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

PWR Owners Group

May 8, 2012

AGENDA

- Background and History
- Overview of WCAP-16793-NP, Revision 2
- Fuel Debris Capture Testing
  - Facility Description
  - Test Protocol
  - Results
- Test Constraints
- LOCADM
- Defense-in-Depth Calculations
- Conclusions

Issue History

- GL 2004-02 required utilities to address adverse affects of containment debris not filtered by the sump screens in the recirculation flow on long-term core cooling (LTCC)
- GL required that utility response include:
  - Basis for concluding adequate emergency core cooling system (ECCS) flow is available for long-term core cooling in the presence of debris blockage at the sump screens and downstream of the sump screens (i.e. downstream effects including in-vessel)
  - Description of modifications, if needed, to provide for adequate ECCS flow to ensure LTCC

Background

- Program Objective:
  - Demonstrate sufficient long-term core cooling achieved for PWRs to satisfy requirements of 10 CFR 50.46
    - Address debris and chemical products that might be transported to the reactor vessel and core by the coolant recirculating from the containment sump
    - Debris types include particulate, fibrous and chemical products
  - Criteria for success:
    - Removal of decay heat
    - Maintain coolable core geometry

WCAP-16793-NP Basis

- Provide an evaluation of long-term core cooling for the PWR design in the presence of debris ingested from the sump following a LOCA that provides reasonable assurance that decay heat is removed
- 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
- Use available tools and information
- Test as warranted
- 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)

WCAP-16793-NP History

- Revision 0 presented to ACRS in March 2008
- Revision 1 developed to address ACRS concerns
  - Included conservative fuel assembly (FA) testing performed to determine debris mass that would not impede core inlet flow and challenge LTCC.
  - Acceptance criterion: Long-term core cooling achieved if collection of sump debris at core inlet and on fuel assembly components will not result in head losses exceeding the available driving head
- Revision 2 (currently under NRC review)
  - A number of successful tests were performed in both facilities at fibrous debris loadings of up to 150 grams per fuel assembly
  - Very conservative fibrous debris limit of 15 grams per fuel assembly limit established for all plants for all conditions
  - However, additional testing in this revision indicated that a limit of ≥ 25 grams per fuel assembly is supported
  - Applicable to all NSSS designs.

Approach Taken in WCAP-16793-NP

- 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:
  - Collection of debris 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

Show: REASONABLE ASSURANCE of LTCC

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Debris Accumulation at 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 driving pressure available for flow into the core is greater than the pressure drop at the inlet due to a debris buildup

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

    - $\Delta P_{available}$ is a plant-specific value.
    - 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 2.

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

Debris Accumulation 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 accumulated debris
  - ANSYS Analysis
    - Finite element analysis demonstrated 50 mils of buildup does not impede core cooling
- Details in Section 4 of WCAP-16793-NP, Rev 2.

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

- 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 2

Fuel Assembly Testing Overview

Debris Accumulation at the Core Inlet

- Fuel Assembly (FA) testing performed to assess behaviors and limits
  - Westinghouse design
  - AREVA design
- Partial-height assemblies
- Range of debris types
  - Particulate (P)
  - Fibrous (F)
  - Post-accident chemical products (C)
- Considered hot-leg and cold-leg breaks
- Testing established fibrous debris limits per FA
- Details follow

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 is conservatively demonstrated that the driving pressure available to drive flow into the core is greater than the pressure loss at the inlet due to a possible debris buildup

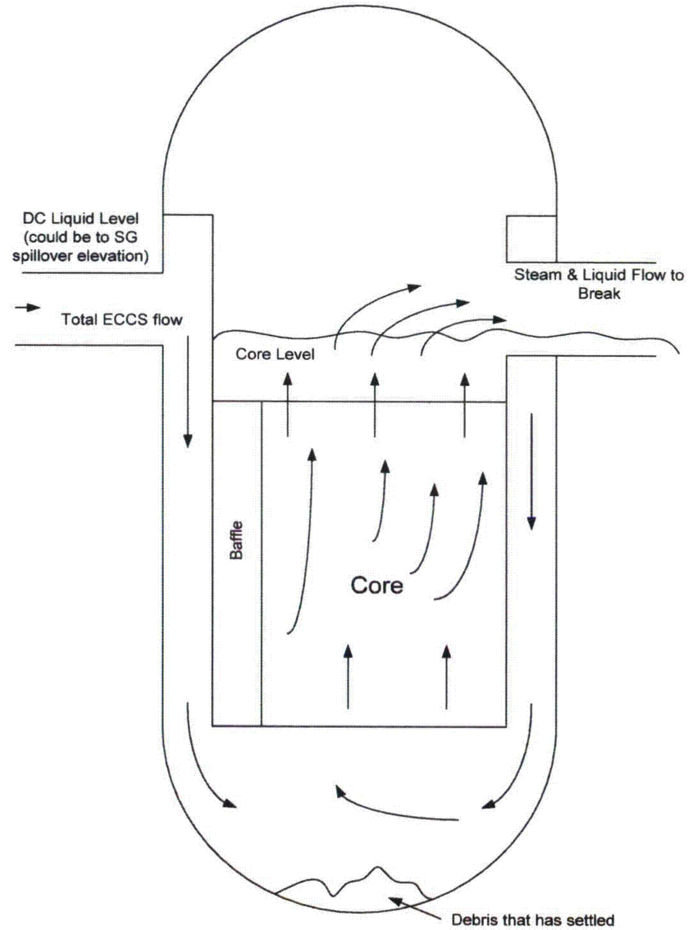
$$\Delta P_{available} > \Delta P_{debris}$$

- $\Delta P_{available}$ is a plant-specific value.
- ΔP_{debris} is determined by testing.

dP_{avail} – HL Break

Hot Leg Breaks

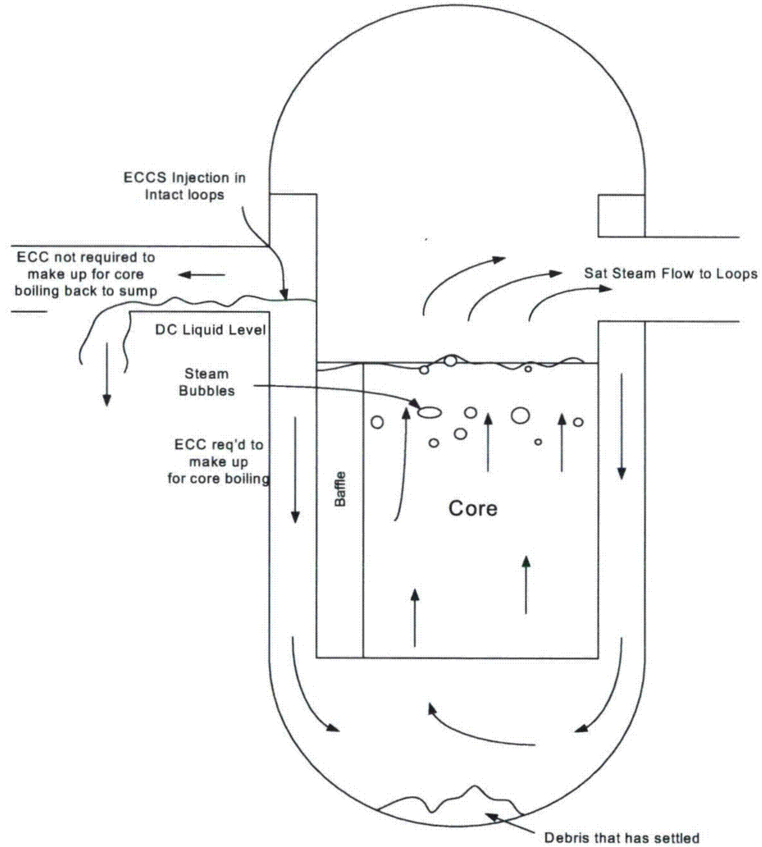
- ECCS must pass through core to exit break
- Driving force is manometric balance between the liquid in the downcomer and the core
- As debris bed builds in the core, the liquid level will begin to build in the cold-legs and flow will spill back through the reactor coolant pumps into the pump suction 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)



dP$_{avail}$ – CL Break

Cold Leg Breaks

- Downcomer (DC) is full to at least the bottom of the cold leg
- Core level is established by the manometric balance between the DC liquid level and the core level and RCS pressure through the loops (or reactor vessel vent valves for B&W plants)



ΔP_{debris} – Pressure Drop from Debris

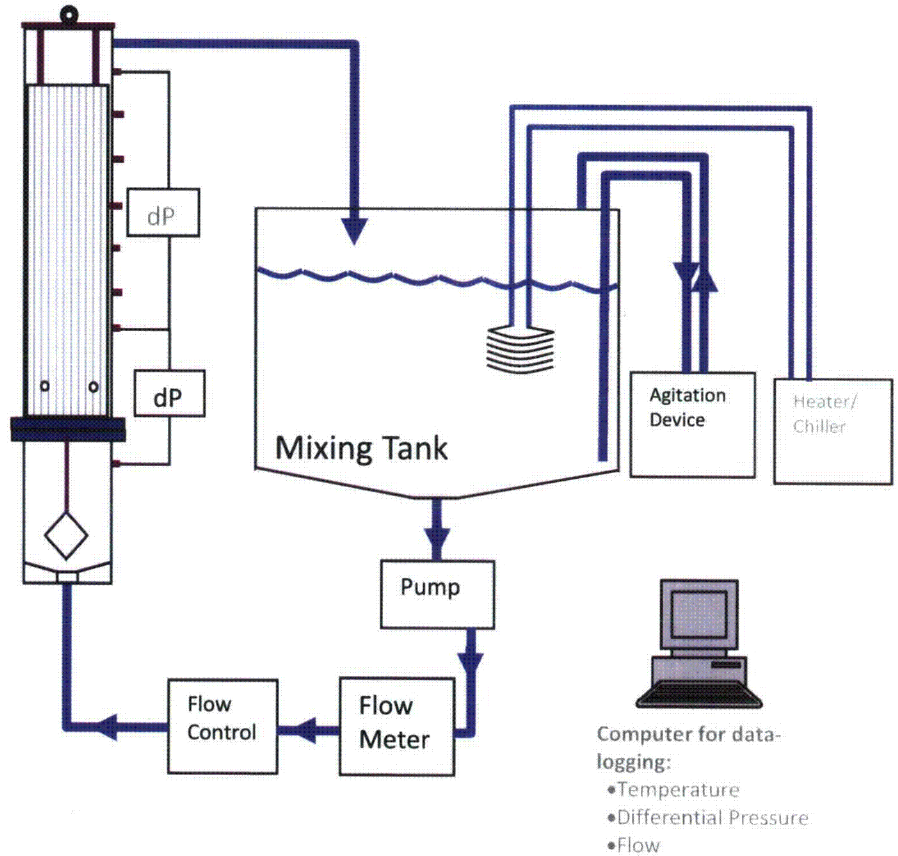
- The pressure loss through a possible debris buildup at the core inlet is a function of the amount and type of debris that reaches the RCS

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

- 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 total debris load is tested in order to produce a bounding limit

FA Testing

- Closed loop system, continually circulating fluid/debris through single FA
- Distance from end of FA to chamber wall is half distance between adjacent FAs
- Flow entering bottom of fuel is constant and initially relatively uniform
- All debris is available to form debris beds at inlet or spacer grids



Key Features of Test Protocol

- Debris Preparation Identified
  - Fibrous debris – three size ranges
  - Particulate debris – silicon carbide 10μm ± 2μm
  - Chemical surrogates – $AlOOH$ (WCAP-16530-NP-A)
- Test Method Identified
  - Sequence of debris addition (particulate first, then fiber and chemical surrogates last)
  - Bounding, constant flow rate
- Test Termination Criteria
  - Goal is to define ΔP_{debris} for pre-determined fiber load

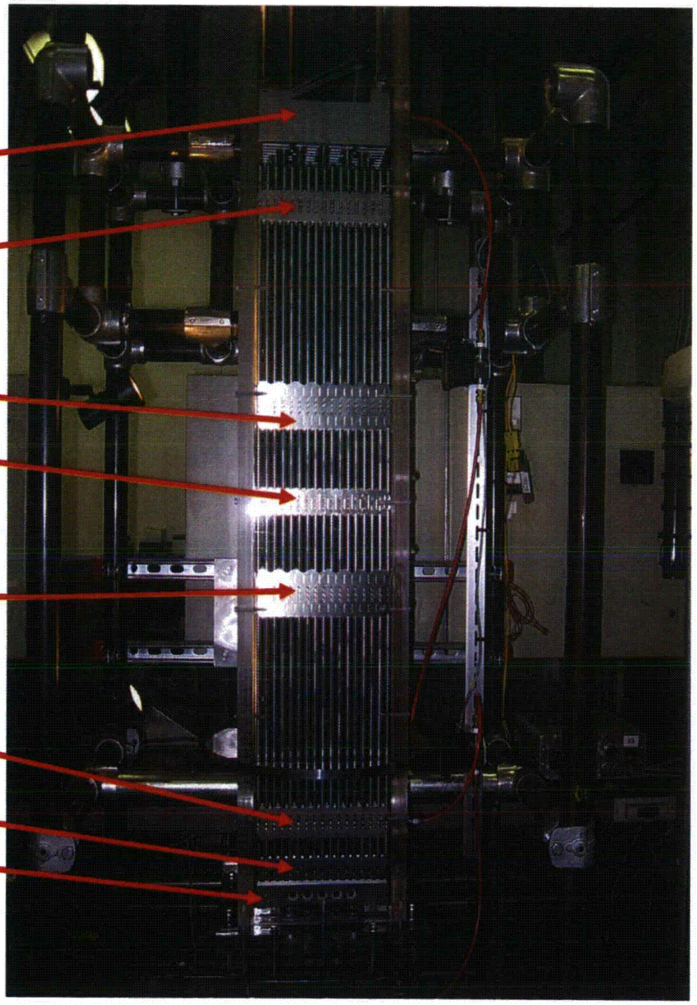
Test Facilities

- PWROG conducted FA testing to establish limits on debris mass that would not impede core inlet flow and challenge LTCC
- Westinghouse and AREVA conducted FA tests at independent facilities:
  - AREVA → Continuum Dynamics, Inc. (CDI)
  - Westinghouse → Research and Technology Unit (RTU)
- Common test protocol followed by both facilities
  - Protocol developed with thought that more debris = higher head loss

Test Rig – Westinghouse FA

- Assembly Height: 4 ft

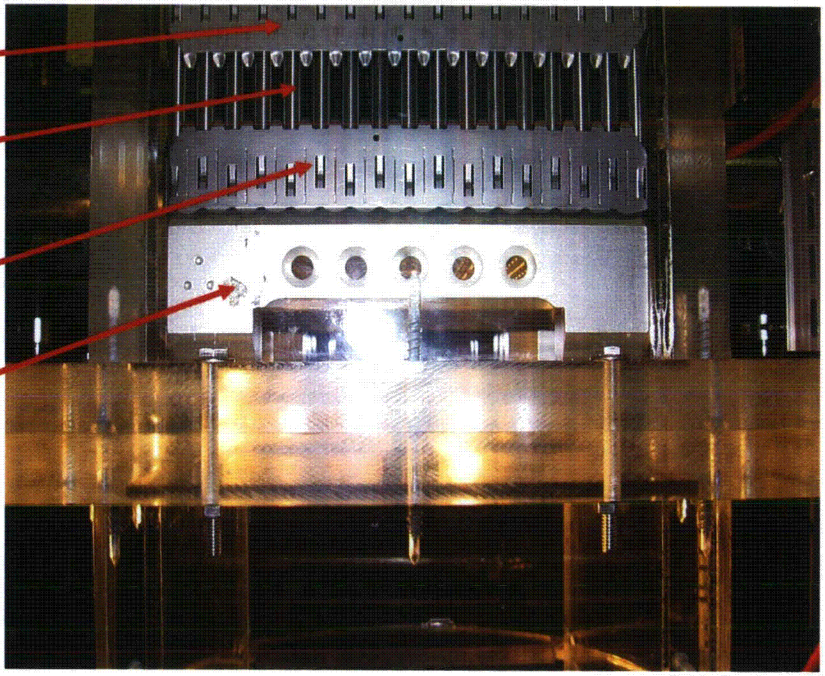
- Top Nozzle
- Inconel top grid
- Intermediate grid
- Intermediate Flow Mixing (IFM) grid
- Intermediate grid
- Inconel bottom grid
- Standard p-grid
- Debris Filtering Bottom Nozzle



Test Rig – Westinghouse FA

Close-up view of:

- First Support Grid
- Fuel Rods
- Protective Grid
- Bottom Nozzle



FA Testing: Overview

- 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 fiber limit that would not compromise LTCC.
  - Debris loads included representative fibers, particulates, and chemical precipitates that may form in the containment water pool.

FA Test Matrix

Westinghouse Fuel Assembly Test Matrix							
Test No.	Flow Rate (gpm)	Nukon (g)	SiC (g)	Microtherm (g)	Cal-sil (g)	AlOOH (g)	Final P:F Ratio
CIB01	44.7	680.4	6,350	-	-	N/A[1]	9.3
CIB02	44.7	53	1,361	-	-	66	25.7
CIB03	44.7	53	6,350	-	-	66	119.8
CIB04	44.7	90	1,361	-	-	66	15.1
CIB05[1]	6.25	53	6,350	-	-	66	119.8
CIB06	44.7	53	6,350	-	1,452	484	147.2
CIB07	44.7	53	6,350	667	708	689	145.8
CIB08	44.7	200	13,154	-	-	4,180	65.8
CIB09	3.0	100	13,154	-	-	4,536	131.5
CIB10	44.7	200	1,361	-	-	3,386	6.8
CIB11[1]	17.0	200	13,154	-	-	836	65.8
CIB21	3.0	75	363	-	-	830	4.8

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FA Test Matrix

Westinghouse Fuel Assembly Test Matrix							
Test No.	**Flow Rate (gpm)**	**Nukon (g)**	**SiC (g)**	**Microtherm (g)**	**Cal-sil (g)**	**AlOOH (g)**	**Final P:F Ratio**
CIB22	3.0	75	0	-	-	830	0
CIB23	3.0	75	75	-	-	830	1.0
CIB24	3.0	30	630	-	-	830	21.0
CIB25	3.0	20	600	-	-	830	30.0
CIB26	3.0	30	-	30	-	830	1.0
CIB27	44.7	60	140	-	-	416	2.3
CIB28	44.7	60	600	-	-	416	10.0
CIB29	3.0	18	90	-	-	830	5.0
CIB30	3.0	18	270	-	-	830	15.0
CIB31	3.0	18	540	-	-	830	30.0
CIB32	3.0	18	810	-	-	830	45.0
CIB33	3.0	18	1,080	-	-	830	60.0

FA Test Matrix

Westinghouse Fuel Assembly Test Matrix							
Test No.	**Flow Rate (gpm)**	**Nukon (g)**	**SiC (g)**	**Microtherm (g)**	**Cal-sil (g)**	**AlOOH (g)**	**Final P:F Ratio**
CIB34	44.7	125	250	-	-	830	2.0
CIB35	44.7	150	300	-	-	830	2.0
CIB36	44.7	150	2,250	-	-	830	15.0
CIB37	44.7	150	750	-	-	830	5.0
CIB38	44.7	150	4,500	-	-	830	30.0
CIB39	44.7	150	150	-	-	830	1.0
CIB40	3.0	18	135	-	-	830	15.0
CIB41	15.5	150	150	-	-	830	1.0
CIB42	15.5	50	50	-	-	830	1.0
CIB43	15.5	50	750	-	-	830	15.0
CIB44	44.7	150	150	-	-	N/A[1]	1.0
CIB45	44.7	150	750	-	-	N/A[1]	5.0

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FA Test Matrix

Westinghouse Fuel Assembly Test Matrix							
Test No.	Flow Rate (gpm)	Nukon (g)	SiC (g)	Microtherm (g)	Cal-sil (g)	AlOOH (g)	Final P:F Ratio
CIB46	44.7	150	150	-	-	830	1.0
CIB47	15.5	50	50	-	-	830	1.0
CIB48	15.5	50	50	-	-	830	1.0
CIB49	44.7	50	50	-	-	830	1.0
CIB50	44.7	50	50	-	-	830	1.0
CIB51	44.7	50	50	-	-	830	1.0
CIB52[1]	44.7	65	65	-	-	830	1.0
CIB53[1]	44.7/19[2]	65	65	-	-	830	1.0
CIB54[1]	44.7	25	25	-	-	830	1.0
W-1-FPC-0811[1]	44.7	25	25	-	-	830	1.0

FA Test Matrix

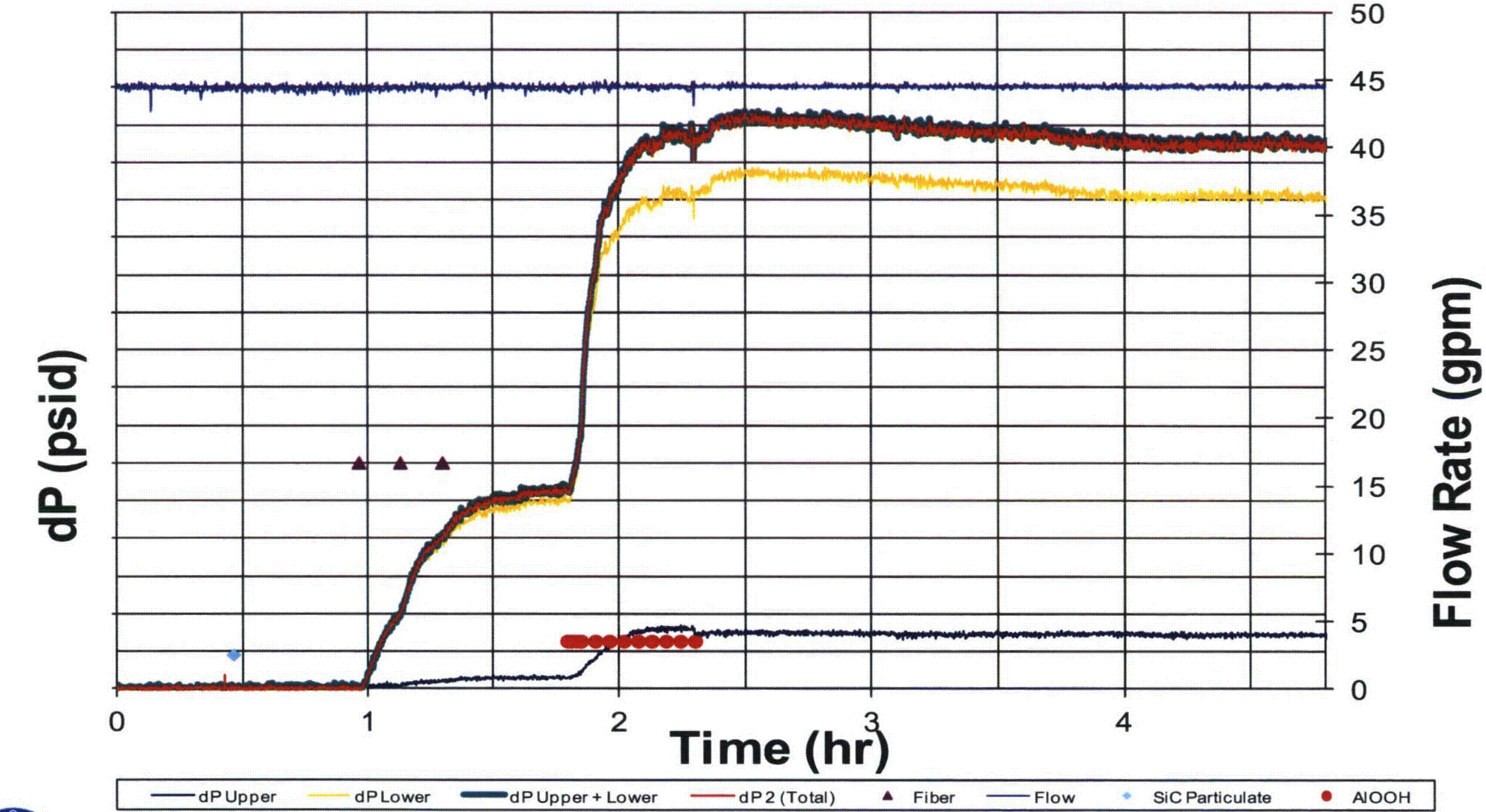
AREVA Fuel Assembly Test Matrix							
Test No.	Flow Rate (gpm)	Nukon (g)	SiC (g)	Microtherm (g)	Cal-sil (g)	AlOOH (g)	Final P:F Ratio
FM-FPC-W-1	44.7	110	13,152	-	-	4,540	88.0
FG-PFC-W-2	44.7	150	13,152	-	-	4,540	88.0
CM-FPC-W-3	44.7	150	13,152	-	-	4,540	88.0
FG-FPCSC-W-5	44.7	150	13,152	-	2,722	4,540	105.8
FG-FPMC-W-6	44.7	150	13,152	544	-	4,540	91.3
FG-FPC-CE-7	11.0	150	454	-	-	5,900	53.0
FG-FPC-W-10	3.0	100	13,152	-	-	4,540	146.0
1-FG-FPC	3.0	75	380	-	-	833	5.0
2-FG-FPC	3.0	18	810	-	-	833	45.0
3-FG-FPC	45.0	150	1,500	-	-	833	10.0
4-FG-FPC	45.0	150	1,500	-	-	833	10.0

FA Test Matrix

AREVA Fuel Assembly Test Matrix							
Test No.	Flow Rate (gpm)	Nukon (g)	SiC (g)	Microtherm (g)	Cal-sil (g)	AlOOH (g)	Final P:F Ratio
5-FG-FPC	45.0	150	150	-	-	833	1.0
6-FG-FPC[1]	45.0	100	150	-	-	833	1.5
7-FG-FPC[1]	44.7	60	60	-	-	833	1.0
8-FG-FPC	45.0	60	150	-	-	833	2.5
9-FG-FPC	44.7	20	20	-	-	833	1.0
10-FG-FPC	44.7	46	150	-	-	16.5	3.3
11-FG-FPC	44.7	60	150	-	-	417	2.5
12-FG-FPC	44.7	15	15	-	-	833	1.0
13-FG-FPC	44.7	15	30	-	-	833	2.0
14-FG-FPC[1]	44.7	25	25	-	-	833	1.0

Representative Test History

Test CIB61: 25 g Particulate, 25 g Fiber, and 104 g AlOOH



Key Finding: Pressure Drop from Debris

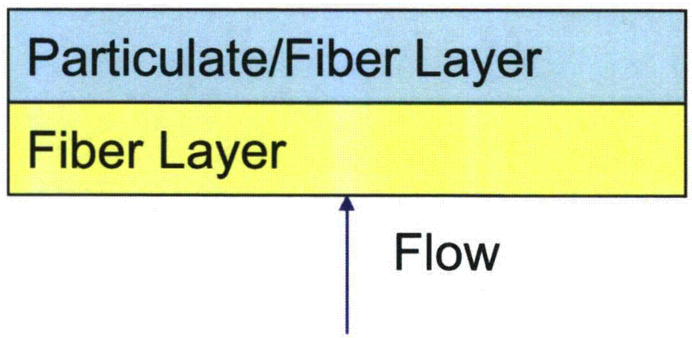
- A fiber bed must be present to collect the particulates at the core entrance
  - Otherwise, the particulates will simply pass through and no blockage will occur
- The presence of fiber is the limiting variable.
- However, amount of particulate influences resulting ΔP.

Test Observations

- Testing demonstrated that the amount of particulate affects debris bed formation and the resulting pressure loss across the FA
  - If particulates are available in abundance (a high p:f ratio), the chemical precipitate introduction has little to no effect on the ΔP across the debris bed
  - However, if all the particulates are filtered by the debris bed (a low p:f ratio), then the compression of the bed by chemical precipitates has an effect on the resistance of the debris bed, resulting in conservatively high pressure loss across the FA

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:



Original Comparison of FA Test Results

- Upon receipt of RAIs from WCAP-16793-NP, Revision 1, AREVA and Westinghouse compared ΔP results from respective test programs.
- Comparison of test results from high particulate tests showed similar trends.
- Concluded generic testing could be conducted at Westinghouse to address RAIs.
- Confirmatory testing would be conducted at AREVA upon update of acceptance criterion.

Confirmatory Testing

- Particulate-to-fiber (p:f) ratio key factor
- Tests results at high p:f ratios similar between facilities
- Tests results at low p:f ratios different
- This observed difference at low p:f ratio resulted in additional study of low p:f ratio behavior

Test Conclusions

- Testing demonstrated fiber is the limiting variable and, due to the effect of interaction between fiber and the other debris types on head loss, is the only debris type that requires a limit
- The HL break flow rate (i.e., the highest flow rate) represented the limiting head loss test condition
- The FA test facilities and procedures are repeatable if all variables remain constant
- However, slight changes in test loops (i.e., mixing methods, air entrainment, geometry, etc.) can result in differences in test results

Fuel Assembly Testing: Bounding Fiber Limits

- Due to the conservative test design used to define fiber limits, a very bounding fiber limit may be suggested
  - Bounding tests conducted at CDI demonstrated that 15 g of fiber/FA does not cause a debris accumulation that will challenge LTCC
  - All PWROG plants have an available driving pressure (ΔP_{avail}) that is considerably greater than the test value
  - Therefore, all PWROG plants can demonstrate LTCC is not impeded if the plant-specific fibrous debris load is less than or equal to 15 g of fiber/FA
    - This is with full FA flow
  - Due to the low ΔP_{debris} value recorded with 15 g of fiber/FA, plant-specific testing with test parameters representative of a specific site may be performed to increase this fiber limit

Fuel Assembly Testing: Bounding Fiber Limits (cont.)

- Testing at CDI with both Westinghouse and AREVA fuel to evaluate test facilities was run with 25 g fiber/FA
  - Same initial test conditions (130°F water temperature)
  - Tests demonstrated flow continued to enter the core after debris bed formed, even though the flow rate had to be reduced during the test
  - Therefore, plants that operate at conditions similar to the test can withstand 25 g fiber/FA
- A FA fiber limit in excess of 25 g fiber/FA is supported

Constraints in Fuel Debris Capture Tests

Conservatism: Constant flow rate

- Hot-leg FA testing was conducted at constant, maximum hot-leg break flow rates and the available driving pressure calculations assumed a water solid core
  - The maximum flow rate ensured the ΔP due to fiber was calculated at the most limiting condition and did not credit the reduction in ΔP that would be caused due to a reduction in the flow rate through the core
  - Long-term core cooling requires much less than maximum hot-leg flow rate (~4 gpm vs. 44.7 gpm)

Conservatism: Constant flow rate

- Cold-leg FA testing conducted simulating a constant boil-off rate
  - Ensured the development of debris beds with maximum resistance and highest pressure loss
  - Available driving pressure calculations assumed a water solid core; did not credit increase in available driving pressure if considering core void fraction
  - Decreasing flow rate commensurate with debris build up would be prototypic; result in a reduced FA head loss
  - This is a significant test conservatism that results in very restrictive fiber limits

Conservatism: Ambient temperature

- FA testing was conducted at ambient conditions
  - Temperature was chosen to
    - Maximize viscosity, and,
    - Provide for higher pressure drop through the debris beds
  - Most tests conducted at ambient conditions (~ 72°F)
  - Plants expected to have higher sump temperatures
  - Higher temperature will decrease the water viscosity and minimize chemical precipitates
  - This is a significant test conservatism that results in very restrictive fiber limits

Conservatism: Uniform flow

- Testing assumes every FA in the core has same flow conditions
  - Leads to assumption of uniform debris bed formation across core
  - Post-accident flow conditions into the core post accident will be non-uniform
  - Regions with highest velocities will have larger debris loading, resulting in these regions having larger debris beds.
  - Regions with lowest velocities will have smaller debris loading, resulting in these regions having smaller debris beds
  - Areas that collected smaller amount of debris will have lower pressure drop and ensure LTCC
  - This may be a test conservatism that contributes to very restrictive fiber limits

Conservatism: Recirculating Debris

- Testing was conducted using a closed loop system
  - Debris continually recirculated until captured by the FA
  - Feed tank for the FA testing continuously agitated
    - No settling of debris allowed
    - Ensured that debris was well mixed and recirculated to the FA
  - Actual sump conditions contain stagnant areas for debris to settle and not transport to the sump screen
  - Also, debris that is not captured by the core will exit the break and enter the sump to settle or be rescreened before entering the ECCS again
  - This is a significant test conservatism that results in the definition of very restrictive fiber limits

Conservatism: Surrogate Chemical Effects

- FA testing used AlOOH as a surrogate for all chemical precipitate products
  - ALOOH prepared in accordance with the method provided in WCAP-16530-NP-A
  - Use of the WCAP surrogate has been the limiting debris source in the FA testing.
  - Test and analysis performed by PWROG and NRC has shown the WCAP surrogate is the most effective chemical agent for causing pressure drop across a debris bed
  - Using plant specific chemical precipitates would reduce the pressure drop due to chemical effects for many plants
  - This is a significant test conservatism that results in the definition of very restrictive fiber limits

Conservatism: Staging of Debris Additions

- FA testing designed to consider worst case debris bed formation
  - Particulate (P) added first; provides for them to be available to the bed as the fiber collects and promotes the lowest porosity debris bed.
  - Fiber (F) added after particulates in small increments; precludes "clumping", promotes slow buildup of the debris bed
  - Chemical Surrogate (C) added after the particulate and fiber bed has formed; observed effect was to compress the established debris bed and increase pressure drop across the bed
  - This may be a test conservatism that contributes to the definition of very restrictive fiber limits

Conservatism: Limiting Particulate-to-Fiber Ratio (p:f)

- FA tests conducted at the limiting p:f ratio (1:1)
  - Resulted in conservatively high head loss upon the introduction of chemical precipitates.
  - As p:f becomes greater than 1:1, effect of chemical precipitates lessens
  - Debris generation calculations and latent debris walkdowns show particulate debris is generally in much larger quantity than fibrous debris; p:f ratio will not be exactly 1:1
  - This is a significant test conservatism that leads to the definition of very restrictive fiber limits

Conservatism: Absence of Boiling

- FA tests did not simulate boiling within fuel bundle
  - Industry data indicates that debris beds will not form in the presence of boiling
  - This may be a significant test conservatism that contributes to the definition of very restrictive fiber limits
  - Discussion for cold leg and hot leg breaks follows

Conservatism: Absence of Boiling

- Cold-Leg Break Effect:
  - During cold leg recirculation, there will be boiling in the core that prevents buildup of debris on spacer grids
  - Voiding in the core due to boiling provides for a greater available driving head, which, in turn, allows for a greater head loss due to debris.
- Hot-Leg Break Effect:
  - Boiling is minimized for this scenario
  - If sufficient debris accumulation occurs at the core inlet to reduce flow below boil-off requirements,
    - The coolant will begin to boil, disrupting debris beds higher in the assembly, causing the coolant at the core inlet to be more turbulent
    - Disrupt the debris accumulation at the inlet, allowing flow to enter the core

Conservatism: Absence of Alternate Flow Paths

- Current FA testing ignores Alternate Flow Paths
  - These include, but may not be limited to;
    - Baffle region
    - Possible Spillover of the SG tubes or hot legs
  - For plants with upflow baffle geometries;
    - Some debris accumulation in the core inlet may divert flow into these regions
    - This will result in debris and additional flow introduced higher in the core
    - These paths are available to provide flow to the core in the unlikely event the core inlet is completely blocked with debris
  - This may be a test conservatism that contributes to the definition of restrictive fiber limits

Prediction of Post-Accident Chemical Deposition on Fuel Cladding; LOCADM

Collection of Material on Fuel Clad

- A method to predict chemical deposition of fuel cladding was developed (LOCADM spreadsheet)
  - Uses an extension of the chemical effects method developed for sump chemical effects (WCAP-16530-NP-A)
  - Assumes that deposition is driven by boiling
  - All chemical impurities, regardless of form, that are transported to the fuel surface would be deposited by boiling
  - Once plated out, remains on rod (no re-dissolution)
- Used to demonstrate < 50 mil build-up on clad

Thermal Conductivity Values Used

- Three different materials considered:
  - **Cladding Oxide:** The corrosion product caused by oxidation of the cladding, either during normal operation or after the LOCA
  - **Crud:** The deposits on the fuel before the LOCA
  - **LOCA Scale:** Deposits formed on cladding by deposition of corrosion products and scale after the LOCA

Clad Oxide Thermal Conductivity

- Cladding Oxide is primarily the reduction of zirconium cladding with oxygen; ZrO_2
- The most definitive thermal conductivity measurements were performed at Halden and are reported in WCAP-15063-P-A and EPRI TR-107718-P1 and P2
- Parametric Clad Heat-up Calculation
  - A value of 2.20 W/m-K (1.27 BTU/(hr-ft-°F)) provides maximum rod heat-up calculations
- LOCADM Deposition Calculation
  - A value of 2.79 W/m-K (1.61 BTU/(hr-ft-°F)) was used in scale build-up calculations
  - Reported in WCAP-15063-P-A, Revision 1 (1999)

Crud Thermal Conductivity

- Crud is typically composed of nickel ferrite, nickel metal, nickel oxide and nickel-iron-chromium spinels
- Crud thermal conductivity is dependent on many variables such as porosity, thickness, and heat flux
- For fuel rod heat-up calculations
  - A value of 0.5 W/m-K (0.3 BTU/hr-ft-°F) was used

LOCA Scale Thermal Conductivity

- LOCA Scale
  - Likely to be rich in calcium at many plants
  - Literature searched for bounding value for boiler scale deposits
- Limiting value from data research is 0.2 W/m-K (0.11 BTU/hr-ft-°F)
- The limiting value is recommended for industry use in scale build-up calculations (LOCADM)
- A parametric study with thermal conductivity values from 0.17 to 1.5 W/m-K (0.1 to 0.9 BTU/hr-ft-°F) was performed in the rod heat-up and the grid study

Long-Term Core Cooling Criteria

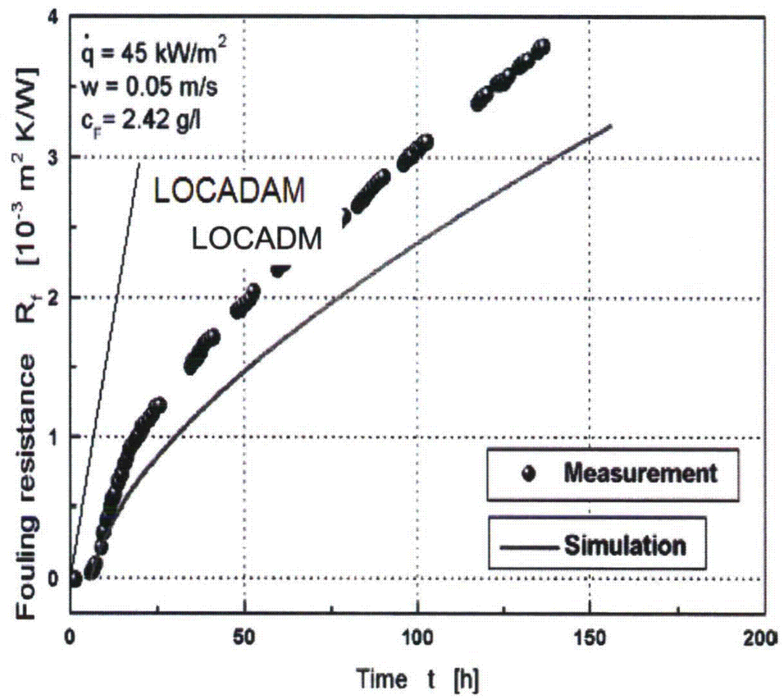
- Long-term cool cooling (LTCC) criteria:
  - Maximum clad temperature < 800°F
  - Thickness of cladding oxide and fuel deposits < 50 mils in any fuel region.
- These success criteria are:
  - Applicable after the initial quench of the core
  - Consistent with the long-term core cooling requirements of 10 CFR 50.46 (b)(4) and 10 CFR 50.46 (b)(5).
    - Provide for demonstrating that local temperatures in the core are stable or continuously decreasing, and,
    - Debris entrained in the cooling water supply will not affect decay heat removal
- These criteria do not present, nor are they intended to be, new or additional long-term core cooling requirements

Basis for LTCC Success Criteria

- The 800°F temperature
  - Selected based on autoclave data that demonstrated oxidation and hydrogen pickup to be well behaved at and below the 800°F temperature and the reduction (oxidation) of cladding is small
- The 50 mils limit for oxide plus deposits
  - Selected so as to preclude the formation of deposits that would bridge the space between adjacent rods and block flow between fuel channels

LOCADM - Validation of Core "Boiler Scale" Model

- LOCADM is an automated (spreadsheet) calculation of post-LOCA material deposition
- Model conservatively assumes that all fiber and chemical products passed by the sump screen and transported to fuel surfaces by boiling will deposit
- Verification of the model performed by comparison of calculations to literature data
- As shown in the comparison to the right, deposition is conservatively predicted



Fahmi Brahim, Wolfgang Augustin, Matthias Bohnet, "Numerical simulation of the fouling process" International Journal of Thermal Sciences 42 (2003) 323-334

Summary of Fuel Rod Dimensions Used in Parametric Study

rod length (in)	144
rod outside diameter (in)	0.36
clad thickness (in)	0.0225

Variable Values

- Crud Thickness:

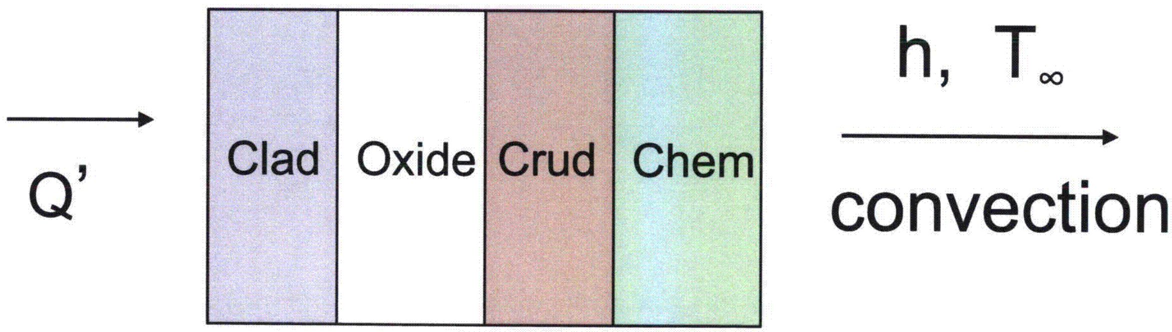
  0.000 – 0.050 in

- Crud Thermal Conductivity:

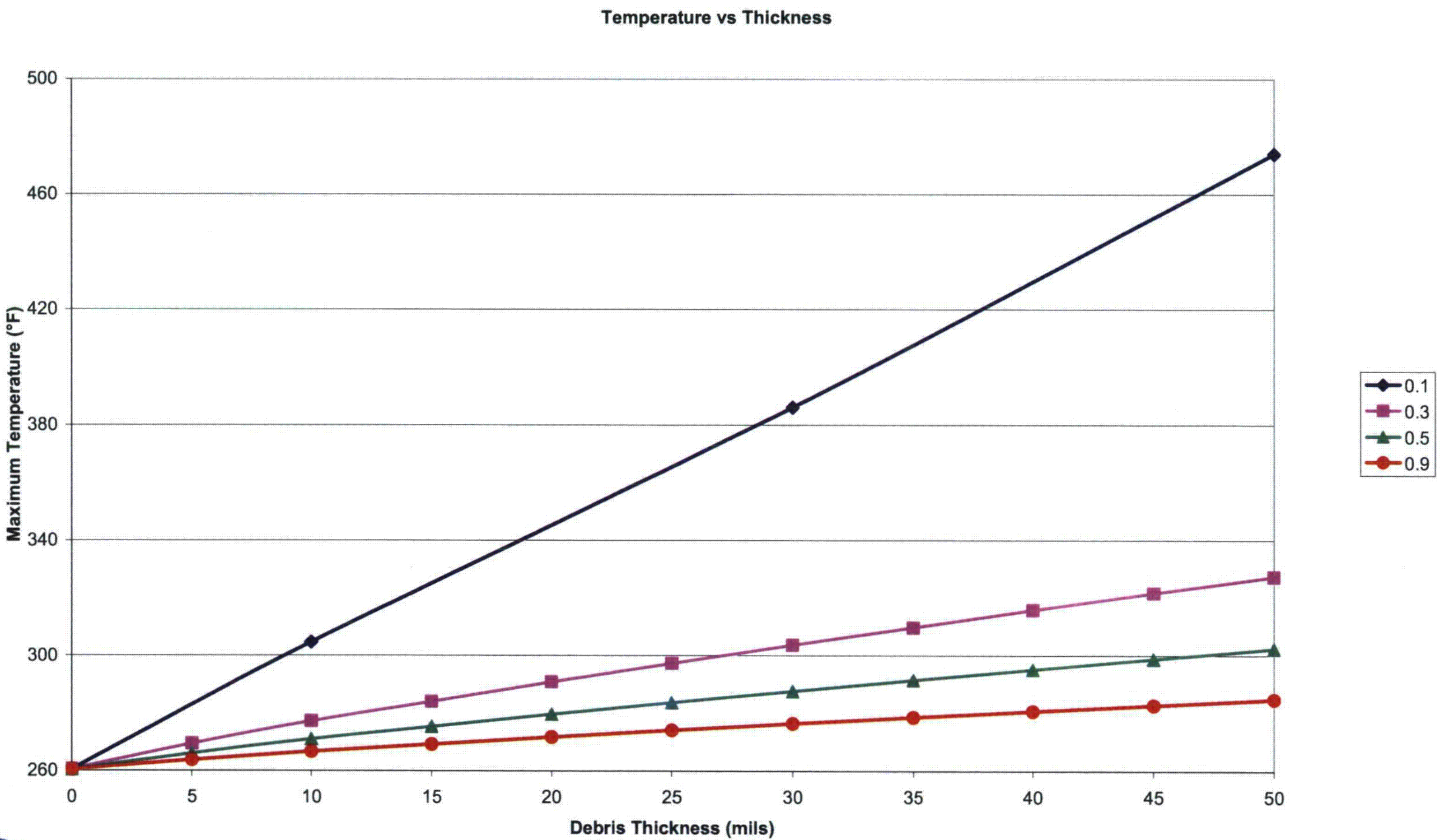
  0.3 – 0.9 BTU/(hr-ft-°F)

Model and Assumptions

- Steady-State, no Axial Conduction
- Uniform layer thicknesses (except chem.)
- Acceptance Criteria
  - Clad/Oxide interface < 800°F



Clad-Oxide Temp vs. Precip Thickness



Collection of Material on Fuel Clad

- Three categories of protective coatings used inside containment have been evaluated to have no effect on the generation of precipitate
- Protective coatings used inside a PWR containment will not adhere to clad surface due to low temperatures
  - Zinc
  - Epoxies
  - Other

Boric Acid Dilution

- Previously, NRC staff had not combined GSI-191 with boric acid precipitation (BAP) concerns
- A separate PWR Owners Group project was addressing BAP concerns
  - Debris suspended in the delivered ECCS coolant was included in that program
- Recently, NRC has indicated that plants desiring to increase their fiber limits over that approved in their Safety Evaluation for WCAP-16793-NP Revision 2 must also address BAP
- The PWR Owners Group is assessing a path forward

Defense In Depth Calculations of Long-Term Core Cooling to Support GSI-191

Defense In Depth Calculations

- These calculations performed to demonstrate defense in depth
- Extreme cases
- Two calculations performed
  - Blockage at core inlet
  - Local fuel rod blockage

Core Blockage Evaluation

- A blockage of about 99.4% of the core inlet area was evaluated
- The evaluation demonstrated that negligible impact on clad temperature would be expected due to blockage alone.

Problem Statement

- For a Double-Ended Guillotine Break, RWST/BWST can be depleted and sump recirculation begun within ~ 20 Minutes
- Fibrous debris and particulates can pass through the sump screen
- Results in the potential for debris build-up at core inlet
  - Fuel assembly bottom nozzle, debris filter, grids
  - In the limit, collection of fibrous and particulate debris might cause high pressure drop

Selection of Limiting Break

Double-Ended Cold Leg

- Spilling of ECCS to containment
- Gravity head to loop level only
  - True for no single failure also
- Lower flow results in slower debris build-up

Double-Ended Hot Leg

- No spilling of ECCS
- Additional driving head from liquid level SGs
  - more for no single failure
- Higher flow results in faster build-up

Use Double-Ended Cold Leg Break With No Delay in Debris Build-up

Vessel Design Considerations: (Westinghouse OEM)

- Plants With ECCS Delivered to Cold/Hot Legs
  - Designed Upflow is Least Limiting
    - Numerous large pressure relief holes in baffle wall allow flow to bypass core inlet if blocked
  - Converted Upflow is More Limiting
    - No pressure relief holes, limited flow to top of core (if any)
  - Downflow is Most Limiting
    - Flow must enter core through lower core plate
- Upper Plenum Injection Plants also Evaluated

Other PWR Vessel Designs

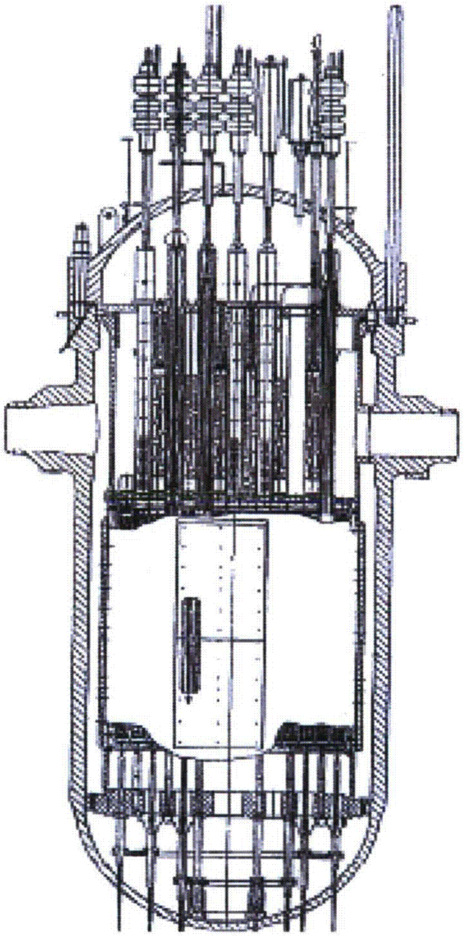
- B&W design similar to Westinghouse upflow design
  - Numerous large pressure relief holes in baffle wall allow flow to bypass core inlet if blocked
  - Barrel vent valves located above loop level
    - No impact on this issue
- CE Design Similar to Westinghouse Converted Upflow
  - No pressure relief holes
  - Limited flow to top of core (if any)

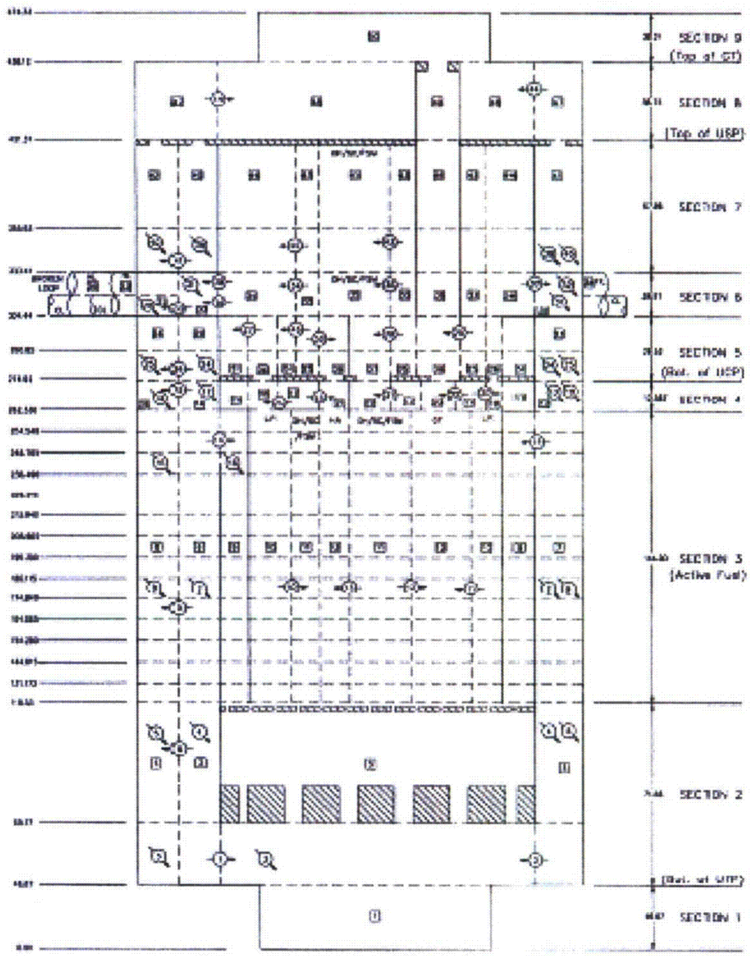
Westinghouse Downflow Design is Bounding

Plant Selection

- Downflow Most Limiting Configuration
- Core Power Density Also Important for Heat Removal
  - Use available 3-loop downflow model for plant rated at 2900 MWt
  - Core model conservatively has power profile skewed to the top of the core; maximizes boiling

Vessel Sketch and Node Diagram





WCOBRA/TRAC Modeling Approach

- Run Problem from Break Initiation
  - Create Single Use code version which ramps in high resistance as specified by User
  - Ramp in large increase in resistance at core inlet of PWR model
    - 1st node of core channels

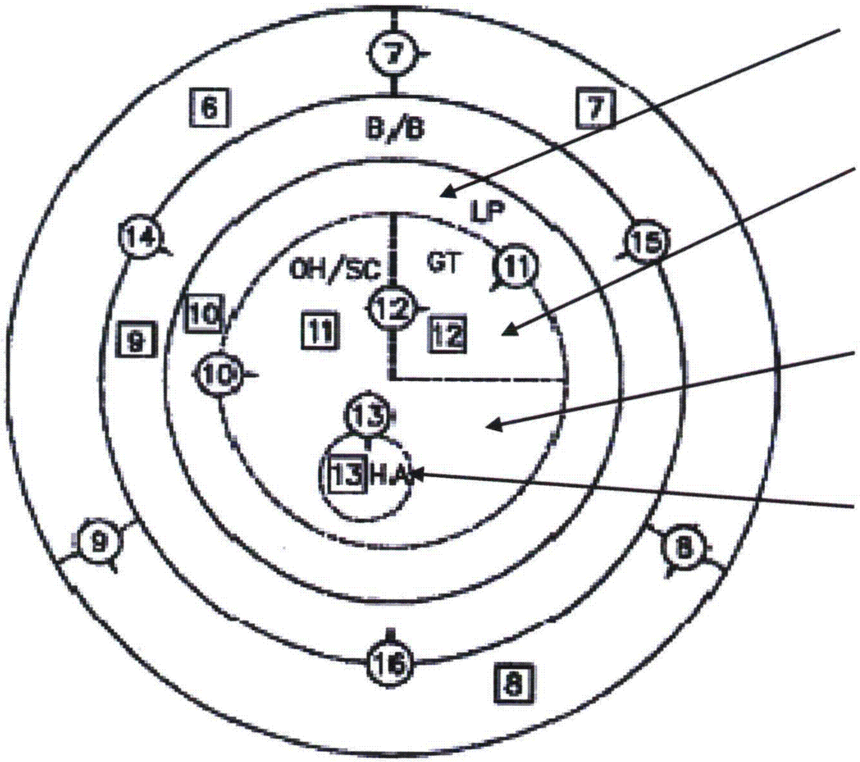
WCOBRA/TRAC Modeling Approach (cont.)

- Blockage Cases Run to 40 Minutes
  - Blockage ramped in from 20 to 20.5 minutes
  - $K = 1x10^9$ simulates complete channel blockage
- Increased injection temperature
  - Modeled at 20 minutes
  - Temperature ≈ RHR heat exchanger outlet
    - 190°F injection temperature used
    - Current LOCA Mass and Energy analysis uses 180°F

WCOBRA/TRAC Modeling Approach (cont.)

- Two simulation cases performed
  - 82% blockage, K ramped in all core channels except Lower Power periphery channel
  - 99.4% blockage, K ramped in all core channels except one assembly

Standard Core Modeling



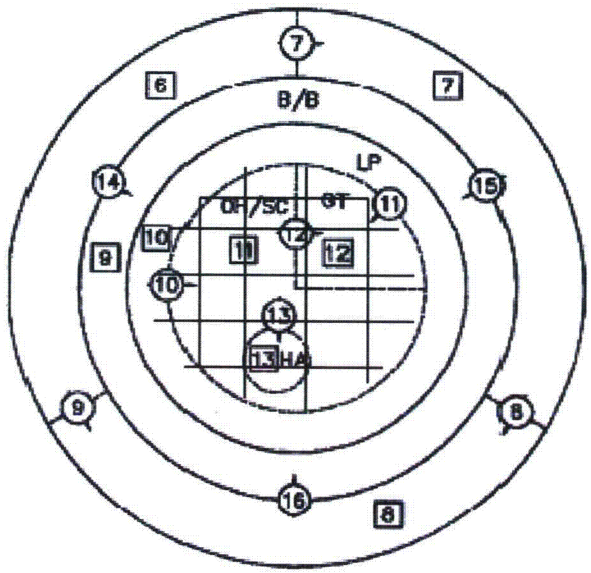
Peripheral Assemblies (28)

Interior Assemblies Under Guide Tubes (53)

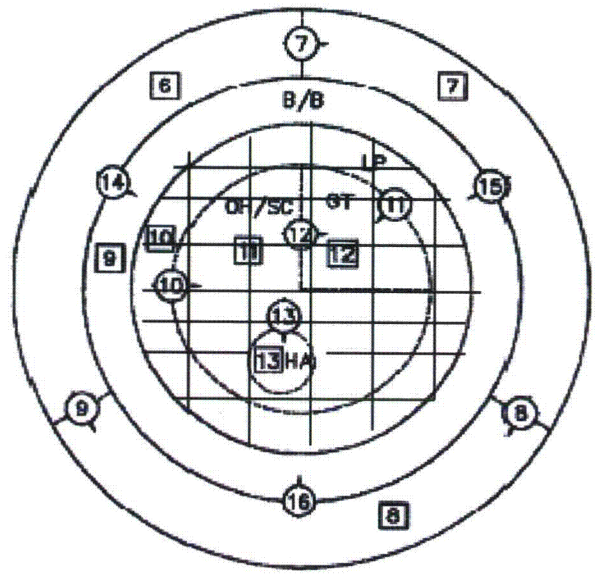
Interior Assemblies Under Other Structures (75)

One Assembly Under a Restricted Structure (1)

Blockage Approaches



Block All Except Peripheral
(82%)

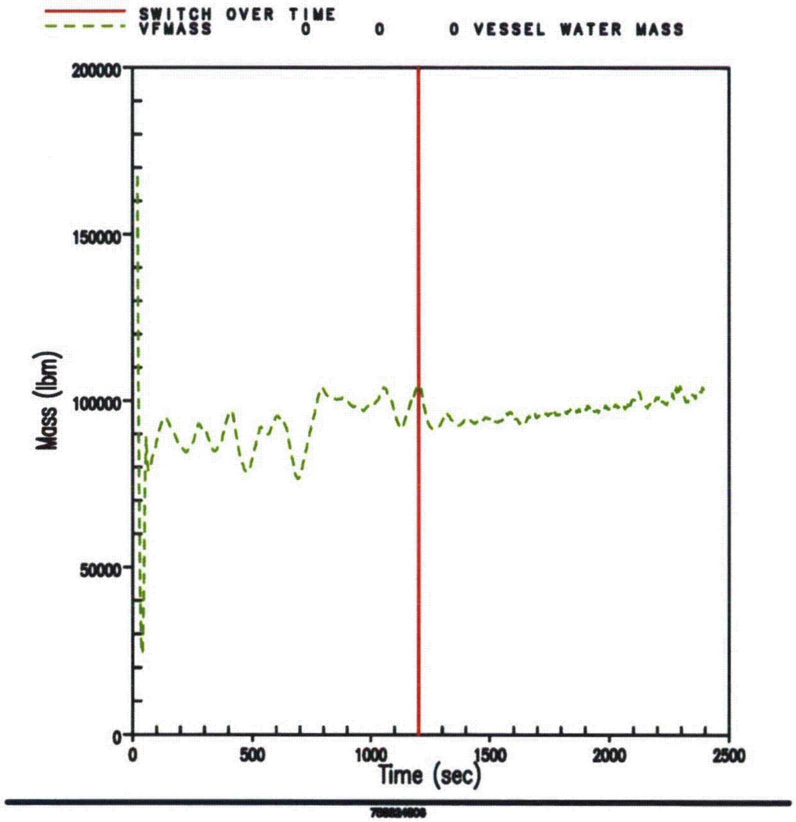


Block All Except One Assembly
(99.4%)

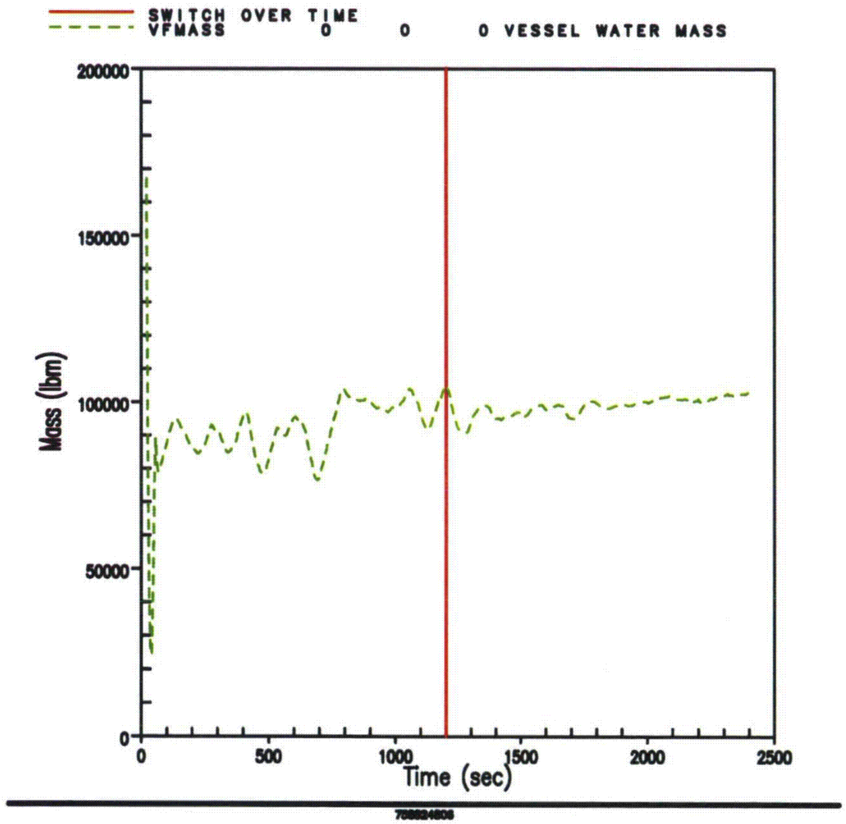
WCOBRA/TRAC Modeling Approach (cont.)

- Containment pressure at atmospheric conditions by switchover to sump recirculation
  - Extrapolated pressure vs. time table used in Best Estimate LOCA analysis

Total Vessel Mass



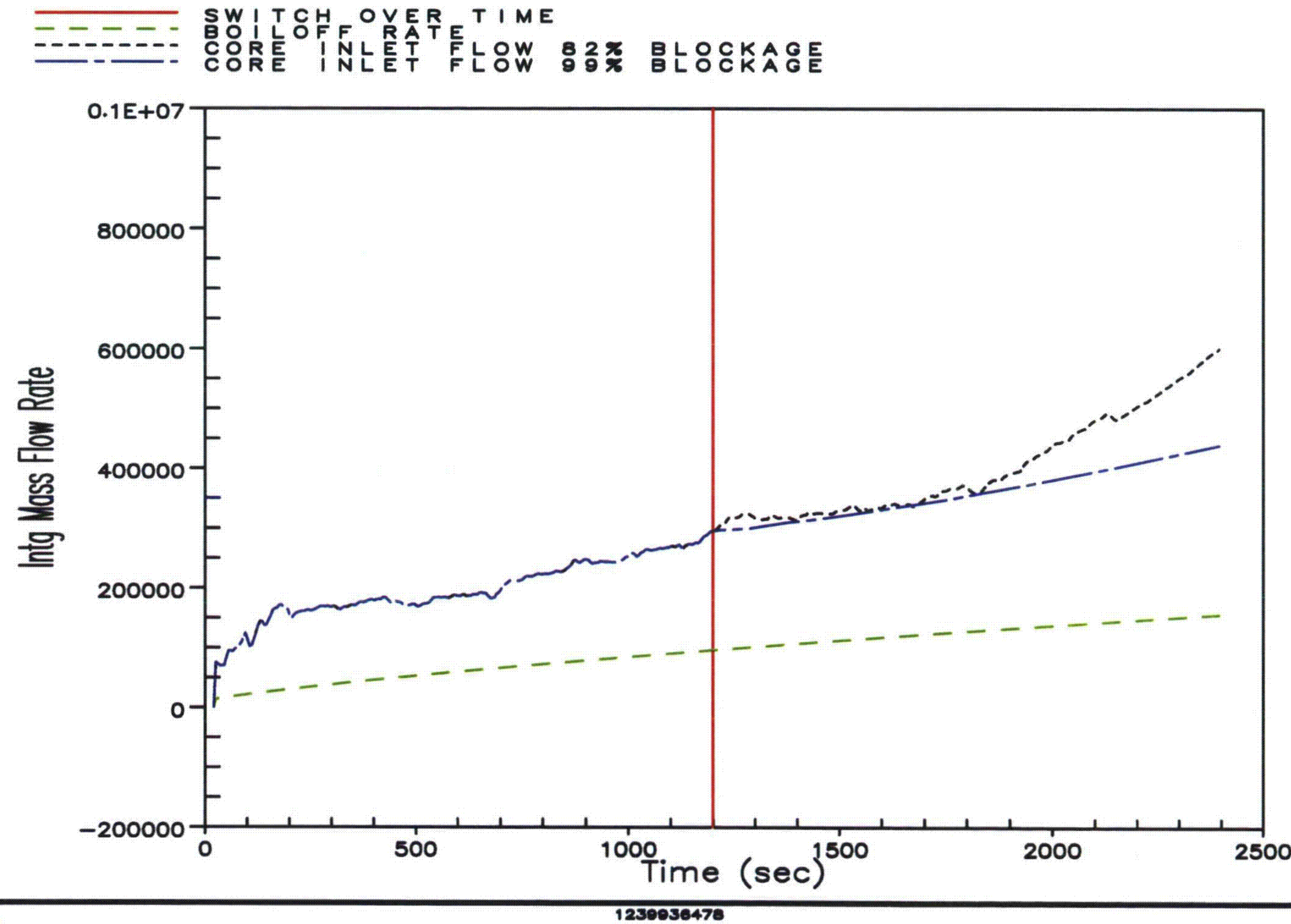
82% Blockage



99.4% Blockage

PWROG
PWR Owners Group

Core Flow Rate vs. Boiloff Rate



Summary of Blockage Calculations

- Flow diversion into unblocked channels observed in calculations
- After blockage simulated
  - Core flow rate > boil-off rate after blockage occurs
  - Difference in core flow between 82% and 99.4% blockage due to difference in resistance at core inlet
  - Increase observed in calculations of
    - Core collapsed liquid level, and,
    - Total core mass

Local Blockage and Plate-Out

- Two phenomena studied parametrically:
  - Reduction of flow at a fuel grid,
  - Precipitation of chemical product on the surface of fuel cladding was evaluated
- A range of thermal conductivities for the precipitation were considered
  - Maximum value = 0.9 Btu/(hr-ft-°F)
  - Minimum value = 0.1 Btu/(hr-ft-°F)
- For all cases, over the range of conditions considered, the cladding surface temperature was evaluated to be below 800°F

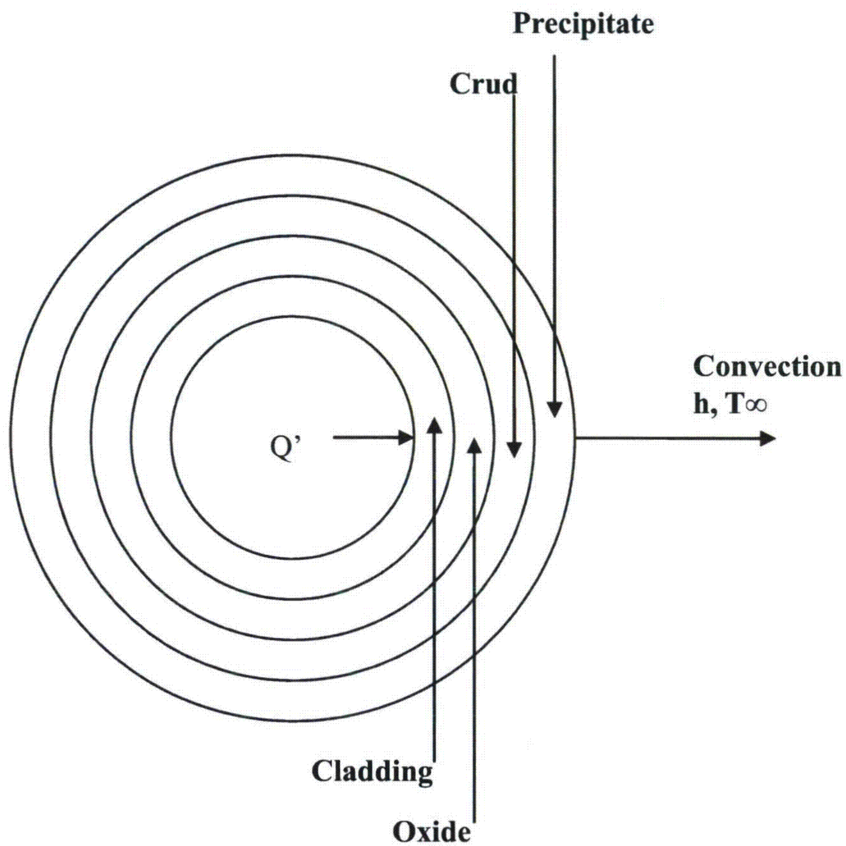
Effect of Debris Collection on Hot Spots

- Source of heat post-LOCA is from decay heat in the fuel rod
  - This source is limited to the fuel in the rod and decreases with time
  - "Hot spots" can arise only if the local flow is severely restricted
  - Local temperature increases would be mitigated by the boil-off in the region
  - Heat will be dissipated:
    - Grids act as radiators
    - Axial conduction along the fuel rod
  - Sustaining quench and replacing boil-off maintains clad temperatures < 800°F
- If deposition of chemical products or debris were to form a "hot spot":
  - Conservative calculations of cladding temperatures demonstrate coolability of the clad with deposition on clad surface and blockage at a grid
    - Decay heat levels at time of initiation of recirculation from the containment sump
    - Between grids, chemical product and debris deposition less than 50 mils yields clad temperatures < 800°F
    - At grids, assuming no flow through the grid yields clad temperatures < 800°F

1-D Clad Hot Spot Calculations

Clad/Oxide Interface Temperature vs. Chemical Precipitate Thickness				
Chemical Precipitate Thickness (mils)	$k_{precipitate}$ (BTU/hr-ft-°F)			
	0.1	0.3	0.5	0.9
0	273°F	273°F	273°F	273°F
10	336°F	293°F	285°F	279°F
20	396°F	313°F	296°F	286°F
30	453°F	331°F	308°F	291°F
40	508°F	350°F	318°F	297°F
50	560°F	367°F	328°F	302°F

Clad/Oxide Interface Temperature vs. Chemical Precipitate Thickness		
Chemical Precipitate Thickness (mils)	$k_{precipitate}$ = 0.1 BTU/hr-ft-°F	
	0.422" OD rod	0.416" OD rod
0	283.6°F	283.6°F
10	377.0°F	376.9°F
20	466.4°F	466.2°F
30	552.1°F	551.9°F
40	634.5°F	634.1°F
50	713.8°F	713.2°F



Defense in Depth Conclusions

- Defense in depth analysis demonstrate that if a large blockage occurs, core decay heat removal will continue
  - Collection of debris on fuel grids
  - Collection of material on fuel cladding
- When considered collectively, 10 CFR50.46 long-term core cooling criteria satisfied

SUMMARY

Summary

- WCAP-16793-NP and supporting work has demonstrated reasonable assurance of LTCC
- Conservative fuel assembly debris capture testing has been performed for both AREVA and Westinghouse fuel designs under a range of debris loading conditions
  - Using the most conservative test data, WCAP-16793-NP suggests that the FA fiber loading be 15 g/FA
  - Significant test constraints result in this low fiber limit
  - Test data and an evaluation of conservatisms support a per FA fiber limit of ≥ 25 g