DRAFT NRC STAFF REVIEW GUIDANCE FOR EVALUATION OF DOWNSTREAM EFFECTS OF DEBRIS INGRESS INTO THE PWR RCS ON LONG TERM CORE COOLING FOLLOWING A LOCA

1. TECHNICAL RATIONALE

During the long-term cooling (LTC) phase of a loss-of-coolant accident (LOCA) in a pressurized water reactor (PWR), water is supplied from the containment sump to the reactor coolant system (RCS) by the emergency core cooling (ECC) pumps. As part of the technical efforts for resolving GSI-191, “Assessment of Debris Accumulation on PWR Sump Performance”, consideration is needed for the consequences of debris penetrating the sump screen and propagating downstream into the primary coolant system. Injection of debris into the RCS during the LTC recirculation phase needs special attention to assure that reactor core cooling is maintained. The point of concern is the potential for debris to adversely affect the reactor core flow paths or heat transfer. The main success criteria that need to be satisfied for all encountered core-cooling conditions is maintaining the fuel peak clad temperature below 2,200^{o}F, limiting the cladding oxidation below 17%, and maintaining a coolable geometry for LTC (assumed to be 30 days); along with other acceptance criteria specified in 10CFR50.46.

This document identifies the major areas of concern related to the downstream effects of debris injection into the RCS on the reactor core coolability. It does not include guidance for evaluation of downstream effects on other ECCS components, as these components and systems are evaluated under other processes included in the resolution of GSI-191. Guidance is included for identification of key factors and contributing phenomena (Section 2) that can have an adverse impact on LTC capability and possible approaches for assessing their effects (Sections 3 & 4). Licensee submittals for final evaluation of emergency core cooling system (ECCS) sump screen performance should contain a level of detail such that there is reasonable assurance that the issue is adequately addressed.

2. CONTRIBUTING PARAMETERS CONSIDERATION

With respect to debris behavior in the RCS and reactor core region, some specific conditions and associated key parameters can play a catalyzing (accelerating) role for participating processes that can adversely affect core coolability. Such conditions can promote the occurrence of phenomena that individually, or in a synergistic way, lead to a degree or distribution of core flow that might result in less than adequate cooling of the fuel rods. The following sections point out the importance of specific parameters and discuss possible ways in which certain RCS conditions can influence debris behavior to potentially lead to inadequate core cooling.

2.1 Fluid and Metal Component Temperatures

The source of decay heat following a reactor shut down is the reactor fuel. As such, the most elevated temperatures during the post-LOCA phase are encountered in the reactor core area, provided there is no fuel relocation within the reactor pressure vessel. This is also true with respect to fluid and metal surface temperatures. Therefore, any temperature-enhanced processes

will take place at elevated rates in the reactor core region and the adjacent volumes in the reactor vessel.

The temperature of the coolant is limited by the saturation temperature of the liquid phase. In turn, the saturation temperature is influenced by the RCS pressure. During the LTC recirculation phase, the RCS pressure is very close to the containment backpressure level. Under two-phase flow conditions, thermal equilibrium between the liquid and vapor phases is expected whereas uncovered core fuel regions can produce superheated steam.

Under saturated fluid conditions with boiling in the core, gravitational head will produce a pressure gradient that, in turn, will result in a saturation pressure distribution. Thus, the water in the bottom region of the core may be at slightly elevated temperature levels in comparison to the upper core region. As a result, for a substance whose solubility in water increases with temperature, any precipitation-type process will tend to occur first in the upper core region. One example of this is the process of boric acid precipitation.

2.2 RCS Flow Conditions

The transport medium for the debris in RCS is the injected ECC water. For purposes of evaluating downstream effects in the reactor vessel, there is one important active component in the flow path from the containment sump screen to the RCS injection port, the ECC pump. A pump will mix debris pieces and fibers, resulting in a homogeneous process fluid; and may fragment larger pieces of debris to produce smaller particles and fibers.

For all PWR reactor designs, the ECC water entering the core from the downcomer region experiences a reversal of direction. At the same time, the total makeup of the core may be limited to the core decay heat boiloff rate, resulting in very low average vertical velocity components. As a result, the larger and denser debris particles may separate and settle in the lower plenum without being entrained into the core. The possibility of entraining finer debris particles and fibers into the core still needs to be carefully considered. The low vertical velocity may also provide an advantage in that it may not be sufficient to compress the debris bed to the point that interstitial volumes become reduced to the point where flow through the debris bed is affected.

Other major factors that can influence debris-laden coolant streams inside the RCS include the location of the break, the location of the ECC water injection port, and Core Bypass. These items will be discussed separately below.

2.2.1 Break Location

The break location is mainly characterized with respect to its position on the cold leg (downcomer side) or the hot leg (upper plenum side) in relation to the reactor core. A break on the downcomer side has four major implications with respect to the flow distribution of the injected ECC water.

(1) It offers a leak opening for a fraction of the ECC water that is injected into the intact cold legs of the reactor. A portion of the ECC water would bypass circumferentially around the core barrel in the downcomer and eventually find its way to the break opening in the broken cold leg.

(2) A large break in a cold leg will limit the liquid level in the downcomer to an elevation of the cold leg nozzle. Additionally, in some LOCA scenarios, the reactor vessel may remain hot for a period of time. This can cause boiling in the downcomer region and reduce the driving head for core makeup.

(3) If hot leg injection is used, water will be injected into the upper plenum of the reactor vessel. For the purposes of this evaluation, this injection water is assumed to be laden with debris. As boil-off occurs, the debris will precipitate and settle down through the core, possibly accumulating on fuel grid straps or other vessel internal structures.

(4) As the LOCA progresses, decay heat is reduced. This results in a reduction of ECCS injection flow. Additionally, to address Boron precipitation concerns, plant operators will initiate hot leg recirculation some time significantly after the LOCA event, but still early a far as the overall mission time of 30 days. This may result in flushing some debris that has built up in the bottom of the reactor pressure vessel out the break onto the containment floor (some debris may be too heavy to be flushed out of the vessel during the lower flow/pressure core backflush conditions). Since this debris will not be subjected to high energy blowdown/high velocity sheeting flow from the LOCA, pool turbulence/washdown from containment spray, and high ECCS injection flowrates; the potential for debris transport across the containment floor to the ECCS screen will be greatly reduced. For many plant configurations, this transport may be negligible or non-existent.

If the break is located on the hot leg (upper-plenum side of the core), then almost the entire flow of ECC water fed into the cold legs would be directed through the downcomer into the lower plenum and subsequently through the reactor core. As a result, there is a possibility that a substantial amount of debris present in the ECC water will be transported to the core. Under these conditions, the probability for debris to impinge on or interact with reactor pressure vessel internal structures is greatly increased. This type of "mechanical filtration" of debris by the reactor internals should be evaluated. However, flow paths for bypassing the core also exist in this situation, as will be discussed later.

2.2.2 ECC Water Injection Location

Besides break location, the locations of ECC injection into the RCS and number of ECC trains operating determine the flowpath and amount of water that will be directed into the core region. With respect to the ECC injection ports, the plant-specific design can provide for cold-leg injection, combined cold-leg/hot-leg injection or direct vessel injection. Plant emergency procedures can also provide for alternating cold-leg and hot-leg injection. Such procedures are needed to flush boric acid out of the core as it accumulates during the boil-off of coolant

following a LOCA. Alternating the flow direction through the core will also affect the debris accumulation and behavior in the core region.

Upon switching from cold-leg to hot-leg injection, the ECC flow is delivered to the upper plenum and the core region without passing first through the reactor vessel lower plenum that acts as a separation volume for fibers and particulates. At this time, any fibers or particulates that remain entrained in the ECC water and pass through the ECC sump screen will be deposited directly into the core region. In addition, the hot-leg injection mode may flush out debris that was previously deposited in the lower plenum region. Some of this debris may be flushed from the RCS to the containment floor, and could be available for transport to the ECC sump screen. As mentioned above, this debris will not be subjected to high energy blowdown/high velocity sheeting flow from the LOCA, pool turbulence/washdown from containment spray, and high ECCS injection flowrates; the potential for debris transport across the containment floor to the ECCS screen will be reduced. For many plant configurations, this transport may be negligible or non-existent.

The combination of a large cold-leg break with cold-leg ECC injection represents the most limiting condition with respect to the available mechanisms for coolant supply to the core. In such a situation, the core flow driving force is the gravitational head in the downcomer that is limited by the cold-leg break elevation. Under such a limited driving force, an increasing degree of flow blockage at the core inlet, caused by debris clogging, would decrease the upward flow through the core; while at the same time increasing the fraction of ECC water expelled directly from the downcomer through the break, thus bypassing the core. A complete flow blockage at the core inlet would redirect the entire amount of injected ECC water directly from the upper downcomer region directly to the pipe break, starving the core completely from a fresh supply of coolant.

2.2.3 Core Bypass Flow Paths

Design features that provide for flow paths bypassing the core can have an effect on the ECC flow distribution in the reactor vessel. Such features include the gaps formed in the downcomer between the mating surfaces of the hot-leg nozzles and the core barrel opening flanges. At temperatures lower than the nominal operating levels, the gap openings widen and provide for a larger bypass flow area. Normally these gaps are not credited in analyses of reactor core flow distribution. The presence of core barrel vent-valves in the Babcock & Wilcox (B&W) reactors and small downcomer holes in some Westinghouse reactors can also lead to a direct flow from the upper plenum to the downcomer. Other possible core-bypass features are the core reflector design involving flow openings needed to vent the reflector metal structures.

2.3 Chemical Considerations

There is concern that the substances entrained in the debris laden water could interact under the influence of increased levels of boric acid and elevated temperatures in the reactor core region. It is postulated that this could potentially lead to an environment that accelerates certain reactions and chemical effects that could increase the risk of debris clogging in the reactor core. Preliminary chemical effects testing data indicates that the interaction of spray additives (sodium

hydroxide, borate, lithium) boric acid, and other chemicals/component materials may interact to produce precipitants and gelatinous material [Ref. 1]. These may be particularly problematic because of their abilities to change shape under differential pressure (flattening out to fill debris bed voids) and/or adhere to fibers and each other to form larger particles. It is unknown at this time if heat from the reactor or localized chemistry would exacerbate the formation, coagulation, or adhesion of these precipitants and gelatinous materials. These preliminary results also indicate that typical debris and chemical byproducts do not tend to adhere to metal surfaces. Therefore, a reviewer should refer to the latest chemical effects test results to ensure potential consequences from these attributes are properly addressed.

3. MECHANISMS OF DEBRIS CLOGGING

Major contributing mechanisms to flow obstruction in the core region due to debris clogging can be grouped into three categories:

(1) local hydraulic deposition of debris at critical locations,
(2) accumulation of debris due to settling and/or phase separation by boiling, and
(3) debris adherence to solid surfaces.

The ability of a specific debris type to participate in the formation of a clog depends on the debris properties. The following is a classification of debris by their properties:

(1) debris physical state: solid, gelatinous or liquid,
(2) type of solid debris: particulate or fibrous,
(3) debris size distribution (particulate and fibrous),
(4) debris shape characteristics (particulate and fibrous),
(5) debris density,
(6) debris chemical reactivity and precipitate formation by chemical/corrosion products,
(7) debris susceptibility to change in properties.

3.1 Hydraulic Deposition of Debris

The location of critical areas with respect to possible deposition of fibrous and particulate debris entrained by the ECC flow into the core depends on specific features of the fuel bundle design. Such features can include the debris filter in the fuel bundle bottom nozzle and the fuel spacer grids. Since all PWR fuel bundle designs include some sort of end and intermediate spacer grids, all types should be evaluated for the risk of clogging associated with the presence of debris in ECC injection flow.

For all PWR fuel designs, the fuel nozzle includes small holes and a protective grid to act as a debris filter to prevent debris ingress into the core during normal operation. This debris filter protective grid represents the location of the most restricted flow area. At fuel grid spacers, fine fibers can wedge between the grid spacer straps and the fuel rods and begin forming a debris bed. It is believed that this clogging process may be enhanced at a local level at specific core locations due to higher local fluid velocities resulting from phase separation by boiling. It is suspected that bulk flows/velocities at grid strap areas may prevent any localized capture of

fibers or particulates from coalescing into larger debris formations. Additional analysis and/or testing may be required to support any position in this area.

3.2 Debris Accumulation Due to Phase Separation by Boiling

Under post-accident conditions in the reactor core, the decay heat may generate steam from the injected debris laden coolant once the ECC water has been heated to saturation conditions. When the water is evaporated, most solid debris will remain in the liquid phase, and the generated steam will be practically free of impurities. As this process continues over time, the amount of debris present in the liquid continually accumulates causing an increase in the debris concentration in the liquid solution. This phenomenon is also applicable to any dissolved substance in the reactor coolant, such as boric acid (up to the solubility limit for the specific substance determined by the liquid temperature). Elevated concentrations of debris in the core region need to be accounted for when considering any possible mechanism of formation of flow obstructions in the core. One possible way to prevent accumulation of debris in the core region due to this mechanism is to provide sufficient ECC flow so that single-phase cooling is maintained in the core.

A common practice for addressing boron precipitation concerns post-LOCA at PWR's is to periodically swap ECC injection from the cold legs to the hot legs. Injecting ECC flow through the hot legs would reach the core from the upper plenum. This alternative flowpath could result in reversing flow downward through the core, and reduce the concentrations of unwanted species in the core region. It must also be noted that hot leg injection and flow reversal in the core region may cause a debris bed to form on the upper core plate or upper side of the spacer grids.

3.3 Debris Adherence (Sticking) to Solid Surfaces

The mechanism of adherence (sticking) can be of a mechanical or chemical nature depending on the properties of the debris material. Preliminary results of Integrated Chemical Effects Testing (ICET) jointly sponsored by the NRC & EPRI indicate that typical debris and chemical byproducts do not tend to adhere to metal surfaces. However, there was one case (ICET #3 TSP buffer with high CalSil + Nukon) where some plate-out did occur on piping. The ICET tests did not simulate boiling of the coolant by the heated fuel rods such as would occur for an extended period of time following a large cold leg break. The boiling process may result in plate-out of dissolved and suspended material (boiler scale) which may result in a reduction in surface heat transfer. If subsequent ICET or other testing results or analysis indicate that this is more probable than previously estimated, additional testing or analysis will be needed.

4. APPROACHES FOR ASSESSING THE IMPACT ON REACTOR SAFETY

Both analytical and experimental types of work have been carried out assessing detrimental effects on core coolability caused by debris ingress into the reactor coolant system. The following sections are intended to illustrate some of the approaches used, and point out some specific findings. Insights from investigations and evidence from both analytical and experimental studies should be used to address uncertainties in the final evaluation.

4.1 Analytical Modeling Approaches

Detailed deterministic codes have been applied to assess the effects of blocking a certain fraction of the core inlet flow area due to filtered debris on long term core coolability.

When quantifying the effects of flow obstruction by possible clog formation in the core, the possible effects of suspended debris and dissolved substances on the thermodynamic properties of the ECC water coolant should be considered. Some available evidence suggests that dissolved boric acid may have a noticeable effect on water viscosity and other thermodynamic properties [Ref. 2]. At the same time, the effects of the flow velocity on debris bed structure and head losses in fuel bundles need adequate treatment. Products of chemical reactions may also affect the clogging process and its associated effects. Another associated safety concern is whether there would be sufficient core flushing flow to avoid boric acid precipitation in the core.

Analyses performed by the Westinghouse and B&W Owners Groups for Westinghouse fuel examined the transport of particulate debris into the core. Up to 80% blockage of core area at the first grid strap was evaluated for a large four-loop PWR. The evaluation concluded that no clad damage would result, although no peak clad temperature was indicated [Ref. 3]. In an earlier generic study performed for a reference Westinghouse plant design, an analytical methodology for assessing the gravitational separation of paint debris in the reactor vessel lower plenum was proposed [Ref. 4].

Loss coefficients that account for blockage by rock wool fines present in the coolant were experimentally obtained and applied by Framatome in a RELAP large-break LOCA analysis to quantify the effects of debris blockage at the lower tie plate on the core reflood process [Ref. 5]. While it did not mention the degree of blockage investigated, the analysis showed no significant impact on the reflood rate and core coolability. Additional analyses indicated that paint chips with diameters equivalent to, or larger than, the lower tie plate openings would settle at the bottom of the lower plenum and would not block the fuel inlet tie plate.

As part of its PWR advanced fuel developmental efforts, KEPCO estimated that up to 25% of the bottom nozzle flow area for its 16x16 PLUS7 fuel design could be blocked by debris smaller than the sump screen dimension that are transported to the core during post-LOCA LTC. The bottom nozzle of the new advanced PLUS7 fuel design has small holes and an additional protective grid to prevent debris ingress into the core during normal operation, thus providing maximum restriction of the flow area. KEPCO performed LTC analyses for standard Korean nuclear power plants to determine the effects of reduced core flow due to core inlet flow area blockage by filtered debris on the fuel coolability while avoiding boric acid precipitation in the core region [Ref. 6]. The analysis, performed for various break sizes, determined that the core can be maintained under safe conditions assuming a blockage fraction of up to 35% and applying the existing LTC procedures.

Core cooling calculations performed for the German TÜV also accounted for the effects of deposited mineral wool debris on the head loss in fuel bundles through the implementation of experimentally obtained data [Ref. 7]. Analyses performed with S-RELAP5 to study the effects on the coolant flow using such data showed that up to 20 kg of insulation material did not cause

an unacceptable influence on core cooling. This amount of debris corresponded to 80% of the suspended debris material that reached the reactor core.

4.2 Experimental Investigations

Experimental efforts to study debris behavior in Reactor Coolant Systems have been undertaken and reported.

Experiments performed by the German company VGB included fuel assembly tests that studied the deposition of mineral wool debris at the lower tie plate and grid spacers [Ref. 8]. It was found that all mineral wool debris that passed the 9x9 mm-screen was deposited at the debris filter or at the first spacer of the fuel assembly. In addition, the experimental data obtained on head loss suggested a nearly linear dependence on liquid velocity and that the derived pressure loss correlations for fuel assemblies were comparable to those obtained for strainers.

Experimental studies performed by Framatome investigated fuel blockage effects involving an amount of debris equivalent to 18 kg of rock wool fibers downstream of the sump screen [Ref. 5]. The experiments provided blockage and pressure drop data for the Framatome debris resistant lower tie plates.

Experiments on debris transport in fuel assemblies were also performed in Germany using various types of mineral wool and mixtures of mineral wool and MINILEIT and strainers with different mesh sizes [Ref. 7]. The experiments provided data regarding head losses in the fuel elements needed for subsequent core cooling calculations.

Transport characteristics and behavior of insulation material debris in water flow such as subsidence, drift, sedimentation, re-suspension, and agglomeration were experimentally studied at the University of Applied Sciences Zittau/Goerlitz (Germany) [Ref. 9]. Results of these experiments were presented at an international NEA/NRC workshop in Albuquerque, New Mexico in February 2004. The goals of the experiments were also to investigate the processes of deposition and penetration of insulation debris at hold-up devices like strainers, perforated plates and grids and to determine the resulting head losses. The experiments, carried out at acrylic glass test facilities with modern instrumentation and analysis methods, were demonstrated to be appropriate for generating useful data describing multidimensional behavior of two-phase flow involving a liquid phase (water) and solid particles and can be used for computational fluid dynamics (CFD) code development and validation purposes.

5. CONCLUSIONS

As part of the effort to resolve GSI-191, “Assessment of Debris Accumulation on PWR Sump Performance”, consideration needs to be given to assessing the consequences of debris penetrating the sump screen and propagating downstream into the primary coolant system. Injection of debris into the RCS to the point where reactor core cooling can be degraded needs special attention to ensure that the core is maintained safe during the long term cooling recirculation phase. A number of factors have been identified that require technical evaluation for assessing the overall contribution to this phenomenon. A checklist of these items is included

in this paper. Licensee submittals for final evaluation of emergency core cooling system (ECCS) sump screen performance should contain a level of detail such that there is reasonable assurance that these issues are adequately addressed. It should also be noted that experience at TMI shows that adequate core cooling can be achieved even with significant blockage of a number of core flow channels.

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GSI-191 Downstream Effects on Fuel Checklist

Source Term Determination:

- Debris Generated from break – use GSI-191 SER methodology or accepted alternate
- Latent Debris - use GSI-191 SER methodology or accepted alternate
- Debris Characterization - use GSI-191 SER methodology or accepted alternate
- Debris Transported to Sump Screen - use GSI-191 SER methodology or accepted alternate
- Debris penetrating sump screen – evaluate amount of debris transported to the sump screen and the debris characterization against the screen design (hole size, velocity, etc..) FOR PASSIVE SCREEN DESIGNS - usually assume all debris that arrives at the screen that is equal to or less than the size of the largest dimension of the screen hole size plus 10% penetrates through the screen. A time dependent calculation may be used for reduction of debris penetration load if it can be supported by design calculation or testing. The screen vendor may also provide a debris penetration value if it is supported through design calculation or testing. FOR ACTIVE SCREEN DESIGNS - need debris transport and characterization information from the debris source term evaluation, and design information from the screen vendor, for the plant specific configuration.
- If a time dependent calculation is used, consideration must be given to concentration of debris in the RPV due to boiloff.
- An additional particulate source term in the bottom of the RPV will be boron precipitation – this will be plant specific, but should be known based on previous analyses.

Analyses that should be provided:

- Potential to clog lower core due to flow induced debris bed (velocity and debris concentration/characterization. Need to also consider potential for debris bed compaction due to flow & potential head loss from a mixed debris bed. Need to include boron and other chemical effect precipitants if applicable. Uniform thin beds are not plausible due to non-uniform vertical flows in the lower vessel region).
- Potential to clog lower core due to filling the lower vessel with a volume of debris (need to estimate total debris volume in the RPV vs. the plant-specific available volume).
- Potential for a mid-core blockage (Potential for capture of debris at grid straps or buildup via adhesion (most likely more of a CL LOCA concern)).
- Potential for heat transfer loss from a chemical film (interaction of high boric acid concentration with debris characterization).
- Potential for hot leg recirculation to clog upper core – by flow induced debris bed (same considerations as above. May not be a problem for late/boron precipitation control operation, more applicable to plants with early simultaneous HL/CL injection)
- Potential for hot leg recirculation to clog upper core – by volume of debris (same considerations as above. May not be a problem for late/boron precipitation control operation, more applicable to plants with early simultaneous HL/CL injection)

Success Criteria (Mission time assumed to be 30 days)

- Peak Clad Temperature <= 2200 degF
- Cladding Oxidation <= 17%
- Core geometry maintained in a coolable configuration