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U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Subject: Transmittal of White Paper NEI HCVS-WP-03 – *Hydrogen/Carbon Monoxide Control Measures,* Revision 1, October 2014

Project Number: 689

Dear Dr. Auluck:

The Nuclear Energy Institute (NEI),[1] on behalf of the nuclear industry, is pleased to submit to the U.S. Nuclear Regulatory Commission (NRC) NEI HCVS-WP-03 – *Hydrogen/Carbon Monoxide Control Measures*, Revision 1, October 2014. The information contained in this white paper will be used, in part, by NRC licensees to implement the requirements of NRC Order EA-13-109, *Order Modifying Licenses with Regard to Reliable Hardened Containment Vents Capable of Operation Under Severe Accident Conditions*, June 6, 2013. We request that the NRC review and endorse NEI HCVS-WP-03, Revision 1.

Revision 0 and earlier drafts of this white paper were presented and discussed at several NRC public meetings. We believe that Revision 1 responds to NRC staff comments. If the NRC staff wishes to hold additional meetings to further discuss this or other topics related to licensee implementation of EA-13-109, please let us know.

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[1] The Nuclear Energy Institute (NEI) is the organization responsible for establishing unified industry policy on matters affecting the nuclear energy industry, including the regulatory aspects of generic operational and technical issues. NEI's members include all entities licensed to operate commercial nuclear power plants in the United States, nuclear plant designers, major architect/engineering firms, fuel cycle facilities, nuclear materials licensees, and other organizations and entities involved in the nuclear energy industry.

If you have any questions or require additional information, please do not hesitate to contact me.

Sincerely,

Steven P. Kraft

Attachment

1.0 Purpose

The purpose of this paper is to present a series of options, which meet requirements 1.2.10 and 1.2.11 of Vent Order EA-13-109 (Reference 1).

> **Order Element 1.2.10 –** The HCVS shall be designed to withstand and remain functional during severe accident conditions, including containment pressure, temperature, and radiation while venting steam, hydrogen, and other non-condensable gases and aerosols. The design is not required to exceed the current capability of the limiting containment components.
>
> **Order Element 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.

Only the options that address the first part of Order element 1.2.11 "The HCVS shall be designed and operated to ensure the flammability limits of gases passing through the system are not reached" are provided in sufficient detail in this white paper to obtain NRC endorsement.

Options presented for compliance with the remainder of element 1.2.11, "the system shall be designed to withstand dynamic loading resulting from hydrogen deflagration and detonation" are presented in this paper to define the concept of the option. However, any licensee utilizing these options will require a submission to the NRC documenting the actual application of the option and how the system is designed and operated to withstand the loads expected.

2.0 Introduction

In consideration of the events at the Three Mile Island Nuclear Power Plant in March of 1979 and the Fukushima Dai-ichi Nuclear Power Plant in March of 2011, it is understood that hydrogen buildup in a nuclear plant containment is a significant concern once fuel damage has occurred. In response to the events at Fukushima Dai-ichi, the United States Nuclear Regulatory Commission (USNRC) has issued an Order (EA-13-109 – Reference 1) requiring all Mark I and Mark II Boiling Water Reactor (BWR) nuclear plants incorporate a Hardened Containment Vent System (HCVS), which will facilitate containment venting should a beyond design basis accident occur. Most affected plants have installed hardened vent systems per Generic Letter 89-016, but the capabilities of those vents to function adequately during severe accident conditions vary. The Order (this term may be used interchangeably with EA-13-109 in this document to refer to Reference 1) states that the HCVS shall be made "severe accident capable." Part of the severe accident capable requirement is the understanding that the system be able to either have the ability to mitigate hydrogen in the effluent or accommodate reasonably expected hydrogen deflagration and detonation. This is due to the need to potentially vent multiple times (in a severe accident scenario) to prevent containment overpressurization after the majority of the inerting nitrogen in containment has been vented off. Such vent cycling may allow air to be pulled back into the vent line between vent cycles due to cool down of the vent lines and condensing of steam. With hydrogen available in the line due to fuel damage, there is the potential that a deflagrable mixture could be realized.

Applicability

This paper applies to all BWRs with Mark I and II containment systems.

This paper is written to address strategies and options to prevent vent failure due to deflagration/detonation of combustible gases for Phase 1 (Order Section A) of the Vent Order (Reference 1). That section of the order address vent systems which emanate from a Mark I or Mark II containment's wetwell. This is the recommended vent path from such a containment due to the effluent first being scrubbed through the wetwell water phase prior to release through the vent. However, many of the strategies and options described in this white paper could be applied to venting from the containment drywell (Order Section B).

3.0 Actions for Compliance

Strategies and options that "ensure the flammability limits of gases passing through the system are not reached" shall document the following items in a six month update:

1. Declare option or options selected (valid for use of Options 3, 4 and/or 5)
2. List any deviations relative to the selected option(s) along with justification
3. Synopsis of venting operation and design
4. Sketch of vent path from associated PCIVs to release point, with delineation of which option applies to each portion of the vent system

Strategies and options (as presented in Section 6.0) that are "designed to withstand dynamic loading resulting from hydrogen deflagration and detonation" shall document the following items in a letter to the NRC requesting approval:

1. Synopsis of venting operation and design utilizing Option 1 and/or 2
2. Sketch of vent path, with delineation of which option applies to each portion of the vent system
3. Tabulation of the design parameters used for design each portion of the vent system
4. Justification for selection of design parameters

If the design and operation does not meet the criteria as specified in either portion of order element 1.2.11 then the licensee must request special handling by the NRC in regard to the requirements of the order.

4.0 General Discussion

A series of very specific assumptions must be accepted, and evolutions must occur in a somewhat specific order for a pressure spike high enough to potentially damage the vent pipe to be possible (refer to Appendix A for more discussion). It should also be realized that the occurrence of such a set of conditions is extremely unlikely due to several reasons including the understanding that the process of venting will purge the vent system of available oxygen prior to a combustible mix of sufficient length to support Deflagration to Detonation Transition (DDT) occurring. After a venting evolution, the vent pipe would contain the same inert mixture of steam and hydrogen along with potential carbon monoxide (the predominant constituents of the effluent) as existed in containment. The term 'venting evolution' is intended to describe a complete opening (to facilitate venting) and closing (securing from venting) cycle such that the end result is a vent pipe (downstream from the control valve) containing this steam/hydrogen mixture. This mixture will be removed from the vent pipe as a result of mixing in the pipe due to the Rayleigh-Taylor instability mechanism in which higher density fluid overlaying a less dense fluid mixes with and replaces the less dense fluid due to the action of buoyant forces. For an open pipe containing an air-hydrogen mixture (potentially with carbon monoxide), this will result in dilution of the hydrogen until the mixture is below the lower limit of flammability. Steam condensing in the pipe (primarily as a result of heat transfer through the pipe wall) will tend to concentrate hydrogen in the lower part of a vertical pipe and draw air into the upper part of an open pipe. This configuration of a lower layer filled primarily with hydrogen and an upper layer filled with air will then be subject to the same Rayleigh-Taylor instability mechanism as previously described. While the same mechanism that results in generation of a combustible mixture in an inactive vent pipe will later lead to a mixture that is incapable of supporting combustion, there will be an interval of time during which ignition and DDT, although highly unlikely, is possible if significant quantities of oxygen enter the pipe and sufficient mixing occurs.

4.1 Generation of Hydrogen

Hydrogen may be generated during an accident at a nuclear power plant by one of two fundamental methods: radiolysis and metal-water reaction (MWR). Radiolysis generates both hydrogen and oxygen both during power operation and after shutdown by a process involving energy absorption by the water molecule. This process causes the disassociation of the water molecule into its fundamental elements. Both elements are released stoichiometrically and exist in their diatomic molecule gaseous form: H_2 and O_2. The process of radiolysis, however, wanes after shutdown in near direct proportion to the waning of decay heat in the reactor core. As such, this is not considered as a strong contributor to a dangerous combustible mix. The significant contributor to the mix is the MWR. MWR is the oxidation of zirconium in the fuel cladding. Once the fuel cladding reaches a temperature of approximately 1500ºF, zirconium begins to scavenge available oxygen from adjacent water molecules to form zirconium oxide (ZrO_2) and in the process liberating two diatomic molecules of hydrogen for each molecule of the oxide created. The process is exothermic and self-supporting once started so long as water/steam is available.

From Reference 13, it is understood and accepted that a large amount of hydrogen can be generated from a nuclear accident involving extensive core damage. A value of 1700 pounds of hydrogen is cited for in-vessel core damage and as stated, "substantially more hydrogen to be produced as a result of ex-vessel metal-water reactions." Carbon monoxide may be produced in addition to the hydrogen (see Section 4.2 for further discussion on carbon monoxide). Considering a median-sized BWR containment (~250,000 ft^3) at near design pressure (~74psia), this amount of hydrogen (1700 lbs, or 850 lb-moles) would fill approximately 1/3 of the containment volume. This would be a significant constituent of the vented gas.

From the base case presented in Reference 14 (Station Blackout [SBO] w/ RCIC lost at 4 hours), gross hydrogen generation may begin as early as 6.1 hours. From this point on, a hydrogen constituent in vented effluent can easily be in the range of 25% by volume and more. This is further exacerbated (again using the EPRI-supplied base case) by reactor vessel breach at 12 hours due to the accompanying continuation of hydrogen being produced by the MWR outside the vessel in addition to the potential for carbon monoxide.

4.2 Detonable Mixtures with Carbon Monoxide

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, under some accident scenarios, MCCI may produce carbon monoxide in excess of the hydrogen potentially produced by the metal-water reaction.

Appreciable research and testing with respect to the DDT associated with CO is not readily available. There has apparently been little call for research into this phenomenon as associated with CO. There is, however, data associated with detonation pressures for various mixes of combustible gases including CO. A key reference in producing the values found in Table 1 of Reference 4 is NASA's CEARUN computer program. The user's manual for that program is listed as Reference 15 of that document (Reference 4). That manual is also listed as Reference 8 to this document. The Chapman-Jouguet pressures (highly indicative of final equivalent static detonation pressures) produced by combustible gas mix designs of both hydrogen and air mixtures and carbon monoxide and air mixtures are quite similar to the point that there is little value found in distinguishing between the two. This is based on numerous iterations of Chapman-Jouguet pressure calculations (of reasonable mixtures and conditions for each key fuel) performed using the CEARUN program. Although it is understood from those iterations that a detonation of CO with no hydrogen will produce a slightly higher Chapman-Jouguet pressure than that of hydrogen, the addition of a slight amount of hydrogen (3% or more) to a CO/air mix will bring the Chapman-Jouguet pressure down to that of a mixture of H_2/air. It is also understood that it is quite difficult to achieve carbon monoxide combustion without a small amount of hydrogen in the mixture. Based on the severe accident scenario being considered, that amount of hydrogen is assured in the vented effluent such that use of the peak pressure associated with detonation of a pure hydrogen mixture is justified.

A fundamental conclusion that may be drawn from the information which has been discussed in Appendix A, as related to combustible gas concentration and composition of mixtures involving hydrogen and carbon monoxide, is that neither the concentrations nor the composition matter once it is reasonably assured that hydrogen (and carbon monoxide) concentration may be beyond 11%. When a DDT is considered feasible, use of the peak Chapman-Jouguet pressure for evaluation of piping system response (as discussed in section 5.2.1) will provide conservative results and eliminates uncertainties associated with evaluating the actual combustible gas composition that may be associated with a particular event.

It should further be noted that the run-up distance for facilitating a carbon monoxide (coupled with hydrogen) DDT is considered bounded by the hydrogen run-up distance. See Appendix B for further information.

5.0 Operating Experience

5.1 Operating Experience Research

Much research has been performed with respect to Operational Experience (OE) in the area of hydrogen detonations and burns in both nuclear power plants and in the power industry at large.

The operational experience cited does not present a compelling case to accept detonations as a realistic and achievable occurrence. Explanations and discussions related to the OE are as follows:

1. The Hamaoka and Brunsbuttel events of 2001 – These are probably the best known (and perhaps the only) examples of actual hydrogen detonations in piping at a nuclear power plant. Both of these events were based on a stoichiometric hydrogen and oxygen mix being captured in stagnant process piping sections in a nuclear power plant. Both involved radiolytic hydrogen and oxygen released from nuclear steam (again into stagnant piping legs) over a long period of time. As such, there was no air (w/ a 78% nitrogen constituent) involved. Such an occurrence (condensation of main steam from a reactor vessel) leaves an almost ideal stoichiometric mix of hydrogen and oxygen. That is to say, the mix would be characterized by two moles of hydrogen to every one mole of oxygen released. This is a near perfect condition for a detonation. The mix contained in the affected pipes would be on the order of 67% hydrogen to 33% oxygen by volume.

   There has been much research into the probable ignition source(s) for these detonations. Research shortly after the event (See Reference 20) cited the potential for the gases in this event to have been ignited by a large temperature rise in the combustible gas at the gas to steam boundary layer in the presence of catalyst particles. In any case such a source must be of markedly high energy to initiate such a prompt reaction. It should also be considered that both of the affected systems at these plants were confined and at pressures well above that of an idle HCVS.

   Neither of these events can be considered analogous to the issue to be addressed by the cited requirements of EA-13-109. An HCVS cannot achieve the near perfect stoichiometric mix of these two gases at these high concentrations that were made available in the two events cited; the HCVS would include nitrogen (from ingested air) which dilutes the mixture. There is also minimal chance of an ignition source in an HCVS especially considering the filtering and quenching afforded by blowdown through the wetwell.

2. Evolutions associated with Main Electric Generator gassing and associated hydrogen venting - –

   Pre-maintenance process of venting and purging hydrogen from a generator as well as the routine venting of hydrogen for purity maintenance are the likely processes which could set up conditions for a DDT to occur. Similar to reopening the HCVS vent after previous venting of hydrogen, pressing air out of the vent pipe with the vented hydrogen has not resulted in detonations. The situation at the gas (hydrogen/air) interface, although there would be some forced mixing at the interface, the mixed layer would be very shallow so there would be no opportunity for a DDT while there is bulk flow. The period after venting occurs offers the same opportunity for a hydrogen/air exchange during the time that the hydrogen clears the vent pipe and is replaced with air as an HCVS vent would during repeated venting evolutions. After the generator vent is closed, some mixing will occur with the buoyant diatomic hydrogen molecules rising and mingling with the heavier oxygen molecules entering the vent pipe and settling down through the vent pipe volume.

The mixing evolution during generator venting is quite similar to the air/hydrogen interfacing discussed in the 'Mixing Discussion' section following the Assumptions Table presented in appendix A. However, there are no reported instances of detonation occurring. Based on the OE reviewed coupled with an interview with GE personnel familiar with generators and the gassing and venting processes, detonations simply do not occur during or after hydrogen venting. It is also understood that a typical design specification for these systems does not call for any special grade of piping or support system for the associated piping. It is treated in a similar manner to other Balance of Plant piping systems. And these systems have piping up to 6" in diameter. There are instances of hydrogen burns as evidenced by visual flames and scorched paint on the vent pipe. As per an informal review of an associated design specification, such flames are expected at some point in time in these systems. But there has been no evidence of detonations actually occurring during such evolutions. This holds true for OE relative to PWR operation as their Waste Gas Decay Tank venting which uses a similar venting strategy and also involves hydrogen. And although the same forces as discussed in Appendix A would act to mix the gases in this case, the likely reason that a DDT has not been recorded in such a situation is the inability to achieve a well-mixed and continuous run-up distance length of fuel and oxidizer to support it (also see Assumptions 5, 6, and 7 in Appendix A).

3. Evolutions associated with Offgas System Operation – An offgas system at a nuclear power plant serves two purposes; to vent off and filter (hold up to facilitate decay) gases pulled from the top of the Main Condenser and to recombine hydrogen and oxygen in that gas mix which was generated by radiolysis. This is a continuous process during the time that the plant is being operated. These gases are carried in the main steam and are released as the steam condenses (much the same as the H_2/O_2 release from leaked steam in the

Brunsbuttel and Hamaoka events). The gases which are created in the vessel aside from the hydrogen and oxygen are trace Krypton and Xenon with a small amount of iodine. The vast majority of the collected gases are hydrogen and oxygen (unless there are substantial leaks in the associated condenser systems). As such, there is an ample stoichiometric mix of hydrogen and oxygen available in the system during power operation.

The Offgas System's recombiner recombines hydrogen and oxygen into water vapor through a catalytic process typically using a highly efficient platinum/rhodium catalyst. This catalyst metal is either coated onto a metal ribbon mesh or onto ceramic pellets; either of which are contained in the recombiner vessel. In either case, the hydrogen and oxygen pass through the recombiner (with ample steam to both steam inert and cool the process flow) and are recombined on the catalyst. This is an exothermic reaction as evidenced by the relatively high operating temperature of these recombiners during power operation.

Although some OE on Offgas burns are associated with simply overheating and igniting the downstream charcoal beds (with heaters), the OE associated with H_2/O_2 recombination are typically due to either leakage of hydrogen and oxygen laden steam into an idle train (in which the steam inerting is reduced due to condensation) or an inadvertent valve lineup which introduces steam into a cool offgas train without the normal steam dilution flow in service (which allows condensation and again loss of steam inerting). In either case the catalyst in the idle train provides a means of introducing a point of elevated temperature due to the catalyzation process so as to quickly raise the temperature of the near perfect stoichiometric mix of hydrogen and oxygen to allow a deflagration. Although at least one of these instances has been characterized as a 'detonation' in OE, it is much more likely that it was simply a fast deflagration front which forced the migration of either catalyst or charcoal (based on the minimal damage incurred).

Such occurrences are somewhat unique to the Offgas System. Again by nature of such a system two conditions required for a deflagration are present and quite enhanced; ample highly efficient catalyst to cause a point of high temperature which would act as an ignition source and a near perfect mix of confined hydrogen and oxygen to deflagrate if inerting is not available. Another potential that the recombiner of an Offgas System introduces is the possible migration of dust off of the catalyst bed. Even a very small particle of this type of catalyst in a pipe associated with the system (if separated from the pipe wall enough such that the pipe does not act as a heat sink) can initiate a deflagration if a mix of H_2/O_2 is available.

The conclusion is that the OE does not support the notion that there may be a detonation after closure of the HCVS vent valve.

5.2 Associated Research into Non-US Vent Systems

It is understood that the US BWR fleet is a part of a much larger family of BWR, PWR and CANDU reactors which are operated worldwide. Some of these international plants have vent systems in place currently and some are intending to install them in the future. In order to give consideration to all available options and variations of such systems, research into these plants' systems and methods of preventing damage from combustible gas detonations has been (and is still being) conducted. The following table provides an outline of information gained to date. Note that this is considered as the best information readily available. It should not be considered as verified information.

Country	Method
1	At present, this country's fleet is working to incorporate vents and vent filters into their nuclear plants. Although they're aware of hydrogen concerns, they have not begun to address that issue at this time.
2	This country's plants pre-heat their vent pipe prior to venting so as to prevent steam condensation. This does not address the post venting time period however. They're currently considering whether or not their vents will be able to cope with combustion loads.
3	From a single plant, their Filtered Containment Vent System (FCVS) has no special provisions for hydrogen. Note that this is a Mark III containment with active igniters and recombiners.
4	This country's regulating authority is requiring that the 2 BWRs there (Mark I and Mark III) install filtered containment vent systems. We are not yet aware of any provisions for design of the vents for hydrogen control.
5	Several sites have inerting systems associated with their vents.
6	This country's PWRs limit risk of hydrogen combustion in the venting line by pressure reduction upstream of the line to limit condensation. After Fukushima their regulator asked the plant collectively to reconsider the potential of hydrogen detonation at the plants. This work is considered ongoing.
7	Based on EU stress test this country's plants will be installing vents and filters during the 2015 – 2017 timeframe. No word on venting hydrogen control.
8	This country's plant is equipped with a FCVS. This vent uses a wet scrubbing filter and purges its vent line downstream to address hydrogen.
9	All plants in this country have an FCVS. The wet filters remain purged with nitrogen until use and are then refilled to prevent hydrogen accumulation.

With respect to this listing, the most common method cited is the addition of nitrogen as a diluter of the combustible gas. Many such systems are inerted during “standby” (non-use). Although some plants have not yet committed to perform the inerting operation post-venting (in order to press out the steam/combustible gas mix and re-purge the system), there are several that have. A general note about this is that it indeed is an active function which, for most cases if not all, will require an operator to monitor the venting and perform the task in relatively short order after venting ceases. Although this is seen as a reasonable option, the disadvantages of the need for operator action and the potential for multiple active failures must be accepted if this option is used.

6.0 Presentation of Options

By the writing of the Order with respect to the cited requirements, a site may design an HCVS to address the hazards of such an occurrence using one of two philosophies: either design the system so as to accommodate the expected loading produced by the ignition of a combustible gas mixture (Options 1 and 2), or design it such that a combustible gas mixture is not reasonably expected (Options 3, 4 and 5). The first philosophy alludes to a passive system, which will remain in place and operable after designed to the parameters derived from reasonably expected hydrogen deflagration and detonation. In effect, such a system would retain its ability to vent following reasonably expected hydrogen deflagration and detonation. The second ‘family’ of systems would have more active features than the former. There are several variations of such an active system and there are several hybrid systems considered.

Based on research into OE relative to this concern, two avenues are seen as applicable to designing the system to the reasonably expected dynamic loading induced by a combustible gas ignition event such that damage in HCVS piping is not expected. A more direct approach (based both on OE and the technical realizations from research performed since the event at Fukushima) is to use all technical and historical information available and design such a system as presented as Option 1 or 2 in the table below. However the precise design elements selected by a licensee as detailed in Appendix A is required to use these options.

The following table outlines the key options considered, and includes primary advantages and disadvantages of each. There are obviously variations on these central themes which may be used along with other options which system designers may choose to pursue.

Option	Description	Advantages	Disadvantages
1	Design the HCVS to withstand the reasonably expected hydrogen deflagration and/or detonation present in the system while venting under severe accident conditions, using both technical and OE lessons learned	1. Completely passive	1. Requires attention to detail as related to the specific design attributes
2	Design the entire vent piping beyond the primary containment isolation valves to withstand any flammable gas detonation.	1. Completely passive	1. May require higher rated valve(s) due to loading 2. Potentially requires thicker wall piping 3. May requires upgraded pipe supports 4. May requires complex dynamic analysis to develop pipe and support loads and design
3	Install a purge system to prevent flammable gas deflagration and detonation.	1. Requires minimal modification to existing or as designed system 2. Eliminates detonation concern	1. Active feature 2. Manpower requirement 3. Additional maintenance and testing 4. Additional failure mode 5. Potentially difficult to operate manually at the remote panel
4	Install an additional control valve downstream of the PCIVs and either design the system downstream of the control valve for detonation/purge (Options 2 or 3) or minimize length such that run-up distance is not achieved. Once CIVs are opened, subsequent vent	1. Minimizes piping potentially affected by detonation, or 2. Eliminates detonation concern (depending on placement of valve)	1. Active feature 2. Downstream portion of piping potentially still subject to disadvantages listed for Option 2 or 3 3. Additional maintenance and testing of the added valve 4. Additional failure mode (potential failure of the additional valve)

Option	Description	Advantages	Disadvantages
	start/stop cycles are controlled by the single downstream valve.		5. Adds challenges to support and maintain a large mass with an offset actuator at the end of the vent. 6. An external valve is susceptible to tornado missiles.
5	Install a check valve near or at the exhaust end of the vent stack to eliminate the ingress of air to the vent pipe when venting stops and the steam condenses.	1. Eliminates detonation concern 2. No operator action required	1. Additional maintenance challenges because of valve location 2. Additional failure modes (inability of check valve to open or to close once opened) 3. Adds additional mass at the end of the vent that needs to be supported.

6.1 General Notes Relative to the Options

1. In researching any given piping system's susceptibility to a hydrogen detonation, it was realized that there are many real world examples of common industrial evolutions that closely mimic the proposed venting scenario that could potentially allow for a DDT to occur. However, there have been no instances such that piping systems have failed when following approved design parameters for the combustible gas of interest. The most common use of this design philosophy is the venting of hydrogen from the generator at a power plant. As hydrogen is the typical cooling gas used in industrial electrical generators, this evolution occurs quite frequently at both nuclear (BWR and PWR plants) and non- nuclear power plants. Such venting occurs when the purity of contained hydrogen (in a generator) diminishes and higher purity hydrogen is to be added. In such a process, the contained air is vented out, pressing air out in front of it, and high purity hydrogen is injected into the generator. After such a process, the vent line is full of hydrogen. In the time period that follows, a scenario quite similar to that of the proposed HCVS post-venting evolution occurs. In the minutes to hours that follow, the hydrogen contained in the line, based on its diffusion and buoyancy properties, will escape from that line and be replaced with air during each evolution. During that replacement/exchange process, this mixture is also susceptible to the same conditions described in Assumptions 5, 6, and 7. Flames from the release

point along with burnt paint on the outside of the piping have been reported extensively, but no damage to the piping has been reported. The best explanation is that the piping is able to withstand hydrogen deflagration .

2. During the development of these options it was understood that, if a defense in depth approach is considered, any piping upstream of the valve which controlled the venting (opened to allow venting and closed to cease venting) is protected against a DDT based on the inability to get oxygen into that isolated volume. Effluent upstream of such a valve would be made up of steam, hydrogen, and trace nitrogen (and any other non-condensables available), but would not have an oxidizer due to isolation from normal atmosphere (such as from the reactor building or outside the plant buildings). As such, it was apparent that placing such a control valve further downstream was to the design's advantage with respect to protection against detonation. And it should be noted that the piping up to the control valve will experience containment pressure during the time the vent is not in use (after initiation of the venting process). The use of such a design philosophy is considered in Options 4 and 5. With both options, this philosophy may be taken a step further and the additional valves (isolation valve, control valve, or check valve) may be placed at the end of the vent pipe (which would remove the ability of any of the vent pipe to be susceptible to a DDT). As placing the valve upstream from the actual release point may be more attractive to some sites based simply on the inability to place such a device at the end of the pipe run (due to system configuration or available support structure), the run-up distance for a DDT (see Assumption 7) becomes of marked importance. As such, Appendix B has been developed to provide guidance relative to an accepted run-up distance.
3. Although the defense in depth option of designing for detonation beyond the last valve is passive in nature, it is also realized that it will require extensive dynamic analysis and modification to accomplish. Although many reasonably common grades and schedules of pipe are able to accommodate the equivalent static pressure of a detonation, components such as valves may require a higher pound class to accommodate a detonation, and a much more complex dynamic piping and support analysis must be used to design the system. Support systems for existing piping may need to be upgraded/modified. More specific information is to follow on this subject in the upcoming sections.

6.2 Basis for and Discussion of Given Options

1. **Design Relative to Hydrogen Detonation Related OE and Lessons Learned -** This option involves using lessons learned from OE and other industry sources to design the HCVS for reasonably expected hydrogen deflagration and detonation.

   Design Considerations for a Design using Related OE:

   a. Smooth ID piping should be used in the vent application (inherent in typical HCVS design). Relative roughness of the pipe ID should not be greater than 0.01D (i.e., ~1/8" for a 12" pipe). In addition, any obstructions which could facilitate turbulent flow during a DDT should be avoided or eliminated (e.g., extraneous valving, rupture disc housing).
   b. There should be no system ties to any system which would potentially contain loose catalyst which could migrate to the HCVS.
   c. The use of Non-sparking valves will provide additional assurance that there will be no viable ignition source.
   d. There should be no system ties to any system which contain reactor steam during power operation. This will eliminate the potential for leakage into the vent system which could allow for steam condensation and radiolytic gas pocketing.
   e. It is understood that vent piping may need to travel some distance horizontally to get to the release point (i.e., the release point will not be situated directly over the downstream controlling PCIV or (other) control valve). However due to the buoyancy of hydrogen, any piping that will have the potential to have a stagnant leg which contains hydrogen should be sloped up (as best possible) toward the release point. That will provide for a driving force (the buoyancy of the hydrogen) to move the hydrogen out and not pocket in the piping. If this is not done, hydrogen may collect in any high point in the piping. As such there would be some mixing at the interface of the hydrogen pocket and the heavier gases which may exist below it. However in such a case the creation of a section of a combustible gas mixture capable of supporting a DDT is extremely unlikely. This is due to the near complete absence of mixing forces available in such a situation and the stagnant gases will tend to stay separated.

   Option 1 involves designing to the dynamic loading conditions of deflagration and/or detonation that are reasonably expected in the pipe. As detailed above, the experienced pressure is no greater than normal system design pressure. Therefore any added design features are considered defense in depth.

2. **Design for any Detonation** –This defense in depth option addresses the philosophy that detonations may occur in the vent system. The development of a mixed atmosphere which will support a DDT evolution is not mitigated in any way. As such, all piping, components, supports and other ancillary appurtenance of the

system are designed with the understanding that multiple detonations may occur during periods of vent system use when the vent is isolated and outside atmosphere is drawn in.

In order to support this type of design, Reference 2 was developed to provide basis for both an equivalent static pressure load for a hydrogen detonation and for a carbon monoxide detonation. These two gases were referenced in the Order relative to their potential to cause a detonation. In developing this reference, numerous texts and academic papers were used to develop a reasonable and defendable value. The main results of Reference 2 were design values for hydrogen and carbon monoxide. The maximized static equivalent pressure loads at detonation (from Reference 2) are as follows:

Hydrogen – 1,204 psia (8,300 kPa)
Carbon monoxide – 1,397 psia (9,631 kPa)*

* It must be noted, and as discussed in Appendix A, further research (since the time of the generation of Reference 2) into the area of carbon monoxide combustion behavior has provided assurance that the CO value from Reference 2 was overly conservative. The more recent (and more contemporary) Appendix A discussion justifies dropping the aforementioned carbon monoxide static equivalent pressure such that the design value (which envelops the combustion effects of both gases) is that of hydrogen; 1,204 psia.

Based on Reference 2, ASME stress evaluation was performed on several sizes and grades of commonly used piping with respect to accommodating such loads (from a hydrogen detonation). The following table provides a sampling of piping which may be used in such a system. <u>It is however incumbent on the pipe and support design engineers to verify acceptability of such piping in this use with respect to actual pipe stress loading and specific site requirements</u>.

Pipe Size ->	12”	14”	16”	18”
Grade A	Schedule 40	Schedule 40	Schedule 40	Schedule 60
Grade B	Standard	Schedule 40	Schedule 40	Schedule 40
Grade C	Standard	Standard	Standard	Schedule 40

Notes:

1. **Schedule 40 pipe use for Grade A 14” and schedule 40 use for Grade B 18” are considered marginal**
2. **Color for effect only, indicates departure from Std. schedule**

3. **It is understood that such static loading will mainly manifest in pipe hoop stress**
4. **Corrosion Allowance of 0.020” is Considered**
5. **All Piping SA-106 - Service Level C Allowables**

In addition to the pressure loads, Reference 2 also provides loading conditions and Service Level loading to be used with such calculations. These may be found in Reference 3, Appendix H.

The information presented above with respect to the equivalent static pressure load, and the accompanying information on piping loads, is presented to make the engineer aware of the potential magnitude of loading associated with a combustible gas detonation. It is not recommended that the information provided be taken as the sole basis for design for detonation. A dynamic analysis is recommended to assure that the actual system piping and support configuration is considered such that supports and piping geometry may be optimized. There is a reasonable potential that actual piping pressure loads will be less than that stated above but it is not the intent of this paper to provide a ‘cookbook’ method of performing such an analysis. Such an analysis is understood to be detailed for a relatively complex system.

Further research was performed into component and support loading relative to a detonation tolerant HCVS. References 4, 5, and 6 provide further basis that both valving and system supports will require significant upgrading for a detonation tolerant system. The following is a comprehensive set of considerations that must be taken into account if such a system is to be designed and used:

Design Considerations for a Detonation Tolerant System:

a. Piping may require upgrading based on pressure pulse loading.
b. As per ASME B16.34 – 2009 (Reference 7), butterfly valves which form any of the boundaries for (either PCIVs or boundary valves – e.g., to SGTS) may require upgrading to Class 900 or above (this would roughly double the weight of the valve depending on manufacturer).
c. Valve Class will also affect the associated valve actuator.
d. Consideration must be given to “Torus Attached Piping” if the system is completely designed for detonation. May not be required for systems with downstream control valves.
    i. See NUREG-0661 (for Mark I), Section 4.1, Subsection 3.
    ii. See NUREG-0487 (and Supplements) for Mark II plants.
e. Must consider FEM type analysis for stress and support design.
f. Instead of lumped mass, must consider a ‘traveling detonation’, need to perform a series of time history type dynamic loading cases to determine worst case for support design
    i. Reasonable example using ANSYS found in PVP 2011-57278 (Reference 6)

Note –Research and analysis revealed the acceptance that, if a dynamic analysis is performed, advantage may be taken of the use of flexible supports and design using 'expansion loops' (much like is used with main steam piping). The use of non-rigid supports coupled with pipe bends upstream from a detonation location can significantly reduce support loadings that would be realized by more rigid supports and similarly supported valves. As such, this option may provide some advantage for those plants performing a complete (or near complete) system design.

3. **Install an Active Purge System** – This defense in depth option involves the installation of an active purge system on either any existing system, or designing it into a new system. The purpose of this type of (as opposed to that in Option 2) is to address the first portion of Order Element 1.2.11 so as to, "ensure the flammability limits of gases passing through the system are not reached." This is done by actively purging (injection of a gas which will displace the steam and hydrogen [plus any other incidentals] which may be present in the now isolated vent before condensation draws in a substantial amount of air/oxygen). Based on the relative atomic weights, argon is the gas of choice for this operation. It is typically available and reasonably inexpensive. And it will disallow oxygen to re-enter the vent line based on its atomic weight being higher than that of oxygen.

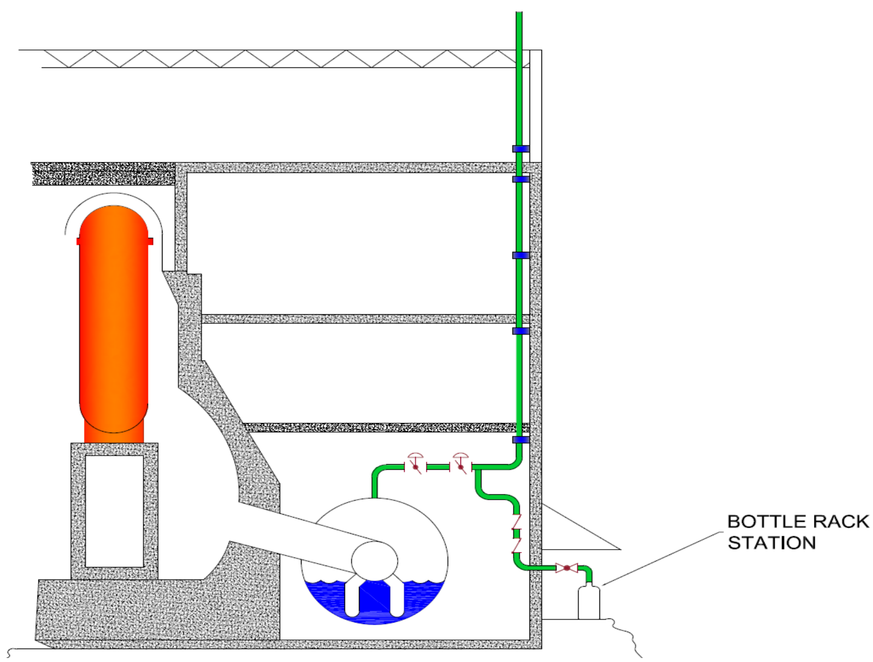
   System Design Concept - The system provides an argon purge downstream of the PCIV (or downstream control valve) upon PCIV closure. The function may be automatic or manual. Such a system may be configured as simply as routing purge gas tubing from just downstream of the last PCIV (or alternate control valve) to a purge gas bottle station convenient for system operation.

   Argon will stay at the bottom of the vent pipe up against the PCIV. As time passes from PCIV closure, the argon will remain in the bottom of the exhaust vent because there are no mechanisms to drive the argon out. Small amounts of hydrogen that may leak through the PCIV will not create a detonation potential because the leak rate will be low, there will not be any oxygen; and leaking hydrogen will move through the argon blanket and up the exhaust stack.

   Upon reopening of the PCIV, the atmosphere in the pipe upstream will contain steam and may also contain hydrogen or carbon monoxide. The upstream mixture is absent of oxygen. Downstream of the PCIV the pipe is inerted with argon. The Staff has also postulated that the friction of opening a metal seated butterfly valve could provide an ignition source. The result of opening the PCIV does not cause a deflagration or detonation because there is no oxygen present. Thus using the PCIV for vent control with the argon purge precludes detonation in any portions of the HCVS.

Design Considerations for an Active Purge System:

a. For the affected site, a maximum steam condensation rate must be calculated
    i. Worst case ambient temperature of outside must be considered
    ii. Worse case internal temperatures must be considered
    iii. Insulation must be considered.
b. Given the rate at which air could enter the piping and act to create a combustible gas mixture, the timing of either manual injection or automatic injection must be aligned to minimize or preclude such a mixture occurring.
c. The current accepted value for vent cycles is 12 although site specific analysis may indicate deviations from this value. Although it is also accepted that operation of the vent system will be tied to a given site's incorporation of affecting EPG/SAGs. It must be noted that purging a complete HCVS may require a significant amount of purge gas. And if this must occur multiple times, the complexity and potential for mistakes and failures increases. Another consideration with active purge systems is the understanding that gas injected at high velocity into a confined space with a combustible gas mixture may cause ignition of that mixture. As such, a site-specific evaluation of how quickly a combustible gas mixture may be realized should be performed (based on worst case ambient temperature along the vent pipe run). Purge gas injection should be performed prior to that timeframe.



Simplified Sketch – Purge Concept

4. **Install a Secondary Control Valve Near or at the Exhaust End of the HCVS** – This option involves the design/operating concept involving the placement of a HCVS control valve well downstream of the PCIVs such that, once the HCVS has

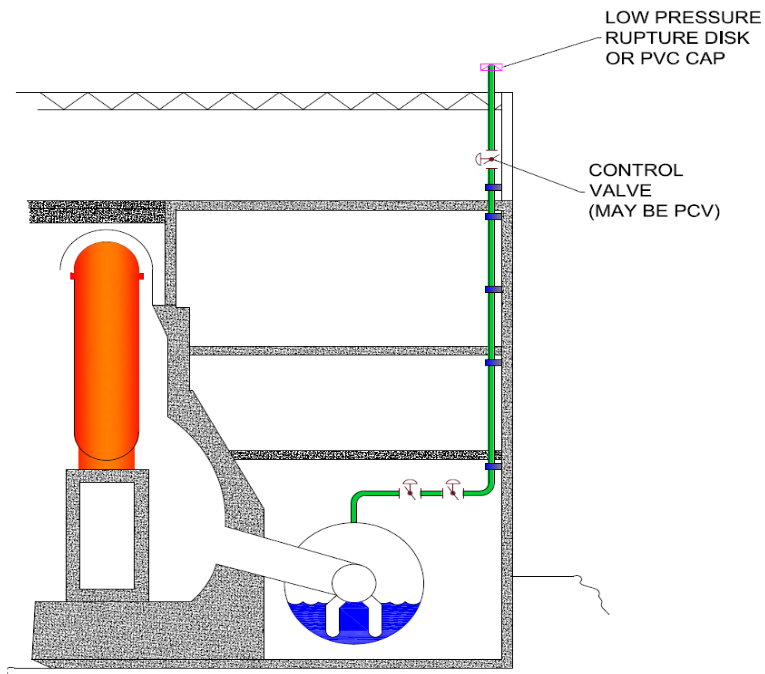
been placed into operation, the PCIVs will remain open and venting will be controlled by the aforementioned downstream control valve.

As has been noted previously, once the HCVS has been placed into service, the piping upstream of the control valve will not be subject to combustible gas deflagration/detonation as there will be no available oxidizer in that volume. It will essentially be an extension of containment once the HCVS is lined up to vent.

This option creates the opportunity to use either philosophy from Option 2 or 3 with respect to the remaining section of pipe downstream of the control valve. In situating the control valve location, the amount of downstream piping can be greatly minimized such that either a relatively short (and potentially uncomplicated) section of pipe may be designed for detonation or a short section may require a simple low capacity purge system. This can be carried a step further if the piping length downstream can be designed less than the run-up distance provided in Appendix B (up to and including placing such a control valve at or very near the release point).

Design Considerations for a System with a Downstream Control Valve:

a. With respect to Design for Detonation
    i. Consider placing the Control Valve just upstream of the last vertical section of pipe, this will simplify pipe stress analysis
    ii. As the Control Valve will need to potentially be Class 900, design for a support opportunity (close to existing substantial steel frame or structure or close to concrete beam or pier)
b. With respect to Design for Active Purge System
    i. Consider opportunity for easy tie-in to argon feed
    ii. Potentially consider manual system based on placement of valving (minimal purge time and opportune location)
c. HCVS-FAQ-05 should be consulted for valve and valve testing requirements.
d. Appendix B (reference for further information) provides a value of $L/D \geq 30$ (total pipe length divided by pipe diameter) as a reasonable minimum required run-up distance. An open ended pipe with a closed valve upstream which is equal to or longer than this can conceivably sustain a detonation by the DDT process. Sections of pipe shorter than this will not experience a detonation by DDT.



Simplified Sketch – Downstream Control Valve Concept

5. **Install a Check Valve Near or at the Exhaust End of the HCVS** – The design concept of this option is to bottle up the steam and hydrogen in the pipe volume between a downstream check valve and the upstream control valve (typically a PCIV). There are check valves available currently which have near zero leakage for applications such as this. Such valves are typically configured with (but not limited to) a double door arrangement much like a tornado damper. Stainless steel soft seated versions of this type of valve could be mounted vertically (with the double doors swinging upward) up near the exit point of a HCVS (potentially at reactor building roof level such that they are available for maintenance) with a few feet of pipe left to the actual release point. Based on the run-up distance required for a DDT to occur, detonation loading would be ruled out for the downstream piping. With the 'doors' swinging up, gravity would assist the spring closure mechanism to limit leakage to an absolute minimum.

   According to suppliers, this type of valve (capable of operating at wetwell venting design temperatures) can be expected to have an effective maximum leakage of approximately 2 cc/hr/inch of seat. As an example, a 14" valve this equates to 0.005ft^3/hr of inleakage (0. 001ft^3/hr of oxygen). With a pipe run using 14" pipe (volume = 1.07ft^3/ft of pipe length) it would take many weeks to reach an oxygen concentration which would support a DDT (considering a ~5.5% oxygen concentration in a full run-up length of pipe – see Appendix B). In comparison, an expected usage cycle for venting during a severe accident would be on the order of 4 - 5 cycles per day. Considering this cycle interval, coupled with the referenced leakage, less than 2 in^3 (<33 cc) of oxygen would leak into the space behind the check valve. Any ancillary PCIV leakage from the other end of the system (made up of mainly steam, hydrogen, and trace nitrogen) would purge the system and slow the process toward supporting a flame. That leakage (past the PCIV) would be driven by the higher pressure containment volume on the upstream side.

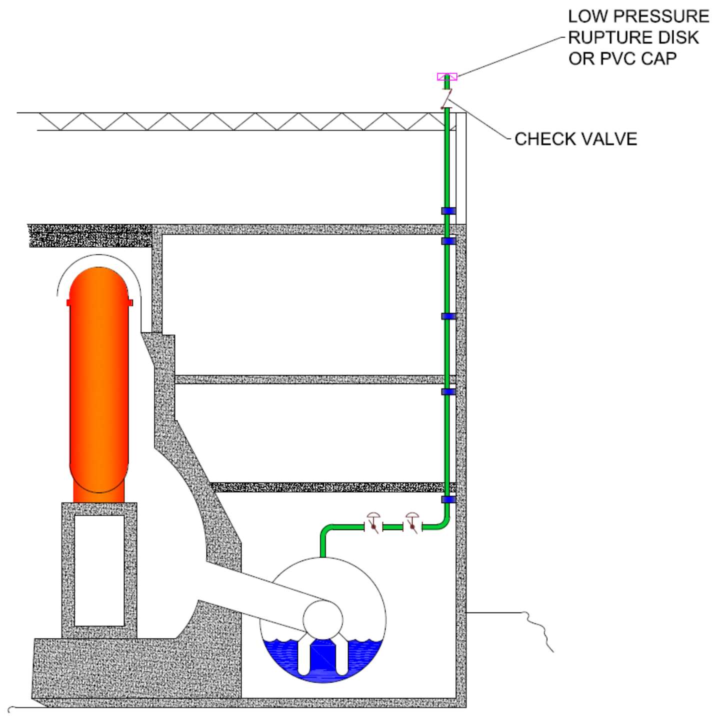
With respect to potential fouling of the check valve due to release debris during a severe accident, scrubbing through the wetwell provides reasonable assurance that the soft seat valve will continue to perform its expected function. SECY-12-0157 (Reference 27) provides a maximum particle size, downstream from the wetwell, of 0.3μm. These are minute particles. This type of valve is manufactured such that the irregularities of the seating surface of the valve are of greater magnitude than this particle size. As such, these particles would not be expected to adversely affect valve operation. Again these are soft seated valves; when the valve is closed the soft seat will conform to the aforementioned seating surface. The majority of vented effluent that will pass through this valve is expected to be at a substantial velocity. At such a velocity, the potential to have a buildup of material near or around such a valve will be inconsequential; and as such would not adversely affect the assumed valve leakage.

This type of valve has been used in various industries in gas applications in which they cycle multiple times during normal associated equipment and system operation. There is operating history on this type of valve assuring continued rugged, reliable operation.

Once venting has ceased, the atmosphere in the contained volume in the HCVS will become relatively stagnant with the only driving force for advection being condensation of steam in the contained mixture. As steam condenses out of the mixture, pressure in the pipe will lower and a small amount of air may slowly leak into the volume through the closed check valve. Initially, there will be extremely low differences in density between the fluid at the top of the pipe and that at lower levels (assuming a vertical pipe) so the only mechanism for gas movement will be diffusion. The air will slowly diffuse into and mix with the combustible gas (hydrogen or a hydrogen/carbon monoxide mix) in the piping as the result of differences in gas concentrations. At very low differences in density between the more dense top layer of air and the less dense lower layer of combustible gas there is insufficient driving force for buoyancy driven mixing of the layers (i.e., there is a limiting density gradient required for initiation of the previously described Rayleigh-Taylor instability). As more air accumulates in the upper section of the piping and bulk density differences are established, bulk fluid motion as a result of buoyancy forces will also become possible. As the density gradient between the upper and lower layers increases, buoyancy-driven flow will initially enter a counter-current flow regime in which there is separation between the downward travelling denser fluid and the upward travelling lighter fluid. While this flow will lessen the density difference (and occurs at a much higher rate than that driven by diffusive forces), diffusion would still tend to equalize gas concentrations across horizontal planes in the pipe. At higher density gradients, the buoyancy-driven flow enters convective-diffusive and turbulent-diffusive regimes, in which mixing occurs across the horizontal planes in the pipe. In summary, as steam condenses in the isolated vent pipe, lowering pressure may draw a small amount of air into the pipe by leakage through the check valve. This air will mix with the non-condensable combustible gas in the pipe due to the action of buoyancy and diffusion to reduce density and concentration gradients respectively. Due to the small amount of air available at the top of the pipe, and the very small density differences required for buoyancy-driven flow to mix the air throughout the pipe, there is an extremely remote possibility of developing a uniform combustible gas mixture capable of supporting a DDT within the isolated piping.

Design Considerations for a System with a Downstream Check Valve:

a. Consider placing the check valve just above roof level or adjacent to the parapet on a single plant system that either runs through the reactor building roof or up the side of the reactor building. This will allow ready access to the valve for maintenance and testing. It will also simplify support design. This valve may be moved upstream based on plant needs and convenience however run-up distance (or design for detonation or a purge system) must be considered. (The mass of the valve at that location may introduce design challenges to seismically support it.)
b. Consider placing a PVC cap or low pressure rupture disc downstream of the valve to protect it.
c. Consider installing a permanent work platform for maintenance. (Since the location may present maintenance challenges over the life of the plant.)
d. The pipe volume will experience negative pressure with respect to atmospheric. This must be evaluated.
e. HCVS-FAQ-05 should be consulted for interim valve and interim valve testing requirements.
f. It should be noted that a reasonable variation of this concept would be to place such a check valve upstream of the actual release point at a distance of just less than the run-up distance stated in 3.d above if such a configuration is more advantageous and convenient for the affected plant. If located further than the run-up distance then design for detonation or a purge system may need to be considered.



Simplified Sketch – Downstream Check Valve Concept

7.0 Multi-Unit Venting Control

Although this paper is written to be used primarily to provide guidance relative to the design of a single unit vent system, concerns related to the venting of hydrogen bearing effluent at multi-unit sites must also be considered. This section is written relative to those sites which vent multiple units through a single Plant Stack (chimney). The typical configuration in such a case is for the HCVS from 2 or more units to be routed to a single (typically 100 meter tall) Plant Stack which services the HCVS pipes along with numerous other effluent sources (typically Offgas, SGTS, and other systems susceptible to contamination such as Radwaste HVAC, etc.).

The concern for this type of vent configuration is based on accepted knowledge of the venting efforts at the Fukushima Daiichi Nuclear Plant in March of 2011. Fukushima Daiichi Units 3 and 4 used a similar configuration as is mentioned above in that they shared a single Plant Stack which was designed to provide a vent path for both units. During the course of the accident coping period, after venting was initiated in Unit 3, that unit experienced a substantial hydrogen explosion which extensively damaged the reactor building walls (both lower concrete walls and the upper steel panels). Some 19 hours later, with venting still occurring from the Unit 3 containment, Unit 4 (which was not operating at the beginning of the earthquake/tsunami event) experienced a similar hydrogen explosion. Evidence found during the investigation after the Fukushima units were stabilized pointed to hydrogen migration into the Unit 4 reactor buildings from the venting of Unit 3. This migration was understood as occurring through the common stack vent path. At Fukushima, the temperature inversion between the atmosphere both above and in the stack with respect to that of the vented effluent exacerbated the situation by working to slow the escape of the vented effluent from the elevated release point (i.e., the heavier air outside the Stack impeded the high temperature/lighter effluent from free flowing out the Stack). It must be understood that there had been no power to the HVAC fans that normally facilitated stack flow for at least 36 hours prior to Unit 3 beginning to vent. In the interim time, the stack (which was a metal pipe) had cooled and along with the stagnant air contained therein. This understanding of flow being routed back into the buildings is based on understanding of the associated systems' configuration at the time of the accident (with an open path back into the reactor building areas) coupled with post-accident radiation readings of both units' standby gas treatment systems. Had there been better isolation of the associated valving of related systems which connected to the Unit 4 reactor buildings, those explosions would not (in all likelihood) have occurred.

As such, there are special and unique circumstances which must be considered during the venting of a single unit using such a configuration using a common stack. In addition to the 'boundary valve' discussion from HCVS-FAQ-05 (Reference 16), all valving associated with systems which flow into a common plant stack must be closed and leak tight to the point that they will not allow leakage of vented effluent into their associated systems. That is to say, any and all valves which serve to form a boundary to an affected unit's HCVS vent path must be guaranteed closed (either procedurally or by interlock) prior to venting commencing. (These elements are addressed specifically in order requirements for multi-unit venting and interfacing systems which will not be covered in this white paper) Due to the nature of a typical plant stack mixing chamber, these valves need not be designed to venting temperature and pressure. However they must have the capability to prevent significant amounts of hydrogen from migrating into those systems should venting be necessary. If venting from multiple units is to occur through the main Plant Stack/Chimney, this same consideration (closed and effectively leak tight valves) must apply to all other isolation valves that are associated with the vent path boundary.

There are other stipulations that must be considered when using the Plant Stack as an elevated release point. If there are dilution fans involved in the venting at the Plant Stack, priority must be given to providing suitable power to those fans once venting has been initiated such that hydrogen will not collect in the base of the Stack. These fans should also be seismically rugged such that they can be depended on to perform this function. If the vent from the HCVS and the flow from the dilution fans flow into a mixing chamber, it is important to ensure that the mixing chamber is of rugged construction. Such a release point will inherently be fed by underground piping. Such piping is typically quite robust and well confined structurally, based on its typically being heavy grade carbon steel pipe bedded in highly compacted safety related fill (based on the shared function of the piping). Although deflagrations may be considered as possible, this piping will maintain cool, damp interior surfaces due to ambient soil temperatures coupled with high humidity effluent (and potentially vented steam). This would serve to minimize the possibility of ignition sources. It is noted that the use of the Plant Stack as the containment vent release point is in agreement with the design philosophy specified in Option 1.

8.0 Conclusions

This document is written to provide guidance to BWRs with Mark I and Mark II containments in the designing of, or modification of their Hardened Containment Vent Systems. Options provided and design discussion contained herein is intended to be used, as endorsed by the USNRC, for the design and modification of such systems in order to meet the requirements set forth in NRC Order EA-13-109 under Section A. Phase 1 (reliable, severe accident capable wetwell venting system). The options presented are intended, when used, to provide for a vent system which will remain functional regardless of adverse conditions realized due to the release of combustible gases through the vent as generated based on degrading accident conditions (i.e., hydrogen and carbon monoxide).

Based on the above, a given site would be expected to make use of a supplied option (or combination of options) in defining the design attributes of their HCVS. Note that using an option or design concept not presented in this document is considered acceptable so long as it is deemed effective for this purpose per evaluation and endorsement by the NRC. In specifying a design/modification methodology for a specific HCVS, a site would be expected to document the selected method of compliance in accordance with section 3 of this white paper

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Appendix A: Achieving a Detonable Mixture

The Order presupposes that conditions may be reached, post severe accident, which would be conducive to a detonation. Although this sounds simple, a number of special and unique circumstances must align in an ideal manner to allow for such a consequence. The following is a table of fundamental assumptions that must exist for just such an occurrence. Further discussion is provided after this table to explain the conditions and evolutions leading up to a detonation. Note that the first three assumptions address the actual plant condition that is required for such an occurrence along with the potential for containment de-inerting. The remainder of the assumptions deal with the actual creation of a detonable mixture.

Item	Assumption	Basis
1	Core damage is considered	Hydrogen production from radiolysis alone is not sufficient to produce a mixture capable of sustained deflagration without the additional hydrogen produced by the metal water reaction (MWR).
2	The design configuration and operation of the vent will prevent oxygen from entering containment through the vent line.	In order to facilitate a combustible mix of hydrogen and oxygen, the vent must not be in use (i.e. the associated isolation valve closed). In addition to the isolation valve being closed, the containment pressure will be controlled in a pressure band higher than ambient. This upstream isolation of the vent would allow steam in the line (from the last venting) to condense. Condensation with the consequent introduction of oxygen would not occur until the venting process has been secured.
3	The process of radiolysis is not able to generate enough oxygen to support a hydrogen burn in a site's HCVS	Radiolysis is a relatively minor producer of hydrogen in an accident scenario. The volumetric rate of hydrogen and oxygen generation due to radiolysis is very small relative to the steam generation rate such that a significant concentration of combustible gas is not created in containment or the vented fluid due to this source. Due to the waning of oxygen production (proportional to waning decay heat), it will take many hours to days for enough oxygen to be generated to support a simple hydrogen/oxygen flame. By the time the scenario that generates sufficient hydrogen is considered (due to MWR), oxygen produced by radiolysis would be greatly depleted by the prior venting operations.

Item	Assumption	Basis
4	There is some type of ignition source available in the vent flowpath (e.g., catalyst particles, spark, etc.) such that ignition of a deflagrable mixture is possible.	This is considered as a low probability occurrence because the effluent will be scrubbed through the suppression pool. Although there is the potential for some lower energy catalyst particles (e.g., iron oxide, silica) existing in the vent pipe, they would much more likely adhere to the walls than free float in the effluent during and after steam condensation. This would serve to greatly dissipate any heat (or heat from the catalyzation process) they would carry thereby rendering their effectiveness to initiate a deflagration very improbable. Condensation of the steam in the pipe would further enhance the adhesion of any such particle to the piping walls due to the moist surface. In addition, any unattached particle would likely act as the nuclei for the formation of water drops during the condensation process (which would drive them to attachment to the pipe wall).
5	There must be, at a minimum, enough hydrogen available such that a flammable mixture (hydrogen combined oxygen) sufficient to support a deflagration to detonation transition (DDT) is achieved.	This must be achieved for the detonation cited in Requirement 1.2.11 (Reference 1) to be realized. As per NUREG/CR-5525 (Reference 26), 9.4% is the minimum hydrogen concentration by volume that would allow for a prompt detonation to occur (not a DDT). However, from research into this issue, DDT wave speeds have been approached in a hydrogen concentration as low as 11.0% hydrogen (by volume). However this was in a special “rough piping” case developed to enhance the DDT capability (see Reference 23, Figure 3.2.2-2). Although concentrations in this range are possible considering hydrogen release from the metal water reaction, they would tend to be non-uniform and short lived based on the dynamic nature of air exchange/ condensation after venting has occurred.

Item	Assumption	Basis
6	Prior to ignition of the flammable mixture, it is assumed that a homogeneous mixture of hydrogen and oxygen (in sufficient proportions to support uniform flame propagation) exists such that the post-ignition pressure wave may be allowed to travel so that sufficient turbulence and velocity can be reached to support a DDT.	This is an unlikely case based on the requirement of a homogeneous mixture (with little appreciable mixing force aside from steam condensing and buoyancy to support a sufficient length of such a uniform mixture) for a potentially long length of pipe. However this assumption must be made in order to consider such an ignition and pressure wave to be credible. See explanation of DDT (below) for further information. See also final paragraph in in this appendix, specifically addressing mixing.
7	Assume sufficient pipe length available to allow DDT to be reached.	There must be a combustible mixture of sufficient length that the run-up distance for DDT is achieved. That run-up distance is based on pipe diameter and is understood as having L/D ≥30. If the mixture is less than the run-up distance or is a ‘broken’ (intermittent) mixture, it will not produce a detonation. See Appendix B for further information.

Prompt Detonation versus DDT Discussion -

From research into hydrogen deflagrations and detonations it is reasonably understood that a large amount of energy is required to facilitate a prompt detonation of a mixture of hydrogen and air. Reference 24 speaks of an energy requirement of 4100 Joules to initiate such a detonation in Section 4.3.2. Both Reference 10 and Reference 21 cite the use of a "high explosive" in their large test tube (for prompt detonations) as opposed to setting up the conditions required for a DDT. In speaking of a prompt detonation, the evolution cited is an immediate combustion of hydrogen and the oxygen (contained in air) such that an immediate detonation pressure spike is realized. This requires at least 11.6% (cited for 20ºC at 1 atm) hydrogen by volume (Reference 26) in the mixture effectively mixed and readily available to be oxidized. As has been stated, a series of research papers on hydrogen detonations speak of the large amount of energy required for prompt detonation to occur. A Deflagration to Detonation Transition (DDT) evolution however, may be initially started by a much smaller amount of energy and (if conditions are ideal) may lead to a detonation pressure spike. As such, a DDT is assumed if a detonation is to be considered. This is also due to a reasonable combustible mixture being much more likely to occur with a lower combustible gas concentration than the higher concentration needed for a prompt detonation. For a DDT to occur, a confined or semi-confined section of pipe must have a gas mixture which will support a deflagration. Once ignited, the flame front accelerates and presses the unburnt gases ahead to the point that the autoignition temperature of the gases is reached. Reflection of the pressure wave off of an effective pipe end will also work to enhance the approach to detonation. The point at which the autoignition temperature is reached is considered the transition from deflagration to detonation. This creates a detonation wave equal in pressure profile to that of a prompt detonation. The shock wave from this detonation causes the highest pipe stresses in a straight pipe section.

Mixing Discussion –

Assumption 6 speaks to an acceptance of a homogeneous mixture of gases being required in order to facilitate a continuous deflagration (that has the potential to transition to a detonation). Many of the references used in the development of this paper were generated as a part of academic studies and papers designed around creating conditions that would support a DDT. As with many such studies, the actual testing was performed under ideal laboratory conditions. Volumes and mixes of various gas combinations were typically captured in a closed volume as a beginning state for the ensuing tests. An ignition source was then introduced to start the flame front and various parameters and test boundary conditions were altered to facilitate the transition. Based on inherent stratification and diffusion of the various gases, mixing pumps were sometimes used to ensure the ideal combustible gas mix. Several articles spoke of the difficulties realized in maintaining these mixtures. This is in contrast to how non uniform mixing would possibly occur in an HCVS. References 28 and 29 segregate the "pre-mixed" gas experiments and conclusions from those of "non-premixed" experiments.

Reference 28 provides a compilation of information related to hydrogen combustion. The last chapter of that book begins with this short paragraph:

"Two significantly different fuel and oxidizer forms are considered while analyzing potentially combustible systems: pre-mixed and non-premixed mixtures. The previous chapters are devoted to combustion modes in pre-mixed mixtures."

This statement basically separates out the first 10 chapters of the book from this last chapter which predominantly addresses diffusion type flame fronts in non-premixed flammable gas mixtures. Further down that first page is the statement, "Unlike the combustion modes of pre-mixed mixtures, in which dynamic loads are the most dangerous, the main threat of a diffusion flame" (inherent in non-premixed gases) "is the long-term heat effect of high temperature combustion products." Note that this statement discounts dynamic loading if the gases are not pre-mixed. The following paragraph continues to define the somewhat benign nature of non-premixed mixtures. It reads as follows:

"Diffusion flame can be characterized as a quasi-stationary, nearly isobaric flame initiated in a non-premixed mixture; the chemical reaction (in the case of a laminar flame) occurs within a narrow zone. This zone can be assumed to be the flame surface. The key difference between the diffusion flame and the pre-mixed mixture flame is the chemical transition velocity that is limited by fuel/oxidizer mixing rate in the diffusion flame. Fuel/oxidizer flows have a stoichiometric ratio at the flame surface. However, when the fuel/oxidizer flow getting into the diffusion flame is large, there is no time to start the chemical reaction and the flame dies out."

To paraphrase simply, a non-premixed collection of gases including fuel and an oxidizer (even though they may be in the correct bulk volume percentages to support combustion) characteristically does not have a continuous <u>mixture</u> of gases (local gas concentrations are non-uniform) sufficient to maintain the combustion reaction to the point that a flame front is free to travel and gain momentum.

Additional supporting information may be found in Reference 25 (NUREG/CR-4534) which considers testing performed in a closed volume involving hydrogen and steam injected into a test volume containing air (along with some degree of steam) plus electrically powered igniters. The third paragraph from the Executive Summary of that document makes some reasonable overarching statements tying mixing and the maintenance of a flame front. It reads as follows:

“Mixing and ignition processes have been examined as a function of source parameters and igniter locations. The source Froude number has a profound influence on the degree of mixing during the injection process. The lack of multiple deflagrations and the phenomena of nonignition can be explained on this basis. Tests using a buoyant plume source (low source Froude number) probably have a strongly stratified initial hydrogen concentration and a distinct moving front between mixed and unmixed fluid. As the source Froude number increases, the Vessel contents become better mixed. Tests using jet-like sources (large source Froude numbers) will exhibit good mixing and a distinct front will not form.”

In this context, the Froude number is a dimensionless number characterizing the relative role of inertial and gravitational forces with respect to mixing of the fuel (hydrogen) into the oxidizer (in this case air containing oxygen). It is a measure of how quickly (based mainly on driving forces) that the hydrogen may (or may not) be able to mix with the air. A low Froude number is indicative of buoyancy and gravitational forces being the dominant drivers of mixing. This is considered analogous to the situation experienced in an HCVS once venting has ceased. Intermediate Froude number hydrogen introduction involves forcing hydrogen and steam into the test volume through a nozzle at the base of the volume facilitating circulation and mixing.

Per Reference 25 with low Froude number hydrogen introduction, the worst case flame front developed was characterized as “erratic burning.” Only after the Froude number was raised to an “intermediate Froude number” was an actual deflagration accompanied by a rise in pressure realized (~1.7 atm from 1 atm, - keeping in mind that these tests were conducted in a closed volume). Injecting at an intermediate Froude number, in this case, was facilitated by forcing the hydrogen and steam into the volume such that mixing was induced and the stratification (allowed by low Froude number hydrogen introduction) was not allowed to develop. It should be realized that, at the point in the HCVS venting process where mixing becomes a concern, there is no injection of either hydrogen or air and any flow is primarily gravitationally driven.

APPENDIX B: Consideration of Run-up Distance

If a defense in depth approach is to be taken, the information in this appendix should be considered relative to run-up distance needed to facilitate a DDT. By nature of the deflagration to detonation transition process, there must be a minimum length of pipe available, with sufficiently mixed gas to form a combustible mixture, to allow the flame front velocity buildup to achieve a detonation. This distance is necessary for the flame front to increase velocity, go turbulent (with the associated transitional velocity jump), and then continue with the velocity increase until the mixture in front of the pressure wave is compressed to the point of auto ignition. This run-up distance becomes a critical factor (if the ability to create/facilitate a DDT is a concern) in configuring an HCVS with a control or check valve placed well downstream of the PCIVs. The following guidance is provided to allow plants to set that downstream pipe length such that there is not enough run-up distance for a DDT to occur. This provides reasonable assurance that the downstream piping will not be susceptible to a detonation pressure wave.

A series of experiments were performed during the early 1960s at Ohio State University on run-up distances (listed as “Induction Distance” in many of these older references). One such study concentrated on hydrogen-air mixtures (Reference 30). From Table 2 of that reference, it is understood that the experimental run-up distance is ≥~99L/D. Note that this is at atmospheric pressure (as would be the case for a vent line) and at maximum flame propagation rates. Using average propagation rates would increase this slightly to 100L/D. It should be noted that this information is reasonably assumed to be based on information from smooth pipe.

More contemporary research shows that the run-up distance is dependent on many factors, not the least of which being the Blockage Ratio (BR) of the associated piping. That ratio is defined as the height of obstructions or roughness on the ID of an associated pipe divided by the total pipe inside diameter (Reference 17). As this directly affects how quickly a flame front goes turbulent, it has a marked effect on run-up distance. As an increase in the BR (equating to an increase in obstructions in a pipe) tends to increase the potential for turbulent flow and increased flame acceleration, there have been many studies performed on controlled BRs and the associated run-up distance. By nature of a normal vent pipe, the BR is thought to be relatively low. Piping used for such applications is relatively smooth along the ID. Considering that it would take over an inch of obstruction along one side of the ID of a 12” pipe to produce a blockage ration of 0.1, a BR of <0.01 may be safely assumed for such an application (equates to just less than a partial obstruction of ~1/8”).

As has been stated, there are several available studies related to run-up distances as associated with BR factors. One such study by S. B. Dorofeev (Reference 18) presents a set of experiments and explanations on how and why such influences occur. Conveniently one of the predominant combustible gas mixtures used in the study is a mixture of hydrogen and air. The pipe sizes used in the cited experiments closest to the vent pipes which would be used in an HCVS are 0.174m (~7”) and 0.52m (~20”). As the smaller pipe is shown to have the shorter run-up distance in all cases cited, those run-up values will provide basis for a conservative run-up distance to be presented in this appendix.

Figure 2 of Reference 18 shows experimental run-up distance (stated as Xs) values for a number of pipe sizes, BR factors, and combustible gas mixtures. The values provided for the ~7” and ~20” pipes with a BR of 0.09 (much higher than that we may reasonably assume for vent pipe) have a minimum of 38 for a run-up distance (note that the run-up distance is provided as a ratio as related to the pipe diameter Xs/D). This same value is again provided in Figures 3 and 4 for various traits and correlations. Appendix B of the paper ties the experimental data with reasonable run-up formulae to produce result predictions for hydrogen and hydrocarbon mixtures. By observation, the information provided by the formulae (as depicted in Figure 6) is slightly more conservative than the results of the experiments. Figure 6 provides a value for an 18” pipe (~0.5m) of 30 for Xs/D. This is thought to be one of the larger pipes considered for an HCVS. As the pipe size drops, the run-up distance ratio increases (in agreement with Section 3.3 of Reference 18). For a 12” pipe, Xs/D appears to be approximately 33.

The experiments outlined in this reference (Reference 18) were cited as based on prior studies and academic papers. As temperature control is not cited in as a controlling parameter, it is reasonably assumed that they were conducted at or near standard temperature of 298K. A temperature range from this standard up to ~350K may be reasonably assumed for the HCVS application. It should be noted that Reference 19 states that decreasing initial temperature tends to cause the run-up distance to decrease. The converse can reasonably be assumed. This is also in agreement with information provided by Reference 15. This is further backed up by experiments performed on hydrogen mixtures at various initial mixture temperatures and depicted in Reference 12 in Figure 3. As such it may be reasonably accepted that the findings and recommendations based on Reference 18 are applicable to this application.

Based on the papers cited, it is reasonable to recommend a run-up distance/pipe diameter ratio of 30 for design. This should be considered reasonable and bounding. An interesting side note to this discussion is that Reference 18 makes a point to mention that the combustible gas mixture significantly affects the run-up distance. As stated, "Any reduction of the hydrogen concentration below the stoichiometry results in the significant increase of the run-up distance." This provides further basis that the use of 30 as a reasonable run-up distance value is conservative with respect to the reality of such a mixture forming and allowing a flame front to move toward a DDT condition. A cautionary note about this value however, it is to be used for relatively smooth pipe (again as expected for normal vent piping, note discussion on assumed BR). If there are known obstructions along a potential flame front travel path (due to rupture disc housing, open valve seat, etc.) then an evaluation based on Reference 18 is recommended.

Carbon Monoxide and Run-Up Distance –

Carbon monoxide is not considered in many of the references cited in HCVS-WP-03. It is not known as a predominant cause of deflagrations and detonations in normal industry processes. However it is recognized for its potential in a severe nuclear power plant accident. Fortunately, much of the data provided in many of the references listed address the attributes of various hydrocarbons. Hydrogen based combustible gas mixtures are known to have relatively short run-up distances based on the slight cell sizes of their progressing flame fronts. The cell sizes of associated hydrocarbons are understood to be larger. As such, reasonable parallels may be drawn to the run-up distance of a flame front based principally on carbon monoxide, as opposed to one based on hydrogen (the former being longer).

Another indicator of run-up distance is the Chapman-Jouguet velocity (U_{CJ}) of given fuel mixtures. If such a mixture has a relatively high velocity, it will have a relatively short run-up distance due to the reactivity of the mixture. The lower the velocity, the longer the run-up distance. Table 6 from Reference 11 (an explosion dynamics lab report from Cal Tech) provides a set of values for carbon monoxide/air mixtures (including a hydrogen constituent) and the corresponding CJ velocities. It is easily seen that none of the CJ velocity values provided are greater than the U_{CJ} stated in Table 1 of Reference 4 for a hydrogen/air detonation (with no other fuel). Note that the U_{CJ} values given in that table (Table 1) are in line with the hydrocarbon U_{CJ} values given in the other associated tables in Reference 11. Note also that Table 1 of Reference 4 provides values for hydrocarbon cell sizes that are markedly larger than those for a simple hydrogen/air mix. Based on this information, the hydrogen mixture run-up distance may be reasonably accepted as bounding.

Adverse Effects of Allowing Deflagrations -

- **Within the Run-Up Distance Allowance:**

Based on using the methodology of not exceeding the prescribed Run-Up Distance in designing an extended tailpipe for such vent systems, it is understood that a deflagration may be realized in the tailpipe of either a downstream check valve or a downstream control valve. Although this does represent a somewhat rapid combustion of gases in such a portion of the vent, this does not pose a threat either to the piping itself nor to the piping support system. This is based on the nature of how a deflagration occurs as opposed to that of a detonation.

The pressure pulse of a deflagration is markedly lower than that of a detonation. Reference 25, Figure 6 points at a peak deflagration pressure on the order of ~1.7 X P_o. Understand however that the cited testing was conducted in a large, yet sealed, test volume. Although there would be some nominal local pressure rise due to the deflagration, the use of 1.7 as a multiplier is conservative. Considering a dynamic load factor of 2 (Based on Reference 2), this would yield an effective hoop stress of (2 * 1.7 * 14.7 psia) 50 psia. Comparing this to the static equivalent pressure provided in Section 5.2, Item 2 of this white paper along with the discussion on common piping capabilities, regardless of the conservatisms of using Reference 25 as a starting point, it is easily assumed that this is well within the capabilities of piping which would be used in a vent pipe.

Deflagration wave travel is subsonic ($w_1 < a_1$) and the associated propagating wave causes flow both upstream and downstream of the deflagration wave (See Section 3.5 of Reference 22). As deflagration pressure waves travel out in both directions (as is expected to be the case because the run-up distance is not exceeded), such a combustion event traveling sub-sonically, will relieve the majority of the pressure build up out the open end of the vent system. The following should be noted simply to contrast the difference in the characterization of a deflagration and that of a detonation; With respect to axial loading, by nature of a detonation wave, the force of the associated shock wave travels forward of the shock wave only. This is in stark contrast to that of a deflagration. In such a case, even if a complete DDT were to occur at a minimal distance into an open ended pipe and travel up the pipe toward the last isolation valve in that piping system, that valve would have the potential (depending on the configuration of the piping system) to experience a large percentage of the full magnitude of the force of that shock wave. This is better stated in the wording of Section 3.5 of Reference 22, "…detonation waves are supersonic ($w_1 > a_1$) and a propagating wave will not induce flow upstream but only downstream." Again, this is not the case for a deflagration wave.

Reference 21 provides information which appears to be in agreement with the above in that reference's Section 2.3. Although this document is written mainly to address deflagrations and detonations which occur in a nuclear plant's containment structure proper, the terminology and descriptions used are in agreement with the statements relative to the differences in the 2 phenomenon (deflagration and detonation) from Reference 22. As stated, “Deflagrations are combustion waves in which unburned gases are heated by thermal conduction to temperatures high enough for chemical reaction to occur. Deflagrations normally travel sub-sonically (consideration for run-up distance assures this) and result in quasi-static (nearly steady state) loads on containment.” That statement is followed by more information tying detonations to their relationships to shock waves and state, “Detonation waves travel supersonically and produce dynamic or impulsive loads on containment in addition to the quasi-static loads,” (i.e., in addition to deflagration induced loads). This is stated again to note the contrast between the two.

In addition to the deflagration loading discussion above, it may be assumed that if the downstream check valve configuration (Option 5) were used and it leaked by on a gross scale in contrast to its expectations (See Design Considerations for Option 5 for more information) only a minimal deflagrable mixture could be produced (again considering gross leakage and ideal mixing conditions conditions). If such a mixture ignited, based on the information above the check valve would have sufficient time to crack open and prevent any pressure buildup in the vent line.

- **Within the Piping System Proper Considering Downstream Elbows and an Open Release Point (as is the case for Option 1) –**

As has been stated, the deflagration wave front will travel sub-sonically (up to near sonic velocity) in both directions. Accepting that the potential that a DDT will indeed occur is negligible (see discussion in Appendix A), the maximum dynamic loading from such a pressure wave will be based on that pressure front moving at near sonic speed. Based on a review of several calculations of vent flow at the conditions specified in the Vent Order (Reference 1), it is reasonably accepted that vent flow will be at a similar (near sonic) velocity as the pressure wave associated with a deflagration. And considering that the thrust load of venting (with the potential to have a heavier contingent of nitrogen than the deflagration flame front) will be equal to or greater than the deflagration load, the dynamic loading induced by a deflagration should be enveloped by that of the venting process itself.

With respect to the thermal load induced by the deflagration (See Mixing Discussion in Appendix A), it must be understood that although the burning gases will have a higher temperature than system design temperature, the combustion will not be sustained due to the limited supply of hydrogen. As such, the total heat input into the system is limited. Such a short duration burst of high temperature will be easily accommodated and quickly dissipated by the steel piping.