## Control of Hydrogen during Normal Operations

The nuclear industry has previously recognized the potential effect on nuclear safety from the production of hydrogen and oxygen gas during normal power operations. A detonation of combustible gases in the reactor coolant system (RCS), if energetic enough, could result in rupture of piping or damage to a safety relief valve (SRV) upon rapid opening, resulting in a loss-of-coolant accident (LOCA). However, a LOCA is an analyzed condition in every licensed nuclear power plant's design-basis analyses. All licensees of nuclear power plants must show that they can safely mitigate a LOCA; therefore, a LOCA event does not constitute an unanalyzed safety hazard. Therefore, in the event a hydrogen detonation did occur and the RCS piping did rupture, the emergency plant response systems have sufficient makeup water to maintain RCS inventory to prevent core damage. Nonetheless, a detonation in the RCS is not a desirable event.

The radiolytic generation of hydrogen and oxygen is a known phenomenon in nuclear reactors. However, there is a difference in how the radiolytic generation of hydrogen and oxygen is disposed of in pressurized water reactors (PWRs) and in boiling water reactors (BWRs). In PWRs, reactants remain in the primary system water and rapidly recombine. As a result, PWR hydrogen control is easily accomplished. In fact, hydrogen is routinely injected into the RCS to control the concentration of oxygen. Both the concentration of hydrogen and oxygen are monitored daily and technical specifications limit the maximum concentrations. In BWRs, some reactants are carried out of the primary system within the steam into the main turbine and condenser. To dispose of these gases, BWRs have an extensive off-gas system, and accumulation of explosive hydrogen mixtures was considered in the design of these systems. The Nuclear Regulatory Commission (NRC) issued Bulletin No. 78-03[1] to direct BWR licensees to review their off-gas systems in light of operating experience to minimize potential accumulations and detonations of hydrogen.

The detonation in piping at Hamaoka Unit 1 BWR on November 7, 2001, and at the Brunsbuttel BWR illustrated that the accumulation of combustible gases can occur in the primary system for BWRs. On December 14, 2001, the Boiling Water Reactor Owners Group (BWROG) reported that General Electric (GE) formed a task force to study these events. Industry experts at General Electric Nuclear Energy (GE-NE) issued Rapid Information Communication Service Information Letter No. 85[2] to advise BWR owners of the Hamaoka-1 event. In addition, GE-NE issued Service Information Letter No. 643[3] to advise BWR owners of the event at Brunsbuttel. The group identified several piping configurations susceptible to the accumulation of combustible gases. These areas (1) are stagnant during normal plant operation, (2) are not continuously or periodically vented or purged, (3) are connected to the steam-filled areas of the nuclear steam supply system (NSSS), (4) are lines isolated from higher pressure systems by a potentially leaky valve, (5) can allow accumulation of noncondensable gases, and (6) have continuous steam condensation and drainage.

In response to this safety issue, the NRC also communicated extensively with the nuclear industry, issuing generic communications to all licensees. These communications included NRC Information Notice (IN) 2002-15[4] followed by Supplement 1[5].

In 2002, the BWROG formed the BWROG Hydrogen Accumulation Committee, This committee provided detailed guidance to the BWR utilities for the identification, disposition, and mitigation of the potential accumulation of radiolytic hydrogen and oxygen in plant piping and equipment. The committee's recommendations were documented in GE NE 0000-00007-4008-01.[6] The committee's documents strongly urging all BWR licensees to "perform detailed evaluations and implement mitigating actions as appropriate." Additional GE documents included recommendations to utilities to: (1) review piping systems to identify any potential vulnerabilities for the accumulation of radiolytic gases, (2) assess the detonation potential of vulnerable piping, (3) consider design or system operation modification(s), and (4) consider the potential for accumulation and detonation of radiolytic gases. The BWR licensees addressed the recommendations in the report on a plant-specific basis.

Nonetheless, issues with gas accumulation continued because a comprehensive, in-depth resolution of the issue was not achieved. This situation changed because the Institute of Nuclear Power Operations (INPO) issued significant operating event report (SOER) 2-05, Revision 1, "Gas Intrusion in Safety Systems" (January 9, 2008)[7], and the NRC issued GL 2008-01 "Managing Gas Accumulation in Emergency Core Cooling, Decay Heat Removal, and Containment Spray Systems" (January 11, 2008) (Agencywide Documents Access and Management System (ADAMS) Accession No. ML072910759)[8]. GL 2008-01 requested that each addressee evaluate its emergency core cooling system, decay heat removal system, and containment spray system licensing basis, design, testing, and corrective actions to ensure that gas accumulation is maintained less than the amount that challenges operability of these systems. The INPO SOER 2-05 Rev. 1 also recommended that licensees take appropriate action when conditions adverse to quality are identified. The combination of GL 2008-01 and INPO SOER 2-05 Rev. 1 resulted in an in-depth industry effort to address many of the issues. This effort has resulted in a significant and continuing improvement in addressing gas management issues. The nuclear industry has conducted an extensive assessment that resulted in Nuclear Energy Institute (NEI) 09-10, Revision 1a-A, "Guidelines for Effective Prevention and Management of System Gas Accumulation" (ADAMS Accession No. ML13136A129)[9] as an acceptable and recommended approach to managing gas accumulation in power reactor piping systems. NEI 09-10 was endorsed by the NRC in NRC Regulatory Issue Summary 2013-09[10].

<u>NRC Staff Evaluations of GI-195 and GI-198</u>

The NRC determined that the possible combustion of hydrogen inside RCS piping was a generic safety issue, and evaluated it as part of GI-195[11] for BWRs and GI-198[12] for PWRs. The results of those evaluations can be found in NUREG-0933, "Resolution of Generic Safety Issues, Main Report, with Supplements 1–34."[13] The following is a summary of the findings from the screening evaluations performed for BWRs and PWRs regarding whether the issue should proceed in the generic issue (GI) process.

For BWRs, the scenario of interest was a loss of coolant accident (LOCA), caused by a detonation inducing an un-isolatable pipe rupture or safety relief valve (SRV) to fail open. There have been three industry events where a combustible gas mixture accumulated inside piping connected to the primary system, which subsequently detonated and ruptured the piping containing the mixture. Fortunately, the associated piping was isolated from the primary system by a check valve. In three other events, a combustible mixture accumulated in the vicinity of a SRV. When the mixture ignited, the force caused the valve to fail open, resulting in a blow down of the primary system. The NRC staff evaluated both scenarios and developed a quantitative risk analysis showing the risk for core damage frequency (CDF) and large early release frequency (LERF) to be well below the designated threshold to proceed in the GI process. Therefore, the screening analysis of GI-195 concluded that there was insufficient safety significance to justify additional regulatory action on BWRs given the estimated low quantitative risk for a hydrogen combustion event in a BWR causing core damage or a large early release.

The staff also considered the many diverse systems a BWR has available to mitigate a pipe rupture in the primary system.

For PWRs, the scenario of interest was a breach in the reactor coolant piping pressure boundary caused by a detonation in the pressurizer steam space or associated piping. The quantitative analysis results for PWRs showed the risk for CDF and LERF was below the threshold values to proceed in the GI process. In PWRs, there have been reports of a hydrogen fire occurring during maintenance activities; however, no events were reported to occur in the primary system during power operations. In PWRs, the common industry practice is to operate with an excess of dissolved hydrogen in the primary coolant in order to scavenge any oxygen produced by radiolysis. The dissolved hydrogen level is maintained by a hydrogen cover gas in the volume control tank, which supplies makeup fluid to the primary system. Normally, the dissolved hydrogen concentration in the primary system is kept in the range of 25 to 35 cubic centimeter (cc) per kilogram of water, which corresponds to 2.2 to 3.1 parts per million (ppm). The level of dissolved oxygen is maintained below 0.1 ppm. At these concentrations of hydrogen and oxygen, gas bubbles are not expected to form in the liquid-filled portions of the primary system. If such gas bubbles were to form, they would be expected to dissolve into the liquid coolant over a period of time. Therefore, the NRC staff concluded that the collection and detonation of these gases in the liquid-filled portion of the primary system did not appear to be credible.

The only credible region for hydrogen and oxygen gases to accumulate in the primary system is in the vapor space of the pressurizer. In theory, if the vapor pressure were exactly equal to the saturation pressure of its water at that temperature, then the partial pressure of hydrogen and oxygen would be zero. Then any dissolved gases would be driven out of solution until some partial pressure of hydrogen and oxygen built up in the steam space. At a hydrogen concentration of 3.1 ppm, the partial pressure of hydrogen in the pressurizer steam space would correspond to approximately 2.27 pounds per square inch absolute (psia). For a nominal pressurizer steam volume of 720 cubic feet at 2250 psia and 653 degrees Fahrenheit (F), if all this hydrogen gas in the vapor space collected into one volume, then it would form a bubble approximately 14 inches in diameter. Similarly, if the oxygen concentration in the liquid coolant is 0.1 ppm, the partial pressure at equilibrium conditions would be 0.00647 psia. If all the oxygen were to gather together in one volume, then it would create a bubble approximately two inches in diameter.

Depending on the degree of stagnation in the pressurizer steam space, these gases may tend to collect at the top of the pressurizer steam space. But in reality, the pressurizer steam space is likely to have convection currents, especially if the plant operates with the pressurizer heaters in operation or operates with a small amount of flow in the pressurizer spray line. Therefore, mixing is likely to occur in the pressurizer steam space; hence, the hydrogen and oxygen gases are unlikely to form in well-defined, horizontal layers. The only feasible area for any significant amount of a combustible gas mixture to accumulate in the pressurizer is in the attached piping. The pressurizer has various instrument taps, such as the level instrumentation, sampling lines, and valve leak off lines. If hydrogen associated detonation did happen to occur in one of these associated small bore piping, the resulting force could cause a breach in the reactor coolant pressure boundary. However, the effects would be limited to only small break LOCA, which has been analyzed as part of the design basis of the plant, well within the makeup capacity of the safety systems.

The NRC staff used computer models to calculate the CDF and LERF for a breach in the reactor coolant pressure boundary caused by a detonation in the pressurizer steam space or associated piping. Three different break sizes were postulated. The results of these quantitative risk evaluations showed the probabilistic risks for CDF and LERF associated with this type event were well below the screening thresholds to continue in the GI process. Therefore, the staff concluded that there was insufficient justification for GI-198 to continue to the technical assessment stage, and the staff concluded that the issue should exit the GI process.

References:

Note: Publicly available NRC published documents are available electronically through the NRC Library on the NRC's public Web site at http://www.nrc.gov/reading-rm/doc-collections/ and through the NRC's ADAMS at http://www.nrc.gov/reading-rm/adams.html. The documents can also be viewed online or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD. For problems with ADAMS, contact the PDR staff at 301-415-4737 or (800) 397-4209; fax (301) 415-3548; or e-mail pdr.resource@nrc.gov.

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[1] NRC Bulletin 78-03, "Potential Explosive Gas Mixture Accumulations Associated with BWR Offgas System Operations," U.S. Nuclear Regulatory Commission, February 10, 1978, [ADAMS Accession No. ML112200762].

[2] Rapid Information Communication Service Information Letter (RICSIL) No. 85, "HPCI/RHR Steam Supply Line Rupture," November 20, 2001.

[3] Service Information Letter (SIL) No 643, "Potential for Radiolytic Gas Detonation," General Electric Nuclear Energy, June 14, 2002.

[4] NRC Information Notice 2002-15, "Hydrogen Combustion Events in Foreign BWR Piping," April 12, 2002, [ADAMS Accession No. ML020980466].

[5] NRC Information Notice 2002-15, Supplement 1, "Potential Hydrogen Combustion Events in BWR Piping," May 6, 2003, [ADAMS Accession No. ML031210054].

[6] BWR Owners' Group Actions in Response to Pipe Ruptures in Non-U.S. BWRs, BWROG Project Number 691, BWROG, December 20, 2002, [ADAMS Accession No. ML023610269].

[7] Nuclear Power Operations (INPO) Significant Operating Event Report (SOER) 2-05, Revision 1, "Gas Intrusion in Safety Systems" (January 9, 2008)

[8] NRC Generic Letter (GL) 2008-01 "Managing Gas Accumulation in Emergency Core Cooling, Decay Heat Removal, and Containment Spray Systems" (January 11, 2008) [ADAMS Accession No. ML072910759]

[9] Nuclear Energy Institute (NEI) 09-10, Revision 1a-A, "Guidelines for Effective Prevention and Management of System Gas Accumulation" (ADAMS Accession No. ML13136A129)

[10] NRC Regulatory Issue Summary 2013-09," Guidelines for Effective Prevention and Management of System Gas Accumulation" Washington, DC, August 23, 2013

[11] Resolution of Generic Safety Issues: Issue 195: Hydrogen Combustion in BWR Piping (NUREG-0933, Main Report with Supplements 1–34), http://nureg.nrc.gov/sr0933.

[12] Resolution of Generic Safety Issues: Issue 198: Hydrogen Combustion in PWR Piping (NUREG-0933, Main Report with Supplements 1–34), http://nureg.nrc.gov/sr0933.

[13] "Resolution of Generic Safety Issues" (Formerly entitled "A Prioritization of Generic Safety Issues") (NUREG-0933, Main Report with Supplements 1–34) http://nureg.nrc.gov/sr0933.

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Additional References:

1. Generic Letter 93-06: Research Results on Generic Safety Issue 106, "Piping and the Use of Highly Combustible Gases in Vital Areas," October 25, 1993.

2. Resolution of Generic Safety Issues: Issue 106: Piping and the Use of Highly Combustible Gases in Vital Areas (Rev. 2) (NUREG-0933, Main Report with Supplements 1–34), http://nureg.nrc.gov/sr0933.

3. Information Notice 89-44, "Hydrogen Storage on the Roof of the Control Room," U.S. Nuclear Regulatory Commission, April 27, 1989. http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/1989/in89044.html.

4. NUREG-0933: “Resolution of Generic Safety Issues: Item A-48, Hydrogen Control Measures and Effects of Hydrogen Burns on Safety Equipment (Rev. 1)”