General Staff Comments on HCVS-WP-03, Rev. 0

1. The paper appears to suggest a design that would "preclude" a DDT occurring would establish acceptability for vent operation with combustible mixtures up close to the DDT threshold without designing for detonations or preventive measures such as inerting (sufficient to prevent any ignition). Given the uncertainties involved with the DDT phenomena, the staff believes that it would require more detailed and time consuming reviews and audits with less likelihood of staff determination of acceptability than either the detonation tolerant or inerted approach.

2. Based on the OIP submittals, there seems to be two broad concepts in the vent pipe configurations, one consisting of long lengths of piping (underground and above ground) routed to the plant chimney and the other consisting of shorter lengths of piping where the vent pipe is routed to the RB roof line. In addition, some of the OIPs show a control valve, while others do not explicitly identify one. However, it appears that both broad concepts could be represented by a few common schemes. It is recommended that the industry propose an approach or combination of approaches that will be used for these common schemes. A reasonable convergence on the acceptability of the approaches would eliminate the potential for a long review process with individual OIP submittals.

1.0 Purpose

The purpose of this paper is to present a series of viable options which a site may use to meet requirements 1.2.10 and 1.2.11 of Vent Order EA-13-109 (Reference 1). Those requirements are written to address the potential dangers of venting combustible gases during a severe accident which involves fuel damage.

It should be noted that this paper is not intended to address the sizing, configuration or functional capability of the vent system as related to other requirements set forth in the Vent Order (Reference 1). It is written only to address strategies and options to prevent vent failure due to deflagration/detonation of combustible gases.

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 that 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 must be enhanced and made "severe accident capable." Part of this 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 multiple potential hydrogen detonations. This is due to the need to potentially vent multiple times (in a severe accident scenario) to prevent containment over pressurization 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.

2.1 Applicability

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

Relevant Order EA-13-109 Requirement
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.

3.0 Achieving of a Detonable Mixture

By the referenced Order Elements the vent system must either be designed to assure that a detonable mixture cannot accumulate (more specifically, oxygen cannot be provided to and mixed with the combustible gas[es] such that a detonation can occur) or the vent piping system must be able to accommodate multiple detonations and remain functional. These requirements presuppose 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 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 that 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 evolution has been secured.

Summary of Comments on Staff Comments on White Paper NEI HCVS-WP-03_Attachment (3).pdf

Page: 2

Number: 1 Author: nrk1 Subject: Highlight Date: 08/18/2014 3:34:32 PM

Number: 2 Author: nrk1 Subject: Sticky Note Date: 08/18/2014 3:40:56 PM
Documents focuses only on detonable mixtures. There is no discussion on deflagrations which should also be avoided.

Number: 3 Author: nrk1 Subject: Highlight Date: 08/18/2014 4:26:44 PM
than

Number: 4 Author: nrk1 Subject: Highlight Date: 08/19/2014 9:35:13 AM
Not clear what this term means in relation to this document.

Item	Assumption	Basis
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 would be greatly depleted by the prior venting operations.
4	[1]There is some type of ignition source available in the vent flow path (e.g., catalyst particles, spark, etc.) such that ignition of a deflagrable mixture is possible.	[2]This is considered as a low probability occurrence. 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 adherence of any such particle to the piping walls due to the moist surface. In addition, any unattached particle would likely act at the nuclei for the formation of water drops during the condensation process (which would drive them to attachment to the pipe wall.

Page: 3

Number: 1 Author: nrk1 Subject: Highlight Date: 08/18/2014 4:27:23 PM

Number: 2 Author: nrk1 Subject: Highlight Date: 08/18/2014 5:48:09 PM

Given that the system is for severe accident venting and the uncertainties associated wit it, there must be always an assumption of an ignition source such as fission product collection points.

Item	Assumption	Basis
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-4905 (Reference 10), 13% is the minimum hydrogen concentration by volume that would allow for a detonation to occur in a prompt detonation. However, from research into this issue, DDTs have been initiated in as little as 11.5% hydrogen (by volume). However this was in a special "rough piping" case developed to enhance the DDT capability (see Reference 9). 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.
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.
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 a DDT is achieved. That run-up distance is based on pipe diameter and is understood as being ≥30L/D. If the mixture is less than the run-up distance or is a 'broken' (intermittent) mixture, it will not produce a detonation. See Appendix A for further information.

As stated, 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. It should also be realized that the occurrence of

Number: 1 Author: nrk1 Subject: Highlight Date: 08/18/2014 5:59:44 PM

The value of 11.5% hydrogen by volume corresponds to a gas temperature of 293 deg K. A later research report (NUREG/CR-5525) puts the minimum hydrogen concentration at 9.4% by volume for a gas temperature of 373 deg F. DDT is possible at a relatively low hydrogen concentration and variation exists in laboratory in laboratory experimental results so considerable uncertainty exists for in-plant severe accident venting conditions and potential for a DDT.

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 DDT occurring. After a venting evolution, the vent pipe would contain the same inert mixture of steam and hydrogen (the predominant constituents of the effluent) as existed in containment. 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, 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.

[1] From research into hydrogen deflagrations and detonations since the events of March 2011 at the Fukushima nuclear facility, 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 10 cites the use of a “high explosive” in their large test tube 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 13% hydrogen by volume (Reference 10) in the mixture readily available to be oxidized. Notes from a series of research papers on hydrogen detonations speak of the large amount of energy required for such 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

Page: 5

Number: 1 Author: nrk1 Subject: Highlight Date: 08/18/2014 6:09:54 PM

Large energy requirement for prompt detonation has been known for some time. What are the published references on hydrogen research, post 2011 Fukushima events, that are cited here to backup the mentioned research.

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.

3.1 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 1500^0F, zirconium begins to scavenge available oxygen from adjacent water molecules to form zirconium oxide (ZrO_2) and in the process liberating 2 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 3.2 for further discussion on carbon monoxide). Considering a median sized BWR containment (~250,000 ft³) 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 to be produced.

Page: 6

Number: 1 Author: nrk1 Subject: Highlight Date: 08/18/2014 6:12:18 PM

Combustion that comes short of DDT (e.g. deflagration with FA) can also cause pipe stresses.

Number: 2 Author: nrk1 Subject: Highlight Date: 08/19/2014 9:26:30 AM

Ex-vessel core-concrete-interaction can generate as much combustible gases in the long-term as in-vessel metal-water reaction. The WP does not appear to sufficiently emphasize this.

3.2 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.

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 (very much 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 Section 3 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 concentration may be beyond 13.5%. 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 bounded by the hydrogen run-up distance. See Appendix A for further information.

4.0 Discussion

In consideration of the basis and discussion in Section 3, 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 this phenomenon as a realistic and achievable occurrence. Explanations and discussions related to the more closely associated OE are as follows:

1	The Hamaoka and Brunsbuettel events of 2001	These are probably the best known (and perhaps the only) examples of 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 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 67% hydrogen to 33% oxygen by volume. Research at the time of, and shortly after, the event investigation (Reference 21) cited the potential for the gases in this event to have been ignited by a catalyst existing in the volume containing the stagnant gases. Recent Noblechem injections (which act as an inter-vessel catalyst) and an upstream catalytic recombiner were cited as possible catalyst sources. More contemporary research (Reference 20) however, points at the distinct possibility that pressure spikes (due to valving operation relative to adjacent process flow) more likely causing the prompt detonations at both plants. 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 2 gases at these high concentrations that were made available in the 2 events cited. There is little chance of an ignition source in an HCVS and no possibility of a similar (relative to initial) pressure spike (as proposed in Reference 20).

Number: 1 Author: nrk1 Subject: Highlight Date: 08/18/2014 6:22:42 PM
This paper (Reference 20) is unproven theory. Note that INPO SER indicated that T/H transients were conducsted and not shown to ignite the mixture. Reference 20 is questionable, an therefore, staff recommends removing the reference and any statements that are based on the reference.

2	Evolutions associated with Main Electric Generator gassing and associated hydrogen venting	After a shutdown period, the Main Generator must be purged of air and pressurized with hydrogen (generator gassing). This is done by first purging the air out with carbon dioxide, then filling and pressurizing with hydrogen. The generator gassing process is not conducive to producing a mixed section of hydrogen and air unless it is done improperly. The use of carbon dioxide as a blanketing gas serves to prevent hydrogen and oxygen (from air) from mixing and creating a deflagration potential. Prior to a maintenance period, the hydrogen is purged to atmosphere with carbon dioxide, then the carbon dioxide is purged with air. The pre-maintenance process of venting and purging hydrogen from a generator, as well as the routine venting of hydrogen for purity maintenance, are the more likely processes which could, conceivably, set up conditions for a DDT to occur. Although pressing air out of the vent pipe with the vented hydrogen should not create such a 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 does offer the opportunity for a hydrogen/air exchange during the time that the hydrogen clears the vent pipe and is replaced with air. During that time mixing will indeed 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. It should be noted that this mixing evolution is quite similar to the air/hydrogen interfacing discussed in the paragraphs following the Assumptions table presented in Section 3.0. However, there are no reported instances of detonation occurring. Based on the OE reviewed coupled with an interview with GE personnel very familiar with generators and the gassing and venting processes, detonations simply do not occur during or after hydrogen venting. There are certainly instances of hydrogen burns as evidenced by visual flames and scorched paint on the vent pipe. 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 uses a similar venting strategy and also involves hydrogen. And although the same forces as discussed in Section 3.0 (just after the assumption table) 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).

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. Radiolysis is the separation of water into its fundamental elements in the reactor vessel. 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 from the steam in the condenser when the pressure drop is realized (much the same as the H_2/O_2 release from leaked steam in the Brunsbuettel 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 leakby 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 an ideal ignition source as it quickly raises the temperature of the near perfect stoichiometric mix of hydrogen and oxygen to allow a deflagration. Although at least one of these instances have 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. 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 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.

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 such detonations, or design it such that a combustible gas mixture cannot be realized. [1] The first philosophy alludes to a passive system which will remain in place and operable after multiple instances of the DDT evolution. In effect, such a system would be able to sustain and accommodate several detonations and retain its ability to vent. 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, these two design avenues are seen as defense in depth against the potential for hydrogen detonation damage in HCVS piping. A more direct approach (based both on the aforementioned 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 to avoid a hydrogen detonation altogether. This design philosophy is presented as Option 1 in the table below.

Table 1 (Section 5.0) 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.

Number: 1 Author: nrk1 Subject: Highlight Date: 08/18/2014 6:34:40 PM

Severe accidents vent systems were engineered and installed in many countries outside of USA. There is no indication if this document draws upon such experience. Please describe any other severe accident vent installations and experiments that support the basis for the dominant approach promulgated by this paper, that DDTs are not likely to occur in the vent pipe.

5.0 Options

Option	Description	Advantages	Disadvantages
1	Design the HCVS, using both technical and OE lessons learned, such that a hydrogen detonation is avoided.	1. Completely passive	1. Requires attention to detail as related to those design attributes which could potentially introduce hydrogen detonation susceptibility.
2	Design the entire vent piping beyond the primary containment isolation valves to withstand flammable gas detonation.	2. Completely passive	1. Requires valve(s) to be upgraded due to loading 2. Potentially requires upgraded piping 3. Requires upgraded pipe supports 4. Requires more rigorous stress and support analysis
3	Install a purge system to prevent flammable gas detonation.	1. Requires minimal modification to existing or as designed system 2. Minimizes or 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 (may be PCV) downstream of the PCIVs and either design the system downstream of the secondary isolation 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 start/stop cycles are controlled by the single downstream valve.	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) 5. Adds challenges to support and maintain a large mass with an offset actuator at the end of the vent.

Page: 12

Number: 1 Author: nrk1 Subject: Highlight Date: 08/19/2014 10:08:34 AM

The table appears to be lacking the inclusion of designing the vent to support open and leave scheme (until other means of containment cooling were to be established that allow for pressure control. The advantage would be that flow would be continuously moving out the vent line minimizing the possibility of air entering the vent line minimizing the possibility of air entering the vent line from the discharge point, a form of inerting strategy. Disadvantage is that an external filter may be necessary to ensure radioactive aerosols is acceptably low.

Number: 2 Author: nrk1 Subject: Highlight Date: 08/19/2014 8:18:04 AM

Should this be flammable mixtures?
Should deflagrations also be avoided?

Number: 3 Author: nrk1 Subject: Highlight Date: 08/19/2014 9:10:29 AM

Does this mean if the system is designed for the design attributes in Section 5.2 (1.) of this WP, then there is nothing else that needs to be done to comply with the requirements of Order EA-13-109 regarding hydrogen?

Option	Description	Advantages	Disadvantages
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 2. Additional failure modes (inability of check valve to open or to close once opened) 3. Adds challenges to support and maintain a large mass at the end of the vent.

5.1 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. But such detonations do not occur. The most common 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 (once again as with each such evolution) with air. 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 detonations have been reported for such occurrences. The best reasonable explanation may be that there simply isn't enough homogeneous mixing occurring such that Assumptions 5, 6, and 7 have ever been met. Option 1 is written to collectively consider this and other lessons learned from related industry OE coupled with information from engineers familiar with systems associated with generator and system venting such that the opportunity for such detonations to occur becomes inconsequential.

Number: 1 Author: nrk1 Subject: Highlight Date: 08/19/2014 8:44:45 AM

Multiple open/close cycles also need to be evaluated as part of the industry proposed filtration strategies. Potential for manufacturer's testing for leakage and periodic testing after implementation. installedduring addr seting lyLeakage reqTighfor cn

2. During the development of these options it was realized 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) was 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, PCV, or check valve) may be placed at the end of the vent pipe (which would remove the ability of the downstream 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 A has been developed to provide guidance relative to an accepted run-up distance.
3. Although the defense in depth option of designing for detonation is the cleanest method to use due to its passive nature, it was also realized that it may require extensive 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 must be upgraded to accommodate a detonation, and a much more rigorous piping and support analysis must be used to design the system. Along with this, the support system for such piping will need to be upgraded/modified. More specific information is to follow on this subject in the upcoming sections.

5.2 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 to minimize any opportunities to create/facilitate a venting environment conducive to a DDT.

   Design Considerations for a Design to Preclude a DDT Occurring:

   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 (typically inherent in HCVS design).
   e. It is understood that vent piping will typically 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's diffusive properties would allow mixing of the hydrogen with any other gases which may collect in pockets created by poor sloping.

2. **Design for Detonation** – This 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

Page: 15

Number: 1 Author: nrk1 Subject: Highlight Date: 08/19/2014 8:55:51 AM

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 Section 3, 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) Section 3 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. 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.

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 rigorous 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 quite detailed and sometimes quite arduous 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:

3. 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 – Recent research and analysis has brought to light 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.

4. **Install an Active Purge System –** This 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 1) 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's 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 SCIV or flow control valve) upon PCIV closure. The function may be automatic or manual. The purge system is an argon purge that is automatically injected into the vent piping downstream of the PCIV.

   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.

A variation on this option is setting this up as a manual system and procedurally controlling its operation. 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.

5. **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.

6. **Install a Secondary Control Valve Near or at the Exhaust End of the HCVS** – The design/operating concept in this case is to have 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 A (up to and including placing such a control valve at or very near the release point.

7. **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 A (reference for further information) provides a value of 30L/D (total pipe length divided by pipe diameter) as a reasonable maximum 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.

8. **Install a Check Valve Near or at the Exhaust End of the HCVS** – The design concept, in this case, 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 a “barroom swinging door” arrangement much like a tornado damper. Soft seated versions of this type of valve could be mounted vertically (with the ‘barroom 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.

Per vendor catalogues and conversations with vendors of such components, it is understood that soft seated versions of such valves (capable of operating at wetwell venting design temperatures) can be expected to have an effective leakage of approximately 2 cc/hr/inch of seat. For a 14" valve this equates to 0.005ft³/hr of inleakage (0. 001ft³/hr of oxygen). With (for example) a 300' run of 14" pipe (volume = 321ft³) it would take many days/weeks to reach an oxygen concentration of 5% (which would only support a low flame – no detonation potential). In addition, any ancillary PCIV leakage from the other end of the system (made up of mainly steam, hydrogen, and trace nitrogen) would 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 a check valve's sealing ability, if drywell venting is considered, the seals for any valve used must meet the design temperature requirements for venting that volume (drywell).

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 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 will draw 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.

9. 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.
b. The mass of the valve at that location may introduce design challenges to seismically support it.
c. Consider placing a PVC cap or low pressure rupture disc downstream of the valve to protect it. Also consider nitrogen blanketing the HCVS.
d. Consider installing a permanent work platform for maintenance.
e. The location may present maintenance challenges over the life of the plant.
f. The pipe volume will experience negative pressure with respect to atmospheric. This must be evaluated.
g. HCVS-FAQ-05 should be consulted for interim valve and interim valve testing requirements.
h. 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.

6.0 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 is written relative to those sites which vent multiple units through a single Plant Stack. 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) chimney (Plant Vent 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 be used 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. 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). 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. In addition to the 'boundary valve' discussion from HCVS-FAQ-05 (Reference 16), all valving associated with systems which release into a common plant stack must be closed and leak tight to the point [1]hat 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. 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 a common such 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. [2]In addition, if there are dilution fans involved in the function of the Stack, priority may need to be given to providing power to those fans once venting has been initiated such that undue amounts of hydrogen will not collect in the base of the Stack.

Page: 23

Number: 1 Author: nrk1 Subject: Highlight Date: 08/19/2014 9:17:45 AM

Number: 2 Author: nrk1 Subject: Highlight Date: 08/19/2014 9:17:45 AM

When supporting severe accident venting function, powering any fans for dilution purposes could not rely on FLEX portable equipment for the first 24 hours. Also, any fans needed for dilution air flow would need to be seismically rugged and have power connections suitable for severe accident use.

7.0 References

1. USNRC, Order EA-13-109, Order Modifying Licenses with Regard to Reliable Hardened Containment Vents Capable of Operation under Severe Accident Conditions, June 6, 2013.
2. BWROG Document GEH #000N2731, "Guidance for Vent Pipe Design Considering Potential Hydrogen Deflagration and Detonation"
3. NEI 13-02 Rev. 00, Industry Guidance for Compliance with Order EA-12-109 – BWR Mark I & II Reliable Hardened Containment Vents Capable of Operation Under Severe Accident Conditions, November 2013.
4. PVP2006-ICPVT11-93670, "Structural Response of Piping to Internal Gas Detonation," Dr. J. E. Shepherd, July 2006.
5. G. O. Thomas, "The Response of Pipes and Supports to Internal Pressure Loads Generated by Gaseous Detonations," Journal of Pressure Vessel Technology 124, no. 1 (2002): 66-73.
6. PVP2011-57278, "Forces on Piping Bends Due to Propagating Detonations," Ligon, Gross, Shepherd, July 2011.
7. ASME B16.34 – 2009, "Valves – Flanged, Threaded, and Welding End"
8. McBride, B., and Gordon, S., 1996. Computer program for calculation of complex chemical equilibrium compositions and application: II. Users manual and program description. NASA Reference Publication 1311, June.
9. Kuznetsov, Alekseev, and Dorofeev, "Comparison of Critical Conditions for DDT in Regular and Irregular Cellular Detonation Systems," May, 2000.
10. NUREG/CR-4905, "Detonability of H_2-Air-Diluent Mixtures," Tieszen, Sherman, Benedick, Berman.
11. J.M. Austin and J.E. Shepherd, "Detonations in hydrocarbon Fuel Blends," Explosion Dynamics Laboratory Report FM99-6, July 10, 2000.
12. Card, Rival, and Ciccarelli, "DDT in fuel-air mixtures at elevated temperatures and pressures," Shock Waves (2005).
13. NUREG/CR-2475, "Hydrogen Combustion Characteristics Related to Reactor Accidents," July 1983.
14. EPRI Report 1026539, "Investigation of Strategies for Mitigating Radiological Releases in Severe Accidents," 2012.
15. NUREG/CR-6509, "The Effect of Initial Temperature on Flame Acceleration and Deflagration-to-Detonation Transition Phenomenon."
16. HCVS-FAQ-05, "HCVS Control and 'Boundary Valves'."
17. Gamezo, Ogawa, and Oran, "Deflagration-to-Detonation Transition in H_2-Air Mixtures: Effect of Blockage Ratio." January 2009.
18. S.B. Dorofeev, "Hydrogen Flames in Tubes: Critical Run-Up Distances."
19. Wingerden, Bjerketvedt, and Bakke, Christian Michelsen Research, "Detonations in Pipes and in the Open."

20. PVP2010-25261, "Hydrogen Ignition Mechanism for Explosions in Nuclear Facility Pipe Systems," Robert A. Leishear, July 2010.
21. INPO SER 1-03, based on WANO SER 2003-2, "Piping Ruptures Caused by Hydrogen Explosions," 2003.

Page: 25

Number: 1 Author: nrk1 Subject: Highlight Date: 08/19/2014 9:11:20 AM
Recommend removing this reference, no experimental basis, just a theory.

Number: 2 Author: nrk1 Subject: Highlight Date: 08/19/2014 9:18:11 AM

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. Section 3.0 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.

APPENDIX A

Consideration of Run-up Distance

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.

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 an easily understood 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