ENCLOSURE 4

BWR MARK I AND MARK II CONTAINMENT PERFORMANCE DURING SEVERE ACCIDENTS

Contents

BWR Mark I and Mark II Containment Performance during Severe Accidents

1.0 Introduction

This enclosure provides an overview of various plant design features that help protect boiling water reactors (BWRs) with Mark I and Mark II containments from certain severe accident challenges, a brief assessment of these design features for reducing radiological releases resulting from severe accidents, as well as an assessment of external containment filters commercially available today. In addition, Enclosure 4 provides the NRC staff's initial assessment of a report that was prepared by the Electric Power Research Institute (EPRI) on the topic of limiting radiological releases and made available to the public through its web site.

2.0 Containment Systems and Severe Accident Management

Emergency operating procedures (EOPs), severe accident management guidelines (SAMGs), and extreme damage mitigation guidelines (EDMGs) for BWRs with Mark I and Mark II containments provide strategies for protecting the containment under accident conditions or the loss of large areas of the plant. These strategies include use of drywell and wetwell spray systems and venting to remove heat, steam, and non-condensable gases from the containment, and protect the containment from structural failure as a result of overpressure challenges. In addition, if molten core debris were to melt through the reactor pressure vessel (RPV) and relocate to the drywell floor, the procedures instruct plant operators to flood the containment to assist in cooling the core debris, minimize core-concrete interactions and protect the containment wall (Mark I liner melt-through containment breach) and drywell floor penetrations (Mark II suppression pool bypass).

2.1 Containment Spray Systems

Containment heat removal may be accomplished during and after design basis accidents by the containment cooling modes of the residual heat removal (RHR) system. Containment cooling includes suppression pool cooling and containment spray (drywell and wetwell) modes. The containment spray mode is accomplished in most Mark I and II containments by diverting water flow from the RHR system to the drywell or suppression chamber spray headers. The purpose of these two RHR modes is to prevent containment temperatures and pressures from exceeding design values in order to maintain containment integrity following an accident. Under postulated accident conditions, water is drawn from the suppression pool, pumped through one or both RHR heat exchanger loops, and delivered to the drywell spray header or to the suppression chamber spray header. For design basis accidents, the RHR system is only realigned for the containment spray mode by the plant operator after verifying flow is not needed for RPV injection or suppression pool cooling. If the operator chooses to use containment spray, the associated low-pressure coolant injection (LPCI) valve to the core is closed (low pressure water sources are no longer sent to the RPV to cool the core) and the spray valves are opened. Under postulated accident conditions, the typical containment drywell spray system design flow rates range between 3,000 and 10,000 gallons per minute. If RHR pumps are not available, such as during an extended station blackout (SBO), the portable temporary pumps currently required by (10 CFR 50.54(hh)(2)) provide flow rates in the range of 100 to 300 gallons per minute.

2.2 Containment Flooding

Another severe accident management strategy included in EOPs, SAMGs and EDMGs is containment (drywell) flooding. The drywell flooding strategy is intended to provide water on the lower drywell floor should core melt appear imminent, or by the time a melted core breaches the RPV. Water on or around the core debris on the drywell floor serves to quench, immobilize, and inhibit the molten core debris from flowing across the drywell floor and melting through the drywell wall (i.e., Mark I liner melt-through containment breach) or penetrations that would result in bypassing of the suppression pool (i.e., Mark II suppression pool bypass). Water on the drywell floor would also reduce core-concrete interactions and the resulting flammable and non-condensable gases that contribute to containment pressurization. An additional strategy involves flood up of the containment into the drywell to a level as high as the top of the fuel zone elevation in the reactor vessel. This strategy is designed to provide RPV exterior cooling for the damaged core debris remaining in the vessel and water depth over exposed core debris.

BWRs with Mark I and Mark II containments are required to be capable of injecting water into the drywell by an AC-power-independent means as a result of Section B.5.b of Order EA-02-026, “Order for Interim Safeguards and Security Compensatory Measures,” the corresponding license conditions, and 10 CFR 50.54(hh)(2). Nuclear Energy Institute (NEI) 06-12, “B.5.b Phase 2 & 3 Submittal Guideline,” Revision 2, Section 3.4.9, identifies the objectives of injecting the water as providing cooling of core debris and scrubbing of fission products, in the event core damage and vessel failure cannot be prevented. The injection flow could use a portable pump or other existing sources. Detailed procedural guidance for implementing this injection capability is also required. The injection flow, using a portable pump or other existing sources, could be routed through the drywell spray system, emergency core cooling system, or any other system providing a suitable pathway to the drywell. Following core melt-through of the RPV, injection of water into the reactor vessel would reach the drywell floor through the opening in the RPV caused by the core melt-through. Although some scrubbing of fission products will likely occur, injection flows in the range of the required capability are primarily for decay heat removal and would not be expected to result in appreciable fission product decontamination of the containment atmosphere. The required AC-power-independent injection capability is 300 gallons per minute or less, and the low pressure portable pumps are not expected to provide much more flow than that through the entire range of flow resistances and back pressures that could be experienced.

The drywell flooding strategy may completely flood the wetwell within 12 to 24 hours, as the water drains from the drywell floor into the suppression chamber through the drywell to suppression chamber vent system. The amount of time to fill the suppression pool with water depends upon the portable pump’s flow rates, and how long these flow rates exceed the amount necessary to remove decay heat. Prior to the suppression pool becoming fully flooded with water and sealing off the wetwell vent penetrations, emergency procedures direct operators to vent the containment through the drywell without regard to the potential radiological consequences.

2.3 Containment Venting

The EOPs, SAMGs, and EDMGs for BWRs with Mark I and Mark II containments include provisions for venting containment prior to the pressure exceeding the primary containment pressure limit (PCPL). Due to the small size of the Mark I and Mark II containments and their response to severe accidents, the need for containment venting has been recognized for a long time. In 1983, the NRC approved Revision 2 to the Boiling Water Owners’ Group Emergency Procedure Guidelines which included guidance for operators to vent Mark I and Mark II containments in response to containment overpressure conditions. The Emergency Procedure Guidelines are used to develop plant specific Emergency Operating Procedures. In 1988, the NRC approved Revision 4 to the BWR Emergency Procedure guidelines, which provided improved guidance for venting, in particular guidance on establishing the containment vent initiation pressure. In approving venting for the BWRs with Mark I and Mark II containments, the staff noted its basic concern that:

> [V]enting even if it results in some radiological consequences should only be undertaken as an extreme means to prevent core melt or as a last resort measure to prevent the irreversible and unpredictable rupture of the containment which could otherwise lead to a large release.

Though procedures have existed for some time for Mark I and Mark II containment venting systems for beyond design basis accidents and severe accidents, the NRC's actions to date have not specifically required that plants with Mark I and Mark II containments be designed with systems, structures, and components to limit the releases from potential beyond design basis scenarios, such as an extended station blackout involving significant core damage and an inability to remove energy from the suppression pool (primary containment) by means other than containment venting. In the staff's evaluation of Revision 4 to the emergency procedure guidelines, the staff noted the following concerns with venting wherein the venting systems where not designed for the expected loadings:

> However, there are downsides to a strategy which intentionally releases containment atmosphere to the reactor building or the environs. If the vent path is not capable of bearing the associated pressure and consequently ruptures upon initiation of venting, then the reactor building could become highly contaminated and operator access will be impractical. Thus, recovery of failed equipment may be prevented. Further, rupture of a vent line in the reactor building will unnecessarily threaten the functioning of safety equipment or instrumentation which was operating by exposing that equipment to a high temperature, steam, and radiation environment.

In 1989, the NRC issued Generic Letter 89-16, "Installation of a Hardened Wetwell Vent," to all licensees of BWRs with Mark I containments to encourage licensees to voluntarily install a hardened wetwell vent. In response, licensees installed a hardened vent pipe from the wetwell to some point outside the secondary containment envelope (usually outside the reactor building). Some licensees also installed a hardened vent branch line from the drywell. Because the modifications to the plant were performed in accordance with 10 CFR 50.59, "Changes, tests and experiments," detailed information regarding individual plant configurations was not submitted to the NRC staff for review.

On March 11, 2012, the NRC issued an order (EA-12-050) to all licensees of BWR facilities with Mark I and Mark II containment designs to require a reliable hardened vent (RHV). The order provided requirements to ensure reliable operation of the hardened venting system in support of strategies relating to the prevention of core damage. EA-12-050 did not include requirements for reliable operation under severe accident conditions. Because the order focused on requirements prior to the onset of core damage, EA-12-050 did not prescribe the venting location (drywell or wetwell) as essentially all vent flow prior to RPV breach would pass through the suppression pool regardless of vent origination from wetwell or drywell. Nevertheless, the existing EOPs, SAMGs, and EDMGs for BWRs with Mark I and Mark II containments contain provisions for venting containment following core damage.

2.3.1 Wetwell Venting

Venting from the wetwell is preferred because a wetwell vent ensures the maximum available decontamination scrubbing action from the suppression pool. However, there are circumstances where suppression pool scrubbing may be bypassed or, otherwise, unavailable. For example, wetwell venting would not be available in the event of failure of the venting valves, loss of motive power to venting valves, lack of operator access to actuate the venting valves, or high level in the suppression pool.

A reactor vessel breach would result in a flow of the drywell atmosphere to the wetwell via the downcomer pipes with much-reduced scrubbing effect when compared to releases through the safety relief valve lines. In addition, the suppression pool may be bypassed if efforts employed by operators to flood the lower drywell floor are unsuccessful and result in a Mark I drywell liner melt-through or a Mark II vessel drain line or downcomer melt-through. Also, as previously noted, wetwell venting may become unavailable within 12 to 24 hours following efforts to flood the drywell floor under the RPV in order to prevent the complete bypass of containment.

2.3.2 Drywell Venting

EOPs and SAMGs direct operators to vent the containment to avoid exceeding the primary containment pressure limit (PCPL) or avoid combustible gas concentrations in the primary containment. Venting from the wetwell is the preferred venting path; however, if the wetwell vent is not available or effective at reducing pressure or hydrogen concentration, then the operators are directed to vent from the drywell regardless of the radiological release consequences. This is in accordance with existing procedures.

A drywell vent would provide the same suppression pool scrubbing for the steam, radionuclides, and hydrogen gas that is discharged into the suppression pool via the safety-relief valve discharge line and T-quenchers. In this case, the wetwell atmosphere (i.e., nitrogen/air, steam, and other non-condensable gases) exhausts to the drywell atmosphere via vacuum breakers, and the resulting drywell atmosphere is vented. However, for accident sequences involving breaks in piping within the drywell or for accident sequences where the molten core exits the RPV, any discharge from drywell venting would be unscrubbed by the suppression pool.

A drywell vent, especially if it exits high in the drywell, will discharge more drywell heat and hydrogen, and reduce the potential for drywell penetration gross leakage and the amount of hydrogen available for leakage into the secondary containment (reactor building).

3.0 Containment Design Features to Limit Radiological Releases

3.1 Decontamination by Drywell Spray

In international severe accident strategy, the drywell spray headers are used as the pathway for getting water into the primary containment to cover core debris and to provide makeup for feed-and-bleed heat removal using the filtered containment venting system. This provides a means to stabilize the core melt to protect penetrations and avoid containment breach and bypass. The spray is not relied upon for fission product removal because the decontamination provided by the limited capacity severe accident spray has not been demonstrated to provide sufficient coverage and performance.

Reactors with Mark I and Mark II containments have drywell spray systems or subsystems for design basis accidents. Their function is to provide a means of containment pressure control and, using emergency service water cooled heat exchangers, to remove heat from the containment. They were not designed or intended for aerosol particle decontamination. Drywell spray pumps and valves are dependent on alternating current (AC) electrical power, and are not functional in a prolonged station blackout as was experienced at Fukushima. The drywell spray equipment useable under prolonged SBO is the passive drywell spray ring headers. Their use also presumes a flow path to the header unobstructed by several inoperable valves. Because of the potential for opening containment vacuum breaker valves and letting air/oxygen in, or of collapsing the containment by inadvertently operating drywell spray, the decision to initiate containment sprays requires due consideration, even at the low flow rates considered for severe accident purposes. The use of containment sprays might also present a concern due to the potential for condensing steam. Steam assists in maintaining an inert environment in the containment to avoid any burning of hydrogen gas produced during a severe accident, in the event air is introduced into the containment.

In contrast with BWRs with Mark I and Mark II containments, PWRs with large dry containments have containment spray systems that were originally designed to provide a decontamination function and many included a means to add pH elevating chemicals to the spray flow for improved iodine retention in the emergency sump water**.** The testing of spray for PWR atmosphere decontamination has been performed in geometries that attempt to model the large free volumes of large dry PWR containments. The vast majority of this testing has been performed by France, which uses large dry containments for their PWRs (they have no BWRs) and the results are not in the public domain. The spray testing cited in the literature and known to the staff consists of 20 data points for a single set of steady state conditions in a large volume from an experiment by the Department of Energy (DOE), Office of Scientific and Technical Information (OSTI), and documented in BNWL-1592, “Removal of Iodine and Particles from Containment Atmospheres by Sprays: Containment Systems Experiment Interim Report,” July 1971.

The many variables and uncertainties which must be understood to assess the value of drywell spray for fission product decontamination using computer models include: the rate and pressure of the flow through the drywell header nozzles, which affect droplet size, spray trajectory, and velocity; the volume of the drywell that will be swept by the spray due to drywell geometry, structures and equipment installed in the drywell between the spray header and the drywell floor; the height through which the spray droplets will fall; the thermodynamic conditions in the containment that will affect spray distribution, e.g., convection currents; and the uncertainties inherent in modeling complex aerosol physics, in particular the removal efficiencies. The uncertainties in modeling aerosol physics have been exhaustively analyzed in NUREG/CR-5966, “A Simplified Model of Aerosol Removal by Containment Sprays,” June 1993. Estimates for drywell spray decontamination factors, including estimates of uncertainty, were calculated in NUREG-1150, “Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," for Mark I containments and the results are shown in Figure 1.

The 2009 Organization for Economic Co-operation and Development (OECD) report, the Nuclear Energy Agency Committee on the Safety of Nuclear Installations, “State-of-the-Art Report on Nuclear Aerosols,” December 2009 (ADAMS Accession Number ML11355A245), gave the following summary of the state of knowledge for fission products in the containment atmosphere:

> ***Mixed aerosols in condensing atmospheric conditions:*** Although there has been considerable progress in modeling aerosol deposition as a function of relative humidity, a comparison of the adequacy of code results from ISP 37 and ISP 44 indicate that there is still some work to be done to ensure satisfactory coupling between thermal hydraulic and aerosol models so that these capture correctly aerosol behavior in most environments. An additional uncertainty in modeling aerosol behavior in the containment in humid conditions arises from determining the hygroscopicity associated with a mixture of aerosols of different compositions. Finally, there is some uncertainty regarding the density of multi-component aerosols, and whether this parameter is important for accident conditions with a wide variety of aerosol components.
>
> ***Removal by sprays:*** This issue has been extensively investigated by the French organizations CEA and IRSN using specific apparatuses and the CARAIDAS, MISTRA and TOSQAN test facilities. The data should be made accessible to the nuclear community, at least the OECD partners. Validated modeling based on these experimental investigations has been implemented in the codes ASTEC and TONUS. The ASTEC model can be found in the open literature. Further work on containment sprays is low priority for countries that have access to this data but in other countries and for certain advanced designs it remains important to establish effective removal by spray systems and both experimental and analytical efforts continue.

With respect to the Mark I containment spray system, the staff reached the following conclusion through the Containment Performance Improvement Program (CPIP):

> A review of some BWR Mark I facilities indicates that most plants have one or more diesel driven pumps which could be used to provide an alternate water supply. The flow rate using this backup water system may be significantly less than the design flow rate for the drywell sprays. The potential benefits of modifying the spray headers to assure a spray were compared to having the water run out of the spray nozzles. Fission product removal in the small crowded volume in which the sprays would be effective was judged to be small compared to the benefit of having a water pool on top of the core debris. Therefore, modifications to the spray nozzles are not considered warranted. (SECY 89-17)

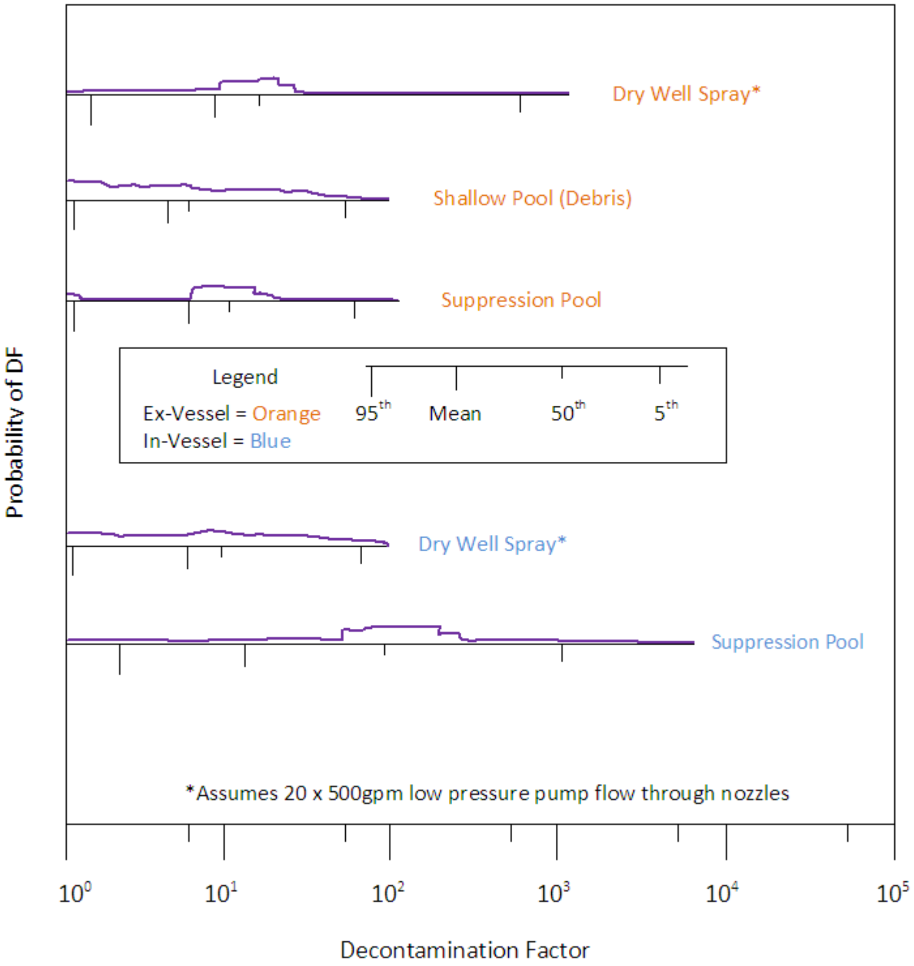

Figure 1 – Uncertainty distributions for Cesium decontamination factors (DFs)
Mark I Containment – Peach Bottom

Source: "Assessment of In-Containment Aerosol Removal Mechanisms."
BNL Technical Report L-1535, 1992

3.2 Decontamination by the Wetwell (Suppression Pool)

BWR Mark I and Mark II pressure suppression primary containments include a large pressure suppression water pool within a pressure suppression chamber (wetwell). As the name "suppression pool" implies, the wetwell was designed to condense steam from a design basis accident and limit the peak design basis accident pressure in the relatively small total volume of the drywell/wetwell combination. The suppression pool was not designed with a fission product decontamination function in mind. However, because of its size (depth and capacity) and the possible routing of fission products through the pool prior to release from containment, it has been analyzed as a passive "ad hoc" filter for severe accident mitigation. This was the basis for preferring a wetwell hardened vent in Generic Letter 89-16, "Installation of a Hardened Wetwell Vent."

3.2.1 Mark I Containments

As a potential fission product filter, the wetwell has its greatest value when (1) the core damage is arrested in the reactor vessel, (2) the reactor vessel and attached piping remain intact relieving through the safety relief valves (SRVs), (3) the SRV tailpipes to the T-quenchers (spargers, pipes with many holes approximately 1 centimeter in diameter to spread the discharge and assist with pool mixing to avoid local boiling and containment pressurization above the pool) at the bottom of the wetwell remain intact, and (4) the wetwell water remains substantially subcooled. At Fukushima Units 2 and 3, extended reactor core isolation cooling (RCIC) and high pressure coolant injection (HPCI) operation resulted in SRV discharge pathway transfer of enough decay heat from the RPV to the suppression pools to bring them to saturation conditions.

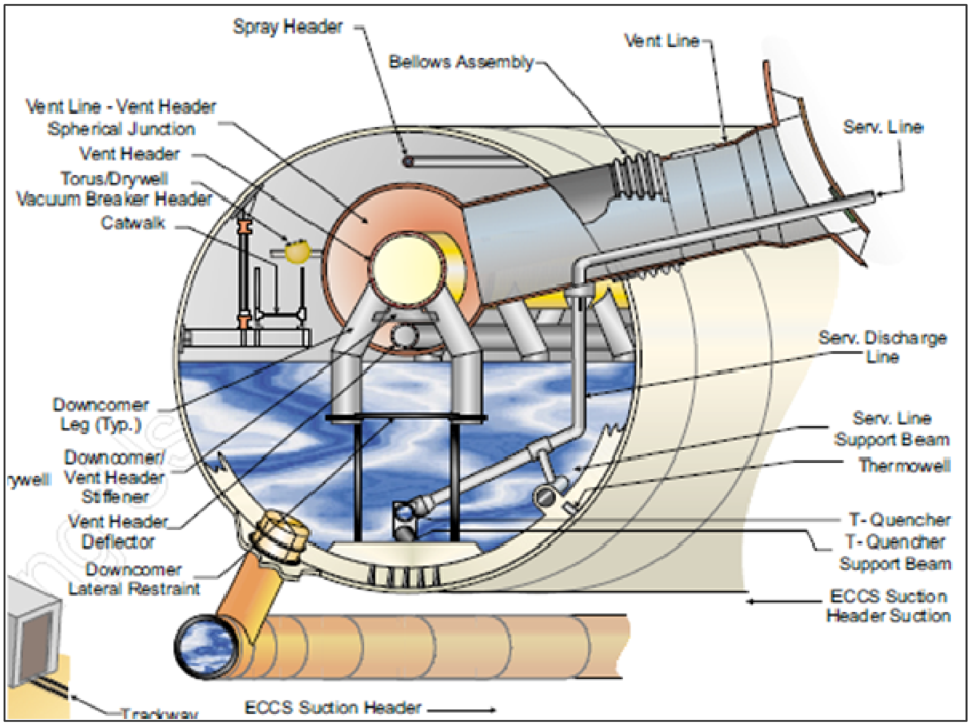

Figure 2 - Suppression chamber cross-section

The suppression pool scrubbing effect diminishes as the pool temperature approaches saturation, especially when non-condensable gasses are a significant portion of the flow entering the pool. A decrease in pool water pH (i.e., acidification) also results in further reducing the scrub effect by lessening the capture and retention of iodines. SRVs discharge near the bottom of the suppression pool through diffusers (T-quenchers). When the reactor vessel boundary is breached, the reactor vessel communicates directly with the drywell and the flow path into the suppression pool is via the downcomers, which are many large pipes with open ends with much less submergence in the suppression pool. The decay heat generated steam and non-condensable gas flow through these downcomer pipes hours after reactor shutdown would be relatively non-energetic (low velocity) and removal of entrained aerosol radionuclides via this pathway is thus much less effective than via the SRVs. With the transition from SRV discharge to downcomer discharge, the bottom third of the suppression pool becomes thermally uncoupled from the upper portion requiring less decay heat passing through the downcomers to keep that upper portion of the pool involved with scrubbing at or very close to saturation temperature. A cross-section of the Mark I suppression chamber is provided in Figure 2.

Some important variables and uncertainties in calculating the DF for the wetwell are: pool temperature, submergence of injection point, size of the bubbles, injection flow velocity and gas composition (percent noncondensables) and temperature. Other variables related to the physics of aerosol removal are also important and uncertain, but probably less so than the variables mentioned, with one exception, which is important in considering the efficiency of an engineered filter on the vent from the air space of the wetwell. That variable is the distribution of aerosol particle sizes leaving the wetwell and going through the engineered filter, if installed. The physical processes involved in wetwell or pool scrubbing are described and analyzed in NUREG/CR-6153, "A Simplified Model of Decontamination by BWR Steam Suppression Pools." The overall DF of the suppression pool and external filter or drywell spray and an external filter is not a direct multiple of their individual DFs given that the filtration efficiency is different for different particle sizes. This is not an overriding concern since currently available external filters have very high removal efficiencies for even the most difficult particle sizes. Wetwell decontamination factors were calculated in NUREG-1150, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," for Mark I containments. The calculated estimates and uncertainties are shown in Figure 1 and Table 1**.**

Table 1 – Uncertainty Distributions for Cesium Decontamination Factors (DFs)
Mark I Containment Suppression Pool – Peach Bottom

	Decontamination Factor (DF)			
Conditions	5th Percentile	Median	Mean	95th Percentile
During In-vessel Release Phase (through T-Quenchers)				
Peach Bottom	2.3	81	14.5	1,200
LaSalle & Grand Gulf	1.8	56	10.5	2,500
During Ex-vessel Release Phase (through Vent Pipes)				
Peach Bottom	1.2	9.5	5.1	50
LaSalle & Grand Gulf	1.2	6.8	4	72

Source: "Assessment of In-Containment Aerosol Removal Mechanisms."
BNL Technical Report L-1535, 1992

The 2009 OECD state of the art report (SOAR) gave the following summary of the state of knowledge for wetwell (pool) scrubbing:

> ***Pool scrubbing***: Some BWR and PWR severe accident scenarios involve transport of radioactive aerosols through pools of water where particles can be retained. This phenomenon, known as pool scrubbing, has the potential to

> reduce the source term. Results provided by both stand-alone and integral code models indicate satisfactory agreement with simple experiments for integral retention. However, a systematic experimental database is required for validation purposes. Particular attention should be given to removal of aerosols during formation and subsequent disintegration and coalescence of bubbles, and the effects of submerged structures and contaminants (surfactants).

3.2.2 Mark II Containments

In the Mark II containment design, a severe accident proceeds in a similar manner to that in a Mark I containment. Before vessel breach, the SRVs discharge to the bottom of the suppression pool and aerosol fission products not retained in the suppression pool pass into the drywell with accumulated gasses via the suppression chamber-to-drywell vacuum breakers. Barring significant leakage from the RPV and attached piping boundary in the drywell, any containment atmosphere leakage or vent discharge from either the wetwell or drywell benefits greatly from suppression pool scrubbing. Once the core debris breaches the bottom of the RPV, SRV flow to the suppression pool ceases and any steam and other noncondensables generated will enter the suppression pool via the downcomers , unless exiting containment via a drywell vent. However, molten core debris on the drywell floor may enter and melt through and breach the drain lines or downcomer pipes that pass through the drywell floor. When this happens, there is a direct pathway from the drywell to suppression chamber atmosphere and nearly all the scrubbing subsequently performed by the suppression pool is of that portion of the core debris that falls into and is submerged in the pool. Analyses of severe accident progression have concluded that this bypass of the suppression pool in Mark II containments may occur soon after molten core debris reaches the floor under the reactor vessel.

The details of the design of the Mark II containment drywell floor directly below the reactor vessel, the in-pedestal region, greatly affects the accident progression, and thus the uncertainty in predicting consequences of a severe accident. The design of this in-pedestal region varies from plant to plant (Figures 3 and 4). The Nine Mile Point 2 containments have downcomers inside the pedestal region. The La Salle, WNP-2 and Nine Mile Point 2 primary containments have an in-pedestal region at a lower elevation than the surrounding ex-pedestal drywell floor. Nearly all Mark II containments have drain lines through the in-pedestal drywell floor. Failure of a drywell floor penetration (drain line or downcomer), or the floor itself (by core-concrete attack and stress from the core debris weight) would allow fission products in the drywell atmosphere to bypass the suppression pool, thus resulting in much higher release of radioactivity via a hardened vent, even if from the wetwell air space.

NUREG/CR-5528 stated for the Mark II containment:

> [G]iven a severe core damage accident, there is a 55% chance of recovering the sequence in-vessel, with no significant release from containment. Should the sequence progress to vessel failure, there still is a 24.9% chance of establishing a coolable debris bed inside containment, again with no significant release to the environment. However, there is an 11.8% chance that a severe core damage sequence will lead to early overpressure containment failure. Of these early failures, ~90% will involve suppression pool bypass, because of either in-pedestal drain line failure or a failure location in the drywell.

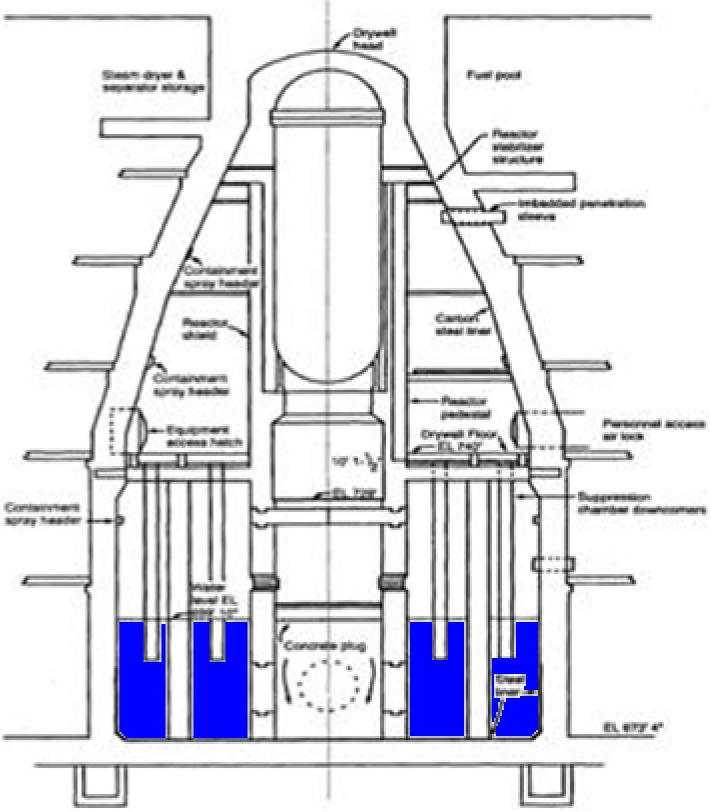

Figure 3 – BWR Mark II containment with lowered floor below RPV (pool not below floor under RPV)

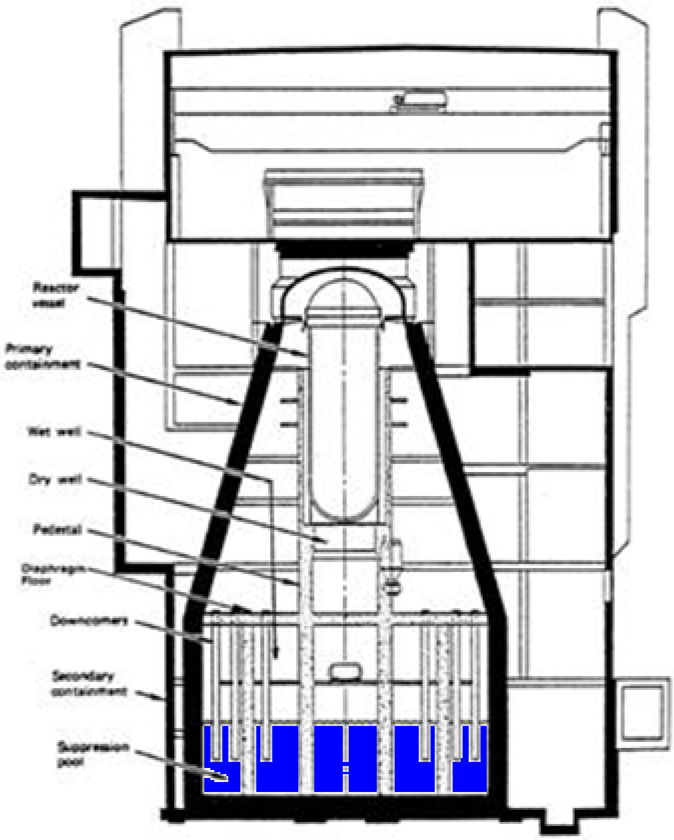

Figure 4 – BWR Mark II containment with level floor (pool below floor and under RPV)

3.3 Decontamination by External Engineered Filter Systems

Engineered containment external filter systems deployed throughout the world have evolved considerably since the first gravel bed filter was installed at the Barsebäck Nuclear Power Plant in Sweden in the mid-1980s. Since that time, engineers have been able to significantly reduce the physical size of the filter and improve the decontamination efficiency for iodine and aerosols. In particular, designers have developed and tested the technology to better retain organic iodine, and to trap more of the most penetrating aerosol particle sizes (less than one micron), those in the mid-range referred to as “the filter gap.”

The benefits of current filter designs, shown in Table 1, rest primarily on extensive full-scale vendor testing. Many of the individuals involved in this testing participate as experts in international efforts such as the preparation of the OECD/SOAR on aerosols referenced earlier. The validity of the testing has been accepted by regulators and plant owners and operators outside the U. S. In preparing this paper, the staff had extensive interaction with foreign regulatory authorities and owner/operators of plants equipped with primary containment external filters (see Enclosure 3, “Foreign Experience.”) The staff was also briefed by representatives of AREVA, IMI Nuclear, Paul Scherrer Institute, and Westinghouse. During the public meetings, AREVA, IMI Nuclear, PSI and Westinghouse provided extensive information regarding filter designs, capabilities and validation testing.

3.3.1 Removal of Radioactive Aerosols

The staff's assessment did not have the benefit of independent testing of the current filtered vent technologies. However, the staff notes that two vendors are getting similar results using multi-venturi nozzle sparger arrays. In 1992, the Electric Power Research Institute (EPRI) published the results of extensive third-party testing of eight filter designs of late 80s vintage as part of the Advanced Containment Experiments (ACE) Project. The testing of the containment venting filtration devices was done by Westinghouse Hanford Company as a subcontractor to Battelle Pacific Northwest Laboratories. Both DOE and NRC were members of the consortium led by EPRI.

Decontamination Factor (DF) values claimed and/or warranted by the current containment filter vendors are shown in Table 2. These values are consistent with DF values measured in the ACE Program. The staff notes that the sand and gravel filters are considered obsolete as the size/volume of the filters necessary to achieve the DFs makes them impractically large for installation at most nuclear plant sites.

External wet filters are specifically designed for achieving high DFs when operating at saturation temperatures. Vent flow enters the filter pool through either high speed venturi nozzles or high speed convergent jet nozzles and impingement/baffle plates. The resultant process maximizes the interface area of the filter liquid and the high relative velocity of entering gas for maximum particulate capture across the particle size distribution. Subsequent bubble rise is either

Table 2 – Containment Severe Accident External Filter Designs

Type	Aerosol Particulate DF	Elemental Iodine DF	Organic Iodine DF	Current Vendor
Dry – Sand Bed	100	10		Installed on French PWRs, design not currently marketed
Dry – Large Gravel Bed	10,000	100		Swedish FILTRA project early design installed at Barseback, not currently marketed
Wet – Multi-venturi + water pH elevation + metal fiber filter	10,000	10,000	5	Westinghouse FILTRA-MVSS
Wet – Multi-nozzle + impingement plates + mixing elements + elevated pH and enhanced iodine capture and retention chemistry	10,000	1000	1000	IMI (Paul Scherrer Institute, PSI-CCI AG)
Wet – Venturi + Metal Fiber	10,000	200		AREVA FCVS
Dry – Metal Fiber + Silver Zeolite	10,000	100	10	Westinghouse Dry Filter Method (DFM)

Note: Decontamination Factors (DFs) are the filter vendor literature stated minimums for a defined range of operating variables with the dominant variable being vent flow rate.

through a deep water pool or through a mixing section that ensures a long dwell time with small bubbles for maximum diffusion capture of aerosol small particles. Alternatively, many filter designs have a second stage filter of small diameter metal fiber beds that remove water droplets and small aerosol particles. See Figures 5 through 7 showing the design features utilized by various filter manufacturers that are currently available on the market.

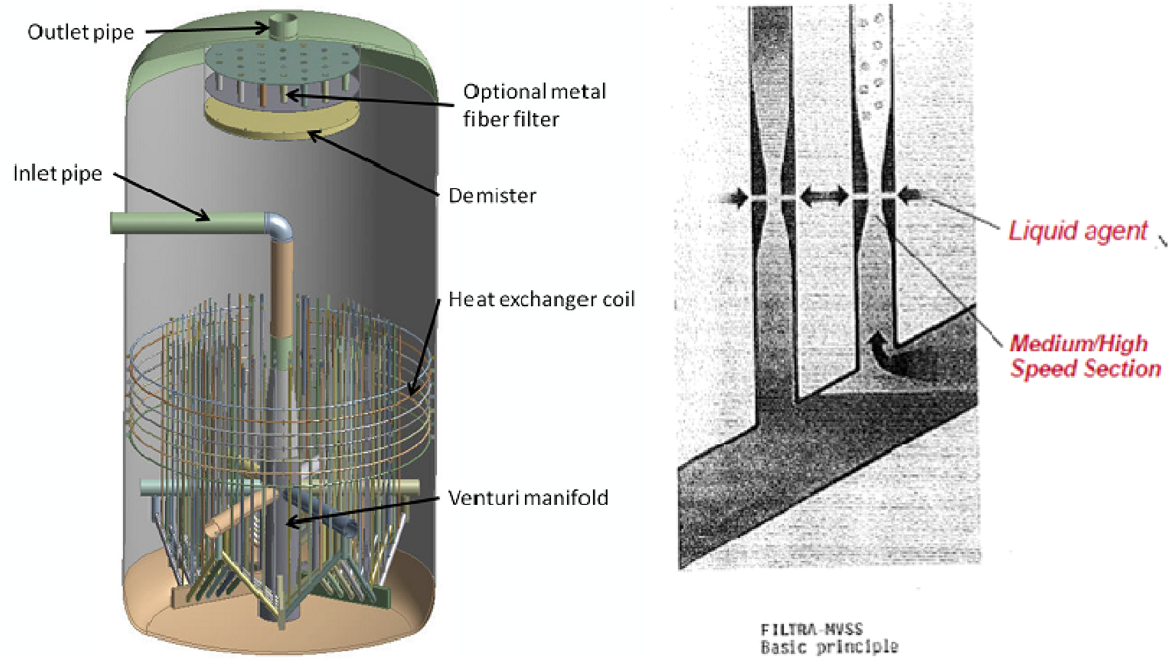

Figure 5 – Westinghouse FILTRA/MVSS multi-venturi scrubber technology

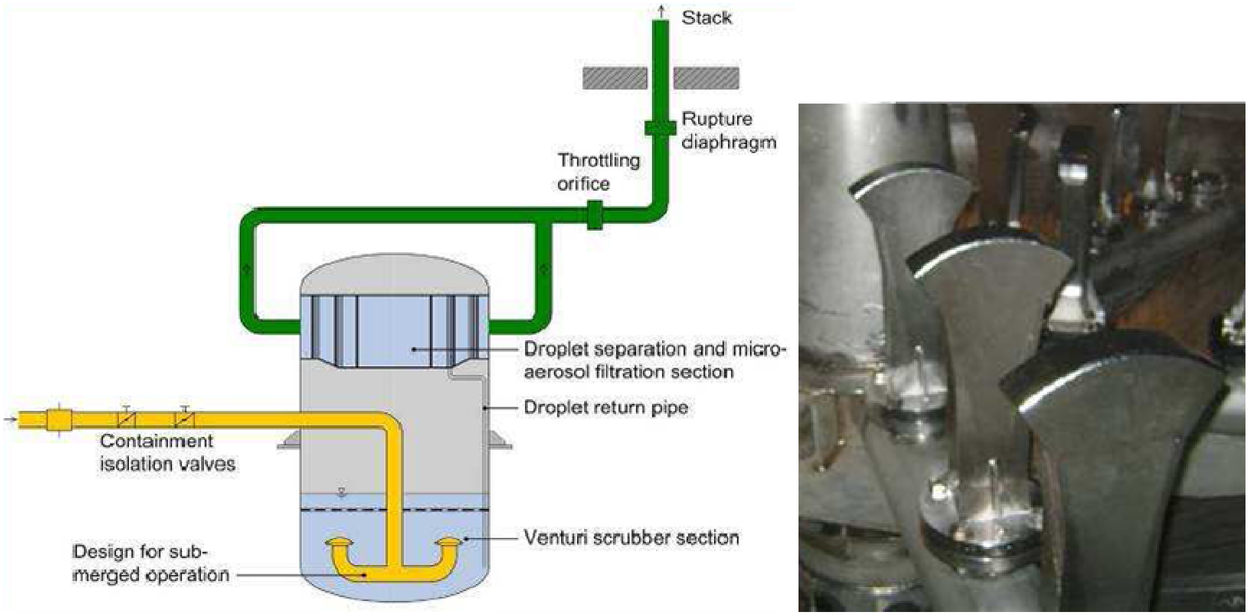

Figure 6 – AREVA venturi nozzle filter technology

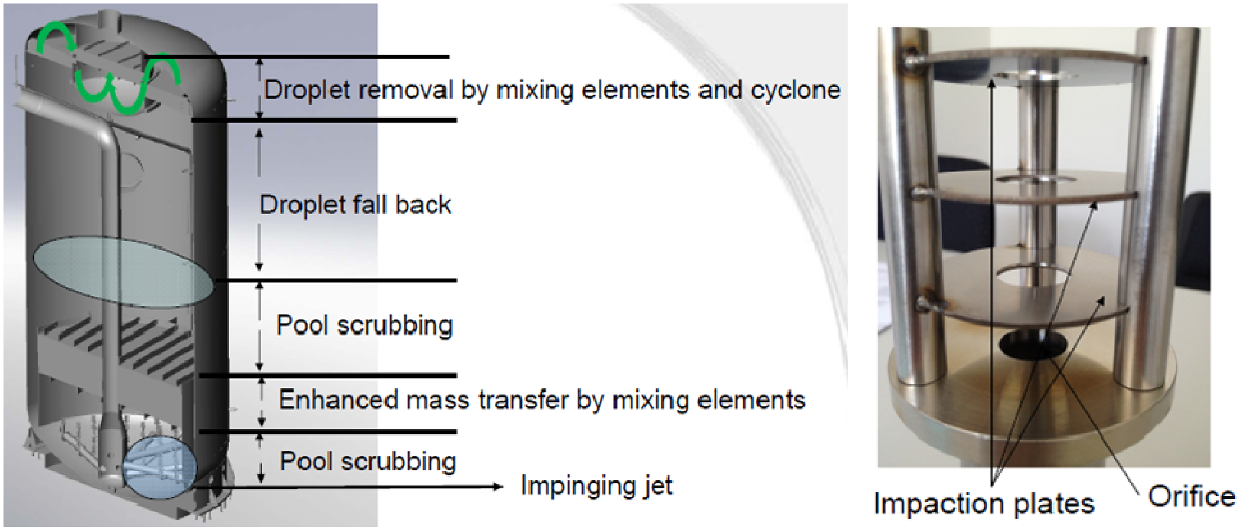

Figure 7 – IMI Nuclear (CCI) filter technology with impaction plate nozzles

3.3.2 Removal of Iodine

Chemicals present in the filter pool water elevate the pH and catalyze iodine's for high levels of short term retention in the filter pool. Some use additional chemicals for essentially 100 percent iodine capture and long term retention. Some foreign PWRs have used dry filters of metal fibers and silver zeolite beds where venting strategy involves delay of more than a day after reactor shutdown resulting in much lower decay heat loadings consistent with the heat dissipation capability of the metal fiber filters and the longer time for particulate settling in containment, reducing the likelihood of fiber filter clogging and blockage.

3.3.3 Wet vs. Dry Filter Technology

The wet filters appear more suitable for venting BWR containments as the filter can be placed in service early in the event given their inherent higher tolerance for particulate loading and decay heat dissipation capacity. The wet filters with venturi nozzles achieve a high DF over a large containment pressure range by having nozzles inject into the filter pool at different elevations such that the nozzles are operating at high efficiency through a large filter flow range. This does require a deeper pool and thus a larger filter vessel. Alternatively, the filter outlet line can be throttled to choke and control flow such that all filter venturi's can be at the same injection submergence and near constant nozzle flow velocity but the filter operates at a higher pressure. This achieves a somewhat different form of "sliding pressure control" and allows for a smaller filter vessel size, but may limit the rate of containment depressurization. Wet filters can be designed/sized with a water volume capable of from 24 hours to several days' operation without operator action. With wet filters, water over the injection nozzles forms a loop seal, thus the containment would not depressurize all the way down to atmospheric through the filter. Most existing wet filter installations include a nitrogen blanket within the filter and inlet/outlet piping to maintain inert conditions for combustible gas control and minimize chemical degradation.

4.0 Electric Power Research Institute (EPRI) Evaluation of Severe Accident Venting Strategies for Mitigation of Radiological Releases

4.1 Background

On September 25, 2012, the Electric Power Research Institute (EPRI) published a study relating to BWR Mark I and Mark II containment venting. The report titled, "Investigation of Strategies for Mitigating Radiological Releases in Severe Accidents - *BWR Mark I and Mark II Studies*," (EPRI Final Report 1026539), was made available to the NRC staff through EPRI's public Web site (http://my.epri.com/portal/server.pt?Product_id=000000000001026539). The report was not provided directly to the NRC, and it is not expected to be formally submitted to the staff for review.

The purpose of the report was to document research on investigations into potential strategies for reducing the environmental and public health effect consequences of severe reactor accidents. The essence of the report was also the subject of two public meetings. On August 8, 2012, the staff held a public meeting where representatives from EPRI provided an overview and preliminary results of the research efforts documented in the September 25 report. In addition, EPRI briefed the Advisory Committee on Reactor Safeguards (ACRS) Fukushima Subcommittee on September 5, 2012, providing information relating to computer modeling and preliminary evaluation of strategies for mitigating radiological releases during severe accidents at BWRs with Mark I and II containments.

By letter dated October 5, 2012, the Nuclear Energy Institute (NEI) presented the industry's position with respect to possible implementation of the results of EPRI's research. In the letter, NEI recommended that the NRC staff pursue a more performance-based approach to ensure that radionuclide aerosols are filtered and retained in containment during severe events. NEI stated that:

> [EPRI's] findings demonstrate that substantial decontamination factors for radioactive releases can be achieved by a comprehensive strategy that includes installed equipment, operator actions and capabilities that are largely consistent with the diverse and flexible coping strategy (FLEX).

In addition, the October 5th letter stated that:

> A combination of these actions would result in 99.9 percent removal of radionuclides that have the potential to contaminate the environment. (They provide for a containment system decontamination factor (DF) of greater than 1000, which is a common international requirement.)

The following represents the NRC staff's preliminary assessment of EPRI's September 25, 2012, study. Because of the report's timing, and the fact that it was not submitted to the NRC for review, the staff is only able to provide its initial impressions of the report.

4.2 Overview

The EPRI report evaluates certain strategies that are intended to maintain or enhance the containment function in scenarios involving long-term loss of electric power. The strategies evaluated include water injection (by flooding or spraying), alternative containment heat removal, venting, controlled venting, filtered venting, and combinations of these plant features. Based on the results of its research, EPRI noted seven “key insights” from the analysis, including:

- No single strategy is effective
- Active core debris cooling is required
- Existing severe accident management guidelines (SAMGs) strategies provide substantial benefit
- Spraying the containment atmosphere is beneficial
- Venting prevents uncontrolled release and manages hydrogen
- Control of the vent provides benefit
- Low-efficiency filters can further reduce radionuclide releases

The staff is in general agreement with many of the report’s insights; however, many concerns remain about strategies that use existing containment features and their ability to achieve a dependable and adequate decontamination of radionuclides following a severe accident. The staff’s preliminary assessment of EPRI’s key insights is presented below.

4.3 Staff Assessment

4.3.1 No Single Strategy is Effective

The EPRI report concluded that “no single strategy is optimal in retaining radioactive fission products in the containment system.” The NRC staff agrees with this conclusion. Uncertainties surrounding severe accidents resulting from accident progression, status of plant systems and components, and operator response make it highly unlikely that accidents can be modeled and procedures developed to account for all potential scenarios.

4.3.2 Active Core Debris Cooling is Required

The insights presented included confirmation that sufficient water injection into the drywell was needed, whatever the pathway, to cool core debris on the drywell floor to immobilize it and prevent molten core debris flow out to and melt through of the drywell wall in Mark I containments or of the downcomer or drain pipes in the drywell floor below the reactor vessel in Mark II containments.

The staff agrees that an active debris cooling strategy is essential to protecting the containment wall at drywell floor level in Mark I containments, and it supports the following conclusion:

> Core debris cooling is an important element of a robust strategy for mitigating releases. If debris cooling is not provided through water injection or spray into the drywell, containment failure or bypass is likely. Without core debris cooling, the containment can be challenged in several ways. Molten debris can come into direct contact with the containment wall, melting the liner and providing a release path to the environment. Elevated drywell temperatures in the containment atmosphere can cause seals and other containment penetrations to fail, leading to containment bypass. Finally, core–concrete interactions can generate large quantities of noncondensable gases that increase containment pressure and also can accelerate concrete erosion that could challenge containment integrity over time.

The analysis also confirmed that Mark I drywell wall breach would largely negate any additional benefit of a hardened vent and external filter, if installed, in reducing releases or in preserving secondary containment (reactor building) accessibility and subsequent usefulness of equipment installed there for stabilizing plant conditions and avoiding or minimizing additional releases.

Mark II containment downcomer or drain line breach would result in suppression pool bypass and a potentially marked increase in radioactivity released if an external filter was not in the vent pathway.

4.3.3 Existing SAMG Strategies Provide Substantial Benefit

The EPRI study also addressed strategies defined in existing Severe Accident Management Guidelines (SAMGs). The guidelines assist operators with symptom-based strategies and include provisions for active debris cooling and containment flooding by using temporary portable equipment. However, the ability of portable pumps to provide sufficient flow rates and provide even limited decontamination of radionuclides raises serious doubts. Drywell spray systems are designed for flow rates that range from 3,000 to 10,000 gallons per minute (GPM). Portable pumps normally provide a maximum flow rate of 300 GPM; however, some pumps may provide up to 500 GPM but require larger and heavier hoses that are more difficult to position for use. As discussed further in section 4.3.4, the staff is concerned that reduced capacity drywell sprays will not provide a reliable means to scrub radioactive aerosols to sufficiently limit releases during venting operations.

4.3.4 Spraying the Containment Atmosphere is Beneficial

The staff recognizes that spraying the drywell atmosphere provides a benefit; however, because of inherent uncertainties in spray systems’ capability to provide adequate decontamination factors (DFs), questions always remain as to how much, and whether or not they are reliable. The Mark I and Mark II containment drywells are highly congested areas that contain numerous piping systems (e.g., reactor recirculation, emergency core cooling). In addition to the piping itself, there are numerous piping supports, snubbers, sway struts, catwalks, and other interferences that limit the spray systems’ ability to provide adequate spray coverage even under ideal conditions. Therefore, the ability of computer models to accurately calculate decontamination factors presents a significant challenge.

The report presented an optimum outcome and involved a water injection flow rate of 500 GPM. This would be well in excess of what is needed for decay heat removal, and it will maintain considerable suppression pool subcooling while providing some drywell spray scrubbing of the containment atmosphere. The staff considers this spray scrubbing to be very limited given the spray headers are typically designed for several thousand gallons per minute flow rate (up to 10,000 GPM) and flow rates of 500 GPM or less would yield a spray of pattern, droplet size and velocity with minimum decontamination potential, especially with obstructions in the drywell removing most of the spray flow from the atmosphere long before reaching the floor. The benefit of this low spray flow beyond pool subcooling may be more from the cooling of core debris on the floor and cooling of drywell surfaces for better aerosol settling and plate-out with less revolatilization.

4.3.5 Venting Prevents Uncontrolled Release and Manages Hydrogen

The severe accident scenarios evaluated in this report assume that core debris is discharged into the containment. As previously noted, water is needed to cool the debris. The quenching of the debris is beneficial; however, it produces a large amount of steam which contributes to containment pressurization. Unless active heat removal systems are available to remove the steam, pressurization will continue beyond containment design pressure to the point of containment failure. Therefore, even if water is available to cool the core debris, containment venting is required to avoid containment failure. Venting also helps manage the buildup of hydrogen and other noncondensable gases generated during the core melting and relocation process. Up to 20 percent of the pressure inside containment can be the result of hydrogen and other noncondensable gases. Venting could maintain the containment pressure below the design pressure and removes hydrogen and other gases from containment.

4.3.6 Control of the Vent Provides Benefit

The innovative feature developed in the EPRI study involve the active management and control of containment venting by plant operators during severe accident conditions in order to achieve sufficient decontamination of radioactive aerosols to limit releases to the public. The report concludes:

> The key to controlling the amount of radioactive material released to the environment is minimizing the amount of contaminants that are airborne in containment during venting. Opening and closing the vent at the most appropriate times is essential. Such controlled venting strategies could be beneficial, but additional analysis is needed to more fully understand this option and ensure coordination with the plant's emergency procedures.

As previously noted, there are many unknowns and variables that affect the conditions in the containment during in a severe accident. These unknowns include:

- pump start and stop times
- ability to sustain an injection flow rate close to 500 GPM
- severe accident phenomenological uncertainties
- rate of hydrogen generation
- success in setting up emergency pumps
- timing and availability of AC power
- battery life
- human reliability
- collateral damage from external events

The strategy presented would require a significant number of operator actions in order to obtain the decontamination factors achieved by the model. Operators must actively manage containment DF by simultaneously controlling containment pressure, water level and temperature (and hydrogen) under conditions that may not include reliable instrumentation and involve the burden of continuous operator monitoring and repeated actions.

In its letter dated October 5, 2012, NEI appears to acknowledge that significant challenges remain to be solved before such a single scenario-specific strategy could even be implemented in the field:

> Applying the findings of the EPRI study to individual plants will take significant effort and time. At a minimum, each plant (or class of plants) will have to perform a specific evaluation based on the EPRI methodology to determine the appropriate strategy to implement. This would require, prior to initiation of the study, alignment with NRC on the filtering strategy performance-basis, development of a regulatory vehicle, implementation guidance, design basis assumptions, severe hazard considerations, accident scenario requirements, etc. Experience suggests that this will involve numerous meetings among NRC staff, industry and other stakeholders over at least 24 months.

Additionally, the October 5 letter recognizes that operator actions and containment venting control remain concerns by the NRC staff:

> We understand the need to provide appropriate reliability to this operation whether it will be a self-actuating relief valve, an instrumented valve capable of operating during station blackout conditions, a manual valve or a combination. The actual duty cycle for this valve will be determined by plant specific analysis. While not downplaying the importance of the reliability of this operation and potential service conditions, the valve would not have to actuate repeatedly throughout the life of the plant.

This scheme also allows for more settling and plate-out of airborne radioactivity in containment and subsequently a more energetic discharge into the suppression pool or more dwell time for the spray header flow to scrub drywell atmosphere aerosols than would occur with continuous venting.

The modeling results indicate an effective overall containment decontamination factor of a 1,000 or more can be achieved by sequential opening and closing of the wetwell vent in order to maintain containment pressure between 60 pounds per square inch gauge (psig) and 40 psig. When the wetwell water level rises to where it prevents further wetwell vent use (approximately 18–20 hours from event start), any benefits of wetwell scrubbing is lost, a drywell vent path is needed and is subsequently cycled opened and closed for containment pressure control. Because suppression pool scrubbing is lost, radioactive releases are expected to be much greater.

In their presentation to the NRC staff, EPRI suggested that to accomplish the automatic vent cycling suggested in their report as being means to achieve the high DFs, the vent valves could be outfitted with a programmable controller to reduce the uncertainty of operator ability to maintain the venting strategy given other demands of the event on their time and attention. This scheme would also place continuous reliance on containment water level and pressure instrumentation as well as that of the vent status and valve actuators and power supplies to achieve the maximum possible reduction in airborne radioactivity released. The staff notes that the containment barrier has traditionally been recognized as a passive barrier with the exception of the need for an initial isolation of any open valves. The EPRI concept appears to potentially change the passive barrier concept, and result in the containment being an actively managed system.

EPRI stated that the drywell was modeled as a single node and no evaluation was made for thermal stratification and temperatures that could be experienced by penetration/seals located in the Mark I containment upper cylindrical section, the higher drywell spray ring header normally being just below the transition to the spherical portion of the drywell. The water injection would appear to provide little cooling effect above the spray ring header elevation and maintaining containment at or near 60 psig may not be prudent with potentially large quantities of light combustible gases being generated within containment and susceptible drywell penetrations potentially compromised by excessive temperatures. Gross leakage into the reactor building may be much larger with pressure being maintained near 60 psig if susceptible penetrations have been overheated rather than reducing pressure to lower values by continuous venting. The EPRI analyses were conducted for 72 hours. At the end of this time period, the containment pressures and bulk average temperatures are still significantly elevated at 60 psig and 300 degrees F. While probably an artifact of the analysis, the staff notes that success in mitigating severe accidents should not be dependent upon elevated containment pressures and temperatures for extended periods. A safe steady state end point should be identified that is not challenging barriers to the release of radioactive material.

In summary, the study's models focused on identifying actions that could be taken given a few plausible but specific severe accident event scenarios with existing equipment, or with modifications short of installing external vent filters, that could reduce airborne releases to levels approaching those reliably obtainable with the external filters. However, the conceptual strategy requires a high degree of confidence that current plant systems (i.e., suppression pools and sprays) can achieve a reliable DF under accident conditions. There is limited availability of testing data (if any) supporting the efficacy of sprays using FLEX flow rates within crowded BWR Mark I containments. Decontamination effectiveness highly depends upon containment conditions, and DFs of 1,000 are possible only if containment conditions are controllable and controlled. The industry acknowledges that further and significant developments, including plant-specific analyses, will be required over the next two or more years before it can be confirmed that the concept strategy is even feasible.

4.3.7 Low-efficiency Filters Can Further Reduce Radionuclide Releases

The EPRI report also mentions the possibility of installing a new design, low efficiency filter in order to further reduce radiological releases:

> The analyses conducted for this research indicate that several of the combined strategies could reduce radiological releases significantly, with DFs greater than 1000. These combined strategies could potentially be enhanced by adding a low efficiency filter to the vent path to provide additional fission product capture. However, the aerosol remaining after using the strategies would be composed of much smaller particles, and the efficiency of the removal of these very small particles has not been demonstrated with current filter designs. Additional research is needed to assess the efficacy of current filter designs when used in combination with the combined strategies to evaluate whether new filter designs significantly change radiological releases.

The report states that the removal of "very small particles has <u>not been demonstrated</u> with current filter designs" (emphasis added). The staff believes this effectively ignores the significant developments and advancements made by filter design engineers and manufacturers over the past 25 years to specifically capture these hard-to-remove particle sizes.

During the course of its investigations, the NRC staff has had the opportunity to discuss filter designs and decontamination effectiveness with filter manufacturers (AREVA, IMI Nuclear, and Westinghouse) as well as with representatives from foreign regulatory authorities in Sweden, Switzerland, and Canada. All parties recognize that submicron particles (penetrating particles) are hard to stop with sprays and simple water pools (e.g., suppression pool). As a result, filter design engineers and scientists have come up with innovate ways to specifically address and improve submicron particle capture. These innovations include improved venturi scrubbers, nozzle designs with impaction plates, methods to recirculate water within filters, and dry filter technology to enhance submicron particle removal. Manufacturers have cited thousands of tests performed by reputable testing agencies and laboratories (e.g., Paul Scherrer Institute, Battelle, and the U.S. Department of Energy National Laboratories (ACE testing)). Although the NRC staff has not performed a detailed review of test reports provided by the laboratories, foreign nuclear safety regulatory authorities have reviewed test results and have accepted decontamination factors of at least 1,000 (aerosols) for designs currently on the market. The ability of these external filters to capture and retain radioactive iodine is similarly recognized and impressive. Therefore, based on its review, the staff has reason to believe that the various engineered filter designs readily available today will provide a more effective, and at a minimum, a more reliable and predictable means of capturing all particle sizes, including submicron particles, than a wetwell with an unknown temperature and length of decontamination (bubble rise) path.

4.4 Other Concerns

In a letter dated July 24, 2012, the BWR Owners' Group (BWROG) submitted a request to the NRC to review and approve changes to the BWROG emergency procedure guidelines (EPGs) and severe accident guidelines (SAGs) for venting operations during station blackout scenarios. These changes are referred to as the "early venting concept." Under the early venting concept, containment pressure would be kept below 25 psig. The NRC staff understands that early venting may be necessary in order to maintain RCIC injection flow cooling to the reactor as well as be necessary to support certain strategies under NEI's FLEX response strategy. In contrast, the EPRI strategy/concept requires that the containment pressure be kept between 40 and 60 psig in order to achieve proper hold up and decontamination factors. This strategy may be inconsistent and at odds with BWROG early venting concept (<25 psig). As such, the EPRI optimum decontamination strategy may not allow the implementation of venting strategies that are necessary to support certain FLEX strategies designed to maintain RCIC and provide alternate water supplies to cool the core and/or limit core damage. The emergency procedures are developed to guide the operator's response to the "symptoms" that the plant is showing in response to an accident, rather than requiring the operator to determine the actual accident underway. The notion of early venting for certain accidents would have to be evaluated in terms of consistency with the development and purpose of symptom-based procedures.

5.0 Passive Containment Vent Actuation Capability

Many of the Mark I containment plants in the U.S. have a rupture disk in the hardened vent line in series with normally closed valve(s). The burst pressures range from about one-half of containment design pressure up to the containment design pressure. Some have the capability of pressurizing between the valve(s) and rupture disk and enabling early venting to better support injection via low pressure, low capacity pumps. Opening the valves requires operator action and active function of the valves. Given the unpredictability of an event and its impact on licensee's performance, a passive activation feature may be appropriate to reduce uncertainty in successful venting when containment conditions are beyond design values. Even close physical proximity to vent valves for local opening and subsequent closing efforts may be extremely difficult or dangerous due to radiological, thermal, lighting, and sound conditions, or other access impairments due to the initiating event or to available capable personnel.

Mark I and II containments typically have maximum calculated design basis accident pressures several pounds per square inch below the containment design pressure. A rupture disk providing for design basis integrity with a burst pressure at or moderately above containment design pressure could support passive initiation of vent function. In addition, early venting may be appropriate to extend RCIC pump operation or ensure low pressure pump injection capability to maintain RPV water level above the fuel to avoid or arrest core damage in the RPV. Valve(s) in series with the rupture disk would normally be open, but capable of closure during or after the event. Early venting with this configuration would require closing a vent line valve, injecting nitrogen/air pressurizing the volume between the valve and rupture disk to the burst pressure. The valve would subsequently have to be opened to vent. This requires two strokes of the valve and availability and introduction of the gas to burst the rupture disk and the additional uncertainty of successful completion and personnel resources required. A simpler arrangement for both active and passive deployment involves having two branches, one passive with an exposed rupture disk and valve(s) for subsequent closure, the other with normally closed valves that could be opened for early venting. This arrangement also provides the feature of redundancy for the vent function in the case a closed valve cannot be opened. Having two valves in series provides for redundancy of containment function in case one of the valves cannot be closed. See Figure 8 for a simplified filtered containment vent system applied to a Mark I containment.

Venting from the drywell after reactor vessel breach would result in a much higher release of airborne radioactivity. This potential release could be greatly reduced by addition of an external vent filter. An external filter would also support justification of exposed rupture disk for fully passive vent actuation as the impact of inadvertent initiation would likely result in a minimal release. It could also support justification for a single containment isolation valve in series with the rupture disk

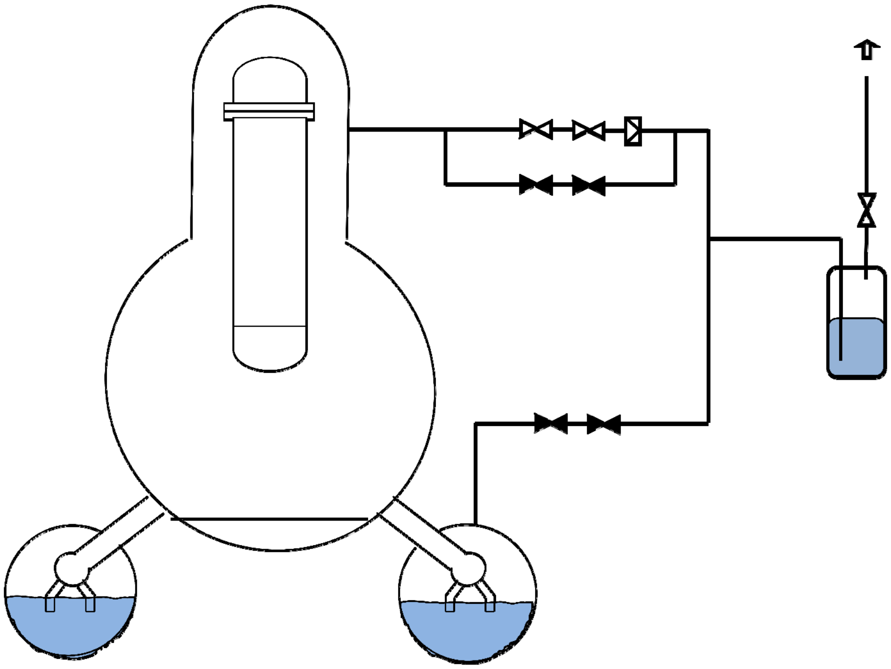

Figure 8 – Potential containment venting arrangement for BWR Mark I containments

6.0 Early Venting

As previously noted, in a letter dated July 24, 2012, the BWROG requested NRC staff review of their Emergency Procedure and Severe Accident Guidelines (EPGs/SAGs) changes recently approved by their Emergency Procedures Committee. The letter states that the primary objective of the changes to the guidance is the maintenance of adequate core cooling and prevention of core damage during extended station blackout conditions. Procedures would be changed to indicate that containment should be vented early, at pressures below the PCPL value, to reduce pressure as necessary to restore and maintain core cooling or reduce the potential total offsite radiation dose. This would be before significant core damage had occurred, in anticipation that containment pressure may well rise above the design or limiting pressure values and the ability to provide adequate low pressure injection for core cooling could become impaired. This guidance would allow for venting and releasing airborne radioactivity in excess of normal release limits in anticipation that the event may progress to a severe accident status with significant core damage and possibly much larger later releases if containment pressure reduction is not accomplished without further delay.

Early venting, similar to full passive activation with an exposed rupture disk, is more easily justified with an external filter that would likely limit early venting releases to the range of normal release limits.