Post-Fukushima Hardened Vents with High-Capacity Filters for BWR Mark Is and Mark IIs

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A Project Completed for NRDC, July 2012

Acknowledgements: The author thanks David Lochbaum of Union of Concerned Scientists for reviewing this report.

I. Why Boiling Water Reactor Mark I Primary Containments have Been Backfitted with Hardened Vents

The U.S. Nuclear Regulatory Commission's (NRC) 2011 Near-Term Task Force report on insights from the Fukushima Dai-ichi accident states that NRC reports from 1975[1] and 1990[2] both concluded that in the event of a severe accident, boiling water reactor (BWR) Mark I primary containments have "a relatively high containment failure probability," because BWR Mark I primary containments have smaller volumes when compared to PWR containments[3]—about one-eighth the volume of PWR large dry containments. (BWR Mark I primary containments have a volume of approximately 0.28×10^6 ft^3; pressurized water reactor (PWR) large dry containments have a volume of approximately 2.2×10^6 ft^3.[4]) BWR Mark II primary containments also have relatively small volumes—about one-sixth the volume of PWR large dry containments. (BWR Mark II primary containments have a volume of approximately 0.4×10^6 ft^3.[5])

A BWR Mark I primary containment is comprised of a drywell, shaped like an inverted light bulb, and a wetwell (also termed "torus"), shaped like a doughnut. The

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[1] NRC, "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," NUREG-75-014, WASH-1400, October 1975.

[2] NRC, "Severe Accident Risks: An Assessment or Five U.S. Nuclear Power Plants," NUREG-1150, December 1990.

[3] Charles Miller, *et al*., NRC, "Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident," SECY-11-0093, July 12, 2011, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML111861807, p. 39.

[4] M. F. Hessheimer, *et al*., Sandia National Laboratories, "Containment Integrity Research at Sandia National Laboratories: An Overview," NUREG/CR-6906, July 2006, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML062440075, p. 24.

[5] *Id*.

wetwell is half filled with water (typically over a million gallons[6])—the suppression pool. A BWR Mark II primary containment also has a drywell and wetwell—both shaped differently than their BWR Mark I counterparts.

In a severe accident, the water pumped into the reactor core to cool the fuel rods would heat up and produce thousands of kilograms (kg) of steam, which would enter the primary containment. The water in the suppression pool is intended to condense the steam and help absorb the heat released by the accident to reduce the pressure in the primary containment. Without the condensation of the steam in the suppression pool, the relatively small primary containments of BWR Mark I and Mark IIs (often termed "pressure suppression containments") would fail from becoming over-pressurized.

In a BWR severe accident, hundreds of kilograms of non-condensable hydrogen gas would also be produced (up to over 3000 kg[7])—at rates as high as between 5.0 and 10.0 kg per second, if there were a reflooding of an overheated reactor core[8]—which would increase the internal pressure of the primary containment. If enough hydrogen were produced, the containment could fail from becoming over-pressurized. To help address this problem, in 1989, the NRC sent Generic Letter 89-16, "Installation of a Hardened Wetwell Vent" to all the owners of BWR Mark Is, *recommending*[9] that hardened vents be installed in BWR Mark Is.[10] Hardened wetwell vents are intended to depressurize and remove decay heat from BWR Mark I primary containments; and the water in the wetwell would help scrub the fission products (excluding noble gases) that had entered the containment.[11]

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[6] David Lochbaum, "Fission Stories: Nuclear Power's Secrets," February 2000, p. 9.

[7] International Atomic Energy Agency (IAEA), "Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants," IAEA-TECDOC-1661, July 2011, p. 10.

[8] J. Starflinger, "Assessment of In-Vessel Hydrogen Sources," in "Projekt Nukleare Sicherheitsforschung: Jahresbericht 1999," Forschungszentrum Karlsruhe, FZKA-6480, 2000.

[9] Generic Letter 89-16 states that "the Commission has directed the [NRC] staff to approve installation of a hardened vent under the provisions of 10 CFR 50.59 ["Changes, Tests, and Experiments"] for licensees, who on their own initiative, elect to incorporate this plant improvement;" see NRC, "Installation of a Hardened Wetwell Vent," Generic Letter 89-16, September 1, 1989, p. 1.

[10] NRC, "Installation of a Hardened Wetwell Vent," Generic Letter 89-16, September 1, 1989, p. 1.

[11] R. Jack Dallman, *et al*., "Filtered Venting Considerations in the United States," May 17-18, 1988, CSNI Specialists Meeting on Filtered Vented Containment Systems, Paris France, p. 5.

II. What Would Be the Features of Reliable Hardened Containment Vents with High-Capacity Filters?

It is widely known that in the Fukushima Dai-ichi accident, hardened vents did not prevent hydrogen from entering BWR Mark I secondary containments and detonating. In fact, hardened vents may have caused the Fukushima Dai-ichi accident to be worse than it would have been if such vents had not been used: "it is postulated that the hydrogen explosion in the Unit 4 reactor building was caused by hydrogen from Unit 3."[12] Unit 3 and Unit 4's containment vent exhaust piping was interconnected, so hydrogen may have been vented from Unit 3 to Unit 4's secondary containment,[13] where it detonated. Thus, one of the NRC's requirements for a new design of a hardened vent is that it "shall include design features to minimize unintended cross flow of vented fluids within a unit and between units on site."[14]

In a nuclear power plant (NPP) accident, venting BWR Mark I and Mark II primary containments could be beneficial; however, venting could also cause negative consequences. For example, a 1988 paper, "Filtered Venting Considerations in the United States" (hereinafter "Filtered Venting Considerations"), states that for some NPP accident scenarios, "venting has been postulated to increase the likelihood of core damage by causing pump cavitation[15] and the eventual loss of injection to the reactor coolant system."[16]

Given the vulnerabilities of BWR Mark I and Mark II primary containments—their relatively small volumes and dependence on suppression pools, which do not mitigate hydrogen—it is essential that a hardened containment vent be designed so that it

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[12] Institute of Nuclear Power Operations, "Special Report on the Nuclear Accident at the Fukushima Dai-ichi Nuclear Power Station," INPO 11-005, November 2011, p. 34.
[13] *Id*., pp. 33-34.
[14] NRC, "Order Modifying Licenses with Regard to Reliable Hardened Containment Vents," EA-12-050, March 12, 2012, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML12054A694, Attachment 2, p. 1.
[15] Cavitation is "[t]he formation of…vapor-filled cavities in liquids in motion when the pressure is reduced to a critical value while the ambient temperature remains constant. … Cavitation causes "a restriction on the speed at which hydraulic machinery can be [operated] without noise, vibration…or loss of efficiency;" see "A Concise Dictionary of Physics," Oxford University Press, 1990, p. 34.
[16] R. Jack Dallman, *et al*., "Filtered Venting Considerations in the United States," p. 3.

would be reliable in a wide range of different severe accident scenarios. If such a vent cannot be developed,[17] the NRC should perhaps consider either shutting down or not relicensing BWR Mark I and Mark IIs.

It could be difficult to design a hardened vent that would perform well in scenarios in which there were rapid containment-pressure increases. The report "Filtered Venting Considerations" discusses the importance of considering these scenarios: "[f]iltered venting may have positive benefits for those sequences in which the rate of containment pressure rise is relatively slow. Filtered venting is less feasible for those sequences resulting in early over-temperature or over-pressure conditions. This is because the relatively early rapid increase in containment pressure requires large containment penetrations for successful venting."[18] This indicates that a reliable hardened vent's piping would possibly need a greater diameter and thickness than those of the hardened vents presently installed at U.S. BWR Mark Is.[19]

A 1993 OECD Nuclear Energy Agency paper, "Non-Condensable Gases in Boiling Water Reactors" (hereinafter "Non-Condensable Gases"), discusses severe accident scenarios in which there would be a rapid accumulation of steam in the drywell and non-condensable gas accumulation (nitrogen[20] and hydrogen) in the wetwell; in such scenarios, the primary containment's pressure could *rapidly* increase "up to the venting and failure levels."[21] "Non-Condensable Gases" states that for a 3300 megawatt thermal BWR Mark I, in scenarios in which hydrogen would be produced from a zirconium-steam reaction of 40 percent, 70 percent, and 100 percent of all the zirconium in the reactor core,[22] if the total quantity of non-condensable gases (including nitrogen) were to

[17] It is noteworthy that a 1983 Sandia National Laboratories manual cautions that "it may be difficult to design vents that can handle the rapid transients involved [in a severe accident];" see Allen L. Camp, *et al*., Sandia National Laboratories, "Light Water Reactor Hydrogen Manual," NUREG/CR-2726, August 1983, p. 2-66.

[18] R. Jack Dallman, *et al*., "Filtered Venting Considerations in the United States," p. 3.

[19] The piping of hardened vents currently installed at U.S. BWR Mark Is is typically 8-inches in diameter.

[20] Nitrogen is used to inert BWR Mark I and Mark II primary containments.

[21] T. Okkonen, Nuclear Energy Agency OECD, "Non-Condensable Gases in Boiling Water Reactors," NEA/CSNI/R(94)7, May 1993, pp. 4-5.

[22] Equivalent to the quantity of hydrogen that would be produced from a zirconium-steam reaction of 72 percent, 126 percent, and 180 percent, respectively, of the active fuel cladding length.

accumulate in the wetwell, the primary containment's pressure would increase up to 107 pounds per square inch (psi), 161 psi, and 215 psi, respectively.[23]

If a hardened vent were designed to have a rupture disk, the vent would work passively, ensuring that the venting of the primary containment commenced once its internal pressure reached the point at which the rupture disk was set to rupture. A reliable passive venting capability would satisfy two of the NRC's requirements for a new design of a hardened vent: 1) it "shall be designed to minimize the reliance on operator actions" and 2) it "shall include a means to prevent inadvertent actuation."[24] A reliable passive venting capability could also be advantageous in severe accident scenarios that had rapid containment pressure increases; however, there could always be other severe accident scenarios in which plant operators would want to vent the primary containment before the primary containment's internal pressure reached the point at which the vent's rupture disk was set to rupture.[25]

In a December 2011 article, Saloman Levy[26] stated that in the event of a U.S. BWR Mark I severe accident, "[e]arly venting [would be] preferred, when the containment pressure and hydrogen concentration are low and not prone to explosions and fires" and that in the Fukushima Dai-ichi accident, plant operators should have "[c]onsider[ed] early venting rather than waiting for containment pressure to reach or exceed design pressure."[27] Levy does not refer to high-capacity filters in his statements; however, it could be argued that implementing a policy of early venting would require installing a high-capacity filter to help protect the surrounding population, who would not have time to evacuate and prevent becoming exposed to radioactive releases.

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[23] T. Okkonen, "Non-Condensable Gases in Boiling Water Reactors," p. 6.

[24] NRC, "Order Modifying Licenses with Regard to Reliable Hardened Containment Vents," Attachment 2, p. 1.

[25] In a telephone conversation with the author on May 18, 2012, David Lochbaum of Union of Concerned Scientists said that there could be severe accident scenarios in which plant operators would want to vent the primary containment when the internal pressure was relatively low.

[26] "How Would U.S. Units Fare?" states that "Dr. Levy was the manager responsible for General Electric (GE) BWR heat transfer and fluid flow and the analyses and tests to support [GE's] nuclear fuel cooling during normal, transient, and accident analyses from 1959 to 1977." See Saloman Levy, "How Would U.S. Units Fare?," Nuclear Engineering International, December 7, 2011.

[27] Saloman Levy, "How Would U.S. Units Fare?," Nuclear Engineering International, December 7, 2011. Levy makes the point that his observations are not intended to be criticisms of the actions of the Fukushima Dai-ichi plant operators.

A high-capacity filter would also be needed for scenarios in which there was a reflooding of an overheated reactor core, which would rapidly generate hydrogen, thereby possibly threatening containment integrity and increasing the risk of radioactive fission product releases.[28] Additionally, a 1988 Oak Ridge National Laboratory (ORNL) paper suggests installing high-capacity filters at BWR Mark IIs because "[i]t is much more probable that operation of simple 'hard' venting systems in [Mark] II plants would result in the discharge of aerosols directly into the environment."[29]

"Filtered Venting Considerations" states that "[v]enting could be from the drywell or the wetwell, but wetwell venting is preferred to allow for fission product (excluding noble gases) scrubbing in the suppression pool."[30] However, according to the same paper there could be a wide range in the effectiveness of suppression pools in scrubbing and retaining radionuclides in the event of a severe accident. The paper states that "[t]he decontamination factor[31]…associated with suppression pool scrubbing can range anywhere from one (no scrubbing) to well over 1000 (99.9 [percent] effective). This wide band is a function of the accident scenario and composition of the fission products, the pathway to the [suppression] pool (through spargers, downcomers, etc.), and the conditions in the [suppression] pool itself. Conservative [decontamination factor] values of five [80 percent removal] for scrubbing in Mark I suppression pools, and 10 [90 percent removal] for Mark II…suppression pools, have recently been proposed for licensing review purposes."[32] Clearly, a high-capacity filter would help protect the public from becoming exposed to radioactive releases if there were venting from either the drywell or wetwell (in cases in which the suppression pool was ineffective at scrubbing and retaining radionuclides).

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[28] OECD Nuclear Energy Agency, "In-Vessel Core Degradation Code Validation Matrix: Update 1996-1999," Report by an OECD NEA Group of Experts, October 2000, p. 13.
[29] Sherrell R. Greene, Oak Ridge National Laboratory, "The Role of BWR Secondary Containments in Severe Accident Mitigation: Issues and Insights from Recent Analyses," 1988.
[30] R. Jack Dallman, *et al*., "Filtered Venting Considerations in the United States," p. 5.
[31] The decontamination factor is "[t]he ratio of the initial amount of a nuclide in a [gaseous or liquid] stream (specified in terms of concentration or activity of radioactive materials) to the final amount of that nuclide in a stream following treatment by a given process;" see T. Chandrasekaran, *et al*., NRC, "Calculation of Releases of Radioactive Materials in Gaseous and Liquid Effluents from Pressurized Water Reactors: PWR-GALE Code," NUREG-0017, Rev. 1, March 1985, p. 1-4.
[32] R. Jack Dallman, *et al*., "Filtered Venting Considerations in the United States," p. 4.

III. The Need for Installing High-Capacity Filters at BWR Mark I and Mark IIs in Addition to Hardened Vents

> The nuclear industry and NRC staff appear generally to be in alignment on a variety of issues regarding the implementation of orders incorporating safety lessons from the agency's Fukushima tack force, though some differences remain to be worked out.[33]—Nuclear Energy Institute

In October 1985, the Swedish Barsebäck Power Plant completed the installation of a hardened venting system and high-capacity filter system (FILTRA),[34] a gravel filter with a volume of 10,000 cubic meters,[35] for its two BWRs, which were constructed by Asea-Atom.[36] Barsebäck's FILTRA system was "designed so that 99.9 [percent] of the core inventory of radioactivity, excluding noble gases, [would be] retained in the reactor containment and filter system in the event of containment venting" in a severe accident.[37] Interestingly, in the 1980s, the Long Island Lighting Company had plans to install a hardened venting system and high-capacity filter system, similar to the FILTRA system, at the Shoreham Plant, a BWR Mark II.[38, 39]

The combined cost of Barsebäck's hardened venting and FILTRA systems for its two BWRs, was approximately 15 million dollars (1985 U.S. dollars).[40] In other words, Barsebäck's high-capacity filter system was not very expensive, considering that in the event of a severe accident it could significantly reduce the quantity of radioactive particulates discharged to the environment, which, in turn, reduces offsite contamination

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[33] Nuclear Energy Institute, "NRC, Industry Discuss Details of Fukushima Response," April 12, 2012.

[34] R. Jack Dallman, *et al*., "Filtered Venting Considerations in the United States," p. 6; and Sherrell R. Greene, "The Role of BWR Secondary Containments in Severe Accident Mitigation: Issues and Insights from Recent Analyses."

[35] OECD Nuclear Energy Agency, "Filtered Containment Venting Systems," Note on the Outcome of the May 1988 Specialists' Meeting on Filtered Containment Venting Systems, CSNI Report 156, 1988, p. 17.

[36] Barsebäck Power Plant Unit 1 and Unit 2 were permanently shutdown in November 1999 and May 2005, respectively.

[37] A. H. Persson, "The Filtered Venting System Under Construction at Barsebäck," Nuclear Technology, Vol. 70, No. 2, August 1985, Abstract.

[38] Sherrell R. Greene, "The Role of BWR Secondary Containments in Severe Accident Mitigation: Issues and Insights from Recent Analyses."

[39] The Shoreham Plant never operated.

[40] A. H. Persson, "The Filtered Venting System Under Construction at Barsebäck," Abstract.

and damage to economic activity. (Barsebäck is located in southern Sweden about 12 miles from Copenhagen, Denmark.)

By the end of 1988, all Swedish NPPs had high-capacity filter systems, intended to limit the contamination of the environment to 0.1 percent of the reactor core's inventory of radioactive material in the event of a severe accident. In Sweden, the FILTRA-MVSS (Multi Venturi Scrubber System) system—designed to handle flow rates of up to 12 kg per second—was installed in seven BWRs and three PWRs.[41] An OECD Nuclear Energy Agency report states that Sweden's FILTRA-MVSS system cost less than five million dollars (1988 U.S. dollars) per reactor and opines that, because Sweden's high-capacity filter systems were inexpensive, "all criteria of the cost-benefit type are irrelevant."[42]

A number of nuclear power plants in Europe currently operate with high-capacity filter systems, including designs other than the FILTRA-MVSS system. In France, hardened vents with high-capacity filter systems were installed in *all* French PWRs in the 1990s.[43] And in Germany, *all* of the BWRs have hardened vents with high-capacity filter systems.[44] Unfortunately, U.S. BWR Mark Is and Mark IIs are *not* presently operating with high-capacity filter systems. A 1988 ORNL paper reports that U.S. utilities believe that high-capacity filter systems have "unacceptably low cost-benefit ratios."[45] And a 2005 Nuclear Energy Institute (NEI) document on severe accident mitigation alternatives analysis states that the estimated cost of a filtered containment vent would be three million dollars and that the "upper bound estimate benefit" of installing a filtered vent would be zero dollars.[46] An April 30, 2012 *Huffington Post* article, which discusses the monetary values provided by the 2005 NEI document, states that a spokesperson for NEI

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[41] OECD Nuclear Energy Agency, "Filtered Containment Venting Systems," pp. 7, 8.
[42] *Id*., p. 4.
[43] E. Raimond, *et al*., "Continued Efforts to Improve the Robustness of the French Gen II PWRs with Respect to the Risks of Severe Accidents: Safety Assessment and Research Activities," Eurosafe, 2011, p. 7.
[44] Martin Sonnenkalb, Manfred Mertins, "Severe Accident Mitigation in German NPP: Status and Future Activities," Eurosafe, 2011, p. 7.
[45] Sherrell R. Greene, "The Role of BWR Secondary Containments in Severe Accident Mitigation: Issues and Insights from Recent Analyses."
[46] NEI, "Severe Accident Mitigation Alternatives (SAMA) Analysis: Guidance Document," NEI 05-01 [Rev. A], November 2005, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML060530203, p. 43.

said the estimated cost of three million dollars dated back to 1994 for a filtered vent, which would not have been "seismically designed;" the article also states that Dale Klein, a former NRC commissioner, estimates that a filtered vent might now cost about 15 million dollars.[47]

When evaluating the cost of a filtered vent, it is pertinent that some U.S. BWR Mark Is and Mark IIs are located in proximity to areas with large populations. For example, the Limerick Nuclear Power Plant, which has two BWR Mark IIs, is located about 21 miles from Philadelphia. The potential impact of an unfiltered radioactive release in the event of a severe accident is quite large when considering the possible loss of agricultural economic activity and associated lands, the evacuation and suspension of industrial centers, and the cost of the decontamination of farmlands and city housing. However, even after the Fukushima Dai-ichi accident, the U.S. nuclear energy industry does not seem too keen on installing high-capacity filter systems,[48] in addition to the new hardened vents, which the NRC has required to be installed in BWR Mark Is and Mark IIs by December 31, 2016.[49]

According to an April 12, 2012 NEI article "[i]ndustry participants [in a public meeting] said that other safety modifications could result in a level of safety benefit similar to that of filtered vents."[50] And Maria Korsnick, Chief Nuclear Officer of Constellation Energy Nuclear Group, is quoted in the April 12, 2012 NEI article as stating that "[i]f you are managing a damaged core, managing containment, you are addressing the heart of the issue and there are modifications that are more beneficial than filtration."[51]

Indeed, managing a damaged core and protecting the containment would be very important in a severe accident; however, the fact that severe accident computer safety models, instrumentation, and management procedures could be vastly improved is a separate safety issue than requiring that hardened venting systems have high-capacity

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[47] Tom Zeller, "Nuclear Safety Advocates Accuse Industry and Regulators of Foot-Dragging on Basic Safety Measure," Huffington Post, April 30, 2012.
[48] Jordan Weaver, NRDC, "Nuclear Safety Deferred: The U.S. Nuclear Regulatory Commission's Inadequate Response to the Lessons of the Fukushima Dai-ichi Nuclear Accident," March 2012, p. 12.
[49] NRC, "Order Modifying Licenses with Regard to Reliable Hardened Containment Vents."
[50] NEI, "NRC, Industry Discuss Details of Fukushima Response."
[51] *Id*.

filters. The nuclear power industry's comments seem disingenuous: if the industry is confident that "there are modifications that are more beneficial than filtration," why did the industry not suggest implementing such modifications well before the Fukushima Dai-ichi accident occurred, in the 1980s and 1990s, when Europeans were installing hardened venting systems with high-capacity filters in NPPs?

The nuclear power industry's "modifications" for managing a damaged core seem to be predicated on at least three conditions: 1) computer safety models would accurately predict the progression of reactor core damage in different severe accident scenarios; 2) plant operators would know the condition of the core throughout the progression of a severe accident; and 3) there would not be circumstances in which plant operator error would make a severe accident far worse.

There is reason to doubt that these three conditions would be fulfilled in the event of another severe accident. Regarding the first condition: computer safety models under-predict the rates of hydrogen production that would occur in a severe accident, if there were a reflooding of an overheated reactor core.[52] Regarding the second condition: given the fact plant operators did not know the condition of the reactor cores during the progression of the TMI-2 and Fukushima Dai-ichi accidents, there is reason to doubt that plant operators would know the condition of the core during the progression of another severe accident. (To help enable plant operators to accurately measure a wide range of in-core temperatures, under typical and accident conditions, NPPs need to operate with thermocouples (temperature measuring devices) placed at different elevations and radial positions throughout the reactor core.[53]) Regarding the third condition: given the fact that plant operator errors made the TMI-2 and Chernobyl accidents far worse, there is reason

[52] IAEA, "Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants," p. 14; and Report by Nuclear Energy Agency Groups of Experts, OECD Nuclear Energy Agency, "In-Vessel and Ex-Vessel Hydrogen Sources," NEA/CSNI/R(2001)15, October 1, 2001, Part I, B. Clément (IPSN), K. Trambauer (GRS), W. Scholtyssek (FZK), Working Group on the Analysis and Management of Accidents, "GAMA Perspective Statement on In-Vessel Hydrogen Sources," p. 9.

[53] In February 2012, the author of this report submitted a rulemaking petition (PRM-50-105) to the NRC requesting that the NRC require that NPPs operate with in-core thermocouples at different elevations and radial positions throughout the reactor core to enable NPP operators to accurately measure a large range of in-core temperatures under typical and accident conditions; see Mark Leyse, PRM-50-105, February 28, 2012, available at: www.nrc.gov, NRC Library, ADAMS Documents, Accession Number: ML12065A215.

to doubt that there would not be circumstances in which plant operator error would make another severe accident far worse.

The NRC is presently considering if it should require high-capacity filtration for hardened vents in order to reduce radioactive releases to the environment in the event of severe accidents. The NRC staff is scheduled to prepare a policy paper on this issue by July 2012.[54] NEI's April 12, 2012 article reports that Martin J. Virgilio, the NRC's Deputy Executive Director for Reactor and Preparedness Programs, "said that NRC staff also is working on a paper on the 'economic consequences of land contamination' from radioactive materials following a reactor accident" and "that cost-benefit analysis would be one of the tools used to analyze the land contamination issue."[55]

The NRC should also consider that not all severe accidents would be like the Fukushima Dai-ichi accident: "slow-moving" station-blackout accidents caused by natural disasters. Fast-moving accidents could also occur; for example, a large break loss-of-coolant accident could rapidly transition into a severe accident—a meltdown could commence within 10 minutes after an accident initiated.[56] Early venting might be necessary in a fast-moving accident scenario: a high-capacity filter would help protect the surrounding population, who would not have time to evacuate and prevent becoming exposed to radioactive releases.

IV. Recommendations Regarding Hardened Vents with High-Capacity Filters for BWR Mark Is and Mark IIs

The author recommends that a hardened vent be designed so that it would perform well in scenarios in which there were rapid containment-pressure increases; for example, in scenarios in which there was a reflooding of an overheated reactor core. If such a vent cannot be developed, the NRC should perhaps consider either shutting down or not relicensing BWR Mark I and Mark IIs.

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[54] NRC, "Order Modifying Licenses with Regard to Reliable Hardened Containment Vents," pp. 4-5.
[55] NEI, "NRC, Industry Discuss Details of Fukushima Response."
[56] Peter Hofmann, "Current Knowledge on Core Degradation Phenomena, a Review," Journal of Nuclear Materials, Vol. 270, 1999, p. 205.

The author also recommends that the NRC require that high-capacity filters be installed at BWR Mark Is and Mark IIs, in addition to hardened vents.

To uphold its congressional mandate to protect the lives, property, and environment of the people living within proximity to BWR Mark Is and Mark IIs, the NRC needs to require that hardened vents have high-capacity filtration systems, in order to reduce radioactive releases to the environment in the event of severe accidents. (Some BWR Mark Is and Mark IIs are located in proximity to areas with large populations. For example, the Limerick Nuclear Power Plant, which has two BWR Mark IIs, is located about 21 miles from Philadelphia.)