APPENDIX H - METHODS TO ADDRESS CONTROL OF FLAMMABLE GASES

H.1 Bases & Methodology

Order Reference 1.2.11 – The HCVS shall be designed and operated to ensure the flammability limits of gases passing through the system are not reached; otherwise, the system shall be designed to withstand dynamic loading resulting from hydrogen deflagration and detonation.

Hydrogen will be produced as a result of core damage during a severe accident. Although not cited in the requirements section of Reference 2 (in particular Requirement 1.2.11 relative to consideration of “hydrogen deflagration or detonation”), carbon monoxide is cited as a combustible gas in the introduction paragraph to Attachment 2 to that reference. Carbon monoxide (CO) can be produced in sufficient quantities to deflagrate and potentially detonate (in a vent pipe) by the process of Molten Core Concrete Interaction (MCCI). This would occur in the most severe of accidents once the reactor vessel is breached and corium has reached (and interacted sufficiently with) the pedestal or lower liner protecting concrete. It should be noted that the potential to produce sufficient quantities of CO is dependent on the aggregate used in the drywell concrete. The chemical makeup of limestone (which contains large amounts of calcium carbonate - $CaCO_3$), will produce CO with a corium interaction. Although the amount of CO produced is relatively small as compared to hydrogen produced by gross metal-water reaction, the potential for a deflagration/detonation cannot be ruled out with limestone aggregate. Basalt based aggregate (which has no appreciable carbon constituents) will produce only minor amounts of CO due to MCCI. Therefore CO production for those plants that utilize that type of aggregate should be considered inconsequential (although a final evaluation should be made by the affected plant).

Detonation of either Hydrogen or CO is not expected to occur in containment, given existing plant controls to ensure the containment remains free of Oxygen. Detonation in the HCVS may occur if venting occurs and Oxygen is allowed to enter the HCVS discharge piping. Air/Oxygen would most likely enter the HCVS piping following a vent cycle, either through steam collapse or by rising Hydrogen leaving the HCVS piping (replaced by inflow of air).

Preventing the detonation in HCVS is possible, either through design of the HCVS to ensure Oxygen is not allowed to enter the piping, or by inerting the HCVS piping after venting. If a detonation is not prevented, the piping should be designed to withstand the detonation without failing.

The size of the vent must meet the criteria cited in Section 4.1.1 of this guidance for the primary design objective of the HCVS is to prevent overpressure failure of the containment prior to core damage and subsequent to core damage. In addition, the consideration of the dose impact on such a method of operation is required.

The following sections provide high level methodology and discussion on possible approaches to either prevent or withstand a detonation during or following venting through the HCVS. The approaches discussed below are not considered to be the only possible approaches to protecting the HCVS. Alternative approaches are considered acceptable, given that either detonation in the HCVS is prevented or the system is designed to withstand the possible detonation of Hydrogen or CO.

H.2 Design Systems to Prevent Detonation/Deflagration

Design of the HVCS may include features that prevent air/oxygen backflow into the discharge piping. Use of design features in sections of pipe susceptible to air intrusion from intermittent HCVS operation can also be used to minimize detonation/deflagration potential.

There are several possible approaches to be able to prevent air from entering the discharge piping. One approach is to use an isolation valve or other device (e.g., similar to a loop-seal device) at the discharge point of the vent. If an isolation system is used to prevent air back-flow, the system should account for the possible vacuum created by the cooling of steam in the susceptible piping sections once the HCVS isolation valves are closed. A water-based filter may also prevent air from entering the upstream piping entering the filter. The design should consider that the vacuum generated in the piping could result in sufficient air leakage that can result in a mixture that can detonate.

Another possible approach to prevent detonation is to size the vent such that continuous venting occurs, once the vent is opened. This can also be accomplished through use of a flow-control valve restricting vent flow. This approach would be used if the containment would be expected to remain pressurized for an extended period (e.g., beyond 7 days) given a severe accident has occurred and no containment cooling is provided. The use of a continuous vent operation should include several high level features:

1) Procedural guidance should ensure the HCVS operation begins prior to the production of Hydrogen or CO. This will prevent any detonation when the initial venting occurs.
2) Spurious Closure of the HCVS isolation valves should be prevented through the use of designing valves using this guidance. Protection from automatic closure signals should be provided.
3) The design should include methods for purging the HCVS piping following completion of the containment venting. Use of portable bottles or similar is considered sufficient for this process. See discussion below for attributes important to the use of a purge system.
4) As with any containment atmosphere control/venting strategy, controls must be in place (administrative or otherwise) to prevent negative pressure inside containment drawing air/oxygen back into that volume.

H.3 Vent Path Inerting

Use of a purge system in sections of pipe susceptible to air intrusion from intermittent HCVS operation can also be used to minimize detonation/deflagration potential. Given the pressure and significant flow through the HCVS when the vent is initially opened, it is not expected that a detonation would occur in the HCVS line when the vent process begins. Detonation is a concern; however, once the vent line is closed, as air enters the piping following steam condensation or Hydrogen gas leaving the discharge. Therefore, purging of the line may be considered as a mitigation strategy immediately following the closure of the HVCS isolation valves.

Additionally, purge system operation should account for any piping elevation changes, where oxygen, Hydrogen or CO might accumulate at a high point in non-inerted piping in the HCVS.

Alternatively; the design may utilize an inert gas system which provides positive pressure in the vent pipe above atmospheric. Use of a continuously operating system should consider the elevation of the HCVS discharge to ensure positive flow through the system when containment vent is not occurring.

H.4 Design HCVS Piping for Detonation

Methods of designing the HCVS piping/components against flammable gas detonation/deflagration are discussed below. Susceptible portions of the piping should be determined based on where oxygen can be drawn into the piping/interfacing piping.

The evaluation of gas ignition is to document the capability of the HCVS piping to maintain integrity should deflagration or detonation occurs. Deformation of the pipe is acceptable given the integrity of the pipe is shown to be maintained.

The design of the HCVS is required to withstand the dynamic loading resulting from hydrogen deflagration/detonation. For design purposes, the HCVS is not required to consider assumed simultaneous loads that would not be present or occur during the venting of hydrogen (e.g. seismic loads).

The following provides a list of steps to be considered to ensure the HCVS is properly designed to tolerate a possible hydrogen deflagration/detonation:

1. Review the history/commitments of associated site equipment
   a. Research existing/similar piping system(s) for:
      i. ASME Code commitments.
      ii. Seismic Classification.
      iii. Current Service Level of like/similar equipment.
2. Establish classifications of new piping or piping to be modified (See Section H.2)
   a. New loading combinations for pipe in standby (with Containment Isolation Valves -CIV(s) closed
      i. Consider hydrogen detonation pressure loading (7878 kPa/1143 psia - See H.2 below).
      ii. If it is determined that a potential carbon monoxide detonation could occur, consider a detonation pressure loading of 9393 kPa (1362 psia) instead of the value for hydrogen cited in 2.a.i (See Note 1).
      iii. Determine the dynamic loadings both coincident with and caused by the detonation event. Note that, if a filter is used in the vent system, its ability to accommodate a potential hydrogen detonation should be a consideration.

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[1] Note: Although Reference 2 cites carbon monoxide as an example of a "severe accident condition" combustible gas in the introduction paragraph of Attachment 2, that compound is not cited again in Requirement 1.2.11 as having the potential to deflagrate or detonate. See further information on carbon monoxide in Section A.4.2.2.1.1.

  b. New loading combinations for pipe in operation
      i. Determine max pipe metal temperature.
      ii. Determine max pressure based on “Order” sections 1.2.1 and 1.2.8.
      iii. Determine applicability of seismic loading.
      iv. Determine the probability of occurrence and the ASME classification as suggested in the next section.

3. Establish configuration for new/modified pipe
    a. Configure piping to meet applicable requirements of the “Order.”
4. Determine maximum stresses on vent piping
    a. Considerations
        i. Set load combination using detonation load as dominant for each stress category. For example:
            1. General membrane (pipe pressure retaining material shell).
            2. Local membrane.
            3. Bending.
        ii. Consider worst case thrust load due to detonation, for example:
            1. Maximum pressure.
            2. Maximum temperature.
            3. Acoustic wave load for each pipe segment.
            4. Dynamic responses and bending moments.
        iii. Design the pipe supports
            1. Evaluate the existing pipe supports (if applicable) and allowable loads.
            2. Perform stress analysis of the pipe to determine the support system so that all the stresses meet allowable limits.
            3. Perform support design and also determine whether the existing supports meet the design requirements.
        iv. There are many pipe stress analysis codes available in the market and each utility may have their own standard. Individual sites are expected to use pipe stress analysis codes that comply with that station’s design process.

H.4.1 Suggested Classification Approach based on Contemporary Guidance

Code Class - Document 10CFR50.55a recommends RG 1.26 (Reference 9) as offering guidance for Quality Groups which provide an indication for ASME Code classifications. Per the cited regulatory guide (see Section 2. (d)), the piping associated with the HCVS downstream from the second containment isolation valve should be considered as Quality Group C based on the risk of ground level release due to vent integrity failure. This is considered analogous to ASME Code Class III. As such, ASME Section III, Subsection ND is used to provide guidance for the allowable stresses for this material. ND-3600 is used for piping design.

Service Level – NUREG-0661 (Reference 11) provides guidance for consideration of service “limits” in Section 4.3. Note that “limit” and “level” are considered to be interchangeable. Both Service Level C and Service Level D are cited under sub-sections 4.3.1.3 and 4.3.1.4 (respectively). Both of these service levels are considered to be associated with low-probability events. However, combining this reference with Reference 10, Service Level C is the only level which is cited as applicable to hydrogen detonations (see further information below relative to RG-1.57). As such, Service Level C is considered appropriate for this loading.

Load Combinations - In the “Background” Section of RG 1.57 (Reference 10), 10 CFR 50.44(b)(5)(v)(B) is cited as the basis for a statement saying that, “systems and components necessary to…maintain containment integrity will be capable of performing their functions during and after exposure to the environmental conditions created by the burning of hydrogen, including local detonations, unless such detonations can be shown to be unlikely to occur.” This statement specifically refers to Mark III containments as Mark I and Mark II containments require an inert atmosphere. However, in the venting case considered, the isolated vent systems in these models can no longer rely on the inerted containment effluent to prevent hydrogen detonations; therefore, these loads typically reserved for Mark III containments should be considered for this isolated extension of containment in this particular scenario. Such a scenario (conducive to a local detonation) can only be typified as a severe accident.

With respect to the SSE it is understood that (based on the example of Fukushima Dai-ichi) a SSE may well be the precursor to an accident which could evolve into a severe accident (including core damage and hydrogen generation). And aftershocks will likely occur after the initial earthquake. However these aftershocks (along with the earthquake itself) are typically not long duration events. They are more typically lower in magnitude, short and sporadic. Note also that, under the Service Level C load combinations in the referenced regulatory guide (Section 1.2.3.3), all load combinations consider the SSE except for those combinations which deal with pressure from hydrogen generation or hydrogen burning. Considering the minimal opportunity for a hydrogen detonation to occur in a vent pipe, that pipe would not be expected to experience these 2 unlikely loading conditions simultaneously.

H.4.2. Methodology

The loading being considered (hydrogen detonation) is considered as a Service Level C (Emergency) condition. As such the allowable stress allowance provided in ND-3654.1 may be utilized. Section 4.3 of NUREG-0661, Service Level C is characterized as applicable to design basis type events. As the precursor to such a detonation (release of hydrogen during a severe accident) would be characterized as a well beyond design basis accident that deteriorates into a severe accident with core damage followed by vessel breach , and the aforementioned required conditions for an actual detonation to occur are so remote, Service Level D allowable stresses may be considered
appropriate for this scenario. However, it is understood that the intent of the Level D limit is to withstand a single occurrence. It is expected that the vent be capable of withstanding multiple hydrogen detonations; therefore, Service Level D alone would not provide the margin required to ensure system functionality.

The purpose of this evaluation is not to consider the vent system function, only that the occurrence of hydrogen detonations (as stated in this document) will not cause a failure of the pipe’s pressure retaining capability. System function will be addressed in the final design detailed analysis for the system.

H.4.2.1 Bases for Loading due to Detonation

In order to address the Reference 2, Requirement 1.2.11 statement that the system shall be designed to withstand dynamic loading resulting from hydrogen deflagration and detonation, a simplified evaluation can be performed using standard methods.

H.4.2.2 Detonation Pressure Considered for Carbon Monoxide

Once CO is a part of the vented gas, deflagration/detonation (of CO) will occur much the same as it would for hydrogen as outlined above.

H.5 Discussion

Based on the conclusions/positions stated above, the potential scenario of concern would be one in which steam collapses in an HCVS after fuel damage (and after the venting off of the majority of the original nitrogen loading) and draws outside air back into the vent system. This is the only scenario with reasonable potential to cause the formation of a deflagrable mixture. As such, it is the scenario to be considered in an evaluation of a potential hydrogen deflagration and the worst case damage which could occur.

As is understood from the initial conditions discussed above, the likelihood of a hydrogen detonation in a vent line from an inerted containment is extremely remote. However it is understood that it may be required to consider it in the design of such a system. In light of this probable requirement there is reasonable capability that a hardened containment vent system can be designed to accommodate a hydrogen detonation.

With typical calculated pressure loadings using methods above, many standard grades and thicknesses of the commonly used SA-106 pipe could accommodate the stresses from such a loading condition. Stress calculations utilizing contemporary ASME Section III formulae show that such a loading can be accommodated by standard SA-106 Gr A 12” pipe. However, due to the dynamic loading induced on a typical piping system (with bends and elbows) by such a pressure spike, the actual stresses experienced for any given vent system will be dependent on the piping system configuration and support structures.

Gneral Conclusion

(Staff will also have a review done by code, piping and stress analysts)

H.6 References

H.6.1. J. E. Shepherd, “Structural Response of Piping to Internal Gas Detonation.” ASME Pressure Vessels and Piping Conference, 2006. VP2006-ICPVT11-93670, presented July 23-27, 2006 Vancouver BC, Canada.

H.6.2. USNRC EA-13-109, “Issuance of Order to Modify Licenses with Regard to reliable Hardened Containment Vents Capable of Operation Under Severe Accident Conditions, “ dated June 6, 2013. ML13143A321.

H.6.3. C-J Detonation Studies in Hydrogen-Chlorine, Carbon Disulfide-Oxygen and Carbon Monoxide-Hydrogen-Oxygen-Nitrogen Mixtures, Christiane M. Guirao,

et al, McGill University, July 1972.

H.6.4. "Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants," International Atomic Energy Agency, Vienna, 2011.
H.6.5. NUREG-1367, "Functional Capability of Piping Systems."
H.6.6. J. E. Shepherd, A. Teodorcyzk, R. Knystautas, J. H. Lee, "Shock Waves Produced by Reflected Detonations." Progress in Astronautics and Aeronautics 134, 244-264.
H.6.7. "Combustion of BWR-Typical Radiolytic Gas Mixtures," Final Report for the International Radiolytic Gas Combustion Project, VGB-Contract SA "AT" 13/04, December, 2007.
H.6.8. ASME Boiler and Pressure Vessel Code, Section III.
H.6.9. Regulatory Guide 1.26, "Quality Group Classifications and Standards for Water-, Steam-, and Radioactive-Waste-Containing Components of Nuclear Power Plants," revision 4.
H.6.10. Regulatory Guide 1.57, "Design Limits and Loading Combinations for metal Primary Reactor Containment System Components," Revision 2.
H.6.11. NUREG-0661, "Safety Evaluation Report, Mark I Containment, Long-Term Program," March 1980.
H.6.12. Comparison of critical conditions for DDT in regular and irregular cellular detonation systems; M.S. Kuznetsov et al, May 2000.
H.6.13. NRC Inspection Manual, Temporary Instruction 2515/121, (as associated with) Verification of Mark I Hardened Vent Modifications (GL 89-16), 5/24/94.
H.6.14. JLD-ISG-2012-02, Compliance with Order EA-12-050, Reliable Hardened Containment Vents, Interim Staff Guidance, Revision 0, August 29, 2012.