Detailed Description of the Proposed Generic Issue

In a letter dated October 27, 2014[1], and an updated letter dated November 29, 2014[2], Dr. Robert A. Leishear submitted a proposed generic issue (GI) for evaluation in the Nuclear Regulatory Commission's (NRC) Generic Issues Program. He postulated that an auto-ignition of a hydrogen-oxygen mixture can occur in reactor coolant system (RCS) piping due to a sudden compression of the mixture during a fluid transient. He further postulated that the auto-ignition can cause a pressure increase that lifts a safety valve or ruptures the RCS, which can expel a flame that causes a hydrogen burn or explosion inside containment under severe accident conditions.

Dr. Leishear presented his theory[3] on how fluid transients (water hammer) can cause a sudden compression of trapped hydrogen gas in reactor coolant piping. Dr. Leishear stated that he believes these conditions need to be present for auto-ignition to occur:

- Hydrogen and oxygen need to be present in the piping. Dr. Leishear postulated that the hydrogen and oxygen are formed during radiolysis, which is the radioactive breakdown of water because of the high energy flux inside the reactor.

- A pressure transient similar to water hammer has to occur in the piping containing the hydrogen. Condensate-induced water hammer occurs when water and steam flow together in piping systems. Steam vapor bubbles, or steam voids, collapse to induce shock waves and pressure spikes that resonate through the piping system. Dr. Leishear postulated that slugs of liquid propelled by these pressure transients can squeeze a combustible gas until it gets hot enough to burn or explode.

He cited two examples of events in foreign countries during which hydrogen ignitions occurred during normal operations: one case was in the residual heat removal steam condensing line at the Hamaoka Unit-1 plant, and the second case was in the reactor vessel head spray line at the Brunsbuttel plant.

Dr. Leishear stated that his theory would change the NRC staff's previous evaluations relating to the generic concern of hydrogen explosions inside piping. His theory addresses the accident that occurred at Three Mile Island Nuclear Station, Unit 2 (TMI-2), where the melted zirconium holding the fuel initially reacted with the steam to form approximately 126,000 cubic feet of hydrogen inside the reactor vessel. Because no oxygen was present in the vessel, the hydrogen initially did not react. However, he postulated that a quantity of oxygen was later formed by radiolysis inside the reactor vessel. He further postulates that 10 hours after the fuel melted during the accident at TMI-2, a water hammer occurred inside the RCS, which compressed a volume of hydrogen and oxygen trapped inside the piping leading to the pressurizer safety valve, causing the mixture to auto-ignite. The subsequent pressure increase resulted in the safety valve lifting, expelling a flame and igniting the hydrogen mixture in the containment atmosphere. He stated that approximately 700 pounds of hydrogen had been previously discharged into the containment atmosphere through a safety valve, where the hydrogen mixed with the oxygen to form a combustible environment (i.e., greater than 4 percent oxygen and 8 percent hydrogen present). Supporting his theory, he stated that data from TMI-2 show that a hydrogen burn occurred one minute after the safety valve lifted, and that the temperature near the safety valve increased in temperature immediately prior to the hydrogen burn.[4]

Dr. Leishear stated that further research is required because this new ignition theory has yet to be fully evaluated. He stated that the potential for hydrogen explosions is greater than actually

occurred at TMI-2 because slower operator response could have resulted in the entire core being destroyed (vice only approximately half), which would have more than doubled the amount of hydrogen in containment, which may have been sufficient to cause an explosion rather than a fire.

Dr. Leishear stated that the NRC has closed previous GIs without the benefit of considering his theory, and proposed that the following documents should be considered for reevaluation, based upon the additional information he provided in the proposed GI:

1. NUREG-0933: "Resolution of Generic Safety Issues: Issue 195: Hydrogen Combustion in BWR Piping." The safety analyses for the TMI-2 accident did not include this additional information, where a slower reactor response after the accident could have caused an explosion rather than a fire in the reactor building. Specifically, the TMI-2 fire could have led to an explosion, if more hydrogen were released during the reactor meltdown, or if a water hammer and auto-ignition had occurred before the homogeneous mixing of air with hydrogen in the reactor containment building. Risks to the public should also be evaluated in light of this additional information.

2. NUREG-0933: "Resolution of Generic Safety Issues: Item A-48, Hydrogen Control Measures and Effects of Hydrogen Burns on Safety Equipment (Rev. 1)." The additional information was unavailable at the time that this report on hydrogen deflagration was issued, and this additional information could affect the findings of NUREG-0933, where the possibility of a hydrogen explosion should be further considered.

3. NRC Bulletin 2011-01: "Mitigating Strategies,"[5] issued May 11, 2011. According to Dr. Leishear, this new information could affect mitigating strategies, because the "Events at the Fukushima–Daiichi Nuclear Power Station after the March 11, 2011, earthquake and tsunami highlight the potential importance of…mitigating strategies in responding to beyond design basis events." Dr. Leishear notes that, according to the Tokyo Electric Power Co. (TEPCO), "Fukushima Nuclear Accident Analysis Report," issued in 2012, the cause of ignition for reactor explosions was unknown, and he states: "in my opinion the research presented herein is likely pertinent to those explosions. Additionally, an explosion of unknown origin and location was also noted by TEPCO, where this ignition mechanism may have caused a reactor explosion."

4. NUREG-0927: "Evaluation of Water Hammer Occurrences in Nuclear Power Plants,"[6] Water hammer events can affect hydrogen and oxygen accumulation in piping. In fact, past water hammer events could have very well been accompanied by hydrogen and oxygen explosions in reactor piping.

Dr. Leishear contended that other NRC documents are also affected and that, during a GI evaluation, the NRC should undertake a comprehensive review to determine all affected documents. He postulated that, when previous accident scenarios and damages were analyzed, risks were calculated using frequencies and consequences that may be affected by his additional information.

Dr. Leishear also stated that, in addition to research directed toward nuclear reactor meltdowns, research should investigate the causes of reactor explosions and possible actions to prevent

explosions in the event of a nuclear accident. He believed that more research can also determine an appropriate operator response to prevent explosions during off-normal conditions. The risk and safety significance may be evaluated once the potential explosions and preventive actions are evaluated through research.

Previous NRC Staff Response to Submitter

Dr. Leishear had previously approached the NRC staff with his theory on a detonation in primary piping attributed to hydrogen accumulation. The NRC staff in the Office of Nuclear Regulatory Research (RES) investigated his concerns and concluded that no additional actions were required, based upon the information submitted. The NRC staff responded to Dr. Leishear by email dated March 31, 2014. The NRC staff's response to Dr. Leishear is available in Agencywide Documents Access and Management System (ADAMS) under Accession Number ML16063A003.

Staff Observations of the Material Presented by Dr. Leishear

The submitter, Dr. Leishear, provided his theory on how a combustible mixture of hydrogen and oxygen gases can form and be pressurized to the point of ignition in the RCS. His theory is technical and based upon basic scientific principles.

The physical design of the RCS piping system (e.g. exhausts from all pressurizer safety valves and power operated relief valves) is that it is hard piped to the primary relief tank. This configuration would create a long torturous pathway, making it unlikely that an ignition source inside the RCS could migrate through the relief valves, down the exhaust piping, and up through a tank mostly filled with water. If a flame were to exit through the pressurizer relief valves, the flame would likely be extinguished by the sudden pressure drop when the valve opened, or extinguished when passing through the body of water in the relief tank.

Nonetheless, a scenario could possibly exist where there was a path created for a flame to reach the containment atmosphere from the RCS. One scenario includes a rupture of the RCS piping, providing a direct path to the containment. Another scenario is where a flame could propagate out of the RCS through a relief valve into the primary relief tank; if the tank was not filled with water or steam, then the flame could propagate into the containment. In addressing such scenarios, the NRC has previously taken regulatory action to address the control of hydrogen during severe accidents, such that ignition sources, regardless of their cause, would not result in unacceptable consequences. This is discussed further in Enclosure 3.

References:

[1] Leishear, Robert A., "Proposed Generic Issues Submittal on Trapped Hydrogen and Oxygen Fire and Explosion During Fluid Transients," [Agencywide Documents Access and Management System (ADAMS) Accession No. ML14304A653, "Proposed Generic Issue submittal on H2"].

[2] Leishear, Robert A, "Updated Proposed Issue submittal on H2," [ADAMS) Accession No. ML15245A508].

[3] American Society of Mechanical Engineers (ASME),"A Hydrogen Ignition Mechanism for Explosions in Nuclear Facility Piping Systems," published by the ASME Journal of Pressure Vessel Technology in 2013 (135(5), 054501).

[4] Leishear, Robert A., "Proposed Generic Issues Submittal on Trapped Hydrogen and Oxygen Fire and Explosion During Fluid Transients," [ADAMS Accession No. ML14304A653, "Proposed Generic Issue submittal on H2"].

[5] NRC, NRC Bulletin 2011-01: "Mitigating Strategies," May 11, 2011, [ADAMS Accession No. ML111250360].

[6] NRC, "Evaluation of Water Hammer Occurrence in Nuclear Power Plants," NUREG-0927, March 1984, [ADAMS Accession No. ML071030267].