Detailed Assessment of Generic Issue (GI)-193

The proposed issue was initially evaluated by a Generic Issue Review Panel (GIRP) (hereto referred to as the original GIRP) and determined the issue met the seven screening criteria. The original GIRP submitted an initial screening report[1] on October 16, 2003, in accordance with Management Directive (MD) 6.4. Based upon its findings noted in the screening report, the original GIRP recommended that the issue should continue into the assessment stage as described in MD 6.4. The purpose of an assessment stage is to determine, through additional research activities, if the issue presents a significant safety hazard that merits further regulatory action.

Following the completion of an Office of Nuclear Regulatory Research (RES) project to gather additional information regarding the safety significance of the issue, a new GIRP was established in 2015 (hereto referred to as the new GIRP) to perform the assessment as prescribed in MD 6.4. Because the original GIRP members were no longer available to participate, the new GIRP was formed of Nuclear Regulatory Commission (NRC) staff with specific knowledge pertaining to this issue. The new GIRP members were appointed via memorandum from the Division of Policy and Rulemaking dated August 15, 2015.[2] The official members of the panel were:

- Robert M.Taylor, Deputy Director, Division of Safety Systems, Chairman.
- Victor Cusumano, Division of Safety Systems, Safety Issue Resolution Branch.
- Mehdi Reisifard, Division of Risk Assessment, Probablistic Risk Assessment Licensing Branch.
- Robert Wolfgang, Division of Engineering, Component Performance, Non-Destructive Examination, and Testing Branch.

The RES project manager assigned to this issue was Stanley Gardocki from the Division of Engineering.

The new GIRP held its first official meeting on September 24, 2015, and continued to meet regularly over the next six months. In addition to the appointed panel members, additional RES staff (i.e., William Krotiuk and Scott Elkins, who prepared the supporting technical report[3]) attended most of the meetings to assist in clarifying any technical issues with the report findings. Based upon the results of the RES report and plant-specific information, the new GIRP concluded that the proposed GI-193 issue did not present a significant safety hazard and recommended that the issue should not continue to the regulatory office for implementation. The basis for their determination is documented in the assessment that follows.

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[1] "Results of Initial Screening of Generic Safety Issue 193, "BWR ECCS Suction Concerns," ADAMS Accession No. ML032940708.
[2] Request for Generic Issue Review Panel Members for GI-193, Boiling-Water Reactor (BWR) Emergency Core Cooling Systems (ECCS) Suction concerns," ADAMS Accession No. ML15132A607.
[3] Assessment Report, "GI-193 BWR ECCS Suction Concerns Study Results and Recommendations," ADAMS Accession No. ML15160A262, and Assessment Report, "GI-193 BWR ECCS Suction Concerns Following a LOCA Updated Literature Search and Recommendations, ADAMS Accession No. "ML15147A625.

Description of Proposed Issue

The issue was proposed as a generic issue on May 10, 2002, by an NRC Region III inspector.[4] The inspector identified a potential concern for the emergency core cooling system (ECCS) during large or medium break loss-of-coolant accidents (LOCAs) for Mark I or Mark II containments. The concern focused on the force of the escaping steam from the reactor coolant system (RCS) causing a blowdown of containment gases into the suppression pool/torus where the ECCS pumps are designed to take suction.

This proposed generic issue hypothesizes that these gases could impair operation of the low-pressure ECCS pumps if a large quantity of gas is drawn into their suctions. The result may be gas binding, flow instability, and high vibrations. If these conditions persist, the pumps may suffer impeller damage and eventually trip on high vibration or on electrical supply instability. If the damage is significant, then the low-pressure ECCS pumps may become irrecoverable, and the safety function for core cooling may be lost. However, the NRC is not aware of any operating experience or testing that supports this particular sequence of events will occur.

Original GIRP Screening Report

When the original GIRP initially evaluated the proposed issue, the panel members found the issue potentially applied to Mark I, II, and III containments during large and medium-break LOCAs and could potentially cause pump failure or degraded performance due to gas binding, vapor locking, or cavitation. Although the GIRP screening analysis was performed on a Mark I containment design, the phenomena of interest are also possible in the Mark II and III designs. For this reason, the panel members recommended those designs should be included in any task action plan for this issue.

The original GIRP determined that the issue met the screening criteria specified in MD 6.4 for continuation in the Generic Issue program. The panel members found the safety concern warranted the issue continuing into the assessment stage and recommended that RES perform a detailed technical evaluation to thoroughly understand the phenomena.

RES Follow-on Detailed Technical Evaluation

Following the initial screening evaluation, the RES technical staff completed its technical evaluation in 2015 and provided their results in a report titled, “GI-193 BWR ECCS Suction Concerns Study Results and Recommendations.”[5] This report is not currently publicly available; however, it will be published as NUREG-2196 and made publicly available in middle of 2016. The report addresses the issues raised by the original GIRP and provides a method to calculate the size and duration of the large bubbles created during containment blowdown. It also discusses other pertinent issues such as the potential effect of small bubbles breaking away from the large bubbles and the effect on pump performance. The new GIRP used this information to perform its assessment.

[4] "Potentially Generic Safety Issue - BWR ECCS Suction Concerns," ADAMS Accession No. ML021340802

[5] "GI-193 BWR ECCS Suction Concerns Study Results and Recommendations," ADAMS Accession No. ML15160A262, and "GI-193 BWR ECCS Suction Concerns Following a LOCA Updated Literature Search and Recommendations, ADAMS Accession No. "ML15147A625.

New GIRP Assessment Report

In accordance with the guidance in MD 6.4, “Generic Issues Program,” the purpose of an assessment is to determine if the proposed issue presents a significant safety hazard that merits further regulatory action. For this specific issue, the new GIRP reviewed the qualitative and quantitative risk assessments presented in the original GIRP screening report. Because of the low risk significance of the event and the high dependency of sensitivity studies to assumptions related to phenomena following an accident, the new GIRP focused its review on understanding the technical aspects of this issue, mainly assessing the adequacy of the low-pressure ECCS pumps following a design basis accident.

Postulated Event

To determine the affected area, the RES study used computational and experimental evaluations to analytically characterize the size, shape, and duration of gas bubbles introduced into a boiling-water reactor (BWR) Mark I torus following a large break LOCA. The bubbles have been determined to exist in two phases. Initially, large bubbles of non-condensable gas exit the downcomers and penetrate into the torus's water reservoir. Computational analyses modeling the behavior of the large bubble formation following the postulated event show that the large bubbles penetrates about 3.5 pipe diameters below the downcomer exit. Depending on plant-specific configurations, this penetration depth may be sufficient for the large bubbles to engulf all or part of at least some suction strainers for the ECCS pumps. Analyses indicate the large bubbles will then quickly rise back up past the downcomer pipe exit within 2 to 3 seconds. A possibility exists that the large bubbles could be ingested if the pumps were operating during the initial 2 to 3 seconds. Should this gas travel through the suction strainer and piping into an operating ECCS pump, that pump could experience short or long-term detrimental effects. The evaluation discussed later in this assessment describes why the low- pressure ECCS pumps will not be challenged by the large bubbles developed during the first phase of the event based upon a combination of several factors.

The second phase of this event consists of smaller bubbles that break away from the main bubbles. Following the LOCA initiating event, the amount of non-condensable gas decreases quickly, within 2 to 3 seconds, and reaches very small levels that may last up to 20 seconds. The RES study concludes that the void fraction, a measure of the amount of gas present in a liquid, from small bubbles in the region below the downcomer exit will be reduced to less than 1 percent within 2.5 seconds. The RES study indicates that the inlet void fraction from these small bubbles will not exceed the operational criteria outlined in the report for low, high, transient, or steady flow operations. Therefore, the small bubbles will not challenge the operation of the low-pressure ECCS pumps. The new GIRP concluded that small bubbles do not pose a credible threat to the pumps' operability; hence, the scope of this generic issue should be limited to the effects from the large bubbles.

Background: Typical Low-Pressure ECCS System Designs

The typical BWR 3 and 4 system designs consist of two separate low-pressure ECCS systems to mitigate a large break LOCA in the RCS. One of the low-pressure ECCS injection systems is the residual heat removal (RHR) system, which has a mode of operation that provides low-pressure core injection (LPCI). The RHR system typically consists of four pumps that take suction from the torus. The four pumps receive an automatic start signal upon a low reactor vessel level, a high drywell pressure, or a combination of these signals. The RHR pumps run on minimum recirculation flow until the reactor pressure decreases below a designated

pressure, about 338 psig, at which time the injection valves open and full flow is directed into the core.

The other low-pressure ECCS system used for LOCA mitigation is the core spray (CS) system. The typical BWR 3 and 4 CS system design for consists of two or four pumps that also take suction from the torus. The CS pumps have a similar starting signal as the RHR pumps; they receive an automatic start signal immediately upon low reactor vessel level and a high drywell pressure. The CS pumps initially start with a minimum flow recirculating back to the torus. When reactor vessel pressure decreases to less than 465 psig, the injection valves receive a permissive signal to open; however, flow to the core does not begin until RCS pressure decreases to less than pumps shut off head, about 333 psig. When injection flow reaches about 650 gpm, the minimum recirculation flow valves close, and full flow is directed to the core.

In addition, some BWR 2 designs vary slightly. They rely primarily on the CS system to maintain core cooling to prevent significant fuel damage. The typical BWR 2 CS system design has four primary spray pumps and four CS topping pumps. However, this BWR 2 design does not have a LPCI mode. Instead, the BWR 2 design has an isolation cooling system and a containment spray system to maintain the integrity of the containment.

Applicability

The pumps susceptible to damage from this postulated event are the low-pressure ECCS injection pumps that take suction from the torus. Based on the analysis provided in the RES study and a review of the information provided by the licensees in their Updated Final Safety Analysis Reports (UFSARs), the new GIRP narrowed down the scope of this assessment to BWR plants that could have low-pressure ECCS pumps susceptible to gas entrainment.

Based upon RES study, the blowdown event occurs very rapidly upon the initiation of the RCS pipe break. The large bubbles last for only 2 to 3 seconds. After exiting the downcomer, the gas has to expand enough to reach the low-pressure ECCS pumps' strainers to present a hazard. The new GIRP determined only the smallest containments (i.e., Mark I designs) would be candidates for this situation because the large bubbles may travel this shorter distance in the 2-3 seconds they exist. The BWR plants with larger containments were scoped out because the possibility of gas ingestion is significantly lower due to the greater separation between the gas introduction points and the ECCS pumps' suction piping inlets. Therefore, the new GIRP concluded that Mark II or larger containments have sufficient volume to exclude those designs from the scope of this generic issue, and the scope of this assessment should be limited to plants that have a Mark I containment design.

Because the large bubbles will only last 2 to 3 seconds following the blowdown, the new GIRP finds that those plants having a delayed start time greater than 5 seconds for their low-pressure ECCS pumps will have allowed sufficient time for the large bubbles to clear the immediate vicinity of the ECCS pumps' suction piping inlet prior to pumps starting. Therefore, the new GIRP concluded that plants with ECCS pumps with delayed starts greater than 5 seconds should be excluded from the scope of this generic issue. The scope of this assessment should be limited to plants that start their low-pressure ECCS pumps during the time the large bubbles exist.

During a loss-of-offsite-power (LOOP) event, the low-pressure ECCS pumps have to wait until power is restored to their respective emergency buses before the pumps receive a signal to start. The emergency diesel generator takes a few seconds to start and accelerate up to

operating speed to energize their respective emergency buses. This delay should allow sufficient time for the large bubbles to clear the immediate vicinity of the ECCS low-pressure pumps' suction piping inlet. Therefore, the new GIRP concluded large break LOCAs involving a LOOP should be excluded from the scope of this assessment, and the scope limited to conditions and start times associated with low-pressure ECCS pumps starting on a normal power source.

Information from the individual BWR Mark I plants' UFSARs revealed that several plants staggered the start of their low-pressure ECCS pumps. Only the first pumps to start during the 2-3 seconds that large bubbles exist would be exposed to the possibility of gas being drawn into their suctions. Typically, BWR 3 and 4 plants have six low-pressure ECCS pumps, two CS pumps, and four LPCI pumps. The plants' accident analyses do not require all six pumps to operate to successfully mitigate a large break LOCA. If only the first or second pumps are adversely affected, the plant would still have sufficient capability in the remaining four ECCS pumps to provide adequate mitigation capabilities. Therefore, the new GIRP concluded that plants with low-pressure ECCS pumps with staggered starts will have sufficient mitigation capability with the pumps that start after the large bubbles exits the exclusion zone; therefore, they should be excluded from the scope of this assessment.

After reviewing the information supplied in BWR Mark I plants' UFSARs, the new GIRP noted that several plants had low-pressure ECCS pumps that start immediately upon an initiation signal of a LOCA if the plant is on normal power supply. In this scenario, all low-pressure ECCS pumps are potentially exposed to the large bubbles created during the blowdown. Therefore, the new GIRP concluded that a conservative evaluation for possible adverse consequences from the conditions described in this generic issue would be limited to those plants in which all low-pressure ECCS pumps start at the same time the plant detects a large break LOCA.

New GIRP's Detailed Evaluation

Based upon the above-mentioned evaluation of plants and configurations, the new GIRP reduced the scope of their evaluation to BWRs with a Mark I containment design having low-pressure ECCS pumps that start immediately upon the detection of a large break LOCA. The new GIRP finds that an evaluation of this select group would be the most conservative and reasonably bound remaining plant configurations.

The new GIRP evaluated several plant specific factors that could possibly affect the impact of the gas bubbles on the low-pressure ECCS pumps' performance. The ability of the gas to reach the pumps is influenced directly by the plant's specific configuration. These factors include the design of downcomers, suction piping, and strainers; the distance between the downcomers and the pumps' suction piping inlets; the elevation between pumps' suction piping inlets and pumps' inlets; the recoverability of the pumps after short-term gas ingestion while in recirculation flow mode; and the timing of the formation of the bubbles relative to pumps' start logic. The results of the following detailed evaluation helped determine whether these additional factors provided a reasonable assurance of sufficient safety margin to prevent core damage.

Understanding the configuration and duration of the gas bubbles was a key factor missing in the scoping review performed by the original GIRP, but the referenced follow-on RES study provided new information regarding the duration and size of the large bubbles. The analysis discussed in the RES report was by design conservative and limited in scope. The conservatisms in that analysis, as well as application of realistic conditions outside the scope of the report, can provide greater understanding of existing safety margin in several areas. The

RES report examined the potential problem of gas entrainment of low-pressure ECCS pumps based upon whether their suction piping inlets are within an “exclusion zone” and whether the pumps are operating during the time the large bubbles exist. The most limiting scenario challenging the operation of the low-pressure ECCS pumps is a simultaneous, non-delayed start of all low-pressure ECCS pumps immediately upon the detection of a large break LOCA.

Pump Start Timing

The time the low-pressure ECCS pumps start following an initiation signal of a large break LOCA is one of the most important considerations in evaluating whether the gas entering the torus through the downcomers will impact the pumps. The new GIRP realizes that a sufficient safety margin (conservatism) exists due to the delay between the time the break initiates and the pumps draw suction.

Assuming the large break in the RCS occurs rapidly, the rate in which the energy is expelled from the RCS would cause high drywell pressure and the blowdown of containment gases into the torus to occur almost immediately, within the first second. However, a small delay exists between the time the high drywell pressure signal is activated and the time the logic sends a signal to the low-pressure ECCS pumps to start (about 1 second). An additional amount of time is required for the low-pressure ECCS pumps to physically start after receiving a signal. Also, large pump motors take a finite amount of time to accelerate up to normal operating speed, depending on the size of the motor. An additional 1 second is a reasonable approximation for the minimum time for a low-pressure ECCS pump to accelerate up to operating speed.

These time delays would very likely allow time for the large bubbles to clear the area around the pumps’ suction piping inlets. By the time the pumps reach operating speed, the large bubbles will most likely already be rising, traveling away from the pumps' suction piping inlets. It is highly reasonable that the large bubbles will already have risen up past the downcomer exit and out of the “exclusion zone” before the pumps’ suction velocity becomes significant. Therefore, the new GIRP finds a time difference exists from when gas is expelled from the downcomers until the time in which the ECCS pumps reach sufficient operating speed enough to draw gas into their suction. This time difference considerably minimizes the potential for gas ingestion that would impair the pumps’ ability to perform their safety function, supporting the conclusion that a sufficient safety margin exists for low-pressure ECCS pumps to perform their safety function.

Pump Start in Recirculation Mode

Conservatively, there are other factors that significantly reduce the possibility of gas ingestion adversely affecting ECCS pump performance during this event. For example, when the low-pressure ECCS pumps initially start, they operate in a minimum flow recirculation mode until injection valves open, permitting injection flow into the reactor vessel. This alignment typically takes up to a minute. While operating in a minimum flow recirculation mode, the approach velocity for the fluid at the suction strainer is a very small fraction of the flow velocity at normal operating flow. Therefore, bubbles are less likely to be drawn down against their buoyant force towards the suction strainers and into the pumps’ suction piping inlet. Even if a small amount of gas from the blowdown travels into the suction strainers due to the low flow velocity in the suction piping during the pump start up sequence, only the smallest bubbles would be drawn into the pumps’ suction piping inlet.

The void fraction developed by these small bubbles would be very small in comparison with the impeller eye; hence, the small bubbles present little impact on the pumps' performance. Therefore, the new GIRP concluded that the small bubbles should pass through the pump without any significant degradation of pump performance while the pumps are in minimum recirculation mode, thus supporting the conclusion that a sufficient safety margin exists for low-pressure ECCS pumps to perform their safety function.

Pump Survivability of Gas Entrainment

Given the timing considerations described above, significant gas ingestion is unlikely. However, to provide a conservative analysis, the new GIRP explored the possibility that some amount of gas may be ingested into the pumps during the time the large bubbles exist in the torus. Therefore, the new GIRP evaluated the likelihood of recoverability of the low-pressure ECCS pumps after a short-term gas ingestion.

The literature search in the RES study provided pump performance data that was helpful in evaluating a pump's survivability during the period of low transient flow. The study included references to the amount and duration of gas entrainment that would exceed the pump's capability to recover. The staff discussions with pump specialists resulted in the opinion that pump inlet void fractions between 1 to 3 percent would result in negligible degradation; that air binding might occur for flows less than 50 percent of best efficiency; that pump degradation occurs with void fractions between 3 and 15 percent, dependent on individual pump design and operating conditions; and that air quantities greater than 15 percent would result in full degradation in most pumps.[6]

The RES study cites industry experience that predicts pumps can successfully survive short periods of gas ingestion. The BWR Owners' Group (BWROG) performed its own study on the effects of void fraction on pumps.[7] Based on information from the three major pump vendors, the BWROG concluded that little to no degradation in pump performance occurs between the void fraction range of 0.5 to 5 percent, but it recommended an acceptable limit of 2 percent void fraction would be acceptable for continuous operation. For transient operation, industry supported using a conservative guideline, an average 10 percent void fraction for no greater than 5 seconds is recommended for use.[8]

The RES study provided the basis for the GIRP determination on whether the void fraction due to containment blowdown would cause pump damage. As described in the study, during transient conditions, at low flow rates (e.g., on minimum recirculation flow), pumps are likely to incur damage if exposed to a void fraction of 5 percent over 5 seconds. In the event of a large break LOCA, the low-pressure ECCS pumps' exposure to the greatest void fractions occurs during the first few seconds, the time when the initial large bubbles exist. In the most conservative case, the inlet void fraction may exceed 5 percent; however, only for a very short period of time (less than 5 seconds). The large bubbles are expected to dissipate after the first

[6] "GI-193 BWR ECCS Suction Concerns Study Results and Recommendations," ADAMS Accession No. ML15160A262, and Assessment Report, "GI-193 BWR ECCS Suction Concerns Following a LOCA Updated Literature Search and Recommendations," Section 4.2.2, Page 30, ADAMS Accession No. ML15147A625.
[7] Kalra, A., "Task 5 – Effects of Non-Condensable Gases on Seals (CVDS Pumps)," BWR Owners Group, BWROG-TP-12-013, Revision 0, August 2012. *Proprietary information.*
GI-193: "BWR ECCS SUCTION CONCERNS," ECCS Pump Performance Literature Report. March 31, 2005. [ML050910465]
Fleischer, L., "Assessment of NRC Generic Issue # 193 Prepared for the Generic Issue #193 Committee of the BWR Owner's Group", GE-Hitachi Nuclear Energy LLC, October 2009.
[8] Rogers, R. M., "BWR Owners' Group Technical Report ECCS Pumps Suction Void Fraction Study," General Electric Hitachi Nuclear Energy, 0000-0101-3794-R0-NP, April 2009. [ML091250320]

2 to 3 seconds of the event. Afterwards, the inlet void fraction quickly drops below 1 percent. Because an inlet void fraction greater than 5 percent is not anticipated to last for more than 5 seconds, the new GIRP does not find conclusive evidence that the pumps will incur degradation or damage. This conclusion agrees with industry's experience that after short exposure to gas, a pump will continue to operate and return to its pre-transient flow after the voids clears. Therefore, the new GIRP finds that the probable ability of the low-pressure ECCS pumps to survive a short exposure time of gas without permanent damage further supports the conclusion that a sufficient safety margin exists for low-pressure ECCS pumps to perform their safety function.

Gas binding also may present a threat to pumps subject to air ingestion. A gas forms a pocket around the impeller eye, resulting in the impeller rotating in gas with no flow out the pump. Normally, a pump operates at rated flow, and any gas voids in the suction line would most likely be swept through the pump due to system's flow inertia. However, when pumps initially startup, they operate at reduced flow rates (e.g., minimum flow recirculation during startup). The flow velocities are not high enough to transport minor voiding into the pump suction.[9]

The only time the ECCS low-pressure pumps are exposed to a significant amount of gas is immediately when a large break LOCA occurs, during the first few seconds of the event when the containment gas is blown down into the torus in the vicinity of the pumps' suction inlet piping. At this time, the pumps are entering their startup phase and operating in minimum recirculation flow mode. Because of the short duration of time (generally less than a minute) that these pumps are expected to run on minimum flow recirculation and the low intake flow velocities, the accumulation of sufficient gas to cause binding is not expected. Therefore, the new GIRP finds that gas binding of low-pressure ECCS pumps is not a credible event pertaining to this assessment.

Physical Configuration

Because such a wide variety of plant-specific configurations exist, the actual physical design configuration of each plant's low-pressure ECCS was not thoroughly analyzed in the RES study. Therefore, the RES study conservatively assumed no effect. Modeling and analyzing the impact of these physical factors on gas transport and resulting void fractions at pump inlets would be extremely difficult, time consuming, and resource intensive; and it may vary depending on modeling approaches and assumptions. Given the significant variations in plant configurations and uncertainty in modeling, a low likelihood exists that the results for such analyses would be conclusive.

However, the new GIRP recognizes that the gas transport out of the downcomers to the pumps' suction piping inlets will be affected by both the distance between and the elevations of the downcomers and the pumps' suction piping inlets. In addition, the flow of gas would be obstructed by the physical configuration of ECCS pumps' suction piping, the torus geometry, and the large, complex suction strainers. Although these physical design features can vary significantly between plants, the new GIRP finds that each individual plant's physical design attributes would contribute to impeding the gas transport and entry into the low-pressure ECCS pumps' suction piping, thereby confirming the pumps can successfully survive the short period the containment gas is blown down into the torus after a LOCA.

[9] Fleischer, L., "Assessment of NRC Generic Issue # 193 Prepared for the Generic Issue #193 Committee of the BWR Owner's Group", GE-Hitachi Nuclear Energy LLC, October 2009.

Conclusion

Based on the detailed assessment performed and the information provided in the RES study, the new GIRP concluded that the influx of noncondensable gas into the torus immediately following a large break LOCA is very unlikely to adversely affect the ability of low-pressure ECCS pumps to perform their safety function. The new GIRP based its conclusion on having sufficient safety margin resulting from a combination of factors including the short-lived characteristics of the bubbles and their rapid dissipation; the reduction of gas flow to ECCS pump inlets due to obstruction by physical configuration of strainers, piping, and torus geometry; the small approach velocity of the fluid at the suction strainer due to ECCS pumps operation in a minimum flow recirculation mode; and the high survivability of ECCS pumps after short-term gas ingestion. The new GIRP could not identify any credible combination of physical and operational conditions that would jeopardize the safety function for core cooling due to air entrainment following the postulated accident, and applied engineering judgement to inform conclusions. Therefore, the new GIRP recommended closure of GI-193 with no further action.