1. Purpose and Scope

The purpose of this report is to offer some thoughts on improving containment vent systems in United States Mark I and Mark II BWRs in light of the accident at the Fukushima Dai-ichi nuclear power plant in Japan.

What follows is a description of the major benefits of containment venting and some possible detriments. To illustrate these benefits and possible detriments, a number of hypothetical scenarios are examined where venting could affect their outcomes. While emphasis is given to station blackout scenarios (SBO), like the accident at Fukushima Dai-ichi, other venting scenarios without SBO conditions (Loss of offsite power or LOOP events) are discussed. A set of comparatively simple improvements in the design of hardened vents is offered and a discussion is presented on how to use the SOARCA computer code to create a more comprehensive containment venting analysis. There are two containment vent systems; one that originates in the wetwell gas space and the other that originates in the drywell. The containment vent system that originates in the drywell is used to purge the drywell and is not reviewed in this report. A number of other related subjects are touched upon including the value of a systems approach to resolving the venting issue, the need for other radionuclide filters, and the safety significance of inerting.

Of equal importance, a modern regulatory process is proposed for making further progress in plant safety, without relying on the Backfit Rule.

2. General Discussion

Nuclear power plants have significant redundancy, diversity, and design margins so that the probability of a core melt situation from at power internal event sequences is quite low. Nuclear power plants also have significant capability to handle large external events such as earthquakes, hurricanes, tornadoes, floods, etc. A number of nuclear plants in the United States have had these capabilities tested by actual severe natural phenomena and all achieved safe shutdown conditions. Among these severe natural phenomena challenges was the Category 5 hurricane Andrew that struck the Turkey Point nuclear plant in Florida and the recent beyond design basis earthquake that struck the North Anna plant in Virginia. These power plants safely shut down. Nuclear plants have also safely withstood tornadoes and external flooding conditions. Even the accident at Fukushima Dai-ichi showed significant capability to withstand a huge earthquake. It appears that the structural integrity of the containment system and the spent fuel pool at these power plants were sufficient to withstand the effects of this magnitude 9.0 earthquake and all onsite emergency diesel generators (EDGs) started as designed. These EDGs apparently operated for about 40 minutes until waves of water from the tsunami inundated the site. If there had not been a huge tsunami that ended the capability of these EDGs, the Fukushima Dai-ichi plant might be remembered today as an example of the robust nature of nuclear power plant designs in coping with very large earthquakes. However, a lesson learned from the effects of the tsunami was that the hardened containment vent system, originally designed to reduce the risks of a loss of suppression pool cooling event, can be redesigned to minimize the effects of a long term station blackout.

A recent analysis by the Health Physics Society concluded that the health effects due to exposure to radiation from the Fukushima accident would be very small; essentially no early health effects and long term health effects that would not be statistically discernable compared to normal background cancer fatalities from non-accident causes. One can surmise that, in general, a natural phenomenon strong enough to cause fuel damage at a nuclear power plant, would itself likely cause economic and health consequences far in excess of any health and economic consequences from a nuclear accident initiated by this huge natural phenomenon.

Even though US nuclear power plants have locations where large tsunamis are not a significant risk, other large, but infrequent, natural phenomena can occur that might contribute to an SBO condition. The first effect of the earthquake in Japan was the loss of offsite power (LOOP). Nuclear power plants are designed to cope with LOOP situations. The second effect was the impact of the tsunami which converted a LOOP type event into an SBO event. Nuclear power plants also have capabilities to withstand SBO conditions for a number of hours by using steam driven safety equipment where the plant itself generates this steam. Further, nuclear plants in the United States have enhanced their capability to withstand SBO conditions when they installed post 9/11 safety equipment and this SBO capability has been further supplemented in the wake of the Fukushima accident. Additionally, in many postulated SBO scenarios not involving large natural phenomena a fair percentage of the time off site power would be restored within the window of time that the facility can operate under SBO conditions without fuel damage.

Nonetheless, it is reasonable to assume that in the vicinity of a large natural phenomenon, grid-based electricity will be unavailable to nuclear plants. Terrorist acts also could readily interrupt grid-based electricity and, far less likely, cause SBO conditions. It can be postulated that there might be subtle, but quite important, secondary events that result from the primary large natural phenomenon could cause the loss of the EDGs like the secondary event of a large tsunami following the earthquake at Fukushima. For example, one might <u>speculate</u> a very large flood that shuts down the electrical grid and later establishes a pathway though the floor drains in the structure that houses the EDGs and water backflow disables these EDGs. Another <u>speculation</u> could be that a large earthquake causes a loss of offsite power and also starts fires or internal flooding at locations within the electrical distribution system in a nuclear power plant. The EDGs might still be operable, but the electricity they could produce would not be deliverable to the safety systems they were intended to supply. Even without such speculations, Individual Plant Examinations have calculated a small probability of SBOs just from a loss of grid based electricity plus a series of internal failures. So what is being examined here is a subset of the SBO sequences where the accident continues beyond the coping time at Mark I or II BWR power plants, as presently updated. Further , this report addresses what might be done to improve the containment hardened vent system to minimize safety concerns for this very small subset of sequences.

Because there are a number of low frequency pathways to reach SBO conditions, it is necessary to examine how hardened containment vent systems in Mark I and II BWRs might be made to work under SBO circumstances. It is also necessary to expand this SBO related venting analysis to other scenarios such as a loss of offsite power (LOOP) condition to get a complete picture of the benefits and possible detriments of containment venting.

3. Benefits and Detriments of Containment Venting

Containment venting of BWRs is a complex subject, perhaps more than some people realize. Venting can enhance the operation of some safety systems and help maintain containment integrity in some scenarios, but can also reduce the operability of some safety systems and possibly increase the risks of a loss of containment integrity or damage to safety systems in other scenarios.

3.1 Benefits of Containment Venting

An operational hardened vent safety system does more than prevent containment overpressure. This safety system also:

A. Increases the chances of aligning low pressure reactor vessel injection systems by depressurizing the containment. High containment back pressure would limit the capability of the reactor safety relief valves to depressurize the reactor vessel. With containment venting, once the reactor vessel is depressurized, low pressure injection of emergency water into the vessel could begin.

B. Causes much of the radioactive iodine and cesium released from damaged fuel, and no longer within the reactor vessel, to be trapped in the suppression pool. By doing this the need for additional filters in the power plant is greatly reduced. By capturing radioactive material in the suppression pool plant recovery actions and longer term clean-up actions are simplified. The water in the suppression pool offers some shielding capability, thereby lowering dose rates in the working spaces near the outside of the torus that contains the suppression pool. Because of the large heat capacity of the suppression pool, the heat load from the fission products trapped there do not present an overheating problem.

C. Determines the pathway for non-condensable gases such as inert nitrogen, explosive hydrogen, and radioactive noble gases so that these gases are carried away from the power plant's structures and plant personnel along a controlled pathway. If other non-condensable gases are generated from an accident, such as from some kind of core-concrete interaction in the drywell, these non-condensable gases would also be discharged to the environment along a controlled pathway. This same controlled pathway would also conduct steam within in the wetwell gas space to the outside environment.

D. Reduces the likelihood of hydrogen explosions within the containment that might overpressurize the containment. This reduction in the likelihood of overpressurizing the containment through hydrogen explosions comes about in three ways. First, venting reduces the inventory of hydrogen inside the containment. Second, as the inventory of hydrogen in the containment decreases, the hydrogen concentration may drop below the level required for an explosion. Third, by lowering the containment pressure, venting increases the pressure margin between the containment failure pressure and this lowered accident pressure. This larger pressure margin reduces the likelihood of having a

hydrogen explosion pressure spike big enough to exceed the containment's failure pressure.

E. Avoiding hydrogen explosions enhances recovery actions by preventing the creation of debris generated by hydrogen explosions within the secondary containment that could hinder access to safety equipment or enter the spent fuel pool and damage the spent fuel stored there .

F. Reduces the likelihood of containment overpressurization from suppression pool bypass events.

3.2 Detriments of Containment Venting

A. In some accident scenarios venting might lead to damage of the pumps used to cool the reactor core due to low Net Positive Suction Head conditions in the containment.

B. In some accident scenarios venting might lead to subatmospheric conditions in the containment.

4. Illustrative Containment Venting Scenarios

4.1 Introduction

Four containment venting scenarios are described below to help identify the benefits and detriments of venting and also to indicate how venting might affect the performance of different safety systems during different accident scenarios. First, a general description of these four scenarios is given in this section. This is followed up by more detailed descriptions in Sections 4.2, 4.3, 4.4, and 4.5. These four scenarios are not an exhaustive list. For example, the role of containment venting in ATWS scenarios was not examined. Scenarios A and B illustrate the benefits of a hardened containment vent system. Scenarios C and D illustrate some potential detriments of containment venting. The general description of these four scenarios follows:

A. A large natural phenomenon has occurred causing a complete loss of electric power (SBO). Because of this complete loss of electricity, it is then not possible to open the isolation valves in the containment hardened vent system. It is assumed that opening these isolation valves by hand is too difficult and therefore not done. Pressure buildup in the containment would then disable steam driven

emergency core cooling systems, leading to a core melt and the generation of hydrogen which initially remains within the containment. The partial pressures of this accident generated hydrogen, and those of the steam, and nitrogen, used as an inerting agent, continue to rise until containment integrity is lost through overpressure. Further destruction of the power plant occurs because the release of hydrogen gas near or within plant structures, which soon leads to an explosion. The combination of a core melt and a loss of containment integrity results in a release of radioactive material into the environment. In this scenario, a functional hardened vent system would have reduced the likelihood of core damage and reduced the containment pressure thereby maintaining containment integrity. Simultaneously, a functional hardened vent system would have prevented damage to the secondary containment structures from hydrogen explosions and the creation of debris within the secondary containment building. Hence, a functional hardened containment vent system would have been a significant safety and economic benefit.

B. A large natural phenomenon or terrorist event has occurred causing a loss of offsite power. Onsite electric power is available from the emergency diesels plus some from portable electric power sources. However, it is assumed that this large natural phenomenon or random failures have also caused the hardened vent system to become inoperable. Even if onsite electric power were available to the hardened vent isolation valves, one can postulate that the large forces associated with this large natural phenomenon caused a misalignment of these isolation valves or a disruption of the electric power supply to the isolation valves, thereby precluding the opening of these valves. It can be further assumed that this large natural phenomenon also caused a small steam leak into the drywell. This small steam leak later causes the suppression pool water to be bypassed, which then quickly leads to a containment overpressure failure. In this scenario it is assumed that although containment integrity has been lost, this in itself does not cause core damage or the release of radioactive material or the generation of hydrogen. The loss of containment integrity through overpressurization might still result in a permanent shutdown of the power plant, even though no core damage had occurred. If venting would have worked, it would have been a significant economic benefit to the plant owners because the containment would not have become overpressurized..

C. A large natural phenomenon has occurred causing a loss of offsite power and a steam leak into the drywell. Because there are sources of onsite electric power, the isolation valves in the hardened vent line are opened. After most of the non-condensable gases in the drywell have been driven out by the steam leak and released to the environment via the hardened vent pathway, the drywell sprays are inadvertently actuated, leading to containment failure due to rapidly creating subatmospheric conditions. It is assumed that the vacuum breakers between the

containment and the outside environment whose purpose is to restore non-condensables (air) to the containment to prevent subatmospheric conditions, could not overcome the rapid depressurization caused by the initiation of the drywell sprays. In this scenario, venting, coupled with inadvertent initiation of drywell sprays, could have been a detriment to safety if this led to subatmospheric conditions.

D. A large natural phenomenon has occurred causing a loss of offsite power, but onsite electric power is available and the suppression pool water cooling system is operating. After a period of time, the isolation valves in the hardened vent line are opened. Prior to opening these isolation valves enough heat had been added to the suppression pool water to raise its temperature above 100 degrees Centigrade. When the hardened vent system is opened the containment pressure drops to near atmospheric conditions causing the water in the suppression pool to boil, possibly causing NPSH or pump cavitation problems in the suppression pool water cooling system. Poor timing of when the vent system is opened could be a detriment.

4.2 Scenario A

This scenario is essentially the Fukushima Dai-ichi situation. The loss of both offsite electric power and onsite emergency diesel electric power, only leaves a limited amount of battery power. Under SBO conditions The power plant would be darkened and only emergency lighting might be available. If there has been fuel damage radiation levels in the plant might be rising. Opening the isolation valves in the containment vent system by hand may be difficult, especially if valve accessibility adds to this difficulty.

As described in EA-12-050 and elsewhere, the inability to reduce containment pressure inhibits efforts to cool the reactor core. Hence the inability to vent high containment pressure, in turn affects the ability of steam driven emergency core cooling systems to keep working during SBO conditions. At Fukushima this led to reactor fuel melting, the generation of explosive hydrogen that exploded within the secondary containment building. Note that functional with a hardened containment vent system hydrogen ignition outside of the secondary containment building would have had inconsequential effects.

Two possible ways of overcoming SBO conditions that prevent vent isolation valves from opening are (1) install a dedicated source of electric power that is designed to open these valves and, (2) change the initial hardened vent isolation valve positions from “normally closed” to “normally open”. Other hardened containment vent configurations are presented later in this report.

Some BWRs with Mark I containments already have dedicated electric power sources to move the vent isolation valves into the open position. It may be that some of the additional electric power capability introduced as post 9/11 anti-terrorist equipment could also serve to supply power to open the hardened vent isolation valves. One would have to examine all the scenarios

where portable electric power was to be used to open the vent valves to determine if this can be done and done quickly enough, i.e., before the containment became overpressurized.

Alternatively, the two hardened vent isolation valve positions could be changed from “normally closed” to “normally open”. This converts an active safety system to a passive safety system in that neither electric power nor operator actions are needed in order to carry out the most important hardened vent safety functions. Once electric power is restored, these hardened containment vent isolation valves could be closed or even reopened, at times when changing the valve positions would be beneficial. It can be argued that even those BWRs that have dedicated electric power to open their hardened containment vent isolation valves would still benefit from changing the vent system valve positions to a “normally open” configuration. Under these circumstances the dedicated electric power supply to these isolation valves in the hardened vent system would be primarily used to close, not open, these valves.

It is possible to determine which initial valve position, “normally closed” or “normally open”, is preferable. The SOARCA program, discussed later, could compare off site releases of radioactive material, particularly cesium, for both the “normally closed” to “normally open” configurations by running a series of accident analyses covering all the sequences in which the hardened vent has a role to play. If the cesium release profile with the isolation valves with a “normally open” configuration is lower than the “normally closed” configuration, then the preferred valve position would be “normally open”. In other words, SOARCA analyses can be used to determine the preferred initial configuration of the vent isolation valves. Determining the preferred valve position would be an advancement in the application of PRA analyses combined with source term technology, using the SOARCA analytical capability.

Both the dedicated electric power supply vent design and the passive design with the isolation valves in a “normally open” configuration would have greatly reduced the impact of the Fukushima accident. Both would have enhanced core cooling and, at the very least, would have helped trap much of the radioactive iodine and cesium in the suppression pool, thus greatly mitigating the release of these radioactive materials into the environment. Hydrogen explosions, if any, would have occurred outside of the plant structures, thereby reducing the difficulties of achieving accident recovery. The dedicated power design has the advantage that the plant operators can select the timing when the vent system would be opened or closed. The simpler passive design has the advantage of eliminating any concern that a large natural phenomenon, like a severe earthquake, could itself cause some kind of a misalignment of a vent isolation valve causing it to be blocked from opening or some other unidentified cause of preventing hardened vent operation, such as human error when trying to open the vent valves or the loss of local dedicated electric power to these vent valves.

4.3 Scenario B

In this scenario it is assumed that there is a small steam leak into the drywell, the hardened vent is initially closed, there is no active heat removal from the drywell, but onsite electric power is available. Both large and small break situations were investigated by GE in its original Humboldt Bay and Bodega Bay pressure suppression experiments in the late 1950s and early 1960s. The

small break experiments revealed containment responses that were different from the large break experiments. For the small break experiments, the steam that entered the drywell mock up largely pushed the non- condensables (air in the experiment) out of the drywell, and eventually over to the air space above the water pool in the suppression chamber. The air above the pool water was compressed by this process and the containment pressure was elevated compared to its normal pressure near atmospheric levels.

In these early experiments, after driving out the drywell air over into the suppression chamber air space, steam from a simulated small break slowly began to flow into the downcomers. These downcomers were submerged about four feet into the water in the suppression pool. At first the steam from the drywell condensed inside the downcomer piping as it came into contact with the cold water in these downcomer pipes. The top layer of water in the downcomer reached saturation temperatures and the next increment of steam entering the downcomers could not condense there any more. The water in the downcomers was then pushed lower and lower by the steam until such time that it was completely pushed out of the downcomers. Once the temperature saturated water in the downcomers was expelled from the downcomer, the steam in the downcomer came into contact with the cold water in the suppression pool. This caused an instantaneous condensation of some of the steam in the experiment's downcomer, thereby creating a partial vacuum in the downcomer. The water in the suppression pool, already under pressure from the compressed non-condensables in the air space above the pool, rushed up into the downcomer, causing a further very rapid decrease in the pressure in the downcomer, i.e., a larger partial vacuum. It appears that shock waves were generated in the downcomer mock-up in the original BWR pressure suppression tests by this rapid depressurization of the steam in the downcomer followed by the surge of cold water up into the downcomer. After a while things calmed down again, cold water returned to fill the downcomer, and the cycle started over. This situation has been called "chugging" and is much more associated with small pipe breaks than big ones.

In these early experiments there was a vacuum breaker in the wetwell air space along the pathway between the drywell and wetwell. The purpose of this vacuum breaker was to return non-condensables in the wetwell air space to the downcomer to equalize the pressure inside of the downcomer with that in the wetwell air space. Without equalizing the air pressure in the downcomer with that in the wetwell air space, the height of the water column inside the downcomer could become excessive and diminish the usefulness of the pressure suppression concept. The shock waves that occurred in the downcomer during chugging events appears to have caused this vacuum breaker to open and close very rapidly, many times. This created the possibility that this rapid back and forth motion might cause this vacuum breaker valve to stick open. If that occurred, the steam coming down the downcomer might no longer be fully condensed in the suppression pool, with some of the steam flow going into the air space above the suppression pool. This would raise the pressure both in this air space and in the drywell. Because of the comparatively small volume of Mark I plants and the fact that the steam from the small break would have pre-heated the containment surfaces eliminating them as heat sinks, it would not take very long for a small break in this suppression pool bypass situation to cause pressures that might cause a loss of containment failure integrity.

It can be speculated that containment overpressure conditions can be reached from suppression pool bypass events if a large natural phenomenon caused a small steam leak and shook the vacuum breakers in the downcomer to the point that it stuck open, thereby accomplishing a similar suppression pool bypass situation as described above due to "chugging". Note that in this case, even though onsite electric power would be available and core damage would have been avoided, but containment integrity might be still be lost. Loss of containment integrity through overpressure could well result in the end of the useful life of such a plant, even without any reactor fuel damage. It is noted that steps have already been taken to lessen the probability of having a suppression pool bypass situation by putting two vacuum valves in series. Further, there have been a number of more recent Mark-I containment design improvements to minimize hydrodynamic forces in the suppression pool. These suppression pool hydrodynamic improvements may minimize the possibility of pool bypass events.

Venting would prevent the containment from reaching overpressure conditions during a suppression pool bypass situation. However, this accident scenario may not be over, as explained in Scenario C.

4.4 Scenario C

As described in Scenario B, steam entering the drywell would push the non-condensable gases in the drywell over to the air (or nitrogen) space above the suppression pool water. Once venting commences the compressed non-condensable gases in this suppression chamber space would be released to the environment via the hardened vent line. The pressure in both the drywell and the wetwell gas space would largely be the partial pressure of the steam with some minor contribution from the partial pressure of the remaining non-condensable gas that did not flow out the hardened vent line.

As this steam begins to condense on cooler surfaces in the drywell or by contact with colder pool water, the concern is that the containment could become subatmospheric. Heat losses from the outside metallic surface of the drywell and wetwell to the cooler environment in the reactor building would also serve to condense steam within the primary containment, i.e. the whole outer surface of the primary containment building could act like a large heat radiator. Although BWR Mark I plants have considerable capability to withstand high pressures, their capability to withstand subatmospheric conditions is quite limited, perhaps in the range of -2 psid. Significant subatmospheric conditions might lead to deforming or even crumpling the containment. The safety implications of a deformed/crumpled containment, which has steam lines running through it, may not have been investigated. Analyzing this situation is complicated. Saturated hot water in the suppression pool might flash to steam as the total containment pressure decreased. This flashed steam would be added to the drywell and wetwell gas spaces stretching out the time to arrive at subatmospheric conditions.

There are vacuum relief valves in BWR designs whose function is to prevent subatmospheric conditions from developing by allowing outside air to flow into the drywell whenever drywell pressures drop below atmospheric conditions. Two considerations are important here. First, actuation of the drywell sprays must be inhibited until such time as the containment is refilled

with outside air or another non-condensable. It is not clear if the vacuum breakers that permit outside air to flow back into the drywell, even if they were opened, could offset the very rapid pressure reducing effects of an actuated spray system quickly enough to prevent damage to the containment due to temporary subatmospheric conditions. Second, the operability of drywell -to-outside -air vacuum breakers after a large natural phenomenon has occurred may have to be reconfirmed.

Venting would be a detriment if it caused the release of non-condensable gases in the containment which later led to subatmospheric pressures that caused deformations in the primary containment building.

4.5 Scenario D

In this scenario on site electric power is assumed to be operating and the suppression pool cooling system also operating.

One of the purposes of the suppression pool is to absorb the energy from steam flow via the safety relief valves which connect the reactor vessel with the suppression pool. Additionally, steam that flowed into the drywell and then down the downcomers also adds energy to the pool water. As more energy is added to the pool the water temperature will rise.

If the pool water is above 100 degrees centigrade, the pool water would boil once the pressure in the wetwell air space drops to saturation pressures upon opening the hardened vent system. It may be possible that the pumps taking suction from the suppression pool will then sustain damage if they cavitate because venting lowered the pressure in the space above the suppression pool to atmospheric conditions.

5.0 Short Term and Longer Term Actions

It appears possible to improve hardened vent performance in two phases. The first phase should be capable of being completed quickly and at minimal expense: Change the hardened vent isolation valve positions from “normally closed” to “normally open”, provided that this results in a lower overall cesium release profile.

The second, longer term, phase would be the insertion of a “spool piece” into the hardened vent at a location downstream from the present outer hardened vent isolation valve. This downstream location should be easily accessible to plant operators. Within this spool piece there should be one or two rupture discs. There is some experience in using rupture discs in Mark I containment vent systems The bursting pressure of this rupture disc(s) would best be determined by a SOARCA analyses, discussed in Section 6 of this report, but might be estimated by present engineering analyses and the experiences at plants that already utilize rupture discs in their hardened vents.

Assuming that the present vent isolation valves were placed into the "normally open" configuration, three spool piece designs are possible. The simplest and least expensive spool piece design would just contain the rupture disc(s). Such a vent could not be opened until containment pressures caused the rupture disc to burst. This design does allow for vent closure and further vent opening, if desired, once electric power is returned to the present isolation valves.

A more complicated spool piece, but one with greater control capability, would have an isolation valve upstream (closer to the reactor) of the rupture disc(s). This isolation valve that would be in the "normally open" position. Its position, open or closed, would be indicated on the valve. The design of this spool piece isolation valve would be such that it could be closed manually (without electric power). The benefit of this arrangement is that the hardened vent could be closed manually, if so desired, before electric power was restored to the present isolation valves. This design does not permit the opening of the hardened vent prior to the time that the rupture disc has burst.

The spool piece design that gives the maximum control to the plant personnel has a bypass line that connects to the hardened vent line upstream and downstream of the rupture disc(s). As in the design description above, one isolation valve in this spool piece, normally in the open position, would be placed would be placed upstream of the rupture disc. A second isolation valve, normally in the closed position, would be in the bypass line. Both spool piece isolation valves would be operable by hand. This arrangement permits plant personnel to open and close the hardened vent line whenever there are safety reasons to do this. This design is passive in that it does not require electric power to perform its safety function nor does it require operator actions to open the vent line upon high pressure in the containment because the rupture disc would burst, opening up a pathway to the outside environment. This third possible spool piece design effectively doubles the control of the hardened vent system. In addition to the existing capability to open and close vent isolation valves using existing supplies of electricity, this arrangement permits opening and closing of the vent system completely without electricity by using hand driven means.

For all three spool piece designs analyses need to be made to determine if there might be excessive radiation levels in the vicinity of these hand operated valves, including the effects of radioactive noble gases. If so, the design or operation of these spool pieces need to take these radiation levels into account. In general, these spool pieces should be readily accessible with emergency lighting and not affected by the possible ignition of hydrogen just beyond the end point of the hardened vent.

In summary, there appears to be five choices in responding to the Fukushima Dai-ichi accident in the domain of improved venting systems. In all of the following five designs it is assumed that the present vent isolation valves are placed into a "normally open" position. These five designs vary in complexity, cost, and capability. These designs are listed in order of increasing capability and cost:

1. Change the present vent system from "normally closed" to "normally open" and rely upon the restoration of onsite electric power or post 9/11

sources of electric power to control the opening and closing of these isolation valves.

2. Add a dedicated source of electric power to control the opening and closing of the present hardened vent system isolation valves, or use portable sources of electric power to control these isolation valves, if this is practical.

3. Same as option 1, but install a spool piece that has a rupture disc(s) within it.

4. Same as option 3, but add a normally open, hand operable isolation valve in the spool piece upstream of the rupture disc.

5. Same as option 4, but add a bypass line with a normally closed, hand operable isolation valve within it. This bypass line would be part of a more complex spool piece. It would be connected on one end at a location that is upstream of the normally open isolation valve and the rupture disc and at the other end at a location that is downstream of the rupture disc.

In the five containment vent designs, above, none of the existing isolation valves or their electrical connections would be removed. In the three designs with spool pieces additional barriers would be put into place outside of the containment by the addition of a rupture disc(s) Inside the containment the suppression pool itself acts like a passive isolation valve. Unless there is a suppression pool bypass situation, the pool water would, to a very high degree, prevent the passage of soluble radioactive elements and compounds from entering the environment. Since the suppression pool itself acts like a passive isolation valve, there would be a form of isolation on both the inside and outside of the containment boundary.

6.0 The Need for a Systems Approach to Analyzing Venting

While it is essential to respond to the venting failures that occurred at the Fukushima Dai-ichi power plant, this response must be done in a comprehensive, systematic way otherwise new risks may be introduced. A course of action should be taken that is not likely to introduce unintended safety issues or worsen known safety concerns associated with venting.

The NRC now has the capability to evaluate various vent configurations in a technically advanced, comprehensive, and consistent way. Sandia National Laboratory's SOARCA program investigated peach Bottom, a BWR with a Mark-I containment, in order to calculate source terms for several dominant accident scenarios. This same SOARCA BWR program can do far more than determine source terms. It can be the "workhorse" for evaluating any number of venting designs in a consistent and comprehensive manner that includes all the scenarios where venting has a possible role to play. A risk-optimized hardened vent design should come out of such a set of analyses. Further, this same set of SOARCA analyses could address a number of related venting issues such as the need for additional filters, the net safety significance of inerting, the optimum initial vent isolation valve position, i.e., "normally closed" versus "normally open", and the optimum pressure at which venting should commence, including the optimum rupture disc bursting pressure. This optimum bursting pressure for the rupture disc might exceed the present primary containment pressure limit (PCPL). If a rupture disc bursting pressure in excess of the

PCPL is selected it would have to be shown that it is still below the pressure at which containment integrity might be lost, including the containment integrity of the hardened vent system itself and all its valves and spool piece.

Venting affects both accident frequencies, because it affects the operation of the emergency core cooling systems, and source term magnitudes because it affects the pathways of radioactive material through the highly effective filtering capability of the suppression pool. The SOARCA program integrates both accident frequency analyses and source term analyses into a modern computer program and therefore would be ideally suited for vent system analysis. Further, the SOARCA program is a large advance over earlier containment computer programs because it has a large number of spatial node points. This very detailed spatial capability should make it possible to track time and location dependent steam and hydrogen concentrations from within the damaged reactor vessel to the elevated exit point of the containment hardened vent.

The four illustrative accident scenarios demonstrate that venting affects many safety systems, such as core cooling systems, drywell sprays, drywell-to-wetwell vacuum breakers, drywell-to - outside air vacuum breakers, and suppression pool cooling pumps. Venting also affects different pathways such as the pathway for trapping radioactive iodine and cesium in the suppression pool water and the pathway of non-condensable gases. Venting also affects the importance of hydrogen. Some venting actions have safety benefits while others might be detrimental if not conducted properly. Therefore, since venting is such a complex subject, how to respond to the Fukushima accident should be conducted in a sophisticated, methodical, and transparent manner such as using the SOARCA computer code.

7. Need for Additional Filters

Improving the hardened vent design to enables the suppression pool to capture a very high percentage of the radioactive iodine and radioactive cesium released from the fuel under SBO conditions. Because of these possible improvements in vent design and operation, the safety significance of an additional filters within the power plant appears to be minimal.

8. Need for Inerting

Inerting, like venting, is a complex subject and its safety benefits can now be more accurately quantified through the use of the SOARCA computer code.

As stated before, SOARCA analyses could be used to evaluate various designs of an improved hardened vent systems. A by-product of such a vent analyses could be a re-evaluation of the safety significance of nitrogen inerting in Mark I BWRs. It is already known that with an improved venting system it would be less likely to generate the hydrogen in the first place under SBO conditions since venting enhances the operation of the emergency core cooling systems. Core damage, and therefore hydrogen production, has also become less likely with the availability of additional post 9/11 safety equipment.

With an improved venting system, the safety significance of nitrogen inerting is further diminished. Whenever the vent system was opened, such as during a loss of suppression pool cooling event, the inerting agent, nitrogen, would be discharged into the environment thereby ending its safety role. Nitrogen also would be discharged to the environment if there is some kind of a venting process during ATWS conditions. Inerting would have no safety significance if there is a loss of containment integrity that releases hydrogen to the outside air, as was the case in Fukushima During plant shut down with an open primary containment the safety significance of both inerting and containment venting is zero.

Whenever the drywell and wetwell air spaces have sufficient steam in them, the presence of hydrogen may not be important due to steam inerting, i.e., steam replaces nitrogen as the inerting agent. Whenever the vent system is used, the inventory of hydrogen within the containment is decreased as hydrogen flows out the hardened vent into the atmosphere. The concentration of hydrogen may become too low to form an explosive mixture, even if oxygen were present. Venting also increases the pressure margin between the containment pressure during an accident and the containment failure pressure. The larger the pressure margin, the less likely a pressure spike from ignited hydrogen would cause a loss of containment integrity. Whenever the vacuum breakers between the drywell and the outside air are opened to prevent subatmospheric conditions from arising, oxygen (in the air) would be introduced into the containment. It would appear that the safety significance of preventing subatmospheric conditions, even though it would introduce oxygen into the drywell, outweighs the inerting safety significance of the limited amount of nitrogen that might still be present at the time when these drywell-to-outside-air vacuum breakers were opened. In the event of a steam or liquid break of the primary system within the drywell, most of the nitrogen would be compressed into the gas space above the suppression pool within the torus in the Mark I design. Under these circumstances some of the safety benefits of inerting ends for the drywell since the nitrogen would no longer be there.

The SOARCA program should be capable of tracking hydrogen inventories and concentrations in the reactor vessel, in the drywell, in the gas space above the suppression pool and in all connecting piping and downcomers, including the hardened vent when opened, for each important accident scenario, but especially for SBO scenarios. Using this information, the probability of having a hydrogen explosion can be determined as well as the size of any pressure spike that might result from a hydrogen explosion and , finally, if this pressure spike would be large enough to challenge containment integrity.

9. Regulatory Basis for Requiring Plant Modifications

1. Introduction

Modifying the designs of nuclear power plants should be justified on the basis of sound and defensible regulatory processes. Two regulatory processes that deal with modifying plant designs

are the Backfit Rule and Reg[1]. Guide 1.174. As shown below, application of the Backfit Rule today would only justify small amounts of money, thereby limiting the range of possible safety improvements through design changes. On the other hand, a modernized version of Reg. Guide 1.174 would offer significantly greater opportunities to make safety improvements while reducing operating costs.

2. Use of the Backfit Rule

The Backfit Rule is based on assigning $1000 per mean number of person-rem averted to determine if a plant improvement, like improved containment venting, can be economically justified. With the low frequencies of releases of radioactive material into the environment from very large natural phenomena and with small source terms, as calculated by the SOARCA BWR program and supported by measurements made in areas surrounding Fukushima, the dollar amount that could be justified for any plant improvement is likely to be small. Perhaps the only hardened containment vent system improvement that could be justified using a Backfit Rule approach would be design improvement number one: change the positions of the present vent isolation valves from " normally closed" to "normally open". This may be adequate.

3. Use of Reg. Guide 1.174

Section 2.1.1 "Combined Change Requests", or CCRs, of this Reg. Guide discusses how several changes to the design of a nuclear power plant might be combined and possibly approved by the NRC. The combination of several design changes would yield a <u>net</u> Core Damage Frequency (CDF) change and a <u>net</u> Large Early Release Frequency (LERF) change. The acceptability of a CCR would then be determined by the magnitude of the change in CDF and change in LERF numbers relative to the original CDF and LERF values calculated for the plant whose operators are seeking a modification in the plant's design basis.

However, insights gained from SOARCA analyses of source terms from Mark I BWRs indicate that LERF is essentially zero. For example, data on the Mark I Peach Bottom plant presented at the 21st Regulatory Information Conference, March 11, 2009 had a release time of 8 hours for a short term station blackout and 20 hours for a long term station blackout. Both of these scenarios had a cesium release fraction of ~ 0.02. Based on these figures these releases would not be "early" or "large". Even the radioactive releases from the accident at Fukushima might not be classified as early and large, i.e., it appears that this very serious accident had a LERF value at or near zero. Therefore in order to continue to use Reg.Guide 1.174 some other figure of merit must be substituted for LERF.

The regulatory process of combining change requests in Reg. Guide 1.174 as a method towards making regulatory decisions is still valid. However, instead of using net CDF and a net LERF parameters, an updated version of this regulatory process needs to be put in place. It is proposed that the general approach would be to make regulatory decisions based on comparing the

[1] "An Approach to Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis." November, 2002.

calculated sum of the frequency weighted number of curies of cesium released to the environment before and after a specific design change(s) had been implemented. If a design change(s) is calculated to produce a smaller sum of the frequency weighted released cesium curies than this sum without the proposed design change(s), then the proposed design change(s) improves safety and should be accepted.

The above general approach to utilizing a modern version of Reg. Guide 1.174 can be expanded to handle CCRs. A specific example of a CCR would combine two design changes; an improved hardened containment vent system and the removal of nitrogen inerting. the first step would be to select those accident sequences that are equal to or more frequent than some mean value, such as 1E-7/yr. The cesium release fraction would then be calculated for each of these sequences and then the sum of the frequency weighted number of released cesium curies would be determined, assuming that nitrogen inerting was in place with the present vent design that would be inoperable during SBO conditions. Then the same analyses would be repeated, but with air replacing the nitrogen and the first of the five vent design modifications listed in Section 5.0, above also in place. If the frequency weighted sum of the cesium curies in the second analysis with the two design changes is smaller than this sum as determined in the first analysis, then this vent design improvement, along with the elimination of using nitrogen inerting, should be an acceptable CCR. If, however, the use of the first vent design improvement does not result in a net decrease in the frequency weighted cesium release number, then more capable vent designs, such as designs 2 through 5, should be analyzed until a net decrease in the frequency weighted cesium release value is achieved.

This approach builds on the regulatory concept of combined change requests already established in Reg.Guide 1.174, emphasizes improving safety by decreasing the calculated release of radioactive cesium, and uses the best technology available today, the SOARCA computer code. By using the same computer code throughout, by examining the same sequences, and by subtracting the calculated, frequency weighted, released cesium curie sum of the unchanged power plant from a similarly calculated, frequency weighted, released cesium curie sum of the modified power plant, calculational uncertainty issues should be minimized.

This approach uses radioactive cesium as the figure of merit instead of delta CDF and delta LERF. This is appropriate since LERF is effectively zero and because radioactive cesium is the dominant contributor to calculated long term health effects and to offsite economic consequences and land contamination. This approach avoids the complexities and limits inherent in the Backfit Rule. It should be comparatively simple to use since it is site independent and could be used for all light water reactors.

This modernization of Reg. Guide 1.174 could also serve as a template for further improvements in the fleet of nuclear power plants during the remainder of their operating lives. Utilities would be encouraged to seek cost saving submittals that, when put together with safety improvements, show a net improvement in safety, i.e., win-win situations.

Finally, the use of metrics based on cesium releases has the advantage that it aligns reactor accidents with potential spent fuel accidents where the release of cesium is the dominant concern.

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