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Assessment of NRC Generic Issue # 193

Prepared for the

Generic Issue # 193 Committee

of the

BWR Owners' Group

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REVISION SUMMARY

Rev	REVISION HISTORY	Date
A	GEH draft report for BWROG GI-193 Committee review	July 2009
0	GEH report issued	August 2009
1	Revised per comments from BWROG Challenge Board	October 2009

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PURPOSE

This report provides responses to US Nuclear Regulatory Commission (NRC) staff questions on Generic Issue # 193 (GI-193) that were submitted to the Boiling Water Reactor Owners Group (BWROG) in September 2008 (Reference 1). After receipt of the NRC questions, the BWROG established a committee on GI-193 and authorized GEH to prepare question responses.

In addition to the NRC question responses, this report also includes a GI-193 technical assessment to determine whether additional analysis, testing, or plant modifications are needed to improve plant and public safety.

1.0 BACKGROUND

In May 2002 an NRC inspector identified an issue that is now identified as Generic Issue # 193 (Reference 2). The issue concerns the possibility that during a postulated Loss of Coolant Accident (LOCA) in a Boiling Water Reactor (BWR) power plant, the Emergency Core Cooling Systems (ECCS) pumps might ingest sufficient non-condensable gas while drawing water from the suppression pool to damage the pumps such that the pumps could not continue to inject water into the reactor vessel.

GI-193 addresses the possible failure of low-pressure emergency core cooling systems in BWRs with Mark I containments due to quantities of entrained gas in the suction piping and from bulk water in the suppression pools. Some excerpts, with incorporated editorial changes, from NRC staff writings (Reference 2) on this issue are provided below.

> "The pressure suppression chamber, or torus, in a BWR Mark I containment, is a steel pressure vessel in the shape of a torus below and encircling the primary containment drywell. In the event of a LOCA, steam released into the drywell airspace is forced, along with the inerted drywell atmosphere, through (typically) eight large vent pipes to the suppression chamber. The vent pipes exhaust into a large ring-shaped continuous vent header within the torus. The header is connected to a set of downcomer pipes, which extend into the suppression pool water, and end about four feet below the water surface. The steam/inerted gas mixture can undergo both a chugging and condensation oscillation phenomena as the mixture is injected into the suppression pool water. The condensation of the steam limits the peak containment pressure.
>
> The basic questions are first, whether the design of the ECCS suction configuration will be able to keep significant quantities of entrained gas away from the various pump inlets, and second, whether voids in the pool will have sufficiently been reduced by the time the pumps are delivering significant flow.
>
> Some of the ECCS pumps will be starting during the gas mixture blowdown and pool voids, i.e., entrapped non-condensable gases, may migrate into the pump suction piping. At first, the pumps will be at minimum flow (about 500 gpm), with return flow back to the suppression pool, until valves open and the reactor vessel pressure decreases. The pumps require about 30 elevation feet of water (about 13 psi) for Net Positive Suction Head (NPSH), which should not be a problem, since the blowdown will pressurize the suppression chamber to at least this level. However, if large air bubbles are drawn into a pump, the result may be air binding, flow instability, high vibration, and ultimately impeller damage if the pump does not trip."

On September 4, 2008, the NRC submitted to the BWROG an information request with multiple questions on GI-193 (Reference 1). These questions are answered in Section 8.0 of this report.

2.0 MARK I BWRS AND LOCAS

2.1 Overall Considerations

The Emergency Core Cooling System is designed to protect the fuel from damage following a postulated LOCA. The ECCS provides water to the reactor vessel by drawing from various water sources including the suppression pool, which contains a large volume of water. Water or steam exiting from a broken pipe, or other damaged primary system BWR pressure boundary, will increase the drywell pressure; and, because of the increased drywell pressure, a mixture of steam and non-condensable gases will be forced into the suppression pool through the drywell vent system.

For BWR plants with Mark I containments, the suppression pool consists of a large torus located at a lower elevation than the drywell. The steam and non-condensable gas mixture from a LOCA would enter the suppression pool through vertical downcomer pipes that are submerged in the suppression pool. The steam portion of the drywell gases would condense in the suppression pool water while the non-condensable gases would initially be dispersed as bubbles in the suppression pool water. These bubbles would rise to the surface of the pool and be released into the suppression pool gas volume.

The larger the postulated LOCA break size, the sooner drywell gases would be pressurized and vented to the suppression pool and produce bubbles in the suppression pool water. Also, with the larger the break sizes, the ECCS pumps would be called upon earlier in the LOCA to inject makeup water into the reactor vessel.

Therefore, large breaks would quickly increase drywell pressure and quickly drive the non-condensable gases from the drywell into the suppression pool while smaller breaks would increase drywell pressure more slowly and therefore drive non-condensable gases into the suppression pool at a slower rate but for a longer time. Because the ECCS pumps start and come off their minimum flow condition based on permissive signals that delay ECCS pump full flow and these signals occur at different times for various break sizes, the most challenging LOCA for potential ingestion of non-condensable gases by the ECCS pumps may not be the largest postulated break.

This report describes an investigation of the impact of break size on potential damage to pumps within ECCS from non-condensable gas ingestion. The ECCS are designed to maintain core cooling over the entire spectrum of potential break sizes, the ECCS coolant injection rates (and particularly that of the low pressure injection systems) are sized for the largest possible break sizes. For smaller postulated breaks, replenishment of cooling water to the reactor vessel does not require as large a volume flow rate or as early an initiation of pump flow. There are many other both safety-related and non-safety-related systems that can provide the required make-up volume and flow rate for breaks smaller than the maximum postulated LOCA. Therefore, if a pump trips in the ECCS, or otherwise stops functioning, for a smaller LOCA break the operator would be able to mitigate the consequences of the LOCA using other systems.

Another GI-193 concern raised by the NRC questions is that some licensing basis LOCA analyses assume a single failure plus a loss of offsite power. However, for GI-193, where the early ingestion of non-condensable gases is the concern, the availability of offsite power could cause earlier pump initiation. This is particularly true for the postulated large break LOCA used in licensing basis calculations. For smaller break accidents, whether off-site power is available or not has little to do with the overall ECCS pump timing because of the inherent delays in ECCS injection valve opening. Also, if off-site power is available, the possibility of a single failure of an electrical division is less likely.

3.0 PUMP ACCEPTABILITY CRITERIA

3.1 Conservative Acceptability Criteria for a Low Probability Event

Non-condensable gas bubbles in the suppression pool following a LOCA could potentially lead to the ingestion of gas bubbles through the strainers attached to the ECCS suction from the suppression pool and these bubbles could be transported to the ECCS pumps. The gas bubbles, or voids in the liquid flow, could damage the pump impellers or cause a pump to become air bound such that it would not continue to pump water. LOCA debris materials trapped on the strainer surfaces would impede bubble passage through the debris and into the strainers.

A set of pump acceptability criteria are used in this report to evaluate whether the ECCS pumps would be damaged by non-condensable gas bubbles reaching the pumps. Because the NRC postulated event for GI-193 is an already extremely low probability event (Reference 19), the use of large conservatisms in the pump acceptability criteria might produce misleading conclusions which could result in plant or procedure modifications that do not improve overall plant safety. Therefore, for GI-193 the pump acceptability criteria represent conservative, but not overly conservative, pump failure criteria.

It should be noted that recent NRC staff reviews on Generic Safety Issue #191, a Pressurized Water Reactor (PWR) LOCA issue, indicate that the NRC considers a long-term pump void fraction criterion of 3% to be appropriate for LOCAs. For example, the NRC Safety Evaluation Report (SER) on Nuclear Energy Institute (NEI) Guidance Report 04-07 (Reference 3), Appendix V, page V-27, states, " it has been reasoned that voiding in the flow exiting the [strainer] debris bed is acceptable provided that voiding does not exceed 3%."

The pump acceptability criteria defined herein includes consideration of the recent pump test data collected as part of the industry response to the NRC Generic Letter (GL) 2008-01 on Gas Accumulation in ECCS (Reference 4), but considers this data from a more realistic perspective because the GI-193 issue already addresses a low-probability LOCA event which is analyzed with many existing analytical conservatisms.

3.2 Non-condensable Gas Ingestion at Pump Minimum Flow

Representative plant calculations from the industry response to GL 2008-01 demonstrated that non-condensable bubble voids would not transport down BWR ECCS suction piping when the ECCS pumps are operating at minimum flow conditions (Reference 5). This analysis uses the Froude number to ratio the drag force to the buoyant force on the bubble. It is a relatively straightforward calculation once bubble sizes and pipe velocities are determined.

The circumscribed approach velocity, i.e., at the strainer's outer circumference, for stacked disk strainers in BWR Mark I plants is typically less than 0.1 ft/sec when at ECCS minimum flow conditions and less than 0.5 ft/sec when at full pump flow. Non-condensable gas bubble rise velocities have been estimated by the NRC (Reference 2) to be between 1.7 and 3.3 ft/sec. Finnish tests (Reference 6) of compressed air discharge into downcomer pipes submerged within a pool showed that the non-condensable gas would exit the downcomers, strike the bottom of the pool, break into small bubbles, and rise from the bottom of the test pool to the pool surface in about 1.3 to 1.6 seconds. Because the depth of the test pool was 10.5 feet (3.2 meters), this indicates a non-condensable bubble rise velocity of about 6.6 to 8.1 ft/sec. Therefore the nominal bubble rise velocities can range from being multiple times larger than the strainer circumscribed approach velocity to being more than an order of magnitude higher. Strainer approach velocities decrease further as the distance from the strainer increases. With stacked disk strainers, the flow velocities through the perforated plate area on the strainer are even lower than the circumscribed approach velocity. Therefore, except for the smallest bubbles, most of the non-condensable gas should rise to the pool surface without being drawn into the suction strainers, particularly when the pumps are at minimum flow conditions.

While ECCS pumps are at minimum flow conditions, the strainer flow field would generally not cause non-condensable gas bubbles to be transported to the suction strainers unless there are some very small bubbles with rise velocities so small that they would not overcome the small circumscribed approach velocities for the strainer. If very small non-condensable gas bubbles do reach the inside of a strainer, the internal flow velocities would only transport the smallest bubbles to the suction piping. The resulting void fraction from such very small bubbles would be quite small and the bubbles should be swept through the pump without any significant impact on performance.

3.3 Generic Letter 2008-01 Gas Intrusion Event Studies

After issuance of NRC Generic Letter 2008-01 in January 2008 (Reference 4), the BWROG formed a Gas Intrusion committee and authorized GEH to review available pump data regarding suction side gas void effects on BWR ECCS pumps. Westinghouse performed a similar study for a committee of the Pressurized Water Reactor Owners Group (PWROG), in parallel with GEH. The final conclusions of the BWROG and PWROG studies were compared to ensure that all pertinent information was incorporated and that consistent guidance is available to the BWR and PWR industry. After performing the requested evaluation, GEH submitted a report, ECCS Pumps Suction Void Fraction Study (Reference 5), to the NRC.

The pump industry testing and analysis identified for GEH review typically considered continuous air injection. A range of void fraction testing, analysis, and expert opinions were reviewed, with a 2% void fraction being the most recurring conservative value deemed to cause little or no degradation in pump performance. The same conservative value was identified in the Westinghouse review for the PWROG.

Long-term continuous gas intrusion into the pump suction, as typified by pump industry testing, is not expected during the postulated GI-193 event. Short duration gas intrusion transients are more probable. The GEH report on GL 2008-01 qualitatively determined that an appropriate short-term acceptability value to use for assessing pump and system operability is an average void fraction of less than 10% for a period of less than 5 seconds. This is a conservative estimate based on the reports and data obtained for the GEH/BWROG void fraction study report. The Sulzer and Flowserve pump suppliers were requested to review preliminary report conclusions and Sulzer provided input on the report.

Westinghouse also developed conservative short-term criteria. Westinghouse has access to recent Arizona Public Service (APS) pump test data that allowed for validation of the Westinghouse criteria. The Westinghouse criteria are divided between single-stage (5% for 20 seconds), multi-stage stiff shaft (20% for 20 seconds), and multi-stage flexible shaft (10% for 5 seconds) pumps. Westinghouse indicated that their criteria are based on APS pump test data, but the allowable times are significantly reduced from the actual APS pump test times to ensure a conservative estimate. The Westinghouse report is proprietary, but its conclusions are reflected in the NRC and NEI guidance documents (References 7, 8 and 9).

Based on industry responses to Generic Letter 2008-01 and the BWROG and PWROG guidance documents, the NRC developed draft guidance for plant and regional inspectors to assess gas movement in suction lines and pump response to gas intrusion (References 7 and 8). The initial NRC draft guidance was provided as a meeting enclosure (Reference 7) and indicated that the NRC would accept a 2% void fraction for normal steady-state pump operation, but 1% shall be used if the pump is running at < 40% or >120% of the Best Efficiency Point (BEP), due to the lack of test data at these conditions. The NRC meeting enclosure also stated the NRC would accept a 10% maximum void fraction for 5 seconds if the pump was operating between 70% and 120% of BEP, or a 5% maximum void fraction if outside that range.

The proposed 10% void fraction for 5 seconds criterion was later changed in a revision to the NRC Draft Guidance (Reference 8) to 10% peak void fraction over 20 seconds (calculated for 0.5 second time spans for the duration of the transient). The NRC Draft Guidance states that an event being investigated will be acceptable without further justification if bounded by the above values, and values above those specified may be acceptable pending additional justification. Additionally, the NRC Draft Guidance for gas transport in the piping is only applicable to pipe diameters of less than 8 inches. BWR ECCS pump suction lines are generally greater than 8 inches in diameter.

The Gas Intrusion BWROG and PWROG committees, working with NEI, have issued an NEI working document (Reference 9) for utilities to assess gas intrusion issues. The NEI guidance adopts much of the BWROG (GEH) and PWROG (Westinghouse) report guidelines with consideration of the NRC limitations. However, because gas is not generally transported under low flow conditions, this guidance was annotated that, "Further review by the respective Owner's Groups may determine that the criteria for pump operation below 70% BEP may not be required."

The BWROG agrees with the NRC Draft Guidance that large 'slugs' of gas approaching 100% void fraction should not be allowed. The NRC Draft Guidance references guidance from pump supplier Flowserve that degraded pump performance will begin at a 2% void fraction, the pump can handle up to

5% without distress, and at 20% there is a good chance the pump would lose prime and become gas bound. The NRC also stated if a slug were large enough to gas-bind the pump, pump seizure would be almost immediate. If the slug void were small enough to be swept through the pump, it might cause hydraulic unbalance resulting in possible contact between the wear rings. However, pump vendor test data applicable to slug flow has not been provided to the BWROG for evaluation.

The NRC Draft Guidance (Reference 8) states that the Arizona Public Service (APS) data indicated a substantial void fraction can be tolerated for some time in a PWR high-pressure safety injection (HPSI) pump provided the flow rate remains high and the gas is suitably distributed at the pump inlet.

The Finnish testing discussed in the GEH report (Reference 5) included suction strainer air ingestion testing and pump suction air ingestion testing. The strainer tests were performed without debris and thus are conservative with respect to air ingestion. For these Finnish pump tests (200 gpm to 1200 gpm) it was found that pump flow and head did not decline significantly for suction void fractions of less than approximately 4%. With lower flow rates (approximately 30% of BEP), flow and head started to decline with the introduction of air and collapsed totally when the air volume was more than 7% of the volume in the intake pipe. However, it is important to note that in all tests the pump flow returned to normal after the injected air flow was terminated (it took about 30 seconds to normalize during the low flow test). A later inspection of pump internals after the testing was completed did not identify damage or degradation.

The Finnish suction strainer testing (the Finnish strainers differ in design from domestic BWR strainers) also demonstrated that some small air bubbles did get inside the suction strainers when pump suction was at full flow during maximum blowdown rates, but the bubbles internal to the strainers disappeared 30 seconds after blowdown. The pump head and flow rate did not decline due to air bubbles reaching the pump in any of the tests. In the low velocity blowdown test cases, no significant volume of air was detected inside the strainer during blowdown or in the pump suction pipe.

At an NEI Gas Intrusion Meeting in February 2009, a presentation on pump air intrusion testing was given by Mitsubishi Heavy Industries, LTD (Reference 10). The Mitsubishi testing was performed with a horizontal single stage double suction pump at 2000 gpm. The results indicate that with 8% air entrainment in the pump suction a total head loss of 5% was observed. A 50% air entrainment test caused a significant pump head reduction. Pump component torsional stresses also increased with 50% entrainment, but were considered to be within an acceptable range. Also, after stopping the air entrainment (for 5 to 6 seconds duration), the total pump head quickly recovered and returned to normal (similar to the Finnish testing discussed above).

The Mitsubishi presentation provided test and analysis results for a 3-stage pump and for a 10-stage pump (where the critical condition is the integrity of the thrust bearing) and the results indicated an allowable void fraction for the pump of approximately 10% for a "short time" without affecting the bearing force of the thrust bearing.

3.4 LOCA Blowdown Pump Acceptability Criteria

Because the potential ECCS pump gas ingestion during a LOCA blowdown differs from the GL 2008-01 pump startup event with a gas void already in the pump suction, LOCA blowdown pump acceptability criteria should differ from the GL 2008-01 pump criteria. The following criteria were developed from an assessment of the pump test data discussed in Section 3.3 above as the data applies to the transient GI-193 event. Void fraction values at the pump suction that meet the following conditions are considered acceptable:

- < 2% average void fraction for 120 seconds or greater
- < 3% average void fraction for less than 120 seconds
- < 5% average void fraction for less than 20 seconds
- < 10% average void fraction for less than 8 seconds
- < 20% void fraction for any calculated transient step of 0.5 seconds or longer

These criteria apply to full flow conditions at the pump entrance (regardless of pump type), after strainer and piping void reduction or averaging are considered. The void fraction values are not applicable to pumps operating near runout flow (>120% of the BEP) because of insufficient information on testing or research at runout flow. If required, low flow conditions will be addressed with Froude numbers to show that void transport is not expected at low flow rates, such as minimum flow.

The criteria envelope industry pump test results. The 2% continuous void fraction criterion is consistent with the GL 2008-01 conservative guidance based on pump tests and analysis. Test results indicate the 3% transient void fraction will not produce pump damage within 120 seconds and most ECCS pumps should be able to tolerate this void fraction for very extended periods of time, or indefinitely, without pump damage. The 3% void fraction value for LOCAs was previously quoted in the NRC SER on NEI 04-07 without a time duration limitation.

As noted in Section 3.3 there is limited testing, e.g., APS and Mitsubishi test results that confirm pump operability is not challenged by 5% to 8% void fractions with continuous suction and 10% void fractions over various time durations. Also, as discussed in the GEH report (Reference 5), void fractions on the order of 10%, over a short period of time, have been determined to be acceptable. The transient time durations for the 5 and 10% void fraction criteria were established as conservative values when compared to test data.

The 20% void fraction limit provides an upper void fraction limit to ensure that large slugs are not allowed. The LOCA methods used to evaluate the transient blowdown event provide a detailed calculation of void fraction versus time with suitably short time steps, thereby providing an assessment of the peak void fraction.

3.5 ECCS Pump Restart Limitations

ECCS pump trips can be caused by a variety of reasons. Depending on pump trip logic and set points, water hammer can cause high or low-pressure related pump trips. Pump trips can also result from breaker trips due to electrical problems or due to logic ties with other equipment in the system such as isolation valves. As such, a criterion for preventing pump trips is difficult to quantify.

BWR operators are trained to recognize various symptoms of pump problems such as low Net Positive Suction Head (surging flow indications, and voltage swings) and take actions to respond to these symptoms in these circumstances. Pump restart will depend on the operator diagnosis of the cause of the trip, possible damage to the pump or motor if restart is performed, and the availability of other pumps for accident mitigation.

3.6 Conclusions

The GI-193 pump acceptability criteria, presented in Section 3.4, provide a conservative estimate for evaluating ECCS pump performance with respect to void fraction during LOCA blowdown events. Pump trips are caused by a variety of events as discussed in Section 3.5. As such, a criterion for operators to prevent pump trips cannot be proposed. Pump restart will depend on the operator diagnosis of the cause of the trip, possible damage to the pump or motor, and the availability of other pumps for accident mitigation.

4.0 POSTULATED EVENT TIMING

4.1 Approach

This discussion provides a representative time history for a typical BWR Mark I following onset of a large break LOCA and an intermediate break LOCA. SAFER[1] LOCA files available in the GEH BWR database were reviewed to identify typical time histories. The ECCS configurations are based on a sample of BWR 3 and 4 plants with Mark I containment design. Note that ECCS pump configurations and the details of the onsite and offsite power systems can vary from plant to plant.

SAFER LOCA methodology (Reference 11) requires that the limiting condition, either availability or unavailability of offsite power be considered with respect to the performance of safety systems. Currently, GEH does not request that the customer identify the limiting condition. Therefore, it is assumed that the data extracted from the existing cases represents the condition with the longest delay in ECCS injection because that would be most conservative for ECCS LOCA analyses. A survey of the BWROG owners with Mark I containments indicated that the first-sequenced ECCS pumps for a Design Basis Accident (DBA) LOCA would typically start pump runup on the order of 10 seconds sooner when off-site power is available than when there is a loss of offsite power.

4.2 BWR LOCA Data Base Search Results

Table 4-1 provides SAFER LOCA analysis outputs from the GEH database for a sample of BWR 3 and 4 plants. SAFER typically models BWR responses to a LOCA that occur in the first 200 to 300 seconds after event initiation. Table 4-1 summarizes the LOCA operational sequence and timing for a DBA LOCA and for a 1.0 ft^2 break-size LOCA. The Table identifies ECCS pumps in both the Low Pressure Coolant Injection (LPCI) mode of the Residual Heat Removal (RHR) system and the Core Spray (CS) system. It also shows the timing of ECCS pump initiation permissive signals such as low Reactor Pressure Vessel (RPV) pressure and water level.

[1] SAFER is the USNRC-approved ECCS performance methodology utilized by GEH.

Table 4-1: Plant Specific ECCS Time History Data

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4.3 AC Power Availability

The data extracted from existing SAFER cases represents the ECCS pump initiation sequencing condition with the longest delay in ECCS injection because that would be most conservative for ECCS LOCA analyses. Furthermore, examination of the data shows that pump sequencing is not critical as long as the ECCS pumps would be ready to inject by the time reactor vessel pressure drops sufficiently to allow injection. The limiting factors in overall delay of ECCS injection are (1) reaching the reactor vessel low pressure permissive, and (2) the injection valve stroke time delay after reaching the low pressure permissive.

A survey of the BWROG owners with Mark I containments indicated that the first-sequenced ECCS pumps for a DBA LOCA would typically start on the order of 10 seconds sooner when off-site power is available than when there is a loss of offsite power. Pump initiation sequencing can delay the start of other ECCS pumps and is designed to limit the severity of the loading transient on the power distribution system. The exact pump sequence timing varies among the Mark I BWR plants; although typically it can range from a 3 to 11 second delay.

There would be no low-pressure system ECCS flow into the reactor vessel until the vessel pressure drops to below the shutoff head of the ECCS pumps. Thus, if pumps sequence on faster for the off-site power available sequence versus the loss of offsite power sequence, the only difference will be the length of time that the ECCS pumps operate on the minimum flow path. There is no significant difference in the time at which ECCS pump full flow occurs whether offsite power is available or not.

4.4 Summary of DBA and Intermediate LOCA Results

The low-pressure ECCS initiation sequences have several steps. Upon receipt of an initiation signal at most Mark I BWRs, the LPCI mode for the RHR pumps is automatically sequenced to start after AC power is available. Valves are automatically positioned to ensure the proper flow path for water suction from the suppression pool to inject into the primary system once reactor pressure has decreased to below the low pressure permissive.

Similarly, upon receipt of an initiation signal, the low-pressure CS pumps are automatically sequenced to start after AC power is available. Once reactor pressure has decreased to below the low pressure permissive, the CS injection valves will automatically open. When the Reactor Pressure Vessel (RPV) pressure drops sufficiently, CS system flow to the RPV begins to ramp up.

Table 4-2 provides typical Mark I LOCA timing for both a DBA and an intermediate LOCA.

Table 4-2: Typical LOCA Timing - DBA And Intermediate Break

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5.0 POTENTIAL OPERATOR ACTIONS

5.1 Objective

A review was conducted of operating plant Emergency Operating Procedures (EOPs) with the intent of identifying any additional operator actions needed to mitigate an ECCS pump air-binding event.

5.2 Inputs and Assumptions

The BWROG Emergency Procedure and Severe Accident Guidelines (EPGs/SAGs) (Reference 12) provide generic symptomatic direction for BWR emergency response and severe accident mitigation. It is assumed that operating BWRs have implemented EPG/SAG Rev 2 (Reference 12) as the basis for the plant EOPs and the operators possess the skills defined in NUREG-1123 on operator knowledge and abilities (Reference 13).

5.3 Effect of Entrained Air on Centrifugal Pumps

The hypothesis of GI-193 is that the blowdown into the suppression pool is of sufficient severity and duration to cause a performance degradation to the RHR and low-pressure Core Spray pumps because of the entrained gas. Gas entrainment includes a variety of conditions where the air bubbles are already in the liquid before the liquid reaches the pump. The presence of air bubbles in the liquid could cause pump damage (Reference 14).

Gas binding of a centrifugal pump is a condition where the pump casing becomes filled with gases or vapors to the point where the impeller is unable to contact enough fluid to function correctly. A centrifugal pump is a constant head pump. The theoretical head developed by a centrifugal pump is a function of impeller speed (N), radius of impeller (r), and the velocity of fluid leaving the impeller (V). If the factors (N, r, V) are constant, the developed head is the same for fluids of all densities and is the same for liquids and gases. However, the increase in pressure is the product of developed head and the fluid density. For example, if a centrifugal pump full of water develops a high head, the increase in pressure could approximate 3 atm. If the same pump is full of air at ordinary density, the pressure increase is around 0.007 atm. As such, when a centrifugal pump casing becomes gas bound the impeller spins without providing full flow. Water flow into the pump is reduced so the impeller is unable to force liquid through the pump and the pumping force is reduced. Once a centrifugal pump becomes gas bound the pump casing must be vented and filled with water in order to resume normal pump operation.

The most important effect of sustained gas entrainment or gas binding is a reduction in pump performance and potential erosion of the pump impeller. Pump performance degrades because air ingestion could lower the generated head.

Gas entrainment in the fluid entering the pump may create crackling and popping noises in the pump, similar to the sound of marbles flowing through a pipe. Other indications that can be observed from a remote operating station are fluctuating discharge pressure, flow rate, and pump motor current. The occurrence of gas binding in a motor-operated centrifugal pump is indicated by very low flow and discharge pressure readings while the motor draws minimum current.

5.4 Plant Operating Procedure Review

During the initial stages of a postulated LOCA, a significant amount of gas from the containment atmosphere, along with the steam and water from the reactor, is transferred from the drywell volume to the suppression pool in the Mark I containment design. The plant EOPs do not explicitly address how an operator would monitor for potential gas binding in an ECCS pump during the early stages of a large break LOCA. This is appropriate because symptom-oriented EOP guidelines must address a full spectrum of initial plant conditions and postulated transients without requiring diagnosis of the initiating event.

The EOPs are purposely written to provide an operator with the flexibility to control available systems as appropriate for existing plant conditions. For example, all ECCS pumps may automatically initiate and inject following a large pipe break, but a single pump may be sufficient to maintain reactor water level once it is restored within the specified range. Continued manual control and adjustment of system lineups and injection flows may be required in order to remain within the preferred reactor water level control band. Furthermore, Licensed Operators are required to demonstrate a fundamental knowledge and understanding of centrifugal pump theory of operation as well as being able to diagnose improper centrifugal pump operation under any system operating condition (Reference 13).

Explicit guidance on ECCS pump operation with respect to Net Positive Suction Head (NPSH) and vortex limits is provided in the EOPs as a Caution. The EOP NPSH limits are utilized to preclude pump damage from cavitations while vortex limits are utilized to preclude operation that can lead to air entrainment at the pump suction strainers.

Specifically, the EPGs/SAGs state that Caution #3 is applicable to steps RC/L-2, RC/P-2, SP/T, C1-3, C5-5, and the overrides at the beginning of the Primary Containment Control EPG.

The symptom-based response strategies prescribed in the EPGs/SAGs maintain the reactor plant in a safe condition without requiring diagnosis of the initiating event. The EPGs/SAGs identify when systems should be operated within the NPSH and vortex limits. Also, the EPGs/SAGs provide guidance to assist the operator in judging when the limits may be exceeded if the situation warrants. Immediate and catastrophic failure is not expected if a pump is operated with vapor bubbles present in the pumped fluid. The undesirable consequences of uncovering the reactor core for a period of time could thus outweigh the risk of equipment damage.

5.5 Conclusions

During the early stages of a large break LOCA an operator would monitor ECCS system flow rates, pump discharge pressures, and pump motor currents to verify proper operation of ECCS pumps in accordance with plant EOPs.

The indications to the operator of gas binding due to gas entrainment in a motor-operated centrifugal pump under any system operating condition are characterized as follows[2]:

- Reduced and potentially fluctuating system flow rate
- Reduced and potentially fluctuating pump motor current
- Reduced and potentially fluctuating pressure at pump discharge and/or suction
- Frequent adjustment required to ECCS system discharge valves to maintain conditions

If a centrifugal pump becomes completely gas bound, the pump casing must be vented and filled with water in order to resume normal pumping.

The plant EOPs do not explicitly address how an operator would monitor for potential gas binding in an ECCS pump during the early stages of a large break LOCA. However, this is appropriate because symptom-oriented EOP guidelines must address a full spectrum of initial plant conditions and postulated transients, without requiring diagnosis of the initiating event.

Licensed Operators are required to possess the requisite knowledge to diagnose improper centrifugal pump operation under any system operating condition.

It is concluded that existing plant procedures, including EOPs, and Licensed Operator knowledge requirements are sufficient to mitigate an ECCS pump gas-binding event. Therefore, no additional operator procedures are recommended.

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[2] Some BWR Licensees also identified an abnormal core spray vent accumulator level switch indication would help the operator diagnose gas binding in ECCS pumps.

6.0 ANALYSIS OF LARGE SCALE CONTAINMENT TEST DATA

6.1 Representative Test Data

Available video from large-scale pressure suppression pool containment loads tests were reviewed, specifically with regard to the extent of non-condensable gas plumes and the distribution of gas bubbles within suppression pools. Approximately 10 videos were reviewed as part of this activity. It should be noted that:

- All of the test conditions are such that, from a licensing perspective, they would be considered large break LOCAs. While some of the tests range down to about 50% of a DBA, these conditions are still significantly above what is considered to be an intermediate break size[3],

- The only conclusions that may be drawn are subjective and qualitative, and

- It is not possible to draw any definitive conclusions on bubble size or bubble rise velocities.

The video observations are based on review of videos from the tests (References 15 and 16) performed at the Mark I Full Scale Test Facility (FSTF). This facility was used to perform a series of large-scale tests of the Mark I containment. GE performed these tests for the Mark I Owners Group in the late 1970's. The test configuration consisted of a full-scale segment of a Mark I vent system, suppression pool and torus, containing full size downcomers (the 2 ft diameter pipe that passes the steam and gases into the suppression pool) with the associated ring header, vent pipe, and drywell volume. Videos from these tests provided the best available data on plume sizes in the Mark I suppression pool during LOCAs. Video records were taken both above and below (through windows) the suppression pool surface.

Additional videos from the Kraftwerk Union (KWU) Full-Scale Condensation and Chugging Tests (Reference 17) were reviewed. This set of tests was performed by KWU at the GKSS research institute in Germany, also in the 1970s. These tests were scaled to match the KWU standard BWR containment design. The KWU design is similar to the GE Mark II containment, and although somewhat dissimilar from a containment layout perspective, the flow rates and other hydrodynamic parameters are similar to a GEH Mark II containment. Compared to the Mark I geometry, the primary difference is vent exit submergence, which is approximately a factor of two deeper than in the Mark I configuration. Videos were only taken below the suppression pool surface.

[3] It is recognized that depending on the containment type, the drywell non-condensable gases may be pure nitrogen (Mark I and II), or air (Mark III). For simplicity, "air" and "non-condensable gases" are used interchangeably in this report.

6.2 Observations

The only conclusions that may be reached from review of the video are qualitative and general. The original intent of the video review was to determine approximate bubbles sizes and bubble rise velocities, but that proved impossible based on the video quality, and lack of visual length references in most situations. It is, however, possible to provide some general conclusions, based on the viewing of a number of the tests.

6.3 Initial Vent Clearing and Pool Swell Phase

In all of the tests reviewed (all tests were considered to be large breaks), the high injection rates of non-condensable gases during the initial pool swell period essentially fill the suppression pool with bubbles, to the extent that there is no visibility at all within the pool. During a test, this lack of visibility typically lasts for about 10 to 20 seconds after test initiation, and before any low pressure ECCS injection would occur in a plant LOCA, because the RPV pressure injection permissives would not have been met (Section 4). Typically at fifteen seconds after blowdown start, there are bubbles present throughout the suppression pool, including regions below the vent downcomer exit.

6.4 Condensation Oscillation Phase

Following the pool swell phase, the majority of the non-condensable gases have been transferred from the drywell to the wetwell air space, but air[4] bubbles persist in the suppression pool. The below-surface views are difficult to interpret during this time frame, due to the murkiness of the water. However, the above surface views provide evidence that the bubble distribution is not uniform within the suppression pool, but largely confined to an area, surrounding the vent pipe, which begins at the vent pipe wall and extends radially in the pool between one and two vent diameters (~ 2 to 4 ft) away from the vent pipe wall. Some, but not all, of the underwater views are of sufficient clarity to provide an indication of the extent of bubble penetration below the vent. These views indicate that bubble penetration may extend a similar distance (perhaps 1 or 2 vent diameters below the vent), but the evidence derived from these videos is sketchy, at best.

At about 30 seconds after blowdown start in the FSTF facility, the pool surface is very turbulent in the areas immediately surrounding the vent pipes, but much less active away from the vent pipes. The video clearly shows that the rising bubbles burst when they reach the pool surface and cause turbulence around the vent. A definitive quantitative assessment of the void fraction in the near-vent plume region is not possible. However, a significant fraction of the air being injected into the pool at the vent exit is contained within the near-vent location; 75% is a reasonable estimate.

[4] While it is possible that non-condensable gases are present in the vent flow during chugging, typically the non-condensable fraction is very small.

6.5 Chugging Phase

The KWU/GKSS test videos are more useful than the FSTF video for this phase of the accident. Because of the deeper vent submergence at the GKSS facility, the chugging is more energetic than it would be for a Mark I (i.e. the interface velocities at "vent clearing" between individual chugs are likely higher than in the Mark I configuration, and thus the penetration of the condensation interface into the pool will be more extensive). Therefore, the results are likely conservative with respect to the extent of bubble penetration for Mark I conditions.

For the vent pipe exit from a KWU/GKSS test during a rather typical "chug," the bubbles associated with non-condensable gases are much smaller than in the previous phases of the LOCA, and are limited to the immediate vicinity of the vent pipe, radially extending about a half vent diameter or less from the exterior of the vent pipe. The bubbles can be seen to be several vent diameters below the vent exit before buoyancy overcomes their downward motion.

6.6 Location of Non-Condensable Gas Bubbles in the Suppression Pool

Based on the observations from the reviewed videos, the following criteria were established for the location of non-condensable gases during the various phases of a LOCA:

POOL SWELL: Non-condensable gases are assumed to be uniformly mixed with all of the suppression pool water. Note that the definition of the "pool swell" phase used here is different from that normally associated with the dynamic load on the containment due to pool swell, which typically lasts from 1 to 3 seconds. Here the characteristic of concern is the presence of significant gas content throughout the suppression pool due to non-condensable carryover with steam from the drywell. The pool swell phase lasts about 10 to 20 seconds for a large break LOCA, and only occurs in (relatively) large break LOCA scenarios. Any break size where the drywell pressure at vent clearing exceeds the wetwell air space pressure plus the vent submergence head by 2 psid probably will result in a "pool swell" phase.

CONDENSATION PHASE: Non-condensable gases are assumed to mix non-uniformly with the suppression pool water. 75% of the non-condensable gases are assumed to mix with the volume of water surrounding the vent pipe in a region which extends two vent diameters radially from the vent pipe wall and which extends two vent diameters below the vent pipe exit. The remaining 25% of the non-condensable gases are assumed to mix uniformly with the remaining suppression pool water.

CHUGGING PHASE: Non-condensable gases are assumed to be present only in the immediate vicinity of the vent pipes. The non-condensable gases are assumed to mix uniformly with the volume of suppression pool water within one-half vent diameter surrounding each vent pipe and extending two vent diameters below the vent exit. Non-condensable gas voiding is assumed to be zero in the remainder of the suppression pool.

6.7 Break Size Characterization

Historically, containment performance and loading conditions have been described by the break size and condensation mode that is occurring. The containment loads tests were performed for DBA LOCA conditions. However, for other postulated break sizes, not all condensation modes occur during each break size scenario. The following provides some additional background on characterizations by break size and the associated terminology.

6.7.1 Large Break LOCAs

Large break LOCAs are characterized as events where the reactor vessel would quickly depressurize due to the rapid loss of vessel fluid through the break. The initial drywell pressurization rate would be relatively high (approaching 20 psi/sec) and would induce a pool swell response in the suppression pool. Pool swell is a gross lifting and deformation of the suppression pool water caused by injection of drywell non-condensable gases into the pool at the vent system downcomer exits at pressures well in excess of the local hydrostatic pressure. Essentially, the suppression pool is "shredded" as the higher-pressure bubbles deform the bulk pool.

For large break LOCAs, following pool swell, steam would enter the pool at relatively high mass fluxes and would condense in the sub-cooled pool water, which induces the condensation oscillation phenomena. During this relatively high steam flow period, nearly all of the steam would be condensed by the pool water and non-condensable gases entering the pool would rise at the vent exit location in a plume of smaller size bubbles and higher temperature pool water.

Chugging would subsequently follow condensation oscillation when the vent mass flux falls below the oscillation/chugging threshold. During chugging, condensation is intermittent, with the vent system alternately flooding with pool water and re-clearing to form a steam/non-condensable gas bubble[5], which subsequently collapses due to the heat transfer at the bubble surface exceeding the steam supply from the drywell. For the large break LOCAs, chugging would terminate when the vessel blowdown is completed.

6.7.2 Intermediate Break LOCAs

Postulated intermediate break LOCAs depressurize the vessel at a slower rate than the large break LOCA. The intermediate break LOCA would produce a slower initial drywell pressurization rate and therefore, pool swell would not occur. Steam mass fluxes through the vents would be lower than for the large break LOCA, however they would remain high enough to permit condensation oscillation early in the event. As with the large break LOCA, chugging

[5] While it is possible that non-condensable gases are present in the vent flow during chugging, typically the non-condensable fraction is very small.

would follow condensation oscillation as the vent steam mass flux drops. For intermediate breaks, chugging will typically continue until the operator has taken mitigating action to initiate the ADS to rapidly depressurize the reactor vessel or to initiate drywell sprays. EOPs would typically require emergency depressurization because of the increased drywell temperature.

6.7.3 Small Break LOCAs

Small break LOCAs are break sizes which would not result in depressurization of the reactor vessel. For small break sizes the vessel pressure response is initially controlled by safety relief valve (SRV) operation at automatic pressure set points and later by EOP-directed operator actions to manually depressurize the reactor at a controlled rate. Steam condensation would be characterized by chugging, which will continue until mitigating action by the operator is taken.

7.0 SUPPRESION POOL VOID FRACTION STUDY

7.1 Approach

Using NRC approved LOCA transient computer codes, the suppression pool conditions were determined for a typical Mark I BWR as a function of time for a range of break sizes and types – liquid or steam. These conditions were compared to the pump acceptable performance criteria (Section 3.4) and a worst-case break was selected for further evaluation.

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7.2 Selected Typical Plant and Comparison Plant B

One BWR was selected as an example plant representing Mark I plants, hereafter referred to as the "typical plant." Mark I plants are in general similar to each other in the behavior of fluid discharge from the drywell to the suppression pool during liquid and steam breaks.

The SHEX input parameters for the typical plant were obtained from a containment pressure and temperature analysis. The various cases were analyzed in accordance with GEH technical design procedures for licensing calculations.

A wide spectrum of liquid break sizes ranging from a DBA LOCA to a 0.05 ft^2 break were analyzed so that the sensitivity of the pool void fraction to break size would be considered in the evaluation. In addition, two steam line break sizes were also analyzed: 0.5 and 0.1 ft^2. Note the variance of the gas/steam discharge to the suppression pool resulting from different steam break sizes is addressed by the liquid line break analysis performed for various break sizes.

During a postulated LOCA, the air in the drywell would be pressurized by the flow from the break into the drywell. The drywell air and steam and water would flow through the containment vent system and into the suppression pool because of a differential pressure between the drywell and the wetwell, creating air bubbles in the pool. The drywell to suppression pool volume ratio is one factor used in determining the non-condensable gas void fraction in the pool. To determine if there is any significant effect on the suppression pool void fractions resulting from plant-to-plant differences in the drywell to suppression pool volume ratio, liquid breaks were also analyzed for the plant B of Table 4-1 (note, the typical plant was not one of the selected plants in Table 4-1). Plant B has a relatively low drywell to suppression volume ratio, while the typical plant has a relatively high ratio among Mark I plants, see Table 7-1. (The drywell and suppression pool volumes listed in Table 7-1 are obtained from OPL-4A data[6]).

[6] OPL-4A is a form used by GEH and individual BWR Licensees to define the pertinent numeric input data to be used in LOCA containment analyses. The OPL-4A data is verified by the Licensee.

Table 7-1: Drywell Suppression Pool Volume Ratio - Mark I Plants

Mark I Plants	Volume (ft^3)*		DW to SP Volume Ratio
	DW	SP	
Browns Ferry 1, 2, 3	171000	123000	1.39
Brunswick 1, 2	164100	122000	1.35
Cooper Station	132250	87650	1.51
Dresden 2, 3	158236	112203	1.41
Duane Arnold	130000	58900	2.21
Enrico Fermi	163730	117450	1.39
FitzPatrick	154476	106442	1.45
Hatch 1, 2	146266	87300	1.68
Hope Creek 1, 2	169000	87300	1.94
Monticello	134200	68000	1.97
Nine Mile 1	180000	82500	2.18
Peach Bottom 2, 3	175800	122900	1.43
Pilgrim	148560	84000	1.77
Vermont Yankee	131470	68000	1.93

* Note that the values listed are for comparison purposes only and represent minimum water level in the suppression pool; no other uses are intended.

7.3 Selection of Break Sizes and SHEX Input Assumptions

A total of five break sizes were analyzed. The largest break size analyzed is the DBA LOCA. For this event, the drywell pressure would increase rapidly early in the transient, which results in the highest air discharge into the pool early in the transient. As the air content in the drywell is depleted and the vent flow decreases, the air discharge to the pool decreases with time. For smaller break sizes, the air discharge to the pool would be less in the early part of the transient, but would be higher later in the transient in comparison to the DBA LOCA.

In addition to the DBA LOCA, four medium to small liquid break-sizes were analyzed: 1.0, 0.5, 0.1 and 0.05 ft^2 break-sizes in a recirculation line. A total of two steam break-sizes were also analyzed: 0.5 and 0.1 ft^2 break-sizes in a main steam line. The 0.5 ft^2 break-size is considered to represent a break size at which steam discharges without a pool swell inside the suppression pool. As far as the air discharge into the suppression pool is concerned, no significant difference is expected between liquid breaks and steam breaks. Because a wide spectrum of liquid break sizes were analyzed, two steam break sizes were considered to be sufficient for use in the gas ingestion evaluation.

The containment analyses are based on the typical plant's DBA LOCA analysis performed to maximize the pool temperature response at Extended Power Uprate (EPU) conditions. [[

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7.4 SHEX Output Parameters

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7.5 LOCA Analysis

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7.6 LOCA Results

Figure 7-1 shows the void fraction of the suppression pool as a function of time for the five liquid line breaks and two steam line breaks for the selected typical plant. Examination of Figure 7-1 shows that for the DBA LOCA the void fraction increases rapidly shortly after initiation of the event, as the air in the drywell is quickly discharged into the pool. As the air content is depleted in the drywell, the discharge from the drywell is mostly steam and the void fraction becomes [[ ]] With smaller break sizes, the initial spike of the void fraction becomes diminished, but a higher void fraction is maintained for a longer period when compared to the DBA LOCA. For steam line breaks, there is no significant difference in the void fraction trend for liquid line breaks, thus confirming the assumption that the break type has no significant impact on the void fraction results. Therefore, the liquid line break analysis also addresses steam line breaks.

The liquid line breaks analyzed for the typical plant were also analyzed for plant B, which has a lower drywell to suppression pool volume ratio. The void fraction results for plant B are plotted in Figure 7-2. These results show that the void fraction trends for plant B are similar to those for the typical plant. However, the magnitude of the void fraction is lower for plant B. For instance, the plant B void fraction [[

]] This result is expected because the initial air volume in the drywell relative to the suppression pool volume is smaller for plant B. Thus the selected typical plant, which has a relatively high drywell to suppression pool volume ratio, provides a conservative generic representation of Mark I plants in evaluating the void fraction in the pool during a LOCA, while plants with lower drywell to wetwell volume ratios would be expected to have lower void fractions.

The DBA LOCA is the most limiting break size with respect to the maximum void fraction. [[

]] During these first seconds of the DBA LOCA, void transport into the ECCS pump suction is not expected because the pump flow is at minimum flow and the voids would not transport though the strainer and down the ECCS suction piping. Accordingly, the early void fraction values for the DBA LOCA are not critical in selecting the limiting break size for gas ingestion into ECCS pumps. The limiting break size was selected considering the following:

- The HPCI system would typically not be used for a DBA-LOCA because of the rapid vessel depressurization,

- Low-pressure Core Spray (CS) and Residual Heat Removal (RHR) pumps may be turned on early in the transient when a LOCA signal is generated with off-site power available. However, the pump flow rates during this time period are expected to be at their minimum, and

The void fraction profile for the 1.0 and 0.5 ft^2 liquid line breaks is similar to that for the DBA LOCA; [[

]] For all of the break sizes, the void fractions reach an acceptable level prior to the ECCS pumps reaching full flow.

Based on a review of the base case results presented above, the 0.1 ft^2 liquid line break was selected as providing the greatest potential challenge to the void fraction pump acceptance criteria, and therefore this break size was used for the parametric evaluations.

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Figure 7-1: Base Case Void Fraction Profile for Liquid and Steam Line Breaks Analyzed for the Typical Plant

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Figure 7-2: Base Case Void Fraction Profile for Liquid Breaks Analyzed for Plant B

7.7 Parametric Evaluations

7.7.1 Parametric Evaluation with Bubble Rise Time

The base case assumes the bubble rise time to the pool surface is [[

]] The void fraction results for the limiting break size (0.1 ft^2) for the two rise times are plotted in Figure 7-3. As the bubble rise time increases, air bubbles remain in the pool longer, the resulting void fraction at a given time is higher, and the duration of higher void fractions is longer. Alternatively, the shorter bubble rise time results in a lower void fraction, as air bubbles flow into the wetwell airspace more quickly.

7.7.2 Parametric Evaluation with Pool Participation Factor

For the base case, [[

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The pool void fraction results for the selected limiting break size (0.1 ft^2) with the two above pool participation factors are plotted in Figure 7-4. Compared to the base case, [[

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Figure 7-3: Void Fraction Profile for Typical Plant 0.1 ft^2 Liquid Line Break Analyzed for Various Bubble Rise Times with Full Pool Participation Factor

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Figure 7-4: Void Fraction Profile for Typical Plant 0.1 ft^2 Liquid Line Break Analyzed for Various Pool Participation Factors with [[ ]]

7.8 Void Fraction Results Compared with Pump Acceptability Criteria

Parametric cases were evaluated for two key analysis parameters. For the pool participation factor, the uniformity of the void fraction distribution within the pool was evaluated, which addresses pool water void fractions entering the pump suction depending upon the relative vertical location of the ECCS suction strainer to the downcomer vent system exit. The pump must meet all of the following criteria (Section 3.4) for acceptable full flow conditions:

< 2 % average void fraction for 120 seconds or longer,

< 3 % average void fraction for less than 120 seconds,

< 5 % average void fraction for less than 20 seconds,

< 10 % average void fraction for less than 8 seconds, and

< 20 % void fraction for all SHEX time steps.

Note that void transport is not expected at low pump flow, such as the minimum flow through the minimum bypass valve. The ECCS pumps start early in the LOCA, but full pump flow would not occur until later depending upon the accident scenario and the injection valve opening time delay.

The void fraction results obtained for the base and parametric cases were checked against the pump acceptability criteria for the time period when full pump flow is achieved and all cases showed the acceptable pump performance criteria were not exceeded. For all cases, the void fractions were below the duration-based pump acceptability criteria with significant margins.

For some plants the HPCI system draws water from the Condensate Storage Tank (CST) for the time period of concern. For these plants, the void fraction does not affect the HPCI pump since it does not draw water from the suppression pool. For other plants the HPCI suction is aligned to the suppression pool and its operation will depend on reactor vessel depressurization and system timing.

For the low-pressure CS and RHR systems, full pump flow for a 1 ft^2 break would [[

]] Some interesting trends were noted during this study in the interrelationship between the break size, void fraction and full pump flow timing. As the break area becomes larger, the void fraction is diminished significantly at the time full ECCS pump flow starts because the larger breaks deplete the air content in the drywell early in the LOCA. For a smaller break size, the drywell air is discharged more slowly, but the void fraction is relatively small and at an acceptable value when the ECCS pumps reach full flow because the ECCS start-permissives are reached later in the event, if at all. Additionally, review of the test videos indicate that for all but the largest break sizes, the voids would be limited to the immediate location of the downcomers, and the distances between the ECCS suction strainers and the downcomers in most plants, as well as any assumed strainer debris loading, would preclude significant gas entrainment.

8.0 NRC QUESTIONS AND RESPONSES

Question 1.1: To what extent are the low-pressure ECCS pumps, LPCI and core spray, capable of operating in an environment with potential voiding/air binding which may occur during the first few moments of the LOCA accident?

Response 1.1: During the first moments of a large break LOCA the ECCS pumps would start and operate in the minimum flow condition while the reactor pressure vessel is depressurizing and ECCS injection valves have not opened. At minimum flow, the strainer approach velocity would be significantly lower than the bubble rise velocities. Additionally, the flow rate would be such that voids would not transport down the ECCS suction piping and into the ECCS pumps. Regardless of the size of the postulated LOCA break, the void fraction in the suppression pool is expected to be acceptably small once the ECCS pump flow rate increases above minimum flow. See Section 7.8 for further detail.

Question 1.2: Have any studies been performed, for purposes not associated with GI-193, which might provide insight into the extent of voiding in the suppression pool during and immediately following blowdown during a large break LOCA and the effect it might have on low pressure ECCS pump performance? Examples of previous studies which may be of tangential assistance include those industry studies associated with LOCA pool dynamic loads, the impact of pool swell and local pool temperature limits.

Response 1.2: Yes, various containment loads programs have studied steam and non-condensable gas injection into BWR suppression pools. However, these programs did not specifically address the suction by ECCS pumps. A GI-193 specific study has recently been performed by GEH for the BWROG and is contained in this report. The study demonstrated that for a large break LOCA the non-condensable gases would have been nearly completely released from the suppression pool before the start of full flow by the ECCS pumps and the residual void fraction in the suppression pool is acceptable for pump performance. The study also showed that a LOCA with a smaller break size would provide a higher void fraction at the time of ECCS pump initiation than the DBA LOCA, but these voids would not cause pump damage or a trip. See Sections 6.0 and 7.6 for further detail.

Question 1.3: How would an operator monitor air binding in ECCS pump during the early stages of a large LOCA?

Response 1.3: Emergency Operating Procedures are based on responding to plant symptoms. The operator would be aware of changes or fluctuations in pump discharge and suction pressure and flow rate, unusual or fluctuating pump motor electrical loads, frequent needed adjustments to ECCS system discharge valves to maintain conditions, and for some plants an abnormal core spray vent accumulator level switch indication. See Section 5.0 for further detail.

Question 2.1: Please provide a representative time history for a typical BWR Mark I for approximately the first 5 minutes following onset of a *large break LOCA* and 15 minutes following onset of *a medium break LOCA*, displaying:

- associated reactor vessel permissives impacting pump start, e.g., reactor low pressure;
- staging of LPCI and core spray trains (i.e., all start at once or in stages), and
- duration of time pumps are in minimum flow

for both:

(1) the DBA case of simultaneous LOCA/LOOP, and

(2) the case of offsite power available, in which the pumps would be started from offsite power.

Response 2.1: The representative time histories for four Mark I BWRs are contained in Table 4-1 of this report. A comparison of a large break and intermediate break LOCA is shown in Table 4-2. The time histories were terminated earlier than 15 minutes after LOCA initiation because no additional pertinent data would have been gained for a longer time period. If off-site power is available, some ECCS pumps may start in their minimum flow condition typically five to ten seconds sooner than when there is a loss of offsite power. The reactor vessel pressure permissives and the ECCS injection valve stroke times remain unchanged. Therefore ECCS full flow would occur at essentially the same time after LOCA initiation regardless of whether or not off-site power is available. The staging for starting low-pressure ECCS pumps depends on the individual plant and typical stage delay times are 5 to 10 seconds.

Question 3.1: Please provide information pertaining to downcomers vis-à-vis the ECCS LPCI and CS suction strainers:

A representative range of downcomer/strainer geometries, specifically, the distance between the downcomer and the suction strainers and relative angle between the two; and an indication if a typical plant has the same geometry across all downcomers.

The worst-case geometry between downcomer and strainer, i.e., the closest in proximity so as to maximize impingement into the strainer during blowdown.

The "typical" geometry between the downcomer and strainer.

Characteristics of a typical ECCS suction strainer in enough detail to allow a computer model to be generated. Include dimensions of the openings and design flow rate/pressure drop.

Response 3.1: BWRs have many more downcomers than strainers. There is no typical location of ECCS strainers relative to a downcomer for all Mark I BWRs, although strainers are generally not located directly below a downcomer. It should be noted that the specific locations of BWR plant strainers relative to downcomers does not affect the conclusions of this report. Because there are multiple BWR strainer vendors, there is no typical ECCS suction strainer drawing.

Question 3.2: Did any analyses or testing related to the suction strainer redesign program (addressing debris blockage) assess whether the revised suction strainers might deter or promote gas entrainment into the ECCS suction? In other words, have any studies taken place to evaluate the extent to which bubbles formed during blowdown would pass through the strainers given their design flow rates and the strainer openings?

Response 3.2: Most of the BWR strainers are constructed with perforated plate. There are no known tests by strainer vendors of whether their designs deterred or promoted gas entrainment in the strainers. It is expected that non-condensable gas bubbles in the suppression pool would normally pass through the strainer surfaces provided the flow field is sufficient to overcome the buoyancy of the bubbles. If fiber and/or corrosion product debris were present on the strainer, as would likely be the case of a large-break LOCA scenario, the flow passages through the debris would be much smaller than the hole size of the perforated plate. Thus, should some bubbles be drawn inside the strainer, they would likely be very small. Whether such bubbles would become trapped in a strainer and coalesce into a larger bubble internal to the strainer would depend on the strainer internal flow fields. Most strainers have sufficient perforated area and low approach velocities such that if a larger bubble with greater buoyancy would form inside the strainer, it might exit the strainer back into the suppression pool due to the buoyancy of this larger bubble. The redesigns of the BWR suction strainers in the late 1990's significantly reduced the water approach velocities to the strainer and thus reduced the likelihood of the bubbles being drawn into the strainers. See Section 3.2 for further detail.

Question 3.3: Other than the Brown's Ferry plants, do any other Mark I's have a common ring header below the suppression pool used for ECCS suction?

Response 3.3: The other Mark I plants besides the three Brown's Ferry plants that have a common ring header are Dresden 2 & 3, Monticello, Quad Cities 1 & 2, and Oyster Creek.

Question 4.1: Are any tests facilities still available for Mark I containments that could be instrumented to measure voiding and void transport under LOCA blowdown conditions?

Response 4.1: The test facilities used for the Mark I containment loads tests have been disassembled. Videos of some of the BWR containment loads tests were recently reviewed as part of the BWROG review of GI-193. The previous containment loads tests were performed for postulated large-break LOCA conditions. If additional tests were to be performed, the BWROG GI-193 committee members have identified the following potential facilities: Alden Labs, Creare, Continuum Dynamics, and EPRI-Charlotte.

9.0 CONCLUSIONS

Following a postulated LOCA, the injection of water into the pressure vessel using the RHR and CS ECCS pumps is delayed because of the elapsed time to reach the associated reactor vessel pressure permissive set points and the subsequent time for the injection valves to stroke open. Whether there is off-site power available has only a minor, if any, effect on the pump injection timing.

The ECCS pumps will run in a minimum flow condition until the associated injection valve begins to open. At ECCS minimum flow conditions, the non-condensable gas bubbles of a typical size range as produced in a suppression pool blowdown event would not be drawn into the ECCS suction strainers because the buoyancy force on the bubbles is greater than the downward velocity field adjacent to the ECCS strainers. Therefore, the non-condensable gas bubbles from the LOCA blowdown event would not be drawn into the ECCS suction piping when the ECCS pumps are at minimum flow conditions.

A range of LOCA break sizes and break types (liquid and steam) were analyzed with NRC-approved LOCA computer codes to determine the void fractions in the participating portion of the suppression pool. Suppression pool participation values were determined with a detailed review of archived videos from the full-scale Mark I and KWU containment tests. The void fraction analysis determined that the largest challenge to the ECCS pumps would occur with a LOCA liquid line break size of about 0.1 square feet because the blowdown of non-condensable gases from the drywell would last longer than a DBA-LOCA. There was no difference observed in void fractions between steam and liquid line breaks.

The calculated suppression pool void fractions were compared to acceptable pump performance criteria and it was determined that pump failure or air binding would not occur for any of the selected break sizes. Because the analyzed break sizes ranged from a DBA-LOCA to a 0.05 square foot break, the analysis covered the spectrum of LOCA breaks of concern. As the assumed LOCA break area increases, the suppression pool void fraction peaks very earlier in the event and quickly decreases because the large break purges the air content in the drywell earlier. For smaller breaks, the drywell air would be discharged more slowly but the pool void fraction is acceptably small when the ECCS pumps come off minimum flow because the ECCS start permissives are reached later in the event, if at all. Additionally, review of the full-scale containment test videos indicate that for all but the largest break sizes, the voids would be limited to an area adjacent to the downcomers, and the locations of the ECCS suction strainers in most BWR plants would thus also preclude significant gas ingestion.

Emergency Operating Procedures and Severe Accident Guidelines were reviewed to determine if procedural steps should be modified to address the GI-193 issue. It was determined that the current symptomatic procedures properly address potential operator actions should ECCS pump performance be affected by a LOCA blowdown.

10.0 REFERENCES

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2. NUREG-0933- Issue 193: "BWR ECCS Suction Concerns Description," August 2008, **http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/ sr0933/ sec3/193.html**. (ML082410719)

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