PWROG
PWR Owners Group

Program Management Office
4350 Northern Pike
Monroeville, Pennsylvania 15146

WCAP-16793-NP, Rev. 0 (Non-Proprietary)
Project No. 694

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Subject: Pressurized Water Reactor Owners Group
Responses to the NRC Request for Additional Information (RAI) on WCAP-16793-NP, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid" (PA-SEE-0312)

References:

1. PWROG Letter, F. Schiffley to Document Control Desk, "Submittal of WCAP-16793-NP, Revision 0,"Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid" OG-07-264, June 4, 2007.

2. NRC letter from Tanya Mensah of NRR to Gordon Bischoff of PWROG dated September 10, 2007 "Request For Additional Information Re: Pressurized Water Reactor Owners Group (PWROG) Topical Report (TR) WCAP-16793-NP, Revision 0, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid" (TAC NO. MD5891)

3. NRC letter from Tanya Mensah of NRR to Gordon Bischoff of PWROG dated September 20, 2007 "Request For Additional Information Re: Pressurized Water Reactor Owners Group (PWROG) Topical Report (TR) WCAP-16793-NP, Revision 0, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid" (TAC NO. MD5891)

In June 2007, the Pressurized Water Reactor Owners Group (PWROG) submitted WCAP-16793-NP (Non-Proprietary), Rev. 0, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid" for review and approval (Reference 1). In September 2007, the NRC provided the formal Request for Additional Information (RAI) (Reference 2 and 3) for WCAP-16793-NP.

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Enclosure 1 to this letter provides the RAI responses to the 45 questions received in Reference 2. Enclosure 2 presents the RAI responses to the 30 questions in reference 3.

These RAI responses are being provided to support issuance of the draft Safety Evaluation on WCAP-16793-NP.

If you have any questions concerning this matter, please feel free to call Reginald Dulaney at (412) 374-6549.

Sincerely yours,

Christine A. D'Mgi for

Frederick P. "Ted" Schiffley, II, Chairman
Pressurized Water Reactor Owners Group

FPS:RRD:las

Enclosures: 1. RAI Responses to RAI's dated September 10, 2007
2. RAI Responses to RAI's dated September 20, 2007

cc: Systems and Equipment Engineering Subcommittee
Steering Committee
S. Peters, NRC
T. Mensah, NRC
S. Rosenberg, NRC
W. Rinkacs, Westinghouse
P. Pyle, Westinghouse
T. Andreychek, Westinghouse

RAI #1

What is the basis for stating blockage of the core will not occur on page xviii? What is the maximum amount of debris that can enter the core and lower plenum and what is the maximum potential blockage from debris at the core inlet and the first spacer grid location?

RESPONSE TO RAI #1

The basis for the statement on page xviii that blockage of the core will not occur is the derived from the four (4) bulleted statements on page xvii and the supporting discussion presented in Section 2 of the main body of the report. The conclusion is based on the following:

1. Test data demonstrating sump screen bypass fiber does not completely block flow to a fuel assembly which allows for decay heat to be removed. This is true even for large quantities of fiber and particulate debris as discussed further in RAI #2.

2. Fibrous debris, if it enters the core region, does not tightly adhere to the surface of the fuel cladding as demonstrated by testing reported in NEA/CSNI/R (95)11.

3. A calculation using limiting inputs to the sample problem described in Appendix E and listed on the response to RAI # 6(b), and a conservative deposition model, also described in Appendix E, demonstrated that the calculated deposition thickness would not result in long-term cladding temperatures in excess of the 800°F acceptance basis value.

The maximum amount of debris that can enter the core is based on plant-specific debris generation calculations, the pass-through performance of a plant-specific sump screen design and the scenario considered (flow rate to the sump screen, hot-leg break versus cold-leg break).

Therefore, as noted from the first bullet item on page xvii and Item 1 above, based on available test data of debris collection by a debris-capturing grid at the bottom nozzle of a modeled fuel assembly for an active replacement sump screen as described in the response to RAI #2, no potential blockage that terminates flow into or through the core is expected.

RAI #2

On page 2-3 it is stated that recent observations from testing of a partial-length fuel assembly using plant-specific fibrous and particle debris have confirmed that the NUREG/CR-6224 correlation is quite conservative for application at the core inlet. Please provide a complete description of this test facility, the tests that were performed and the results.

RESPONSE TO RAI #2

Testing has been performed to determine the effects of collection of fibrous debris on the debris capturing grids located at the bottom nozzle of a simulated fuel assembly. The testing was performed at a licensee's replacement sump screen vendor's test facility. The test conditions were for a high-fiber plant and an active sump screen, which provided for a large amount of fibrous debris to bypass the sump screen.

Conditions for the test were:

Screen Design:	Active sump screen (plow and blade design)
Core Simulation:	Single assembly
Core Flow:	6 gpm from a simulated lower plenum upward into a partial length fuel assembly. This flow rate was determined to be a maximum fuel grid flow rate for the plant. The total maximum core flow rate is 1060 gpm total for this plant under long-term core cooling conditions.

Description of Test Loop

Flow Diagram

A schematic of the test loop is shown in Figure 2-1 below. The test article was mounted approximately 12 inches above the bottom of a Lexan test chamber. Flow entered from the bottom of the chamber. An inverted solid circular cone directed flow along the bottom of the chamber to minimize the settling of debris. Flow exited the top of the chamber and returned to the mixing tank. The taps for a differential pressure transmitter were connected to the test chamber above and below the test article. The mixing tank allowed debris to be added to the system near the pump suction.

Instrumentation

The primary purpose of the test program was to measure the head loss across the test article as a function of flow rate and debris load. Appropriately calibrated and ranged differential pressure and flow instruments were used to measure head loss and flow rate for each test. Unless specifically noted to the contrary, the instrument errors were assumed to be independent and the square root of the sum of the squares was used to determine the instrument loop uncertainty. All measurement and display devices were calibrated to NIST traceable standards.

A thermocouple was used to measure the working fluid in the mixing tank.

Test Article Description

The test article consisted of a simulated core support plate, a bottom nozzle, a debris-capturing grid, an intermediate support grid, simulated fuel rods and simulated control rods. Figure 2-2 is a diagram of the test article in the test chamber.

A 1-inch thick simulated core support plate was fastened to the test chamber. The core support plate was sealed to the test chamber walls to prevent flow around the edge of the support plate. The plate supported the weight of the bottom nozzle / fuel filter grid assembly.

The fuel rods were simulated with 3/8" plastic rod. The simulated control rods were sized such that they would extend to the same height as the simulated fuel rods.

The bottom nozzle used in the testing was similar to other debris capturing bottom nozzle designs used in PWRs. The bottom nozzle sat on the simulated core support plate. The test facility provided for a gap between the edge of the debris capturing grid and the side walls of the Lexan test chamber, simulating the gap that would exist between adjacent fuel assemblies[1].

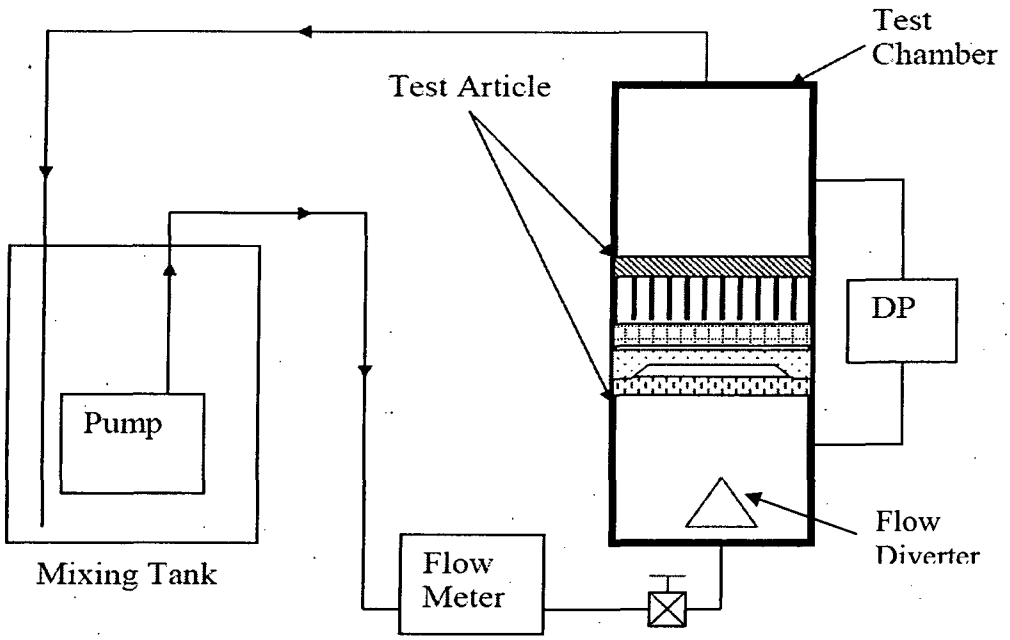

Figure 2-1: Schematic of Fuel Assembly Fibrous Debris Capture Test Loop

[1] Once the normal flow path had collected debris, more of the debris would go into the gap. Even with a gap that was 1.5 times the replacement sump screen strainer hole size, it was observed that this gap between the debris capturing grid and the Lexan sidewalls would collect fiber as well which, in turn, limited the bypass of fiber beyond the debris capturing grid.

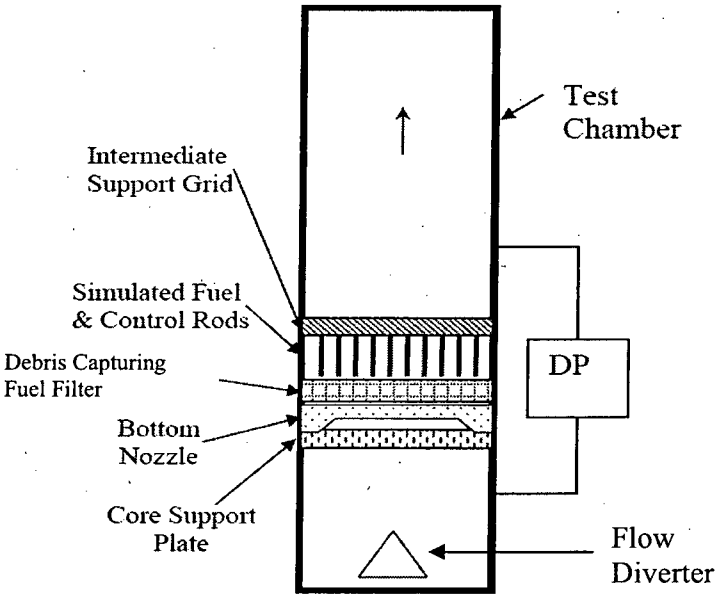

Figure 2-2: Schematic of Test Article in Test Chamber

The fuel rods were located on the bottom nozzle between the fuel rod flow holes by the debris-capturing grid. The tapered ends of the simulated fuel rods were pushed against the bottom nozzle. Control rod simulations were screwed into the control rod holes in the bottom nozzle and sealed these holes. The instrumentation tube hole was also plugged.

The licensee supplied the debris-capturing grid used in the testing. This grid accurately simulated the grid used the plant. The debris-capturing grid was fastened and positioned to the bottom nozzle as would be in the plant. An intermediate support grid was mounted near the top of the simulated fuel rods, and was used in the test primarily to maintain the orientation of the fuel rods.

Description of Debris

A brief description of the debris used in the test is presented in the sections below.

Fibrous Debris

The fibrous debris used in the fuel filter tests was obtained from fiber that bypassed the active sump screen in the bypass testing. The fibrous debris was supplied and shredded by the licensee or selected and approved by the licensee for the bypass tests.

The fiber was dried and weighed prior to use in the fuel filter tests. The fiber was not separated by type for the fuel filter tests.

Particulate Debris

A particulate insulation / dust / dirt mixture was identified by the licensee as appropriate for testing.

Quality Assurance Program

All quality-related activities were performed in accordance with the test performer's Quality Assurance Program. Quality-related activities were defines to be those which were directly related to the planning, execution and objectives of the test. Supporting activities such as test apparatus design, fabrication and assembly were not controlled by the test performer's Quality Assurance Program. These activities included fabrication of the tank, platform, and piping. The important information concerning the test facility was documented after fabrication. The test performer's Quality Assurance Program provides for compliance with the reporting requirements of 10 CFR Part 21. All instrument certifications, instrument calibrations, testing procedures, data reduction procedures and test results are contained in a Design Record File which will be kept on file at the test performer's offices.

Key Observations from Testing

Key observations from testing were:

- Almost all of the fibrous debris collected at the first grid (Debris Capturing Fuel Filter).
- No significant collection of fiber was observed to be above the first grid.
- The fibrous debris collected at the first grid during testing was not observed to compact or compress.
- Complete "blockage" of the fuel assembly tested was not observed in testing. Coolant flow through the fiber collection at the bottom of the first grid was maintained.
- Fiber debris did not adhere to the grid; the loose fiber mass was observed to drop from the first grid (Debris Capturing Fuel Filter) when flow was stopped and did not transport back to the grid when flow was reinitiated.

Active replacement sump screens are known to maximize debris passed through the screen. Comparing the two right-most columns in Table 2-1, the test results clearly provide conservative amounts of fibrous debris at the inlet to the fuel and, in fact, bound the fiber bypass through passive replacement sump screens for high-fiber plants.

Fibrous Debris Loading from Testing:

Using the debris loading for the single assembly tests described in this RAI response, calculations were performed to extrapolate those debris loadings used in the tests performed for single assembly to the core of the plant. These calculated values were then compared to expected fibrous debris bypass from testing of replacement passive sump screens. This comparison was made to demonstrate the conservatively large volume of fibrous debris that was used in the test. A summary of the inputs used for these calculations and a summary of the results are listed in Table 2-1. Comparing the calculated fibrous debris at the core entrance from the test given in Column C to the maximum expected fibrous bypass for passive replacement sump screen given in Column D, it is concluded that the fibrous debris used in the test bounds that expected from the largest passive replacement sump screen.

Table 2-1: Comparison of Fiber Load Tested to Expected Passive Replacement Strainer Fiber Load

No.	Fibrous Debris Used in Active Strainer Test			(D) Maximum Fibrous Debris at Core Entrance for a Passive Strainer[3, 4]
	(A) Mass (One Fuel Assembly)	(B) Volume[1] (One Fuel Assembly)	(C) Total at Core Entrance[2]	
1	0.24 lbm of fiber	0.10 ft^3	21.7 ft^3	16.0 ft^3
2	0.84 lbm of fiber	0.35 ft^3	75.9 ft^3	16.0 ft^3
3	0.96 lbm of fiber	0.40 ft^3	86.8 ft^3	16.0 ft^3

Notes:

- The volume of fibrous debris is calculated by dividing the mass of fiber of a test by 2.4 lbm/ft^3, which is the density for low density fiberglass as identified in NEI 04-07 and accepted in the associated NRC Safety Evaluation (SE) on that document.
- The debris at the fuel entrance is calculated by multiplying the volume and mass used in a test by the number of fuel assemblies in the plant for which the test was performed (217 fuel assemblies).
- The median size of the replacement sump screen for a U.S. PWR is about 4,400 ft^2. A 16,000 ft^2 value is conservatively representative of the largest replacement sump screen for U.S. PWRs as identified in a presentation made by NEI at a Public Meeting on GSI-191 held February 9, 2006.
- At the Public Meeting on GSI-191 held February 9, 2006, vendors of passive replacement sump screens shared that, based on flume testing using licensee-specific fibrous debris loadings, about 1ft^3 of fiber bypass is observed per 1000 ft^2 of replacement strainer surface area. The values listed in this column are calculated by multiplying a replacement sump screen surface of 16,000 ft^2 by the ratio of 1 ft^3 of fiber / 1000 ft^2 of replacement sump screen area.

Pressure Drop Measurements from Testing:

Pressure drop measurements were taken during testing performed for the active replacement sump screen. (It is noted that this licensee is no longer pursuing the implementation of an active sump screen.) The conditions under which pressure drop measurements were made, and the corresponding range of values of the measurements, are listed in Table 2-2, given below.

As identified in the fibrous debris loading discussion given earlier in this response, vendors performing testing of passive replacement sump screens have reported that, based on flume testing using licensee-specific fibrous debris loadings, about 1ft^3 of fiber bypass is observed per 1000 ft^2 of replacement strainer surface area. From Note (4) of Table 1 above, the majority of the replacement sump screens for U.S. PWRs are less than 10,000 ft^2 in surface area. However, a value of 16,000 ft^2 value was selected to conservatively represent the largest replacement sump screen for U.S. PWRs. As described above, with a maximum replacement sump screen area of 16,000 ft^2, no more than about 16 ft^3 of fibrous debris is expected to collect on the core entrance.

From the pressure drop data given in the table below, even with a collection of 21.7 ft^3 of fibrous debris and 1388.8 lb$_m$ of particulate debris at the entrance to the core, a bounding head loss that would be expected is about 10.2 inches of water. The bounding 10.2 inch increase in head loss translates into an increase in pressure drop of about 0.37 psi at the core entrance. Considering the WCOBRA/TRAC calculations of Appendix B that assumed an arbitrary 99.4% reduction in flow area, the bounding head loss increase of 10.2 inches of water are evaluated to not affect long-term core cooling.

Table 2-2: Summary of Head Loss Data for Observation Configuration

Flow Rate (gpm)	Fibrous Debris			Particulate Debris		Measured Head Loss (in_{H_2O})
	Mass - One Assembly	Volume - One Assembly(1)	Volume – At Core Entrance(2)	Mass - One Assembly	Mass – At Core Entrance(2)	
6	0.04 lb_m	0.017 ft^3	3.62 ft^3	0.0 lb_m	0.0 lb_m	0.4
				0.4 lb_m	86.8 lb_m	0.8
6	0.06 lb_m	0.025 ft^3	5.43 ft^3	0.0 lb_m	0.0 lb_m	1.2
				1.2 lb_m	260.4 lb_m	2.9
6	0.12 lb_m	0.050 ft^3	10.85 ft^3	0.0 lb_m	0.0 lb_m	1.9 – 2.5(3)
				1.6 lb_m	347.2 lb_m	4.5 – 7.0(3)
6	0.24 lb_m	0.100 ft^3	21.7 ft^3	0.0 lb_m	0.0 lb_m	3.8 – 5.8(3)
				6.4 lb_m	1388.8 lb_m	10.2
6	0.36 lb_m	0.150 ft^3	32.55 ft^3	0.0 lb_m	0.0 lb_m	12.9
				16 lb_m	3472 lb_m	38.5
6	0.48 lb_m	0.200 ft^3	43.40 ft^3	0.0 lb_m	0.0 lb_m	0.8 – 16.3(3)
				16 lb_m	3472.0 lb_m	> 60
6	0.96 lb_m	0.400 ft^3	86.80 ft^3	0.0 lb_m	0.0 lb_m	24.1
				6.4 lb_m	1388.8 lb_m	> 60

Notes:

(1) The volume of fibrous debris is calculated by dividing the mass of fiber of a test by 2.4 lbm/ft^3, which is the density for low density fiberglass as identified in NEI 04-07 and accepted in the associated NRC Safety Evaluation (SE) on that document.

(2) The debris at the fuel entrance is calculated by multiplying the volume and mass used in a test by the number of fuel assemblies in the plant for which the test was performed (217 fuel assemblies).

(3) Multiple entries indicate more than one (1) test run was made with the fibrous and particulate debris loading identified in the table. The minimum and maximum values of head loss that ere recorded are listed in the table.

Applicability of Test Data and Observations to PWRs:

The data and conclusions presented in this response are applicable to all PWRs with passive sump screens for the following reasons;

- The formation of a fiber bed at the core inlet serves as a collector for particulates which, in turn result in an increase in pressure drop across the core inlet. Since active sump screens are known to maximize debris passed through the screen, the data is applicable and bounding for all PWRs with passive sump screens.
- Without a fiber bed, particulates that are lifted into the core are sufficiently small that they will not collect at and block the core entrance (Reference 2-1). Without a fiber bed to capture particulates, there is no impact on the head loss at the core inlet.

Thus, the fiber bed formation and subsequent collection of particulates and the consequential head loss observed in the test and test data described above is both applicable and bounding for all PWRs with passive sump screens

Applicability of NUREG/CR-6224 Correlation:

The NUREG/CR-6224 head loss correlation is not directly applicable to the head loss associated with the collection of fibrous debris on fuel grids. The NUREG/CR-6224 head loss correlation was developed for a different situation than that seen for the collection of fibrous debris on fuel grids. Thus, for the same fibrous and particulate debris loading, the correlation will be overly conservative in predicting the head loss through the fibrous debris bed on a fuel grid.

This position is supported by the following:

- Replacement sump screen testing has shown that, due to the small hole size used for the replacement sump screens, the fibrous debris bypassed through replacement sump screens is much shorter than the fibrous debris that was used in the testing performed to support the development of the NUREG/CR-6224 head loss correlation due to the small hole sizes of the replacement sump screen. The shorter fibers provide for a different fiber bed morphology than what was used for the development of the NUREG/CR-6224 correlation
- The flow in the test was upward with gravity acting to pull the fiber bed down and away from the bottom of the fuel. For the testing performed to support the NUREG/CR-6224 correlation, the fibrous bed was formed on the top of a mesh or perforated screen and the flow downward through the fibrous bed and the screen which tended to compress the fiber bed.
- Similarly, gravity worked on particulates that were caught in the fibrous bed formed in the test tended to pull the fibrous bed apart, whereas, for the testing performed to support the development of the NUREG/CR-6224 head loss correlation, particulates were trapped on top of the fibrous debris bed and gravity, like the flow, worked to compress the fibrous debris bed.
- The NUREG/CR-6224 head loss correlation was developed from data collected using a vertical loop test facility with a small diameter flow channel in which all of the flow was directed downward through a fixed, predetermined debris bed. In a reactor, the flow area is large and the flow patterns sufficiently varied that the uniform directional flow conditions of the NUREG/CR-6224 test do not apply.
- Finally, the NUREG/CR-6224 correlation was developed from test data for velocities ranging from 0.15 ft/sec to 1.5 ft/sec (NUREG/CR-6224, Section 6.4). As shown in Table 1 of the response to RAI #3, the liquid velocities in the core are at or below the bottom range of the velocities used in developing the NUREG/CR correlation. The lower velocities associated with PWRs would not compact a fiber bed to the same degree as those higher velocities used in the testing that supported the development of the NUREG/CR-6224 head loss correlation. Less compaction of a fibrous bed provides for a smaller pressure drop across the bed.

For these reasons, the NUREG/CR-6224 head loss correlation is not directly applicable to the head loss associated with the collection of fibrous debris on fuel grids and, for the same fibrous and particulate debris loading, will be overly conservative in predicting the head loss through the fibrous debris bed on a fuel grid.

REFERENCE FOR RAI #2 RESPONSE:

2-1 Andreychek, T. S., "Evaluating Effects of Debris Transport within a PWR Reactor Coolant System during Operation in the Recirculation Mode," Particulate Phenomena and Multiphase Transport, Proceedings of the 4th Miami International Symposium on Multiphase Transport and Particulate Phenomena, 15-17 December 1986, published by Hemisphere Publishing Corporation (1988)

RAI #3

To show that the pressure drop correlation of NUREG/CR-6225 is adequate to evaluate core inlet blockage, please provide a comparison of the materials and flow velocities of the test data used to develop the correlation to those which would be expected at a reactor core inlet during long term cooling. UPI plants should be included in this comparision.

RESPONSE TO RAI #3

The NUREG/CR-6224 head loss correlation is not directly applicable to the head loss associated with the collection of fibrous debris on fuel grids. The NUREG/CR-6224 head loss correlation was developed for a different situation than that seen for the collection of fibrous debris on fuel grids. Thus, for the same fibrous and particulate debris loading, the correlation will be overly conservative in predicting the head loss through the fibrous debris bed at the core inlet.

This position is supported by the following:

- Replacement sump screen testing has shown that, due to the small hole size used for the replacement sump screens, the fibrous debris bypassed through replacement sump screens is much shorter than the fibrous debris that was used in the testing performed to support the development of the NUREG/CR-6224 head loss correlation. The shorter fibers provide for a different fiber bed morphology than what was used for the development of the NUREG/CR-6224 correlation
- The flow in the demonstration test was upward with gravity acting to pull the fiber bed down and away from the bottom of the fuel. For the testing performed to support the NUREG/CR-6224 correlation, the fibrous bed was formed on the top of a mesh or perforated screen and the flow downward through the fibrous bed and the screen which tended to compress the fiber bed.
- Similarly, gravity worked on particulates that were caught in the fibrous bed of the demonstration testing tended to pull the fibrous bed apart, whereas, for the testing performed to support the development of the NUREG/CR-6224 head loss correlation, particulates were trapped on top of the fibrous debris bed and gravity, like the flow, worked to compress the fibrous debris bed.
- The NUREG/CR-6224 head loss correlation was developed from data collected using a vertical loop test facility with a small diameter flow channel in which all of the flow was directed downward through a fixed, predetermined debris bed. In a reactor, the flow area is large and the flow patterns sufficiently varied that the uniform directional flow conditions of the NUREG/CR-6224 test do not apply.
- Finally, the NUREG/CR-6224 correlation was developed from test data for velocities ranging from 0.15 ft/sec to 1.5 ft/sec (NUREG/CR-6224, Section 6.4). As shown in Table 3-1 below, the liquid velocities in the core are at or below the bottom range of the velocities used in developing the NUREG/CR correlation. At lower velocities associated with PWRs, there would be less compaction of any fiber bed.

For these reasons, the NUREG/CR-6224 head loss correlation is not directly applicable to the head loss associated with the collection of fibrous debris at the core inlet and, for the same fibrous and particulate debris loading, will be overly conservative in predicting the head loss through the fibrous debris bed on a fuel grid.

Finally, based on the observations and data presented in the response to RAI #2, core "blockage" is not experienced over the range of conservative fibrous and particulate debris loadings on debris capturing features of current fuel design. These observations and data confirm that the same type of debris bed head loss seen in the tests to develop NUREG/CR-6224 does not form for fuel geometries and orientations.

The table below lists representative velocities that are expected to occur in the core during long-term core cooling when the ECCS is realigned to recirculate coolant from the reactor containment building sump into the cold leg. These velocities were evaluated are prior to initiating hot-leg recirculation.

Table 3-1: Representative Core Velocities at Time of Initiation of Recirculation from the Reactor Containment Building Sump			
NSSS Design	**Break Location**	**ECCS Operation**	**Core Velocity**
B&W, CE and W 3- and 4-loop plants	Cold-leg Break	1 or 2 trains	0.10 ft/sec(1)
	Hot-Leg Break	1 train	0.20 ft/sec(2)
		2 train	0.40 ft/sec(2)
W 2-loop plants	Cold-Leg Break	Max. UPI flow	0.10 ft/sec(3)
	Hot-Leg Break	Max UPI flow	N/A(4)

Notes:

(1) Velocity is based on making up for core boil-off. The value listed is considered a maximum core velocity as it is taken at time of ECCS switchover from RWST/BWST injection to recirculation from the sump when the core decay heat is a maximum.

(2) All ECCS flow is taken to flow through the core.

(3) Assumes all ECCS flow to the core is through the UPI port.

(4) For the hot-leg break, the core is deluged by the UPI flow and excess coolant flows out the hot-leg break. While there is recirculation of flow in the core for a hot-leg break in a Westinghouse 2-loop PWR with the UPI flow, a bulk core velocity (such as would be occur with bottom-flooding of a 3-loop or 4-loop PWR) is not meaningful for a 2-loop PWR plant.

RAI #4

On page xvi and xvii, it is stated that 99.4% blockage results in adequate flow to the core to provide cooling. This results is not surprising since the vessel is in a boiling pot condition which will enable the fluid levels to balance under such low flow hydrostatic conditions. However, the injection water contains boric acid. Since the core in boiling, the boric acid will buildup in the core and because the 99.4% of the core inlet is blocked, the higher density boric acid solution in the core will not mix with the lower plenum. The boric acid concentration in the core will increase until precipitation occurs. As such, because the evaluation did not consider the buildup of boric acid, adequate core cooling is not assured and the statements guaranteeing adequate core cooling are unfounded. Evaluations need to be performed to show that with the maximum credible blockage, boric acid precipitation is assured. The evaluation and analysis with COBRA/TRAC performed with 99.4% blockage is meaningless. Furthermore, what is the minimum blockage that enables the boric acid to mix sufficiently with the lower plenum to preclude precipitation? Can the concentrated boric acid mixture combine with the blockage materials at the inlet can prevent flushing of the core following the switch to simultaneous injection? What happens as boric acid settles on top of potential blockages at the inlet to the core of the core and spacer grid locations?

RESPONSE TO RAI #4

The condition of 99.4% blockage scenario was presented as a demonstration case representing extreme conditions where core cooling would still be maintained. As discussed in Section 2.1, significant blockage of the core is not expected even for the most limiting case of a hot leg break and maximum core SI throughput. The limiting scenario for boric acid precipitation is a cold leg break were the core flow is stagnant with only enough core inlet flow to replace core boiloff. A stagnant core region provides the only scenario for which boric acid will accumulate. For this scenario, core inlet SI throughput is an order of magnitude less than the hot leg break case. For a hot leg break, all cold leg injected SI flow is forced through the lower plenum; whereas for a cold leg break, all cold leg injected SI flow in excess of that required to

replace core boiloff spills out the break. Furthermore, since the excess SI flow spills out the break, it would be repeatedly re-filtered through the sump screens. Only high levels of core inlet blockage would have an effect on core region / lower plenum mixing. However, since a high level of core inlet blockage will not occur even for the worst case of maximum core SI throughput (see discussion in Section 2.1), and since for the limiting scenario (i.e. cold leg breaks), the amount of core inlet blockage would be an order of magnitude less than the worst case, lower plenum mixing is justified and licensing basis boric acid control analyses remain valid.

A high level of core inlet blockage will not occur. Therefore no testing to determine the mixing behavior between the core and lower plenum with a blockage at the core inlet has been performed to date.

After the switch to simultaneous injection, SI flow injected into the hot leg will initiate the dilution process for a highly concentrated core. Since the break must be in the cold leg (to get a highly concentrated core), the driving head for the core dilution flow can extend well up into the intact hot legs and SGs. This driving head would force flow through the core and therefore the conditions for boric acid precipitation will not exist.

RAI #5

On page 2-4 it is stated that analyses using WCOBRA/TRAC demonstrated that with even as much as 99.4% of the core blocked, core decay heat was adequately removed.

a. So that this analysis may be related to a plant specific core blockage condition, please relate the results of the WCOBRA/TRAC analyses for the minimum blockage for which adequate core cooling can still be provided to an equivalent fiber bed using the pressure drop correlation of NUREG/CR-6224.

b. As debris and chemicals are concentrated within the core by the boiling process, the density of the fluid in the core will increase. This increase in density will act to retard core flow. Provide an evaluation of the effect of increased core density on the results from the WCOBRA/TRAC analysis of core blockage.

RESPONSE TO RAI #5

a. As noted in the responses to RAI #2 and RAI #3, the pressure drop correlation of NUREG/CR-6224 is not directly applicable to fibrous debris collected at the core inlet for PWRs.

The response to RAI #2 provides observations and data from tests of the collection of bypass debris, both fibrous and particulate, from an active replacement sump screen for a high fiber plant on debris capturing grids for a fuel assembly. The data testing provided in the response to RAI #2 shows that, even if a fiber bed with particulates forms at the bottom of the fuel, coolant will continue to pass through the bed.

Finally, the NUREG/CR-6224 correlation was developed from test data for velocities ranging from 0.15 ft/sec to 1.5 ft/sec (NUREG/CR-6224, Section 6.4). As shown in Table 1 of the response to RAI #3, the liquid velocities in the core are at or below the bottom range of the velocities used in developing the NUREG/CR correlation.

Thus, it is concluded the requested comparison cannot be performed such that it is meaningful to evaluating long-term core cooling.

b. An increase in the core fluid density due to concentration of debris and chemicals will result in an unstable configuration leading to natural convection flow patterns between the core and the less dense lower plenum, which will limit the density build-up. This was demonstrated in the BACCHUS test results previously provided to the NRC in the following reference:

Entergy Letter to NRC, W3F1-2005-0012, "Supplement to Amendment Request NPF 38 249, Extended Power Uprate, Waterford Steam Electric Station, Unit 3," February 16, 2005.

The effects of an increase in density in the core (and eventually, lower plenum) due to concentrating debris and chemicals would not be expected to affect the main conclusions of the WCOBRA/TRAC study; namely, that core cooling would be expected to be maintained even with significant blockages. This cannot be quantitatively demonstrated by WCOBRA/TRAC, as it is beyond the code's modeling capability. Also, the resulting density would be dependent on a number of plant-specific factors. However, it can be qualitatively supported by responses to recent NRC questions on an Extended Power Uprate application. Actions are taken to initiate core dilution measures prior to reaching the solubility limit of boric acid. In this RAI response, it was shown that a boric acid and water solution that approaches the solubility limit would have a density increase on the order of 10%, based on information provided in EPRI NP-5558. Such an increase would not be expected to offset the available driving head seen in the WCOBRA/TRAC calculations presented in Appendix B. (This density increase did not include any effects of debris in the core. However, build-up of any debris in the core would be expected to be very gradual, and not significant enough to alter this conclusion.)

(RAI #4 commented that the WCOBRA/TRAC study performed with 99% blockage is meaningless. It should be noted that the primary purpose of the calculations summarized and presented in Appendix B was to complement similar studies performed by NRC staff with the RELAP-5 and TRACE codes. Similar modeling assumptions and simplifications were made in the NRC assessments; the results of the NRC studies were presented at a NRC/industry meeting held on August 2, 2006.)

RAI #6

On page 2-7 it is stated that two sample calculations were provided in Section 5 for predicting chemical deposition on fuel cladding.

a. The staff was only able to find one sample calculation in Section 5 and in Appendix E. Please provide the other sample calculation.

b. For a plant specific submittal to reference a sample calculation as bounding for that plant, a list of critical input parameters would need to be compared. Please provide a table giving these parameters and the values assumed in the sample calculations.

RESPONSE TO RAI #6

(a) The text incorrectly identified that two (2) sample calculations were provided in Section 5. Only one was provided. The text will be corrected to reflect that only one (1) sample calculation is presented.

(b) A table showing the input values for the LOCADM sample calculation has been provided. (See Attachment 1.)

RAI #7

On page 2-12 it is stated that the effect of settled debris in the lower plenum on licensing basis boric acid precipitation analyses is judged to be small and plant-specific evacuations are not required. Please provide evidence that this statement is true for all PWRs or provide criteria that plants should meet to demonstrate that this concern is not an issue in plant specific submittals.

RESPONSE TO RAI #7

Section 9.1 in Reference 7-1 (below) discusses the impact of settled debris on the reactor internals and advises licensees to evaluate the volume of settled debris against the available volume of the lower plenum. The calculation of the amount of

settled debris in the lower plenum would be based on the limiting scenario of a hot leg break and maximum reactor vessel throughput.

Boric acid precipitation is not an issue for a hot leg break since there will be forced flow through the reactor vessel such that boric acid accumulation will not occur. For a hot leg break, the licensees will demonstrate that the volume of debris that settles in the lower plenum is less than the available free volume in the lower plenum and therefore a flow path to the core is assured.

The limiting scenario for boric acid precipitation is a cold leg break where the core is stagnant with only enough core inlet flow to replace core boiloff. For this scenario, lower plenum flow is an order of magnitude less than the hot leg break case where the lower plenum sees maximum throughput. Furthermore, the vast majority of SI flow would go out the break and would be repeatedly re-filtered through the sump screens. Since the volume of settled debris in the lower plenum would be approximately proportional to the flow into the lower plenum, the maximum volume of settled debris in the lower plenum for a cold leg break would be less then one tenth of the available volume of the lower plenum (based on an order of magnitude difference cold leg break and hot leg break core flow).

In response to recent NRC concerns, evaluations have been performed so that there are now few, if any, plants that rely on the total lower plenum volume when calculating core region boric acid buildup. A clarification letter has been sent to licensees advising of the need to consider displaced lower plenum volume on these calculations.

NRC reviewers have requested examples of licensing basis boric acid precipitation analyses under this RAI. The references listed below are examples of licensing basis boric acid precipitation analyses that have been recently submitted to NRC for Westinghouse PWRs:

Plant Type	ADAMS Accession Number
Westinghouse 2-Loop PWR	ML060180262
Westinghouse 3-Loop PWR	ML053290133
Westinghouse 4-Loop PWR	ML072000400

These submittals were made with the appropriate affidavit of withholding, as applicable, and should be handled accordingly.

It is should be noted that each plant has a boric acid precipitation strategy as part of their licensing basis. While the methods described in the examples identified in this RAI response may not be exactly the same from plant to plant, the examples are representative of the approach taken throughout the PWR industry with respect to establishing a core mixing volume.

REFERENCE FOR RAI #7 RESPONSE:

7-1. WCAP-16406-P, Evaluation of Downstream Sump Debris Effects in Support of GSI-191, June 2005.

RAI #8

On page 2-13 it is stated that for limiting boric acid precipitation scenarios (i.e. relatively stagnant core region) the alternate core flow paths would not see significant blockage since the flow areas are not effective debris traps or filters. Please demonstrate that for such a cooling scenario that boric acid and other dissolved and suspended substances would not accumulate in the core and precipitate.

RESPONSE TO RAI #8

The licensing basis for US PWRs includes analyses that demonstrate boric acid precipitation will not occur for the limiting cold leg break and stagnant core region scenario. Typically the purpose of these analyses is to verify the timeliness of an active or passive core dilution mechanism. Nearly all of these analyses credit alternate flow core flow paths either to support an expanded mixing volume or to provide core dilution. Active or passive core dilution mechanisms will keep boric acid and other dissolved and suspended substance from accumulating in the core. There are no credited alternate flow paths that would have minimum flow restrictions less than the particle size that might pass through the sump screens.

NRC reviewers have requested examples of licensing basis boric acid precipitation analyses under this RAI. The references listed below are examples of licensing basis boric acid precipitation analyses that have been recently submitted to NRC for Westinghouse PWRs:

Plant Type	ADAMS Accession Number
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These submittals were made with the appropriate affidavit of withholding, as applicable, and should be handled accordingly.

It is should be noted that each plant has a boric acid precipitation strategy as part of their licensing basis. While the methods described in the examples identified in this RAI response may not be exactly the same from plant to plant, the examples are representative of the approach taken throughout the PWR industry with respect to establishing a core mixing volume.

RAI #9

Page 2-15 states that debris buildup on mixing vanes, fuel grids will occur over time. Since the boric acid is also concentrating over time, combination of the debris in vanes and grids over time may form a localized blocked region or regions (containing debris and boric acid) that could cause localized precipitations that could collectively build over time and eventually block large regions of the core. The combination of the debris and the higher concentrate boric acid could form sustained blockages at the vanes and or grids or core inlet. Please explain. Please also discuss the calculations performed to show how the boric acid mixes through the core and lower plenum with debris in the vanes/grids and lower plenum. Current long term cooling analyses assume perfect uniform mixing of the boric acid in the core, lower and upper plenum. Localized gradients that may occur due to the debris/boric acid concentrations could cause local concentrations to exceed the precipitation limit. Since the lower plenum contains cooler injection water plus debris, a higher concentration will be needed in the core to initiate mixing into the lower plenum during the long term. Please demonstrate that the worst plant would not develop boric acid concentrations that approach the precipitation limit with the largest amount of debris. Also, how does high concentrate boric acid (up to 32 wt%) diffuse downward through fibrous and/or debris blockages plus the strainers at the core inlet while the water flows upward to keep the core covered? Please explain.

RESPONSE TO RAI #9

As mentioned previously, there are three considerations that minimize the potential for the postulated blockage of large regions of the core.

1. Ingested debris will not begin to collect until the ECCS enters recirculation phase. Since the core boiloff rate decreases with time, the period of the greatest rate of boric acid accumulation will occur prior to recirculation.

2. For a hot leg break, the scenario for greatest debris accumulation is not a concern. Conversely, for a cold leg break, which is the boric acid precipitation scenario of concern, core flow is stagnant and therefore debris accumulation is minimal. (See response to RAI#7 for additional discussion.)

3. All plants have boric acid precipitation control measures that promote core dilution after a LOCA. These measures typically rely on an operator initiated action, at some specified time, to start core dilution prior to reaching the boric acid solubility limit. These measures will serve to dilute concentrated sump chemical and suspended debris that might accumulate in the core region. Core dilution flow will flush concentrated chemicals and suspended debris out of the vessel and out the break.

With little debris accumulating in the core, at the core inlet, or in the RV lower plenum regions, mixing will continue due to convection, diffusion, local turbulence, and bubble mixing phenomena.

For the stagnant flow conditions of the boric acid precipitation scenario, there will not be sufficient core region, core inlet and lower plenum debris accumulation to invalidate licensing basis boric acid precipitation analyses. When considering the potential for boric acid precipitation after the switch to sump recirculation, the calculations in Appendix F indicate that the sump chemistry is such that boric acid precipitation will not occur, even in high concentrations. For example, Runs 1 and 3 in Appendix F indicate no boric acid precipitates when the sump solution is concentrated to a factor of 20, and then cooled to 212°F.

RAI #10

On page 2-14 in Section 2.7.2 dealing with upper plenum injection at UPI plants, it is stated that for a hot leg break, the coolant flow-through from the cold leg through the core and out the break is sufficiently large to maintain debris introduced by the UPI flow, entrained in the flow and transported it out the break. Please provide justification for this statement. The NRC staff understands that for some UPI plants, cold leg ECCS flow is terminated when sump recirculation begins. Under these conditions core flow would be stagnant and debris will accumulate.

RESPONSE TO RAI #10

The statement in the WCAP is incorrect. The licensing basis for Westinghouse 2-loop PWRs is for the recirculation flow to be provided through the UPI ports and for all cold-leg flow to be secured. This statement in the WCAP will be corrected.

The UPI nozzle for a Westinghouse 2-loop PWR has an inside diameter of about 4 inches. These nozzles are located approximately 180° opposite of each other. Assuming a minimum total UPI flow of 1200 gpm and an equal flow distribution between the two UPI nozzles, the flow rate through each nozzle is 600 gpm or approximately 1.34 ft^3/sec. Thus, the minimum velocity of the UPI flow through each UPI nozzle is calculated to be approximately 15.3 ft/sec. At these jet velocities, the upper plenum coolant inventory is not stagnant. Rather, the UPI jet flow, in conjunction with impingement of the jets on upper internals structures, generates turbulent mixing of the UPI flow with the coolant inventory in the upper plenum.

The volume between the top of the active fuel and the bottom of the hot-leg for a Westinghouse 2-loop PWR is about 190 ft^3. For a UPI flow of 1200 gpm, the equivalent volumetric flow is about 2.68 ft^3/sec. Neglecting any water level above the bottom of the hot-leg, which would be small for a double-ended guillotine hot-leg break, and assuming a constant volume of water in the upper plenum, approximately 71 seconds are required to "turn over" the entire fluid inventory of the upper plenum. This quick turn-over time further supports that the upper plenum is well mixed by the UPI flow.

The turbulent mixing, in turn precludes settle-out of debris in the upper plenum. With the turbulent flow and mixing in the upper plenum precluding debris settle-out in the upper plenum, debris will be carried with the expulsion of UPI flow out the hot-leg break.

RAI #11

On page 2-15 it is stated that complete compaction of debris that might collect at the bottom of the fuel at the debris trapping features will not occur for a UPI plant and that the packing will likely be less than 60 percent. Please provide the flow loss coefficient which would occur for this condition and give guidance as to what maximum loss coefficient would be acceptable.

RESPONSE TO RAI #11

The 60% voiding can be conservatively approximated as a 60% blockage of the core. This would present a bounding or maximum resistance to flow through the debris bed.

The WCOBRA/TRAC evaluations described in Section 6 demonstrate that adequate flow is maintained with a deterministically assigned blockage of 82% to provide for long-term core cooling. Thus, conservatively taking the 60% packing factor to be representative of a 60% blockage, adequate long-term core cooling will be provided for.

RAI #12

On page 2-15 regarding UPI plants, it is stated that if coolant flow is sufficiently restricted through a debris bed that clad temperatures increase to about 15°F to 20°F above the coolant temperature, the coolant would begin to boil. The steam formed would be about 40 to 50 times the volume of the water, and would cause the debris bed to be displaced, allowing for coolant to flow and to cool the cladding surface. Please justify that cooling will be maintained for a debris bed blocking the bottom of the core with steam rising through the top. Provide justification that boric acid and chemicals dissolved in the coolant would not increase to an unacceptable concentration under these conditions.

RESPONSE TO RAI #12

Blockage of the core may occur only by debris-laden coolant being provided to the core. The refueling water storage tank (RWST) does not have debris in it. Therefore, during injection of the RWST inventory, no debris is provided to the core for PWRs.

Westinghouse 2-loop plants with upper plenum injection (UPI) do not maintain flow into cold legs once the switchover of the emergency core cooling system (ECCS) from injecting from the RWST to recirculating coolant from the reactor containment building sump is accomplished; the recirculating flow is ducted to the reactor vessel through the UPI penetrations in the reactor upper plenum. For cold leg breaks, coolant is introduced into the reactor vessel from the UPI nozzles and flows down though the core and out the break. If blockage due to the accumulation of debris were to occur, it would occur at the top of the fuel. As was the case with bottom-up flooding of the core, and as demonstrated in the data presented in the response to RAI #2, a complete blockage is not expected because of the short fibers that pass through the sump screen do not provide for a bed formation as demonstrated in the replacement sump screen tests.

The switchover of the ECCS from injecting from the RWST to recirculating coolant from the reactor containment building sump is accomplished by operators taking the actions identified in their plant-specific Emergency Operating Procedures (EOPs). Each of the UPI plants has a licensing basis analysis for addressing boric acid precipitation that has been reviewed and approved by NRC. This same flow that provides for core cooling and boric acid precipitation will dilute the core and keep boron compounds and other chemicals that may be dissolved in the recirculating coolant from accumulating in the core.

As described in the response to RAI #10, for hot leg breaks, the upper plenum will be well mixed in the upper plenum with excess UPI flow exiting out the break. Debris accumulation in the upper plenum and upper fuel region will be minimal since debris will be carried out the break with the excess ECCS flow.

In case of either a hot-leg or a cold-leg break, the formation of a debris bed on the bottom of the fuel is not considered credible.

A representative evaluation of core dilution for a 2-loop PWR was identified and provided in the response to RAI #7 and RAI #8.

The evaluation of effect of chemicals dissolved in the UPI flow for a hot-leg break are performed on a plant-specific basis using the LOCADM calculation tool described in Appendix E of WCAP-16793-NP.

RAI #13

Calculations for cladding heat up behind fuel grids are presented in section 4.1 and Appendix C. The ANSYS code was used in these calculations. Please provide a reference for this computer code and for the review of this computer code by the NRC staff.

RESPONSE TO RAI #13

The ANSYS Mechanical software was used for the cladding heat up behind fuel grid. This software is in common use internationally to solver a wide range of mechanical engineering problems. The use of the thermal analysis capability of the ANSYS Mechanical software for WCAP-16793-NP was in accordance and consistent with standard industry practices for both ANSYS Mechanical software, and other similar engineering problem solving software.

The ANSYS Mechanical software offers a comprehensive product solution for structural linear/nonlinear and dynamics analysis. The product offers a complete set of elements behavior, material models and equation solvers for a wide range of engineering problems. In addition, ANSYS Mechanical offers thermal analysis and coupled-physics capabilities involving acoustic, piezoelectric, thermal–structural and thermal–electric analysis. For the cladding heat up calculations, only the thermal solution capabilities of the ANSYS Mechanical software were used.

As a clarification, by submitting WCAP-16793-NP, the PWR Owners Group is not requesting NRC review the ANSYS Mechanical software. Rather, the PWR Owners Group is requesting that the NRC concur that the software was appropriately used consistent with industry practice and that the results of the analyses are acceptable.

Additional information regarding the ANSYS Mecahnical software may be obtained from the following website: www.ansys.com.

RAI #14

The maximum debris thickness that was evaluated using the ANSYS computer code was 50 mills. Is 50 mills the maximum acceptable thickness for debris collection behind a fuel element spacer grid? If not, please provide the acceptance criterion. What would be the thickness of debris if a spacer grid were to become completely filled? Provide an analysis of the resulting peak cladding temperature if the location between a spacer grid and an fuel rod were to become completely filled with debris.

RESPONSE TO RAI #14

The minimum clearance between two adjacent fuel rods, including an allowance for the spacer grid thickness, is greater than 100 mils. Therefore, the 50-mil debris thickness on a single fule is maximum deposition to preculde touching of the deposition of two adjacent fuel rods with the same deposition. The 50 mil thickness is the maximum acceptable deposition thickness before bridging of adjacent fuel rods by debris is predicted to occur.

For current fuel designs, the minimum clearance between a the cladding and the spacer grid is about 40 mils; this occurs where the springs and dimples of the grid contact the fuel rod. The maximum clearance between the cladding and the spacer grid occurs along the diagonal of the of a grid cell and is about 110 mils. Thus, if a spacer grid were to become completely filled, the radial thickness of the debris on the oustside clad would vary from about 40 mils to about 110 mils about the circumference of a fuel rod.

The example chemcial product deposition calculation performed in Appendix E of WCAP-16793-NP was performed with inputs intented to maximize chemical deposition. That deposition calculated for the sample case was less than 30 mils. Thus. although the chemical deponsition of fuel is a plant-specific calculation, plants are not expected to calculate deposition thicknesses in excess of 30 mils. Thus, for chemcial depostion, the range of cladding heat up calculations behind spacer grids presented in WCAP-16793-NP is bounding.

The formation of a chemcial deposition layer followed by the collection of fibrous debris in the remaining open channel will not challenge the cooling of the clad.. The response to RAI #15 shows that the effective thermal conductivity of a fibrous debris bed is at least 5 times greater than the minimum thermal conductivity of 0.1 Btu/(hr-ft-°F) used in the cladding heat up calculations. Based on observations from testing of fibrous debris collection on debris capturing grids identified in the response to RAI #2, a complete blockage of a spacer grid with fibrous and particulate debris is not credible. The test data shows that, even under extreme fibrous and particulate debris loads, flow through the resulting debris bed is maintained.

To assess a maximum clad temperature under worst case debris deposition in a single spacer grid/fuel rod configuration, the following assumptions are made:

- A uniform debris layer thickness of 110 mils is assumed on the cladding, and,
- The debris layer is assigned the conservative effective thermal conductivity for a fibrous debris bed recommended in the response to RAI #15 for Debris Thermal Conductivity = 0.1 Btu/(hr-ft-°F).

Under these limiting assumptions, extrapolating the calculated clad temperatures listed in Table 4-3 listed for the effective thermal conductivity k_{EFF} = 0.1 Btu/(hr-ft-°F), it is estimated that the maximum clad temperature behind a grid would be less than 738°F. This is a extremely conservative estimate of the clad temperature for the following reasons;

- A conservatively small value of conduction through the debris bed identified in the response to RAI #15 is used,
- The calculation does not account for circumferential heat transfer about the debris bed which would form in the spacer grid between the dimples and springs and the corners of the spacer grid, and,

- Convection of heat by the flow of coolant through the debris bed is neglected. (The ability of coolant to pass through a fibrous and particulate debris bed under PWR flow conditions was demostrated in the response to RAI #2.)

Therefore, the estimation of an maximum clad temperature of 738°F is a very conservative estimate of the maximum clad temperature if the location between a spacer grid and an fuel rod were to become completely filled with debris.

RAI #15

Section 4.1.4 states that in using the ANSYS code that debris is assumed to have the same thermal properties as crud. A value for thermal conductivity of 0.5 BTU/(hr*ft*deg-F) is recommended and the lowest value of thermal conductivity examined was 0.1 BTU/(hr*ft*deg-F). If a debris bed trapped behind a fuel element spacer grid were composed of fibrous insulation the thermal conductivity would be much lower. Please justify not using a thermal conductivity appropriate for fibrous insulation.

RESPONSE TO RAI #15

NUKON® is a low density fiberglass insulation material commonly used in PWR reactor containment buildings. Performance Contracting, Inc. (PCI), the owners of the NUKON® product line, were requested to provide information they had regarding the effect of wetting NUKON® on the effective thermal conductivity of the insulation. PCI noted that the thermal conductivity of fibrous insulation is a function of the moisture content. Under normal industrial and nuclear applications, NUKON® is used on hot piping and components; thus the moisture content is low. PCI stated they had no data for the thermal performance of wetted insulation as, for industrial applications, when insulation becomes wetted it ceases to perform its function and remedial action are taken. The remedial actions are usually removing the source of moisture and either drying or replacing the affected insulation.

Although they did not have data on the effect moisture had on effective thermal conductivity of NUKON®, based on their experience in both industrial and nuclear applications of NUKON®, PCI noted that as fiberglass wool becomes wetted, the value of the thermal conductivity of the wetted insulation tends towards the value of water. As the insulation becomes fully saturated, or if there is water flow through the wool, then the effective thermal conductivity takes on a mixed conductive/convective value that is greater than the conductivity of water.

WCAP-16793-NP states that fibrous material on fuel structures with at least a porosity of 40%. As the fibrous debris is collected first on fuel structures (grids) at the core entrance, the fibrous collection will be fully saturated with the voids between fibers filled with water. Furthermore, the fibers are expected to collect on fuel structures (grids) in a random orientation. Assuming the water in the fiber bed is stagnant, a volume-weighted thermal conductivity would appropriately represent a minimum thermal conductivity for a saturated fiber bed.

For a saturated fiber bed with a porosity of 40%, a volume-weighted thermal conductivity is calculated as follows;

Thermal conductivity of water and glass:

Water = 0.40 Btu/(hr-ft-°F)

Glass = 0.59 Btu/(hr-ft-°F)

Volume Fraction of water and glass in the debris collection:

Water = 0.40

Glass = 0.60

Effective Thermal Conductivity (k_{EFF})

k_{EFF} = 0.4 x 0.40 Btu/(hr-ft-°F) + 0.6 x 0.59 Btu/(hr-ft-°F)

k_{EFF} = 0.514 Btu/(hr-ft-°F)

Thus, assuming the water in the fibrous debris is stagnant, a minimum effective thermal conductivity of the saturated collection of fibrous debris on fuel components is calculated to be 0.514 Btu/(hr-ft-°F). As demonstrated from the test data presented in the response to RAI #2, there is fluid movement through the fiber collected at the entrance to the core. Thus, the actual effective thermal conductivity through the fibrous debris would be greater than the 0.514 Btu/(hr-ft-°F) value.

As stated previously, the thermal conductivity of fibrous insulation is a function of the moisture content in the insulation. In the case where the insulation contacts a boiling surface, it is a function of both the moisture and steam content. A literature search was performed to support the calculation presented above. Reference 15-1 states that the dry thermal conductivity of fiberglass insulation of 0.05 BTU/(hr-ft-°F) doubles (to 0.1 BTU/ft h °F) with only eight percent of its volume filled with water. Reference 15-2 shows that when a mixture of steam and liquid are present, the thermal conductivity will increase by a factor of approximately 12 when the liquid and steam are present in equal amounts in a porous medium. These references support the value of minimum effective thermal conductivity calculated above, and suggest that a thermal conductivity at least as large as 0.6 BTU/(hr-ft-°F) may be used for fiberglass trapped between fuel element and a spacer gird is reasonable since coolant will have access to the fiber.

Thus, based on the information presented above, the WCAP-16793-NP value of 0.1 BTU/(hr-ft-°F) is an appropriately conservative choice for representing a lower bound thermal conductivity for wet fibrous insulation.

REFERENCES FOR RAI #15 RESPONSE:

15-1 "Joint Departments of the Army and Air Force, USA, Technical Manual TM 5-852-5/AFR 88-19, Vol. 5, Arctic and Sub-arctic Construction: Utilities." Chapter 12

15-2 Ho-Jeen Su and Wilbur Somerton, "Thermal Behavior of Fluid Saturated Porous Media with Phase Changes" Proceedings of the 16th International Thermal Conductivity Conference, November 7-9 Chicago, Published by Plenum Press, New York, page 193-204

RAI #16

Page xvi and Appendix A state that clad temperatures of 800 F are considered acceptable. From a long term cooling perspective, 800 F clad temperatures establish a low rate heat oxidation process similar to the problem that developed at Calvert Cliffs during the late 70's. Clad temperatures were increased to 800 F so that operation for several weeks caused the oxide layer to build on the cladding. Please discuss the impact on long term cooling and the long term build-up of oxide and the potential to approach or even exceed the 17% 10CFR50.46 limit.

RESPONSE TO RAI #16

The core conditions that resulted in the clad oxidation at Calvert Cliffs during the late 1970's would not exist in the core post-LOCA. At-power clad corrosion is driven by temperature, fast neutron flux and thermal feedback through an oxide layer. During long term cooling post-LOCA, the fast neutron flux is negligible and the heat flux is low. Thus, for post-LOCA conditions, only the temperature is directly applicable to corrosion and autoclave data is more representative of the temperature-driven corrosion that would be experienced by cladding. Evaluation of the autoclave data at temperatures at 800° F and below shows only small increases in the corrosion thickness and hydrogen loading compared to the post-LOCA transient conditions immediately following the postulated break and prior to long-term cooling.

Local increases in corrosion due to local hot spots will not impact long term cooling. The impact of corrosion on the clad material properties is small and the heat load continues to decrease with time. The 17% ECR criteria applies to the LOCA

event only. If the local conditions immediately post-LOCA were close to the 17% Equivalent Clad Reacted (ECR) limit (pre-transient corrosion and transient ECR), then the small amount of additional corrosion from a hot spot which resulted in approaching 800° F for 30 days could reach or marginally exceed 17% ECR. However, based on the sample deposition calculation, the conservative core blockage calculations and the parametric clad heat-up calculations presented in WCAP-16793, cladding temperatures approaching 800° F for post-LOCA long-term core cooling are not expected.

Also, the peak ECR region on the rod is not expected to be the same region where a local hot spot would occur. Local hot spots would be expected to occur lower in the core and at or just below a spacer grid. Pre-transient corrosion is suppressed at the spacer grid locations.

In addition, much of the reduction in ductility from high temperature oxidation (> 1832° F) is due to oxygen diffusion ahead of the oxide layer. At temperatures of < 930° F, there is no observation of oxygen diffusion ahead of the oxide layer.

RAI #17

Appendix A states that a peak cladding temperature of 2200 deg F is acceptable for the post-quench, long term evaluation. This limit is inconsistent with previous statements and not supported by the autoclave data. In a telecon on July 26, PWROG representatives acknowledged that this was not the intent - instead, the previously states 800 deg F was the proposed upper limit on local cladding temperature. Please revise the topical report to clarify.

RESPONSE TO RAI #17

The text of WCAP-16793-NP will be amended to clarify that 800°F is the long-term core cooling acceptance basis for cladding temperature by replacing the text in question with the following text:

> "Transitioning the ECCS from RWST/BWST injection to recirculation from the reactor containment building sump is addressed under the current licensing basis of PWRs.
>
> Once the transition of the ECCS from RWST/BWST injection to recirculation of coolant from the reactor containment building sump has occurred, there is no interruption (termination) of coolant flow to the core due to system realignments such as initiation of hot leg recirculation. For plants that have a reduction in flow associated with systems realignments, the supplied flow remains above the core boil-off rate and will not result in a reheat of the cladding. Therefore, for long term cooling, the appropriate acceptance basis for clad temperature is 800°F. This acceptance basis is based on long term autoclave testing in clean water up to about 700°F, and steam above that temperature."

RAI #18

Page A-7 states that the maximum allowable fuel clad temperature for short transients such as hot leg switch over and for localized hot spots is 2200°F during long term cooling. Please provide methodology as to how transient cladding temperatures during hot leg switch over will be calculated. Include processes and phenomena included in the methodology which cause cladding temperatures to increase during hot leg switchover and those which act to mitigate the transient.

RESPONSE TO RAI #18

The reference to hot-leg switch-over as resulting in a heat-up transient for cladding is incorrect. Also, there is no known phenomena that would cause localized hot spots during long term core cooling. The text in the WCAP will be amended as follows:

"During hot-leg switch-over or, for B&W plants, the establishment of a core flushing flow, there is no interruption of coolant to the core. Therefore, there is no clad heat-up transient during this operation."

RAI #19

The proposed 800 deg F upper limit on local cladding temperature is based on long-term autoclave data and focus solely on the formation of nodular corrosion.

a. Long-term oxidation tests need to be conducted on pre-hydrided specimens which have previously been exposed to LOCA heat-up and quench conditions.

b. Post-quench fuel rod damage mechanisms should be identified and dispositioned relative to the proposed 800 deg F limit. Mechanisms include (1) further evolution of post-quench microstructure and its impact on ductility, (2) hydride formation and re-orientation, (3) crack propagation near burst region, (4) cladding creep / ballooning (non-burst rods), and (5) degradation of oxide layer and hydrogen absorption.

The stability of the oxide layer and the tetragonal-to-monoclinic transformation are sensitive to alloying elements, surface finish, and temperature history (due to local stress states within oxide layer). Please address these items with respect to the proposed upper limit and 30 day duration.

RESPONSE TO RAI #19

The autoclave testing was performed to demonstrate that no significant degradation in cladding mechanical properties was expected due to a localized hot spot. The autoclave testing demonstrated that the increase in oxide thickness and hydrogen loading was limited at 800°F. The autoclave test data and a review of literature indicate that susceptibility to localized accelerated corrosion occurred at temperatures greater than 800°F. Therefore no significant degradation in cladding properties would occur due to 30-day exposure at 800°F and there would not be any adverse impact on core coolability. Based on the autoclave results, the data is sufficient to justify 800°F.

RAI #20

Page A-7 gives two examples of when reactor fuel experienced significant damage and a coolable geometry was maintained. One example is operational experience at Three Mile Island. The NRC staff does not believe that the 1979 accident at Three Mile Island Unit 2 resulted in a coolable geometry. The other example given is operational experience at the International PHEBUS-FP Program. Please provide the PHEBUS-FP data referred to and discuss the relationship of this data to local hot spots which might occur during the long term cooling period at PWR following a large LOCA.

RESPONSE TO RAI #20

The reference to the 1979 accident at Three Mile Island Unit 2 will be deleted from the text of Page A-7.

The PHEBUS-FP tests simulated severe accident conditions in order to study fuel degradation and fission product release and transport. As such, they are best considered as a controlled simulation of phenomena experienced as a result of local hot spots that evolve into a damage of the fuel cladding.

The conclusion in this part of Appendix A could be better stated as:

> "In the PHEBUS-FP Program a coolable geometry was lost, but eventually restored. The facility was eventually able to be cleaned up with negligible impact to the health and safety of the public."

The following table lists several ADAMS Accession numbers for PHEBUS-FP presentations made to NRC and the Advisory Committee on Reactor Safeguards. The reference to the PHEBUS-FP tests on Page A-7 was as an example of the coolability of cladding that had damage and cooling of the resulting geometry was achieved.

ADAMS Accession Number	Title	Date
ML031340628	Summary of PHEBU RTF Programme	2000-03-20
ML071240063	Memo to Frank Gillespie, Providing Information on the PHEBUS-FP for ACRS Meeting 543 – June 6-8, 2007	2007-05-04
ML003744641	RES Info Ltr-RIL-0004, "Use of Results from PHEBUS-FP Tests to Validate Severe Accident Codes - 003744641	2000-08-21

As discussed in responses to other RAIs, cladding temperatures of local hot spots, if they occur, are expected to remain below the 800°F acceptance basis identified in Appendix A. At these low temperatures, based on autoclave data, additional clad damage is due to oxidation and hydrogen pickup has been shown to be negligible; no loss of a coolable geometry is expected. Thus, there is no direction relationship of the data PHEBUS-FP program to hot spots that may be expected under acceptance basis of 800°F for long-term core cooling conditions identified in Appendix A.

RAI #21

Section A.4 on page A-5 states that the acceptance basis for boric acid precipitation and chemistry effects of debris will be as follows: A core flushing flow will be established that is sufficient to prevent the calculated maximum boric acid concentration in the core region from exceeding the precipitation limit. Please provide acceptance criteria for other species of chemicals and debris which might be washed into the reactor core during the recirculation process.

RESPONSE TO RAI #21

The acceptance criterion is no rod-to-rod bridging of deposits due to deposit growth and predicted cladding temperature < 800°F after deposition. Both deposit thickness and cladding temperature are predicted by LOCADM using estimates of debris chemicals washed into the core by the recirculation process.

RAI #22

Calculations for cladding heat up between fuel grids are presented in Section 4.2 and Appendix D. The maximum debris thickness evaluated was 50 mills. Is 50 mills the maximum acceptable thickness for debris collection between fuel grids? If not please provide the acceptance criterion.

RESPONSE TO RAI #22

As noted in the response to RAI #14, the minimum clearance between two adjacent fuel rods is greater than 100 mils. Therefore, the 50-mil debris thickness on a single fule is maximum deposition to preclude touching of the deposition of two adjacent fuel rods with the same deposition. The 50 mil thickness is the acceptance basis for maximum deposition.

RAI #23

Methodology for calculating the cladding temperature that would result from post-LOCA crud deposition on the fuel rods is presented in Appendixes C, D, and E. Methodology for calculating crud thickness is only presented in Appendix E. Please describe methodology which licensees would use to calculate crud thickness using Appendices C and D.

RESPONSE TO RAI #23

The method of calculating depositon thickness is given in Appendix E. For a deposition thickness calculated using Appendix E, Appendices C and D may be used to evaluate the change in clad temperature for different themal conductivies of the depositon material.

RAI #24

Appendix C is titled Fuel Clad Heat-up Behind Grids, whereas Appendix D is entitled Fuel Clad Heat-up between grids. Please describe the specific treatment of the grids in Appendix C which make these calculations different from the methodology in Appendix D. Section D.7 indicates that if the same inputs were used for the methodology of Appendix D as was used for Appendix C, similar results would be obtained.

RESPONSE TO RAI #24

The calcuation results presented in Appendix C included conduction in both the radial and the axial directions of a fuel rod. The calcuations in Appendix D accounted for heat transfer only in the radial direction of a fuel. Both calculations are steady state claculations. Reviewing the calculations, it was observed that there is limited axial heat transfer due to a combination of the clad material being thin and the relatively small thermal conductivity of the clad material. The small amount of heat transfer in the axial direction of the model is the basis for the statement that, for similar inputs, similar results would be expected.

RAI #25

Appendix E describes the LOCADM computer code which calculates dissolution of materials from the containment to the sump water and deposition of the dissolved material on the surfaces of the reactor core. Please discuss how the LOCADM code will be made available to utilities to calculate individual plant responses. Discuss the training that the PWROG will provide to utility personnel to assure the code is being used properly.

RESPONSE TO RAI #25

LOCADM is not a multi-dimensional thermal-hydraulic code that models the reactor with a high level of detail. as is RELAP5, VIPRE, and other similar codes. The "A Short Description of LOCADM" (see Attachment 2) gives a description of how LOCADM works and the essential inputs that are needed. At this time we do not believe that any additional training is required.

RAI #26

The LOCADM computer code performs the evaluations for the concentration of debris and chemicals within the reactor core. An important feature in the concentration evaluation is the volume of water which is available to mix with the concentrating material. Please describe how this mixing volume is calculated. Include assumptions for the liquid fraction

within the core, upper plenum and lower plenum. Compare the assumptions used by LOCADM to those which the NRC staff has accepted in licensing calculations for post-LOCA boric acid concentration. Provide a comparison to the volume of water assumed to be available for mixing by LOCADM with that calculated by WCOBRA/TRAC.

RESPONSE TO RAI #26

LOCADM does not calculate the core mixing volume independently. The reactor vessel volume is an input to LOCADM and it can be set to a value which includes only the volume which is considered to be well-mixed with entering coolant. The guidance provided with LOCADM will recommend generic mixing volume assumptions that are typical of those used in licensing basis calculations for a given plant design. Both AREVA and Westinghouse designed plants will be included. Alternately, the licensees can use the mixing volume used in their licensing basis boric acid precipitation analysis. It should be noted that the results produced by LOCADM are not highly sensitive to the core mixing volume, since virtually all of the coolant impurities entering the core are eventually deposited. For example, when the mixing volume used in the sample problem of 2346 cubic feet was reduced to 1100 cubic feet, the final thickness values for the deposits increased by one percent.

RAI #27

Please provide the decay heat model which is used in LOCADM to determine coolant boil off from the core and justify that the model is conservative for safety analysis.

RESPONSE TO RAI #27

The Appendix K decay heat model was used. The Appendix K decay heat model is equivalent to the 1971 ANS model multiplied by a factor of 1.2. The 20 percent increase over the best estimate 1971 ANS model insures that conservative predictions will be made.

RAI #28

On page E-8 it is stated that the LOCADM computer code can model the core with up to 200 radial nodes and 10 axial nodes. Please provide the criteria which should be utilized in selecting adequate noding detail. Please discuss how local chemical and debris concentrations are determined for the fluid volume adjacent to each of the core nodes.

RESPONSE TO RAI #28

The guidance for radial core noding is given in WCAP-16793, Table E-1, where the number of rods in each node and the relative power at each node are specified for different core types. This guidance is consistent with the criteria for selecting radial noding detail as has been described in WCAP-12945-P-A (Proprietary) Volume I (Revision 2) and Volumes II-V (Revision 1), and WCAP-14747 (Non-Proprietary), "Westinghouse Code Qualification Document for Best Estimate Loss of Coolant Accident Analysis," Bajorek, S. M., et al, 1998. Since the radial noding establishes a conservatively high peak rod power (and a conservatively high peak deposit thickness) the choice of axial noding is not critical.

The debris and chemicals in solution are assumed to be evenly distributed among all core nodes. While it is possible that there could be small variations in concentration of debris chemicals between nodes within the mixing volume, large variations are not thought to be possible since large concentration variations would lead to density differences which would lead to convective mixing. The possibility of small variations in concentration between nodes is not expected to result in non-conservative predictions of deposit thickness, because other highly conservative assumptions have been made. LOCADM includes conservative predictions of debris dissolution and corrosion product release. All such released

material which is transported to fuel cladding surfaces is assumed to deposit, and it is assumed that there is no competitive deposition in other system locations.

RAI #29

Page E-11 states that high solubility species will not precipitate, and their concentration is limited to back-diffusion into the coolant or transport along the chimney walls. Boiling in the core before hot leg recirculation is initiated will act to increase the concentration of the high solubility species. Describe how the LOCADM code tracks the concentration of high solubility species to ensure that the solubility limit is not exceeded.

RESPONSE TO RAI #29

LOCADM calculates the concentration of boric acid, sodium tetraborate, trisodium phosphate and sodium hydroxide in the core as a function of time. The results are output in tabular form.

Consistent with current licensing basis calculations for PWRs that demonstrate that the boric acid concentration in the core is limited to values below the solubility limit, the LOCADM does not precipitate boric acid. The existing Plant's EOP provide actions that are required to assure boric acid solubility limits are not reached. The same is true for sodium phosphate, sodium borates and sodium hydroxide, which are also highly soluble.

RAI #30

Describe the treatment of suspended solids by the LOCADM computer code. Discuss the treatment of these concentrated solids in the core as to the effect core density, core heat transfer and plate out on fuel rods.

RESPONSE TO RAI #30

LOCADM makes no distinction between suspended solids and dissolved species. Both are deposited at the fuel rod surface. The density of the deposit is an input to LOCADM as is the thermal conductivity. LOCADM calculates the thickness of the deposit and then the heat transfer resistance using the deposit thermal conductivity. Concentrations of suspended solids are predicted to be low (see RAI #35 response), so there will be no significant effect on the coolant density or thermal conductivity.

RAI #31

On page E-11 it is stated that the LOCADM computer code assumes that deposition occurs through the boiling process if conditions at a core node predict any boiling. Please discuss and provide the calculational methodology by which coolant channel thermodynamic conditions are determined. Include discussions for hot leg recirculation as well as for cold leg recirculation. The NRC staff understands that for some UPI plants, ECCS flow to the cold legs is terminated during recirculation. For a UPI plant which experiences a hot leg break please provide the methodology by which LOCADM would determine core concentrations for the resultant countercurrent flow which would be relied upon to cool the core during the recirculation period.

RESPONSE TO RAI #31

The attached document "A Short Description of LOCADM" (Attachment 2) gives a concise description of how the thermodynamic conditions are determined in coolant channels.

The fluid in all channels is assumed to be at the same temperature, and this temperature is derived from the plant's licensing basis calculations for long term core cooling. Flow is not modeled explicitly. Instead, a generic heat transfer coefficient of 400 W/m^2-°K (70 BTU/ft^2 °F) was assumed for transfer of heat between bulk coolant with the fuel channels and the surface of the deposits since this is a typical heat transfer coefficient for convective flow within natural circulation systems. The channel pressure is the sum of the upper plenum pressure and the pressure exerted by the height of the water column above the node. Coolant flow rates into the reactor mixing volume as a function of time must be provided by the user and are obtained from a plant's safety analysis for long term core cooling. The relative amounts of steam and liquid flow out reactor mixing volume are calculated by LOCADM. The core input is generalized. The coolant flow could be coming from the cold leg, the hot leg, or from upper plenum injection. Various operational modes are accounted for by varying the rate of flow into the mixing volume and the source of the flow (safety injection or recirculated coolant.) Values for generically applicable mixing volumes have been identified and will be provided to users.

Regarding CCFL (Countercurrent Flow Limiting) effects, the limitations on upper plenum injection flow due to countercurrent steam flow must be calculated outside of LOCADM using RELAP5 or another approved code. However, once the effective flow into the mixing volume is calculated, it can be input into LOCADM.

RAI #32

On page E-14 it is indicated that the initial fuel oxide thickness to be input to the LOCADM code for the start of the post-LOCA deposition calculation could be based on post operational fuel examinations. The staff does not believe that use of post operational data would be appropriate for fuel which has experienced a LOCA. Please provide methodology by which the post-LOCA oxide thickness will be determined for input to LOCADM. This concern needs to also addressed for the methodology of Appendix C and Appendix D.

RESPONSE TO RAI #32

The post-LOCA oxide thickness recommended for use as input to LOCADM will be revised to be the maximum peak local oxidation layer allowed by 10 CFR 50.46, or 17% of the cladding wall thickness. A lower value can be used on a plant-specific basis with sufficient justification.
For example, considering a volume increase of 1.56 upon oxidation of cladding metal to oxide, a calculation for a typical cladding thickness of 0.0225 inches would be assumed to start with a reduced metal thickness of 0.0187 inches and an oxide layer of 0.006 inches.

The thermal calculations in Appendices C and D are parametric studies to demonstrate margin to the 800° F acceptance basis. The calculations reported in Table 4-3, Table 4-4 and Table 4-5 of WCAP-16793-NP used an initial oxide thickness of 0.004 inches (0.4 mils). Increasing the initial oxide layer from 0.004 inches (0.4 mils) to 0.006 inches (0.6 mils), using the calculated clad temperatures listed in Table 4-3, Table 4-4 and Table 4-5 and assuming a thermal conductivity of 0.1 Btu/(hr-ft-°F) for the oxide, the increased oxide thickness is evaluated to result in an increased clad temperature of no more than 2° F over those reported in the three tables. Even with the increase of 2° F, the calculated clad temperatures reported in the three tables are well below the 800° F acceptance basis temperature. Thus, increasing the initial oxide thickness by 0.002 inches (0.2 mils) has negligible impact on the margin to the 800° F acceptance basis.

RAI #33

On page E-15 a comparison of the results by the LOCADM computer code and the SKBOR computer code are described for a post-LOCA boric acid concentration calculation. Please provide more details of this comparison including core boric acid concentration as a function of time. Provide a reference available to the NRC staff describing the SKBOR computer code and including any review and approval by the NRC staff.

RESPONSE TO RAI #33

SKBOR has not been reviewed or approved by the NRC. This FORTRAN code is essentially an automated hand calculation that calculates the buildup of boric acid in the core as a function of time after a LOCA. It uses the same calculational approach as LOCADM for boron concentration, but the coding was developed independently. A description of SKBOR is provided below, along with a comparison of the outputs from LOCADM and SKBOR as a function of time.

Description of Westinghouse SKBOR Computer Program

The SKBOR computer program is part of the Westinghouse methodology for long-term core cooling. For plants with cold leg injection, SKBOR is used to determine: (1) the time at which ECCS recirculation should be realigned to the RCS hot legs to prevent the precipitation of boron in the core; (2) the interval at which cycling between hot and cold leg injection should be completed, for plants without sufficient simultaneous hot and cold leg injection; and, (3) the amount of sump dilution at the hot leg switchover time. For plants with upper plenum injection (UPI), SKBOR has been used to determine the time at which UPI injection should be established to prevent the precipitation of boric acid in the core, for breaks where the RCS may stabilize above the UPI cut-in pressure.

A typical SKBOR calculation considers two volumes: one representing the effective vessel mixing volume (denoted as the CORE), and one representing the remaining system inventory (denoted as the SUMP). The CORE and SUMP are initially assumed to contain borated liquid at the system-average boron concentration. Vapor generated due to decay heat boiling exits the CORE with a boron concentration of zero; is assumed to condense fully in containment; and, is returned to the SUMP as unborated liquid. Borated liquid is added from the SUMP as required to keep the CORE volume full. In this way, the SUMP boron concentration gradually decreases, while the CORE boron concentration increases toward the boric acid solubility limit.

Most of the inputs to SKBOR are used to specify plant-specific parameters such as the component masses and boron concentrations, the effective vessel mixing volume, and the initial core power level. These inputs are generally chosen to maximize the rate at which boron accumulates in the CORE, based on information provided by the utility. The results of the analysis are used to establish the times at which the necessary actions should be initiated, and these times are typically reflected in the FSAR and the Emergency Operating Procedures.

The table and figure below show a comparison between the results for SKBOR and LOCADM.

Input Assumption	LOCADM	SKBOR
Core Power	3586.6 MWt	3586.6 MWt
Decay Heat	Appendix K	Appendix K
Liquid Mixing Volume	1050 ft3	1050 ft3
Problem Start Time	100 seconds	100 seconds
Initial Sump Boron Concentration	2550 ppm	2550 ppm
SI Subcooling	None	None
Time to Reach 23.53 wt% Boric Acid	5.97 hr	5.96 hr

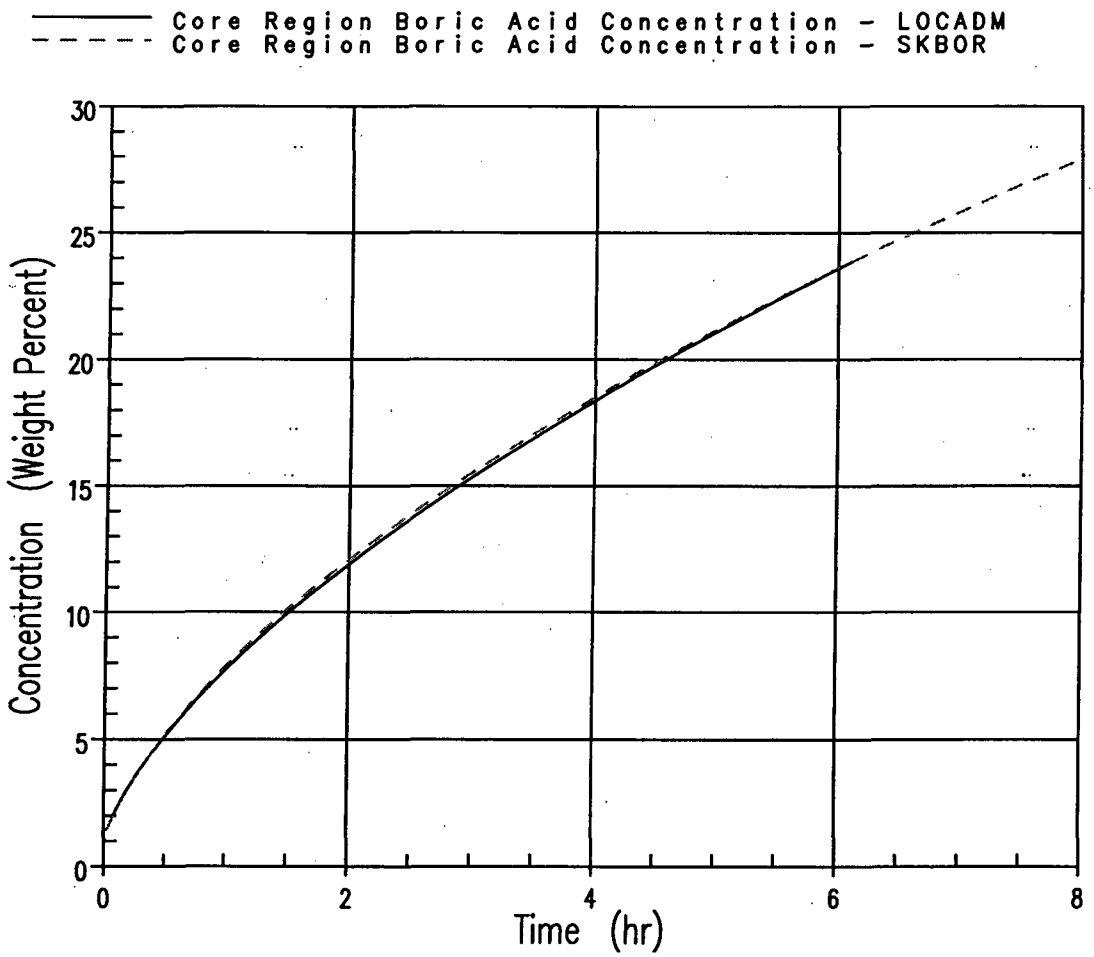


Figure 33-1 Comparison of LOCADM and SKBOR Calculated Core Region Boric Acid Concentration

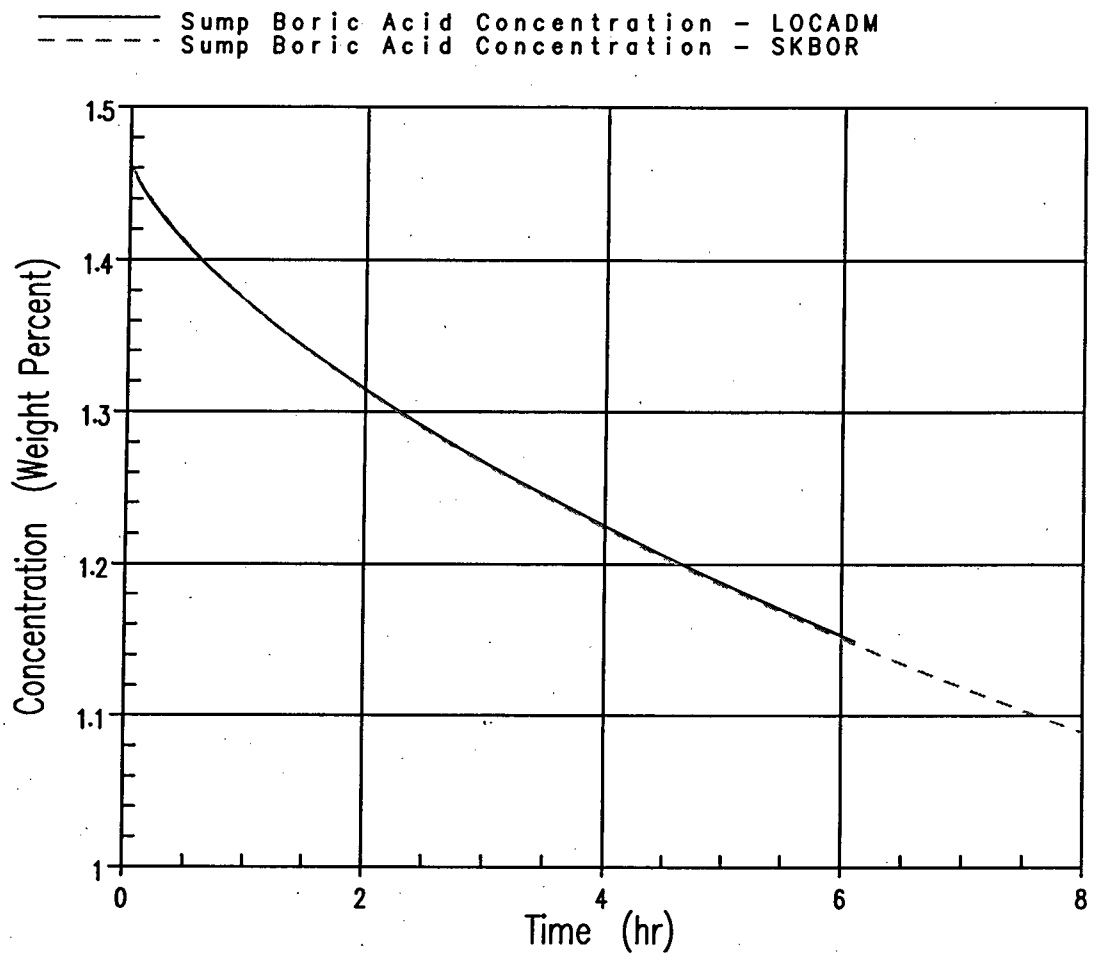


Figure 33-2 Comparison of LOCADM and SKBOR Calculated Containment Sump Boric Acid Concentration

RAI #34

Figure E-3 gives a comparison between an experiment and LOCADM for fouling resistance. The LOCADM results are shown to be conservative. The LOCADM results would be sensitive to the thermal conductivity of calcium sulfate used in the test. Provide a comparison for the thermal conductivity assumed in the LOCADM simulation to experimental values for calcium sulfate. LOCADM is shown to become more conservative as the simulation progressed. Please comment on the effect of the use of slab geometry by LOCADM in modeling heat transfer from a wire as producing this conservatism.

RESPONSE TO RAI #34

A thermal conductivity of 0.52 W/m°K was assumed for calcium sulfate in the LOCADM comparison in Figure E-3. There was no direct measure of thermal conductivity in the referenced experiment (E-19), but another reference, E-5 in WCAP-16793, states that boiler scale deposits of calcium sulfate range between 0.8 and 2.2 W/m°K. Thus, the thermal conductivity value used by LOCADM for this comparison was conservative, but not as conservative as the 0.2 W/m°K which was recommended in WCAP-16793 and is the default value in LOCADM. The progressive increasing

conservatism shown in the example was most likely due to increasing deposit attrition with increasing thickness due to decreased deposit structural stability rather than any assumptions in heat transfer modeling.

RAI #35

Page E-16 describes a sample calculation using LOCADM. A high fiber glass loading of 7000 cubit feet was assumed. Please provide the assumptions regarding transport of this fiberglass into the core including the effect of the sump screen and settling on the containment floor. What fiberglass concentration was assumed in the incomings ECCS flow? Eighty cubit feet of calcium silicate was also assumed to be present. Provide the concentration of calcium silicate assumed in the incoming ECCS flow. Discuss any difference in assumptions for plate out of suspended fiberglass and calcium silicate on the core fuel rods. Compare these assumptions with the PWROG recommendations stated in Section 2.3, Collection of Fibrous Material on Fuel Cladding.

RESPONSE TO RAI #35

In the LOCADM sample calculation, all fiberglass and CalSil were assumed to remain in the sump until they dissolved and only dissolved matter was transported. Any fiber bypassing the sump screen would only collect on the first support grid as indicated in Section 2.3 and would behave no differently than if it was in the sump. Dissolved concentrations are shown as a function of time below:

Time (s)	RV Al (ppm)	Sump Al (ppm)	RV Ca (ppm)	Sump Ca (ppm)	RV Si (ppm)	Sump Si (ppm)
6	0.0	1.0	0.0	1.0	0.0	2.7
30	0.0	1.9	0.0	1.2	0.0	4.3
60	0.0	2.8	0.0	1.4	0.0	5.8
120	0.0	4.0	0.0	1.9	0.0	8.2
180	0.0	5.4	0.0	2.4	0.0	11.3
200	0.0	5.8	0.0	2.5	0.0	12.2
400	0.0	9.5	0.0	4.0	0.0	22.1
600	0.0	13.6	0.0	5.3	0.0	33.2
800	0.0	17.2	0.0	6.3	0.0	42.5
1000	0.0	19.7	0.0	6.9	0.0	49.8
1200	0.0	21.4	0.0	7.3	0.0	55.6
1400	0.0	22.8	0.0	7.7	0.0	60.6
1600	0.0	23.8	0.0	7.9	0.0	65.0
1800	0.0	24.6	0.0	8.1	0.0	68.8
3200	0.0	26.8	0.0	8.7	0.0	79.8
4600	0.0	26.9	0.0	8.8	0.0	79.6
6000	0.0	24.4	0.0	8.6	0.0	76.3
7400	0.0	20.4	0.0	8.5	0.0	72.2
8800	0.0	17.5	0.0	8.3	0.0	67.9
10200	0.0	15.3	0.0	8.1	0.0	63.7
11600	2.5	14.4	1.4	8.4	11.0	63.5
13000	6.4	14.3	3.8	9.0	28.5	66.2
14400	8.9	14.1	5.5	9.5	40.9	68.3
46400	12.9	11.6	13.0	12.4	73.9	67.1
46800	12.6	11.6	12.9	12.5	72.2	67.0
172800	6.7	7.3	21.8	23.7	43.4	47.2
259200	5.7	6.0	28.2	29.8	41.6	43.9
345600	5.8	5.8	38.3	38.4	47.6	47.7
432000	6.1	6.1	46.8	46.9	53.2	53.3
864000	7.3	7.3	69.0	69.0	76.5	76.6
1296000	8.5	8.5	71.5	71.5	75.6	75.7
1728000	9.7	9.7	70.7	70.8	74.8	74.9
2160000	10.9	10.9	70.0	70.1	74.1	74.1
2592000	12.1	12.1	69.4	69.4	73.4	73.4

RAI #36

The Example Run in Appendix Section E.9 states that a high fiberglass loading of 7000 cubic feet was used to determine the thickness of scale which might form on the fuel rods. Section 2.3 indicates that fibrous debris that is carried to the core will not adhere to fuel rod surfaces and therefore will not adversely affect heat transfer. Fibrous material in the core will be concentrated by the boiling process as calculated by LOCADM. Provide a discussion as to the effect on core cooling from high fiber content. What is the maximum loading of fibers which could be concentrated within the core without adversely affecting core heat transfer?

RESPONSE TO RAI #36

The deposition of small fibers that do not dissolve but are small enough to be transported through the sump screen and into the core cannot be ruled out.

The quantity of transported fines is expected to be small compared to both the total amount of debris and the amount of debris that dissolves or corrodes. Thus, if the small fibers were included in model predictions, the effect would be small but would vary from plant to plant depending on the screen design and debris mix. A quantitative estimate of the effect of the fiber on deposit thickness and fuel temperature can be accounted for in LOCADM by use of a "bump-up factor" applied to the initial debris inputs. The method for implementing the bypass bump-up factor is given in the response to RAI#6 in the second set of RAIs.

RAI #37

Appendix F describes AREVA methodology for predicting solubility of containment materials in the containment sump water. Appendix E describes a similar Westinghouse model that is documented in WCAP-16530-NP. Which model should utilities utilize for plant analysis? For a given reactor core how would the results differ in using the two models?

RESPONSE TO RAI #37

Appendix F does not provide an alternative method to the LOCADM model described in Appendix E. The calculations documented in Appendix F were performed to confirm that the model developed in Appendix E identified major chemical species resulting from the post-LOCA chemical reactions.

RAI #38

Please describe StreamAnalyzerVersion 1.2 as it is used to calculate the concentration of post LOCA materials within the core in more detail. How are concentrations determined in the presence of boiling? Are concentration gradients within the core accounted for? How is hot leg recirculation accounted for?

RESPONSE TO RAI #38

(Note: StreamAnalyzer Version 2.0.43 was used for the Appendix F calculation. It was created and is maintained by OLI.)

The concentration of materials in the core was calculated by the following methodology:

- Input concentration of LOCA materials in sump (inputs for different runs are given below)

Input Concentration	Run 1	Run 2	Run 3	Run 4
Ca (ppm)	15	133	15	133
Al (ppm)	17	80	17	80
Si (ppm)	69	156	69	156

- pH adjust the sump solution to the required value using the specified pH additive (NaOH or NaTB).

- Calculate the speciation and solubility at the sump and core temperatures. Calculate the speciation and solubility as water is removed by steaming to a final Concentration Factor of 20.

The OLI software calculates the concentration of solid, dissolved, and gaseous/vapor species based on the solution thermodynamics.

The Appendix F calculations were performed to verify two key assumptions of the Appendix E model: (1) the likely precipitate species and (2) the extent to which Ca, Al, and Si would deposit from solution. Because the Appendix F calculation was not intended as an alternative calculation method to Appendix E, but rather as supporting material, specific reactor conditions like concentration gradients and hot leg recirculation were not utilized. Rather, a conservative final concentration factor of 20 was selected.

RAI #39

What is the significance of the quantities in Table F-2 Steam Masses Utilized in Solubility Calculation? How were they determined? How is the Total Core Feed determined? What is meant by Core Residual After Steaming?

RESPONSE TO RAI #39

The quantities listed in Table 4-2 of Appendix F are water-volume mass inputs to the OLI software evaluation. The 'total core feed' refers to amount of water transported to the reactor. For Runs 1 and 3, this corresponds to the mass of water steamed off and replaced following the accident (with water only replaced at the rate at which boiloff occurs to maintain conservatism) up until hot leg switchover. For Runs 2 and 4, solubility during long-term cooling was evaluated; therefore, it was assumed that the entire sump inventory would be passed through the reactor. These values were determined using the decay heat evaluated from the 1971 ANS model multiplied by a factor of 1.2 and assuming hot leg switchover would take place after 8 hours (total vapor quantity boiled off determined as 570,000 kg). The 'core residual after steaming' input refers to the liquid mass in the reactor vessel after blowdown and refill. These values were based on typical plant values.

Note that these masses are not critical to the final application of Appendix F. The Appendix F calculations were performed to verify two key assumptions of the Appendix E model: (1) the likely precipitate species and (2) the extent to which Ca, Al, and Si would deposit from solution. Therefore, in this respect, the percent deposition figures stated in Appendix F are needed, and the total masses are not critical.

RAI #40

Other inputs in the methodology of Appendix F are described as the sump mass, reactor inventory, and steaming information. Please describe how these qualifies are determined so as to be conservative for reactor safety analysis. For the reactor inventory, discuss how voiding within the reactor vessel and limited circulation in the lower plenum is taken into account in determining the mass of water available to mix with the material being concentrated within the core.

RESPONSE TO RAI #40

The information reported in Appendix F was meant as a supplemental analysis, and not a direct input, to the information reported in Appendix E. The purpose of Appendix F was to determine the reasonability of assumptions within Appendix E, such as percentage and type of precipitate species expected to generate in the core following a LOCA. Appendix F did indicate that the general type and expected percentages of materials that could form in the core were legitimate, as assumed for input into the LOCADM model. The masses determined in the OLI simulations are reported for information only. Appendix E does not use the data from Appendix F as an input to the evaluation. It is a supplemental analysis only.

Because Appendix F was intended for supplemental information only, detailed modeling of the water mass available for mixing was not performed. Rather, a conservative final concentration factor of 20 was utilized in the calculation.

RAI #41

Tables F-5.1 and F-5.3 indicate that chemical precipitates would form in the core for the sample calculations that were performed. Since boiling occurs at the surface of the fuel rods, the staff assumes that is where the chemical precipitates calculated in Appendix F would be located. Please provide a comparison of the deposit thickness calculated by the methodology of Appendix F to that of Appendix E. How will the power peaking in the core be taken into account in determining the Appendix F deposits?

RESPONSE TO RAI #41

As stated in the response to RAI #37, Appendix F does not provide an alternative method to the LOCADM model described in Appendix E. The calculations documented in Appendix F were performed to confirm that the model developed in Appendix E identified major chemical species resulting from the post-LOCA chemical reactions.

RAI #42

It is not clear how a utility will utilize the information in WCAP-16793-NP. Please provide the guidance document that the utilities may utilize to perform specific assessments of (but not limited to) for example :

1) maximum debris that enters the core and lower plenum
2) debris accumulation in the reactor vessel
3) calculation of debris and chemical concentration in the reactor core
4) the maximum debris blockage at the core inlet
5) the debris that collects on mixing vanes and spacers and the impact on boric acid buildup when the debris and boric acid concentrate combines at these locations
6) impact of debris on the long term cooling boric acid precipitation analyses
7) the impact of the debris on boric acid buildup for plants with low elevation suction legs if the break is located on the top of the discharge piping

Also, what calculations are performed to show that once the switch to simultaneous injection is made, that the injection can flush the core with boric acid and debris at all collection locations? How would a utility perform this calculation? It is also suggested that a sample calculation be performed for a plant illustrating how one would utilize the information to show acceptable long term cooling ECCS performance following all break sizes. A plant with the largest potential debris source should be selected. The sample analysis should address all calculations covering the multitude of issues discussed in the report.

RESPONSE TO RAI #42

A guidance document for licensees to implement WCAP-16793-NP is being developed.

Plants will be provided a copy of the LOCADM automated hand calculation tool with insutructions on what inputs are needed to support the calculations. They will also be provided with a sample problem to confirm that the installation of the automated hand calculation tool on their system did not affect the calculation results obtained from LOCADM.

Plant will need to perform a plant-specific calculation using LOCADM. Using plant-specific inputs, plants will first calculate plant-specific chemical deposition on cladding. As part of the deposition calculation, the cladding temperature will with the deposition loading will also be calculated. Plants will them compare the calculated cladding thickness and cladding temperature against the 50 mil maximum deposition thickness and the 800°F clad temperature acceptance basis. If unacceptable comparisons are obtained, plants will need to reduce the matierals contributing to chemical effects by either demonstrating they do not become debris or by eliminating them from containment.

As noted in the responses to RAI #1 and RAI #2, fibrous debris does not block the core. Furthermore, as demonstrated in the sample calculation in Appendix E, preciptiates do not block the core. Thus, the arguments WCAP-16793-NP would become part of the plant licensing basis by reference. Further, current licensing basis calculations for core flushing remain intact and are not affected by the evaluations presented in WCAP-16793-NP.

RAI #43

The NRC staff understands that at some plants the equivalent of hot leg recirculation may be obtained using the pressurizer spray. Under these conditions the pressurizer spray nozzles might become clogged with debris. Does the PWROG have guidance on how the occurrence and consequences of such blockage may be evaluated in plant specific evaluations?

RESPONSE TO RAI #43

Given the bore of the pressurizer spray nozzles is 3/8 inches and the size of the holes in the replacement sump screens is on the order of 0.1 inches, blockage of these nozzles is not considered credible.

Guidance on the evaluation of potential for blockage of containment spray nozzles resulting from debris in the sump fluid is given in WCAP-16406-P, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191." This same guidance is applicable to pressurizer spray nozzles. The following statement will be added to WCAP-16793-NP:

> "Plants that utilize pressurizer spray nozzles to accomplish core dilution should evaluate the spray nozzles using the guidance given in WCAP-16406-P for containment spray nozzles."

RAI #44

Following a large break LOCA, many of the fuel rods in the core may swell and rupture leaving sharp edges at the rupture locations and a diminished channel flow area. Debris may collect in the restricted channels and at the rough edges at the rupture locations. The PWROG should evaluate the possibility of excessive blockage being produced by the combination of swelling and rupture and debris collection. Such blockage might produce the occurrence of the hot spots above the blockage location. Discuss how the occurrence and magnitude of such hot spots might be evaluated.

RESPONSE TO RAI #44

Cladding rupture is only expected to occur in a limited number of fuel rods in the core, namely, the highest power fuel rods in the highest power assemblies. A realistic, yet still quite conservative, assessment of the extent of cladding rupture during a large break LOCA was recently reported in a paper from Reference 44-1 entitled "Realistic Assessment of Fuel Rod Behavior Under Large-Break LOCA Conditions." Estimates of the extent of rupture throughout the core of a typical Westinghouse 4-loop plant were made by considering peak cladding temperature dependence on rod power, rupture temperature as a function of cladding pressure differential, burnup effects on rod internal pressure, and a core-wide census of rod power and burnup. With this information it was estimated that less than 10% of the core (12 of 193 assemblies) would achieve sufficient cladding temperatures to have cladding rupture. Therefore, wide-spread blockage due to swelling and rupture would not be expected in a large break LOCA scenario.

Any debris that did enter the lower plenum for a cold leg injection plant would have had to navigate the bottom nozzles, any debris capturing devices, and a number of structural/heat transfer enhancement grids before reaching the rupture elevation. Build-up of significant debris at the localized rupture locations of the highest power assemblies prior to hot leg switchover is therefore considered highly unlikely.

A somewhat different response is required for plants with upper plenum injection. Prior studies have shown that, through the reflood portion of the transient, the upper plenum drains into the lower powered portion of the core, while the hotter regions of the core are cooled by a bottom-up reflood. This general flow pattern is expected to continue after core quench, resulting in circulation patterns with downflow from the upper plenum in the low powered regions, and continuing upflow in the high powered regions. With such a flow pattern, the debris would have to navigate the top nozzles of the lower powered assemblies and a number of structural/heat transfer enhancement grids before reaching the rupture locations. (Note that rupture would only be expected for the higher powered assemblies in the hotter regions of the core.) Build-up of significant debris at the localized rupture locations in the highest power fuel assemblies is therefore also considered highly unlikely in plants with upper plenum injection.

REFERENCE FOR RAI #44 RESPONSE:

44-1 NUREG/CP-0192, "Proceedings of the Nuclear Fuels Sessions of the 2004 Nuclear Safety Research Conference," 2005.

RAI #45

The mixture of chemicals within the core is postulated to include a mixture of epoxy and non-epoxy paint chips, insulation, ablated structural material, small particles from corrosion of system materials, dissolved corrosion products, buffering agents, boric acid, and lithium hydroxide. This material will be in a high radiation field from release of the fuel rod gap activity as the result of the LOCA and from gamma radiation from the fuel rods. Please describe the chemical and physical changes which may occur within this mixture within the core and the effect on core heat transfer.

RESPONSE TO RAI #45

The modeling which was done assumed that all inorganic impurities entering the core region will either collect at the first grid support (in the case of fiber) or will completely deposit on the fuel. This conservative approach diminishes the importance of impurity chemical or radiochemical reactions since these reactions could not increase the amount of core deposition beyond what was already assumed. Organic coating materials are not expected to experience radiation levels which would cause degradation and subsequent transfer onto heat transfer surfaces.

ATTACHMENT 1
LOCADM SAMPLE INPUTS (REF. RAI # 6(b) RESPONSE)

Table A1-1. Time dependent inputs for LOCADM example

Time (sec)	days	Sump pH	Sump Temp. (°F)	Spray Flow from RWST (lbm/s)	Steam or Spray pH	Containment Temp. (°F)	RV Coolant Temp (°F)	Break Flow (lbm/s)	Clean SI Flow into RV (lbm/s)	Clean SI Bypass Flow (lbm/s)	Recirc Flow into RV (lbm/s)	BOP Blowdown Flow (lbm/s)
6	0	6	224	0	9.5	215	225	5660	0	0	0	3500
30	0	6.5	252	0	9.5	255	265	4180	0	0	0	2000
60	0	6.9	238	0	9.5	252	262	3600	90	0	0	1800
120	0	7.25	238	0	9.5	252	262	1000	3200	0	0	0
180	0	7.4	240	0	9.5	251	261	1000	1400	0	0	0
200	0	7.4	241	0	9.5	251	261	1000	190	0	0	0
400	0	7.8	247	0	9.5	253	263	210	310	0	0	0
600	0	7.8	250	0	9.5	255	265	230	330	0	0	0
800	0	7.9	254	1	9.5	257	267	320	400	0	0	0
1000	0	8	256	1	9.5	254	264	400	81	319	0	0
1200	0	8.05	257	1	9.5	252	262	400	77	323	0	0
1400	0	8.15	258	1	9.5	252	262	400	74	326	0	0
1600	0	8.2	259	1	9.5	249	259	400	71	329	0	0
1800	0	8.2	260	1	9.5	248	258	400	68	332	0	0
3200	0	8.2	254	1	9.5	240	250	400	58	342	0	0
4600	0	8.2	246	1	9.5	238	248	400	52	348	0	0
6000	0	8.2	238	0		243	253	400	49	351	0	0
7400	0	8.2	232	0		244	254	400	46	354	0	0
8800	0	8.2	222	0		245	255	400	44	356	0	0
10200	0	8.2	218	0		245	255	400	42	358	0	0
11600	0	8.2	217	0		245	255	400	0	0	40	0
13000	0	8.2	214	0		244	254	400	0	0	39	0
14400	0	8.2	211	0		243	253	400	0	0	38	0
46400	1	8.2	163	0		220	230	400	0	0	27	0
46800	1	8.2	158	0		205	215	400	0	0	200	0
2E+05	2	8.2	156	0		198	208	400	0	0	200	0
3E+05	3	8.2	156	0		193	203	400	0	0	200	0
3E+05	4	8.2	156	0		185	195	400	0	0	200	0
4E+05	5	8.2	156	0		180	190	400	0	0	200	0
9E+05	10	8.2	156	0		161	171	400	0	0	200	0
1E+06	15	8.2	156	0		138	148	400	0	0	200	0
2E+06	20	8.2	156	0		137	147	400	0	0	200	0
2E+06	25	8.2	156	0		135	145	400	0	0	200	0
3E+06	30	8.2	156	0		134	144	400	0	0	200	0

Table A1-2. Time dependent input for LOCADM, page 2.

Time (sec)	days	NaOH mass flow Spray (lbm/s)	TSP Dissolution Rate (lbm/s)	NaTB Release Rate - Ice or Basket (lbm/s)	Reactor Vessel Liquid Mass (lbm)	Ice Melt Rate (lbm/s)	RV Pressure In Upper Plenum (psia)	Reactor Vessel Steam Flow (lbm/s)
6	0	0	0	0	210000	0	18.85	330.4
30	0	0	0	0	155000	0	38.37	216.7
60	0	2	0	0	110000	0	36.49	178.0
120	0	5	0	0	85000	0	36.49	146.5
180	0	5	0	0	155000	0	35.88	130.7
200	0	5	0	0	162000	0	35.88	126.9
400	0	5	0	0	115000	0	37.11	104.6
600	0	5	0	0	132000	0	38.37	93.5
800	0	5	0	0	142000	0	39.67	86.4
1000	0	5	0	0	143000	0	37.74	81.0
1200	0	5	0	0	143000	0	36.49	76.8
1400	0	5	0	0	143000	0	36.49	73.6
1600	0	5	0	0	143000	0	34.69	70.7
1800	0	5	0	0	143000	0	34.11	68.3
3200	0	5	0	0	143000	0	29.71	57.8
4600	0	0	0	0	143000	0	28.69	52.1
6000	0	0	0	0	143000	0	31.30	48.6
7400	0	0	0	0	143000	0	31.85	45.8
8800	0	0	0	0	143000	0	32.40	43.7
10200	0	0	0	0	143000	0	32.40	41.9
11600	0	0	0	0	143000	0	32.40	40.4
13000	0	0	0	0	143000	0	31.85	39.1
14400	0	0	0	0	143000	0	31.30	38.0
46400	1	0	0	0	143000	0	20.71	26.9
46800	1	0	0	0	143000	0	15.54	26.6
2E+05	2	0	0	0	143000	0	14.70	0.0
3E+05	3	0	0	0	143000	0	14.70	0.0
3E+05	4	0	0	0	143000	0	14.70	0.0
4E+05	5	0	0	0	143000	0	14.70	0.0
9E+05	10	0	0	0	143000	0	14.70	0.0
1E+06	15	0	0	0	143000	0	14.70	0.0
2E+06	20	0	0	0	143000	0	14.70	0.0
2E+06	25	0	0	0	143000	0	14.70	0.0
3E+06	30	0	0	0	143000	0	14.70	0.0

Table A1-3. Materials Input for LOCADM example.

Class	Material	Amount
Coolant	Recirc Sump Pool Volume (ft3)	
Metallic Aluminum	Aluminum Submerged (sq ft)	799
	Aluminum Submerged (lbm)	179
	Aluminum Not-Submerged (sq ft)	15189
	Aluminum Not-Submerged (lbm)	3406
Calcium Silicate	CalSil Insulation(ft3)	80
	Asbestos Insulation (ft3)	0
	Kaylo Insulation (ft3)	0
	Unibestos Insulation (ft3)	0
E-glass	Fiberglass Insulation (ft3)	7000
	NUKON (ft3)	0
	Temp-Mat (ft3)	0
	Thermal Wrap (ft3)	0
Silica Powder	Microtherm (ft3)	0
	Min-K (ft3)	0
Mineral Wool	Min-Wool (ft3)	0
	Rock Wool (ft3)	0
Aluminum Silicate	Cerablanket (ft3)	0
	FiberFrax Durablanket (ft3)	0
	Kaowool (ft3)	0
	Mat-Ceramic (ft3)	0
	Mineral Fiber (ft3)	0
	PAROC Mineral Wool (ft3)	0
Concrete	Concrete (ft2)	736
Trisodium Phosphate	Trisodium Phosphate Hydrate (lbm)	0
Interam	Interam (ft3)	0
	Initial Sump Liquid Volume (ft3)	20
	Initial Boron Concentration in RCS	800
	Initial Lithium Concentration in RCS	2
	RWST/Accumulator Boron Conc. (ppm)	2500
	NaOH Addition Tank NaOH Conc.	200000

Table A1-4. Density values used in LOCADM example

Class	Material	Amount	Density (lb/ft3)	Mass(kg)	Class total (kg)
Coolant	Recirc Sump Pool Volume (ft3)	0	60.957	0.0	0.0
Metallic Aluminum	Aluminum Submerged (sq ft)	799.40		0.0	1626.1
	Aluminum Submerged (lbm)	179.25		81.3	
	Aluminum Not-Submerged (sq ft)	15188.6		0.0	
	Aluminum Not-Submerged (lbm)	3405.75		1544.8	
Calcium Silicate	CalSil Insulation(ft3)	80	14.5	526.2	526.2
	Asbestos Insulation (ft3)	0	14.15	0.0	
	Kaylo Insulation (ft3)	0	14.15	0.0	
	Unibestos Insulation (ft3)	0	14.15	0.0	
E-glass	Fiberglass Insulation (ft3)	7000	2.4	7620.4	7620.4
	NUKON (ft3)	0	4	0.0	
	Temp-Mat (ft3)	0	11.8	0.0	
	Thermal Wrap (ft3)	0	16	0.0	
Silica Powder	Microtherm (ft3)	0	4	0.0	0.0
	Min-K (ft3)	0	4	0.0	
Mineral Wool	Min-Wool (ft3)	0	10	0.0	0.0
	Rock Wool (ft3)	0	10	0.0	
Aluminum Silicate	Cerablanket (ft^3)	0	8	0.0	0.0
	FiberFrax Durablanket (ft3)	0	12	0.0	
	Kaowool (ft3)	0	6	0.0	
	Mat-Ceramic (ft3)	0	12	0.0	
	Mineral Fiber (ft3)	0	21	0.0	
	PAROC Mineral Wool (ft3)	0	21	0.0	
Concrete	Concrete (ft2)	736		0.0074027	0.007402688
Interam	Interam (ft3)	0	54	0.0	0.0
	Initial Sump Volume (ft3)	20		554	
	Initial Boron Concentration in RCS	800			
	Initial Lithium Concentration in RCS	2			
	RWST/Accumulator Boron Conc. (ppm)	2,500		5500	
	Calcium Deposit Density		35		
	Aluminum Deposit Density		34		
	Silicon Deposit Density		31		

Table A1-5. Core data input

Variable	Units	Value
100% Reactor Power	MW Thermal	3188
Crud Thermal Conductivity	W/m-K	0.52
LOCA Deposit Thermal Conductivity	W/m-K	0.2
Fuel Rod OD	Inches	0.36
Pellet Stack Length	Inches	144
Average Cladding Oxide Thickness	Microns	20
Average Starting Crud Thickness	Microns	30
Number Regions	(200 max)	4
Number of Axial Nodes (up and down each region)	(10 max)	3
Distance from Hotlet Inlet to Top of Pellet Stack	Inches	47

Table A1-6. Core axial node definition

Elevation	Relative Power	Relative Oxide Thickness	Relative Crud Thickness
1	0.95	1.5	2.4
2	1.1	0.9	0.3
3	0.95	0.6	0.3

Table A1-7 Core radial node definition

Region	Number Rods	Relative Power	Relative Oxide Thickness	Relative Crud Thickness
1	1	1.80	0.8	3.3
2	263	1.60	0.7	2.7
3	39072	1.23	0.8	1.27
4	11616	0.20	1.68	0.05

ATTACHMENT 2
A SHORT DESCRIPTION OF LOCADM

LOCADM is a calculational tool that can be used to conservatively predict the build-up of chemical deposits on fuel cladding after a LOCA. The source of the chemical products is the interaction of the fluid inventory in the reactor containment building sump with debris and other materials exposed to and submerged in the sump fluid or containment spray fluid. LOCADM predicts both the deposit thickness and cladding surface temperature as function of time at a number of core locations or "nodes". The deposit thickness and maximum surface temperature within the core are listed in the output for each time period so that the user can compare these values to the acceptance basis for long term cooling.

The chemical inputs into LOCADM are the volumes of different debris sources such as fiberglass and calcium silicate (cal-sil) insulation. The surface areas of uncoated concrete, aluminum submerged in the sump, and aluminum exposed to spray are also required. The sump and spray pH are specified as a function of time, as are the inputs of sodium hydroxide, trisodium phosphate, sodium tetraborate, lithium hydroxide and boric acid.

Chemical product transport into the core is assumed to occur by the following process:

1. Containment materials corrode or dissolve forming solvated molecules and ions
2. Some of the dissolved material precipitates, but the precipitates remain in solution as small particles that do not settle
3. The dissolved material and suspended particles pass through the sump screen and into the core during recirculation. For the purpose of adding conservatism, it is assumed that none of the precipitates are retained by the sump screen or any other non-fuel surfaces

Note that the transport of small fibers that do not dissolve but are small enough to be transported through the sump screen and into the core is not considered explicitly in LOCADM. The quantity of transported fines is expected to be small compared to both the total amount of debris and the amount of debris that dissolves or corrodes. Fiber can be accounted for in LOCADM in cases where it is significant by use of a "bump-up factor" applied to the initial debris inputs. The bump-up factor is set such that total mass of deposits on the core after 30 days is increased by the best estimate of the mass of the fiber that bypasses the sump screen.

Coolant flow rates into the reactor mixing volume as a function of time must be provided by the user and are obtained from a plant's safety analysis for long term core-cooling. The relative amounts of steam and liquid flow out reactor mixing volume are calculated by LOCADM. The core input is generalized. The coolant flow could be coming from the cold leg, the hot leg, or from upper plenum injection. Various operational modes are accounted for by varying the rate of flow into the mixing volume and the source of the flow (safety injection or recirculated coolant.) Values for generically applicable mixing volumes have been identified and will be provided to users. The temperature of the sump and reactor coolant as a function of time must also be entered by the user.

Within the mixing volume, the coolant is assumed to be perfectly mixed. Coolant chemical products entering the reactor are distributed evenly between all core nodes before deposition calculations are performed. The entire mixing volume is also assumed to be at the same temperature. Pressure is determined by the upper plenum pressure and the hydrostatic pressure at different elevations in the core. No attempt was made to model flow within the mixing volume and variations in that flow that might be caused by grids and flow obstructions. Since flow was not modeled, a heat transfer coefficient of 400 W/m^2-°K (70 BTU/ft^2 °F) was assumed for

transfer of heat between bulk coolant with the fuel channels and the surface of the deposits since this is a typical heat transfer coefficient for convective flow within natural circulation systems.

LOCADM deposits chemical products that are dissolved or suspended in solution throughout the core in proportion to the amount of boiling in each core node. It is assumed that deposition rate is equal to the steaming rate times the chemical product concentration at each node. If there is no boiling, the chemical products are distributed according to heat flux, at an empirically derived rate that is $1/80^{th}$ of the deposition that would have occurred if all of the heat had gone into the boiling process.

The deposition algorithm does not rely on solubility or any other chemical characteristics of the chemical products to determine the deposition rate. All chemical material that is transported to the fuel surface by boiling is assumed to deposit. LOCADM uses a default deposit thermal conductivity for the deposited material of 0.1 Btu/(hr-ft-°F), which is low enough to bound expected core deposits. Likewise, the default deposit density is low enough (e.g. 35 lbm Ca/ft^2) to bound expected deposits including those that incorporate adsorbed boron or boron bonded to chemical product elements. Consistent with current licensing basis calculations for PWRs that demonstrate that the boric acid concentration in the core is limited to values below the solubility limit, the LOCADM does not precipitate boric acid. The same is true for sodium phosphate, sodium borates and sodium hydroxide, which are also highly soluble.

The core noding within LOCADM can be adjusted by the user. WCAP-16793 provides guidance to the LOCADM user for node selection for different types of cores. The node selection recommended in the WCAP provides conservative power distributions with respect to core deposition.

LOCADM runs within Microsoft EXCEL and should be easy to use for those familiar with EXCEL. The first sheet of the workbook instructs the user on how to enter the chemical and flow inputs into worksheets in tabular form. A macro written in Visual Basic for Applications is then run. The macro reads the input, looks for input errors, calculates core conditions in one second intervals, and then outputs the results within the same workbook.

RAI #1

General: - There are several mathematical models used in deriving predicted solubilities, fuel surface temperatures, etc. Please provide a reference for each model used that identifies the corroborating assumptions described in the WCAP and how these models are appropriate for this scenario.

RESPONSE TO RAI #1

Based on a clarification offered by the reviewers, this question was clarified to be the heat transfer calculations documented in WCAP-16793-NP. The following responses clarify the heat transfer codes and models use in the calculations of WCAP-16793-NP.

1. The core blockage / peak clad temperature calculations were performed using the WCOBRA/TRAC code. The code is described in detail in WCAP-12945-P-A, Volume 1, Revision 2, and Volumes 2 through 5, Revision 1. "Code Qualification Document for Best Estimate LOCA Analysis," Bajorek, S.M., et. Al., 1998.

2. The ANSYS code was used to calculation clad heat-up behind grids. ANSYS has been used to support design and analysese previously submitted to NRC. Additional information regarding the ANSYS code may be obtained from the following website: www.ansys.com.

The clad heat-up between grids was calculated using basic heat conduction in cylindrical coordinates using the commercially available software, 'MATHCAD®". A discussion of heat transfer in cylindrical coordinates can be obtained from an appropriate basic heat transfer text. One example of such a text is "Heat Transmission," by Wm. H. McAdams, McGraw-Hill Book Company (1954).

RAI #2

Page 2-2 - There is a tacit assumption here that the only mechanism for blockage is by single particles bridging across the opening. Operational experience with heat exchangers shows that debris much smaller than the diameter of a tube can build up at the tube mouth, and close down the opening diameter. The deposition mechanism of this smaller debris is via adhesion. For the lower core plate inlet, adhesion may occur due to increased temperature at the surface and the presence of corrosion products which have an irregular surface.

Does the model that is being used account for surface irregularities capturing smaller debris than the span diameter? If not, justify why this could not happen or describe how build up of smaller debris would affect the results?

How long will it take to span the gap if debris build up were to occur from all the particulate passing through the sump screen depositing at the core inlet area?

RESPONSE TO RAI #2

We agree that particles smaller than the gap diameters can build-up to form deposits at the mouths of openings in heat exchangers but it is unlikely that this process could cause a blockage at the lower core plate within 30 days, regardless of the surface roughness of the core plate. Thus, the modeling done in WCAP 16793-NP did not consider preferential build-up of small particle deposits at the lower core plate inlet. The following describes why the formation of this type of deposit was not considered.

Westinghouse and others have studied the build-up of deposits on tube mouths and the mouths of flow passages in tube support plates since such deposits can cause level oscillations and flow instability in steam generators. Such deposits

are observed to grow at the entrance to the passages, and in fewer cases, at the exits. The deposits take the form of thin lips that extend from all sides of the of the flow passages. The deposits are both hard and dense.

There are two predominant deposition mechanisms which explain the broach hole and tube mouth deposition processes (Ref. 2-1). The first is the vena contracta effect. This mechanism is operative when fluid flow is sharply contracted, such as flow through a plate with a hole. The flow separates from the wall following the sharp contraction in the mouth of the restricted passage. In the vena contracta region, there is a low velocity recirculation zone in which particles can deposit. Particle growth and deposit consolidation is accelerated by evaporation of liquid in the vena contracta region due to lowered pressure if the stream is a two-phase liquid/steam mixture. The particles grow and the deposit densifies as fluid is supersaturated with dissolved impurities. The greatest deposition rates are observed in regions where the steam quality is between 30 and 50 percent.

The second mechanism is termed particle trapping. In this case, larger particles such as detached tube scale flakes impact the area at the edge of the flow passage and marginally extend into the flow stream. The particles are cemented to the surface by crystallization growth, and then the newly formed lip is able to create recirculation flow which supports further deposition of large particles that further restrict the flow through the opening.

There are several reasons why these mechanisms would not produce blocking deposits at the inlet to the core which would be sufficient to restrict core cooling.

1. Fluid velocities at the lower core plate are low during recirculation so the vena contracta effect would be minimal. Vena contracta deposition increases with fluid velocity.
2. The flow at the lower core plate will be single phase during recirculation under most circumstances. Thus, vena contracta deposition will be minimized because the two phase flow which accelerates this type of deposition will not be present.
3. The concentration of larger particles that could be deposited via the particle trapping mechanism will be low because of settling and filtration at the sump screen.
4. There is not sufficient time to form such deposits. Several fuel cycles are usually required for flow passages to be closed off in steam generators when the chemistry and thermal hydraulics favor this type of deposition.

Low temperature industrial heat exchanges outside the nuclear industry are also subject to tube sheet fouling. In most cases, the fouling is either due to large debris or biological activity (Ref. 2-2). Neither would be expected in the early stages of a LOCA when flow requirements are high.

REFERENCES FOR RAI #2 RESPONSE:

2-1 Helena E. C. Rummens, J. T. Rogers, and C. W. Turner, "The thermal hydraulics of tube support fouling in nuclear Steam Generators" Nuclear Technology 148, 2004, p 268 to 286

2-2 Mohammad Abdul-Kareem Al-Sofi, Fouling phenomena in multi stage flash (MSF) distillers, Desalination 126 (1999) 61–76

RAI #3

Page 2-2 - The assumption related to largest particle size that passing into the reactor vessel does not account for particulate agglomeration downstream of the screens, particularly during the temperature drop in the Residual Heat Removal (RHR) heat exchangers. How does the model demonstrate that the particle size (due to agglomeration of micron and sub-micron size precipitates) and temperature decrease (causing subsequent precipitation) will not exceed what is predicted here for particle size?

RESPONSE TO RAI #3

On page 2-2 of WCAP 16793-NP the blockage of the core inlet by particles was being discussed and no modeling of the particle size or deposition was performed. Some agglomeration of particles may occur after the sump screen in the RHR heat exchanges but when the resulting flocs are carried to the core, they will not lead to blockages of the lower core plate and do not need to be considered when modeling core blockages.

The primary reason that the flocs would not block lower core plate passages is that large, freshly formed flocs have little strength (1). It was observed during WCAP-16530-NP bench testing (2) that the freshly formed agglomerates formed after cooling of simulated sump solutions were soft and easily broken apart, that is, they had low shear strength. As such, they could not form a blockage by bridging flow openings in the lower core plate.

Another aspect of flocculation that works against formation of large, hard particles that could form blockages is limited time available for agglomeration in the ECCS before the floc enters the reactor. Flocculation is typically not a rapid process and it typically takes on the order of 10 to 15 minutes to grow particles from the sub-micron size range to the size that could be settled even when water treatment chemicals designed to promote flocculation have been added (3). Thus, there would not be enough time for agglomerates to grow to the 0.1 inch size needed to span flow passages in the lower core plate as the coolant traveled from the RHR heat exchanger and to the reactor vessel. If an agglomerate survived its passage through the core, it would likely settle in the sump or be filtered out at the sump screen before it had a chance to grow larger in a second pass through the RHR.

REFERENCES FOR RAI #3 RESPONSE:

3-1 Arthur T. Hubbard, "Encyclopedia of Surface and Colloid Science" (World Scientific, London) 2002, p. 2218

3-2 WCAP-16530, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," February, 2006.

3-3 P. Zhang, H.H. Hahn, E. Hoffmann, "Study on Flocculation Kinetics of Silica Partidle Suspensions" in "Chemical Water and Wastewater Treatment" Hermann H. Hahn, Erhard Hoffmann, Hallivard Odegaard editors., IWA Publishing, London 2004, p. 277

RAI #4

Page 2-3 - Was the partial fuel length assembly pre-conditioned so that the corrosion film on its surface would be representative of that found in a plant in its third fuel cycle? If not, describe how the presence of a representative oxide film could affect the test results.

RESPONSE TO RAI #4

The partial length fuel assembly was not preconditioned to produce a corrosion film that might be representative of that found in a plant during normal operation. The purpose of the test was to specifically evaluate the collection of fibrous debris on debris capturing fuel grids and the consequential head loss of that fiber bed and the particulates collected in that bed when the Emergency Core Cooling System (ECCS) is aligned to recirculate coolant from the reactor containment building sump. As this test facility was a recirculating loop, the use of smooth rods minimized the possible capture of fiber on rod surfaces and maximized the potential for fibrous and particulate debris to be either captured on a second grid or recirculate and be captured on the fiber bed formed at the fuel assembly entrance. Thus, the use of smooth rods was conservative for the purposes of this test.

In the plant, an oxide film may provide sites for the collection of fiber on the cladding surface between support grids. Should this collection occur, it would have negligible affect on the plant for the following reasons;

- From the test observations and data presented in the response to RAI #2 from the first set of RAIs, most of the fibrous debris is captured at the core entrance. Thus, there is only a small amount of fiber that is passed by the support grids at the core entrance and therefore only a small amount of fiber to collect downstream on the cladding surface.
- If the fiber forms a bed, WCAP-16793-NP states that fibrous material on fuel structures with at least a porosity of 40%.
    - Being porous, there would be fluid movement though the fiber bed. This is demonstrated by the data included in the response to RAI #2.
    - The movement of fluid through the porous bed will remove heat from the cladding surface by convection.
- From the response to RAI #15 from the first set of RAI responses, the thermal conductivity of a fibrous bed is conservatively represented as being 0.1 Btu/(hr-ft-°F). This is the same value used to conservatively simulate the thermal conductivity of chemical precipitants on cladding surfaces.
    - The thermal conductivity through glass is about 0.59 Btu/(hr-ft-°F). Explicitly accounting for fiberglass debris in the surface deposition would enhance heat transfer.
    - As noted above, accounting for only conductive heat transfer through a fiber bed conservatively neglects convective heat transfer thorough the porous bed.

Thus, the collection of fibrous material on an oxide layer would have negligible affect on long-term core cooling clad temperatures.

RAI #5

Page 2-3 - Was the partial length fuel assembly internally heated to the temperature anticipated when debris would come in contact with it? If not, please demonstrate what effect heat at the clad surface will have.

RESPONSE TO RAI #5

The partial length fuel assembly was not heated to the temperature anticipated when debris would come into contact with. The purpose of the test was to specifically evaluate the collection of fibrous debris on debris capturing fuel grids and the consequential head loss of that fiber bed and the particulates collected in that bed when the Emergency Core Cooling System (ECCS) is aligned to recirculate coolant from the reactor containment building sump. As this test facility was a recirculating loop, the use of unheated rods minimized the possible capture of fiber on rod surfaces and maximized the potential for fibrous and particulate debris to be either captured on a second grid or recirculate and be captured on the fiber bed formed at the fuel assembly entrance. Thus, the use of unheated rods was conservative for the purposes of this test.

The WCOBRA/TRAC calculations presented in Section 6 and Appendix B of WCAP-16793-NP demonstrate that a reduction in flow associated with potential core blockage has negligible affect on peak clad temperatures calculated anywhere in the core as shown in Figure 6-5 (and Figure B-20). These two figures are temperature history plots of the calculated peak clad temperature anywhere in the core for two (2) blockage cases; 82% of the core blocked and 99.4% of the core blocked, respectively. The calculated peak clad temperatures anywhere in the core are about 270° F, all other calculated clad temperatures are either equal to or less than the calculated temperatures shown in Figure 6-5 (and Figure B-20). These low temperatures are below the melting point of glass and other materials such as epoxy coatings. Thus, heated clad surfaces will have a negligible affect on attracting or holding debris, either fibrous or particulate, to the clad surface in either the test, or in plants.

RAI #6

Page 2-6, Section 2.3 of the WCAP states that fibrous debris entering the core will not tightly adhere to the surface of fuel cladding. The WCAP further states that adherence of fibrous debris is not plausible and will not adversely affect core cooling. During strainer testing, the staff has observed that fiber coated with chemical precipitate can adhere to surfaces, such as plexiglass walls. Therefore, provide a justification for why is it not plausible that fibers that have precipitate or other chemical products attached can tightly adhere to the surface of fuel cladding? If fibers did adhere to the fuel cladding, how would this affect the deposition model predictions?

RESPONSE TO RAI #6

The deposition of small fibers that do not dissolve but are small enough to be transported through the sump screen and into the core cannot be ruled out.

The quantity of transported fines is expected to be small compared to both the total amount of debris and the amount of debris that dissolves or corrodes. Thus, if the small fibers were included in model predictions, the effect would be small but would vary from plant to plant depending on the screen design and debris mix. A quantitative estimate of the effect of the fiber on deposit thickness and fuel temperature can be accounted for in LOCADM by use of a "bump-up factor" applied to the initial debris inputs. The bump-up factor is set such that total release of chemical products after 30 days is increased by the best estimate of the mass of the fiber that bypasses the sump screen. This allows the bypassed material to be deposited in the same manner as a chemical reaction product.

The recommend procedure for including fiber bypass in the LOCADM deposition calculations is illustrated in the example below where the LOCADM example in WCAP-16793-NP is extended to include fiber bypass

A. Estimate the mass of material bypassing the sump screen.

   Example: The sump screen area in the WCAP-16793-NP example plant is 5000 ft^2. The type of screen used at the plant is known to bypass a maximum of 1 ft^3 of fiber for every 1000 ft^2 of screen area, so the volume bypassed is estimated to be:

   $$(1\ ft^3\ fiber\ /\ 1000\ ft^2\ screen) * 5000\ ft^2 = 5\ ft^3\ fiber$$

   Then the volume of fiber is converted to mass using the density of fiberglass. NEI 04-07 (Reference 6-1) identifies that the density for low–density fiberglass is approximately 2.4 lbm/ft^3. This value is consistent with the density range of 2 to 3 lbm/ft^3 identified in NUREG/CR-6808 (Reference 6-2). To maximize the effects of bypassed fiberglass on the LOCADM model, a density of 4 lbm/ft^3 is used:

   $$5\ ft^3\ fiber * 4\ lbm\ ft^{-3} = 20\ lbm$$

   Thus, the bypass bump-up factor must be selected so that the chemical product release (aluminum + calcium + silicon) in LOCADM is increased by at least 20 lbm.

   Note that the bypass mass can be estimated by other techniques such as the direct measurement of bypassed material mass during screen qualification tests.

B. Calculate the "increase factor" for the chemical products.

   Example: LOCADM is run first not accounting for bypass using the plant specific material inputs. The total Ca + Al + Si release is obtained by summing outputs in the "Releases by Material" worksheet of LOCADM (B3:D11). A value of 554.8 kg or 1221 lbs is obtained. The total release after the bypassed matter added is 1221 + 20 lbs or 1241 lbs. Thus, the increase factor is:

(1241 lbs) / 1221 lbs = 1.016 (a 1.6% increase)

C. Adjust the "increase factor" to create the bypass bump-up factor.

If all of the debris material reacts to form chemical products, the increase factor calculated in "B" would be the bypass bump-up factor. However, in cases where the containment materials are not completely dissolved or corroded as is typical, the bypass bump-up factor must be adjusted upward to account for the incomplete reaction. This is a trial and error process. An adequate estimate is usually obtained by doubling the percentage increase in release calculated in "B"

Example:

1.016 + 0.016 = 1.032 (the bypass bump-up factor)

D. Increase all material inputs by the bump-up factor rerun LOCADM.

Example:

Class	Material	Amount	Amount
Coolant	Recirc Sump Pool Volume (ft3)	Before Bump-up	After Bump-up
Metallic Aluminum	Aluminum Submerged (sq ft)	799	825
	Aluminum Submerged (lbm)	179	185
	Aluminum Not-Submerged (sq ft)	15189	15675
	Aluminum Not-Submerged (lbm)	3406	3515
Calcium Silicate	CalSil Insulation(ft3)	80	82.56
E-glass	Fiberglass Insulation (ft3)	7000	7224
Concrete	Concrete (ft2)	736	762

RESULTS:

	Before Bump-up	After Bump-up
Released Material (Ca+Al+Si) lbm	1221	1247
Maximum Deposit Thickness (mils)	10.1	10.3
Maximum Temperature (°F)	323.6	323.6

Note that the released material has increased by 26 lbm, six pounds more that the required 20 lbm needed to account for the fiber material. If the amount of the increase was less than 20 lbm, or if the increase was too conservative, the bump-up factor would be adjusted up or down proportional to the undershoot or overshoot, and LOCADM would be rerun after reapplication of the new bump-up factor to the initial masses.

REFERENCES FOR RAI #6 RESPONSE:

6-1 NEI 04-07, Revision 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology, Volume 1, Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004.

6-2 NUREG/CR-6808, "Knowledge Base for the Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance," U. S. Nuclear Regulatory Commission, February 2003.

RAI #7

Page 2-15 - This section describes the conservative clad heat-up calculations.

A) Is the 50 mils of solid precipitate described here in addition to the normal layer of fuel corrosion product?

B) Is this calculation on a clean fuel basis or a fuel surface that has the maximum allowable crud layer (~100 microns)?

C) Is the 'weighting' factor for the crud and the precipitate the same? Provide a reference for the assumptions made regarding the individual contributions to this term.

RESPONSE TO RAI #7

The text on page 2-15 refers to the calculation summarized in Section 4.2, "Cladding Heatup Between Grids" and the details of those calculations presented in Appendix D, also titled "Cladding Heatup Between Grids." A schematic of the calculation model is given in Figure D-1. The schematic identifies that both an oxide layer and a crud layer are explicitly accounted for in the model used for these calculations and supports the following response.

A) The 50 mils of solid precipitation described in the last paragraph of Section 2.7, page 2-15, are in addition to both a clad oxide and a crud layer. The thickness of the layer of oxide is identified under the third bullet in Section 4.2.3, "Assumptions" as being 100 microns (4 mils). The basis for this thickness is given on page D-4 as PWR industry experience.

   Thus, the 50 mils of solid precipitate thickness is in addition to a layer of fuel corrosion product.

B) Similar to the response to Item A, above, the calculations were performed assuming a layer of crud. Again, under the third bullet in Section 4.2.3, "Assumptions," 100 microns (4 mils) of crud was assumed for the clad heat-up calculations. The basis for this thickness is given on page D-4 as PWR industry experience.

C) There is no reference to a "weighting factor" in the description of clad heat-up calculations given on Page 2-15. A thermal conductivity of 1.27 Btu/(hr-ft-°F) was used to represent the oxide layer and a thermal conductivity of 0.30 Btu/(hr-ft-°F) was used to represent and crud layer (see page D-3). These values are representative of industry experience for the oxide, and a value recommended by the Electric Power Research Institute (EPRI) for crud.

RAI #8

Page 5-3 - One of the stated assumptions in this section is, "The non-boiling rate of deposit build-up is proportional to heat flux and is 1/80th of the rate of boiling deposition at the same heat flux". Please provide the technical basis for this assumption. Also provide a copy of reference E-13.

RESPONSE TO RAI #8

The $1/80^{th}$ factor was empirically derived in reference E-13. This was done by comparing the deposition rate obtained for mixed calcium salts under boiling and non-boiling conditions on a heated surface. The application in the post-LOCA environment is justified since calcium is one of the elements of most concern in fuel deposition. The $1/80^{th}$ factor also seems reasonable when applied to fuel cladding deposits of different compositions. A review of five PWR fuel crud exams showed an average deposit mass per area ratio of 1/92 between non-boiling and boiling regions of the fuel.

Reference E-13 is available in open literature.

RAI #9

Page 5-3 - The relationship between the WCAP-16530-NP dissolution model and WCAP-16793 deposition model is discussed in Section 5.4.1. Please clarify how the output from the dissolution model is related to the input for the deposition model. In other words, is the mass from the dissolution model equal to the mass input to the deposition model, or is the dissolution mass output reduced by precipitate settling, sump strainer debris bed filtering, etc?

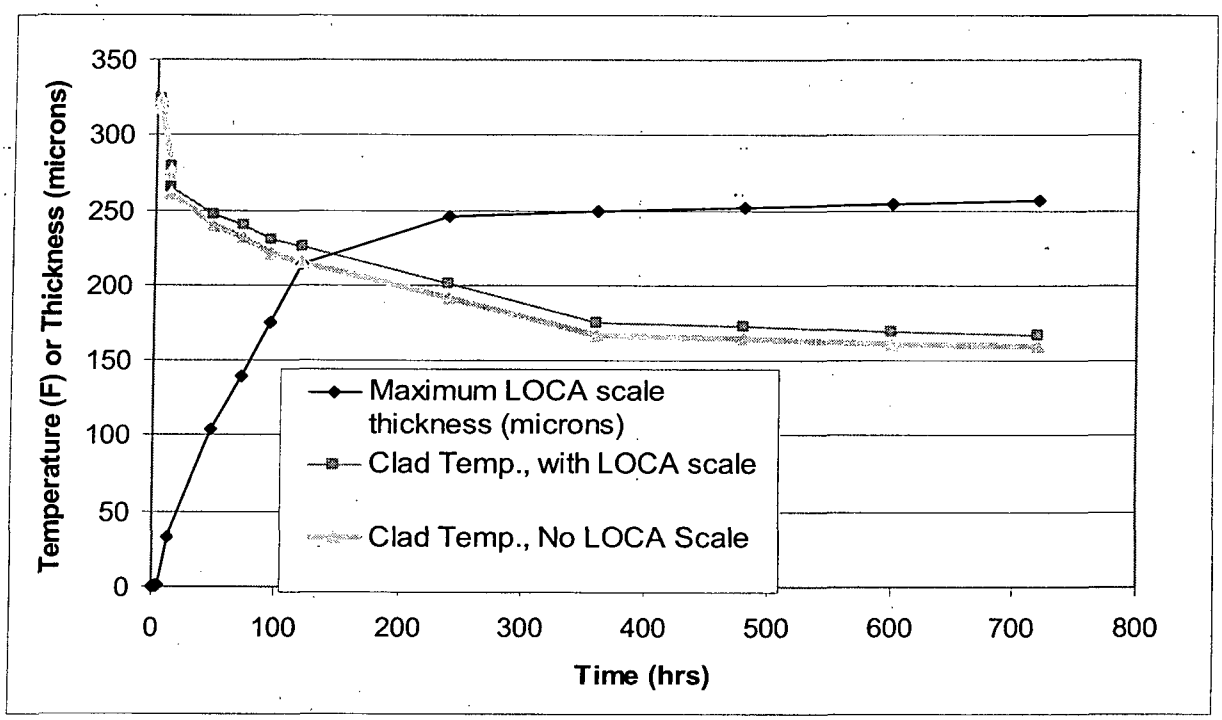
RESPONSE TO RAI #9

Containment materials in non-core locations (in the sump, sump screen, in spray...) release corrosion products into solution at rates determined by the WCAP-16530-NP model. The model takes into account initial amounts of each containment material, temperature, pH, and the concentration of materials released into solution. For the WCAP-16793 LOCADM calculations, it is assumed that once the corrosion products are released, they can only deposit in the core. To establish a high degree of conservatism, no deposition on ex-core surfaces such as the sump screen is allowed. The loss of material to core deposits will increase dissolution of debris outside the reactor, since solution concentrations are lowered.

RAI #10

Page 5-9 - In Figure 5-3, please show what the fuel cladding temperature profile would look like for a case with no debris contamination at the fuel surface?

RESPONSE TO RAI #10



The fuel cladding temperature with no LOCA scale has been plotted above. Other parameters such as core power, initial crud thickness, etc., were the same as in the original WCAP example.

RAI #11

Page 5-9 - Model predictions generally have a confidence level associated with the "calculated" value. The figure here identifies a "maximum" scale thickness. How is this maximum value calculated and does it represent a 50%, 95% or some other confidence level?

RESPONSE TO RAI #11

The scale thickness varies throughout the core and is dependent on the local heat flux and boiling. The maximum scale thickness at each point in time was determined by surveying the thickness predicted at every location, and selecting the largest value.

The confidence interval was not calculated for the maximum scale thickness, but this value is bounding because of the many conservative assumptions that were made in the model. These include conservative chemical product generation rates from the WCAP-16530-NP model, the *highly* conservative assumption that chemical products are not lost on system surfaces outside the core, and the assumption that all material transported to boiling fuel surfaces will deposit.

If refinements are made in the WCAP-16530-NP model to reduce conservatisms, the LOCADM user will have to demonstrate that the results still adequately bound chemical product generation. This will ensure that the deposition calculations are also bounding.

RAI #12

Page C-6 - Please explain the basis for the assumption that the top third of the fuel rod would be covered in debris and not the bottom third. Also demonstrate how this assumption would provide a conservative estimate for (low) heat transfer.

RESPONSE TO RAI #12

The deposition model used in LOCADM assumes deposition of material on the clad is by boiling (page 5-5, Section 5.5, first two paragraphs). For a postulated hot-leg break, all of the coolant flow provided by the emergency core cooling system (ECCS) flows through the core. This flow is in excess of that needed to remove decay heat. For a postulated cold leg break, coolant flow into the core is limited to make-up of boiloff. This limited flow provides for more of the core to be in a boiling heat transfer regime that for a postulated hot-leg break. Thus, for the deposition model assumed by LOCADM, a postulated cold-leg break is the bounding break as it provides for the maximum amount of core to be in boiling and subject to precipitant deposition.

The basis for the assumption that the top one-third of the core is boiling at the time of initiation of recirculation from the containment sump for a postulated cold-leg break is the WCOBRA/TRAC calculations described in Appendix B of WCAP-16793-NP. This assumption is applicable to all PWRs that provide recirculation flow from the bottom of the core.

Consistent with the assumption in the LOCADM code, deposition of material on the clad is by boiling (page 5-5, Section 5.5, first two paragraphs). This is conservative as all deposition was then assumed on only one-third of the cladding. This assumption minimizes the cladding area for deposition which, in turn, maximizes the deposition thickness. The maximization of deposition thickness provides for the calculation of conservatively high clad temperatures.

This deposition assumption, used in concert with the portion of the core calculated to be in boiling from the calculation described in Appendix B, provide for a conservative calculation of cladding temperature. The power shape for the calculation described in Appendix B is skewed to the top of the core (see Figure B-1 of WCAP-16793-NP) which

provides for a relatively high total peak factor ($F_Q = 2.3$). The skewed power shape provides for a conservatively large heat flux along the length of fuel cladding where boiling and deposition is occurring.

Thus, the application of a maximum material deposition, coupled with a maximum fuel rod heat flux, provides for a conservative clad temperature evaluation.

RAI #13

Page C-6 - For modeling purposes it has been assumed that the debris that reaches the fuel rod is evenly distributed over the entire surface. The more likely scenario is that deposits will build up on one spot and continue to grow in the vicinity of the original deposition. Can the modeling be modified to have a non-uniform deposit of debris on the fuel? For example, the curves in Figure C-1 are generated for uniform deposition of debris. What effect would localized debris build up have on the clad peak temperature? Specifically, how much debris would be necessary to exceed clad temperature limits or reduce effective cooling to the fuel assembly due to corrosion product blockage? Demonstrate that the uniform distribution assumption will *not* lead to *non-conservative* heat transfer conclusions.

RESPONSE TO RAI #13

The calculations shown in Appendix C are a parametric study showing a single rod. The calculations were not intended to model the deposition process, only to assess the affect of deposition on clad temperature. The conservative calculation of deposition is performed by the LOCADM calculation aid described in Appendix E. The LOCADM calculation aid accounts for different local rates of deposition based on the local boiling rate and calculates a resulting cladding temperature based on the local chemical deposition on cladding surface. The LOCADM calculations may be performed on a plant-specific basis to account for plant-specific conditions.

However, the affect of non-uniform deposition may be conservatively evaluated from the calculation results already presented in Appendix C. The calculations in Appendix C account for both radial and axial heat transfer behind a grid strap. While the calculated temperature values listed in Table C-7 can be used to evaluate a conservative temperature difference between two adjacent but different deposition thicknesses on the same fuel rod, it is suggested that a more conservative evaluation is derived from the use of the calculations listed in Appendix D. The calculations of Appendix D do not account for axial conduction and therefore allow only heat transfer in the radial direction; this maximizes the calculated clad temperature for any set of inputs used for the calculation. Thus the affect on non-uniform deposition may be conservatively evaluated without modifying the model presented in Appendix C or Appendix D.

For example, assuming a deposition thermal conductivity of 0.1 Btu/(hr-ft-°F), and assuming a deposition thickness of 10 mils, Table D-1 lists a clad temperature of 336°F. For the same conditions, and assuming a deposition thickness of 30 mils Table D-1 lists a clad temperature of 453°F. Thus, assuming a step-change in deposition thickness from 10 mils to 30 mils on a fuel rod, accounting for only radial heat transfer and ignoring axial conduction in the fuel rod, a maximum axial temperature gradient of (453°F - 336°F) or 117°F is conservatively evaluated. This evaluation may be repeated for any of the deposition thicknesses listed in Table D-1.

Thus, a non-uniform deposition due to localized buildup will result in an increase in clad temperature compared to an adjacent location with less deposition.

However, extrapolating the conservative calculated clad temperatures summarized in Table D-1 for a deposition on the fuel cladding having a thermal conductivity of 0.1 Btu/(hr-ft-°F), it is estimated that a deposition thickness in excess of 90 mils would be needed to reach or exceed the 800°F acceptance basis value identified in Section 3 and Appendix A of WCAP-16793-NP.

Thus, the uniform distribution of deposition assumption provides for conservative heat transfer conclusions (it does not lead to non-conservative heat transfer conclusions).

RAI #14

Page C-6 - Show why insulation does not become incorporated into the debris covering the fuel rods. If the debris is insulation based, what would be a realistic heat transfer coefficient for this material? Please provide a reference or technical basis for this value.

RESPONE TO RAI #14

The response to this RAI is similar to the response to RAI #4 of this set of RAIs.

From the test observations and data presented in the response to RAI #2 from the first set of RAIs, most of the fibrous debris is captured at the core entrance. Thus, there is only a small amount of fiber that is passed by the support grids at the core entrance and therefore only a small amount of fiber to collect downstream of the core entrance on the cladding surface.

If debris is insulation based, it would have negligible affect on the removal of decay heat from the fuel for the following reasons;

- If the fiber forms a bed, WCAP-16793-NP states that fibrous material on fuel structures with at least a porosity of 40%.
    - Being porous, there would be fluid movement though the fiber bed. This is demonstrated by the data included in the response to RAI #2.
    - The movement of fluid through the porous bed will remove heat from the cladding surface by convection.
- From the response to RAI #15 from the first set of RAI responses;
    - The thermal conductivity of a fibrous bed is realistically calculated to be about 0.59 Btu/(hr-ft-°F).
    - The thermal conductivity of a fibrous bed is conservatively represented as being 0.1 Btu/(hr-ft-°F). This is the same value used to conservatively simulate the thermal conductivity of chemical precipitants on cladding surfaces.
    - The thermal conductivity through glass is about 0.59 Btu/(hr-ft-°F). Explicitly accounting for fiberglass debris in the surface deposition would enhance heat transfer from the cladding.
    - As noted above, accounting for only conductive heat transfer through a fiber bed conservatively neglects convective heat transfer thorough the porous bed.

Also from the response to RAI #15 from the first set of RAIs, the thermal conductivity of fibrous insulation (not individual fibers, but intact fibrous insulation) is a function of the moisture content in the insulation. In the case where the insulation contacts a boiling surface, such as a fuel rod, it is a function of both the moisture and steam content. A literature search was performed to support the calculation presented above. Reference 14-1 states that the dry thermal conductivity of fiberglass insulation of 0.05 BTU/(hr-ft-°F) doubles (to 0.1 BTU/ft h °F) with only eight percent of its volume filled with water. Reference 14-2 shows that when a mixture of steam and liquid are present, the thermal conductivity will increase by a factor of approximately 12 when the liquid and steam are present in equal amounts in a porous medium. These references support the value of minimum effective thermal conductivity of to 0.1 BTU/(hr-ft-°F), and suggest that a thermal conductivity at least as large as 0.6 BTU/(hr-ft-°F) may be used for fibrous debris incorporated into debris that might cover the fuel rods. Thus, based on the information presented above, the WCAP-16793-NP value of 0.1 BTU/(hr-ft-°F) is an appropriately conservative choice for representing a lower bound thermal conductivity for fibrous insulation that may become incorporated into debris covering fuel rods.

Thus, if debris is insulation based, it would have negligible affect on the removal of decay heat from the fuel.

REFERENCES FOR RAI #14 RESPONSE:

14-1 "Joint Departments of the Army and Air Force, USA, Technical Manual TM 5-852-5/AFR 88-19, Vol. 5, Arctic and Sub-arctic Construction: Utilities." Chapter 12

14-2 Ho-Jeen Su and Wilbur Somerton, "Thermal Behavior of Fluid Saturated Porous Media with Phase Changes" Proceedings of the 16th International Thermal Conductivity Conference, November 7-9 Chicago, Published by Plenum Press, New York, page 193-204

RAI #15

Page C-7 - Regarding Table C-7, identify the change in solubility of sodium aluminosilicate, aluminum hydroxide, and calcium silicate at these temperatures. These compounds and other zeolites that may form have retrograde solubility. What is the rate of build up of these compounds on the fuel clad surface?

RESPONSE TO RAI #15

The calculations presented in Appendix C are a parametric study of the affect of deposition thickness on calculated clad surface temperature behind fuel grids. The sole purpose of the calculations is to parametrically evaluate clad temperature as a function of deposition thickness and deposition thermal conductivity. The calculations did not model, nor did they account for, either the rate of build-up or the solubility of materials (sodium aluminosilicate, aluminum hydroxide, and calcium silicate) or the solubility or change in solubility of these compounds. However, the minimum thermal conductivity used in these calculations, 0.1 Btu/(hr-ft-°F) bounds the thermal conductivity associated with deposition of these compounds. Therefore, the calculation results summarized in Appendices C and D apply to the deposition of these materials on cladding surfaces for the thicknesses considered in the calculations.

The identification and solubility behavior of chemical compounds is discussed in Section 5, "Chemical Precipitation and Subsequent Impact," Appendix E which has the same title as Section 5, and Appendix F, "Supporting Solubility and Precipitation Calculations." The calculations presented in Appendix F support the calculations in Appendix E, including identification of predominant chemical species.

The calculation of deposition rates and total deposition of chemical products on cladding, and the affect of that deposition on cladding temperature, is calculated using the LOCADM tool described in Section 5 and Appendix E. These are plant-specific calculations that use plant-specific inputs to evaluate the chemical products generated and the rate of deposition of those products.

RAI #16

Page D-2 - Deposition of the thickest crud layers on fuel surfaces occurs on the top third of the fuel assemblies. Therefore it seems likely that the heat conduction in the axial direction downward could be significant since there would be decreased cooling water flow.

A) Describe how axial heat conduction would affect the temperature profile calculated assuming radial heat conduction only; which case provides a conservative bound?

B) Demonstrate that the assumption made here represents the most conservative case for build up of precipitates in all interstitial sections of the fuel assembly including the top third.

RESPONSE TO RAI #16

A) The response to this RAI is similar to the response to RAI #13, which also questions the effect of axial conduction on clad temperature. As stated in the response to RAI #13, accounting for axial heat conduction would attenuate (reduce) the calculated clad surface temperatures, particularly near the interface of the clad surface with no deposition and the clad surface with deposition. As the objective of the calculations summarized in Appendix D was to provide conservative and bounding cladding temperatures, neglecting axial conduction in the fuel rod cladding provides for the calculation of maximum clad temperatures. These calculations are conservative and bound all plants.

B) The calculations presented in Appendix D are a parametric study of clad temperature versus deposition thickness on a fuel rod between grids. The conservatism associated with assuming deposition on only the top 1/3 of the fuel is described in the response to RAI #12. The evaluation of precipitates, the rate of deposition and the total deposition of those precipitates is beyond the scope of this parametric study. The identification and conservative treatment of chemical compounds deposited on cladding surfaces is discussed in WCAP-16793-NP in Section 5, "Chemical Precipitation and Subsequent Impact," and Appendix E which has the same title as Section 5.

The rate of deposition and the total deposition of chemical products on cladding, and the consequential effect of that deposition on cladding temperature, is conservatively calculated using the LOCADM calculation aid described in Section 5 and Appendix E of WCAP-16793-NP. These are plant-specific calculations that use plant-specific inputs to assess chemical products produced and deposition rates based on plant-specific parameters.

RAI #17

Page D-4 - Can you describe what this term "contact resistance" between material layers means and why it represents a conservative assumption for these calculations?

RESPONSE TO RAI #17

The term 'contact resistance' refers to the resistance to the transmission of heat across the boundary of two adjacent solids. This resistance to heat flow is due to gases or vacant spaces between the two solids. A discussion of contact resistance and contact coefficients is given on page 17 of the text, "Heat Transmission," by Wm. H. McAdams, McGraw-Hill Book Company (1954).

The development of the oxide layer and the deposition of the crud layer on the oxide, both which occur at power operations, are gradual and occur over time. The oxide provides nucleation sides for the deposition of the crud and the crud adheres to the outer oxide layer. The thermal conductivity of both the clad oxide layer and the crud already account for the morphology of their formation, including gases or vacant spaces. Since the crud adheres to the outer clad oxide layer by attaching itself to surface irregularities in the oxide layer, including additional surface resistance was evaluated to not be appropriate during long-term core cooling operation.

Similarly, the deposition of the chemical layer on the crud surface is also gradual and occurs over time. The chemical product deposition on and adhesion to the surface of the crud layer is evaluated to be similar to that of the crud onto the clad oxide layer. Considering that a conservatively small thermal conductivity value for the chemical deposition of 0.1 Btu/(hr-ft-°F) is used for the parametric study, the use of a contact resistance is evaluated to be both inappropriate and overly conservative..

RAI #18

Page D-6 - The calculations presented here represent the instantaneous clad surface temperature maxima at 20 minutes into the accident. Although the Fuel Centerline Temperature (FCT) and Clad Surface temperatures will decrease with time after this point, the precipitate masses and thicknesses will continue to increase. Please demonstrate:

a) What the buildup of precipitate thickness will be over the next 30 days?

b) How the build up of the precipitates over 30 days affects the fuel clad surface temperature during this time?

RESPONSE TO RAI #18

A) The calculations presented in Appendix D are a parametric study of the affect of deposition thickness on calculated clad surface temperature between fuel grids. The sole purpose of the calculations in Appendix D is to parametrically evaluate maximum clad temperature as a function of a specific deposition thickness and deposition thermal conductivity; not to calculate the time rate of deposition of chemical products on cladding surface. As the purpose of the calculations was to evaluate maximum clad temperatures, not rate of chemical deposition, the calculations of Appendix D did not evaluate lower decay heat rates at various chemical product deposition thicknesses.

   The deposition rate and total deposition of chemical products on cladding is conservatively calculated using the LOCADM tool described in Section 5 and Appendix E of WCAP-16793-NP. This calculation is a plant-specific calculation that uses plant inputs to determine the chemical products formed and calculate the rate of deposition and total chemical deposition. The sample calculation in given in Appendix E provides an example of the precipitant thickness over a 30-day period.

B) As noted in the response to item (A) above, the deposition rate and the total deposition of chemical products on cladding over time are conservatively calculated using the LOCADM tool described in Section 5 and Appendix E of WCAP-16793-NP. The LOCADM code also calculates cladding temperature associated with the calculated deposition over the 30 day time period of interest. This calculation is a plant-specific calculation that uses plant inputs to calculate the clad temperature during the 30-day time period of interest, based on plant-specific rate of deposition and total chemical deposition.

RAI #19

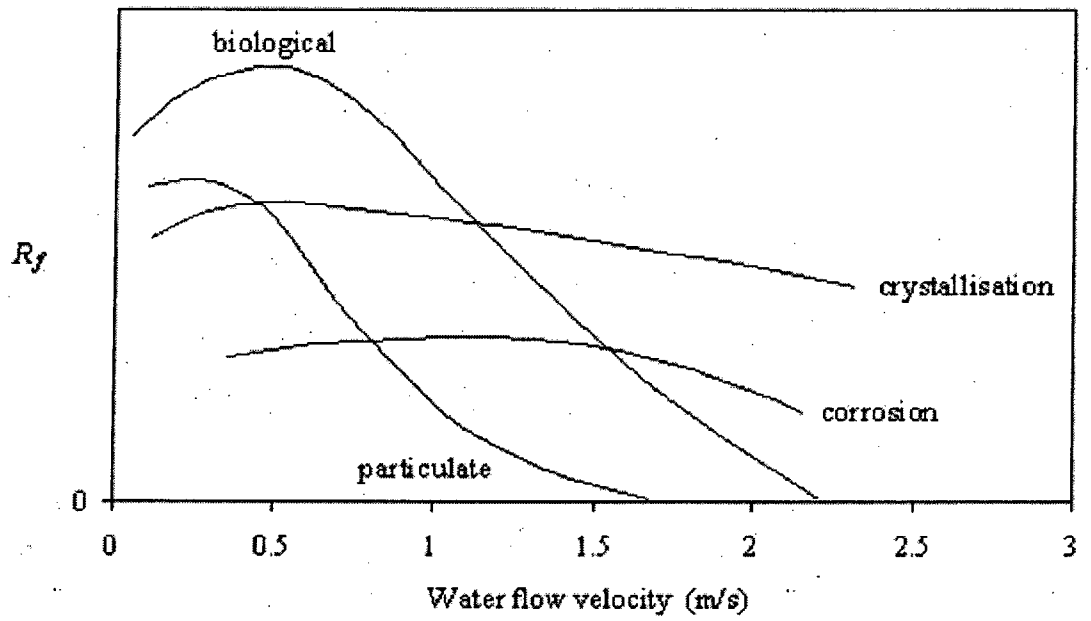
Page E-3 - Can it be shown that precipitate deposition on the residual heat removal heat exchanger surfaces will not lead to reduced flow and heat transfer such that the maximum fuel clad temperature assumption of 800 ^{0}F will not be exceeded? The topical report indicates that all debris and precipitate is transferred to the vessel. Please demonstrate that a drop in the heat exchanger flow is not a more conservative assumption based on reduced heat exchanger cooling capability.

RESPONSE TO RAI #19

It is possible that some debris material will be retained on RHR surfaces, either by the mechanism of particle deposition or by crystallization of solids having a "normal" solubility curve, i.e., one in which the solubility increases with temperature. However, it is not expected that such material will foul the RHR heat exchangers beyond the fouling margins that are already maintained to assure Appendix R cool-down requirements are met.

The precipitates and deposits that have formed upon cool-down in the WCAP 16530-NP testing and in subsequent integrated tests at Westinghouse STD have never formed hard deposits on the cooled surfaces which were available. Precipitates had no strength such would be required to block an RHR heat exchanger. When deposits formed on cooler surfaces, they could be easily removed with a paper towel or soft cloth. Flow rates through the RHR heat exchangers

will be high, 2.5 to 5 ft/second or about 1 meter per second. This flow will keep the thickness of such weak deposits to a minimum, since in general, high flow rates minimize particulate deposition (Ref. 19-1). The generalized effect of flow on particulate deposition is shown in the plot below.



The effect of water flow velocity on particulate deposition (from reference 19-1)

Another factor minimizing the chance of flow blockage by deposits is that the RHR pumps can generate a high pressure differential (>300 psi) to remove an obstruction in the unlikely event that one forms.

Another factor the argues against RHR system heat exchanger fouling problems is the short period of time over which the RHR system must operate near peak capacity (a few days). When similar heat exchanger have been run with a highly flawed chemistry which favored deposition of concentrated coolant chemicals (calcium > 300 ppm and alkalinity > 100 ppm), losses in thermal performance of 16% per year were observed (Ref.19-2). This data has been provided in an attached file.

REFERENCES FOR RAI #19 RESPONSE:

19-1 S. Pugh, G. F. Hewitt and H. Muller-Steinhagen, "Fouling during the Use of Seawater as Coolant - The Development of a 'User Guide', Paper 3", 2003 ECI Conference on Heat Exchanger Fouling and Cleaning: Fundamentals and Applications, Santa Fe, New Mexico

19-2 Loss of Thermal Performance of the Essential Cooling Water (EW) and Emergency Diesel Generator (EDG) Intercooler Heat Exchangers, Palo Verde Report CRDR 2897810, May, 2006

RAI #20

Page E-3

A) Do any of these assumptions account for increase of deposit mass based on incorporation of boric acid into the deposited material?

B) Do these calculations include 10% by weight of the boric acid in the precipitate?

C) Are waters of hydration included in these calculations? If not, please describe the effects of including waters of hydration?

RESPONSE TO RAI #20

The calculations assume an increase in deposit volume (or indirectly, mass) during precipitation due to the incorporation of species such as the waters of hydration or boric acid. However, specific compounds are not assumed. This is done by specifying a deposit density that is sufficiently low to bound possible hydrates and adsorbed species. For instance, for calcium silicate, LOCADM calculates a thickness that is more than three times the amount that would be calculated assuming the theoretical density of 180 lbs/ft^3 for calcium silicate (Ref. 20-1). This 3X margin is sufficient to account for waters of hydration, boron adsorption, and porosity.

REFERENCE FOR RAI #20 RESPONSE:

20-1 CRC Handbook of Chemistry and Physics, 55th addition (CRC Press, Cleveland Ohio) 1975, p. B79 entry c178 for alpha calcium metasilicate

RAI #21

Page E-7 - Should there be parentheses around the term (m_x/m_T)?

RESPONSE TO RAI #21

Yes. The parentheses would clarify the order of operation.

RAI #22

Page E-7 - Should there by parentheses around the terms (C_x*Flowrate*dt)?

RESPONSE TO RAI #22

Yes. The parentheses would clarify the order of operation.

RAI #23

Page E-7 - Does the value for h_{fg} only consider the enthalpy of dissolved boric acid or does it include all other dissolved species as well?

RESPONSE TO RAI #23

The standard enthalpy of vaporization for water was used in the LOCADM code. A formula was used to calculate this value as a function of temperature. The function produces a value near 2250 kJ/kg near 212°F. The standard enthalpy of vaporization for water is a good approximation except for the most concentrated boric acid solution, and then the water value will produce conservative results (more steaming that actual).

RAI #24

Page F-3 - Please demonstrate how the calculations performed here provide the appropriate values for solubility. Specifically:

A) The value of 0.69 ppm is unrealistic for lithium concentration - what happens when this is reduced to 0.2 or less?

B) Calculate the solubilities when aluminum is 100 ppm at fuel temperature of 260 F.

C) Calculate the solubilities when the expected concentrations of hydrogen and oxygen that result from radiolysis exist.

RESPONSE TO RAI #24

A) The lithium concentration was entered for completeness. However, the lithium has very little impact on the solution pH and does not significantly affect speciation at such a low concentration. The concentration of sodium is significantly higher and dominates the solution pH and speciation. Therefore, a reduction in the assumed lithium concentration would have a negligible impact on the calculation results.

B) If an aluminum concentration of 100 ppm was equilibrated at the fuel temperature of 260 F, the OLI StreamAnalyzer™ code predicts that AlO(OH) would precipitate. However, the calculations in Appendix F were performed to verify the chemical deposition model developed in Appendix E. The Appendix E calculation conservatively assumes that all precipitation occurs in the core region. Since the Appendix E calculation will be used by the licensees to evaluate the chemical effects of debris on the core region, evaluating aluminum concentrations of 100 ppm at 260 °F is unnecessary.

C) The Appendix F calculation includes representative concentrations for oxygen and hydrogen in the sump liquid. The oxygen and hydrogen are allowed to partition between the liquid and vapor phases as appropriate. Changes in the Oxidation-Reduction Potential (ORP) of the solution, either by oxygen and hydrogen from radiolysis or through other potential radiolysis products (hydrogen peroxide or nitrate), could slightly decrease the solubility of some of the predicted precipitates. However, because the LOCADM calculation (Appendix E) already assumes 100% precipitation of all solutes present in the liquid that is evaporated, there would be no change in the final LOCADM results.

RAI #25

Page E-11 - Section E.7 describes thermodynamic predictions for chemical compounds that would deposit on the fuel. Results are included from Westinghouse thermodynamic predictions and from thermodynamic equilibrium code calculations performed by AREVA NP. The NRC staff has a number of questions related to these thermodynamic predictions:

What is the basis for the Westinghouse thermodynamic predictions?

How are the AREVA and Westinghouse predictions integrated to model the quantity and compounds that form in the vessel? If only one is used indicate why it is more conservative than the other.

Does the model account for the change of $Ca(BO_3)_2$ to CaB_2O_5 when the precipitate is in contact with the fuel surface above 180 ^{0}F?

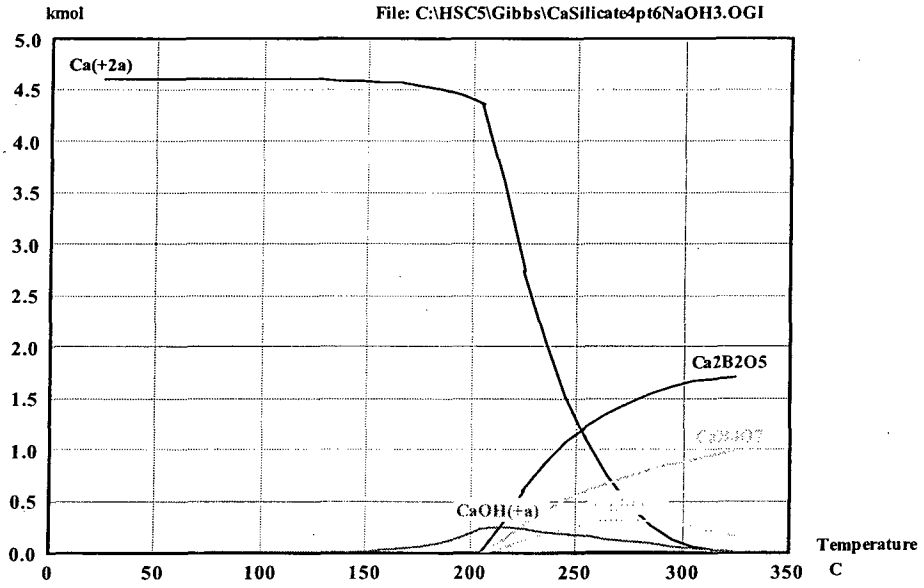
RESPONSE TO RAI #25

The Westinghouse thermodynamic predictions were done using HSC, a thermochemical modeling program from Outokomptu, Inc. Species expected to be in the sump liquid were input into the program which calculated the most stable species using a Gibbs free energy minimization routine. A parameter such as temperature or the amount of sodium hydroxide (pH) was changed, and any changes in solution species or the formation of solid phases was noted. An example is shown below, where the effect of an increase in temperature on dissolved CalSil was explored:

Input species:

Species	Input Amount (kmol)	Species	Input Amount (kmol)
H2O	116640	SiO2(a)	0
BO2(-a)	0	SiO4(-4a)	0
B(OH)3(a)	0	Si(OH)4(a)	0
B(OH)4(-a)	0	Si(OH)3(-a)	0
Ca(+2a)	0	SiO2(OH)2(-2a)	0
Ca(HSiO3)(+a)	0	SiO3(OH)(-3a)	0
CaOH(+a)	0	B2O3	0
H2(a)	0	CaB4O7	0
H(+a)	0.000001	Ca2B2O5	0
H3BO3(a)	0	CaO	0
H2BO3(-a)	0	Ca(OH)2	0
H2SiO3(a)	0	*2CaO*SiO2	0
H4SiO4(a)	0	*3CaO*SiO2	0
HSiO3(-a)	0	*3CaO*2SiO2	0
H2Si(OH)6(a)	0	CaSiO3	4.6
Na(+a)	0	H3BO3	485.5
NaHSiO3(a)	0	Na2B4O7	0
O2(a)	0	Na2B4O7*10H2O	0
OH(-a)	0.000001	NaOH	3
		Na2O*2SiO2	0
		Na2SiO3	0
		SiO2(Q)	0

Results: Equilibrium species at different temperatures



Note that CaB_2O_5 is not predicted, but rather $Ca_2B_2O_5$.

The results of the thermodynamic modeling were not integrated into the LOCADM model even though the original intent was to limit deposition based on solubility. The HSC program and the OLI program used by AREVA produced different results and it was concluded that including solubility calculations in deposition predictions would add too much uncertainty to the LOCADM model if either was used in the calculations. Instead, the Westinghouse and AREVA calculations were simply used as guides when selecting deposit densities. Further the StreamAnalyzer OLI predictions were only used to confirm the conservatism of the LOCADM calculations. The OLI StreamAnalyzer was used for the "quantitative" predictions of Appendix F simply because of ease of use and because the predictions for sodium aluminum silicate were more consistent with the WCAP-16530-NP testing. Since results predicted with LOCADM have been confirmed to be conservative, plant specific analyses using either the HSC or OLI StreamAnalyzer software is not planned and is unnecessary.

RAI #26

Page E-14 - Reference E-18 refers to the scale build up and thermal conductivity in a desalination unit. Please provide the reference and show how the thermal conductivity of scale and insulation on the fuel would be comparable to that in the desalination unit.

RESPONSE TO RAI #26

Reference E-18 is available in open literature. This work is relevant to core deposition after a LOCA in the following respects:

1. Deposits were calcium-rich as would be the case for post-LOCA deposits on the core at many plants
2. The deposits were formed under boiling conditions.

When selecting a limiting thermal conductivity, a variety of literature sources covering other types of deposits were scanned to select a limiting value for LOCADM. (0.1 btu $°F^{-1}$ ft^{-1} hr^{-1})

RAI #27

Page F-2 - The OLI StreamAnalyzer™ thermodynamic code data bank most probably does not include data from concentrated borated water environments. Therefore, justify why the thermodynamic equilibrium code predictions are reliable for use when modeling a concentrated boron environment in the reactor vessel following a postulated loss-of-coolant-accident (LOCA).

RESPONSE TO RAI #27

The current OLI StreamAnalyzer™ database contains thermodynamic information on twenty-two boron species, including various polyborates and borates of calcium, lithium, and sodium. These data were derived, in part, from published solubility data of sodium and boron species over a range of temperatures and pressures (Ref. 27-1 and 27-2). The code utilizes activity models for the aqueous phase (Bromley-Zematis) and the vapor phase (Soave-Redlich-Kwong) to adjust the equilibrium calculations based on compositional effects, allowing predictions for complex mixed-chemistry environments over a wide range of solute concentrations.

Appendix F was utilized to provide verification of the LOCADM model. It was specifically used to identify the most likely precipitate species and to verify the assumption that 100% of the dissolved species are available for precipitation due to boiling in the core (i.e., negligibly low solubility under core conditions). The StreamAnalyzer™ database and calculation framework are sufficiently reliable for the intended purpose.

The Appendix F calculations verified that the assumption of 100% precipitation, while conservative, is reasonable. In addition, the Appendix F results identified additional precipitation species for consideration when selecting the deposit density and thermal conductivity values used in the LOCADM code. While the OLI database does not include all possible species available for precipitation, it includes a large number of species from the relevant categories (i.e., oxides, hydroxides, aluminum-containing silicates, non-aluminum-containing silicates, and borates). It is unlikely that a precipitated species, not included in the thermodynamic database, would have density and conductivity characteristics significantly different from the conservative values utilized in the LOCADM model.

REFERENCES FOR RAI #27 RESPONSE:

27-1 W.C. Blasdale and C.M. Slansky, "The Solubility Curves of Boric Acid and the Borates of Sodium," J. Am. Chem. Soc. 1939, 61, 917-24.

27-2 N.P. Nies and R.W. Hulbert, "Solubility Isotherms in the System Sodium Oxide-Boric Oxide-Water, Revised Solubility-Temperature Curves of Boric Acid, Borax, Sodium Pentaborate, and Sodium Metaborate," J. Chem. Eng. Data 1967, 12(3), 303-313.

RAI #28

Page F-3 - Table F-1 provides an input summary for solubility calculations that are intended to be reasonably representative of the expected post-LOCA conditions and not bounding of all plants and scenarios. Was a parametric study performed to evaluate conditions other than the four results summarized in Table F-1? For example, were sensitivity studies performed to assess effects of pH, temperature, and elemental concentrations?

RESPONSE TO RAI #28

Appendix F is not an independent calculation of core precipitation, nor is it intended as an alternative method to Appendix E. Rather, Appendix F is a small sensitivity study intended to verify key assumptions / inputs of Appendix E with regards to solubility and precipitate form. The four cases analyzed include reasonably representative extremes of temperature, solute concentration, and pH (as a function of buffering media) expected for a post-LOCA environment. No scenarios in addition to those reported were calculated. However, because the LOCADM

calculation (Appendix E) assumes 100% precipitation of all solutes present in the liquid that is evaporated, and because LOCADM uses conservative values for deposit density and conductivity to bound a range of potential precipitates, there would be no change in the final LOCADM results.

RAI #29

Page F-4 - Thermodynamic software results from Run 1 are presented in Section F.5.1. Based on the OLI software, approximately 100% of the aluminum and 77% of the silicon in the sump are predicted to form a sodium aluminum silicate precipitate. No additional precipitation is predicted as the sump liquid is heated to core temperatures. Compare the in-vessel deposition results based on this assumption to the results that would be predicted given the same concentrations but assuming no sodium aluminum precipitate formed in the sump.

RESPONSE TO RAI #29

If sodium aluminum silicate precipitation in the sump were excluded from consideration, the equivalent mass would be expected to precipitate in the core. However, the LOCADM model (Appendix E) already assumes that all solute species are available for deposition in the core, and deposition in the sump is excluded. Therefore, changes in the Appendix F assumptions, as described in the question, would not impact the LOCADM results.

RAI #30

Page F-5, Section F.5.3 – There appears to be an assumption here that any silica specie in the RCS will be present at the starting point as SiO_2. The predominant form of silica in the RCS (RWST and the spent fuel pool) is reactive silica and not SiO_2.

A) Does the model assume that SiO_2 precipitates without starting out as $H2SiO_4^{2-}$?

B) How does the presence of silica as $H2SiO_4^{2-}$ or as $H3SiO_4^{1-}$ affect the potential precipitation of other species such as calcium silicate or sodium aluminum silicate?

C) Even if SiO_2 were to precipitate it would likely be transformed into $H2SiO_4^{2-}$ rather rapidly. How does this change the predictions of the model?

RESPONSE TO RAI #30

A) No. The neutral species (which OLI calls the Apparent Molecular Species) were listed for simplicity. However, the actual aqueous, solid, and vapor phase compositions are determined based on the thermodynamic calculation. In the case of silicon, aqueous speciation is primarily governed by pH. For the pH range in question, the predominant aqueous species predicted are $H_3SiO_4^{1-}$ and $H_2SiO_4^{2-}$.

B) As stated in the response to Part A, the predominant aqueous species predicted are $H_3SiO_4^{1-}$ and $H_2SiO_4^{2-}$; therefore, the effect of these species is already included in the calculation results. It should be noted that SiO_2 (trigonal form) is predicted to form only in Case 3. For this case, the low in-core pH during boil-off, which results from the use of NaTB rather than NaOH for pH adjustment, prevents the precipitation of calcium silicate, calcium borate, or sodium silicate. Sodium aluminum silicate is not predicted to deposit due to the precipitation of essentially all of the aluminum in the sump. It should be noted, however, that the final LOCADM model does not consider sump precipitation; all deposition is assumed to occur in core.

C) As previously discussed, the presence of $H_3SiO_4^{1-}$ and $H_2SiO_4^{2-}$ are included in the model. Additionally, laboratory analyses of crud taken from operating fuel assemblies have shown the presence of silicon in the absence of significant quantities of sodium, calcium, aluminum, or magnesium. Therefore, it must be concluded

that SiO_2 is stable under reactor conditions, even in the presence of operational radiation fluxes. Finally, the LOCADM model utilizes conservative values of deposit density and thermal conductivity to bound a range of expected precipitates. Therefore, the exact structural form of silica; whether trigonal, amorphous, or partially-substituted metal silicates; is not critical to the results of the LOCADM model.