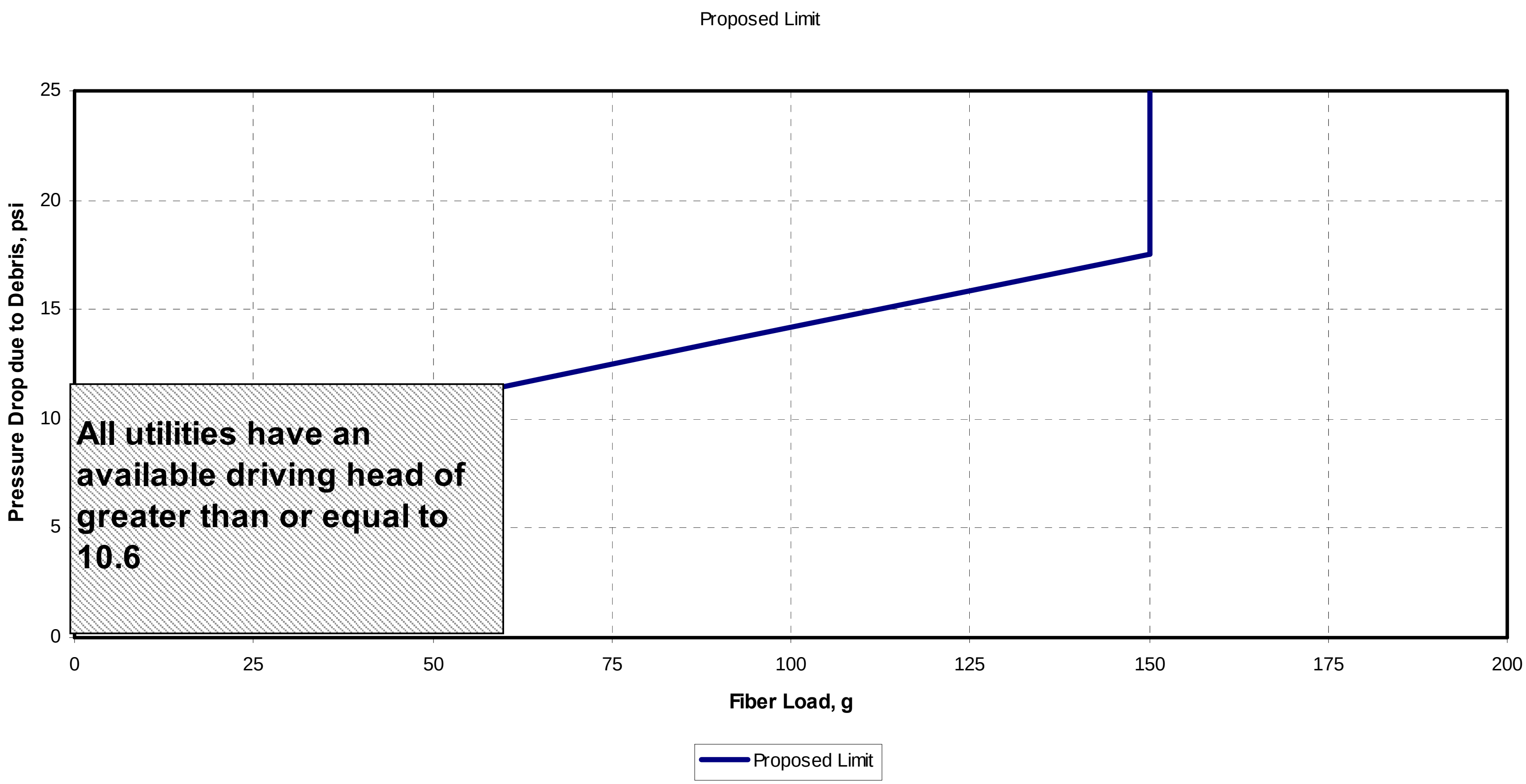
- In order to justify the HL has been fully evaluated and the debris load acceptance criteria is valid, the following sensitivity was evaluated:
  - Particulate-to-fiber ratio study at various fiber loads
  - This data set was used to establish the fiber limit.

Hot-Leg Data

- The following table summarizes key hot-leg data tests.

Test	Particulate (g)	Fiber (g)	Chemical (g)	(p:f)	Max dP before Chem (psid)	Max dP after Chem (psid)
FG-FPC-W-2	13,154	150	4,540	88		
CIB02	1,361	53	66	26		
CIB03	6,350	53	66	120		
CIB04	1,361	90	66	15		
CIB08	13,154	200	4,180	66		
CIB10	1,361	200	3,386	7		
CIB27	140	60	416	2.3		
CIB28	600	60	416	10		
CIB34	250	125	416	2		
CIB35	300	150	416	2		

Hot-Leg Fiber Limit with $\Delta P_{available}$



Hot-Leg Acceptance Criteria

- Plant is assured of meeting FA test criteria as long as fiber load (in g) is bounded by:

$$RCS\ FiberLoad\ /\ FA = \min\left[\left(\frac{\Delta P_{available} - 7.5}{0.0667}\right), 150\right]$$

- This is a refinement in the acceptance criteria of 150 g fiber for all plants that was presented in WCAP-16793-NP, Rev. 1.

Conservatism

- Tested at 44.7 gpm/FA which is higher than expected maximum ECCS flow rate.
  - As flow decreases, ΔP_{debris} decreases.
- $\Delta P_{available}$ will be calculated with conservative conditions
  - No core voiding
  - Liquid density
- Pressure drop caused by debris will be limited to the available driving head defined by the liquid level at or just below the spillover elevation with all of the flow still going though the core.
  - If spillover were allowed, additional debris could enter the core without compromising core cooling.

Hot-Leg Break Acceptance Criteria Margin

- If spillover were allowed, core inlet flow will decrease as debris is added.
  - $\Delta P = Rv^{1.6}$
- That is, $\Delta P_{available}$ is fixed and debris load (R) can continue to increase until flow (v) reaches the boil-off rate + 10%.
- Since the amount of debris allowed is defined by FA tests that maintain the maximum core flow rate and produce results that are below the available dP just before spillover, the allowed debris load retains significant conservatism.
- This conservatism can be quantified by calculating the ΔP needed to supply flow rate equal to the boil-off rate + 10%.

Hot-Leg Break Acceptance Criteria Margin

- For example…
  - $\Delta P_{available}$ = ΔP just before spillover = 10.6 psid
  - ΔP_{debris}(@ 44.7 gpm) = 10.6 psid
  - ΔP_{debris}(@ 3.3 gpm) = 0.17 psid
  - Margin = 10.4 psid

Hot-Leg Break Acceptance Criteria

- Discussions of spillover have led to questions regarding the possibility of siphoning.
- If siphoning is considered, $\Delta P_{available}$ decreases.
  - $\Delta P_{available,siphon}$ = Elevation difference between bottom of SG tube sheet and top of active fuel
  - $\Delta P_{available,siphon}$ is generally greater than or equal to 2 psid.
- Even with siphoning and a pressure uncertainty of 10 psi, sufficient flow to remove core decay heat + 10% is still assured.

Siphon Margin Example

- For example…
  - $\Delta P_{available}$ = 10.6 psid
  - To account for uncertainty, assume constant debris load results in equivalent dP of ~ 20 psid. This value is used to determine the resistance of the debris bed.
    - $R = \Delta P_{debris}/v^{1.6} = 20/(0.2)^{1.6} = 262$
  - After siphoning, $\Delta P_{available} = \Delta P$ of siphon $\geq$ 2.0 psid
    - $v = (2.0/262)^{(1/1.6)} = 0.05$ ft/s
  - Boiloff + 10% is less than 3.3 gpm (0.015 ft/s)
  - 0.05 ft/s > 0.015 ft/s. Therefore, sufficient flow to remove core decay heat + 10% is still assured if siphoning is considered.

Path to Closure

- 3 additional tests will be conducted to provide additional information.
  - Hot leg break flow (44.7 gpm)
  - 150 grams of fiber
  - Various particulate-to-fiber ratios
    - 5:1
    - 10:1
    - 15:1

Conclusions

Conclusion

- Additional FA testing will provide information to answer outstanding RAIs.
- In order to demonstrate assurance of LTCC plants will have to:
  – Meet requirements defined by LOCADM
  – Meet defined fiber load requirements
    - Use the minimum RCS fiber load as defined by cold-leg and hot-leg break criteria.

Cold Leg Acceptance Criteria

- **Fiber $\leq$ 18 g per FA**
  – The plant-specific flow split will be used to translate this value into the equivalent RCS fiber load.
    - Flow split is the ratio of boiloff rate to the total ECCS flow.
  – The flow split is a plant-specific value. The PWROG is providing a tool for utilities to determine their actual flow split.
- **$\Delta P_{available} \geq$ 1.7 psid**
  – The $\Delta P_{available}$ is a plant-specific value. The PWROG is providing a tool for utilities to determine $\Delta P_{available}$.

Hot-Leg Acceptance Criteria

- Plant is assured of meeting FA test criteria as long as fiber load (in g) is bounded by:

$$RCS\ FiberLoad\ /\ FA = \min\left[\left(\frac{\Delta P_{available} - 7.5}{0.0667}\right), 150\right]$$