ENCLOSURE 2

BWROG-13032

Responses to Supplemental RAIs Associated with LTR NEDC-33608P, "Boiling Water Reactor Emergency Core Cooling Suction Strainer In-Vessel Downstream Effects"

Non-Proprietary Information - Class I (Public)

IMPORTANT NOTICE

This is a non-proprietary version of Enclosure 1 to BWROG-13032, from which the proprietary information has been removed. Portions of the enclosure that have been removed are indicated by open and closed double square brackets as shown here [[ ]].

REQUEST FOR ADDITIONAL INFORMATION
BY THE OFFICE OF NUCLEAR REACTOR REGULATION
NEDC-33608P, REVISION 2, "BOILING WATER REACTOR
EMERGENCY CORE COOLING SUCTION STRAINER
IN-VESSEL DOWNSTREAM EFFECTS"
BOILING WATER REACTOR OWNERS' GROUP
PROJECT NO. 691

Request for Additional Information 1 Supplement 1 (RAI 1 S1):

Based on the information presented in response to RAI 1, the U.S. Nuclear Regulatory Commission (NRC) staff could not confirm the original reference analysis is bounding for all operating boiling water reactors (BWRs). Therefore, please address the following requests:

(a) *Please include the supplemental analysis cases in Attachment A of the second RAI response in the topical report's (TR's) reference analysis since some of these scenarios define conditions that are not bounded by the original reference analysis.*

Response:

The supplemental RAI analyses will be added as an appendix to the licensing topical report (LTR) with additional case specific information to facilitate the Staff's review. The significance of the [[ ]] acceptance criteria is to maintain the secondary peak temperature within the same bases as the peak cladding temperature (PCT) from the early dryout and core uncovery. The [[ ]] is not regarded as a limit, as the actual fuel integrity evaluation with a bounding temperature is given in Supplemental RAI 7. However, this temperature shows the consequences of the reference blockage case from the assumed worst case blockage history. It is true that some of the supplementary cases show higher temperatures than the reference case in the LTR; however, it is noted that those cases represent blockage of the bypass region flow into the lower plenum, which is regarded as highly conservative, because of the large flow path and the small flow under long-term conditions. Finally, GE Hitachi Nuclear Energy (GEH) would like to note that no core spray long-term boundary condition (which is no longer applicable) with similar fuel temperatures was documented in the original 10 Code of Federal Regulations (CFR) 50.46 loss-of-coolant accident (LOCA) LTR (NEDE-20566P-A Volume 2, Section 5: 'Long Term Cooling') in Figure 7 on page III-30, and the US NRC accepted those consequences as meeting the requirements.

(b) *Please justify that the generic reference analysis in the TR that is used as a basis for the methodology for calculating plant-specific values of the pre-quench peak cladding temperature (PCT) is bounding and consistent with regulations in response to the following items:*

i. *Relative to the requirements of Title 10 of the Code of Federal Regulations (10 CFR) 50.46, please clarify the statement in Section 3.1 of the TR that the nominal analysis "is selected consistent with licensing procedures that avoid distorted or masked sensitivities that could result from the use of bounding conservative inputs and correlations."*

ii. *Please confirm that the pre-quench heatup rates used in the reference analysis (including the supplemental analysis cases) are bounding for all operating BWRs current analyses, or else commit to using the plant-specific heatup rates in existing licensing analyses for assessing the impact of increases to licensing basis PCTs due to invessel debris blockage delaying quenching of the fuel.*

Response:

i. This statement in the LTR clarifies that the evaluation in support of the blockage consequences follows the standard LOCA licensing process in identifying the limiting break and emergency core cooling system (ECCS) failure calculation basis. Once the limiting conditions are established, an appropriate PCT adder based on both the 10 CFR 50.46 and model uncertainties is applied to establish the licensing basis PCT.

ii. Pre-quench heatup rates, when used for determining the effect on PCT from delayed reflood time, must bound the specific plant application. The BWR Owners' Group (BWROG) no longer proposes an acceptance criterion for Tests 1 and 2 but rather will determine blockage consequences and justification in the test results report.

(c) *Although the selection of certain reference analysis parameters may bound a number of BWRs, the TR and RAI responses do not provide adequate basis for the NRC staff to conclude that the generic reference analysis (including the supplemental analysis cases) is bounding for all operating BWRs for assessing the potential for long-term heatup of the fuel cladding due to debris blockage. Specifically, the TR asserts that the reference analysis may be considered bounding based on consideration of (1) [[ ]] and (2) [[ ]]. However, it is not clear that [[ ]] is strongly correlated with long-term heatup, since some key factors that drive the former, such as pipe diameters and emergency core cooling system (ECCS) pump start times and maximum flows, may have little or no impact on the latter. Furthermore, there is no basis to conclude that [[ ]] is the only other parameter needed to rank BWRs in terms of the potential for long-term cladding heatup. Rather, the potential for long-term heatup due to blockage from debris generated in a loss-of-coolant accident (LOCA) can be a complex evaluation of interactions between a number of factors, such as fuel design parameters, bundle power, core power distributions, total core power (see RAI 42 S1), available driving head, countercurrent flow limitation (CCFL), core spray distribution, etc. Therefore, to support application of the limiting reference analysis cases to operating BWRs, please* *tabulate the key parameters influencing long-term heatup due to debris blockage, along with the reference plant parameter values that should be demonstrated to be bounding. Due to differences in BWR designs (e.g., BWR/2, BWR/4, BWR/6) that are reflected in the reference and supplemental analysis cases, two or three design-specific tables may be necessary to specify appropriate bounding parameter values for the entire BWR fleet. Please further include justification that the chosen set of key parameters is sufficient to ensure the applicability of the reference analysis to all BWRs bounded by these parameters.*

Response:

The objective of the following discussion is to justify that the important factors that influence the long-term reheat temperature have been properly selected and the jet pump (JP) BWR fleet is represented. Thus the short-term PCT does not necessarily lead to reheat bounding conditions. It is also assumed that Tests 1, 2, and 3 demonstrate insignificant debris effect on short-term PCT. The reference analysis demonstrates that adequate flow is allowed by CCFL to produce acceptable PCT consequences for a conservatively selected blockage. Furthermore, the supplementary analytical results (other breaks and plant ECCS configuration, as well as power density) also support the conclusion that the secondary reheat transient variability (see RAI 7 figure of PCT history for all cases) is well demonstrated. Thus, application of these results to different fuel designs must be separately justified both in terms of analytical PCT (same blockage basis) and blockage test results (same flow and debris test basis). However, application of these results to any specific plant, which we expect all BWRs meet, is limited to assuring that: (1) the bundle power is consistent with the evaluation and that (2) the boundary conditions are consistent to provide the cooling that the evaluations provided to the NRC staff in support of the LTR show. This conclusion is justified because the fuel type power and CCFL flow is the same for any plant application, and either minimum core spray or saturated flow from driving head is sufficient for long-term cooling. Specifically, the following parameters must be met for application of the LTR evaluation to any BWR:

(a) Initial absolute power of the LTR fuel (GE14) must be same or lower for plant applications (consistent LOCA GEH bundle power initialization procedure),

(b) The CCFL areas and coefficients must be applicable to the plant,

(c) Minimum core spray flow per bundle for long-term application must be 1.8 gpm or greater,

(d) Long-term cooling of at least one core spray with core elevation head to JP nozzle, or maintain level above top of fuel channels,

(e) Other fuel designs must be analytically demonstrated to produce equivalent or lower temperature consequences when subjected to the LTR blockage history, and

(f) Other fuel designs must be justified to produce equivalent or less blockage than test results.

RAI 3 S1:

(a) *The NRC staff's RAI 3 had requested that the BWROG address inconsistencies between Tables 4-1, 4-2, and 4-3 of the TR and information reviewed by the NRC staff in several BWRs' Final Safety Analysis Reports (FSARs). However, the response to RAI 3 did not provide the requested validation of and/or corrections to this information. Lacking this information, the NRC staff is unable to evaluate the BWROG's contention that the TR bounds all BWRs. Therefore, please provide revised tables for the NRC staff's review that accurately reflect operating BWRs' current licensing bases.*

Response:

Indeed, the requested tables have not been provided as the confirmation from the utilities was not completed. However, the BWROG proposes that in place of the limiting ECCS configuration in Table 4-3, an alternate table be used that provides the minimum and maximum per bundle average values of core spray and of low pressure coolant injection (LPCI), as given below, that can be used to validate the range of flows applied in the debris tests as described in RAI 20 S1. It is also noted that the fuel channel test boundary conditions form the basis for the test parameters, and the information in the tables support the boundary conditions described in Section 4.d for all BWRs. Therefore, because the flow range specific to each plant can be confirmed from the test reports, the application to any plant can be assured.

Table 4-3 Minimum and Maximum Average gpm per Bundle ECCS Capacity

BWR Type	Plant Name	Number of Bundles	Min Core Spray per Bundle	Max Core Spray per Bundle	Min LPCI per Bundle	Max LPCI per Bundle
2	Nine Mile Point 1	532	No Reflood Credit		Not Applicable	
2	Oyster Creek	560	No Reflood Credit		Not Applicable	
3	Dresden 2 & 3	724	6.5	13.1	11.1	17.5
3	Monticello	484	7.3	14.6	16.5	25.6
3	Quad Cities 1 & 2	724	6.5	13.1	11.1	17.5
3	Pilgrim	580	7.1	14.1	16.4	25.0
4	Browns Ferry 1, 2, & 3	764	9.3	18.6	12.7	23.6
4	Vermont Yankee	368	10.9	21.7	17.8	63.9
4	Peach Bottom 2 & 3	764	8.2	16.4	11.4	41.9
4	FitzPatrick	560	9.2	18.4	14.5	52.4
4	Cooper	548	10.2	20.5	11.4	19.5
4	Hatch 1 & 2	560	9.5	19.0	27.8	32.5
4	Brunswick 1 & 2	560	10.4	20.9	16.2	26.5
4	Duane Arnold	368	8.6	17.2	22.3	36.2
4	Fermi 2	764	9.2	18.4	29.8	37.2
4	Limerick 1 & 2	764	8.2	16.4	10.8	43.4
4	Hope Creek	764	9.2	18.3	12.1	48.5
4	Susquehanna 1 & 2	764	10.3	20.7	25.1	50.3
5	LaSalle 1 & 2	764	7.1	16.2	7.8	23.5
5	Columbia	764	8.2	17.4	9.2	27.6
5	Nine Mile Point 2	764	8.6	17.3	8.6	25.8
6	Grand Gulf	800	8.8	17.5	8.3	24.8
6	Perry	748	8.8	17.6	9.4	28.1

BWR Type	Plant Name	Number of Bundles	Min Core Spray per Bundle	Max Core Spray per Bundle	Min LPCI per Bundle	Max LPCI per Bundle
6	River Bend	624	7.9	15.9	7.2	21.5
6	Clinton	624	7.9	15.7	7.7	23.1

(b) *The response to RAI 3 states the BWROG's view that the minimum core cooling has been used in the reference analysis, but does not explain how the limiting single failure for analyzing the impact of debris blockage was evaluated. Furthermore, a limited review by the NRC staff indicates that the bounding single failure assumption analyzed in some BWRs' FSARs results in fewer operating ECCS pumps than assumed in the reference and supplemental analyses. Therefore, please provide the technical basis for concluding that the reference and supplemental analyses used to derive test acceptance criteria have considered the most limiting single failures for analyzing the impact of post-LOCA debris, factoring in the corrections discussed in part (a) above.*

Response:

The reference analysis includes a relatively high PCT resulting from an early and extended core uncovery time. It is expected that the effects of debris during the short-term PCT excursion are critical for this scenario because of higher decay heat (early uncovery) and stored energy (high temperatures). Thus, the limiting single failure is synonymous with highest PCT. However, the BWROG does not propose a pre-approved acceptance criterion for Tests 1 and 2, or Tests 3 and 4, but rather will provide the justification in the test report. The LTR reference analysis is proposed as the basis for acceptable results from blockage effects that the actual blockage test results can be validated against or evaluated to produce less limiting consequences than the LTR PCT evaluations.

RAI 4 S1:

Please adequately address the remaining issues identified in the response to RAI 4:

(a) *An impact of long-term boiling that was not addressed in the response to RAI 4 is the potential for significantly increased concentrations of suspended debris within the reactor vessel. Long-term boiling within the reactor vessel can result in concentrations of suspended debris in the core and its hot channel significantly in excess of the concentration passing through the ECCS suction strainers. Head loss testing experience shows that increasing the concentration of fine suspended debris leads to agglomeration into larger elements. In-vessel agglomeration is a potential concern because larger agglomerates may block clearances within the core more readily and/or more persistently than individual fines. Please clarify how the BWROG has addressed or will address this issue.*

Response:

This concern applies exclusively to long-term Test 4 and only for a scenario where the fuel is submerged and cooled by flow from the upper plenum pool (when the fuel is uncovered it is cooled by core spray flow and debris would not be suspended in the flow). It is proposed that this concern be addressed by establishing a coolant debris concentration, in the test flow, that reflects the debris content accumulated in the channel considering the reduced flows in the fully rodded spacer grid. The reduced flows in the middle section of the hot channel in the SAFER analyses reflect the reduced cooling needs to maintain equilibrium conditions. This reduced flow would be calculated as follows: determine that the bundle outlet in-flow is [[ ]] (for example), and the corresponding flow in the middle fully rodded section is [[ ]]; therefore, the concentration applied would be [[ ]] than established from the core spray or upper plenum basis. This concentration reflects the decreased downward flow at the important spacer location while maintaining the same debris mass; in other words, the concentration increase is proportional to the change in flow (due to flow vaporization and void change) at the spacer. Additionally, once the maximum debris available per bundle is established, an assessment will be made to determine the maximum amount of mass debris that an individual blocked channel may accumulate over the full injection time. This maximum mass, in conjunction with the bundle volume and flow can also determine the maximum concentration for Test 4. This debris content would be calculated as follows: determine that the maximum debris mass available to any one bundle is 20 grams (for example), then a planned test with 1 gram per 10 gallons concentration (for example) would only last a total of 200 gallons of total flow. Similarly: determine that the bundle volume is approximately 10 gallons, then it follows that the entrained debris mass can never exceed 2 grams per gallon (e.g., 20 grams/10 gallons). These limits on concentration have the practical effect of excluding test conditions with high concentration and high flow, which are not realistic for the blocked bundle that only requires decay heat make-up flow. The fully submerged test applies to the condition where a postulated inlet blocked hot bundle

(HB) receives progressively reduced outlet flow (as blockage develops) and may allow a level to be temporarily formed until reduced decay heat leads to level recovery as blockage remains constant.

Attachment B describes the planned benchtop test program. Benchtop Test 1 (BT1) has been defined to help address the consequences of increasing the debris concentration within the bundle.

(b) *Please clarify why the BWROG considers it justified to neglect potential impacts of suspended debris concentration and scale formation if debris accumulation occurs mainly outside the active fuel region in the fuel assembly blockage tests. The impacts of scale formation and suspended debris concentration (potentially in combination with other effects such as thermal adhesion, crud buildup, cladding oxidation, and rod swelling) could change the location where limiting debris accumulation occurs. With reference to the actual clearance dimensions and flow areas requested in RAI 41 S1, please provide adequate technical basis to support the conclusion that the factors discussed above would not result in (1) the limiting condition for debris accumulation occurring within the active fuel region or (2) the creation of additional pressure drop across the reactor core that degrades core cooling.*

Response:

The potential for the listed effects to be important in determining debris accumulation at spacer grids will be evaluated as part of the benchtop test program described in Attachment B. Benchtop Test 2 (BT2) is the specific test aimed at determining whether these effects can be expected to be significant relative to fuel performance post-LOCA.

RAI 5 S1:

The response to RAI 5 proposed to address separately the potential for the concentration of boron in the reactor core beyond its solubility limit due to the continued addition of borated coolant to a fuel assembly, the blockage of flushing paths by post-LOCA debris, and ongoing coolant vaporization. However, the NRC staff has determined that, if the quantity of fibrous debris determined to reach the reactor core is such that the formation of a restrictive debris layer within one or more fuel assemblies may occur, then it is necessary to evaluate the potential for interaction between debris accumulation and boric acid precipitation as part of the in-vessel blockage program. Therefore, please clarify how it will be ensured that the debris limits derived by the BWROG's invessel debris blockage program are sufficient to preclude adverse effects and interactions associated with boron precipitation, accounting for non-uniform core spray and fuel channel inlet blockage distributions as well as differences in the configurations of the ECCS and standby liquid control system that have the potential to affect the potential for boron precipitation in the presence of post-LOCA debris.

Response:

The standby liquid control system (SLCS) is designed to provide an alternate method of reactivity control from the control rods by injecting the boron B-10 isotope into the reactor vessel. The BWR SLCS injects sodium pentaborate (or a similar sodium boron chemical solution) into the reactor vessel and is designed to provide cold shutdown at a natural boron concentration of 660 ppm in the core (for BWRs using solutions enriched with the B-10 isotope, the concentration for cold shutdown is lower). When system design margins are included, the SLCS provides a natural boron concentration in the core of approximately 1,100 ppm. The SLCS injects all of the sodium pentaborate solution from the SLCS tank into the core within about one hour after initiation by the operator.

At cold shutdown conditions (68°F), sodium pentaborate will remain dissolved in water at concentrations up to 11% by weight, and at 212°F, sodium pentaborate will remain dissolved at concentrations of 50% by weight. The 1,100 ppm of boron concentration equates to a 0.61% sodium pentaborate solution. GEH studies of the anticipated transient without scram (ATWS) event have shown that the sodium pentaborate solution rapidly mixes with the core cooling water whether injected through the JP instrument line or through the core spray system. For precipitation of sodium pentaborate to occur in the BWR fuel bundle after a large break LOCA event, the sodium pentaborate concentration in the core would need to increase to in excess of 50% by weight.

A conservative analysis that assumes the SLCS is injecting a 13% sodium pentaborate solution into a fuel bundle through the core spray (this conservatively assumes there is no mixing of the sodium pentaborate solution with other core spray water sources or steam condensation above the core) and no other water enters or leaves the fuel bundle for one hour with an average fuel bundle steam flow of 0.07 lbm/sec predicts that the average concentration of the sodium pentaborate in the fuel bundle would reach 36% after one hour, at which point all of the SLCS boron will have been injected and the core spray will only draw water from the suppression pool.

Because sodium pentaborate has a solubility of 50.3% at the temperature of the water in the bundle (212°F), this conservatively estimated 36% sodium pentaborate solution in the fuel bundle would not result in sodium pentaborate precipitation.

Given the expected temperatures of the water in the bundle, the predicted steam generation from the decay heat of the fuel, and the high solubility of sodium pentaborate at these temperatures, the BWROG and GEH consider any precipitation of sodium pentaborate to be very unlikely to occur during the early phases of the LOCA event.

RAI 6 S1:

(a) *In the long term, scale buildup and crud deposition may lead to reduced clearance dimensions, thereby promoting increased levels of debris blockage and retention relative to a clean assembly. For two main reasons, the response to RAI 6 does not adequately address this issue.*

1. *First, the constituents that form scale need not be suspended debris (e.g., a primary source of scale formation may be dissolved species concentrating in the reactor vessel).*
2. *Second, the marginal harm from scale formation creating nucleation points at minimal clearances that allow filtration of very fine suspended debris may exceed the benefit of debris holdup at non-limiting locations, particularly when considering maximum debris quantities bounding the entire BWR fleet.*

Therefore, please clarify why head loses derived from tests performed with clean assemblies that neglect scale and crud deposition are prototypical of a postulated LOCA.

Response:

The BWROG will, in fact, explicitly consider the effects of scale and crud deposits on debris blockage. As provided below in the response to Part b of this RAI, the total oxide + crud thickness remaining after brushing to remove loose "fluffy" crud is less than [[ ]] at end of life and will be considered in the bench test setup. Bench tests to evaluate the effects of scale in combination with oxide + crud on debris blockage are discussed below and in Attachment B.

Regarding scale thickness post-LOCA, the chemical effects program is currently underway and will evaluate the dissolution rates of various materials and the resulting concentrations of chemical species in the suppression pool based on a number of factors including materials present, containment spray and suppression pool temperature and pH histories, and time during the LOCA event. Although the program has been initiated, the evaluation of the scale thickness resulting from the deposition of chemical species entrained in the safety injection flow on the heated fuel surfaces is not completed at this time. As such, the BWROG will select a conservative value to be used in BT2. An assessment of the effect of scale thickness will be made based on the bench test results.

The potential effects of scale formation and other deposits on the fuel rod surface near the spacer grid will be evaluated as part of the benchtop test program described in Attachment B. BT2 will help determine at what point deposits on the fuel rod begin to affect debris accumulation at the spacer grid. Depending on the outcome, the arrival of calculated deposition thicknesses during or after the conclusion of the full height fuel bundle test program may not be overly problematic.

(b) *Please characterize and quantify typical levels of crud buildup on fuel bundles prior to removal by brushing. Please further clarify the expected behavior of this material during the LOCA and provide justification if it is considered not to affect or contribute to debris accumulation in the core.*

Response:

The previous reply to RAI 6 included numerous fuel bundle photographs that were examples of the appearance due to "dissolved species concentrating in the reactor vessel," or crud from feedwater metals inputs. The range of loose fluffy crud deposits on fuel rods is highly variable and depends mainly on the feedwater metals inputs, which vary by up to two decades from plant to plant. Other important variables are exposure, time in cycle, total residence time, location in core, and the axial power shape late in the cycle. The loose deposit is highly mobile; while it is bottom peaked for much of the cycle, and for lower exposure bundles, it tends to become more top peaked near end-of-cycle (EOC) and later in life. Global Nuclear Fuel (GNF) expects the deposit to be highly mobile in a LOCA situation. Please note that many US BWRs now operate with feedwater iron (Fe) inputs of less than 0.1 ppb; the total mass of Fe input at these plants, over an entire cycle, is small, and the fuel rods will have negligible (non- measureable, in terms of mils thickness) loose crud deposition. For a small number of plants with feedwater Fe inputs in the ~2 to ~3 ppb range (Note: still well below Electric Power Research Institute (EPRI) generic letter's (GL's) Action Level 1 value of 5 ppb), there is a thicker loose deposit, that can reach several mils (peak) in the bottom ~1/3 of the bundle, but tends to be very easily removed via brushing; GNF believes that the LOCA environment is likely to be similar to brushing or hydraulic washing/cleaning of bundles that has been done prior to inspections of fuel rods. Pre- and post-brush photograph examples are shown in Figure 6b-1 for a bundle with feedwater metals inputs on the higher end of the fleet experience base.

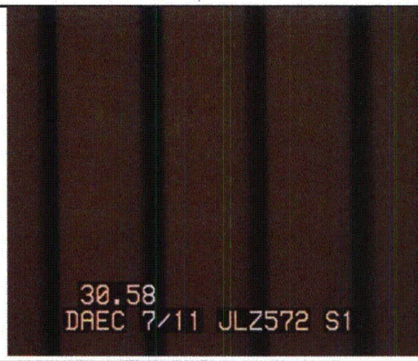	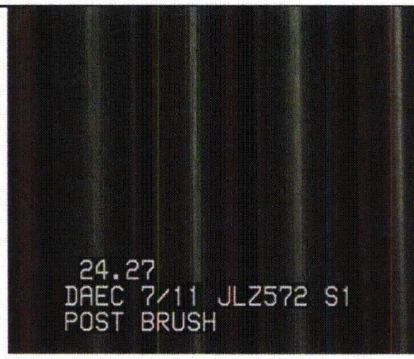
Between Spacer 1 and 2 from bottom (~peak crud thickness) – before brushing	**Between Spacer 1 and 2 from bottom (~peak crud thickness) – after brushing. Note smooth surface layer, oxide + tenacious crud, < 1 mil thickness.**

Figure 6b-1. Loose Crud Thickness at ~ Peak Axial Elevation and Appearance of Same Area After Brushing

The maximum local thickness of the oxide + crud layer (after brushing, or after the loose fluffy crud falls off, for the most part, as is expected in LOCA) for the latest GNF 10x10 fuel design, based on measurement data from a number of plants, is summarized in Figure 6b-2 below. Maximum effective liftoff (MELO) is obtained from axial averaging of four separate traces at 90 degree increments around the rod, over a six-inch axial range, and includes the areas under the spacers. Bundles near the end of the first two-year cycle (~20-25 GWd/MT; highest powered bundles) will have [[ ]]; bundles near the end of the second two-year cycle (~40-45 GWd/MT; now running at lower power) will have [[ ]], and bundles near the end of the third two-year cycle (nearly all of which operate at very low power in the outer periphery of the core) (~50 GWd/MT) will have [[ ]] of external deposits (oxide + tenacious crud). None of these are significant relative to the rod-to-rod spacing which is around 100 mils; tenacious crud or oxide account for only ~1-2% gap closure. It should be noted that the average deposit (along most of the length of all of the rods) will usually be ~50% of the maximums that are plotted in Figure 6b-2.

GNF believes that the existing crud/oxide on the fuel rods is insignificant relative to the postulated debris ingress (e.g., insulation fibers) during a LOCA.

[[

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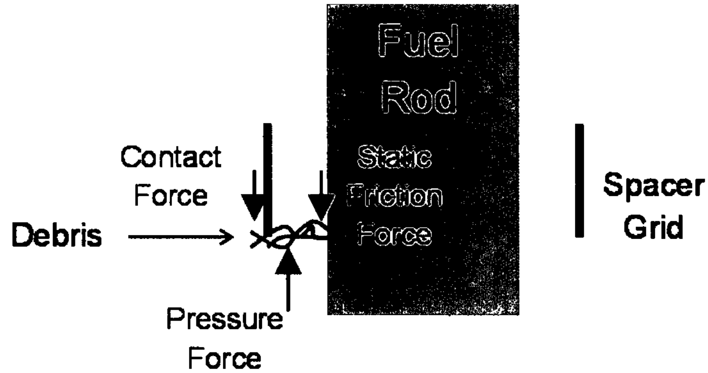
Figure 6b-2, Fuel Deposit Thickness Measurements as a Function of Exposure, in Typical US BWR Plant Chemistries

(c) Crud buildup and oxidation may increase the surface roughness of fuel rods and other susceptible core structures. Consideration of surface characteristics is important because, in contrast with ECCS strainers, debris accumulations in a fuel bundle would not generally be fully supported by contact forces on their reverse face; rather, the persistence with which a debris accumulation is retained against the differential pressure generated by coolant or steam flows would be dependent, not only on contact forces, but also the frictional forces developed at lateral surfaces parallel to the direction of flow. This is illustrated in the figure below for the case of debris accumulation in the gap between a spacer grid and fuel rod. Therefore, please (1) clarify why head losses derived from tests performed with clean assemblies that neglect the influence of surface characteristics on debris retention in the fuel bundle are prototypical of a postulated LOCA, or (2) clarify how the BWROG program will address this issue.



Response:

Although GNF does not have any data on the "surface roughness" of external fuel oxide or crud deposits, GNF does not believe that, at spacer areas, there will be much difference in the tendency to trap foreign material between new and irradiated fuel rods. Crud deposition is actually lowest beneath spacers, based on thousands of fuel inspection observations, because flow accelerates in the reduced area. There can be (usually are) small areas with shadow corrosion oxide under the spacers, because most spacers use parts that are of a different material than the Zry-2 cladding (i.e., Inconel or X-750 spacer springs). These areas are peaked only at the points where physical contact between the spacer and rod occur already (at five or six points, for GNF spacers); therefore, they do not affect clearances. Oxide + crud deposition is minimal relative to the rod-to-rod spacing and the spacing between the fuel rod and the assembly spacer parts.

Surface roughness is usually, after brushing, similar to the appearance in the Figure 6b-1 right figure (in other words, quite smooth). In many plants, at higher exposures (usually above ~35 GWd/MT bundle average) the tenacious crud tends to develop cracking and delaminates upon shutdown (the crud does not contract with the fuel rod and can develop cracks and fall off if rods are removed and brushed for detailed visual examinations and corrosion measurements). This tends to be in mid-span areas, where there should be less concern for friction.

GNF does not believe that surface roughness will be a significant variable in LOCA clogging tests, but has heard that, based on continued questions, that the BWROG is planning to include this variable in the testing. It has been stated that, "The potential effects of increased surface roughness will be examined as part of the benchtop test program. BT2 will examine the effects of a variety of methods simulating increased fuel rod roughness. The test will examine whether or not these surface modifications change the debris accumulation characteristics near the spacer grid."

The potential effects of increased surface roughness will be examined as part of the benchtop test program. BT2 will examine the effects of a variety of methods simulating increased fuel rod roughness. The test will examine whether or not these surface modifications change the debris accumulation characteristics near the spacer grid.

RAI 7 S1:

(a) *The response to RAI 7 did not discuss testing of previously quenched or partially quenched cladding that was subsequently reheated and requenched, as had been requested. As discussed in a letter to the Pressurized Water Reactor Owners Group (Agencywide Documents Access and Management System Accession No. ML062070451), the criteria in 10 CFR 50.46 (b)(1) through (b)(3) are based on testing that considers a single heatup and quench. Therefore, compliance with criteria (b)(1) through (b)(3) does not guarantee that cladding ductility and strength is adequate to satisfy the requirement for adequate long-term core cooling in criterion (b)(5) if the cladding experiences significant reheating (i.e., one or more additional thermal cycles). Further discussion of this topic occurs in Appendix A of TR WCAP-16793-NP, Rev. 2. Considering this information, please discuss testing and/or analysis demonstrating that the ductility and strength of cladding that has been previously heated and quenched remains adequate following subsequent reheating and eventual requenching from [[ ]] (or alternate value).*

Response:

In 10 CFR 50.46, criteria (b)(1) through (b)(3) places requirements on PCT, maximum cladding oxidation, and maximum hydrogen generation respectively. The PCT requirement is in place to ensure avoidance of other cladding integrity concerns that are not addressed through criteria (b)(2) and (b)(3). The criterion on maximum cladding oxidation addresses the cladding ductility following a postulated transient, during which clad-steam oxidation reaction can lead to embrittlement of the clad. The limit on clad oxidation is given in terms of effective cladding reacted (ECR) and is currently set at 17%. The criterion on maximum hydrogen generation addresses hydrogen released from the Zr-water reaction.

Of these considerations, the cladding ductility, as addressed through a limit on ECR, is most relevant to the discussion in this response. As the RAI addresses post-quench temperature effect, the reheat temperatures involved are below the PCT relevant to criterion (b)(1). Maximum hydrogen generation is from hydrogen released from the steam reaction with the Zr-based cladding. The amount of hydrogen generated is related to the amount of Zr-steam reaction, or corrosion. The rate of corrosion reaction typically varies exponentially with the inverse temperature, and is therefore much reduced at lower reheat temperatures compared with the first temperature transient.

With respect to maximum oxidation (i.e., ECR limit), the dominant cladding embrittlement mechanisms are oxygen embrittlement of the beta-layer and beta-layer thinning, and these mechanisms are discussed below.

In WCAP-16793, the accepted maximum reheat temperature is 800°F. The 800°F takes into consideration the cladding corrosion behavior. In recent GEH analyses, the post-transient reheat temperature for certain fuel assemblies has been shown to reach above 800°F, and for BWR/3-6 could be as high as 1,100°F (See RAI 7b S1) for a short duration, followed by a gradual decline to lower temperatures. Such assemblies are the high power assemblies prior to the postulated transient, and are typically fuel assemblies that are in the first cycle of operation (two-year). For this response, focus is on BWR/3-6 plants and a postulated conservative envelope temperature represented by the dashed line depicted in Figure 7a-1. (See RAI 7b S1 for the derivation of the envelope temperature). This bounding temperature can be characterized with a reheat temperature of [[ ]]. In some BWR/4 04 cases, a quenching and reheating cycle of [[ ]] was noted. However, the peak reheat temperatures were lower in these cases. The BWR/2 LOCA with debris blockage is irrelevant for the discussion herein as there is no fuel clad reheat in the post-debris period for BWR/2.

[[

]]

Figure 7a-1. Bounding Composite Clad Temperature for Post-Debris Period

Cladding Corrosion: This is one of the dominant factors contributing to metal thinning which forms the main consideration for criterion (b)(2) of 10 CFR 50.46. The reaction rate with steam increases with temperature. The oxidation rate of Zircaloy-2 in steam between 600°C and 850°C is reported for exposures up to ~ 1,000 minutes (Reference 7a-1). At 650°C (1,202°F), the expected weight gain after 5,000 seconds is about 50 mg/dm^2, or 3.3 microns, assuming 15 mg/dm^2 per micron of oxide. The time and temperature involved conservatively assume that the Zircaloy-2 temperature is at 1,202°F for the 5,000 second duration. However, this level of corrosion is based on fresh Zircaloy-2. As the data in Reference 7a-1 shows, the rate of Zircaloy-2 oxidation follows approximately the cubic rate law, and the logarithmic weight gain is related to the logarithmic time by a slope of 0.38 at 650°C (ideally 1/3) (i.e., the incremental weight gain during a given time increment decreases with exposure time). At long exposure times, Zircaloy-2, like other Zr-alloys such as Zircaloy-4, will undergo accelerated corrosion, sometimes referred to as breakaway oxidation, as the data in Reference 7a-1 shows. Specific to the corrosion behavior following build-up of oxide from previous transient and quench, the corrosion rate during the reheat period is expected to be lower than fresh Zircaloy-2 on account of the cubic corrosion rate, provided transition to acceleration had not occurred. The previous transient and quench could be considered as inducing accelerated corrosion. Alternatively, the multiple cycling could be considered as having the effect of inducing accelerated or breakaway corrosion. Should breakaway corrosion occur due to either one of the postulated causes, Reference 7a-1 contains post-breakaway data that can be used to assess the amount of corrosion that might result. The accelerated corrosion is approximately linear with exposure time, and for 5,000 seconds at 650°C (1,202°F) being considered here, a weight gain of 85 mg/dm^2 or less is expected based on Reference 7a-1. This weight gain corresponds to <0.7% ECR assuming a clad diameter of 404 mils and, conservatively, a clad thickness of 20 mils. The incremental ECR, assuming an accelerated corrosion rate, is small relative to the ECR accumulated during the initial transient. In a compilation of ECR as documented in the analysis of record (AOR) (Reference 7a-2), BWR/3-6 plants have a limiting ECR of 9% or less. The conservatively estimated incremental ECR (<0.7%) is small in comparison to the gap between the AOR ECR and the 17% limit. Cladding integrity degradation due to metal thinning as bound by the 17% ECR limit is therefore not expected to be challenged by residing for up to [[ ]].

Oxygen Embrittlement: Criterion (b)(2) of 10 CFR 50.46 takes into consideration cladding embrittlement due to diffusion of oxygen from the growing oxide into the Zircaloy base alloy and forming the brittle oxygen-stabilized alpha-phase. The rate of oxygen diffusion and hence thickness of the oxygen embrittled zone is temperature dependent. At [[ ]], this effect is small compared with that at 1,500-2,200°F. Reheat for a short duration up to [[ ]] will have minor cladding embrittlement consequences due to this mechanism.

In addition to metal thinning and oxygen embrittlement, Zr and its alloys such as Zircaloy-2 can be embrittled by the presence of excessive amounts of hydrogen. The source of hydrogen is that released by the breakdown of the water molecule as the water reacts with the cladding during the corrosion process, and part of the released hydrogen can be absorbed into the cladding. Hydrogen absorption during three stages is considered below: pre-transient, during transient, and during post-transient reheat periods.

For the pre-transient portion, the cladding hydrogen generally increases with cladding exposure. There is currently a hydrogen limit of [[ ]] on GNF fuel designs. As noted earlier, fuel assemblies that can develop high reheat temperatures are those in the first cycle of operations. The exposures are typically less than 20 GWd/MTU and the expected cladding hydrogen concentration is less than 50 ppm (Reference 7a-3). There is, therefore, little risk of cladding embrittlement from this source of cladding hydrogen.

During the transient stage, tests have shown that a high concentration of hydrogen can accumulate in the burst region, immediately adjacent to the burst (References 7a-4 and 7a-5) and the high hydrogen concentration appears to be associated with the burst process. Away from the burst region, or if the burst opening is small, the cladding hydrogen content does not appear to be significantly modified by the transient oxidation. There is, therefore, little risk of additional embrittlement of the cladding due to hydrogen absorption during the transient.

During the post-transient reheat period at temperatures below [[ ]], hydrogen absorption is possible as additional cladding corrosion occurs. Tests have shown that, even though the corrosion increases with temperature, the absorbed hydrogen can be less with increasing temperature (Reference 7a-6). The increased corrosion at [[ ]] for a short duration relative to that below 800°F, therefore, is not expected to result in proportionally higher amounts of absorbed hydrogen. The presence of hydrogen in cladding, from either pre-transient operation, transient, or post-transient periods, could potentially result in the formation of radial hydrides through reorientation during post-transient temperature cycling. In general, the susceptibility to hydride re-orientation increases with hydrogen content, hoop stress, temperature, and number of cycles. The conservative bounding temperature profile, the dashed line in Figure 7a-1, indicates multiple cycles up to [[ ]], for which there is little information on integrity of the resultant cladding. As shown in Figure 7a-1, the more realistic cases (solid lines) for BWR/6 cases show a gradual decline from [[ ]]. For realistic cases for BWR/4 with 04 blockages, Figure 7a-1 shows periodic quenching and reheating cycles up to near or slightly above [[ ]]. Such temperature cycling is not expected to introduce additional cladding embrittlement concerns due to hydride re-orientation. As hydrides dissolve during temperature ramp up and reform during the cooling portion of a given temperature cycle, only hydride formed during the last cool down is relevant. Based on the solubility limit for hydride dissolution at 800°F, hydrogen in cladding up to about 200 ppm hydrogen is expected to be dissolved during the temperature ramp up stage. As the pre-transient hydrogen content in the cladding is low for fuel assemblies that can develop reheat temperature cycles, all pre-transient hydrides are expected to be dissolved during the temperature ramp up stage, and reform during the last cool down. The risk of cladding degradation due to hydride re-orientation is therefore low. In addition, recovery of cladding ductility through annealing of pre-transient irradiation damage is expected during transient and subsequent thermal cycling.

The discussion above addresses potential embrittlement of cladding due to known mechanisms that includes metal thinning, oxygen diffusion, and/or embrittlement due to absorbed hydrogen (away from the burst region). Based on the discussions above, it is concluded that significant degradation of cladding integrity is not likely for reheat up to [[ ]].

References:

7a-1. R. E. Westerman, "High Temperature Oxidation of Zirconium And Zircaloy- 2 In Oxygen And Water Vapor," HW-73511, Hanford Laboratories, 1962.

7a-2. BWROG-TP-11-010, "Evaluation of BWR LOCA Analyses and Margins Against High Burnup Fuel Research Findings," BWR Owners' Group, 2011.

7a-3. K. Geelhood and C. Beyer, "Hydrogen Pickup Models For Zircaloy-2, Zircaloy-4, M5 and Zirlo," 2011 Water Reactor Fuel Performance Meeting, Chengdu, China, 2011, Paper T2-011.

7a-4. NUREG/CR-6967, "Cladding Embrittlement During Postulated Loss-of-Coolant Accidents," Office of Nuclear Regulatory Research, 2008.

7a-5. G. Hache and H. M. Chung, "The History of LOCA Embrittlement Criteria," Proceedings of the 28th Water Reactor Safety Meeting, Washington, 2001 .

7a-6. B. Cox, "Some Factors Which Affect the Rate of Oxidation and Hydrogen Absorption of Zircaloy-2 In Steam," U K. AEA Rep. AERE-R4348, 1963, referenced in IAEA TECDOC-996 "Waterside Corrosion of Zirconium Alloys In Nuclear Power Plants," IAEA, 1998.

(b) Please clarify the intent and significance of the [[ ]] Fahrenheit (°F) acceptance criterion established by the BWR Owners Group (BWROG) as a reheatup cladding temperature limit, since one of the supplemental analysis cases (Figure 1 from Attachment A of the second RAI response) exhibits a PCT in excess of this value.

Response:

The [[ ]] is used as a target temperature for the secondary PCT excursion as a result of maximum assumed outlet blockage. However, it is not intended as an absolute limit but rather as a representative excursion that will not be limiting in terms of PCT and oxidation. An appropriately bounding value of PCT is considered in response to RAI 7a S1 (Figure 7a-1) and derived as follows:

Postulated Limiting Peak Clad Temperature Envelope After Commencement of Debris Blockage

A limiting PCT envelope is developed herein to encompass all the SAFER predicted post-debris clad temperature excursions for BWR types 3-6 with 04 and A1 blockage scenarios. Ample temperature margin and quenching/reheating cycles are factored into the postulated temperature response envelope to ensure that adequate conservatism is included.

SAFER LOCA cases used in deriving the temperature envelope are listed in Table 7b-1. PCTs after full debris blockage for each case are also listed in this table.

Table 7b-1 [[ ]]

[[				
				]]

RAI 7a S1 Figure 7a-1 depicts the temperature transients of the cases listed in Table 7b-1.

It can be seen from Table 7b-1 that the highest post-debris blockage PCT is [[ ]]. From Figure 7a-1, it can be observed that the quenching and reheating cycle with an approximate cycling time of [[ ]].

A limiting PCT envelope with a peak temperature of [[ ]] is derived. The composite temperature maintains [[ ]].

In summary, the derived temperature envelop provides a temperature margin of [[ ]].

(c) *Please clarify the BWROG's analytical predictions regarding the timing and impact of scale formation in relation to the proposed [[ ]] reheatup limit. In certain cases, the TR's supplemental analyses demonstrate that the proposed debris blockage limit could result in cladding being reheated to temperatures near or even in excess of [[ ]]. Please clarify whether the formation of scale, in concert with debris blockage, could result in even higher cladding temperatures and discuss how the combined impact will be assessed relative to the acceptance criterion for cladding temperature.*

Response:

The effect on the cladding temperature due to scale formation on the fuel rods during the reheating stage has been conservatively calculated. The temperature effect is shown to be relatively small, comparable in magnitude to the variation among different operating conditions.

In this study, the scale is assumed to start to form when the HB inlet is completely blocked at [[ ]] after emergency core cooling (ECC) injection. Also, a scale conductivity of [[ ]] is used. The [[ ]] conductivity value is very conservative as EPRI study shows that the nominal conductivity of cladding crud is 0.68 BTU/hr-ft-°F.

[[ ]].

It is concluded that the effect on clad temperature during the long-term blockage reheat phase is small, with very conservative assumptions for formation and conductivity of scale on the fuel clad. Therefore, no further examination of scale formation with respect to scale conductivity is needed.

RAI 11 S1:

The response to RAI 11 states that the BWROG considers the blockage multiplier for the geometrically restricted area affected by CCFL to serve as a "knob" for simulating the impact of debris blockage. However, this response does not adequately address the distinction made in RAI 11 between the use of a blockage multiplier as a knob for tuning (1) differential pressure due to single-phase flow and (2) CCFL. In the former case, the tuned parameter is measured during the experiment; thus, the blockage multiplier can be considered a "calibrated knob." However, with respect to CCFL, because the tuned parameters are not experimentally measured, the blockage multiplier represents an "uncalibrated knob." Ultimately, because there is no general analytic relationship between an arbitrary cross-sectional flow geometry and the empirical constants required by a CCFL correlation, when considering significant blockage of unspecified geometry covering up [[ ]] of the area of the fuel assembly outlet, it cannot be presumed in generality that the CCFL constants determined for an unblocked fuel assembly outlet geometry continue to apply. Therefore, following the debris blockage testing, please commit to either (1) providing validation and justification that debris blockage had a negligible effect on the geometry of the fuel assembly outlet such that continued applicability of CCFL constants for unblocked fuel assemblies may be assumed or (2) if testing indicates that debris blockage may influence CCFL, performing additional testing and/or analysis to assess the impact of debris blockage on CCFL realistically, and, if warranted, reanalyzing the consequent effect on PCT with modified CCFL constants appropriate for a blocked fuel assembly.

Response:

The BWROG agrees to address the CCFL validity based on the Test 4 results, on examination of blockage homogeneity, and subsequently justified or modified. This will be addressed in the blockage test report for Test 4.

RAI 13 S1:

The response to RAI 13 states that a flow reversal occurs at the fuel channel-bypass leakage flowpaths between the times simulated in Tests 1 and 2. Please clarify whether this statement applies to BWRs with low-pressure coolant injection (LPCI) discharging into the bypass region and provide justification.

Response:

Following a postulated large break in the recirculation pipe, ECCS flow from inside shroud injection (core spray and, if applicable, LPCI) and optionally from JP injection (if applicable) will fill the lower plenum prior to the two-phase mixture rising through the core inlet and into the fuel bundles. Therefore, the flow through the bypass to lower plenum leakage paths will initially be downwards (opposite compared against normal plant operation) and upwards following the level rise (except for the case where all ECCS flow is injected inside the shroud). Later, once the elevation head (from the two-phase mixture) inside the shroud equalizes with the JP elevation head (from the single phase coolant), leakage flow will reverse again, establishing natural circulation phenomena into the fuel channels, with any excess inside shroud injection flowing to the lower plenum and eventually out of the vessel through the pipe break. This is observed in Figures 3-2 (bypass region level) and 3-4 (leakage flow): the flow is negative during the lower plenum refill, then positive during core refill, and finally negative during natural circulation.

RAI 16 S1:

(a) *The NRC staff agrees with the clarification in RAI 16 that fuel designs with enhanced thermal performance may require additional analysis to demonstrate acceptable performance under post-LOCA debris blockage conditions. However, designs involving reductions to minimum flow areas (e.g., at the limiting CCFL elevation or at critical debris accumulation points) or the potential creation of new critical debris accumulation points (e.g., new type of inlet filter or grid design) may also require additional fuel assembly blockage tests to validate acceptable performance under post-LOCA debris loadings. Please specify conditions under which additional fuel bundle blockage testing shall be necessary to support the loading of fuel designs not analyzed in the TR.*

Response:

We agree with the NRC discussion; new fuel justification criteria must include other key parameters (minimum flow area reduction, debris accumulation points, new inlet filter or spacer design concepts) and possibly other undetermined fuel features as evidenced from the blockage testing. It is possible that application of blockage test results to other fuel designs requires conservative assumptions such that testing is more practical than accepting significant performance penalties.

(b) *The comparison of relative peaking factors between different plants proposed in response to RAI 16 may introduce error if the reference value of average power per bundle differs. Therefore, please replace the relative peaking factor proposed in the TR with an appropriate absolute metric, or else justify that use of a relative peaking factor has equivalent precision.*

Response:

It is correct that the absolute power would affect the results of the secondary, long-term PCT history (no effect is expected for the short-term limiting PCT from blockage). However, the intent of relative peaking factor is meant to apply to a specific fuel type that is initialized to the same initial thermal margin parameters (e.g., minimum critical power ratio (MCPR), linear heat generation rate (LHGR), and maximum average planar linear heat generation rate (MAPLHGR)), and thus it represents approximately the same absolute power level for all plants applying the same initial conditions. Therefore, the relative peaking factor proposed is the same only for plants with the same power density, with small differences for core flow, reactor pressure, and feedwater temperature variation. In other words, the specific bundle type power peaking factors (radial, axial, and local) required to set the HB at the LOCA initial conditions yield similar power in absolute terms for different plants. [[

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Table 16b-1 [[ ]]

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RAI 18 S1:

(a) *For Test 1, please clarify and provide justification regarding whether separate tests with differently scaled lower plenum volumes are planned for BWRs with LPCI injection into the bypass region and those that inject into recirculation lines. If a single test is planned, please clarify whether the contribution of LPCI flow into the recirculation lines to refilling the lower plenum is neglected in Test 1, or how it is accounted for only where appropriate.*

Response:

Test 1 is exclusively focused on ECCS flow from the bypass region into the lower plenum leakage paths. Because all BWRs (with and without JPs) inject some ECCS flow inside the shroud it is applicable to all. The planned Test 1 flow range and duration bound both low and high injection capacity BWRs as well as different lower plenum sizes. Test 1 ceases to apply when the lower plenum is full, either from ECCS injection into the lower plenum or leakage from the bypass region into the lower plenum. Please see the response to RAI 13 S1 regarding flow direction through leakage paths.

(b) *For Test 2, please clarify and provide justification regarding whether separate tests planned for BWRs with LPCI injection into the bypass region and those that inject into recirculation lines. For BWRs with LPCI injection into the bypass, could the limiting restriction be associated with downflow from the bypass to the lower plenum? Please explicitly specify and provide justification for the minimum and maximum rates in Test 2 for upflow and downflow for BWRs with LPCI injection into the recirculation lines and BWRs with LPCI injection into the bypass region.*

Response:

Test 2 is exclusively focused on flow into the dry fuel bundle through the lower tie plate grid to simulate the level rise. This phenomenon applies to all BWRs with break and ECCS conditions which uncover the fuel. The planned Test 2 flow range and duration reflect a slow level rise rate [[ ]] as given in a relatively high PCT case, such as the reference analysis, to a fast level rise rate [[ ]] that would represent a non-limiting PCT. Test 2 ceases to apply when the shroud level elevation head equalizes with the JP elevation head. Please see the response to RAI 13 S1 regarding flow direction through leakage paths.

RAI 20 S1:

The NRC staff considers the fuel assembly blockage testing to be applicable only to those BWRs that are bounded by the test parameters. While the test parameters proposed appear indicative of the upper range of values, since they come from the specification of flows via percentages and the basis of a reference calculation that has not been demonstrated to be bounding for all BWRs, it is not clear that the flowrates are bounding on an absolute basis when considering factors such as the number of pumps that may operate, plant-specific pump capacity differences, variations in fuel bundle power, and the potential for variation in the flow splits between the side entry orifice (SEO) and bypass leakage paths for different break scenarios. Therefore, please confirm and provide the basis for concluding that the planned test flowrates bound the minimum and maximum values for all BWRs on an absolute basis (e.g., mass flow to the limiting bundle).

Response:

The approach used to define the test flow range is focused on the bundle boundary conditions during the postulated LOCA and on plant parameters as much as they influence the boundary conditions. The discussion in LTR Sections 4.d and 4.e describes the short and long-term boundary conditions for all BWR types, breaks, and system availability. The important parameters for Tests 1 and 2 are limited to the short-term refill and reflood. Therefore, Test 1 boundary conditions reflect a minimum to maximum available bypass head. Similarly, Test 2 boundary conditions reflect a minimum to maximum level rise rates for LOCA conditions with limiting PCT results (e.g., fast reflood rates not limiting). A survey of US operating BWR/3-6 ECCS capacity shows that the minimum core spray average flow per bundle is 6.5 gpm (one system) and the maximum is 21.7 gpm (both systems). Similarly, the survey shows a minimum LPCI flow per bundle of 7.2 gpm (one pump in one recirculation loop) and maximum of 63.9 gpm (four pumps in two recirculation loops, exceeds the four pumps inside the shroud configuration). Test 1 will cover the range of the bypass region injection subject to maximum head as described above. Test 2 will cover the range of two-system minimum flow to maximum flow subject to the fast non-limiting reflood rate described above. The important parameter for Test 3 is the elevation head difference between the inside voided fuel channel and resulting flow rate. The reference calculation provides the typical HB flow rate and a variation of 50% to 200% provides a bounding range for bundle power level over the applicable few minutes for Test 3. Should Test 3 develop significant blockage, then a maximum DP of 4 psi is applicable, as this represents the maximum head available from the solid coolant to the JP elevation level. The Test 4 flow rate range includes two separate considerations: one is the long-term core spray distribution flow rates of approximately 2 to 10 gpm per channel, and another is the CCFL limitation of approximately 1 gpm for the postulated outlet blocked channel (Note that lower flow rates will also be tested to simulate reduced flow at spacers as described in RAI 4a S1). It should be noted that Test 4 ECCS flow rates may be limited by CCFL when both air upflow and high coolant downflow rates are tested; under these conditions, test monitoring of liquid accumulation will further support the evaluation of blockage resistance and flow behavior to be documented and justified in the test reports. Therefore, the planned test flow rates apply to all US operating BWRs.

RAI 21 S1:

Please provide further description of the parameters and assumptions for the supplemental analysis calculations in Attachment A to the second RAI response:

(a) *Please clarify how the inlet blockage timing is determined for different scenarios for which the timing of events varies (e.g., initiation of low-pressure ECCS injection). For example, complete blockage of the hot channel SEO and bypass leakage paths at [[ ]] is assumed in the TR's reference analysis for a double-ended suction line break. However, in a similar scenario in Case A-1 of the supplemental analysis in Attachment A to Enclosure 2 of the second RAI response, blockage for the hot and average channel inlets is assumed to depend on flow history in a manner that is not fully specified. Adequate clarification and justification for the flow history-dependent blockage model appears necessary to support assumptions made in calculations for smaller break sizes that have been modeled (e.g., core spray line break) as well as to confirm that explicit analysis of other break locations (e.g., discharge line break) is not necessary. Therefore, please explain the assumptions and/or models used to determine when blockage initiates for the SEO and bypass leakage paths in the reference and supplemental analysis scenarios and justify their adequacy.*

Response:

The inlet blockage of the hot channel (SEO and various leakage paths) is assumed at a fixed time after low pressure injection for all cases. Similarly, the outlet blockage of the hot channel is assumed at a fixed time after low pressure injection for all cases. However, when the average channel is assumed to also block (Cases A-1 and A-4), this blockage (SEO and leakage) is applied at a later timing based on an approximate ratio of average to hot inlet flow (0.5) after reflood. This approach allows for a more realistic representation of the hot channel and the core conditions under a postulated full core blockage. The exact timing of the full core blockage is not important but rather the boundary conditions on the hot channel once the average channel is blocked, which naturally occurs later because the lower powered bundles experience reduced flow. Therefore, the progression on the hot channel thermal response being fully blocked as the average channel becomes fully blocked is realistically represented. The bypass leakage is assumed to block at the same history as the average channel inlet. No outlet blockage is applied to the average channel as this would not affect the boundary conditions of the hot channel.

(b) *Regarding Case A-4 of the supplemental analysis (i.e., core spray break / opposite core spray train failure), please clarify the steam separator water return elevation(s), clearance dimension(s), and flow area(s) for the reference plant and confirm whether the modeling of the steam separator in SAFER is prototypical with respect to calculating the downflow of water into the core shroud in this scenario. Please further clarify whether the reactor vessel water level necessary to provide adequate downflow through the steam separators is above or below the minimum water level specified in the applicable* *emergency operating procedure. If the vessel water level necessary for adequate spillback through the separators cannot be confirmed to be above the minimum water level required by emergency operating procedures, then please further provide justification for the operator behavior and human factors / timing assumptions regarding manual control of ECCS flows for Case A-4 of the supplemental analysis relative to the guidance for controlling water level in the emergency operating procedures.*

Response:

The specific scenario being examined has a core spray line break with a failure in the second core spray system. The expected LOCA behavior is that water level will be recovered with automatic LPCI injection to the elevation of the core spray nozzle level in the reactor pressure vessel (RPV), 451 inches above vessel zero for the plant in the A-4 study. The level will be slightly lower outside the shroud because of the lower density of the coolant inside the shroud where excess LPCI injection will leak through the spray spargers to the break. Then, containment debris is postulated to eventually cause blockage of the fuel inlet filters and the bypass region leakage paths. As the full core becomes blocked and inside shroud level drops from vaporization, any flow out of the core spray line break would stop momentarily, and the level outside shroud would rise into the normal range of 507 to 532 inches (for the plant in the A-4 study). Coolant will spill inside the shroud at the steam separator return elevation of 525 inches (top of the separator barrel), to recover the level in the fuel channels, bypass region and upper plenum, until it reaches the core spray nozzle elevation of 451 inches again and break flow resumes. This scenario is expected to be representative of the entire BWR/3 and BWR/4 plant types that do not inject LPCI inside the shroud because the water level is established similarly in terms of the separator level to achieve the optimum separator performance. The major difference being that most of the BWR/4 plants will have a two stage steam separator, rather than a single stage as the plant in the A-4 study, whereby a liquid return elevation would be lower than in the A-4 analysis. This scenario presents some challenges to the operator, in that the initial level corresponds to the break elevation and subsequently it would rise to the separator level. However, operator actions prioritize core cooling and a single LPCI pump devoted to core cooling is sufficient to compensate for core steaming and maintain level inside the shroud, should other LPCI pumps be diverted to containment cooling. Furthermore, because level outside the shroud is not so excessive as to fill the RPV, there will not be a need to throttle back the LPCI pump devoted to core cooling and, absent a high level trip for low pressure ECCS, the results of the A-4 study are reasonable for the BWRs with outside shroud injection.

(c) *Please provide information similar to that provided in Table 3-1 for each of the supplemental analysis cases (no need to repeat the initial sequence common to all large suction break cases). Please clarify other differences in the major assumptions of the supplemental calculations relative to the original reference analysis (e.g., difference in fuel types, peaking factors, ECCS flows, etc.).*

Response:

Table 21c-1 includes key plant and case parameter information for each of the supporting calculations requested. Cases A-1, A-2, and A-4 utilize the same plant as the reference LTR analyses, whereas the other two cases utilize typical plants with the identified characteristics (e.g., inside shroud LPCI and non-JP plants).

Table 21c-1 [[ ]]

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(d) *Please specify the area of the small break simulated in Case A-2.*

Response:

The small break for Case A-2 represents that which yields maximum PCT for ECCS high pressure system failure assumptions. Depending on plant type and available ECCS capacity, this break size may range from as small as 0.05 to as high as 0.13 ft^2. However, the small break LOCA behavior is the same, fast core level recovery by low pressure ECCS injection once vessel pressure depressurizes from automatic depressurization system (ADS) actuation. The specific parameters for Case A-2 are a 0.06 ft^2 size break and ECCS injection at 364 seconds, therefore, [[ ]] for inlet and outlet blockage respectively, with a PCT time of 385 seconds.

(e) *Please identify the axial power shape used in the simulation of debris blockage for the BWR/2 case in the supplemental analysis and justify that it is conservative.*

Response:

The BWR/2 LOCA fuel type power initialization differs from that applied to later BWRs because of power limitations due to BWR/2 ECCS performance. The initialization for the standard licensing LOCA considers the sensitivity to the limiting LOCA characteristics as described in Attachment D. The same conservative phenomena applies under the conservative upper blockage assumptions for both cases shown in the A-4 calculations, with and without inlet blockage.

(f) *Please state whether leakage between the lower plenum and core bypass region was assumed in the analysis for Cases A-1 and A-4 in Appendix A of the second RAI response. If so, please identify the flow area assumed and the minimum clearance dimensions associated with these flowpaths. Please provide justification that any flowpaths credited will not become blocked by debris during a LOCA or have a negligible impact on the calculation; otherwise, please perform a revised analysis demonstrating acceptable results with an appropriate degree of blockage imposed at these flowpaths.*

Response:

No credit for flow between bypass region and lower plenum, paths are assumed to be blocked at the same history as the average channel inlet. Other than Cases A-1 and A-4, all other cases had no blockage on either SEO or leakage for the average channel.

(g) *Please confirm whether CCFL would have a significant effect in the steam separators for a core spray break scenario with the coincident single failure of the opposite train of core spray. If CCFL may occur in the steam separators, please clarify whether it is necessary to model this phenomenon in the analysis.*

Response:

The steam separator geometry and steam flow characteristics pertaining to the core spray line break and failure are discussed in detail in Attachment E. Based on this discussion, it does not appear that CCFL will occur at the steam separators.

(h) *Please provide additional explanation regarding the lack of long-term heatup following fuel channel outlet blockage for supplemental analysis Case A-3, which simulates BWRs with LPCI injection into the shroud. Considering Case A-3 relative to the reference analysis Case 4, based on conditions just prior to [[ ]], it is not obvious why one case experiences a heatup and the other does not. Please clarify whether the difference is attributed to differences in channel power, ECCS flows, or other factors.*

Response:

Case A-3, with several ECCS pumps injecting into the bypass region, provides a significant heat sink to help maintain low temperatures and reduce steam generation in the blocked HB. A new Case A-3 calculation whereby LPCI injection is inhibited at 10 minutes after LOCA shows a long-term PCT increase. Please see Figure C-15 in Attachment C.

(i) *Please clarify the ECCS fluid temperature and containment pressure boundary conditions used in the analysis and provide justification for the selected values.*

Response:

Both ECCS fluid temperature and containment pressure boundary conditions applied in these calculations are the same as standard LOCA licensing bases. Specifically, [[

]]. A sensitivity analysis was performed using more representative containment conditions as described in Attachment F summary. The results of the sensitivity on the highest PCT case, Case A-1, show that the standard licensing LOCA containment conditions produce slightly more conservative consequences to the blockage analysis.

(j) *The formation of scale on fuel rods due to materials suspended or dissolved in the post-LOCA coolant may reduce heat transfer from the core (e.g., via convection, radiation, conduction), especially for the BWR/2 analysis. Therefore, please (1) clarify how heat transfer assumptions in the analysis were modified to account for scale formation, or (2) confirm that additional analysis will be performed if future testing or analysis demonstrates that scale formation may impact cladding temperature limits.*

Response:

With respect to clad temperature effects due to scale formation from suspended or dissolved materials, the scenario of interest is the post-blockage long-term reheat in JP BWRs. This scenario involves a slow fuel uncovery and clad reheat as a flow blockage is developed and scale forms as decay heat vaporizes the in-channel coolant inventory. The potential clad temperature effect was assessed with the calculation of reduced clad conductivity documented for RAI 7c S1. The conservative assumptions and PCT sensitivity from the calculation indicates that the effect is not significant. Additionally, for BWR/2 limiting LOCA conditions, the fuel remains uncovered for the duration of the ECCS injection, and thus debris would not be suspended but rather sprayed on the fuel surface. The heat transfer mechanism is of greater importance for the BWR/2 scenario because the temperatures and resulting oxidation are higher than for later plants. However, the A-5 calculation shows how blockage has either beneficial or no effect on the limiting licensing LOCA case and thus detrimental heat transfer effects from scale formation can be offset by some blockage effects. Therefore, it is proposed that the specific BWR/2 assessment of clad scale heat transfer be evaluated and justified after blockage and debris on hot surface tests are performed.

RAI 23 S1:

(a) *The results from the international knowledgebase report on strainer clogging, NEA/CSNI/R(95)11, presented in the response to part (a) of RAI 23 pertain to hot, submerged surfaces. The response does not provide adequate basis to conclude that thermal adhesion can be neglected for hot, unsubmerged surfaces that were the subject of part (a) of RAI 23. Thermal adhesion to unsubmerged, hot surfaces may affect all BWRs, but is presumably most significant for those without jet pumps, since the fuel cladding of hotter channels may remain at elevated temperatures for extended periods of time (e.g., [[ ]]). In these limiting scenarios, post-LOCA cladding temperatures could exceed the melting point for some types of debris (e.g., fiberglass). Although the period of spraying unquenched rods is expected to be significantly shorter for BWRs with jet pumps, thermal adhesion may still prove to be an important phenomenon that (1) increases the resistance of debris accumulations to removal by countercurrent steam flow and (2) generates nucleation sites for debris accumulation at larger grid openings where very fine debris that passed through the ECCS strainer might otherwise have significant difficulty being captured. Finally, as noted in RAI 24 S1, with [[ ]] blockage imposed at the fuel assembly outlet and CCFL present, the BWROG has not demonstrated that liquid coolant will be distributed to all fuel rods. Therefore, in light of the discussion above, please provide adequate technical basis to disposition the issue of thermal adhesion to unsubmerged, hot surfaces, or discuss plans to address the issue experimentally.*

Response:

It is understood that the primary concern of this RAI is the potential contribution of debris adherence to hot fuel surfaces in contributing to increased blockage at generally open spacer areas. Indeed, under the limiting assumed blockage scenarios in the reference and supplementary calculations, fuel surface temperatures are predicted to reach approximately [[ ]]. It is important to keep in perspective that long-term hot fuel surface temperatures are developed in JP BWRs only after the blockage has developed inside the bundle from outlet flow with debris, thus the outlet blockage precedes the hot fuel temperatures and level formation. Therefore, only if the test result blockage approaches the maximum assumed in the LTR evaluation would the high fuel temperatures be expected and debris adherence likely. Also, it is important to consider that for BWR/2 plants, significant blockage does not affect the design basis core spray flow, because of the insignificant steam up-flow present. Therefore, debris adherence to hot fuel surface consequences would be limited to heat transfer considerations rather than blockage magnitude.

Cladding temperature trends for JP and non-JP plants are provided in Attachment A, "Supplementary RAI Evaluations" in Enclosure 2 to BWROG-12016. Figure 1 is applicable to the hot channel in a JP plant design; Figure 13 is applicable to the hot channel in a non-JP plant design. While the PCT predicted for the non-JP plant is substantially higher than that predicted for a JP plant, the duration of the temperature excursion is shorter and non-JP plants do not exhibit secondary heatup with outlet blockage. The PCT for a non-JP plant is calculated to exceed the fiberglass fiber softening temperature (see below) so that the formation of a glassy deposit might be possible. For JP plants, the PCT is calculated to remain below the fiberglass melting temperature. In both cases, however, fibrous and particulate debris would be expected to remain on the hot cladding surface under high cladding temperature conditions – water containing debris would likely flash to steam leaving the debris behind as a deposit.

The BWROG is proposing to evaluate the effect of debris adhesion on hot surfaces through bench tests.

To address the potential for thermal adhesion of debris in the post-LOCA environment, a benchtop test has been defined and described in Attachment B. Benchtop Test 3 (BT3) is specifically designed to determine whether thermal adhesion is possible and to what extent for the un-submerged bundle case.

Softening and melting temperatures for fiberglass materials are observed to vary significantly from supplier to supplier. Performance Contracting, Inc. (PCI) provides a melting temperature for NUKON® insulation of 1,300°F (http://pciesg.com/media_library/NUKON_MSDS.pdf). Another supplier (i.e., BGF Industries, http://bgf.com/fiberglass_cloth/default.asp) provides the fiberglass softening temperature as 1,555°F and the melting temperature as 2,075°F.

(b) *Although testing of a submerged core is appropriate, Tests 4b and 4d do not address the issue raised in part (b) of RAI 23 related to boiling in the fuel assembly. The issue is associated with the redistribution and nonuniformity of debris transport and accumulation in the fuel channel, namely, the excessive washing of debris out the bottom of the fuel assembly by liquid water, some of which would have been vaporized under realistic thermal conditions. The transport of debris tends to correlate with the transport of liquid water via the entrainment process. Therefore, performing Test 4 at room temperature will result in excess liquid downflow through the fuel channel, which presumably will lead to excess debris entrainment and transport to lower spacer grids and potentially out the bottom of the fuel bundle. Whereas, in the plant condition, vaporization of the liquid coolant in which the debris is entrained would presumably result in substantially more of the debris being retained at the locations where vaporization occurred. Because all tests will be performed at room temperature, the potential for excessive washdown exists in 4b and 4d just as it does in 4a and 4c. Therefore, in light of the discussion above, please provide adequate technical basis that excessive washdown of debris with the fuel channel will not adversely affect the planned fuel assembly blockage tests.*

Response:

It is correct that the prototypical inlet blocked bundle condition exhibits an ever decreasing rate of water flowing downwards, as the lower tie plate is approached from above, and debris would be expected to accumulate within the blocked bundle and thus be available to be deposited in greater quantities at spacers. Downward water flow in a given section, in the prototypical condition, is only equal to that being steamed upwards at the same cross section, and therefore by including the lower flow, corresponding to that at the limiting fully rodded spacer section, in the test, the effect of the debris washdown on blockage formation can be determined. Additionally, the effect of the increased debris concentration resulting from coolant vaporization will be assessed and compensated for in the test plan (described in the RAI 4a response). Also, to avoid unrealistic debris injection quantities, the total debris content available to any one bundle will be established before the testing, and injection suspended when this maximum has already been collected in the bundle.

The issue of downwash will be evaluated during full height bundle testing by examining the level of debris that passes through the fuel assembly with time. As flow rate is decreased, the debris concentration in the flow that is recirculated back to the top of the fuel assembly is expected to decrease because lower flow rates will likely result in more hold-up higher in the fuel bundle. However, a point is expected to be reached where further decreases in the flow rate will no longer increase the debris hold up within the fuel bundle. An initial assessment of this lower limit flow rate will be obtained from the benchtop test program described in Attachment B. Specifically, Benchtop Test 4 (BT4) incorporates many relevant phenomena and can be used to determine whether the above strategy for identifying the lower limit of flow rates to be investigated is viable.

RAI 24 S1:

The response to RAI 24 did not fully demonstrate the adequacy of a test acceptance criterion based solely on the coolant flow rate entering the bundle. Please address the following remaining issues:

(a) *Sufficient information was not provided to conclude that a test acceptance criterion of [[ ]] blockage of the fuel channel outlet flow area (or similarly a [[ ]] reduction in flow) is adequate for Test 4. Depending on the specific configuration, blockage of this magnitude could interfere with the formation of falling liquid films on fuel rods and channel walls, result in a flow maldistribution within the fuel bundle, and/or shield some fuel rods from direct exposure to spray. Furthermore, this extent of blockage would presumably tend to reduce the fraction of droplets in the flow. These effects may degrade core spray heat transfer relative to the reference analysis predictions based on the SAFER evaluation model for BWRs with and without jet pumps. It is further unclear whether bench tests such as those alluded to in the response to RAI 24 part (a) would be capable of addressing these unresolved technical issues if significant debris blockage occurs. Therefore, if prior approval of the test acceptance criterion is desired, please provide additional information demonstrating that [[ ]] blockage at the fuel channel outlet will not degrade core spray heat transfer. Alternately, it may be possible to establish the conclusion of negligible degradation to core spray heat transfer due to the accumulation of post-LOCA debris a posteriori based on observed test results.*

Response:

While two-phase flow exists in the BWR core, the upper portion of the core is cooled by water droplets from the core spray injection, liquid film on the clad surfaces, and rising steam flow. The core spray injection is cooler than the steam above the fuel bundle and causes condensation of surrounding steam and therefore increases its effective injection rate. If a debris bed on the upper tie plate causes water entry into the core to be less uniform than it would be without the debris bed, the steam generation within the fuel bundle would redistribute the coolant throughout the fuel bundle.

At the low reactor pressures associated with the postulated LOCA event, the phase change from water to steam inside the fuel bundle increases the volume of the coolant by a factor in excess of 1,000 to one. This rapid increase in coolant volume would cause a rapid movement of coolant from wetted areas where the steam is being generated to other fuel bundle regions where steam is being generated at a lower rate because there is less coolant. Therefore any maldistribution of coolant to the upper portion of the fuel bundle due to debris bed formation on the upper tie plate would be mitigated by the dynamics of steam generation and distribution in the fuel bundle. This steam generation would also cause the flow to wrap around adjacent fuel rods and therefore reduce concerns about view factors. For example, if 0.01 gallons of liquid coolant in the fuel bundle is converted to steam, it would fill roughly the equivalent of a 20 foot length of the fuel bundle with steam.

As noted in the LTR, for BWRs 3 through 6, fuel rod cooling does not require a falling liquid film on the rods and channels because of the rapid core reflooding and resulting steam flow.

The BWROG will observe any non-uniformities in water entering the fuel bundle from above and, if needed, will analyze any conditions that are not representative of the assumed 50% blockage in the LTR.

(b) *The response concerning the potential for debris accumulation at multiple spacer grids does not account for (1) the potential for multiple CCFL locations (e.g., due to variation in flow area and steam flow along the bundle elevation) or (2) the additive nature of differential pressures due to debris accumulation at multiple spacer grids along the elevation of a fuel bundle. In both cases, despite satisfying the test acceptance criterion of no more than [[ ]] blockage at any given spacer grid, cumulative detrimental impacts may occur that are not bounded by the analysis performed by the BWROG which accounts for a single differential pressure drop due to [[ ]] blockage of the fuel channel outlet flow area. Please either (1) provide further technical basis to address the adequacy of the current approach in generality or (2) commit to addressing the technical issue a posteriori based on actual test results (e.g., by providing further technical basis for the adequacy of the current approach, modeling the actual test results in a revised analysis, etc.).*

Response:

The BWROG agrees with the NRC that should testing provide evidence of similar quantities of debris deposition at multiple spacer locations, the BWROG will address the issue of multiple CCFL locations and cumulative delta pressure effects in further detail.

RAI 26 S1:

For the following reasons, the response to RAI 26 does not provide confidence that the technique of measuring differential pressures of post-LOCA debris accumulations with a slight airflow can provide a representative "loss coefficient" applicable under accident conditions with two-phase, counter current flow:

- *Use of the "loss coefficient" concept implies that a flow restriction is geometrically invariant (e.g., as with an orifice). However, in general the dynamic differential pressure response of a compressible porous medium is affected substantially by factors such as the process fluid, flowrates for both liquid downflow and countercurrent steam upflow, and moisture content. Neglecting the impact of these factors on compressibility by measuring a "loss coefficient" under a slight single-phase airflow may significantly underestimate the impact of debris accumulation at the fuel assembly outlet under actual post-LOCA flow conditions.*
- *The references provided in the response discuss metal foams that, although porous, appear to be essentially incompressible under flow. Additionally, the porosities of the metal foams examined in the references generally appear somewhat greater than the porosity range at which post-LOCA debris accumulations are expected to become problematic. Furthermore, the references do not appear to demonstrate the utility and accuracy of single-phase air measurements under variable moisture levels as an estimator for two-phase differential pressure. Therefore, the relevance of the cited references to the proposed measurement technique appears limited.*
- *Staff confirmatory analysis suggests that, in the vicinity of the [[ ]] blockage limit proposed by the BWROG, the post-quench reheatup cladding temperature reached due to the imposition of debris blockage can be sensitive to modest changes in the percentage of area that is blocked. Aside from the potential sources of systematic error noted above, the uncertainty associated with the measurement technique may be significantly larger than the margin between the proposed debris blockage limit and the calculated blockage fraction at which the reheatup temperature criterion is exceeded.*
- *It is unclear that effects such as the stoppage of two-phase flow in the test rig and dryout of a debris accumulation in bench tests will not degrade its structure and properties.*

In light of the issues listed above, please demonstrate that the methods currently proposed are adequate or propose alternate, technically defensible methods for determining the impact of outlet blockage on the capability to provide adequate long-term core cooling.

Response:

In response to the questions posed by the Staff, an alternate methodology is proposed to evaluate the percent open area at each upper spacer grid location to satisfy requirements of the LOCA analysis.

For fuel bundle test conditions with two-phase, countercurrent flow (Test 4), estimates of the percent open area of the upper spacer grids are needed to verify key inputs to the LOCA analyses. Measurements of the post-test percent open area are challenging because debris beds that are postulated to form within the bundle are likely delicate and could be damaged in the post-test fuel bundle disassembly process. Therefore, evaluation of the debris collected at or between spacer grids and the upper tie plate must be conducted immediately following test termination, prior to disassembly, and measurements to determine the associated head loss at the spacer grids must be conducted during the tests. Three techniques will be used to provide information for determining the percent open area of debris beds that form within the fuel bundle at the spacer grids:

1. Fiberscope visual debris bed interrogation: Applicable for all Test 4 conditions

   At the conclusion of each flow test, an articulating fiberscope will be used to photograph the debris beds at the spacer grids. The images will then be processed to determine the percent open area based on the quantitative examination of the obtained images. This methodology is well suited to conditions where there are definable open areas (areas that do not have debris deposition).

2. Dry-bundle testing (Tests 4a and 4b): Monitoring of water level rise above spacer grids

   The effective water level above a spacer will be measured using a piezometric tap. The reference pressure for the tap will be the pressure within the bundle below the spacer grid. The measurement will inherently account for any void fraction of the fluid retained above the spacer grid for the case where countercurrent air flow is applied. While a direct estimate of the percent open area is not possible from these measurements, it is possible to determine: (a) whether a significant blockage exists; and (b) whether this blockage is changing in time.

3. Dry-bundle testing (Tests 4a and 4b): Measurement of outflow rate

   For Tests 4a and 4b, the fuel bundle will be separated from the fuel support piece and the water exiting the fuel assembly will be collected and measured throughout the duration of the test (either using a weight measurement or tank water level). The difference in the flow rate between the case of the clean bundle versus that with debris will be used to conservatively estimate the resistance, if present, imparted by the debris. This estimate can be obtained by calculating the total difference in the hold-up of water within the assembly. This differential hold-up is directly proportional to the total resistance to flow within the assembly. Using this resistance in determining the resistance of the limiting spacer grid may be overly conservative but the integrated hold-up measurement also allows the verification of steady state conditions. Should the very conservative resistance measurement obtained using this method not meet the test success criteria, the more intricate blockage measurement suggested in Technique 1 will be utilized.

4. For submerged-bundle testing (Tests 4c and 4d): Measurement of differential pressure (DP)

   The measurement methods for the submerged bundle case remain unchanged from that provided in the test program description.

Note that the above methods will be evaluated during the benchtop test program described in Attachment B. Specifically, BT4 will share many characteristics with the full height bundle tests and will prove valuable in demonstrating and evolving the measurement techniques outlined above. Furthermore, note that benchtop testing previously discussed in the response to RAI 24d will not be executed because the diagnostics developed here will supersede the diagnostics that are the subject of RAI 24d.

RAI 27 S1:

(a) *The response to RAI 27 does not provide sufficient basis to conclude that satisfying the acceptance criteria for Tests 4a and 4c is sufficient to demonstrate adequate core spray cooling. For example, a [[ ]] (or [[ ]]) flow reduction in Tests 4a and 4c without CCFL suggests that an identical debris blockage restriction in the presence of CCFL would result in a larger reduction in liquid downflow than has been analyzed. Therefore, please justify the compatibility of the acceptance criterion for Tests 4a and 4c (which omits CCFL) with the criterion derived from the reference analysis (which models CCFL).*

Response:

The goal of Test 4 is to establish the maximum blockage possible at any spacer or outlet grid when the inlet is assumed to be fully blocked. Test 4 includes four different dynamic hydraulic boundary conditions to represent possible flow/debris interactions with respect to debris capture in the fuel spacers and upper tie plate. Tests 4a and 4c have no air injection and therefore the blockage will not be influenced by CCFL, whereas Tests 4b and 4d have air injection and therefore the blockage will be influenced by CCFL. It is possible that for Tests 4b and 4d, CCFL may occur at high air flow and high core spray flow conditions and thus provide evidence that developing blockage though high core spray flow would clearly not be limiting for the peak temperature calculation. An inlet blocked bundle only allows outlet flow at the approximate magnitude of the steam flow from decay heat, so high outlet flows are not realistic for a blocked bundle scenario. The submerged Test 4d with increasing air flow will require a higher driving head to produce the same outlet flow for clean conditions, and therefore, the debris test results would reflect the effects of the blockage formation. In any case, Test 4 includes both measurements of pressure loss increase at every restriction (for the submerged bundle subset) and observations of coolant accumulation at spacers that would indicate CCFL. The BWROG is committed to examining the Test 4 results in greater detail than merely degree of blockage area and submitting a test report to the NRC to justify that the analytical assumptions are valid or conservative. Additionally, the NRC is able to include the blockage basis in the SER to ensure to address complex debris deposition such as porous bed or highly localized characteristics.

(b) *The countercurrent upflow of steam may have a significant impact in delaying and/or reducing the impact of debris blockage at fuel channel outlets. However, lacking demonstration of the insignificance of a number of effects that could increase the resistance of debris to removal by steam upflow (e.g., thermal adhesion, boiling agglomeration, scale formation, oxidation, and crud buildup), performing clean-assembly room-temperature tests simulating the effect of steam upflow (Test 4b and 4d) may be nonconservative. Although the BWROG's RAI responses provided some information regarding the perceived impacts of these phenomena, ultimately that information (1) depends on unvalidated assumptions (e.g., regarding where debris blockage would occur, that core spray cooling would not be degraded) and (2) does not* *appear applicable to all operating BWR designs (e.g., BWR/2s). Therefore, please demonstrate that the above effects have a negligible impact on debris accumulation and retention in the core, explain how these effects can be accounted for in room temperature tests, or else refrain from crediting countercurrent gas flow with degradation or removal of debris accumulations from the test assembly at room temperature conditions.*

Response:

The principal concern expressed in this RAI is regarding the over-estimation of the potential benefit of steam flow preventing formation of more limiting debris blockage. The behavior of debris in a steam environment and hot fuel surfaces could adversely affect the steam clearing phenomena such that a more limiting blockage pattern may not develop under cold clean surface conditions. It is important to keep in perspective that long-term hot fuel surface temperatures are developed in JP BWRs only after the blockage has developed inside the bundle from outlet flow with debris, thus the outlet blockage precedes the hot fuel temperatures and level formation. Also, it is important to consider that based on Case A-5 for BWR/2 plants and the BWR/2 steam flows in Figure G-3 of Attachment G, that steam up-flow is insignificant (the break is in the bottom of the vessel), and cooling flow is unaffected for blockage larger than established for JP BWRs. Therefore, credit for steam up-flow is appropriate for the early portion of the LOCA, after the inlet is blocked and fuel surfaces are at low temperatures, should the blockage develop to produce higher fuel temperatures, full credit for steam up-flow can be discarded. The benchtop test program described in Attachment B will address the potential for debris removal by steam up-flow to be inhibited by fuel rod characteristics such as surface roughness or surface deposition (thermal adhesion, scale, and crud). The potential phenomenon of concern will be evaluated using benchtop test BT2.

It is the intention of the BWROG to apply the test results to the analytical evaluation such that the PCT consequences remain bounded. This application includes the full range of both coolant and air flows, as well as the characteristics of the blockage. Finally, the NRC staff may also impose requirements on the application of test result blockage air credit, as well as blockage pattern assumptions that must be addressed so that the BWROG factor those requirements in the testing matrix and/or data collection.

RAI 28 S1:

(a) *The NRC staff considers the countercurrent air flow in Tests 4b and 4d to be a critical parameter that should be chosen to bound operating BWRs. Therefore, please provide a graph of relevant simulation results showing the limiting flowrate and velocity of countercurrent steam flow versus time for the hot bundle and the average bundle at the channel outlet and most restrictive bundle elevation for (1) a partially submerged bundle, (2) a fully unsubmerged bundle, and (3) a fully submerged bundle, for the duration over which Tests 4b and 4d will be performed. Please further identify the air flowrate and injection velocity to be used as a function of time for Tests 4b and 4d and provide justification that these parameters are bounding for operating BWRs with and without jet pumps.*

Response:

The planned Test 4 includes several air injection rates from zero to a maximum range. This maximum reflects the mass velocity corresponding to steam of a high power fuel assembly at the decay heat corresponding to the blockage criteria history assumed in the reference LOCA analysis. The mass steam flow is based on vaporizing saturated coolant, from the total assembly power, at the corresponding system pressure of the long-term LOCA conditions. The SAFER steam up-flow and coolant down-flow under core spray and pool conditions, as well as BWR/2 conditions, are discussed in Attachment G. Therefore, it is possible that for high coolant down-flow Test 4 conditions, CCFL may be observed.

The steam flow from the hot channel at [[

]]. The theoretical maximum steam flow based on a decay heat power of 0.124 MWth is 0.12 lb/sec. It is expected that the reduced steam flow is due to the subcooled core spray flow for Case 04. Therefore, if the simulated steam injection proves to limit debris blockage as expected, the maximum credit steam flow [[
]] of the theoretical maximum.

(b) *Please clarify whether the air and liquid flows considered in Test 4b encompass accident conditions for which the upper plenum is covered and for which it has no accumulated liquid. If both conditions will not be tested, then please provide justification.*

Response:

The Test 4b boundary conditions consider a dry/empty bundle with air upflow against liquid downflow. This test represents accident conditions where the fuel is fully (such as a BWR/2) or partially (such as long-term level collapsed from insufficient cooling or low decay heat) uncovered. The liquid downflow represents either core spray or saturated pool draining into bundle as limited by CCFL. Both types of injection flows are considered equivalent [[
]]. Therefore, the blockage mechanism will depend on the air and drainage flows plus the bundle geometry, not the

injection pattern. However, the upper plenum pool observed in the SAFER simulations is the result [[

]].

(c) *Please clarify whether the proposed Tests 4b and 4d will consider the potential for CCFL at the most restrictive spacer grid that engages all partial length fuel rods. This spacer grid may represent a limiting location for CCFL in the presence of debris accumulation.*

Response:

The air flow range planned in Tests 4b and 4d represents the steam flow calculated for the hot channel LOCA conditions and validated by comparison against analytical calculations as given in RAI 28a. The air flow range will represent appropriate velocities at each spacer type such that the blockage characteristics for those conditions are captured. Tests 4b and 4d at high air and coolant flows are expected to show CCFL interaction between air and water in cold conditions. Therefore, the planned observation and measurement of water accumulation and flow reduction (because the driving head is based on target flow at clean conditions) during the debris injection can be used to evaluate the CCFL behavior as debris are collected in spacers. When test parameters are not near the CCFL, reliance on DP and flow measurements (again because driving head is established for the target flow at clean conditions) and visual assessment of blockage characteristics will be used.

(d) *Please confirm or correct the NRC staff's understanding that the statement in part (e) of the response to RAI 28 that a correction for steam condensation is unnecessary because coolant in a fuel channel is completely saturated is a description of the SAFER evaluation model that approximates the actual post-LOCA condition for the reactor. Please further explain whether the statement holds for all operating BWRs regardless of whether or not the core is fully submerged (as simulated in the newly added Test 4d) or whether coolant has accumulated in the upper plenum.*

Response:

The response is with respect to the determination of the <u>maximum</u> steam flow calculated for the test. It is based on vaporizing saturated coolant by the HB power under postulated LOCA conditions and validated by comparison against predictions by the SAFER model as discussed in RAI 28a. The tests will include lower air flows simulating the steam corresponding to the reduced power in the portion of the bundle below the limiting fully rodded (minimum flow area) spacer. Therefore, steam condensation by saturated or subcooled flow entering the top of the channel, or present within the channel, under LOCA conditions would reduce the maximum steam flow. The test results will be documented in a test report that will evaluate the results and boundary conditions, such as steam and flow rates, against the analytical evaluation used in the LTR.

RAI 31 S1:

(a) *In various places, the TR and RAI responses use percent blockage and percent flow reduction interchangeably, although these parameters are in general not equivalent. Also, while the response to RAI 31 states that Test 4 does not include the CCFL phenomenon, this only appears to be true for Tests 4a and 4c. To avoid ambiguity, please specify the acceptance criteria for Tests 3 and 4 unequivocally and justify the equivalence of the test acceptance criteria with the blockage assumptions made in the reference and supplemental analyses.*

Response:

It is correct that the reference and supplemental analyses apply an area reduction as described in the LTR. The resulting calculated flow reduction is based on assuming the same loss coefficient on the reduced area, and depending on the maximum flow available, the reduction in flow varies. The test result report will use the actual pressure drop and flow data, including visual examination of the blockage characteristics, to justify that the analyses are conservative.

(b) *The requested justification for the acceptance criteria specified for Tests 3 and 4 relative to assumptions in the reference analysis was not fully provided in the responses to RAIs 30 and 31. In particular, the responses do not demonstrate that allowing intermediate flow reductions earlier than has been analyzed (i.e., while fuel temperatures remain elevated) would not result in values of PCT and cladding oxidation that are higher than the BWROG has predicted. Therefore, please provide the results of revised analysis of the limiting case(s) (considering both the reference and supplemental analysis scenarios), demonstrating that a flow reduction schedule commensurate with the actual acceptance criteria proposed for Tests 3 and 4 will not result in increased PCTs or otherwise violate the proposed test acceptance criteria. If this analysis shows the intermediate acceptance criteria proposed for Tests 3 and 4 are nonconservative, then please propose new acceptance criteria that have been shown to be adequate in revised analyses that directly incorporate the allowable flow reductions.*

Response:

It is correct that the reference LOCA analysis does not incorporate the same blockage function originally proposed as acceptance criteria in Table 5-1 of the LTR (these functions are now merely targets for the tests as the justification will be included in the test result reports). Previous fuel blockage sensitivity analyses showed insignificant effects of blockage magnitudes not approaching the values selected for the reference analyses. Therefore, the blockage functions in Table 5-1 [[

]]. The study calculations show that the effect of the limited earlier inlet and outlet blockage does not result in any significant PCT increase. Therefore, the reference analyses used in the LTR and RAI responses remain valid.

(c) *Please clarify the statement that the Case 4 reference analysis applies a spray flow that is lower than allowed by CCFL. Specifically, is the hot bundle spray flow simulated in the Case 4 reference analysis less than the CCFL downflow limit for both [[ ]] and [[ ]] blockage at the fuel assembly outlet? Please further address this question for the spray flow assumed in the BWR/2 supplemental analysis scenario (A-5) in Attachment A to Enclosure 2 of the second RAI response.*

Response:

The HB core spray that is applied is described in Attachment G for both BWR/2 and later JP BWRs. When there is not a pool present, and no blockage at the outlet grid [[

]]

A bounding low core spray flow to hot channel of 1.8 gpm (0.25 lb/sec) is used in the LTR JP long-term analysis; the design minimum is in the range of 2.5 to 3.0 gpm. For BWR/2 plants, the core spray flow is based on each unique available pump and booster pump configuration and is generally higher than that for JP BWRs. Because the core spray flow for BWR/2 is unaffected by blockage (e.g., no CCFL), its magnitude does not need to be confirmed in the LTR.

<u>RAI 32 S1</u>:

(a) *With respect to assessing the impact of debris blockage, post-LOCA core flows for operating BWRs can largely be considered to be driven by static heads (e.g., due to the coolant level in the downcomer, bypass region, or upper plenum), rather than pump discharge heads. Thus, for test conditions where debris accumulations may be sensitive to removal by high differential pressures, ensuring adequate flow at the minimum available driving head represents a realistically conservative test. As such, please clarify the response to RAI 32, which appears to suggest in part (b) that the maximum driving head would be conservative.*

<u>Response:</u>

The statement that the maximum is conservative is only meant to indicate an upper bound. The test is planned to consider the full flow range including trials at lower flow rates as well. However, recognizing that Test 3 is for limited duration, it is expected that high flow will result in more debris being trapped in the lower tie plate grid filter.

(b) *Part (c) of the response to RAI 32 suggests that the BWROG considers it conservative to simulate the fluid velocity with a higher priority than the available driving head. However, due to the potential for excessive differential pressures to break up and/or sweep debris accumulations from the core, it is unclear whether this assessment is correct. Furthermore, rapid flow changes or oscillations induced by automated pump control systems seeking to maintain constant flow in the test could degrade debris accumulations nonprototypically. Therefore, please clarify why it is not necessary to enforce a (time-dependent) limiting driving head for each test flow (i.e., some tests have upflow and downflow) that is based on the minimum driving head for the BWRs being represented by the test (considering the potential for reduced mixture densities under post-LOCA conditions), meanwhile ensuring adequate flow is delivered.*

<u>Response:</u>

Both Tests 2 and 4 are specified with flow ranges that bound the possible coolant velocities (Test 2 slow reflood to fast reflood rates and Test 4 from maximum to minimum spray and/or CCFL/steaming flows) that cover the range of BWR responses. In practice, both of these tests will be run with constant driving head that reflects the specified target flow rates under clean conditions. Also Test 3 (natural circulation flow) is planned as a head driven test that reflects the flow range expected for the bundle void conditions.

RAI 33 S1:

The response to RAI 33 does not distinguish between two cases: (1) a flow area (e.g., tie plate or spacer grid) that is [[ ]] blocked and [[ ]] open and (2) a similar flow area covered by a largely contiguous porous medium that develops a differential pressure equivalent to the first case under single-phase flow test conditions. Although the staff agrees with the technical analysis and reasoning in the BWROG's RAI response for the first case, it is not clear that the response adequately addresses the second case, when the potential for two-phase flows and CCFL are taken into account. Specifically, both from intuitive considerations associated with the change in the effective hydraulic diameter of the flow area, as well as empirical observations of significantly elevated porous medium head losses under two-phase flow, it is not apparent that two-phase flow through an arbitrary porous medium may be accurately modeled as flow through a non-porous flow restriction of equivalent single-phase pressure loss. Therefore, please provide additional technical justification specific to countercurrent flow through a porous medium that demonstrates that flow stoppage and formation of steam bubbles is not a concern for operating BWRs. Alternately, it may be possible to establish this conclusion a posteriori based on observed results of fuel assembly blockage tests.

Response:

Consistent with RAI 11 S1, the BWROG agrees to address the blockage test characteristics with respect to the assumptions applied in the analytical evaluation. It is agreed that significant porous blockage requires different hydraulic loss assumptions, which would be determined by post-test result examination and justified in the test report.

<u>RAI 34 S1</u>:

The time duration of interest for Test 4 covers the full range of post-LOCA upper plenum conditions over the ECCS mission time. To ensure test prototypicality, please clarify the response to RAI 34 part (b) as to how liquid levels and flow conditions in the upper plenum and fuel channel that correspond to times beyond the analytical calculations (e.g., beyond [[ ]]) are identified and simulated in the test condition. In other words, as decay heat diminishes, do the mixture levels, fluid conditions, and flows in the upper plenum and fuel channels deviate meaningfully over the ECCS mission time from the analytically derived values used to define the test condition?

<u>Response:</u>

The analytical results establish a maximum long-term outlet blockage with a corresponding history that meets the acceptance criteria with a fully blocked inlet. The analytical results end with an improving cooling performance and steady conditions with flow from the core spray or upper plenum pool. A sensitivity study that is included in Attachment I shows that the HB condition at the end of the analytical time continues to slowly saturate in liquid inventory as decay heat decreases in time. Long-term Test 4 applies a flow range from minimum CCFL values, as limited by the applied blockage, to maximum core spray values, which bound the expected long-term boundary conditions to demonstrate acceptable blockage against the analytical basis. The debris in the coolant must consider any combination and concentration expected for the long-term. The most limiting Test 4 blockage results will be justified to be bounded by, or lead to no more severe results than, the analyses of the reference LOCA calculation. The complexity of the justification (e.g., a simple flow area or a time dependent blockage), will depend on the margin that the blockage tests demonstrate.

Therefore, the planned Test 4 (including the 4 sub-tests) with constant flow and debris, over the range of flows and debris concentrations, will yield sufficient data to determine what the limiting blockage may be.

RAI 36 S1:

Please describe the sensitivity study that will be used to determine the limiting debris loading for Tests 1 through 3 and provide justification that the sensitivity study is capable of identifying the debris mixture for both the fuel assembly inlet and bypass leakage paths that is conservative in terms of its overall effect on PCT.

Response:

The sensitivity studies will use design of experiment methods (a statistical approach to define tests that determine the effect of multiple variables on experimental outcomes) to determine the critical variables in Tests 1 through 3 that have the largest effect on the measurements of interest, be it lower plenum refill times, bundle flood times, or blockage at the lower tie plate. The experimental data that will be collected from Tests 1 through 3 are described in detail in the test program plan. Parameters to be considered in the sensitivity studies include the debris composition, quantity, concentration, and flow rate (among others). Once the critical test parameters and the dominant effects have been defined by the sensitivity studies, the limiting test cases can be constructed from the known variation of the source term conditions for the BWR fleet. Each of the three tests will have its own sensitivity study so that the most critical parameter conditions for the specified test will be used. This approach may result in the limiting conditions for one test differing from the limiting conditions of another test. The test results will either confirm the conservative assumptions used in the LTR analysis or require changes in the analysis to match the experimentally determined limiting conditions. The LOCA analysis uses the flow blockages (which will either be verified by testing or revised as a result of testing) to define the fuel bundle PCT.

RAI 38 S1:

The response to RAI 38 references as-fabricated bypass clearance dimensions at room temperature. Please justify that any impacts to the clearances credited in the testing program due to installation in a reactor (e.g., thermal expansion, compression forces, crud and oxide buildup) are either negligible or are accounted for in the test setup.

Response:

The thermal expansion issue could be addressed because the coefficient of thermal expansion for stainless steel is about 2.5 times greater than for Zircaloy. Therefore at operating temperature, the bypass region gap would increase, as would the typical rod-to-rod spacing. The only gap that would be reduced by temperature would be the peripheral rods to the channel wall, which would be decreased only by about 0.006 inches. That difference is small relative to component tolerances and may therefore be neglected. Regarding reactor pressure, the main effect would be on channel outward bulge. This would tend to open up the most limiting flow locations inside the bundle and therefore using as-built geometry is conservative for this test. The concern about the crud/oxide buildup is the same as for RAI 6 S1. The change in clearances due to crud and oxide layer can be estimated using Figure 6b-2, Fuel deposit thickness measurements as a function of exposure, in typical US BWR plant chemistries. As stated in the previous RAI 6 response, these values are very small relative to the rod-to-rod spacing and the clearances between rods and spacer parts.

RAI 40 S1:

The benchtop tests discussed in the response to RAI 40 appear useful for characterizing the debris accumulation properties and local impacts. However, factors that may significantly impact the characteristics of an accumulation that may not be modeled in the benchtop tests include (1) thermal adhesion, (2) flow characteristics governing local debris accumulation, (3) boiling/concentration of debris, and (4) the buildup of crud, oxide, and/or scale. Please describe the extent to which these factors will be considered in the characterization and provide a basis for any factors considered to have a negligible effect on the properties of debris accumulations.

Response:

Attachment B describes the full benchtop test program. BT2 is intended to integrate a variety of surface effects and to understand their combined potential effect on debris accumulation. In addition, BT4 is specifically designed to examine the potential for non-uniform debris accumulation considering both non-uniformity in core-spray flow and non-uniformity in the spacer grid openings near the top of the fuel bundle. Because the benchtop tests are intended in part to address the potential for non-uniform debris accumulation at the spacer grid, the benchtop tests will also help address concerns raised in RAI 24a.

RAI 41 S1:

The NRC staff does not agree with the technical justifications for (1) excluding the debris shield porous mesh filter from testing and (2) ranking the fuel filter designs in terms of expected debris accumulation behavior based on projected area that were provided in response to RAI 41. Rather, experience indicates that debris capture at locations with minimal clearance is a determining factor regarding whether and the extent to which blockage occurs. Furthermore, although a general conclusion cannot be made due to the wide variety of possible designs, the dynamic response of head loss per unit of accumulated debris may tend to be more limiting for flat porous mesh fuel inlet filters than those that rely on tortuous geometry. Therefore:

(a) In order to exclude non-limiting fuel designs from testing, at a minimum, please provide the following additional information:

i. Actual minimum clearance dimensions at each flow restriction (e.g., filters, tie plates, spacer grids).

ii. Actual flow areas for each flow restriction.

iii. A diagram of the limiting restriction(s).

iv. An evaluation of inertial capture at the openings of porous mesh fuel channel inlet filters and other restrictions (i.e., filtration), which cannot be determined solely or primarily through consideration of maximum changes in projected area.

v. As applicable, an evaluation of the expected difference in the dynamic response of head loss per unit of accumulated debris for porous mesh and tortuous fuel channel inlet filters, particularly in light of the short mission time the BWROG has proposed for crediting inlet flow.

Response:

[[

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(b) *If test results from a porous mesh filter are to be used to justify not testing tortuous filters (or vice versa), then please justify the applicability of conclusions from one filter design to a fundamentally different design that is governed by different debris capture mechanisms and design parameters, and presumably has a different dynamic response to the accumulation of debris.*

Response:

[[

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(c) *Please confirm that the three fuel designs listed in Table 41b-1 are currently the only General Electric Hitachi (GEH)/Global Nuclear Fuels (GNF) fuel types that may be limiting hot bundles at operating BWRs. If this is not the case, then please provide design information relevant to debris blockage potential for the additional fuel types.*

Response:

[[

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(d) *Please clarify the statement in Table 41b-1 that the upper tie plate grid projected flow area is specified with "All Rods Inserted." Does the quoted phrase denote the projected flow area is for fuel bundles with only full length fuel rods?*

Response:

[[

]]

(e) *Please clarify whether there are GEH/GNF fuel assemblies that may be in service at operating BWRs with smaller fractions of long and short partial length rods than the*

BWROG plans to test. Please further clarify whether other fuel designs may have the uppermost fully rodded spacer grid at a higher elevation than those in Table 41b-1. With regard to the Test 4 condition, as well as the supporting analysis, it is not clear that the BWROG's program would bound such fuel assemblies, even if they are not hot bundles. Therefore, please either (1) include such fuel assemblies in the test program or (2) provide adequate justification if the BWROG intends to apply the results of the test program such assemblies.

Response:

[[

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(f) *Please clarify the location of Flow Area 11 on Figure 41b-1.*

Response:

[[

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RAI 42 S1:

The NRC staff understands GEH's observation regarding the limited influence of the core average power level for extended power uprate calculations. However, it is not clear that this experience applies to the scenario where debris blockage is postulated across the entire core inlet, which the supplemental analyses in Attachment A to the second RAI response now show to be limiting cases for BWRs with jet pumps. As noted by the BWROG in its discussion of these results (i.e., A-1 and the similar A-4), it is the higher coolant enthalpy in the upper plenum that influences the hot channel level and hence the hot channel PCT. Because upper plenum coolant enthalpy is presumably influenced by the core power, please provide additional technical basis and/or analysis showing that core power does not impact the magnitude of the hot channel heatup when debris blockage is postulated across the entire core inlet.

Response:

It is correct that core power does affect the results of the secondary, long-term PCT history (no effect is expected for the short-term limiting PCT from blockage). However, the intent of the reference LOCA hot channel blockage only and supplementary LOCA Case A-4 average channel blockage (fuel and bypass paths) are meant to represent the range of upper plenum boundary conditions experienced by the hot channel. These two cases reflect both an empty and a full upper plenum where core power level only influences secondary LOCA behavior like level formation time and fluid quality. Attachment C shows the behavior of the secondary long-term PCT for different plant types and power levels for both core blockage bases. The results illustrate the similarity of the secondary long-term PCT for the various plant types and conditions, in that a reheat is always present for the specified basis blockage magnitude and timing. However, the specific PCT behavior is somewhat dependent on the timing of pool formation or elimination, which varies as a result of plant/system/condition variation that influence the upper plenum pool formation, and thus the liquid magnitude and enthalpy of the flow into the bundle. The bundle in-flow in turn determines the level inside the fuel channel and the PCT. Therefore, the reference LOCA and supplementary A-4 case results are appropriate representations of specified fuel blockage spanning power uprate conditions.

<u>RAI 46 S1</u>:

Please provide the requested information below that was not included in the RAI 46 response:

(a) *Are minimum ECCS flows for all operating BWRs with jet pumps sufficient to preclude long-term uncovery below two-thirds core height for a pressure boundary rupture on reactor vessel bottom head penetrations (e.g., reactor water cleanup system vessel drain line, control rod drive housing)?*

<u>Response:</u>

That is correct; any ECCS pump can mitigate any leakage from the bottom head drain. The GEH LOCA procedure includes allowance for bottom head drain leakage when not isolated during a postulated LOCA to maintain 2/3 core height.

(b) *If the response to part (a) is negative or undetermined, then please provide a more detailed technical basis and/or analytical calculation demonstrating that the rupture of reactor vessel bottom head penetrations would not become limiting for BWRs with jet pumps when post-LOCA debris accumulation is considered.*

<u>Response:</u>

The response to RAI 46 S1 (a) is positive, unless the debris is assumed to change the licensing basis LOCA AOR conclusion.

RAI 49 S1:

Please provide further clarification regarding the applicability and scaling of Tests 1, 2, and 3.

(a) *Test 1 requires the injected ECCS flows to pass through bundle- or cell-specific leakage paths. For all jet pump BWRs, please identify whether the associated analysis credits additional leakage paths (e.g., bypass-to-lower plenum leakage paths) that are not included in the blockage test program, and whether such leakage paths are susceptible to debris blockage that could increase the time required to fill the lower plenum. If so, please discuss how this was factored into the test scaling.*

Response:

Three leakage paths credited in LOCA analyses are not modeled in the planned blockage test. The relative contribution of the various leakage paths is given in Table 2-2 of NEDE-20566-5P and show the cumulative contribution of those three paths as [[

]]. Therefore, these paths are not significant.

(b) *The description of Test 1 in Appendix A to the TR indicates that this test will be run for five minutes. Please confirm whether the integrated flow through the bypass flowpaths in this test will encompass the calculated integral flows for these flowpaths on a per bundle basis over the full time period these flowpaths are credited in the reference and supplemental analyses (i.e., including BWRs with LPCI injection into the core shroud). If integral flows corresponding only to lower plenum filling will be considered, please clarify whether Test 1 is sufficient to demonstrate that bypass leakage paths will not become blocked over the entire period for which they are credited for BWRs with LPCI injection into the core shroud.*

Response:

The staff description is consistent with the plan; Test 1 will encompass from minimum to maximum flow per bundle injected inside the shroud for any BWR up to the elevation head refilling inside the shroud. The Test 1 duration bounds any reasonable vessel refilling time, including fuel reflood time, and is therefore conservative for the case where higher flows are injected in the bypass region. The coolant enters the fuel assembly through the lower tie plate grid from either the SEO or bypass flow holes. The duration of Test 1 spans the Test 3 time and therefore ensures that the bypass flow paths are available. No credit for inlet flow is required for long-term because BWR fuel can always rely on cooling from the top of the channel. The core spray per bundle range is approximately 6 to 22 gpm, and the inside shroud LPCI per bundle range is approximately 7 to 67 gpm, considering minimum to maximum systems available and plant design differences. Finally, the integrated flows are expected to bound the filling capacity of the vessel because of the longer duration of the test and the higher injection capacity being applied.

(c) *Please clarify whether potential reductions in the flow rate for Test 1 could impact Tests 2 and 3 and associated analysis for BWRs with LPCI injection into the core shroud. Specifically, significantly reduced flow rates in Test 1 at integrated flows corresponding to the reflood phase could imply that the minimum upflow rate intended for Test 2 cannot be provided due to upstream debris restriction at the bypass flowpaths. Similarly, significantly reduced flow rates in Test 1 at integrated flows corresponding to the post-reflood period prior to the assumption of inlet blockage could imply that the minimum flow rate intended for Test 3 is not achievable. How would the BWROG propagate potential flow reductions in Test 1 into succeeding tests and associated analysis if it becomes necessary for BWRs with LPCI injection into the core shroud?*

Response:

It is correct that appreciable flow reduction in Test 1 (flow from the bypass region into the lower plenum and bundle inlet) and/or Test 2 (reflood rate through the bundle length) can affect the calculated PCT by delay in reflood time. Note that the goal of both Test 1 and Test 2 is that there will be no appreciable effect on either flow by the debris. Though any flow reduction effects in Tests 1 or 2 can be assessed by the range reflood rate in Test 2 and delays in full core reflood time prior to establishing the natural circulation corresponding to Test 3. However, it is expected that the debris content in the coolant for this time period is minimal such that insignificant effect is assumed for Tests 1 and 2.

RAI 50 S1:

According to data from the Multirod Burst Test Program in NUREG/CR-0103 and NUREG-0630, fuel cladding swelling of 5 to10 percent was measured adjacent to spacer grids. While this range is significantly lower than the swelling measured between grids, based on typical fuel rod dimensions, it corresponds to an increase in cladding outer diameter greater than the length of over three-quarters of the fibers reported to have passed through the strainers of PWRs in WCAP-16793-NP. As such, it is not clear that the potential for the swelling of fuel rod cladding, when taken in combination with other effects, such as crud buildup, scale formation, and oxide formation, can be considered negligible with respect to the accumulation of the very fine debris that passes through a strainer. In light of the discussion above, please clarify the rod-to-spacer grid dimension and provide additional technical basis that fuel cladding swelling, in concert with other effects that can affect fuel assembly minimum clearances and surface properties, need not be considered in the fuel assembly blockage testing program.

Response:

GEH previously reviewed the data from the Multirod Burst Test Program conducted by Oak Ridge National Laboratory (ORNL) and determined some of the experimental conditions were designed to simulate pressurized water reactor (PWR) fuel conditions and were not representative of a BWR fuel bundle following a LOCA event. GEH reviewed the proposed analytical methods and material properties of NUREG-0630 and also found that some of the recommended methods of NUREG-0630 were not applicable to BWR fuel conditions, although GEH did implement an adjusted cladding rupture temperature profile. GEH has used FLECHT test data from full length 7x7 and 8x8 BWR fuel bundles to characterize fuel rod swelling and perforation parameters. Following the NRC's issuance of NUREG-0630, GEH submitted supplemental information regarding the GEH model for fuel clad swelling and rupture to demonstrate model accuracy for BWR fuel conditions. The NRC reviewed these supplements to NEDE-20566-P and approved the GEH methods and material properties with an NRC letter, H. Barnard to G. G. Sherwood, *Supplementary Acceptance of Licensing Topical Report NEDE 20566 A (P)*, May 11, 1982.

Tests and analysis of BWR fuel and fuel mockups have shown that rod swelling occurs over a short length of two to three inches, and if the swelling results in a perforation of the fuel rod in the swollen area, there will not be any further swelling of the fuel rod. The elevation in the bundle of the fuel rod swelling cannot be determined analytically as it depends on small non-uniformities in the fuel rod construction, heat transfer, and cladding properties. The BWR fuel tests have demonstrated that if swelling occurs in more than one rod in a fuel bundle, it will typically happen at different elevations for the affected rods. Part of the reason that swelling occurs at different elevations, may be that once swelling occurs in one rod, the fuel bundle cross-sectional area will be decreased at the elevation of the swelling, which will cause the convective heat transfer rate from the cladding to increase in all of the rods at that elevation, thus reducing the cladding temperature of the adjacent rods. It is unlikely that multiple rods would swell at the location of a single spacer.

Fuel rod crud, scale formation, and oxide formation is typically a few thousands of an inch thick and this increase in the rod diameter is negligible when compared to the rod-to-rod spacing. The rod-to-spacer dimensions depend on the particular fuel design. For some current GNF fuel designs, the minimum distance between the rod and the spacer can be as small as [[ ]]. However, there are much larger openings in the spacer and between the spacer and the rod where coolant and debris can pass through.

The BWROG is planning bench top tests in addition to the tests previously described to the NRC staff in NEDC-33608P. These bench top tests will provide additional information on any debris accumulation at the locations of the fuel bundle spacer grids.

Attachment A

LTR Appendix A – BWROG Fuels Testing Program Summary

The US NRC has requested additional information regarding the technical basis supporting adequate post-LOCA cooling of BWR fuel considering the potential for downstream effects of debris on fuel blockage (see, for example, References A-1 through A-4). Specifically, it is postulated that debris generated during a LOCA in a BWR may pass through the ECCS suction strainers and affect the performance of the fuel by restricting flow through the fuel bundles. Debris passing through the ECCS suction strainers can persist throughout the accident scenario from the initial "chugging" phase (unsteady oscillation of the vapor-water interface in the downcomers to the suppression pool) through long-term core cooling. However, it is expected that, for plants with debris bed formation across all available suction strainer screen area, the downstream debris load will diminish with time due to suction strainer debris bed filtering. The BWROG ECCS Suction Strainer Source Term Subcommittee will define: (1) the debris characteristics; (2) the debris concentration history; and (3) the total quantity of bypassed debris to be used in the tests described in this section. Appropriate surrogates will be selected to model the debris types observed in-plant that could be drawn into the suction strainers during a LOCA event including fibrous, particulate, microporous, dust, dirt, and latent debris. Although chemical compounds and their characteristics are uncertain at this time, appropriate surrogates will be tested, if necessary. In all cases, conservative and bounding concentrations of the surrogates will be tested to ensure applicability to the full BWR fleet.

The debris material that passes through the ECCS suction strainers and eventually reaches the fuel bundles can arrive from different flow paths depending on the stage of the accident progression. The proposed test program considers the LOCA event progression, available debris, debris types, coolant flow paths in the core, and debris transport into the fuel. A fuel vendor-independent scenario has been defined that follows the progression of a BWR LOCA event. This common scenario considers the effect of debris-induced fuel blockage during the lower plenum refill, core re-flood, and long-term cooling phases of the LOCA event. Each fuel vendor will determine a PCT without blockage for that defined common LOCA scenario. Each vendor will also analytically establish blockage acceptance criteria such that it can be demonstrated that the base PCT is not affected. The objective of testing is to show that the actual flow restrictions resulting from debris introduced from the suppression pool and entrained in the safety injection flow are bounded by the analytical acceptance criteria.

In advance of the development of the subject test scope, GEH conducted LOCA blockage analyses to identify the limiting plant design and limiting break scenario from the fuel blockage perspective as described in Section 3.4.1. From this analysis, the BWR 3 configuration with an associated double-ended guillotine break in a recirculation loop was identified as the limiting scenario for fuels testing. The available ECCS equipment for a limiting BWR 3 event includes one train of core spray and one train of low-pressure coolant injection. However, consideration is also given in the preparation of the proposed test program to LOCA response sequences and systems for the BWR 2, 4, and 5/6 geometries to achieve the most conservative test results.

Summarizing the event progression following a LOCA event, the LPCI is directed downstream of the recirculation pump discharge valves. From there, the LPCI flow fills the discharge line and flows through the JP nozzles, into the JP throat and then into the lower plenum. The core spray is discharged into the upper plenum via the core spray spargers located just above the top of the core and flows into the top of the fuel bundles and into the bypass region surrounding each fuel channel. The core spray water that flows into the bypass region first accumulates in the control rod guide tubes. Once the guide tubes are filled, the water flows into the lower plenum via holes in the transition piece at the bottom of each fuel bundle (i.e., the lower tie plate bypass flow holes) and several other leakage flow paths. The core refills until the collapsed water level in the core corresponds to the head of water in the JPs. Further ECCS injection makes up for boil-off in the core or spills into the downcomer via the JPs. From there, the water flows back through the JP nozzles and into the broken recirculation pump suction line and out the break. For BWR 5/6 plants, LPCI is injected into the vessel through the shroud.

The test program outline described below considers this basic event progression in defining a series of laboratory tests using representative test assemblies for each US BWR fuel vendor. The results will be used to evaluate the effect of the debris-laden water on the flow performance of each vendor's fuel bundle, LOCA event results, or other licensing parameters. All proposed tests will be conducted at room temperature and atmospheric pressure. While these tests are not designed to replicate the prototypical LOCA transient (at prototype thermodynamic conditions), the proposed tests are meant to conservatively bound the effect of LOCA-generated debris on fuel blockage.

The test bundles to be used in the tests will be full height and representative of commercial designs that implement production components with the exception of fuel rods (individual rods will not contain UO_2 pellets). The core bypass region associated with one bundle will be simulated. Tests 1 and 2 characterize debris blockage internal and external to the bundle; therefore, prototypic channels will be used. For Tests 3 and 4, it is not necessary to model the bypass region because only blockage internal to the bundle is to be characterized. Channels with viewing windows or clear channels will be utilized. For conservatism in Test 4, the channel will be raised off of the lower tie plate to ensure that only the upper tie plate and upper spacer blockages are evaluated. A fuel support piece and simulated core support plate will be provided to interface with the bundle.

The acceptance criteria for the tests will be based on the 10 CFR 50.46(b) cladding criteria as evaluated by each fuel supplier using their licensed methods in modeling the limiting LOCA event with fuel component blockage explicitly modeled using a conservative blockage function (i.e., blockage extent as a function of time). The test results, and technical basis for meeting the LOCA criteria, will be documented in reports and submitted to the NRC for approval. Depending on the specific test results, the justification for meeting the LOCA criteria can involve a wide range of potential technical approaches, from simple blockage data to analytical prediction comparisons, to more rigorous data analysis with plant specific applications.

Test 1: Lower Plenum Refilling from Fuel Bypass

Purpose:

The purpose of this test is to confirm that the time for reactor vessel lower plenum refilling is acceptable given potential debris entrapment in bypass flow pathways.

Basis:

During early refilling of the lower plenum of a BWR from the core spray flow through the fuel bypass channels, following a LOCA, it has been postulated that some degree of blockage of the flow paths between the bypass channel and the lower plenum (bypass holes and other clearances) may occur. Flow from the bypass region between the fuel bundles to the lower plenum would be reduced if the two approximately ¼-inch diameter bypass flow holes in the lower tie plate and/or other small clearance gaps became partially or totally blocked by debris passing through the ECCS pump suppression pool suction strainers. A reduction in bypass channel flow might reduce the filling rate of the lower plenum and thus potentially delay the time for core re-flood.

Key Test Bundle Features (Figure A-1):

1) Height of Fuel Bundle: An indicator of the potential blockage is the time-varying water column height in the fuel bypass region during the time flow is injected from the top of the bundle with debris, compared to the case with no debris. Because the water level height with blockage is unknown, the full height of the bundle will be included in the test.

2) Components of Fuel Bundle: Because this and subsequent testing requires the use of an actual (full height) fuel bundle, one-quarter of the bypass region associated with the typical core cell containing four fuel bundles and the associated bypass flow paths will be simulated. The top of the bundle will have a flow diverter to ensure that the water/debris mixture flows into the bypass region and that none enters the bundle. This top flow diverter will not be airtight so that air pressure will not build up in the bundle. Thus, the actual bundle geometry, bypass flow paths, and lower tie plate with its specific features (e.g., debris filter, bypass flow holes, and other clearances) will be used (see Figure A-2). The bundle will sit on a mock-up of the core support plate and associated fuel support piece to simulate all of the prototypic leakage paths between the bypass and lower plenum. The top guide will be simulated because this represents the minimum flow area for core spray to enter the bypass region. Control blade geometry will be simulated to account for the reduced area of the flow path due to the presence of the blade geometry. Surrounding the test fuel bundle will be a watertight chamber providing one-half the clearances to the adjacent fuel bundles (note that the adjacent fuel bundles are not included in the test setup). All sides of this chamber will be transparent to facilitate viewing of the bypass region flow and possible blockage.

3) Interface with Lower Plenum: The reactor vessel lower plenum geometry will not be included, being unnecessary for the proposed scope of the test and because room needs to be provided for the measurement of the bypass flow versus time using a water/debris receiving tank and electronic scale (digital balance).

Test Loop Components (Figures A-1 and A-2):

1) Flow Control: Flow will be withdrawn from a water supply/debris mixing tank by gravity (or a pump, if required) and measured versus time. Piping size and length shall be selected to minimize any settling of debris in the inflow system. The volume of water in the water supply/debris mixing tank shall be the total volume to be introduced during one test.

2) Debris: The total mass of debris to be used in each test shall be mixed in the same water supply tank described above. Mixing shall be by a mechanical device so that no additional flow is introduced into the tank and no debris is lost from the tank.

3) Setting: To make room for the mass per time flow measurement (water/debris receiving tank and digital balance) below the test module, the test rig shall be raised sufficiently off the test lab floor.

4) A computer data acquisition system will be used to control the test loop and collect data.

Test Operating Conditions:

1) Flow and Debris Injection: The top of the fuel channel will be covered and water with fully mixed debris (characteristics to be provided by BWROG ECCS Suction Strainer Source Term Subcommittee) will only be introduced into the bypass region between the fuel channels from the water supply/mixing tank located above the test rig (Figure A-1). The rate of water and total debris mass flux (concentration) shall be controlled by the use of a computer actuated valve to simulate a conservative ECCS flow rate prorated by total bypass area to total area of the entire core and prorated on a per bundle basis for five (5) minutes (approximate lower plenum fill time). The flow and debris will not be recirculated; this is a once-through test.

2) Debris Constituents: The debris constituents and the total mass per constituent to be used during the duration of lower plenum filling, averaged on a per bundle basis, will be provided by the BWROG ECCS Suction Strainer Source Term Subcommittee. If required, debris components may be added in stages to more closely simulate the time history of material passing through the ECCS suction strainers in the suppression pool.

Parameters to be Measured:

1) Water Level in Bypass Region: This water level should be measured in at least two locations versus time with instrumentation that includes high frequency response sensors.

2) Flow measurement for the injected flow may be by the volumetric method (drop in average water level in the mixing tank versus time) or an equivalent method (orifice plate or similar) that is accurate for the debris/water mix.

3) Flow Rate from Bypass Region into the Lower Plenum: Flow and debris draining from the bypass holes and other openings should be collected and weighed versus time (or using some equivalent system to determine the mass flow versus time). An energy distribution grid should be used to dissipate the energy from the falling water to minimize oscillations in the weight measurement.

4) Total Mass of Debris: For each constituent of the debris mix, the total debris mass to be introduced during each test is to be measured (weighed). The total quantity of each constituent to be tested will be provided by the BWROG ECCS Suction Strainer Source Term Subcommittee.

5) Total Mass of Debris Bypassed: Water that drains from the bypass openings into the mass per time measuring system is to be collected, strained, and dried at the end of each test to obtain the total mass of debris bypassed versus that introduced. The difference indicates the mass of debris held up in the bypass region.

6) Photographs will be taken when practical to document each test.

Repeatability:

1) Water Level versus Time: Five tests should be conducted with clean water to characterize the repeatability of making flow and water level measurements. Five tests are deemed sufficient based on experience; however, statistical relevance of the collected data should be analyzed to determine if a larger number of tests are required.

2) Water Level versus Time: Three tests should be conducted with each given debris mix to determine potential debris effects on lower plenum filling.

3) Debris Mix: Each constituent of the debris mix shall be weighed and introduced into the mixing tank in the desired time history.

4) Cleaning: After each debris test, the mixing tank, flow system including the water/debris receiving tank and bundle bypass region is to be cleaned using appropriate methods (including disassembly of bundle components, if needed, and thorough power washing, as necessary) and new "clean" test data (tests conducted with a clean test flow loop, clean bundle, and water only) should subsequently be obtained. Without the variability of debris effects, experience indicates that water level measurements can have an uncertainty of 2 to 3% based on the various instruments involved. To find a true difference between clean tests among this uncertainty suggests that deviations from prior average clean tests should not vary by more than 5%. Greater differences would indicate the need for re-cleaning and a repeat of the clean tests.

The debris test matrix associated with the Test 1 scope of work is to be determined based on input from the BWROG ECCS Suction Strainer Source Term Subcommittee and the expected quantity of material passing through the ECCS suction strainers in the suppression pool.

Acceptance Criteria:

The acceptance criteria for this test will be based on the results of the limiting base LOCA event and fuel bundle blockage analyses performed by each fuel supplier (Section 3.4 summarizes the GEH analyses, Section 3.6 provides proposed test criteria). It is expected that the basis for the criteria will be the differential rate of drainage from the bypass region for clean water versus debris-laden water. A differential in bypass drainage rate can, through analysis, affect the calculated PCT. The acceptable variation is based on the vendor specific analytical relationship between the bypass drainage rate differential and the PCT increase allowance.

Test 2: Core Re-Flood Rate Test

Purpose:

The purpose of Test 2 is to confirm that the time for bundle re-flood is acceptable given the potential for debris entrapment in the lower tie plate and bypass region flow paths.

Basis:

During early refilling of the lower plenum and fuel bundles of a BWR following a LOCA, it has been postulated that some degree of blockage of the lower tie plate debris filter and lower spacers may occur. Blockage of this filter and spacers might impede the flow of water from the lower plenum into the fuel bundles and could consequently affect the calculated PCT margin by delaying the re-flood time. The results of Test 2 will identify the difference (if any) in core re-flood time using clean water in comparison to debris-laden water. While the total time to recover the core to a two-phase cooling condition after filling the lower plenum can vary from a few seconds to approximately 2 minutes, the test will apply a wide range of flow rates to conservatively assess the effect of debris using flow rates representative of the analysis.

Key Test Bundle Features (Figure A-3):

1) Height of Fuel Bundle: An indicator of the potential blockage at the lower tie plate and associated effect on core re-flood is the rate of change of the water column height in the fuel bundle with debris, compared to the case with no debris. Using the same general test rig developed for Test 1, the full height of the bundle shall be included and the test will be terminated when the water level in the bundle reaches an elevation equal to the total height of the fuel bundle.

2) Components of Fuel Bundle: Testing requires the use of an actual (full height) fuel bundle and one-quarter of the bypass region associated with the typical core cell containing four fuel bundles and the associated bypass flow paths will be simulated. This includes the actual bundle geometry, bypass flow paths, and the lower tie plate with the debris filter. As in Test 1, the bundle shall sit on a fuel support piece and a mock-up of the core support plate and a sealed lower plenum tank. Surrounding the test fuel bundle will be a watertight chamber providing one-half the clearances to the adjacent fuel bundles (note that the adjacent fuel bundles are not included in the test setup). All sides of this chamber will be transparent to facilitate viewing of the bypass region flow and possible blockage.

3) Interface with Lower Plenum: Components other than the simulated core support plate, the fuel support piece and bypass region gaps associated with the core support plate will not be simulated. However, a sealed lower plenum tank will be used with a total plan view area equivalent to the prorated per bundle net area to give the correct rate of water rise. Inflow will be upward from the bottom to help maintain the debris in suspension.

4) Interface Above Fuel Bundle: An inlet hopper will be fitted above the upper tie plate to provide an inflow path for water to the bypass region. The fuel bundle channel will be extended up past the inlet hopper to ensure that no bypass flow introduced into the top of the test rig enters the fuel bundle and that the bundle is open to atmospheric pressure.

Test Loop Components (Figure A-3):

1) Flow Control: Flow will be pumped from the water supply/debris-mixing tank into a pipe, which supplies water to both the upper and lower test rig inflow regions. Flow rate will be measured in each supply line with an orifice flow meter (or equivalent) and controlled by a computer-actuated valve. Piping size and length shall be selected to minimize any settling of debris in the supply system. The volume of water in the tank shall be the total volume to be introduced during one test.

2) Debris: The total mass of debris to be used in each test shall be mixed in the same water source tank described above. Mixing shall be by a mechanical device so that no additional flow is introduced into the tank and no debris is lost from the tank. The total debris mass and water tank volume should provide the proper debris concentration.

3) The test rig shall be instrumented with pressure gauges to measure water level rise as a function of time in the lower plenum, the bypass region (four points), and the fuel bundle. A DP measurement with respect to time shall also be made across the lower tie plate.

4) A computer data acquisition system will be used to control the test loop and collect the required data.

5) A flow distributor will be used in the lower plenum tank to ensure uniform, upward flow across the lower plenum cross section.

Test Operating Conditions:

1) Flow and Debris Injection: Flow will be introduced into the test rig from two locations: the hopper at the top of the rig which supplies water to the bypass region and the lower plenum tank which simulates water entering the fuel bundle from below the lower tie plate. At the top of the test rig, the exit of the fuel channel will be isolated from the bypass flow as described previously and water with fully mixed debris (characteristics to be provided by the BWROG ECCS Suction Strainer Source Term Subcommittee) will be introduced into the bypass region from a mixing tank using a pump. The rate of water and total debris mass flux (concentration) shall be controlled by the use of a computer-actuated valve to simulate the target total bypass flow (to be determined from the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses). At the bottom of the test rig, water with fully mixed debris at the proper concentration will be introduced into the lower plenum from the mixing tank. The rate of water and total debris mass flux (concentration) shall be controlled by the use of a computer-actuated valve to simulate the target total plenum flow (to be specified from the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses).

2) The flow and debris will not be recirculated; this is intended to be a short (less than 2 minutes), once-through test. It is expected that the filling rate of the lower plenum tank will preclude settlement of debris in the lower plenum tank.

3) Debris Constituents: The debris constituents, their concentration in the injection flow, and the total mass per constituent to be used during the duration of core re-flood will be provided by the BWROG ECCS Suction Strainer Source Term Subcommittee. If required, debris components may be added in stages to more closely simulate the time history of material passing through the ECCS suction strainers in the suppression pool.

Parameters to be Measured:

1) Debris Mix: Each constituent of the debris mix shall be weighed and introduced to the mixing tank.

2) Water Level in Bypass Region: This water level should be measured versus time with instrumentation that includes high frequency response sensors.

3) Water Level in Fuel Bundle: This water level should be measured within the bundle versus time with instrumentation that includes high frequency response sensors.

4) Water Level in Lower Plenum: This water level should be measured at two locations versus time with instrumentation that includes high frequency response sensors.

5) Debris filter (integral with the lower tie plate) and lower spacer(s) DP change as a function of time: This DP measurement shall be made with an appropriately ranged DP cell connected upstream and downstream of the lower tie plate.

6) Flow measurement for the injected flows shall be by the DP method or an equivalent method that is accurate for the debris/water mix.

7) Bypass Region Flow Rate: Flow injected into the bypass region should be specified from the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

8) Flow Rate into Lower Plenum: Flow into the lower plenum should be specified from the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

9) Photographs will be taken when practical to document each test.

The expected duration of Test 2 is short (less than 2 minutes) based on fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

Repeatability:

1) Water Level versus Time: Five tests should be conducted with clean water to characterize the repeatability of making flow and water level measurements and to set a baseline for the subsequent tests. Five tests are deemed sufficient based on experience; however, statistical relevance of the collected data should be analyzed to determine if a larger number of tests are required.

2) Water Level versus Time: Three tests should be conducted with each given debris mix to determine potential debris effects on core re-flood.

3) Cleaning: After each debris test, the mixing tank, the lower plenum tank, flow system and bundle bypass region is to be cleaned using appropriate methods (including disassembly of bundle components, if needed, and thorough power washing, as necessary) and new "clean" test data (tests conducted with a clean test flow loop, clean bundle, and water only) should subsequently be obtained. Without the variability of debris effects, experience indicates that averaged pressure loss coefficients can have an uncertainty of 2 to 3% based on the various instruments involved. To find a true difference between clean tests among this uncertainty suggests that deviations from prior average clean test loss coefficients should not vary by more than 5%. Greater differences would indicate the need for re-cleaning and a repeat of the clean tests.

The test matrix, specific debris characteristics, and concentration associated with the Test 2 scope of work is to be determined based on input from the BWROG ECCS Suction Strainer Source Term Subcommittee and the expected quantity of material passing through the ECCS suction strainers in the suppression pool.

Acceptance Criteria:

The acceptance criteria for this test will be based on the results and requirements of the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses (Section 3.4 summarizes the GEH analyses, Section 3.6 provides proposed test criteria). It is expected that the basis for the criteria will be the differential rate of fuel bundle flood up for clean water versus debris-laden water. A differential in the fuel bundle re-flood rate can, through analysis, affect the calculated PCT. The acceptable variation is based on the vendor specific analytical relationship between the fuel bundle re-flood rate differential and the PCT increase allowance.

<u>Test 3: Lower Tie Plate Blockage Test</u>

Purpose:

The purpose of Test 3 is to establish the experimental blockage function for the fuel bundle lower tie plate and lower spacers when exposed to debris.

Basis:

During long-term core cooling of a BWR following a LOCA, it has been postulated that some degree of blockage of the lower tie plate debris filter and lower spacers may occur. Blockage of this filter and spacers may impede the flow of water from the lower plenum into the fuel bundle and could affect the available make-up coolant to balance the core-steaming rate. The results of Test 3 will identify the time rate-of-change of head loss across the debris filter and lower spacers using clean water and debris-laden water. This is a recirculation flow loop test with termination to be defined by the limiting debris filter/lower spacer blockage requirements as determined from the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

Key Test Bundle Features (Figure A-4):

1) Height of Fuel Bundle: An indicator of the extent of blockage as a function of time of the lower tie plate and lower spacers is the DP across these components measured with debris, compared to the case with no debris. The bypass region will not be replicated in this test. A fuel bundle with the channel modified to facilitate viewing of the bundle internals will be used for this test.

2) Components of Fuel Bundle: Testing requires the use of an actual fuel bundle (flow through the bypass region is not required). This includes the actual bundle geometry and lower tie plate debris filter. The bundle shall sit on a fuel support piece and a mock-up of the core support plate.

3) Interface with Lower Plenum: Test 3 will utilize the same sealed lower plenum tank used in Test 2.

4) Interface Above Fuel Bundle: The bundle channel extension used in Test 2 will be connected to the return flow line and pass flow back to the water supply/mixing tank.

Test Loop Components (Figure A-4):

1) Flow Control: Flow will be pumped from a debris-mixing tank into a pipe, which supplies water to the lower plenum. Flow rate will be measured in the supply line with an orifice flow meter (or equivalent) and controlled by a computer-actuated valve. Piping size and length shall be selected to minimize any settling of debris in the inflow system. The volume of water in the tank shall be selected based on target debris concentrations as per BWROG ECCS Suction Strainer Source Term Subcommittee specifications. It is expected that the upward flow in the lower plenum tank will preclude settlement of debris; however, mechanical mixers may be required in the lower plenum tank to keep debris suspended.

2) Debris: The total mass of debris to be used in each test shall be mixed in the same water source tank described above. Mixing shall be by a mechanical device so that no additional flow is introduced into the tank and no debris is lost from the tank.

3) The test rig shall be instrumented with the same pressure gauges installed in Test 2 to measure the DP across the lower tie plate/debris filter assembly and lower spacers.

4) A computer data acquisition system will be used to control the test loop and collect the required data.

5) A flow distributor will be used in the lower plenum tank to ensure uniform, upward flow across the lower plenum cross section.

Test Operating Conditions:

1) Flow and Debris Injection: Water with fully mixed debris will be introduced into the lower plenum from the mixing tank. The rate of water and total debris mass flux (concentration) shall be controlled by the use of a computer-actuated valve to simulate the target total plenum flow specified from the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

2) The flow and debris will be re-circulated. Test 3 is intended to be a closed loop test with test termination criteria to be determined based on the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

3) Debris Constituents: The debris constituents, their concentration, and the total mass per constituent to be used during the duration of core re-flood will be provided by the BWROG ECCS Suction Strainer Source Term Subcommittee. If required, debris components may be added in stages to more closely simulate the time history of material passing through the ECCS suction strainers in the suppression pool.

Parameters to be Measured:

1) Debris Mix: Each constituent of the debris mix shall be weighed and introduced into the mixing tank to achieve proper concentration.

2) Change in DP across the debris filter (integral with the lower tie plate) and lower spacers as a function of time: These DP measurements shall be made with an appropriately ranged DP cell connected upstream and downstream of the lower tie plate and spacers.

3) Mixed Debris Concentration: Water samples will be taken during the test from the injection line to verify the debris concentration.

4) Flow measurement for the plenum inflow shall be by the DP method (orifice plate) or an equivalent method that is accurate for the debris/water mix. Total flow for this test will be specified from the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

5) Photographs will be taken when practical to document each test.

Repeatability:

1) ΔP versus Time: Five tests should be conducted with clean water to characterize the repeatability of making flow and water level measurements and to set a baseline for the subsequent tests. Five tests are deemed sufficient based on experience; however, statistical relevance of the collected data should be analyzed to determine if a larger number of tests are required.

2) ΔP versus Time: Three tests should be conducted with each given debris mix to determine potential debris effects on core re-flood.

3) Cleaning: After each debris test, the mixing tank, lower plenum tank, flow system and bundle bypass region is to be cleaned using appropriate methods (including disassembly of bundle components, if needed, and thorough power washing, as necessary) and new "clean" test data (tests conducted with a clean test flow loop, clean bundle, and water only) should subsequently be obtained. Without the variability of debris effects, experience indicates that averaged pressure loss coefficients can have an uncertainty of 2 to 3% based on the various instruments involved. To find a true difference between clean tests among this uncertainty suggests that deviations from prior average clean test loss coefficients

should not vary by more than 5%. Greater differences would indicate the need for re-cleaning and a repeat of the clean tests.

The test matrix, debris characteristics, and concentrations associated with the Test 3 scope of work is to be determined based on input from the BWROG Suction Strainer Source Term Subcommittee and the expected quantity of material passing through the ECCS suction strainers in the suppression pool.

Acceptance Criteria:

The acceptance criteria for this test will be based on the results and requirements of the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses (Section 3.4 summarizes the GEH analyses, Section 3.6 provides proposed test criteria). It is expected that the basis for the criteria will be the pressure differential and its effect on the calculated makeup water required based on core steaming. The relationship between pressure differential and the PCT increase can be developed although it may be fuel supplier specific.

Test 4: Upper Tie Plate Blockage

Purpose:

The purpose of Test 4 is to establish the experimental blockage function of the fuel bundle upper tie plate and upper spacers when exposed to debris during long-term cooling. The test will also quantify local debris accumulation at, for example, interfaces with spacer grids and tie plates.

Basis:

During long-term cooling of a BWR core after a LOCA, it has been postulated that some blockage of the fuel bundle (upper tie plate and upper spacers) may occur. It may take several days for the steam bubble in the upper one-third of the core to collapse and for the flow injected at the top of the core to fully penetrate downward into the fuel bundle. Prior to full penetration, a water pool remains above the steam bubble with limited downflow that assists core cooling. A countercurrent flow regime exists at this time: debris-laden water flows down fuel rod surfaces and flashes to steam, which flows upward and exits the top of the bundle. The downward flowing water may contain debris that has passed through the suction strainers in the suppression pool and this debris could accumulate on the upper tie plate and upper spacers. The upward steam flow limits the amount of water and associated debris that is able to flow into the bundle and may dislodge debris that would otherwise accumulate at the upper tie plate and upper spacers. A reduction in water flowing down into the fuel bundles due to blockage of the upper tie plate and spacers might decrease the rate of core cooling.

As essentially all of the water flowing downward into a given fuel bundle is converted into steam by the hot fuel, very little of the debris-laden water flows through the lower tie plate. As the objective of this particular test is to evaluate the blockage characteristics of the upper tie plate and upper spacers only, the fuel channel will be raised off of the lower tie plate to ensure no impediment to axial flow exists in the upper part of the test bundle due to blockage of the lower tie plate.

Testing of potential blockage of the upper tie plate and upper spacers is performed for the two bounding conditions relative to core re-flood level: (1) core spray only reflecting the condition where the core is not re-flooded (Tests 4a and 4b); and (2) core spray under a fully flooded core condition (Tests 4c and 4d). Tests 4a and 4c will be conducted using only water with debris entering the top of the bundle. Tests 4b and 4d will be conducted using water containing debris entering from the top and countercurrent air flow to simulate upward steam flow. Note that the blockage criteria are given for long-term operating conditions, but are used in early conditions of the analysis, which is considered to be more conservative.

The test matrix, debris characteristics and concentrations associated with the Test 4 scope of work is to be determined based on input from the BWROG Suction Strainer Source Term Subcommittee and the expected quantity of material passing through the ECCS suction strainers in the suppression pool.

Test 4a: Water Only Test, No Core Re-Flood

Key Test Bundle Features (Figure A-5):

1) Height of Fuel Bundle: A full-length bundle will be used for Test 4a. To ensure that blockage of only the upper tie plate and upper spacers is characterized, the fuel channel will be raised to ensure that the lower tie plate does not become blocked and impede axial flow through the bundle.

2) Components of Fuel Bundle: An actual fuel bundle will be tested. The interface between the inlet hopper and the channel will be sealed so that all the flow and debris is conservatively introduced only into the fuel channel and onto the upper tie plate. A fuel bundle with the channel modified to facilitate viewing of the bundle internals will be used for this test.

3) Interface with Lower Plenum: A water collection tank will be used to capture water and debris injected into the top of the channel.

Test Loop Components (Figure A-5):

1) Flow Control: Water mixed with debris will be withdrawn from a debris-mixing tank and measured while discharging to the top of the bundle. The flow rate used in the test will be based on fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses. Piping size and length shall be selected to minimize any settling of debris in the inflow system. A low-pressure sparger system with relatively large holes (so no debris is trapped) will distribute the flow to the bundle above the upper tie plate. Water and debris that passes through the fuel bundle will be collected below the bundle in a tank with mechanical mixers and pumped back to the supply tank. This recirculation system will be designed to operate for a few days, if needed.

2) Debris: The total mass of debris to be used in each test shall be mixed in the water source tank described above. Mixing shall be by a mechanical device so that no additional flow is introduced into the tank and no debris is lost from the tank. Total debris mass and tank

volume shall be selected to reproduce the target debris concentration expected during long-term cooling.

3) Instrumentation: In addition to the sparger flow measurement, pressure taps will be installed just above the upper tie plate, between the upper tie plate and the upper spacer and below the upper spacers to the liquid water level in the core associated with long-term core cooling. DP transducers connected to these taps will be monitored during testing to determine the head loss (coefficient) of the upper tie plate and upper spacers as they may be affected by the accumulation of debris. This method of quantitative headloss measurement will only be applicable if sufficient blockage occurs such that water is retained above the spacer grid. If applicable, the difference in loss coefficients with a clean system in comparison to those with debris accumulation may be used to confirm criteria established from fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

4) The primary method for determining debris blockage function will be optical by inspection and interrogation of the debris bed. Photographs will be taken at the conclusion of each test and digitally processed. It is anticipated that refinements to the optical techniques envisioned to evaluate debris blockage functions will be developed in advance of full height bundle testing.

Test Operating Conditions:

1) Flow and Debris Injection: Water with fully mixed debris will be pumped into the low-pressure sparger above the fuel channel. The rate of injection of the water and debris mixture shall be controlled to simulate a wide rate range from approximately 0.5 to as high as 10 gpm to conservatively assess the effect of debris using flow rates representative of the vendor specific analysis. The flow and debris will be recirculated.

2) Testing: Water tests to determine the possible effects of debris blockage on the loss coefficient for the upper tie plate and upper spacers will be executed with water recirculated throughout the duration of the test. Test termination will be defined by monitoring debris concentration stability downstream of the test fuel bundle.

3) Debris Constituents: The debris components, their characteristics, concentrations and the total mass per component to be used during long-term cooling will be provided by the BWROG ECCS Suction Strainer Source Term Subcommittee. If required, debris components may be added in stages to more closely simulate the time history of material passing through the ECCS suction strainers in the suppression pool.

Parameters to be Measured:

1) Pressure measurements will use pressure cells. Depending on location and related access, they may be flush mounted or use tubing to static ports in the fuel bundle.

2) Flow measurement for the injected water flow will be by an orifice plate or an equivalent method that is accurate for the debris/water mix.

3) Total Mass of Debris: For each constituent of the debris mixture, the total debris mass to be introduced during each test is to be measured (weighed) to achieve the desired initial concentration.

4) Mixed Debris Concentration: Water samples will be taken during the test from the injection line to verify the debris concentration.

5) Photographs of debris accumulation will be taken at the conclusion of the test. Additionally, photographs of debris on and about fuel rods will be taken to characterize local deposition at, for example, interfaces with spacer grids and tie plates.

Repeatability:

1) Tests with a Clean System: Five flow rates shall be used to determine the loss coefficient for the upper tie plate and upper spacers with a clean system and to characterize the repeatability of making pressure measurements. These tests will be conducted with the bundle water-solid. Five tests are deemed sufficient based on experience; however, statistical relevance of the collected data should be analyzed to determine if a larger number of tests are required. The average value of these five loss coefficients will establish the clean system loss coefficient.

2) Test with Debris Accumulation: Five tests with debris shall be used to determine repeatability of the water hold-up measurements within the fuel bundle.

3) Cleaning: After each debris test and the determination of the corresponding (average) loss coefficient, the mixing tank, collection tanks, the flow system, and the fuel bundle shall be cleaned using appropriate methods (including disassembly of bundle components, if needed, and thorough power washing, as necessary) and new "clean" test data (tests conducted with a clean test flow loop, clean bundle, and five flows) should subsequently be obtained. Without the variability of debris effects, experience indicates that averaged pressure loss coefficients can have an uncertainty of 2 to 3% based on the various instruments involved. To find a true difference between clean tests among this uncertainty suggests that deviations from prior average clean test loss coefficients should not vary by more than 5%. Greater differences would indicate the need for re-cleaning and a repeat of the clean tests.

Acceptance Criteria:

The acceptance criteria for this test will be based on the results and requirements of the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses (Section 3.4 summarizes the GEH analyses, Section 3.6 provides proposed test criteria). It is expected that the basis for the criteria will be the percent blockage of the upper tie plate and upper spacers compared to a clean system open flow area. Secondarily, if applicable, measured increases in pressure differential can be compared to the calculated increase (from the LOCA analysis) obtained by assuming a certain percent blockage in flow area. It is postulated that blockage at these locations could affect the calculated makeup water required based on core steaming. The relationship between any pressure differential and the PCT increase can be developed although it may be fuel supplier specific.

Test 4b: Water Down-Flow with Countercurrent Air Flow, No Core Re-Flood

Key Test Bundle Features (Figure A-6):

1) Height of Fuel Bundle: A full-length bundle will be used for Test 4b. To ensure that blockage of only the upper tie plate and upper spacers is characterized, the fuel channel will be raised to ensure that the lower tie plate does not become blocked and impede axial flow through the bundle.

2) Components of Fuel Bundle: An actual fuel bundle will be tested. The interface between the inlet hopper and the channel will be sealed so that all the flow and debris is conservatively introduced only into the fuel channel and onto the upper tie plate. A fuel bundle with the channel modified to facilitate viewing of the bundle internals will be used for this test.

3) Interface with Lower Plenum: The lower end of the fuel channel and lower tie plate will be immersed in a water collection tank. This ensures that air injected into the fuel bundle can only flow upward.

Test Loop Components (Figure A-6):

1) Flow Control: Water mixed with debris will be withdrawn from a debris-mixing tank and measured while discharging to the top of the bundle. The flow rate used in the test will be based on the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses. Piping size and length shall be selected to minimize any settling of debris in the inflow system. A low-pressure sparger system with relatively large holes (so no debris is trapped) will distribute the flow to the bundle above the upper tie plate. Water and debris that passes through the fuel bundle will be collected below the bundle in a tank with mechanical mixers and pumped back to the supply tank. This recirculation system will be designed to operate for a few days, if needed.

2) Debris: The total mass of debris to be used in each test shall be mixed in the water source tank described above. Mixing shall be by a mechanical device so that no additional flow is introduced into the tank and no debris is lost from the tank. Total debris mass and tank volume shall be selected to reproduce the maximum debris concentration expected in the plant spray flow.

3) Air Flow: A separate air flow injection system will be used to introduce a measured air flow into the fuel bundle to simulate the countercurrent steam flow leaving the top of the bundle. Air flow rate will be set to establish the same dynamic head as calculated for the expected conservative, long-term cooling steam flow, thus producing similar effects on redistribution of the debris. A filter will be placed above the sparger ring to capture any debris lost from the system due to the injected air flow. Any debris caught on that filter will be rinsed off periodically to re-suspend the debris and any debris deposited at the end of the test will be measured and added to the total mass used for each test thereafter.

4) Instrumentation: In addition to the sparger water flow and air injection flow measurements, pressure taps will be installed just above the upper tie plate, between the upper tie plate and the upper spacer and below the upper spacers. DP transducers connected to these taps will be monitored during testing to determine the head loss (coefficient) of the upper tie plate and upper spacers as they may be affected by the accumulation of debris. This method of quantitative head-loss measurement will only be applicable if sufficient blockage occurs such that water is retained above the spacer grid. If applicable, the difference in loss coefficients with a clean system in comparison to those with debris accumulation may be used to confirm criteria established from fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

5) The primary method for determining the debris blockage function will be by optical inspection and interrogation of the debris bed. Photographs will be taken at the conclusion of each test and digitally processed. It is anticipated that refinements to the optical techniques envisioned to evaluate debris blockage functions will be developed in advance of full height bundle testing.

Test Operating Conditions:

1) Water Flow and Debris Injection: Water with fully mixed debris will be pumped into the low-pressure sparger above the fuel channel. The rate of injection of the water and debris mixture shall be controlled to simulate a wide rate range from approximately 0.5 gpm to as high as 10 gpm to conservatively assess the effect of debris using flow rates representative of the vendor specific analysis. The flow and debris will be recirculated.

2) Air Injection: Using a suitable air source such as a compressor or blower, a measured air flow will be injected into the fuel bundle to simulate the upward flow of steam leaving the top of the fuel bundle. The injected air flow rate will be set to produce the same dynamic head at the fuel bundle outlet as would the calculated steam flow.

3) Testing: Water/air injection tests to determine the possible effects of debris blockage on the loss coefficients of the upper tie plate and upper spacers will be executed with water recirculated throughout the duration of the test. Test termination will be defined by monitoring debris concentration stability downstream of the test rig.

4) Debris Constituents: The debris components, their characteristics, concentrations and the total mass per fuel component to be used during long-term cooling will be provided by the BWROG ECCS Suction Strainer Source Term Subcommittee. If required, debris components may be added in stages to more closely simulate the time history of material passing through the ECCS suction strainers in the suppression pool.

Parameters to be Measured:

1) Pressure measurements will use pressure cells. Depending on location and related access, they may be flush mounted or use tubing to static ports in the fuel bundle.

2) Flow measurement for the injected water flow will be by an orifice plate or an equivalent method that is accurate for the debris/water mixture used.

3) The air flow injected into the fuel bundle will be measured with an orifice plate or an equivalent method.

4) Total Mass of Debris: For each constituent of the debris mix, the total debris mass to be introduced during each test is to be measured (weighed) to achieve the desired initial concentration.

5) Mixed Debris Concentration: Water samples will be taken during the test from the injection line to verify the debris concentration.

6) Photographs of debris accumulation will be taken at the conclusion of the test. Additionally, photographs of debris on and about fuel rods will be taken to characterize local deposition at, for example, interfaces with spacer grids and tie plates.

7) Any debris caught on the filter located above the sparger ring will be dried and weighed.

Repeatability:

1) Flow Tests with a Clean System: Five flow tests shall be used to determine the loss coefficients of the upper tie plate and upper spacers with a clean system and to characterize the repeatability of making pressure measurements. These tests will be conducted with the bundle water-solid. Five tests are deemed sufficient based on experience; however, statistical relevance of the collected data should be analyzed to determine if a larger number of flow tests are required. The average value of these five loss coefficients will establish the clean system loss coefficient.

2) Test with Debris Accumulation: Five tests with debris shall be used to determine repeatability of the water hold-up measurements within the fuel bundle.

3) Cleaning: After each debris test and the determination of the corresponding average loss coefficient, the mixing and collection tanks, the flow system, and the fuel bundle shall be cleaned using appropriate methods (including disassembly of bundle components, if needed, and thorough power washing, as necessary) and new "clean" test data (tests conducted with a clean test flow loop, clean bundle, and five flows) should subsequently be obtained. Without the variability of debris effects, experience indicates that averaged pressure loss coefficients can have an uncertainty of 2 to 3% based on the various instruments involved. To find a true difference between clean tests among this uncertainty suggests that deviations from prior average clean test loss coefficients should not vary by more than 5%. Greater differences would indicate the need for re-cleaning and a repeat of the clean tests.

4) The above-described cycle of water/air injection tests and cleaned bundle tests should be repeated twice for a total of three tests with each debris mix.

Acceptance Criteria:

The acceptance criteria for this test will be based on the results and requirements of the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses (Section 3.4 summarizes the GEH analyses, Section 3.6 provides proposed test criteria). It is expected that the basis for the criteria will be the percent blockage of the upper tie plate and upper spacers compared to a clean system open flow area. Secondarily, if applicable, measured increases in pressure differential can be compared to the calculated increase (from the LOCA analysis) obtained by assuming a certain percent blockage in flow area. It is postulated that blockage at these locations could affect the calculated makeup water required based on upper core steaming. The relationship between any pressure differential and the PCT increase can be developed although it may be fuel supplier specific.

Test 4c: Fully Submerged Bundle - Water Only

Key Test Bundle Features (Figure A-7):

1) Height of Fuel Bundle: An indicator of the extent of blockage as a function of time of the upper tie plate and upper spacers is the DP across these components measured with debris, compared to the case with no debris. The full height test rig for Test 3 will be used, including a channel with windows or clear sides.

2) Components of Fuel Bundle: An actual fuel bundle will be tested with the fuel channel modified to facilitate viewing. The upper part of the channel geometry in the test rig will be modified so that all the flow and debris is conservatively introduced only into the fuel channel and onto the upper tie plate. For Test 4, the test configuration is therefore different from that in Tests 1 and 2 because the bypass region of the bundle is conservatively not modeled and not available for flow or debris deposition.

3) Interface with Lower Plenum: A water collection tank will be used to capture water and debris injected into the top of the channel. The channel will be raised up off the lower tie plate to ensure little or no head-loss at the lower tie plate such that the lower tie plate plays no role in the measurement of head loss at the upper tie plate and spacers. A standpipe will be installed in the lower plenum which extends vertically to the top of the fuel channel. This standpipe will set the level of the water in the test article at the top of the fuel channel and will be adjustable to ensure that the pressure head above the upper tie plate is consistent with a prototypic bundle.

Test Loop Components (Figure A-7):

1) Flow Control: Water mixed with debris will be withdrawn from a debris-mixing tank and measured while discharging to the top of the bundle. The flow rate used in the test will be based on the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses. Piping size and length shall be selected to minimize any settling of debris in the inflow system. A low-pressure sparger system with relatively large holes (so no debris is trapped) will distribute the flow to the channel above the upper tie plate. Water and debris that passes through the channel will be collected below in a tank with mechanical mixers and pumped back to the supply tank. This recirculation system will be designed to operate for a few days, if needed.

2) Debris: The total mass of debris to be used in each test shall be mixed in the water source tank described above. Mixing shall be by a mechanical device or equivalent so that no

additional flow is introduced into the tank and no debris is lost from the tank. Total debris mass and tank volume shall be selected to reproduce the target debris concentration expected during long-term cooling.

3) Instrumentation: In addition to the sparger flow measurement, pressure taps will be installed just above the upper tie plate, between the upper tie plate and the upper spacer, and in between the upper spacers. Multiple pressure taps will be installed at each plane to allow an average DP measurement to be made. DP transducers connected to these taps will be used to determine the head loss (coefficient) of the upper tie plates and spacers. The difference in loss coefficients with a clean system in comparison to those with debris accumulation may be used to confirm criteria established from fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

4) The primary method for determining debris blockage function will be by optical inspection and interrogation of the debris bed. Photographs will be taken at the conclusion of each test and digitally processed. It is anticipated that refinements to the optical techniques envisioned to evaluate debris blockage functions will be developed in advance of full height bundle testing.

Test Operating Conditions:

1) Flow and Debris Injection: Water with fully mixed debris will be pumped into the low-pressure sparger above the fuel channel. The rate of injection of the water and debris mixture shall be controllable to simulate a wide range of flow rates from approximately 0.5 to as high as 10 gpm to conservatively assess the effect of debris using flow rates representative of the vendor specific analysis. The flow and debris will be recirculated.

2) Test 4c is intended to be a closed loop test with test termination criteria to be determined based on the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

3) Debris Constituents: The debris components, their characteristics, concentrations and the total mass per component to be used during long-term cooling will be provided by the BWROG ECCS Suction Strainer Source Term Subcommittee. If required, debris components may be added in stages to more closely simulate the time history of material passing through the ECCS suction strainers in the suppression pool.

Parameters to be Measured:

1) Pressure measurements will use DP transducers. Depending on location and related access, they may be flush mounted or use tubing to static ports in the fuel bundle.

2) Flow measurement for the injected water flow will be by an orifice plate or an equivalent method that is accurate for the debris/water mix and range of flow rates of interest.

3) Total Mass of Debris: For each constituent of the debris mixture, the total debris mass to be introduced during each test is to be measured (weighed) to achieve the desired initial concentration.

4) Mixed Debris Concentration: Water samples will be taken during the test from the injection line to verify the debris concentration.

5) Where practical, photographs of debris accumulation will be taken after the test. Additionally, photographs of debris on and about fuel rods will be taken to characterize local deposition at, for example, interfaces with spacer grids and tie plates.

Repeatability:

1) ΔP versus Time: Five tests should be conducted with clean water to characterize the repeatability of making flow measurements and to set a baseline for the subsequent tests. Five tests are deemed sufficient based on experience; however, statistical relevance of the collected data should be analyzed to determine if a larger number of tests are required.

2) ΔP versus Time: Three tests should be conducted with each given debris mix to determine potential debris effects on head loss.

3) Cleaning: After each debris test, the mixing tank, lower plenum tank, flow system, and fuel bundle is to be cleaned using appropriate methods (including disassembly of components, if needed, and thorough power washing, as necessary) and new "clean" test data (tests conducted with a clean test flow loop, clean channel, and water only) should subsequently be obtained. Without the variability of debris effects, experience indicates that averaged pressure loss coefficients can have an uncertainty of 2 to 3% based on the various instruments involved. To find a true difference between clean tests among this uncertainty suggests that deviations from prior average clean test loss coefficients should not vary by more than 5%. Greater differences would indicate the need for re-cleaning and a repeat of the clean tests.

Acceptance Criteria:

The acceptance criteria for this test will be based on the results and requirements of the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses (Section 3.4 summarizes the GEH analyses, Section 3.6 provides proposed test criteria). It is expected that the basis for the criteria will be the increase in loss or DP coefficient at the upper tie plate and upper spacers compared to a clean system. This increase in pressure differential can be compared to the calculated increase obtained by assuming a certain percent blockage in flow area. It is postulated that blockage at these locations could affect the calculated makeup water required based on core steaming. The relationship between any pressure differential and the PCT increase can be developed although it may be fuel supplier specific.

Test 4d: Fully Submerged Bundle - Water with Countercurrent Air Flow

Key Test Bundle Features (Figure A-8):

1) Height of Fuel Bundle: An indicator of the extent of blockage as a function of time of the upper tie plate and upper spacers is the DP across these components measured with debris, compared to the case with no debris. A full height test rig will be used including a channel

with windows or clear sides. Minor modifications will be made to the rig to accommodate air injection.

2) Components of Fuel Bundle: The test rig used in Test 4c will be used for Test 4d. As such, an actual fuel bundle will be tested. The interface between the inlet hopper and the channel will be sealed so that all the flow and debris is conservatively introduced only into the fuel channel and onto the upper tie plate. A fuel bundle with the channel modified to facilitate viewing of the bundle internals will be used for this test.

3) Interface with Lower Plenum: A water collection tank will be used to capture water and debris injected into the top of the channel. The channel will be raised up off the lower tie plate to ensure little or no head-loss at the lower tie plate. A standpipe will be installed in the lower plenum which extends vertically to the top of the fuel channel. This standpipe will set the level of the water in the test article at the top of the fuel channel and will be adjustable to ensure that the pressure head above the upper tie plate is consistent with a prototypic bundle.

Test Loop Components (Figure A-8):

1) Flow Control: Water mixed with debris will be withdrawn from a debris-mixing tank and measured while discharging to the top of the channel. The flow rate used in the test will be based on fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses. Piping size and length shall be selected to minimize any settling of debris in the inflow system. A low-pressure sparger system with relatively large holes (so no debris is trapped) will distribute the flow to the bundle above the upper tie plate. Water and debris that passes through the fuel bundle will be collected below the bundle in a tank with mechanical mixers and pumped back to the supply tank. This recirculation system will be designed to operate for a few days, if needed.

2) Debris: The total mass of debris to be used in each test shall be mixed in the water source tank described above. Mixing shall be by a mechanical device so that no additional flow is introduced into the tank and no debris is lost from the tank. Total debris mass and tank volume shall be selected to reproduce the target debris concentration expected during long-term cooling.

3) Air Flow: A separate air flow injection system will be used to introduce a measured air flow into the fuel bundle to simulate the countercurrent steam flow leaving the top of the bundle. Air flow rate will be set to establish the same dynamic head as calculated for the expected conservative, long-term cooling boil-off, thus producing similar effects on redistribution of the debris. A filter will be placed above the sparger ring to capture any debris lost from the system due to the injected air flow. Any debris caught on that filter will be rinsed off periodically to re-suspend the debris, and any debris deposited at the end of the test will be measured and added to the total mass used for each test thereafter.

4) Instrumentation: In addition to the sparger flow measurement, pressure taps will be installed just above the upper tie plate and in between the upper tie plate and the spacers. DP transducers connected to these taps will be used to determine the head loss (coefficient)

of the upper tie plate and spacers as they may be affected by the accumulation of debris. The difference in loss coefficients with a clean system in comparison to those with debris accumulation may be used to confirm criteria established from fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

5) Photographs will be taken as practical to document each test.

Test Operating Conditions:

1) Flow and Debris Injection: Water with fully mixed debris will be pumped into the low-pressure sparger above the fuel channel. The rate of injection of the water and debris mixture shall be controlled to simulate a wide range of flow rates from approximately 0.5 to as high as 10 gpm to conservatively assess the effect of debris using flow rates representative of the vendor specific analysis. The flow and debris will be recirculated.

2) Air Injection: Using a suitable air source such as a compressor or blower, a measured air flow will be injected into the fuel bundle to simulate the upward flow of steam leaving the top of the fuel bundle. The injected air flow rate will be set to produce the same dynamic head at the fuel bundle outlet as would the calculated steam flow. Air flow rate will be measured using an orifice meter or equivalent.

3) Test 4d is intended to be a closed loop test with test termination criteria to be determined based on the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses.

4) Debris Constituents: The debris components, their characteristics, concentrations and the total mass per component to be used during long-term cooling will be provided by the BWROG ECCS Suction Strainer Source Term Subcommittee. If required, debris components may be added in stages to more closely simulate the time history of material passing through the ECCS suction strainers in the suppression pool.

Parameters to be Measured:

1) Pressure measurements will use DP cells. Depending on location and related access, they may be flush mounted or use tubing connected to static ports in the fuel bundle.

2) Flow measurement for the injected water flow will be by an orifice plate or an equivalent method that is accurate for the debris/water mix flow rate range of interest.

3) Total Mass of Debris: For each constituent of the debris mixture, the total debris mass to be introduced during each test is to be measured (weighed) to achieve the desired initial concentration.

4) Mixed Debris Concentration: Water samples will be taken during the test from the injection line to verify the debris concentration.

5) Where practical, photographs of debris accumulation will be taken after the water injection test. Additionally, photographs of debris on and about fuel rods will be taken to characterize local deposition at, for example, interfaces with spacer grids and tie plates.

Repeatability:

1) ΔP versus Time: Five tests should be conducted with clean water to characterize the repeatability of making flow measurements and to set a baseline for the subsequent tests. Five tests are deemed sufficient based on experience; however, statistical relevance of the collected data should be analyzed to determine if a larger number of tests are required.

2) ΔP versus Time: Three tests should be conducted with each given debris mix to determine potential debris effects on head-loss.

3) Cleaning: After each debris test, the mixing tank, lower plenum tank, flow system, and fuel bundle is to be cleaned using appropriate methods (including disassembly of bundle components, if needed, and thorough power washing, as necessary) and new "clean" test data (tests conducted with a clean test flow loop, clean bundle, and water only) should subsequently be obtained. Without the variability of debris effects, experience indicates that averaged pressure loss coefficients can have an uncertainty of 2 to 3% based on the various instruments involved. To find a true difference between clean tests among this uncertainty suggests that deviations from prior average clean test loss coefficients should not vary by more than 5%. Greater differences would indicate the need for re-cleaning and a repeat of the clean tests.

Acceptance Criteria:

The acceptance criteria for this test will be based on the results and requirements of the fuel supplier-specific limiting base LOCA event and fuel bundle blockage sensitivity analyses (Section 3.4 summarizes the GEH analyses; Section 3.6 provides proposed test criteria). It is expected that the basis for the criteria will be the increase in loss or DP coefficient at the upper tie plate and upper spacers compared to a clean system. This increase in pressure differential can be compared to the calculated increase obtained by assuming a certain percent blockage in flow area. It is postulated that blockage at these locations could affect the calculated makeup water required based on core steaming. The relationship between any pressure differential and the PCT increase can be developed although it may be fuel supplier dependent.

Test Debris Preparation (Applicable to All Tests)

Work relative to debris characterization, concentration, total mass and possible time history is being performed by the BWROG ECCS Suction Strainer Source Term Subcommittee. Therefore, the characterization of each debris type to be considered in evaluating the effect of coolant flow on downstream components is expected to be provided as a design level input from work being conducted by that subcommittee. It is also expected that the form of each debris type will be specified as well as the time history of its concentration per unit volume of water. Surrogates for material such as coatings may be identified for testing and should be consistent with surrogates used in the ECCS suction strainer head loss testing program. Some information is available from data obtained for the PWR Owners' Group (PWROG) downstream effects evaluation and subsequent fuels testing; however, it should be noted that the ECCS suction strainer hole sizes and velocities are different between PWR and BWR plants and this could influence the downstream debris characteristics. Although the presence of any chemical compounds and their characteristics are uncertain at this time, appropriate surrogates will be tested, if necessary. In all cases, conservative and bounding concentrations of the surrogates will be tested to ensure applicability to the full BWR fleet.

Once the characteristics of the debris are identified, details of a suitable methodology for preparing the debris for introduction into the mixing tanks for Tests 1 through 4 can be developed.

References for Appendix A

A-1. "Differences in Treatment of Containment Strainer/Sump Clogging Technical Issues for Boiling Water and Pressurized Water Reactors," presentation by R. Architzel (NRC) to BWR Owners Group, dated November 27, 2007. ADAMS Accession Number ML073320414.

A-2. Letter, J. A. Grobe (NRC) to R. Anderson (BWROG), "Potential Issues Related to Emergency Core Cooling Systems (ECCS) Strainer Performance at Boiling Water Reactors," dated April 10, 2008. ADAMS Accession Number: ML080500540.

A-3. Memorandum, J. A. Golla (NRC) to M. L. Scott (NRC), "Summary of June 5, 2008, Public Meeting with the Boiling Water Reactor Owner's Group (BWROG) to Discuss BWROG Proposed Activities Regarding Strainer Clogging Issues," dated June 24, 2008. ADAMS Accession Number: ML081620552.

A-4. Memorandum, M. C. Honcharik (NRC) to S. L. Rosenberg (NRC), "Summary of November 5, 2008, Open Meeting with the Boiling Water Reactor (BWR) Owner's Group (BWROG) with Senior Management (TAC No. MB5757)," dated November 28, 2008. ADAMS Accession Number: ML083260102.

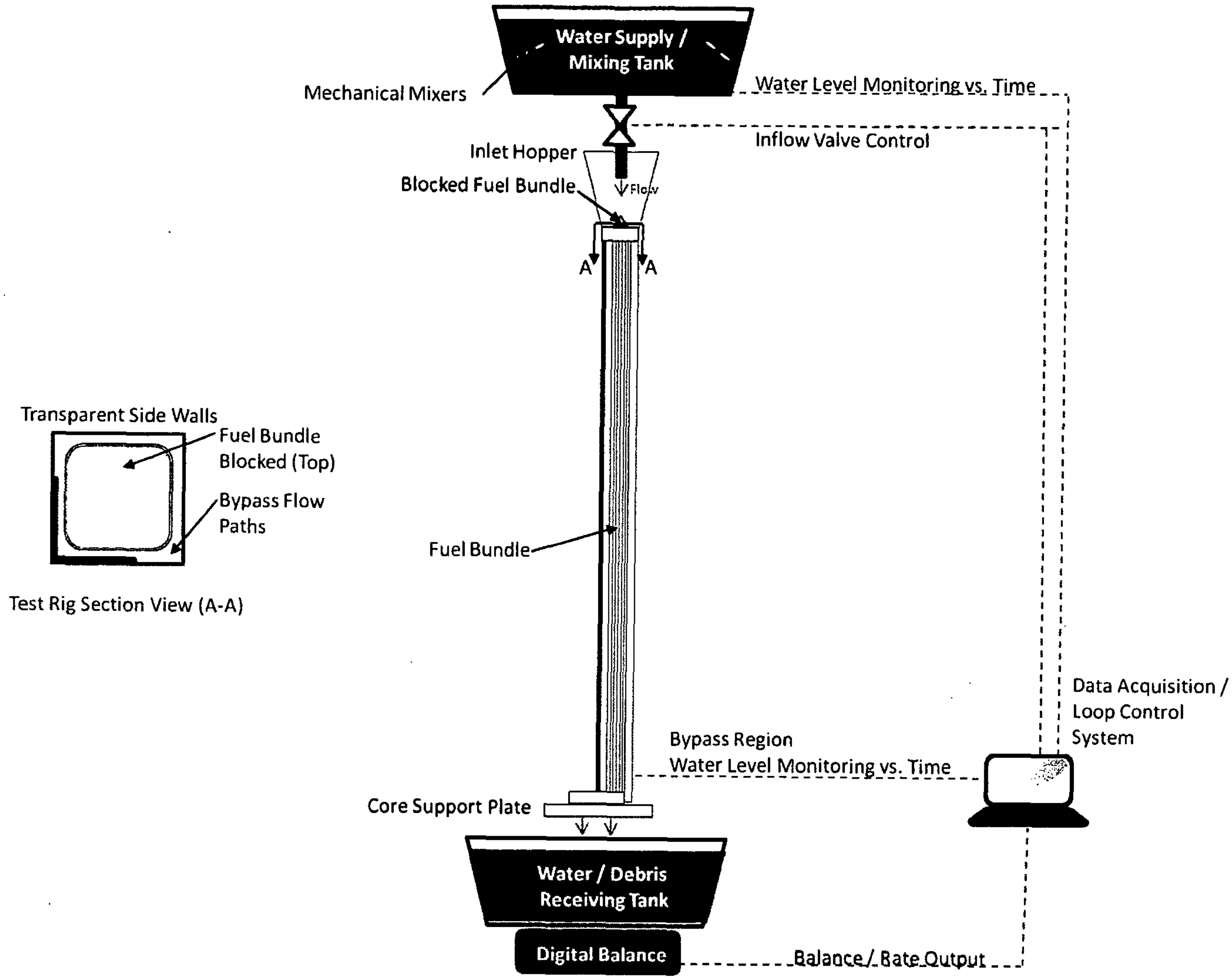

Figure A-1: TEST 1 - Bypass Region Refill Test Rig

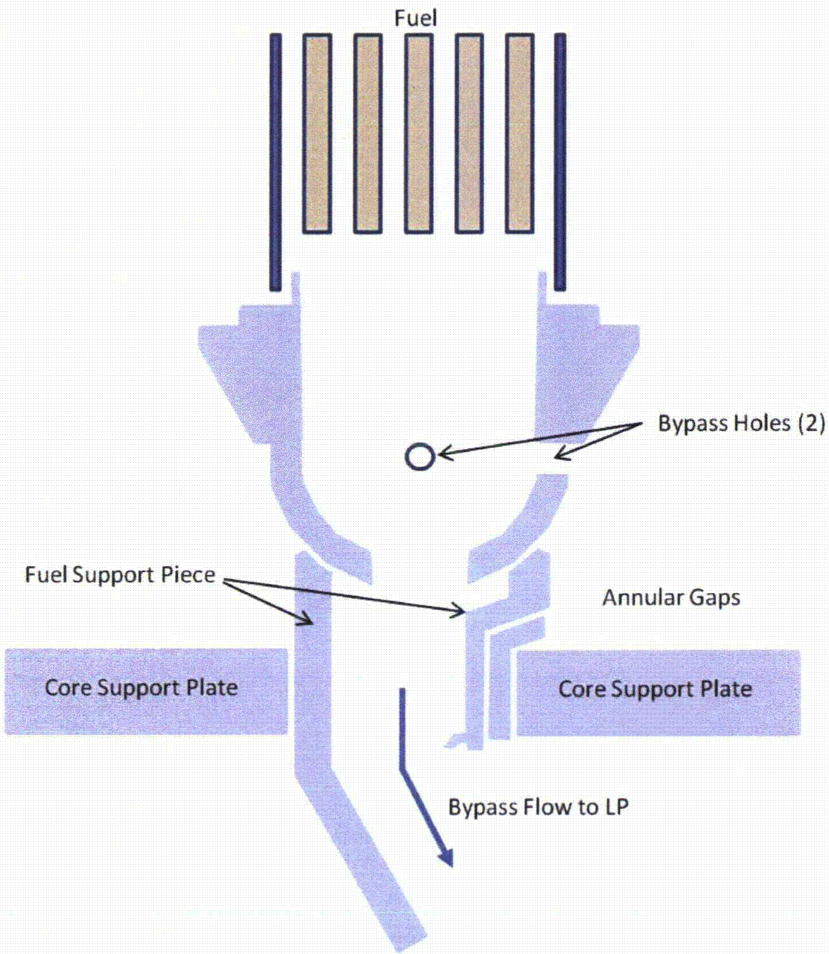

Figure A-2: Fuel Bundle Lower Region and Support Assembly Schematic Showing Bypass Holes and Selected Bypass Region Gaps

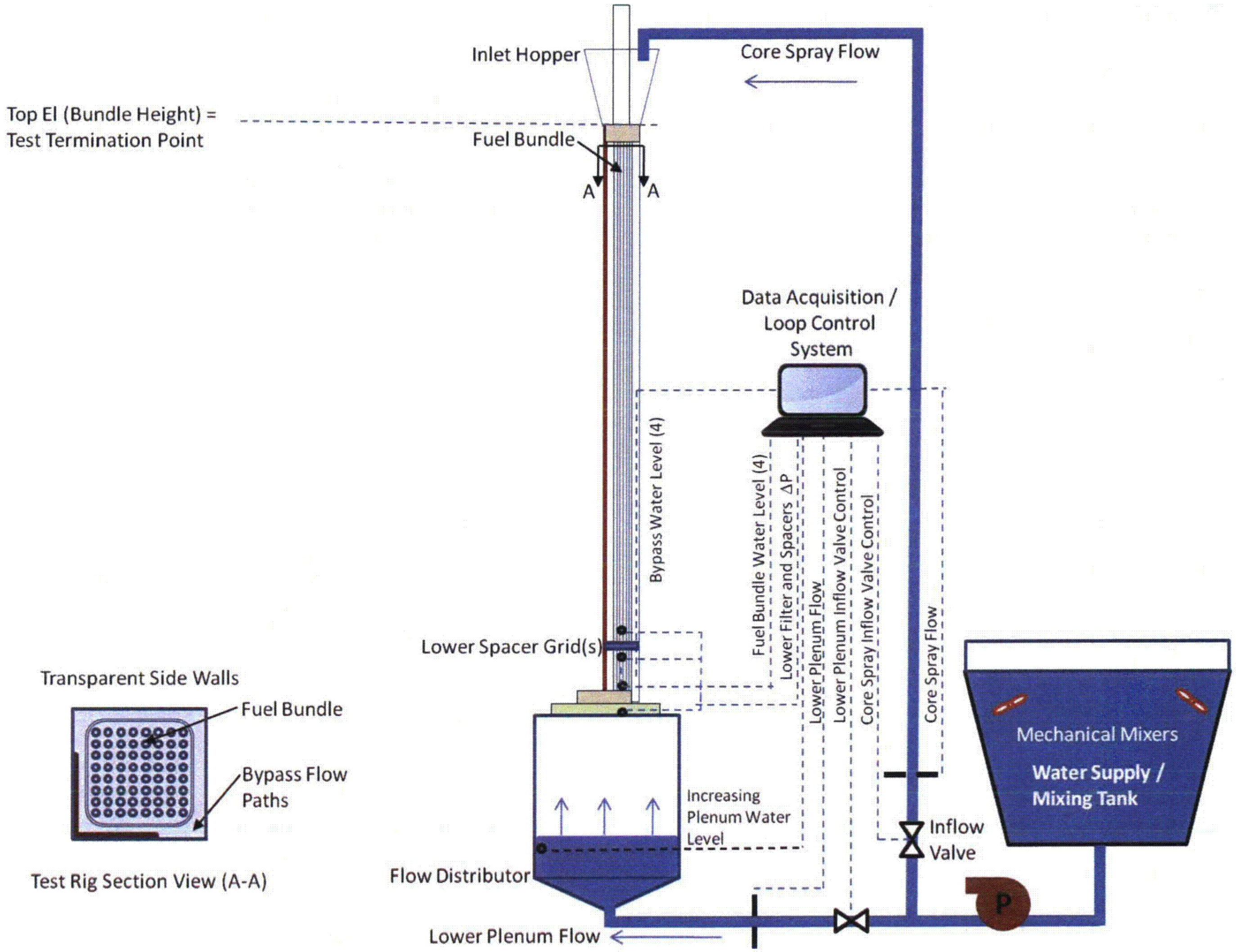

Figure A-3: TEST 2 - Core Re-Flood Rate Test Rig

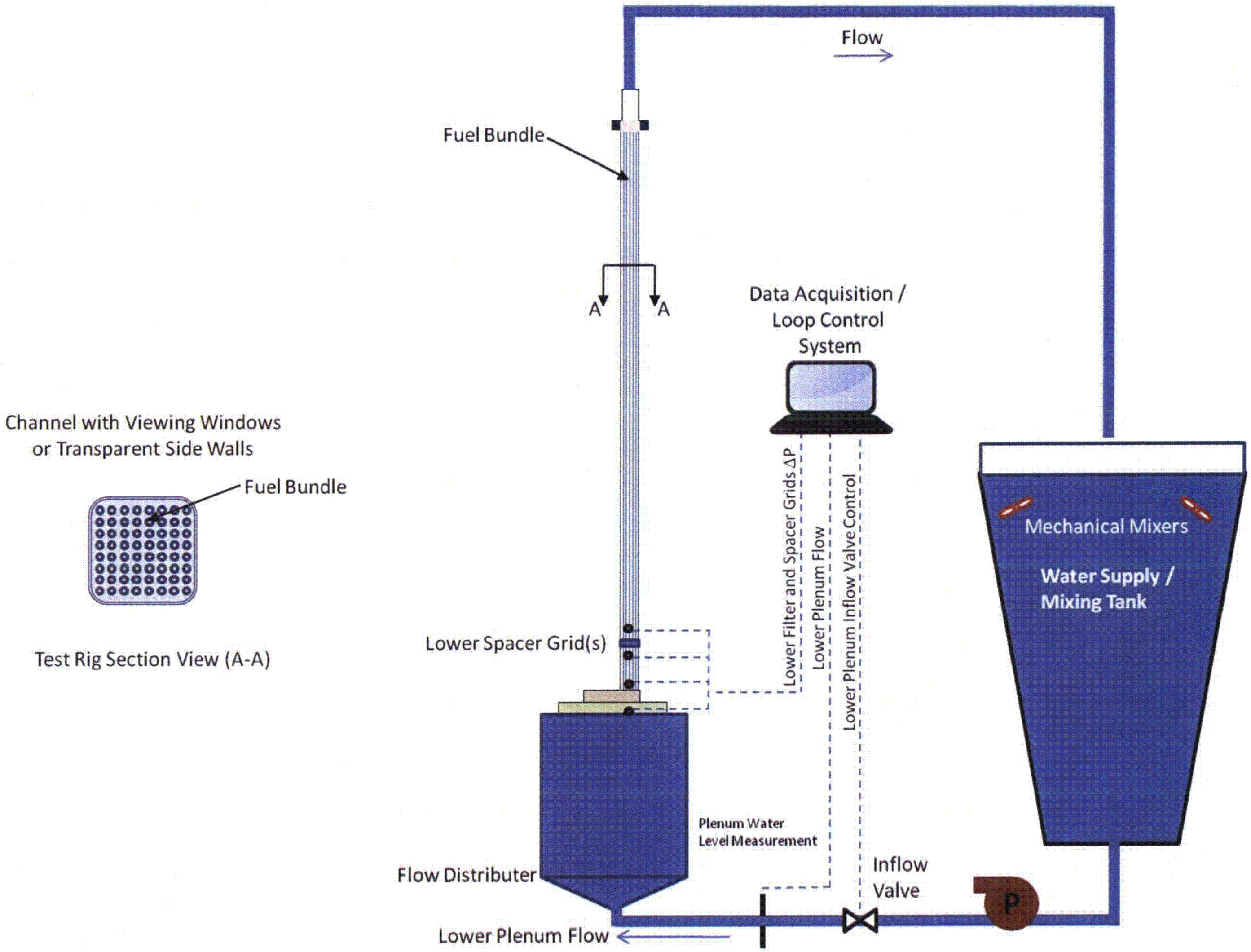

Figure A-4: TEST 3 - Lower Tie Plate Blockage Test Rig

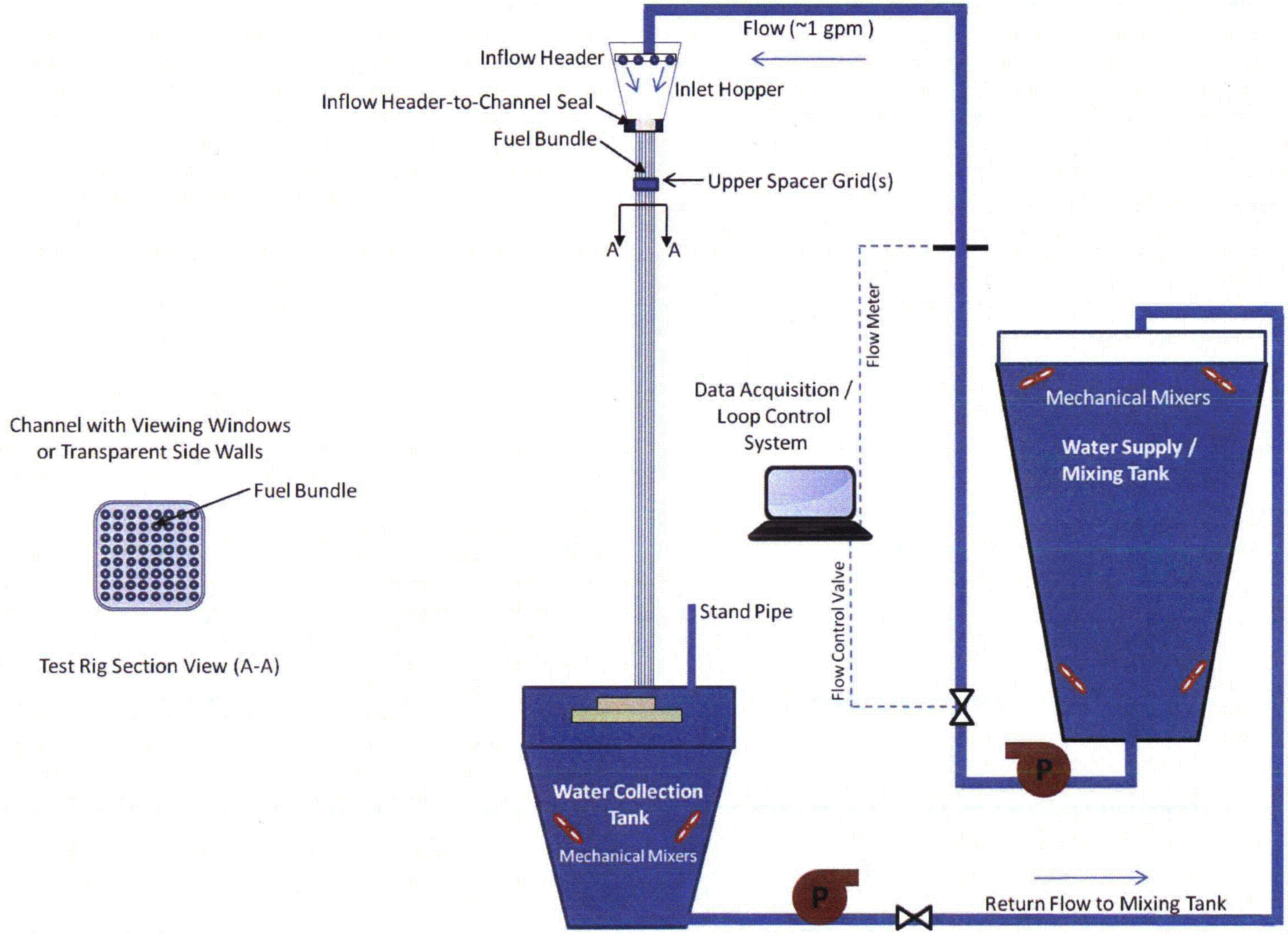

Figure A-5: TEST 4a - Unsubmerged Bundle Test Rig - Upper Tie Plate Blockage without Countercurrent Air Flow

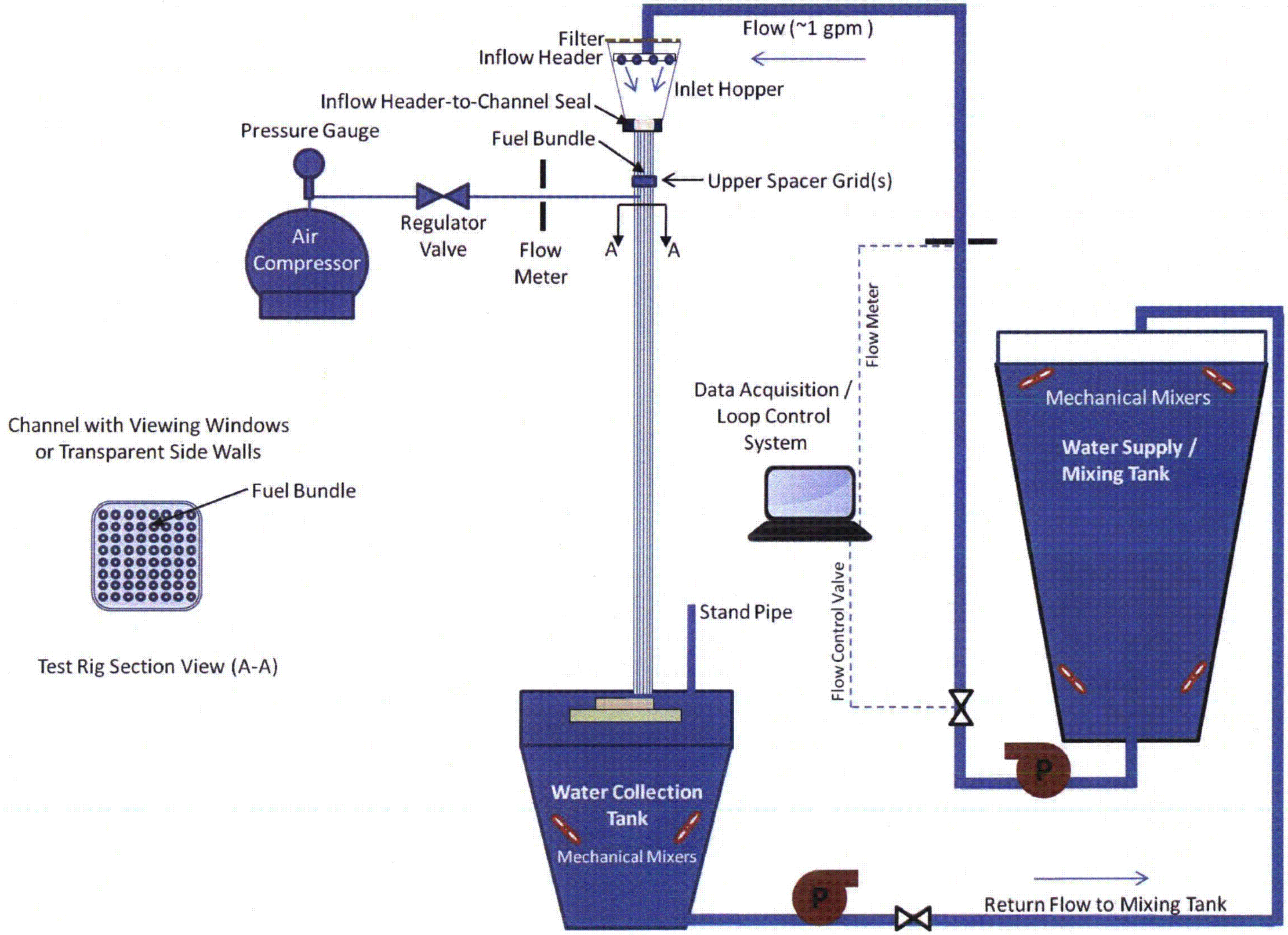

Figure A-6: TEST 4b – Unsubmerged Bundle Test Rig - Upper Tie Plate Blockage with Countercurrent Air Flow

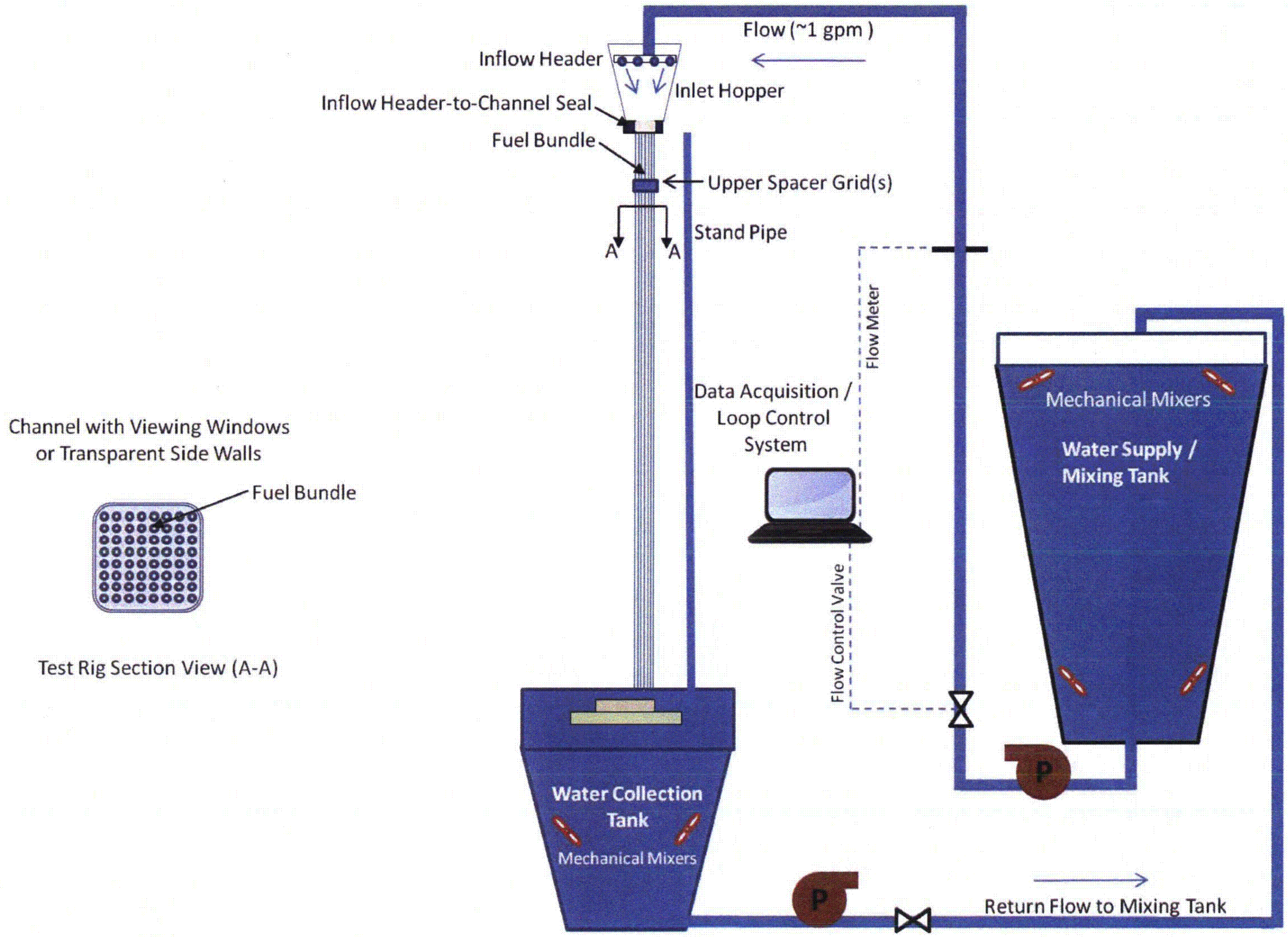

Figure A-7: TEST 4c – Submerged Bundle Test Rig - Upper Tie Plate Blockage without Countercurrent Air Flow

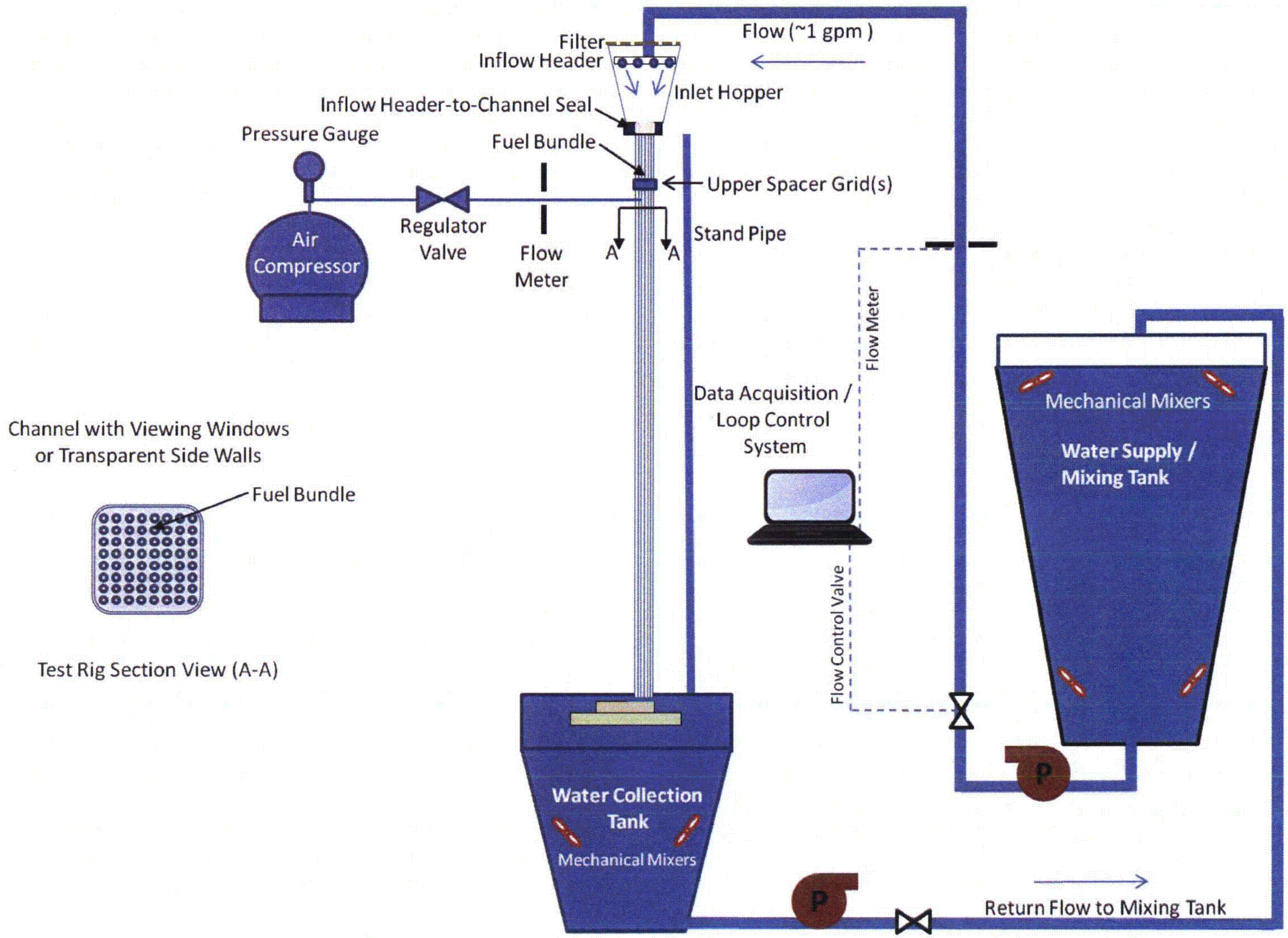

Figure A-8: TEST 4d – Submerged Bundle Test Rig - Upper Tie Plate Blockage with Countercurrent Air Flow

Attachment B

Benchtop Test Program Description

1. Introduction

A full height fuel bundle test program has been proposed to address concerns regarding the ability to maintain adequate cooling in the core in the presence of debris that has penetrated the suppression pool strainers in the aftermath of a LOCA. By virtue of testing at temperatures closer to ambient than boiling and testing with generally clean test bundle fuel rods, certain prototypical fuel and environmental characteristics are not addressed in the full height fuel bundle test program. A benchtop test program has been devised to address the concerns associated with various phenomena that have been identified by NRC staff as not being well represented or targeted in the full height bundle test program. The benchtop test program has been divided into four tests each one dealing with different phenomena. The following sections discuss each test setup in turn describing the objectives of the test, the general test setup, planned measurements, a brief overview of the test procedure, the planned method for evaluating test results and the RAIs addressed by the benchtop test.

2. Benchtop Test 1 (BT1)

2.1 Objective

Debris may enter the fuel bundle and pass through the upper tie plate and one or more spacer grids at relatively low concentration. However, boiling will cause the debris transported into the fuel bundle to concentrate over time. Increasing the concentration within the fuel bundle may result in blockage behavior that is different from that observed by merely testing with elevated debris concentrations at the inflow boundary of the full height bundle test. The intent of BT1 is to demonstrate whether or not concentrated debris (resulting from boiling off a portion of water) is more likely to be withheld at a spacer grid than debris at the nominal starting concentration. The likely mechanism for any observed differences is agglomeration due to increased debris interaction. It is a further objective to assess to what extent agglomeration is more likely in the debris once it has been concentrated from its initial conditions.

2.2 Inputs

In order to conduct these tests, the range of inlet debris concentrations must be obtained. Further, integrated boiling water rates between each fully rodded spacer grid as a function of time will be necessary. Debris concentration via boil-off will be reduced by the amount of through-flow to lower spacer grids that must occur to keep these areas cool. Together these inputs will allow the degree of possible over-concentration to be determined. In addition to the inputs determining concentration, a range of through-flow rates is required to allow the flow rates modeled in the test to remain representative. Finally, the debris composition and quantity must be defined for the range of possible scenarios to determine if the measured effects depend on debris composition or quantity.

2.3 Setup

A simple rectangular drop tube type test is proposed to evaluate the effect of concentration on the ability of the debris to be captured at a fully rodded spacer grid. The general setup is shown in Figure B-1. The drop tube will be clear acrylic and have a cross-section consistent with the interior cross section of the fuel channel. A fully rodded spacer grid will be installed near the lower end of the drop tube. The spacer grid will be equipped with stub fuel rods to ensure the clearances available for passing debris are prototypical. Downstream of the spacer grid, flow rate is controlled such that prototypical through-flow velocities are obtained in testing. Where a prepared debris mixture needs to be concentrated, this will be achieved by boiling the mixture to achieve the desired reduction in water volume. Agglomeration, should it occur, will therefore be represented correctly by this method of debris preparation. As Figure B-1 shows, the debris laden water is placed above a larger volume of clean water in the drop tube. The debris mixture is initially isolated from the clean water layer below and above by drop gates. The clean water layer above the debris laden water is required when the debris is concentrated by boiling to ensure the same total amount of water is passed through the spacer grid whether or not the starting debris mixture is concentrated by boiling. The drop gate structure will be manufactured from metal to support the elevated temperatures of the boiled debris mixture.

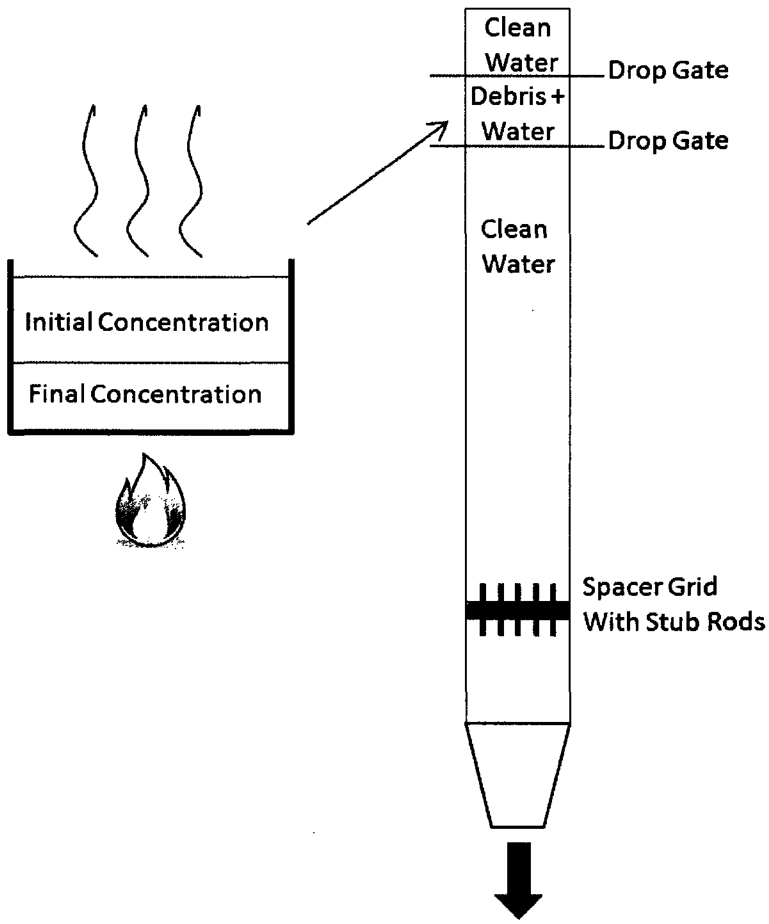

Figure B-1. BT1 Test Setup Sketch

2.4 Measurements

The primary measurement for BT1 will consist of the flow rate through the spacer grid as a function of time along with the corresponding pressure drop across the spacer grid. The tests will always be conducted in pairs where the time evolution of head-loss is compared between the test conducted without concentrating the debris via boiling and the test conducted after the debris has been concentrated via boiling. Tests will be captured using video to allow qualitative comparisons of the debris settling rates and debris distribution within the flow.

2.5 Procedure

The general test procedure outline for BT1 is as follows:

1) Prepare one uniform mixture of debris to cover both tests.
2) Begin heating entire mixture.
3) When mixture begins to boil, remove half of debris mixture.
4) Add the extracted half of the debris to the space above the lowest drop gate (leave upper drop gate open).
5) Continue boiling remaining debris mixture.
6) Ensure instruments are ready for data collection.
7) Open drop gate slowly and begin draining flow from drop tube.
8) Control flow rate to desired set point and continue draining until a free water surface is clearly visible below the spacer grid.
9) Terminate the reference concentration debris test.
10) Clean spacer grid of debris and refill test rig with clean water to just above lower drop gate.
11) When desired water volume reduction has been achieved, add over-concentrated debris to the space above the lower drop gate.
12) Add water above upper drop gate to achieve the same starting water volume as was previously employed for the reference debris concentration test.
13) Open drop gates slowly and begin draining flow from drop tube, controlling the flow rate to the desired set point.
14) Terminate the over-concentrated debris test when a free water surface is observed below the spacer grid.

2.6 Results

The key comparison in the test results will be between the DP that develops for the reference debris concentration relative to the over-concentrated test. If a substantial difference exists, concentrating the debris by boiling is important and methods for incorporating the phenomenon into the full height bundle tests need to be evaluated. If no substantial differences are found, the phenomenon does not affect debris behavior and testing for the full height bundle is unaffected. Note that BT1 is not conducted with recirculation because recirculating highly concentrated debris does not represent a realistic scenario.

2.7 RAIs Addressed

BT1 is intended to address the concerns raised in RAI 4a (Supplement S1).

3. Benchtop Test 2 (BT2)

3.1 Objective

Prototypical fuel rod characteristics post-LOCA may differ from clean fuel rod characteristics in various ways. The objective of BT2 is to determine whether or not these possible differences could be important in terms of the debris accumulation characteristics on the spacer grid. The possible differences that have been identified for evaluation are: scale, crud, thermal adhesion and surface roughness. The extent to which thermal adhesion is likely will be evaluated using BT3. However, the resulting possible effects of thermal adhesion are intended to be evaluated using BT2. The possible differences between clean fuel rods and prototypical post-LOCA fuel rods will be simulated in BT2 to determine their importance in determining debris accumulation on the spacer grid. Because it has been suggested that fuel rods with characteristics that differ from clean fuel rods may influence the resistance to removal by steam up-flow, BT2 testing will include the injection of counter-flow air to evaluate whether these characteristics change the spacer grid blockage behavior in the presence of counter-flow air. Techniques for air injection and distribution will be evaluated in BT2 for application in full height bundle testing.

3.2 Inputs

To adequately define BT2, estimates of the possible ranges of prototype surface roughness, crud deposition, thermal adhesion and scale build up need to be obtained. In the absence of these estimates, testing could be used to define the boundary beyond which these effects, separately or in combination, will affect debris deposition and resistance to removal from steam up-flow. In addition, BT2 requires a target range of through-flow rates that should be evaluated for the spacer grid. Representative debris mixtures and quantities are also required, similar to what is required for BT1.

3.3 Setup

The setup for BT1 is similar to that for BT2 except that the stub fuel rods employed in testing will be modified to represent the various effects of interest. In addition, only a single drop gate will be utilized in these tests. The following methods will be considered for modeling the effects of concern:

1) Bead blasting of slightly oversized rods to generate a roughened larger outside diameter (OD) surface. The metal for the stub fuel rod material would be chosen to be soft enough to be amenable to surface modification by bead blasting.

2) Spray coating of model stub fuel rod.

3) Combination of the above.

The modified stub fuel rod surfaces will be documented by microscope photographs and detailed local diameter measurements. Because the prototypical roughness characteristics are not easily known, the methods above are expected to generate a spectrum of roughness that allows any potential effects on debris retention at the spacer grid to be identified.

In order to prevent the surface / rod modifications from being affected by rod insertion all the way through the spacer grid, the stub fuel rods will be assembled from above and below with a mild interference fit in the center of the spacer grid using a simple pin design, as illustrated in Figure B-2.

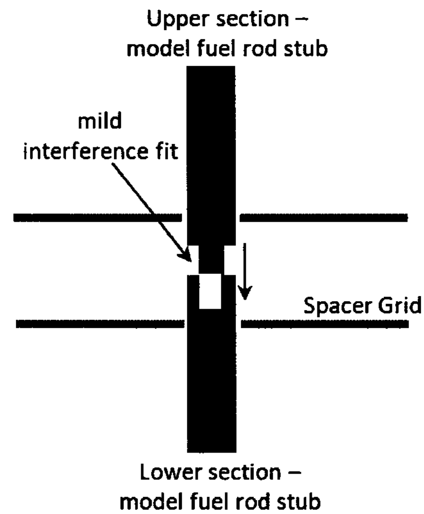

Figure B-2. BT2 Modified Stub Fuel Rod Connection Strategy

A further difference between BT1 and BT2 is the use of counter-current air flow in BT2. Various techniques will be evaluated for air injection below the spacer grid. The setup will allow the introduction location and method of air introduction to be varied to achieve the target, relatively uniform, air distribution across the spacer grid. While uniform air distribution may not be prototypical in all cases, uniform air distribution is considered a more effective evaluation tool in BT2 to determine if debris is more likely to remain lodged in the spacer grid when the fuel rod characteristics differ from clean fuel rod characteristics. The following methods of air injection will be evaluated:

1) Sintered metal air injection
2) Radial air injection
3) Distributed air injection manifold
4) Air injection incorporated into stub fuel rods

Due to implementation difficulties in the full height fuel bundle, Method 4 will not be implemented unless shown to be necessary by the failure of the other methods. Success of the method will not only be judged by the uniformity of the air injection but also by the ability of the method to resist debris accumulation on any air injection hardware that protrudes into the flow because this would be non-prototypical.

3.4 Measurements

Measurements for BT2 will resemble those for BT1 where the DP across the spacer grid is monitored during the drain process of the column. For cases where counter-flow air injection is utilized the injection air flow will be measured to ensure the simulated steam up-flow is consistent with the test water down-flow. Measuring DP across the spacer grid may be problematic during tests with air injection. To ensure relevant measurements are available, BT2 will also monitor the gauge pressure just upstream of the suction pump during the drain process. Tests will also be captured by video to document the interaction of the debris with the spacer grid.

3.5 Procedure

The general test procedure outline for BT2 is as follows:

1) Assemble test rig with target stub fuel rods (i.e., clean or modified stub fuel rods).
2) Prepare debris mixture for testing at a nominal concentration derived from the inputs of BT1.
3) Fill test rig with water.
4) Ensure instruments are ready for data collection.
5) Determine valve setting for required air flow rate if the test is to simulate steam flow.
6) Add debris above lower drop gate.
7) Open drop gate slowly and begin draining flow from drop tube.
8) Start air flow at the valve setting determined previously if test is to simulate steam flow.
9) Control flow rate to desired set point and continue draining until a free water surface is clearly visible below the spacer grid.
10) Terminate the test.

3.6 Results

Similar to BT1, the DP measurement in a given test on its own will hold little value. The tests are intended to determine whether the executed stub fuel rod surface modifications have an influence on the observed development of the DP across the spacer grid, with or without simulated steam up-flow relative to the clean baseline configuration. If prototypical characteristics for the possible fuel rod conditions are not available, the boundary beyond which certain modifications become important will be identified. This approach could be used to assess the likelihood that full height fuel bundle testing conducted with clean rods will be non-conservative. If an unrealistically high surface modification is necessary to affect spacer grid debris interaction then full height fuel bundle testing could proceed even while prototypical surface characteristics have not yet been fully defined (i.e., scale deposition model).

Note that BT2, similar to BT1 is not conducted with recirculation because this is expected to emphasize any differences between clean and modified stub fuel rods. The option of recirculation will be revisited for BT2, should no differences be found with even the most significant surface modifications. The setup modification to enable recirculation is not significant.

3.7 RAIs Addressed

BT2 is intended to address elements of the following RAIs from Supplement 1: 4b, 6a, 6c, 23a, and 27b.

4. Benchtop Test 3 (BT3)

4.1 Objective

Early in the post-LOCA period, fuel cladding temperatures may exceed the melting point of some key constituent debris materials (e.g., fiber glass). The objective of BT3 is to assess whether thermal adhesion of debris is possible under expected conditions. Water contaminant plate-out (i.e., deposition of materials initially dissolved in the water) will not be addressed by these tests.

4.2 Inputs

The inputs for BT3 consist of the peak temperatures of interest and the debris types and forms that may enter the fuel bundle with the cooling flow. Representative debris mixtures will be generated similar to tests BT1 and BT2. In addition, spray flow rates will be scaled based on the represented geometry starting with the range of possible spray flow rates being supplied into the fuel bundle.

4.3 Setup

Figure B-3 shows a sketch of a subsection of the fuel spacer grid (GE14). The sketch also outlines a symmetry boundary that will be used to generate a small hot surface test section. The test section is shown to the right of the fuel rod spacer schematic. The test section is chosen so that the represented hot surfaces can be heated from outside of the modeled portion of the fuel bundle cross-section. At the boundaries of the test section, symmetry boundaries will be implemented using an insulated surface to help preserve heat within the modeled fuel bundle section.

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Figure B-3. BT3 Symmetry Boundary Modeled for Thermal Adhesion Test

Figure B-4 shows a broader view of the test setup. The overall height of the modeled test setup is relatively short (6 in – 12 in). The debris mixture will be injected from the top via a nozzle at a prescribed rate related to the overall water being supplied to the fuel bundle. The lower section of the heated rods may be submerged in water to provide some of the prototypical up-flow steam that would exist under prototypical conditions. Note that prototypical materials will be employed for all elements that represent fuel rod or spacer grid elements within the test.

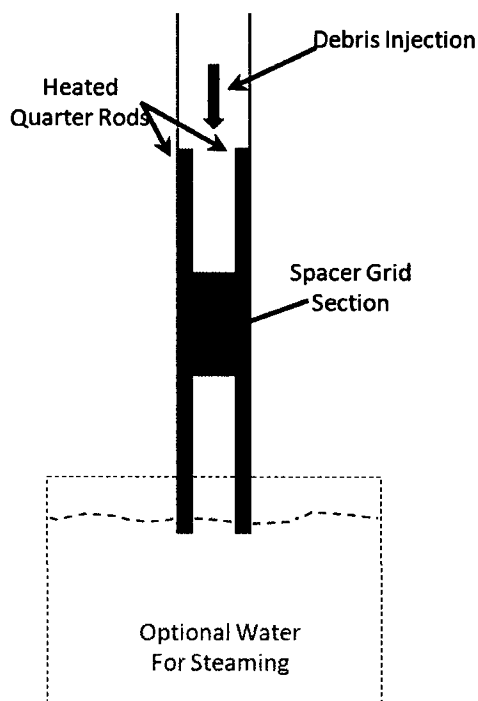

Figure B-4. BT3 Setup for Thermal Adhesion Test

4.4 Measurements

Measurements in BT3 will include the monitoring of the modeled fuel rod surface temperatures at multiple locations along the length of the heated surface but especially focused on the areas immediately above and below the spacer grid hardware. Spray flow rate and the amount of heat being supplied to the test will be monitored. Capture of the generated steam outflow will be attempted to the extent feasible because this flow is the most likely path for debris. After the termination of the test, the heated surfaces will be examined using a fiberscope probe and after careful disassembly with a microscope, all along their length including near the spacer grid hardware. Microscope examination will reveal the extent and type of thermal adhesion that occurred (if any) on the heated surfaces. Thickness measurements will be performed along the heated surface to document any changes due to thermal adhesion.

4.5 Procedure

The following is a general outline of the test procedure.

1) Power is applied to the modeled fuel rod surfaces to bring them up to the correct temperature.
2) When the target temperature is approached, spray flow is started from a tank containing a representative debris mixture.
3) Surface temperatures are monitored and maintained for a total of approximately 15 minutes.
4) While surface temperatures are still being maintained, spray flow is terminated.
5) Surface temperatures are then slowly decreased to ambient to prevent any material adhered to the surface from being removed by the cooling process.
6) Insulating walls are removed to allow access to be gained to the exposed heated surfaces and the spacer grid hardware.

4.6 Results

The post-test surface examination will demonstrate whether or not thermal adhesion is likely for conditions representative of post-LOCA fuel bundle conditions. By examining the extent of any thermal adhesion and characterizing any preferred location for such deposition, the likelihood that thermal adhesion is important can be addressed on the basis of this test result. Note that thermal adhesion away from the spacer grid hardware will not be considered nearly as problematic as thermal adhesion immediately adjacent to the spacer grid hardware due to the small clearances at the fuel rod-to-spacer grid interface.

4.7 RAIs Addressed

Benchtop Test BT3 addresses concerns raised in RAI 23a (Supplement S1).

5. Benchtop Test 4 (BT4)

5.1 Objective

BT4 is intended to address concerns related to the uniformity of flow and debris deposition within the fuel bundle. BT4 addresses issues related to a potential non-uniformity in the incoming spray flow distribution as well as non-uniformity resulting from the likely flow distribution within the fuel bundle given the asymmetric openings in the upper tie plate and upper spacer grids. Aside from providing an indication of whether local debris accumulation may be a concern relative to blockage, BT4 will also serve as the proving ground for several full height bundle test diagnostics including optical blockage evaluation as well as water hold-up measurement and air simulation of steam flow.

5.2 Inputs

Inputs required for BT4 need to define the range of prototypical spray characteristics that may reach the fuel bundle including: flow rate, spray angle and if possible, spray momentum. Debris mixture concentration, composition, size characteristics and quantities are also required inputs because accumulation characteristics may depend on these parameters.

5.3 Setup

Figure B-5 shows a sketch of the setup envision for BT4. The setup represents that of a shortened fuel bundle. The setup models the upper tie plate, a partially rodded spacer grid and a fully rodded spacer grid. The fuel bundle will represent the distance between the upper tie plate and the first partially rodded spacer grid prototypically. Also, the distance between the lowest partially rodded spacer and the first fully rodded spacer grid is represented prototypically in the test bundle. Model fuel rods will have two lengths to correctly represent full-length and part-length fuel rods in the prototype. The upper tie plate will have a prototypical handle to ensure interference between spray and the handle is modeled correctly. The fuel channel of BT4 will be simulated using machined sections of acrylic to enable maximum optical / visual access.

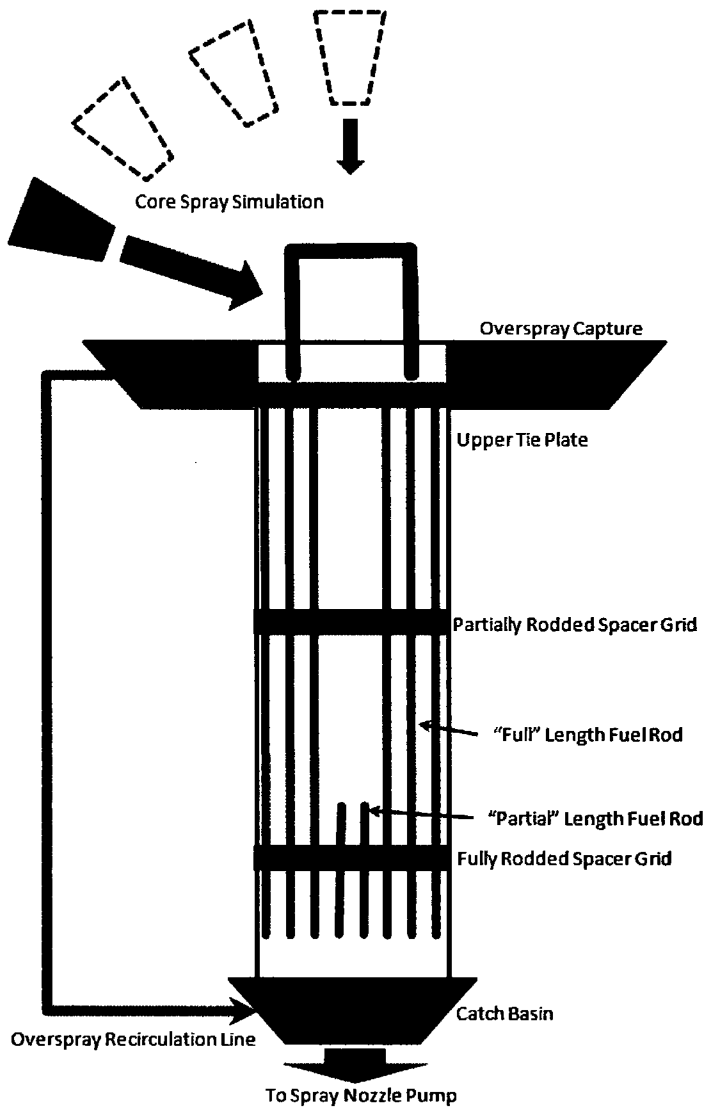

Figure B-5. BT4 Short Fuel Bundle Setup

Spray flow is simulated from an articulated nozzle mounted above the model fuel bundle. Various nozzles will be investigated, all with clearances similar to those of the prototypical core spray nozzles. In order to prototypically vary the momentum as the spray approach angle is manipulated, various nozzle sizes will be required. The currently envisioned spray flow introduction method for full height bundle testing will also be evaluated for comparison. Overspray from the nozzles will be collected and re-introduced from the catch basin where the initial water debris mixture is prepared. A portion of the spray flow pump flow will be recirculated to the catch basin to ensure debris remains in suspension and available for transport to the core spray nozzle.

Note that BT4 can be conducted using both a submerged and dry bundle to simulate both relevant Test 4 scenarios.

While not shown in Figure B-5, methods for the introduction of counter-flow air will also be evaluated during BT4. Methods will be refined from BT2. The potential for axially distributing the air injection flow will be specifically evaluated in BT4.

5.4 Procedure

The following is a general procedure outline for test BT4:

1) Run clean water through system and adjust nozzle alignment at the planned flow rate to minimize overspray.
2) Prepare debris mixture with test water volume and insert into catch basin.
3) For a submerged bundle test, continue filling the catch basin and connected model fuel bundle to the correct water level.
4) Ensure data acquisition systems are ready for data collection.
5) Start spray flow pump and adjust flow rate from spray nozzle to desired level.
6) Continue test until relative debris concentration measurement in the spray flow supply header has stabilized.
7) At termination, the model fuel bundle is drained slowly, observing any debris accumulations on the spacer grid to ensure these are not affected by the draining process.
8) Examine the debris beds using methods that would be available during full height bundle testing.
9) Perform additional debris bed measurements only available for BT4.

5.5 Measurements

Test operational measurements will consist of DPs across each spacer grid, the spray flow rate and the over-spray and catch basin water levels. The concentration of debris in the spray flow downstream of the pump will be monitored on a relative basis to assess when steady state conditions have been reached. For cases that simulate steam up-flow, the air flow will be measured. If air flow is injected at multiple locations, the flow is measured separately for each location. The tests will be recorded using video. The post-test debris bed examination will involve quantitative optical and qualitative visual debris blockage assessments. Measurement techniques will evaluate techniques targeted for use in the full height bundle tests and techniques only available in the simplified setup of BT4. BT4 will be constructed to allow more liberal access to the spacer grid surface than is expected to be available in the full height bundle testing. Some techniques employed to document the condition of the spacer grid will therefore not be able to be transferred to full height bundle testing. However, these more invasive techniques will serve as a meaningful measurement standard for the methods that will be developed for application in full height bundle testing.

5.6 Results

BT4 results will help address the sensitivity of debris accumulation to the manner in which core spray flow is modeled for both dry and submerged bundles. In the case of the latter, little sensitivity is expected. Because it may be difficult to quantify the spray flow momentum exactly, spray flow momentum influence will be evaluated in a realistic range of values. In addition to spray flow modeling behavior, BT4 will evaluate the uniformity of debris accumulations for partially rodded spacer grids and fully rodded spacer grids and any associated influence on the distribution of simulated steam flow within the assembly. BT4 results will also show whether spacer grid DP measurements can be reliably related to blockage. Optical and visual methods for assessing blockage will be evaluated for accuracy and repeatability. Because a range of flow rates will be evaluated, any dependence of the recirculated debris concentration on flow rate can be evaluated to help determine whether or not debris downwash represents an important phenomenon. A lower bound for flow rate will be identified below which the concentration history is no longer affected by further reductions in flow rate.

5.7 RAIs Addressed

The RAIs addressed by BT4 are RAIs 24a, 24d, 23b, 27b, 40a, and 40b (original) as well as RAIs 23b, 26, and 40 (Supplement 1).

Attachment C

Reactor Power Sensitivity Studies

Initial Core Power Sensitivity Studies

Power sensitivity cases have been performed for BWR with JP components to assess the effect of differences in upper plenum inventory enthalpy (due to differences in initial core power level) on the HB heatup when debris blockage is postulated during a LOCA event.

Both plant types with LPCI injection into the lower plenum via recirculation loop (BWR/3 and BWR/4) and with injection into the bypass region (BWR/5 and BWR/6) are considered.

For each plant type, core power levels of 100% and approximately 90% are analyzed. In addition, both Case 04 blockage (total blockage at the bottom and partial blockage at the UTP of the HB) and Case A-1 blockage (Case 04 HB blockage in conjunction with entire core inlet blockage) scenarios are considered.

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BWR/3-4 Plant Type

LPCI is injected into the lower plenum via the recirculation loop for BWR/3-4 plant type. A plant with a higher power density as compared to the BWR/3 reference case in the submitted LTR is selected for the power sensitivity studies herein. Guillotine recirculation line break at the suction location and ECC combination with 1 LPCS and 3LPCI operating are assumed. Initial power levels of 100% and 92%, and blockage Scenarios 04 and A-1 for each power level case are analyzed. These sensitivity studies are performed using the GE14 fuel assembly.

A summary of key results of the four (4) individual cases are listed in Table C-1.

Table C-1. [[ ]]

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BWR/4 Case 04 Blockage Comparison

Two SAFER calculations were performed for the BWR/4 Case 04 blockage scenarios with 100% and 92% initial core power. The results are presented in this section.

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Figure C-1. [[ ]]

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Figure C-2. [[ ]]

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Figure C-3. [[ ]]

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Figure C-4. [[ ]]

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Figure C-5. [[ ]]

BWR/4 Case A-1 Blockage Comparison

Two SAFER calculations were performed for the BWR/4 Case A-1 blockage scenarios with 100% and 92% initial core power. The results are presented in this section.

The difference between the Case 04 and Case A-1 blockage is that for the Case A-1 blockage, in addition to the blockage in the HB, the entire core entrance is blocked [[ ]] into the refill phase. As a result, for the Case A-1 blockage scenario the active core, bypass, and upper plenum are filled with ECC water when the entire core entrance is blocked with debris.

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Figure C-6. [[ ]]

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Figure C-7. [[ ]]

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Figure C-8. [[ ]]

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Figure C-9. [[ ]]

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Figure C-10. [[ ]]

BWR/5-6 Plant Type

One major difference in ECCS configuration between BWR/3-4 and BWR/5-6 is that LPCI is delivered to the top of core bypass region for BWR/5-6 type instead of injecting into the lower plenum via the recirculation loops. The reference cases of BWR/6 guillotine break at the recirculation suction location with 100% initial power are repeated with an initial power of 91% to study the effect on PCT due to core power differences. Both Case 04 and Case A-1 blockage scenarios are analyzed. These sensitivity studies are performed using GNF2 fuel assembly.

Summary of key events of the four (4) individual cases is listed are Table C-2.

Table C-2. [[

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BWR/6 Case 04 Blockage Comparison

Two SAFER calculations were performed for the BWR/6 Case 04 blockage scenarios with 100% and 91% initial core power. The results are presented in this section.

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Figure C-11. [[ ]]

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Figure C-12. [[ ]]

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Figure C-13. [[ ]]

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Figure C-14. [[ ]]

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Figure C-15. [[ ]]

BWR/6 Case A-1 Blockage Comparison

Two SAFER calculations were performed for the BWR/6 Case A-1 blockage scenario with 100% power and 91% initial core power. The results are presented in this section.

The difference between the Case 04 and Case A-1 blockage is that for Case A-1 blockage in addition to the blockage in the HB, the entire core entrance is blocked [[ ]] into the refill phase. As a result, for the Case A-1 blockage scenario the active core, bypass and upper plenum are filled with ECC water when the entire core entrance is blocked by the accumulation of debris.

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Figure C-16. [[ ]]

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Figure C-17. [[ ]]

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Figure C-18. [[ ]]

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Figure C-19. [[ ]]

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Figure C-20. [[ ]]

Attachment D

BWR/2 Axial Power Shape

The axial power shape of the hot bundle for the BWR/2 DBA case is shown in Figure D-1.

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Figure D-1. [[ ]]

Attachment E

CCFL at Steam Separator for Core Spray Line Break

CCFL at Steam Separator

In the BWR/3 reference plant there are 129 2-stage type steam separators. For each 2-stage steam separator, there are three (3) paths that water can flow back into the upper plenum; they are located at the first and second pick off rings and at the separator exit nozzle. The areas of the discharge passage at the first and second pick off rings are 19.33 and 4.7 in^2, respectively, and the separator nozzle exit area is 22.3 in^2.

For the BWR/3 core spray break with single failure of the opposite train of core spray, after the entire core inlet is blocked, LPCI water injected into the lower plenum will cumulate in the downcomer region. SAFER predicts that the downcomer water level rises to the top of separator elevation at about 459.3 seconds after the break occurrence.

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Figure E-1. [[ ]]

Attachment F

Containment Pressure and ECCS Temperature

In the SAFER BWR/3 reference case and the follow up analysis with various blockage assumptions, constant drywell pressure [[ ]] and constant ECC water at [[ ]] were used. To confirm that such boundary condition is conservative for the fuel blockage analyses, a sensitivity study was performed with the BWR/3 A1 Blockage scheme (higher blockage PCT) using a realistic containment response with respect to ECC water temperature and drywell pressure based on results attained from a realistic SHEX containment performance model analyses.

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Figure F-1. [[ ]]

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Figure F-2. [[ ]]

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Figure F-3. [[ ]]

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Figure F-4. [[

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Figure F-5. [[ ]]

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Figure F-6. [[ ]]

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Figure F-7. [[

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Attachment G

CCFL at Hot Bundle UTP

A maximum allowable liquid down flow ($WL_{available}$) at the top of a fuel bundle is calculated in SAFER when a two phase level is established in the fuel bundle using the algorithms described in Table G-1.

Table G-1. [[ ]]

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Figure G-1. [[ ]]

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Figure G-2. [[ ]]

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Figure G-3. [[ ]]

Attachment H

Effect of Intermediate Blockage

The BWR/3 reference case with A-1 blockage postulation is repeated with an intermediate blockage flow scheme to demonstrate that the impact of intermediate blockage on the peak clad temperature is insignificant and the proposed blockage scheme is conservative.

The differences between the BWR/3 A-1 blockage scenario and the intermediate blockage sensitivity case are listed in Table H-1 and they are depicted in Figures H-1a, H-1b. and H-1c.

Table H-1. [[ ]]

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Figure H-1a. [[ ]]

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Figure H-1b. [[ ]]

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Figure H-1c. [[ ]]

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Figure H-2. [[ ]]

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Figure H-3. [[ ]]

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Figure H-4. [[ ]]

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Figure H-5. [[ ]]

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Figure H-6. [[ ]]

Attachment I

Plots for 30 Day Runs

This sensitivity study examines the long-term 30 day ECCS mission bundle conditions in support of the Test 4. Two sets of BWR type calculations are given, BWR/3-4 injection outside the shroud and BWR/5-6 injection inside the shroud. The key results demonstrate that when the hot channel inlet is assumed to be fully blocked, and it is being cooled by flow from the outlet, the coolant in the fuel region will slowly achieve liquid saturation. The coolant flow into the bundle, either by core spray or upper plenum pool, depending on plant type and boundary conditions, reflects approximately the mass loss from decay heat vaporization. The results consistently show that once the fuel is quenched following the long-term reheat from specified outlet blockage magnitude and time, it will remain quenched. [[

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Table I-1. [[ ]]

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Figure I-1. [[ ]]

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Figure I-2. [[ ]]

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Figure I-3. [[ ]]

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Figure I-4. [[ ]]

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Figure I-5. [[ ]]

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Figure I-6. [[ ]]

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Figure I-7. [[ ]]

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Figure I-8. [[ ]]

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Figure I-9. [[ ]]

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Figure I-10. [[ ]]

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Figure I-11. [[ ]]

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Figure I-12. [[ ]]