

Enclosure 1  
Evaluation of Options

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# 1. INTRODUCTION

The purpose of this enclosure is to describe the various technical and policy evaluations that the U.S. Nuclear Regulatory Commission (NRC) staff conducted to support an integrated decision on the need for additional requirements for severe accident containment venting of boiling-water reactors (BWRs) with Mark I and Mark II containments. Fundamental to this evaluation is the regulatory analysis, which is available in the NRC's Agencywide Documents Access and Management System (ADAMS) at Accession No. ML1212A456. This enclosure provides the results of the NRC staff's development and consideration of various factors, and it summarizes the basis for the staff's recommendations.

The NRC performs regulatory analyses as part of its process in evaluating the merits of imposing new requirements on its licensees. Both NUREG/BR-0058, "Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission," and NUREG/BR-0184, "Regulatory Analysis Technical Evaluation Handbook," describe the methodology and standard assumptions. The methodology includes the consideration of various costs and benefits associated with a possible change in regulatory requirements as well as the considerations of qualitative factors and arguments that are difficult to present in quantitative measures, such as financial costs or averted radiation exposures.

Within the regulatory analysis, several key assumptions and factors are important in evaluating the costs and benefits and representing them in a common term (dollars). The development of NUREG/BR-0184, published in 1997, determined many of these factors. The NRC staff considered updating the regulatory analysis guidance before the Fukushima accident. The accident provided other insights into some of the assumptions in the NRC's approach to performing regulatory analyses. An example of a factor that is subject to change in updating the guidance includes the conversion factor of \$2,000 per person-rem for averted radiation exposures. The staff has performed a regulatory analysis of the proposed options (severe accident capable vents order and engineered filtered vents order) using existing guidance. Section 2 of this enclosure summarizes this analysis. To evaluate the possible sensitivity of the regulatory analysis to changes in the standard factors described in existing guidance, the staff provides a summary of a regulatory analysis using revised values for selected assumptions and factors in Section 3 of this enclosure.

## 1.1 Identification of Options

As discussed in SECY-12-0025, "Proposed Orders and Requests for Information in Response to Lessons Learned from Japan's March 11, 2011, Great Tohoku Earthquake and Tsunami," dated February 17, 2012, the staff was asked to evaluate several possible options for revising the severe accident capabilities of BWRs with Mark I and Mark II containments. The possible options evaluated are listed below.

### Option 1: Reliable Hardened Vents (Status Quo or Base Case )

Description: Continue with the implementation of Order EA-12-050, "Reliable Hardened Containment Vents," for reliable hardened vents to reduce the likelihood of core damage and failure of BWR Mark I and Mark II containments and take no additional action to improve their ability to operate under severe accident conditions or to require the installation of an engineered filtered vent system.

The base case used in the regulatory analysis is the current fleet of affected boiling-water reactor plants (31 units located at 20 sites with an average remaining license term of 25 years) assuming, to the extent practical, the completion of the post-Fukushima Tier 1 items (e.g., implementation of mitigating strategies, reliable hardened containment vents, and integration of accident-related procedures). There are, however, significant uncertainties associated with the analyses and consequence evaluations related to the base case and the assessment of options. Some examples include the following:

- The frequency and consequences of severe accident conditions (i.e., core damage, hydrogen generation, and containment challenge from high pressures); the experience at Fukushima; current U.S. plant designs and procedures; and planned enhancements to designs and procedures.
- The efficiency of the suppression pool and plant systems (e.g., containment sprays or systems to flood the drywell cavity) in capturing and removing fission products (i.e., providing a decontamination function), which limits the release of radioactive materials to the site environs.

#### Option 2: Severe Accident Capable Venting System Order (without Filter)

Description: Upgrade or replace the reliable hardened vents required by EA-12-050 with a containment venting system designed and installed to remain functional during severe accident conditions.

This alternative involves upgrading or replacing the reliable hardened vents required by NRC Order EA-12-050 with a venting system designed and installed to remain functional during severe accident conditions (i.e., release of fission products, hydrogen, and high containment pressures and temperatures)<sup>1</sup>. This modification would be pursued to increase confidence in maintaining the containment function following core damage events. Although venting the containment during severe accident conditions could result in a significant release of radioactive materials, the act of venting could prevent gross containment failures that would hamper accident management (e.g., continuing efforts to cool core debris) and result in larger releases of radioactive material.

In addition to ensuring the containment venting system, its supporting equipment, and instrumentation are capable of functioning in severe accident conditions, reviews of plant shielding and other protections for personnel would be required for operation of the vents under harsh conditions. Similar requirements were included in NUREG-0737, "Clarification of TMI [Three Mile Island] Action Plan Requirements," as Action Item II.B.2, "Design Review of Plant Shielding and Environmental Qualification of Equipment for Spaces/Systems which May be

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<sup>1</sup> Varying terms have been used to describe BWR containment venting capability. In accordance with the requirements defined in Order EA-12-050, BWRs with Mark I and Mark II containments shall have a "reliable hardened containment venting system" or HCVS. The HCVS provides improved reliability over the "hardened wetwell vent" or "reliable hardened vents" installed in BWR Mark I containments following the issuance of Generic Letter 89-16, "Installation of a Hardened Wetwell Vent," but do not specifically address operations during severe accident conditions. Option 2 provides additional requirements for the HCVS ordered by EA-12-050 to ensure reliable operation under severe accident conditions (i.e., following core damage). Under Option 3, the severe accident capable HCVS with an engineered filtration capability is designated as the "filtered containment venting system" or FCVS. The FCVS not only provides the venting function to address overpressure and other conditions within the containment, but also uses an engineered filter to limit the release of radioactive materials.

Used in Post-Accident Operations,” and subsequently incorporated into the NRC’s standard review plan for nuclear reactors (NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition”). The TMI action item was developed before the development of severe accident management guidelines (SAMGs) and may not have been performed for some later activities related to responding to severe accidents.

Section 2 provides an analysis of this option, using existing regulatory analysis guidance to determine if the benefits justify the approximate \$2 million cost of plant modifications. Section 3 provides a revised analysis to address concerns about the possible need to update or change the regulatory analysis guidance. The NRC staff notes that Option 2 could be pursued as part of an overall severe accident management strategy, in a manner similar to that proposed by the nuclear industry (see letter from the Nuclear Energy Institute (NEI) on “Containment Filtration Strategies for Mitigating Radiological Releases in Severe Accidents for BWR Mark I and Mark II Plants to Reduce the Risk of Land Contamination,” dated October 5, 2012). The combination of a severe accident capable vent and an accident management strategy that uses various mechanisms to reduce the release of fission products differs from Option 4 described in this paper in that a specific performance measure (e.g., a combined decontamination factor), would not be treated as a firm regulatory requirement.

A complicating factor in developing Option 2 for Mark II containments is the possibility that molten core material on the drywell floor of the Mark II containment may fail the downcomers or the drywell sump drain lines and result in suppression pool bypass. Enclosure 4 describes this issue in more detail. A bypass of the suppression pool would negate the possible benefits of a severe accident capable venting system in terms of avoiding containment overpressure conditions and a scrubbed release through the suppression pool. The staff concludes that Option 2 for Mark II containments may need to include plant design changes to minimize the possibility of such a bypass event. For example, design features were incorporated into the advanced boiling-water reactor (ABWR) to prevent core debris from entering the lower drywell sump and ablating concrete and breaching the embedded drywell liner. These design changes would likely result in higher costs for Mark II containments, but the average plant costs (including Mark I and Mark II) is expected to remain close to the staff’s estimate of \$2 million.

If Option 2 is selected, the staff recommends that it be imposed by issuing a new order or amending existing Order EA-12-050. Enclosure 7 provides a draft proposed order.<sup>2</sup> The upgrading of the venting system to ensure its functionality during severe accident conditions also would be required for Option 3 (filtered vents order) and Option 4 (severe accident confinement strategies) and would need to be addressed within the development and implementation of those options should they be selected. The staff would use the draft proposed order to support interactions with stakeholders and provide the final order to the Commission via a Regulatory Notification. The staff plans to complete stakeholder interactions and issue the final order within 60 days of the staff requirements memorandum related to this paper. To the extent practical, the order would include performance-based attributes, rather than prescriptive requirements, to allow licensees flexibility in determining how to meet the requirements of the order.

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<sup>2</sup> It is likely that the draft proposed order for Option 2, provided in Enclosure 7a, will require revision based on interactions with stakeholders and continuing internal discussions on technical or legal issues. If the Commission approves Option 2, the staff will provide the Commission with the final order via a Regulatory Notification.

### Option 3: Filtered Severe Accident Venting System Order

Description: Design and install an engineered filtered containment venting system that is intended to prevent the release of significant amounts of radioactive material following the dominant severe accident sequences at BWRs with Mark I and Mark II containments.

This option involves the installation of an engineered filtered containment vent system to prevent the release of significant amounts of radioactive material following most severe accident scenarios at BWRs with Mark I and Mark II containments. The filtering system and connections to the containment wetwell and drywell would need to operate during conditions associated with significant core damage, including breaching of the reactor vessel. Similar to Option 2 (severe accident capable venting system), the approach significantly increases the chances of preventing gross containment failure and substantially supports accident management efforts to arrest further plant degradation and the release of radioactive materials. The inclusion of an engineered filter reduces the amount of radioactive material released to the environment during the venting of containments during severe accidents.

The assumed approach involves the installation of filtering technologies that currently exist to significantly reduce the release of radioactive material in the event of a severe accident. Examples of this filtering technology have been installed at some foreign plants following the accidents at Three Mile Island and Chernobyl (see Enclosures 3 and 4). Section 2 provides an analysis of this option using existing regulatory analysis guidance to determine if the benefits outweigh the approximate \$15 million cost of plant modifications. Section 3 provides a revised analysis that addresses concerns about the possible need to update or change the regulatory analysis guidance. If Option 3 is selected, the staff recommends imposing the related requirements by issuing a new order or amending Order EA-12-050. Enclosure 7 provides a draft proposed order.<sup>3</sup> The staff would use the draft proposed order to support interactions with stakeholders and provide the final order to the Commission via a Regulatory Notification. The staff plans to complete stakeholder interactions and issue the final order within 60 days of the staff requirements memorandum related to this paper. Similar to Option 2 and to the extent practical, the order would include performance-based attributes, rather than prescriptive requirements, to allow licensees flexibility in determining how to meet the requirements of the order.

### Option 4: Severe Accident Confinement Strategies<sup>4</sup>

Description: Pursue development of requirements and technical acceptance criteria for confinement strategies and require licensees to justify operator actions and systems or combinations of systems, such as suppression pools, containment sprays, and engineered filters to accomplish the function and meet the requirements.

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<sup>3</sup> It is likely that the draft proposed order for Option 3, provided in Enclosure 7b, will require revision based on interactions with stakeholders and continuing internal discussions on technical or legal issues. If the Commission approves Option 2, the staff will provide the Commission with the final order via a Regulatory Notification

<sup>4</sup> The Advisory Committee for Reactor Safeguards (ACRS) reviewed a draft of this Commission paper in which Option 4 was entitled "Performance-based approach." The NRC staff's internal review and concurrence process led to revisions to the paper, including clarifying the title and descriptions of Option 4 as developing a severe accident confinement strategy for Mark I and Mark II containments. The general proposal and most of the discussions related to Option 4 remain the same as that reviewed and commented on by the ACRS.

A possible approach to containment venting for BWRs with Mark I and Mark II containments involves establishing technical acceptance criteria (e.g., defined decontamination factor or site-specific cost/benefit analysis) and allowing licensees to select and justify systems or combinations of systems, such as suppression pools, containment sprays, or engineered filters, to accomplish the function and meet the criteria. For this option, the staff did not analyze a specific filtering system; instead, it drew on insights from various sensitivity studies to define a possible approach. Section 4 of this enclosure discusses this option in more detail.

Whereas Options 2 and 3 would have performance-based attributes, Option 4 could potentially result in performance-based regulatory requirements. The development of performance-based approaches tends to involve extensive interactions with stakeholders and the preparation of detailed industry and regulatory guidance documents. Since this process and the related extended time periods are envisioned for Option 4, it may be appropriate to proceed with Option 2 and the related order to ensure the venting systems currently being designed and implemented under EA-12-050 are made severe accident capable. The draft proposed order provided in Enclosure 7a includes highlighted language that would be included if the Commission selects Option 4 with a more immediate requirement to make the containment vents capable of operation during severe accidents. This approach would support the longer term development of the severe accident confinement strategies while possibly reducing the net costs for the changes to containment venting systems. Whichever regulatory process is chosen, it would include performing a regulatory analysis for the proposed requirements, which would depend on the chosen performance measure. For the purpose of this paper, the regulatory analysis for Option 4 addresses a more subjective discussion dealing with possible benefits, costs, and uncertainties. If Option 4 is selected, the staff would engage stakeholders to develop appropriate performance measures, identify the appropriate regulatory process for establishing requirements (e.g., order or rulemaking), and develop the necessary project plans and schedules.

## **1.2 Other Items**

As mentioned in the discussion of the proposed options, the uncertainties associated with the assessment of these approaches are important in attempting to reach a regulatory decision. In addition to the quantitative evaluations in Sections 2 and 3, several other qualitative factors and policy issues directly affect the issue of requiring severe accident capable or filtered vents. Section 5 discusses these qualitative factors and policy issues, which include the following:

- providing defense in depth (including importance of containment function);
- addressing significant uncertainties (frequencies and consequences);
- supporting severe accident management and response;
- improving hydrogen control;
- addressing external events;
- addressing multi-unit events;
- considering independence of barriers;
- improving emergency planning;
- considering consistency between reactor technologies;
- considering severe accident policy statement; and
- addressing international experience and practices (including availability of technology).

Beyond these options, there are other issues relating to containment venting that are worth considering.

### **1.2.1 Vents in Areas other than Primary Containment**

This issue involves the possible installation of vents in areas other than primary containment. For example, vents could be installed in other areas to prevent deflagration or detonation of hydrogen within the reactor building, as occurred at Fukushima. Given that this topic is associated with the control of hydrogen, it will ultimately be resolved through the Tier 3 item associated with the Near-Term Task Force (NTTF) Recommendation 6, "Hydrogen Control and Mitigation Inside Containment or in Other Buildings." However, there is a significant relationship between the control of hydrogen within the primary containment and other plant areas and the decisions associated with severe accident capable or filtered containment venting. The staff will consider the outcomes from this paper in its assessment and proposals for possible paths to resolving Recommendation 6. If Option 2 or 3 are pursued, the resulting containment venting system could play a substantial role in resolving Recommendation 6 for Mark I and Mark II containments. The most likely remaining issues would be an assessment of hydrogen release pathways from containment bypass events and the performance of containment seals, drywell head, and penetrations, if post-severe accident high-pressure and high-temperature conditions were maintained in the containment. Resolving this issue would depend significantly on ensuring a reliable engineered pathway for releasing the hydrogen from the containment and ensuring that there was minimal differential pressure across containment seals and penetrations following venting operations. The staff notes that venting strategies involving maintaining containment pressure at elevated levels, or strategies involving containment vent cycling at elevated pressures, would continue to present the potential for hydrogen leakage from the primary containment to other buildings and may not be as beneficial in resolving NTTF Recommendation 6. Industry proposed approaches, as described in the letter from NEI dated October 5, 2012, might employ such elevated-pressure strategies.

### **1.2.2 Drywell Flooding Capabilities**

Various risk assessments that the NRC and industry have performed for BWRs with Mark I or Mark II containments have concluded that adding water to the drywell significantly benefits controlling the release of radioactive materials for those severe accident scenarios involving fuel melting through the reactor vessel. The water added to the drywell cools the molten fuel, which can arrest its progression and prevent a loss of the drywell containment function (e.g., liner melt-through, containment overpressurization failure, containment overtemperature failure). The importance of providing cooling water to protect the containment was a factor in establishing the mitigating strategies and capabilities associated with the possible loss of large areas of the plant due to explosions or fire in Title 10 of the *Code of Federal Regulations* (10 CFR) 50.54(hh). Current capabilities are addressed in the NRC-endorsed guidance document NEI-06-12, "B.5.b Phase 2 & 3 Submittal Guideline," Revision 2, issued December 2006, which calls for adding approximately 300 gallons per minute through a portable pump and flow paths into the drywell or reactor vessel. For the purpose of this assessment, the staff has incorporated this capability into its characterization of the status quo and has not proposed additional requirements within the proposed options for severe accident capable or filtered containment vents. This capability is important to the success of Options 2, 3, or 4 for scenarios in which the core melts through the reactor pressure vessel, which could then lead to containment failure. The importance of this capability to any severe accident venting requirements may warrant a more specific requirement than is currently in place under 10 CFR 50.54(hh) and the related guidance documents. Because there are existing

requirements and guidance related to this capability, the NRC staff has not included a similar requirement in the draft proposed orders provided in Enclosure 7 for Options 2 and 3. However, the longer-term rulemaking associated with the proposed Options 2, 3, or 4 could consider adding more explicit requirements for the capability of core debris cooling during severe accident scenarios. An additional consideration is the degree to which core or drywell sprays are credited for providing a scrubbing or decontamination function for the radioactive materials within the drywell during a severe accident. The staff will, if necessary, address this issue as part of its implementation of the decisions reached on possible requirements for severe accident capable or filtered containment venting systems.

### **1.3 Justification for Imposing Requirements**

In developing new or revised regulatory requirements, the NRC uses regulatory analyses such as those discussed in Sections 2 and 3 to help in the decisionmaking process. However, the agency is not constrained by quantitative cost/benefit calculations. There are two primary cases in which the agency's deliberations might lead to an action even though the costs of that action might appear to outweigh the benefits. These cases involve one of the following:

- (1) finding that one or more of the options discussed is needed to provide reasonable assurance of adequate protection of the public health and safety, or<sup>5</sup>
- (2) finding that one or more of the options justify the associated costs as a result of the combination of the standard regulatory analysis and other qualitative factors.

#### Adequate Protection

The first case involves specific exceptions in 10 CFR 50.109, "Backfitting," on the need to perform cost/benefit analyses for some NRC actions that impose new requirements on licensees. The exceptions listed in 10 CFR 50.109(a)(4) are listed below:

- (i) That a modification is necessary to bring a facility into compliance with a license or the rules or orders of the Commission, or into conformance with written commitments by the licensee; or
- (ii) That regulatory action is necessary to ensure that the facility provides adequate protection to the health and safety of the public and is in accord with the common defense and security; or
- (iii) That the regulatory action involves defining or redefining what level of protection to the public health and safety or common defense and security should be regarded as adequate.

In the case of the potential options under consideration (Options 2, 3, or 4), exceptions (ii) or (iii) could be invoked if the Commission were to determine that such changes were needed to address the current or a revised standard for adequate protection. A discussion of the history

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<sup>5</sup> In the case of a finding that an action is needed for adequate protection of public health and safety, the NRC is actually not allowed to consider costs in its decisions. Therefore, a finding should be made about adequate protection independent of costs instead of invoking the adequate protection provisions because the costs have been found to exceed the calculated benefits.

and traditional use of the NRC invoking the standard of reasonable assurance of adequate protection is provided in SECY-12-0110, "Consideration of Economic Consequences within the U.S. Nuclear Regulatory Commission's Regulatory Framework," dated August 14, 2012.

The NRC staff assessed the possible benefits associated with the options described in this paper for improving containment venting at BWRs with Mark I and II containments. The assessment and lessons learned from the Fukushima accident indicate that functions to delay core damage and containment failure in combination with protective actions taken to evacuate or shelter the public are able to minimize risks to the public health and safety. The NRC has traditionally reserved the use of the adequate protection standard for the protection of public health and safety and has invoked it for design-basis accidents, selected functions to prevent core damage (e.g., EA-12-050), and programs to ensure licensees have strategies or contingencies for severe accidents (e.g., emergency planning, EA-12-049 ("Order Modifying Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events, dated March 12, 2012) and 10 CFR 50.54(hh)). The NRC has previously considered incorporating into its approach to defense in depth a balancing of prevention and mitigation measures. However, such an approach and the related criteria for achieving a balance between elements of defense in depth were not formally adopted nor included in the NRC's guidance documents. For the purpose of this analysis, the staff did not apply any of the exceptions to the Backfit Rule. The staff has proceeded with analyses of proposed venting modifications as possible cost-justified substantial safety improvements. The staff's decision to proceed with a cost-benefit analysis does not represent a staff recommendation regarding whether Option 2, 3, or 4 could be pursued under one of the exceptions to the Backfit Rule.

The NRC staff does not currently consider the potential economic consequences of an accident within its deliberations on adequate protection. A Commission decision to revise the agency's accounting of offsite land contamination (Option 3 in SECY-12-0110) could affect arguments related to finding whether the addition of a filtered vent system for BWRs with Mark I or II containments might be needed for a revised adequate protection standard or a separate equivalent standard for economic consequences. Even in the absence of Commission direction to revise the current focus on public health and safety in deliberations on adequate protection (or equivalent standard for economic consequences), the current assessment process for a regulatory analysis or a backfit analysis includes consideration of offsite costs—a topic discussed within the additional qualitative factors in Section 5.

### Cost-Justified Safety Enhancements

For the purpose of this paper, a two-part backfit analysis is applied, as described in 10 CFR 50.109(a)(3). Before proceeding to a comparison of costs and benefits, the first part of the test under (a)(3) is to determine whether there is a "substantial increase in the overall protection of the public health and safety or the common defense and security derived from the backfit." NUREG/BR-0058 includes the following explanation from staff requirements memorandum (SRM), "SRM-SECY-93-086—Backfit Considerations," dated June 30, 1993, on the need for plant backfits to provide a substantial increase in safety:

The Commission has stated that "substantial" means important or significant in a large amount, extent, or degree. Applying such a standard, the Commission would not ordinarily expect that safety-applying improvements would be required as backfits that result in an insignificant or small benefit to the public health and safety, regardless of costs. On the other hand, the standard is not intended to be interpreted in a manner that would result in disapprovals of worthwhile safety or

security improvements having costs that are justified in view of the increased protection that would be provided. This approach is flexible enough to allow for qualitative arguments that a given proposed rule would substantially increase safety. The approach is also flexible enough to allow for arguments that consistency with national and international standards, or the incorporation of widespread industry practices, contributes either directly or indirectly to a substantial increase in safety. Such arguments concerning consistency with other standards, or incorporation of industry practices, would have to rest on the particulars of a given proposed rule. The Commission also believes that this approach of “substantial increase” is consistent with the Agency’s policy of encouraging voluntary initiatives.

NUREG/BR-0058 describes the use of the NRC safety goals as a way to evaluate if a proposed backfit provides substantial safety improvements. However, it also recognizes the limitations of this approach for modifications that do not change core damage estimates but provide improvements to containment performance. Specifically, the guidance states:

The NRC recognizes that in certain instances, the screening criteria may not adequately address certain accident scenarios of unique safety or risk interest. An example is one in which certain challenges could lead to containment failure after the time period adopted in the safety goal screening criteria, yet early enough that the contribution of these challenges to total risk would be nonnegligible, particularly if the failure occurs before effective implementation of accident management measures. In these circumstances, the analyst should make the case that the screening criteria do not apply and the decision to pursue the issue should be subject to further management decision.

Furthermore, note that the safety goal screening criteria described in these Guidelines do not address issues that deal only with containment performance. Consequently, issues that have no impact on core damage frequency ( $\Delta$ CDF of zero) cannot be addressed with the safety goal screening criteria. However, because mitigative initiatives have been relatively few and infrequent compared with accident preventive initiatives, mitigative initiatives will be assessed on a case-by-case basis with regard to the safety goals. Given the very few proposed regulatory initiatives that involve mitigation, this should have little overall impact from a practical perspective on the usefulness of the safety goal screening criteria.

Senior NRC managers on the Japan Lessons-Learned Steering Committee (SECY-11-0117, “Proposed Charter for the Longer-Term Review of Lessons Learned from the March 11, 2011, Japanese Earthquake and Tsunami,” dated August 26, 2011) assessed the issue of whether the possible imposition of requirements for severe accident capable or filtered venting systems satisfy the “substantial safety improvement” standard. The managers decided that the possible modifications should proceed to the estimation and evaluation of values and impacts within the regulatory analysis process. The following sections of this enclosure provide these estimates and evaluations.

## 1.4 Performance-based Approaches

The Commission provided the staff with direction on the need to consider performance-based approaches in its SRM for SECY-11-0124, "Recommended Actions to be Taken Without Delay from the Near-Term Task Force Report," dated October 18, 2011. In that SRM, the Commission stated:

As the staff evaluates Fukushima lessons-learned and proposes modifications to NRC's regulatory framework, the Commission encourages the staff to craft recommendations that continue to realize the strengths of a performance-based system as a guiding principle. In order to be effective, approaches should be flexible and able to accommodate a diverse range of circumstances and conditions. In consideration of events beyond the design basis, a regulatory approach founded on performance-based requirements will foster development of the most effective and efficient, site-specific mitigation strategies, similar to how the agency approached the approval of licensee response strategies for the "loss of large area" event under its B.5.b program.

A performance-based regulatory approach is one that establishes performance and results as the primary basis for regulatory decisionmaking, and incorporates the following attributes:

- (1) measurable (or calculable) parameters (i.e., direct measurement of the physical parameter of interest or of related parameters that can be used to calculate the parameter of interest) exist to monitor system, including facility and licensee, performance,
- (2) objective criteria to assess performance are established based on risk insights, deterministic analyses, and/or performance history,
- (3) licensees have flexibility to determine how to meet the established performance criteria in ways that will encourage and reward improved outcomes, and
- (4) a framework exists in which the failure to meet a performance criterion, while undesirable, will not in and of itself constitute or result in an immediate safety concern.

In the development and assessment of Options 2, 3, and 4, the staff considered the potential incorporation of performance-based approaches. Options 2 and 3 include performance-based attributes, and Option 4 involves development of a performance-based regulatory requirement.

## 2.0 EVALUATION OF OPTIONS USING EXISTING REGULATORY ANALYSIS GUIDANCE

The staff, with assistance from Sandia National Laboratories, performed analyses using MELCOR and MACCS2 computer simulations to characterize the expected plant response and offsite consequences for an extended loss of electrical power at a representative BWR with a Mark I containment design. The following key assumptions were used in the simplified regulatory analyses provided in this enclosure:

- Base event frequency for events in which the severe accident capable or filtered venting system would add significant value is assumed to be  $2 \times 10^{-5}$  per reactor-year. This value is taken from the results of individual plant examinations, NRC standardized plant analysis risk (SPAR) models, and engineering judgment. This value is considered representative of the core damage frequency for the operating plants with Mark I and II containment designs.
- To address the uncertainties associated with event frequencies, the assessment is also performed assuming a core damage frequency of  $2 \times 10^{-4}$  per reactor-year, which is a factor of 10 above the base event frequency.<sup>6</sup>
- Assuming a lower CDF value would reduce the calculated benefits in a similar fashion but in the opposite direction, thereby making the proposals less cost-effective. Since the reduction is proportional to the CDF assumption (i.e., reducing CDF by a factor of 10 reduces the calculated benefit by a factor of 10), the staff has not specifically included the sensitivity to lower CDFs within the discussions or tables.
- The technical analyses sections included in Enclosure 5 discuss specific assumptions about transients, equipment performance, and recovery actions.

The base case and sensitivity analyses are summarized below in terms of the various factors used in the regulatory analysis guidelines. A more complete assessment of uncertainties and sensitivities can be found in Enclosure 5 and in the regulatory analysis available in ADAMS at Accession No. ML12312A456.

### 2.1 Public Health (Accident)

For the purpose of establishing the base case, scenarios involving the potential for a significant release of radioactive material through a containment vent path are identified and evaluated in terms of consequences and estimated accident frequencies. In the case of BWRs with Mark I and II containment designs, this subset of severe accidents makes up the majority of the sequences involving large releases (with the remainder involving failures of containment and releases through pathways other than a controlled and possibly filtered pathway). Containment failures, for example, could occur as a result of severe accident conditions that involve high pressures in the containment (e.g., venting failures) or scenarios that involve a molten core breaching both the reactor vessel and drywell liner (e.g., lack of drywell spray).

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<sup>6</sup> The range was selected to provide decisionmakers with information about sensitivities to certain assumptions and to address uncertainties, plant-to-plant variations, and the limited number of PRAs including external events. The NRC staff is not placing any particular importance on the upper value used except as a part of sensitivity studies provided for CDF and other parameters. The factor of 10 in the simplified analysis provided in this enclosure generally corresponds to the 95% confidence levels used in Enclosure 5C and the regulatory analysis.

The results from the simulations of an extended loss of electrical power transient are consistent with previous evaluations and the experience from the Fukushima Dai-ichi accident in the viability of avoiding large exposures to the general public by the evacuation of populations near a nuclear power plant. The analysis assumes, however, that populations are instructed to return to their homes following an accident if projected dose rates fall below the defined criteria (e.g., 500 mrem/year). This longer-term exposure of populations from the residual contamination of the countryside is controllable but is assumed to estimate a plausible balancing of public health and economic impacts. In this case, reducing public exposures by limiting the return of populations to affected areas would result in an increase in the economic consequences by preventing the use of homes and businesses.

For the status quo, Case 6, a related scenario described in Enclosure 5, includes failure of containment on overpressure and a long-term population dose of 310,000 rem to the public within 80 kilometers (50 miles) of the site. As discussed in Enclosure 5, consideration of various possible sequences of events, with assumed probabilities, leads to an estimated 80-kilometer (50-mile) population dose risk of 10.2 rem/reactor year (rem/ry).

### **2.1.1 Option 2—Severe Accident Capable Vents**

To estimate the potential benefits of requiring a severe accident capable venting system, the staff used the simulations and risk estimates from Enclosure 5. The estimated population dose risk for a severe accident capable vent is 5.9 rem/ry or a net benefit of 4.3 rem/ry when compared to the base case. Using the existing guidance for NRC regulatory analyses, the staff converted the estimated dose savings into dollars using the following equation:

$$[(\text{Estimated Accident Frequency}) \times (\text{Change in Population Dose})] \times (\$2,000/\text{person-rem}) \times [1 - \exp(-(\text{discount rate}) \times (\text{remaining reactor life}))]/(\text{discount rate})$$

Where: 4.3 rem/ry reflects the frequency and change in estimated dose  
conversion factor of \$2,000 per rem  
discount rates are assumed to be 3 percent<sup>7</sup>  
remaining reactor life assumed to be 25 years

Using the assumptions above, the benefits of the severe accident capable vent in terms of avoiding doses to the population are estimated to be \$150,000 per reactor unit.

The benefits, estimated above, are proportional to the estimated accident frequency and the related uncertainties. If, for example, the estimated frequency related to a severe accident were raised to  $2 \times 10^{-4}$ /reactor year, the associated benefits would increase to \$1.50 million per unit.

### **2.1.2 Option 3—Filtered Vents**

The installation of a filtering system with expected performance requirements would significantly reduce the release and subsequent exposure of the population. For the sake of this evaluation, the values associated with Modification 6 from Enclosure 5 are used. These estimates include a risk evaluation estimate for population dose of 2.0 rem/ry or a projected reduction of

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<sup>7</sup> A complete regulatory analysis is available in ADAMS at Accession No. ML12312A456 and includes an alternate assessment using a 7 percent discount rate. The 3-percent discount rate provides a higher calculated benefit and is used for the remainder of this enclosure.

8.2 rem/ry when compared to the base case. Using the equation above, the reduction in projected dose risks translates into a net benefit of \$290,000 per reactor unit.

The benefits estimated above would increase to \$ 2.90 million per unit if the estimated accident frequency were raised to  $2 \times 10^{-4}$ /reactor year.

The uncertainties associated with expected decontamination factors for suppression pools and sprays were assessed by performing additional simulations with the MELCOR and MACCS2 computer codes. Sensitivity studies related to various scenarios and decontamination factors are provided in Enclosure 5. A very conservative estimate with limited credit for scrubbing by the suppression pool or sprays and venting from the drywell resulted in a reduction in dose for a filtered vent path of nearly 4 million rem for a population within 80 kilometers (50 miles). That value would, in turn, translate into a calculated benefit of \$2.8 million per unit in current dollars using the above equation and core damage frequency of  $2 \times 10^{-5}$  per reactor-year.

## **2.2 Occupational Health (Accident)**

Accidents involving significant core damage will result in an increase in occupational exposures at the plant. A range of estimated occupational exposures were taken from NUREG/BR-0184 to simulate the possible effects of severe accident capable and filtered venting systems.

A containment failure due to overpressure or liner melt-through was assumed to result in the highest estimate of immediate occupational dose from the regulatory analysis handbook, which is 14,000 person-rem. The conditions associated with severe accident capable vents were assumed to reduce the associated occupational exposure to 3,300 person-rem. Finally, the filtered release was assumed to result in the lowest immediate occupational exposure of 1,000 person-rem, which is approximately the occupational dose received from the Three Mile Island accident. The risk assessment provided in Enclosure 5 considered the possible end states and their likelihood for the various possible modifications and provided dose risk for the immediate accident period. The following total occupational dose risks are derived from combining the immediate occupational doses and the longer term (cleanup) doses from NUREG/BR-0184.

- |                                   |                    |
|-----------------------------------|--------------------|
| • status quo                      | 0.88 person-rem/ry |
| • severe accident capable (Mod 2) | 0.56 person-rem/ry |
| • filtered vent (Mod 6)           | 0.33 person-rem/ry |

Using the same equations and assumptions (\$2,000 per person-rem and CDF of  $2 \times 10^{-5}$  per reactor-year) as used above for consideration of public doses results in an estimated benefit of \$11,000 per unit for severe accident capable vents and \$19,000 per unit for filtered vents. Increasing the estimated frequency of core damage to  $2 \times 10^{-4}$  per reactor-year would result in an increase of estimated benefit for the severe accident capable vents to \$110,000 per unit and to \$190,000 per unit for filtered vents.

Another potential impact in terms of evaluating filtered vents would be the number of workers added to participate in offsite cleanup activities following a major release. However, decisions related to cleanup activities for the nearby countryside could consider and assess the expected dose to workers versus the economic impact of not recovering the affected areas. The potential dose-related costs for the cleanup of contaminated offsite areas are accounted for in the assessment of potential effects on offsite property.

## **2.3 Offsite Property**

The United States has an existing structure for nuclear power plants that involves measures to prevent, contain, and mitigate releases of radioactive materials and, if necessary, to compensate individuals for the potential damages to health, property, or income. For the purpose of this discussion, prevention and containment relate to attempts to arrest a nuclear accident and maintain the radioactive material within the plant (including confining materials within containment or within a filter). Mitigation relates to limiting the impact on public health through protective actions such as sheltering or evacuation. The Price-Anderson Act and related NRC regulations address provisions for compensation. Regulatory analyses do not usually address compensation for nuclear accidents since it involves the source and flow of funds but does not influence the actual amount of damages that a potential nuclear accident causes. The funding from current insurance pools available to address a major nuclear accident in the United States is approximately \$12 billion.

The results from the computer simulations include estimates for the amount of land area that could be contaminated following the modeled scenarios as well as an estimate of total economic costs (assuming loss of use of property, businesses, etc.). The results from the analyses for one of the cases (Case 6 with containment failure on overpressure) used in the risk assessments described in Enclosure 5 is a land contamination area of 72 km<sup>2</sup>, and an offsite property damage estimate of \$850 million. Consideration of various possible sequences of events, with assumed probabilities, leads to an estimated offsite cost risk of \$630,000 per reactor-year.

### **2.3.1 Option 2—Severe Accident Capable Vents**

Applying the same assumptions and cases discussed for population doses, the estimated difference in the offsite cost risk for Modification 2 (assumed passive vent from wetwell) is \$19,767 per reactor-year. Using the existing guidance and assumptions for NRC regulatory analyses, the estimated difference in economic consequences in current dollars (i.e., the benefit of the severe accident capable vent) is \$348,000 per reactor unit. Assuming an event frequency of  $2 \times 10^{-4}$  per reactor-year would increase the calculated benefit to \$3.48 million per unit.

### **2.3.2 Option 3—Filtered Vents**

The installation of a filtering system with expected performance requirements would significantly reduce the estimated affected land area and related economic consequences. The filtered venting system in this assessment uses the offsite cost risk reductions from Enclosure 5 for Modification 6 (assumed passive vent from wetwell with filter), which were estimated to be \$34,166 per reactor-year. Using the established assumptions and conversions, the avoided economic consequences translates in current dollars to a benefit of \$600,000 per reactor unit. As with the other factors, this result is directly correlated to estimated accident frequencies and increases to \$6.0 million per unit if a frequency of  $2 \times 10^{-4}$  per reactor-year is assumed. Section 3 provides additional discussion on the uncertainties and other issues associated with estimating economic consequences.

## **2.4 Onsite Property**

A severe accident at a nuclear power plant is assumed to result in the loss of the affected unit in terms of the future electrical output and early decommissioning (complicated by the post-accident conditions). The installation of a filter within the containment vent path would not

likely change the total loss of the unit experiencing significant fuel damage. However, a filter could limit contamination of nearby units and the associated increase in onsite property damage, including loss of generation from the co-located units. The factor related to occupational health was used to address radiation exposure for site cleanup. Other cleanup costs are addressed using guidance from NUREG/BR-0184 and the estimates of risk factors provided in Enclosure 5.

The onsite property costs address the possible loss of electrical generation resulting from an accident. For the purposes of this evaluation, the radioactive releases from either the base case or Option 2 are assumed to result in the permanent closure of not only the unit with the damaged core but also units located on the same site. In accordance with existing practices, the impact of these shutdowns is modeled as the replacement costs for a 10-year period (after which alternate energy supplies would become available). The filtered venting case is assumed to result in the loss of the co-located units for 1 year. Of the 31 BWR units with Mark I or II containments, 8 are single unit sites, 16 could affect one other operating unit, and 7 could affect 2 other operating units. Based on these site combinations, consideration of the loss of co-located facilities on a generic basis for Mark I and II units is addressed by multiplying the loss of electrical generation by a factor of 1.75.

#### **2.4.1 Option 2—Severe Accident Capable Vents**

The estimated difference in the onsite cost risk for Modification 2 (assumed passive vent from wetwell) is \$15,185 per reactor-year. Using the existing guidance and assumptions for NRC regulatory analyses, the estimated difference in onsite costs in current dollars (i.e., the benefit of the severe accident capable vent) is \$268,000 per reactor unit. Assuming an event frequency of  $2 \times 10^{-4}$  per reactor-year would increase the calculated benefit to \$2.68 million per unit.

The cost from the loss of electrical generation from co-located facilities was estimated assuming an average value of \$9.9 million per reactor-year. Using the generic factor of 1.75 and a period of 10 years for needed power replacement results in an undiscounted consequence estimate of \$173.25 million. Considering the likelihood of such events results in a value of \$3,500 for an event frequency of  $2 \times 10^{-5}$  per reactor-year and of \$35,000 for the value of  $2 \times 10^{-4}$  per reactor-year. However, since this loss is the same for the base case, it is not used directly, except to estimate savings for the following filtered vent option.

#### **2.4.2 Option 3—Filtered Vents**

The estimated difference in the onsite cost risk for Modification 6 (assumed passive vent from wetwell with filter) is \$24,485 per reactor-year, which translates into an estimated difference in onsite costs in current dollars (i.e., the benefit of the filtered vent) of \$430,000 per reactor unit. Assuming an event frequency of  $2 \times 10^{-4}$  per reactor-year would increase the calculated benefit to \$4.3 million per unit.

The cost from the loss of electrical generation from co-located facilities was estimated assuming an average value of \$9.9 million per reactor-year. Using the generic factor of 1.75 and a period of 1 year for needed power replacement for the undamaged unit results in an undiscounted consequence estimate of \$106.425 million. Considering the likelihood of such events results in a value of \$2,100 for an event frequency of  $2 \times 10^{-5}$  per reactor-year and of \$21,000 for the value of  $2 \times 10^{-4}$  per reactor-year. This can be represented as a savings of \$1,400 for the  $2 \times 10^{-5}$  per reactor-year frequency and \$14,000 for an assumed event frequency of  $2 \times 10^{-4}$  per reactor-year.

## **2.5 Industry Implementation**

The base case involves implementing current requirements (e.g., EA-12-049, “Mitigation Strategies for Beyond-Design-Basis External Events,” and EA-12-050); therefore, it does not involve additional costs. The implementation costs for providing a severe accident capable reliable hardened vent could vary significantly between plants based on equipment configurations and plans regarding the implementation of EA-12-050. An assumed cost for this evaluation is \$2 million per unit, which is based primarily on judgment and gross estimates of time and materials for many of the plants that would need to perform modifications. As discussed in Enclosure 4, the costs for severe accident capable vents for Mark II containment designs will likely be higher than for Mark I units. The higher cost reflects the likely need to modify containments to prevent a molten core from causing a bypass of the suppression pool because of failure of downcomers and drain lines below the reactor vessel. Given that avoiding bypass of the wetwell is necessary to make the severe accident capable vents a viable option for the Mark II design, protection of the downcomers and drain lines are included in the cost of this option for Mark II containments. The implementation costs for the filtered venting system are estimated based on discussions with foreign plants, vendors, and other stakeholders. The estimated costs used in this assessment are \$15 million per unit.<sup>8</sup>

## **2.6 Industry Operation**

The base case involves implementing current requirements (e.g., EA-12-049 and EA-12-050); therefore, it does not involve additional costs. The upgrading of venting systems to be compatible with severe accident conditions is not expected to add significantly to the operating costs of a nuclear power plant and is therefore not estimated for this evaluation. The operating costs for maintaining the filtered venting system, including training, are estimated based on discussions with foreign plants, vendors, and other stakeholders. The estimated costs used in this assessment are \$60,000 per unit per reactor-year in current dollars for a present value of \$1.1 million (3 percent discount rate and a 25-year license term).

## **2.7 NRC Implementation**

The base case involves implementing current requirements (e.g., EA-12-049 and EA-12-050); therefore, it does not involve additional costs. The implementation costs for developing regulations for a severe accident capable or filtered vent and subsequent reviews and inspections are estimated to involve a total NRC cost of \$830,000 or approximately \$27,000 per unit.

Longer-term NRC operating costs are not expected to change as a result of the possible addition of these requirements and are not included in this evaluation.

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<sup>8</sup> Some stakeholders have noted that an estimate of \$15 million seems low and that the price could be factors of 2 or 3 higher. The costs could be significantly above \$15 million if the system is designed and installed as safety-related equipment or needed to be protected from beyond-design-basis external events.

## 2.8 Summary

The results of the evaluation of the costs and benefits of a severe accident capable and filtered vent system using the existing regulatory analysis guidelines are summarized below.

Table 1: Summary of Quantified Cost/Benefit Assessment for Options 2 and 3

<b>Costs ( ) and Benefits of Severe Accident Capable and Filtered Vent System \$ K Per Unit</b>				
	<b>Severe Accident Capable Venting Systems</b>		<b>Engineered Filtered Venting Systems</b>	
<b>Factor</b>	<b>Best Estimate Frequency of <math>2 \times 10^{-5}</math> / ry</b>	<b>Accident Frequency of <math>2 \times 10^{-4}</math> / ry</b>	<b>Best Estimate Frequency of <math>2 \times 10^{-5}</math> / ry</b>	<b>Accident Frequency of <math>2 \times 10^{-4}</math> / ry</b>
Public Health	150	1,500	290	2,900
Occupational Health	11	110	19	190
Offsite Property	348	3,480	600	6,000
Onsite Property	268	2,680	430	4,300
Industry Implementation	(2,000)	(2,000)	(15,000)	(15,000)
Industry Operation	n/a	n/a	(1,100)	(1,100)
NRC Implementation	(27)	(27)	(27)	(27)
<b>TOTAL</b>	<b>(1,250)</b>	<b>+5,743</b>	<b>(14,778)</b>	<b>(2,737)</b>

### **3. EVALUATION OF OPTIONS INCLUDING POSSIBLE CHANGES TO REGULATORY ANALYSIS GUIDANCE**

The previous section discussed the base case and related sensitivities for the evaluation. Much of that information is used for the revised analysis in this section, which focuses on possible updates or changes to the regulatory analysis guidance or assumptions related to the costs and benefits of a severe accident capable or filtered venting system for BWRs with Mark I or II containment designs. There are several possible changes that would affect the evaluation of the severe accident capable or filtered vent options. In general, the consequence analyses from Section 2 are carried forward to this assessment and revised factors are used to represent those consequences in terms of the cost/benefit calculations.

#### **3.1 Public Health (Accident)**

Section 2 described the evaluation of the base case and options in terms of possible exposures to the populations within 80 kilometers (50 miles) of a plant undergoing a severe accident for which the installation of severe accident capable or filtered vents could reduce the offsite consequences. A discussion of sensitivities to accident frequency and retention of fission products by suppression pools and sprays is provided in Enclosure 5. The other major factor in the assessment of possible public health benefits is the value used to convert population dose (roentgen equivalent man (rem)) into dollars based on various health studies and the valuation of impacts on life and health. The NRC staff is currently assessing a possible revision of the \$2,000 per person-rem conversion factor, including a revision of the factor to \$4,000 per person-rem.

The sensitivity of this assessment of the costs and benefits of installing a severe accident capable or filtered venting system for BWRs with Mark I or II containments is directly proportional to the assumed conversion factor. A doubling of the factor, to \$4,000 per person-rem, would double the previously calculated benefits of the severe accident capable vent to \$300,000 per unit while the benefit of a filtered system would be increased to \$580,000 per unit. An increase in assumed accident frequency to  $2 \times 10^{-4}$  per reactor-year would then increase the benefits to \$3.0 million and \$5.8 million per unit, respectively, for the severe accident capable and filtered venting systems. The estimated benefit of an engineered filter for the case in which possible retention of fission products within the suppression pool is largely neglected by venting from the drywell would increase to \$5.6 million dollars per unit (assuming accident frequency of  $2 \times 10^{-5}$  per reactor-year).

#### **3.2 Occupational Health (Accident)**

As above, an increase in the dollars per person-rem conversion factor to \$4,000 would double the estimates provided in Section 2. The estimated benefits would be \$22,000 per unit for a severe accident capable vent and event frequency of  $2 \times 10^{-5}$  per reactor-year and \$220,000 for an estimated event frequency of  $2 \times 10^{-4}$  per reactor-year. Likewise, the estimated benefits of a filtered vent system would increase to \$38,000 and \$380,000 per unit, respectively, for the frequencies of  $2 \times 10^{-5}$  and  $2 \times 10^{-4}$  per reactor-year.

### 3.3 Offsite Property

Estimates of the long-term economic consequences of the Fukushima Dai-ichi accident continue to evolve and ultimately may be used to update NRC guidance for performing regulatory analyses. As discussed in SECY-12-0110, the NRC staff is evaluating possible updates to the computer codes and models used to assess offsite property damages.

There continues to be a fairly wide range of estimates for the actual economic impact of previous events, such as Hurricane Katrina, which struck the southern United States in 2005. This highlights the difficulty in predicting potential impacts for future disasters, including potential nuclear reactor accidents. Several journals provide estimates of around \$125 billion, including the loss of oil production and refining, for the economic impacts of Hurricane Katrina. Other major disasters, such as Hurricane Andrew in 1992 and Hurricane Irene in 2011, have been estimated to have caused around \$45 billion in economic losses. A conservative simulation using MACCS2, discussed in Enclosure 5, addresses uncertainties in the performance of the suppression pool and sprays in limiting the release of radioactive materials. The simulation calculated total economic costs at \$33 billion for that conservative representation of a large release from the modeled BWR.<sup>9</sup> In terms of a typical regulatory analysis, an estimated offsite cost of \$33 billion translates (assuming an event frequency of  $2 \times 10^{-5}$  per reactor-year) into a net benefit (averted cost) of \$11.6 million per unit. Given the ongoing efforts to assess and update capabilities to estimate economic consequences, the staff is not providing additional sensitivities here about the estimation of offsite property damage. This issue will be discussed again in qualitative terms in Section 5.

### 3.4 Onsite Property

As mentioned in Section 2, a severe accident at a nuclear power plant is assumed to result in the loss of the affected unit in terms of the future electrical output and early decommissioning (complicated by the post-accident conditions) for both the base case and the proposed options. The installation of a filter within the containment vent path could, however, limit contamination of nearby units and the associated increase in onsite property damage, including loss of generation from the co-located unit. The potential impacts could range from a temporary loss of the unaffected unit to its permanent closure because of economic, technical, or societal factors. The regulatory analysis includes sensitivities to a range of electrical energy costs, but these were not found to affect the assessment dramatically. The results from Section 2 are as follows:

Table 2: Onsite Property Damage Estimates for Options 2 and 3

Modification	Unit Cost	
	$2 \times 10^{-5}$ /yr Event Frequency	$2 \times 10^{-4}$ /yr Event Frequency
Severe Accident Capable Venting Systems	\$268,000	\$2.68 million
Engineered Filtered Venting Systems	\$430,000	\$4.3 million

<sup>9</sup> Note that under the provisions of the Price-Anderson Act, damages that exceed the available insurance pools (currently at approximately \$12 billion) would require actions on the part of the U.S. government to increase nuclear utility liability or contribute to the compensation funds.

Although the replacement energy costs for the affected and co-located units do not appear to significantly affect the results of the regulatory analysis, the Fukushima accident also led to the shutdown of other nuclear units located away from the direct effects of the accident. Such shutdowns might result from new regulatory reviews or requirements, caution on the part of plant operators, or other societal factors. The possibility of such shutdowns and the resulting increase in replacement power is addressed as a sensitivity case in the regulatory analysis and could increase the calculated benefits from the installation of a filtering system. Early shutdown of a large number of units would also entail the costs from decommissioning and disturbance of broader energy markets.

### **3.5 Industry Implementation**

As discussed in Section 2, the costs of industry implementation are estimated to be \$2 million for severe accident capable vents and \$15 million for a filtered venting system. While there is considerable uncertainty with these estimates, the handling of industry implementation costs is not likely to be a significant issue within the updating of the regulatory analysis guidance and no additional discussion of sensitivities is provided here.

### **3.6 Industry Operation**

The industry operating costs for maintaining the filtered venting system were estimated in Section 2 to be \$60,000 per unit per reactor-year in current dollars for a present value of \$1.1 million (3 percent discount rate and a 25-year license term). As with the industry implementation costs, there are uncertainties associated with NRC estimates of industry operating costs, but they are not likely to be identified as a significant issue when updating the regulatory analysis guidance. Therefore, no additional discussion of sensitivities is provided here.

### **3.7 NRC Implementation**

As discussed for the previous two factors, NRC implementation costs for the development of regulations have uncertainties, but this element of the regulatory analysis is not likely to be a major issue for updating the regulatory analysis guidance. The NRC implementation costs are estimated to be approximately \$27,000 per unit.

### **3.8 Summary**

The results of the evaluation of the costs and benefits of a severe accident capable and filtered vent system using possible revision of the regulatory analysis guidelines are summarized below:

Table 3: Sensitivity Study for Quantified Cost/Benefit Assessment for Options 2 and 3

Costs ( ) and Benefits of Modified Vent System (\$ K) Per Unit						
Factor	Best Estimate (from Section 2)		Revised to Address Sensitivity to Changes to Regulatory Analysis Assumptions			
	Severe Accident Capable	Filtered	Severe Accident Capable <sup>(1)</sup> (at $2 \times 10^{-5}/ry$ ) (at $2 \times 10^{-4}/ry$ )		Filtered (at $2 \times 10^{-5}/ry$ ) (at $2 \times 10^{-4}/ry$ )	
Public Health	150	290	300	3,000	580	5,800
Occupational Health	11	19	22	220	38	380
Offsite Property	348	600	348	3,480	600*	6,000
Onsite Property	268	430	268	2,680	430	4,300
Industry Implementation	(2,000)	(15,000)	(2,000)		(15,000)**	
Industry Operation	n/a	(1,100)	n/a		(1,100)	
NRC Implementation	(27)	(27)	(27)		(27)	
<b>TOTAL</b>	<b>(1,250)</b>	<b>(14,778)</b>	<b>(1,089)*</b>	<b>+7,353</b>	<b>(14,479)</b>	<b>+353</b>
<p><sup>(1)</sup> As discussed in Enclosures 4, the costs for severe accident capable vents for Mark II containment designs will likely be higher than for Mark I units. The higher cost reflects the likely need to modify containments to prevent a molten core from causing a bypass of the suppression pool due to failure of drain lines and downcomers below the reactor vessel. Avoidance of suppression pool bypass is needed to make the severe accident capable vents a viable option for the Mark II design.</p> <p>* Uncertainties in estimating consequences is addressed further as a qualitative factor in Section 5. As previously mentioned, a largely unmitigated release leads to offsite property damage on the order of \$33 billion, which in turn translates into a benefit for filtered vents of approximately \$11.6 million per unit.</p> <p>** Note that some stakeholders have stated that the price of a filtered vent system could range from \$30 – 45 million</p>						

#### 4. SEVERE ACCIDENT CONFINEMENT STRATEGIES

As previously noted in Sections 2 and 3, there are significant uncertainties associated with some of the key parameters used in the regulatory analyses. These include the frequency of the scenarios that would benefit from severe accident capable or filtered vents, the efficiency of various systems in limiting the release of radioactive materials, and the economic consequences of a severe accident that results in the contamination of environs near a reactor facility. An issue related to uncertainties is the plant-to-plant variations that limit the effectiveness of generic assessments and generic solutions. The various BWRs with Mark I and II containments have similarities, but also differences in design features, system capabilities and vulnerabilities, risk contributors, number of co-located units, and geographic locations. Such differences between plants have given rise to the possible benefits of developing a performance-based approach, which would require each licensee to evaluate the needed performance of the containment venting function and to implement appropriate design and procedure changes to satisfy the performance requirement. While there are performance-based attributes in the orders that would be issued under Options 2 and 3, Option 4 would include broader consideration of a performance-based regulatory approach. A discussion of the Commission's direction on performance-based approaches is in Section 1.4 of this enclosure.

The NRC traditionally has approached the development of performance-based regulations using the rulemaking process to accommodate the necessary interactions with stakeholders and the appropriate development of performance standards. Simpler measures might be effectively imposed through the issuance of orders, but measures for which additional research is needed or involve other policy issues (e.g., broader societal measures such as land contamination) would more likely be pursued through the rulemaking process. The staff would include in any proposed rulemaking for this option an assessment of costs and benefits related to the performance-based approach.

In a letter dated October 5, 2012, NEI proposed that licensees for each plant with Mark I or Mark II containments develop a "filtering strategy" that could include the use of existing systems and, if deemed appropriate, additional equipment such as engineered filters. A performance-based option and the NEI proposal would seem to require, at a minimum, a venting system capable of operating under severe accident conditions (Option 2). The establishment of a performance measure could, for some plants, result in the installation of an engineered filtering system (Option 3) if it is determined that such a system is necessary to meet the performance measure with the required level of confidence.

##### Performance Measures

One potential approach to defining a performance measure would be to define a parameter such as a required decontamination factor (DF) for the available combination of plant systems, such as core or drywell sprays, the suppression pool, the reactor building, and, if necessary, an installed filtering system. The basis for the selected decontamination factor should first be defined, and could potentially range from decontamination factors intended to address issues such as containment performance (conditional containment failure probability), land contamination (extent of contaminated property), offsite consequences (health consequences and population return criteria), economic consequences (monetary value of damages), or an equivalence to available filtering technologies (i.e., Option 3) in terms of reliability of systems and confinement of radioactive releases. A traditional NRC approach would be to define a source term (defined radionuclides and chemical forms) and require licensees to analyze the effectiveness of the various systems and ensure plant capabilities satisfied the acceptance

criteria (including adding an engineered filtering system if necessary). The NRC could prescribe methods for analyses or review the analyses performed for the various plants and their specific configurations. Requirements placed on the analyses could include validation against tests, experiments, and operating histories. This type of approach probably would not specifically account for plant-specific risk profiles but instead establish specific accident conditions to analyze. Defining a specific collective DF also would be consistent with the traditional NRC practice for design-basis accidents of defining regulatory limits in terms of radiation dose to a representative individual (or contamination per unit area) at a specified distance from the release. However, for severe accident conditions, the NRC has more recently required the development of strategies or contingencies and not established specific requirements for individual structures, systems, or components (e.g., the aircraft impact assessment rule in 10 CFR 50.150 and the loss of large area requirements defined in 10 CFR 50.54(hh)). Development of a severe accident confinement strategy without defining a specific performance measure was discussed as a possible approach under Option 2.

Another approach could be to define performance measures based on what can be reasonably achieved using currently available filtering technologies. This concept is used as the basis for the draft proposed order in Enclosure 7b for an engineered filtering system. Such an approach would ensure that the technical requirements associated with Option 4 could provide a comparable decontamination of the containment atmosphere as that provided by an engineered filtering system. Engineered filtering systems could provide the actual means of satisfying the performance measure if the evaluation of other confinement strategies failed to provide the needed confidence in decontamination factors or system reliability. The availability of engineered filtered systems could also provide the basis for establishing schedules for this approach that are consistent with the proposed timeframe proposed for Option 3 (e.g., 2017).

The consideration of risk contributors and importance measures could be included in establishing the performance measure to address significant plant differences. The performance goal could be established for event frequencies above an established criterion, or the event frequency and DF could be considered together in a more complicated consideration of limiting the exposure to a representative individual (or contamination per unit area). This type of an approach recognizes and tries to address the differences in plant designs and related differences in the importance of various accident sequences to core damage and containment failure. The following figure from NUREG-1560, "Individual Plant Examination Program: Perspectives on Reactor Safety and Plant Performance," presents the range in accident sequence contributions for various accident scenarios for BWR 3/4 plants.

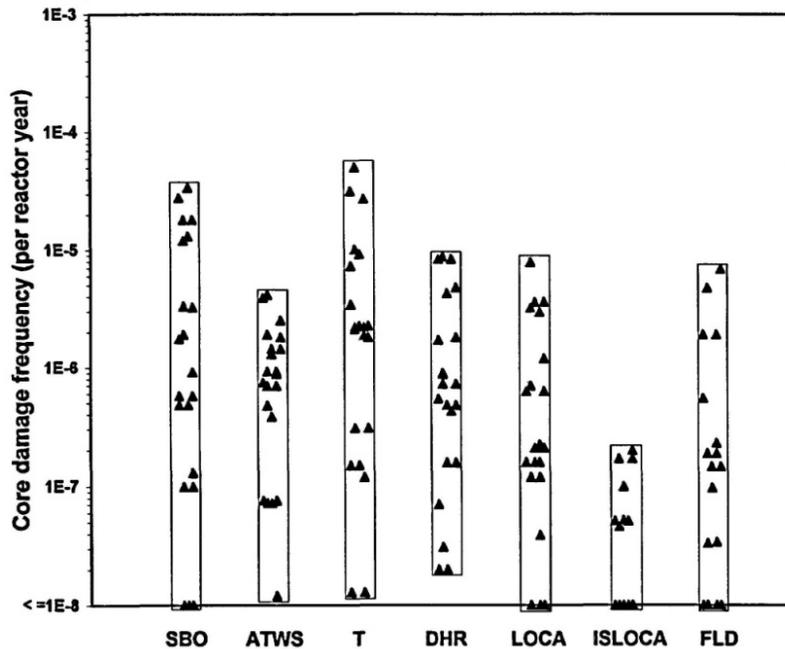


Figure 3.6 Reported IPE accident sequence CDFs for BWR 3/4 plants with RCIC.

SBO – Station Blackout	T – Other Transients
ATWS – Anticipated Transients without Scram	LOCA – Loss of Coolant Accidents
DHR – Transients with Loss of Decay Heat Removal	ISLOCA – Interfacing System LOCA
FLD – Internal Flood Initiators	

Figure 1: BWR Accident Sequence Core Damage Frequencies  
Source: NUREG-1560

A third alternative for a performance-based approach consists of including additional measures in the determination of the required performance of the collective systems to limit the release of radioactive materials. An example would be to define as low as reasonably achievable requirements similar to those described in NUREG-2150, "A Proposed Risk Management Regulatory Framework," issued April 2012, and current severe accident mitigation alternatives (SAMA) assessments. This approach would not only account for design differences but also factors such as the differences in potential economic consequences because of plant location. Such an approach would differ from the traditional calculation of doses to a representative individual, which tends to make requirements largely independent of location. Hypothetically, under this approach a plant located in an economically developed area might need to install additional measures to contain radioactive materials as compared to a very similar plant located in a less economically developed location. It should be noted that the second and third alternatives would likely require the licensees to have and maintain plant-specific PRAs. Therefore, these approaches may have a relationship to activities such as the resolution of NNTF Recommendation 1 on possible changes to the NRC's regulatory framework (which might require the licensees to have and maintain a plant-specific PRA).

The NRC staff envisions that the development of a severe accident confinement strategy would involve many interactions with stakeholders. These interactions would help inform the regulatory analysis that would be performed to support developing regulatory requirements associated with Option 4. Given that the process would involve developing specific performance measures and subsequent analysis of the resultant costs and benefits, the NRC staff has not specifically addressed Option 4 within the regulatory analyses, described in Sections 2 and 3. However, any approach to using the containment venting systems during severe accident conditions would require modifications to existing systems (or planned systems to satisfy EA-12-050) to ensure that they were capable of operating following core damage and related conditions. Option 2 would therefore appear to set the minimum costs and related benefits for the performance-based approach. Additional costs for Option 4 would likely include additional studies and possibly scaled testing or experiments to demonstrate the ability of sprays, pools, and engineered filters to contain radioactive materials through the implementation of a predictable and repeatable strategy as suggested by the recent study by the Electric Power Research Institute (EPRI) report entitled "Investigation of Strategies for Mitigating Radiological Releases in Severe Accidents – BWR Mark I and Mark II Studies (EPRI Product No. 1026539)." The staff expects that the costs and related benefits of Option 4 lies between Options 2 and 3, both of which might be cost-justified safety enhancements upon consideration of uncertainties and qualitative factors.

While the costs of Option 4 could be compared to Option 2 or 3, the completion schedule for the activity would likely be at least several years longer. All of the uncertainties mentioned throughout this paper would complicate any efforts to define, review, and implement a system that meets the selected performance measure with the desired level of confidence. In its letter dated October 5, 2012, NEI noted that considerable time would be required to determine if the EPRI approach was feasible and without unintended consequences:

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.

Following development of the performance-basis, etc., a significant amount of time is required to perform the required analysis, engineering, design, development, procurement, plant walk-downs, installation, testing, training, and so on.

The significance of the longer implementation period for Option 4 depends on the characterization of the safety issue being addressed. For people who consider containment venting improvements an important enhancement or possibly even necessary for reasonable assurance of adequate protection of public safety, a delay of several years would be a significant negative for this option. However, for those who view possible improvements to severe accident features as worthwhile, but not necessarily urgent safety enhancements, the longer schedule can be viewed as providing an opportunity to coordinate the venting issue with other improvement efforts (e.g., NTTF Recommendation 1, SECY-12-0110) and development of policies applicable to all reactor technologies.

## 5. OTHER FACTORS AND POLICY ISSUES

The regulatory analyses in Sections 2 and 3 assessed the possible imposition of requirements for venting systems for Mark I and Mark II containments and whether such requirements met the standard to be cost-effective, substantial safety improvements. The assessments were performed using the process described in established guidance and considered, where possible, uncertainties in the assumptions and possible changes to the guidance under consideration at the time of this assessment. The analyses considered severe accident capable vents and filtered venting systems. Section 4 discusses another option for a performance based approach, which probably falls between the other options in terms of expected costs and benefits.

A regulatory analysis using only quantitative factors, including standard assumptions, would not appear to justify the imposition of additional requirements on the venting systems for BWR Mark I and Mark II containments. However, sensitivity studies and analyses using values of event frequency and accident consequence in the upper range of the uncertainty bands result in the calculated benefits potentially justifying the likely costs of improved venting systems. The existing guidance in NUREG/BR-0058 discusses the consideration of qualitative factors instead of or as a supplement to the quantitative analyses such as those in Sections 2 and 3 of this enclosure, and in more detail in the complete regulatory analysis. In this case, the NRC staff is considering several qualitative factors to supplement the previous discussions. A tool that is sometimes useful to decisionmakers in making cost/benefit decisions is a break-even assessment such as shown in the following figure for the engineered filtered vent modification. The figure shows values of when the modification would be justified in terms of limiting consequences (expressed in dollars) for core-damage events of certain frequencies. In this case, plant modification costs were assumed for the filtered vent (\$15 to \$45 million) with other data associated with the BWRs with Mark I and II containments.

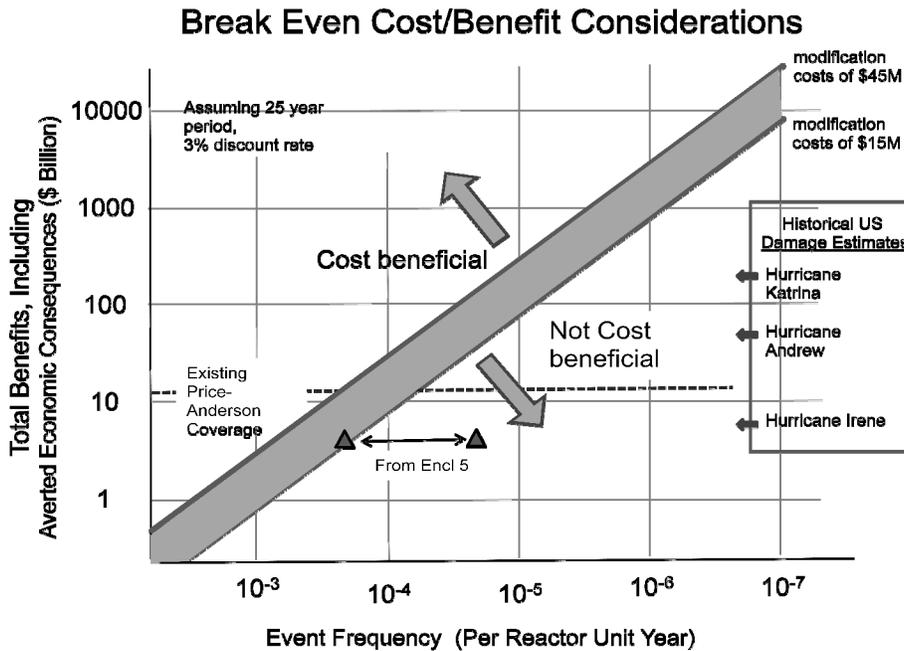


Figure 2: Break-Even Values for Option 3 (Filtered Vent)

As shown above, the “best estimate” valuation (event frequency of  $2 \times 10^{-5}/\text{yr}$ ) is outside the break-even region while assuming an event frequency of  $2 \times 10^{-4}/\text{yr}$  would appear to strengthen the argument for making the filtered vents on the basis of it being a cost justified safety enhancement. Although the staff was not able to assign numerical values to the various qualitative factors discussed in the following sections, they can likewise be viewed as either affecting the frequency of challenges to containment integrity or affecting the release of a large amount of radioactive material from the plant (which results in economic consequences) and thereby moving toward or away from the break-even region shown in the figure.

A discussion of several significant qualitative factors is provided below.

## **5.1 Defense in Depth**

A key principle of NRC’s regulation and oversight of nuclear power plants has historically been and continues to be “defense in depth.” An aspect of defense in depth traditionally has been to have multiple barriers to the release of radioactive materials and to have equipment and personnel to (1) prevent accidents from occurring or progressing, (2) contain radioactive materials if released from the fuel, and (3) mitigate the possible release through protective actions, such as evacuation. The containment systems at nuclear power plants play a key role in helping confine fission products within the plant if an accident progresses to a point where significant core damage has occurred. Containment designs also help to control accidents by absorbing the energy released from the reactor coolant system, holding water for long-term core cooling, and protecting systems from external hazards. Given the key role of containment performance as an essential element of defense in depth, concerns about the performance of Mark I and II containments during severe accident conditions have been discussed for many years.

The logic underlying this set of basic goals is that each level of defense represents a threshold where failure to accomplish the prior goal introduces a significantly greater potential for consequences and a greater uncertainty in the phenomenology, accident progression, and, therefore, the ability to control the outcome of an event.

### Prevention

The first defense-in-depth goal, prevention of severe accidents, recognizes that there is little threat to public health and safety in the absence of core damage, while there is a significant increase in the potential for major consequences once fission products are released from the fuel and cladding. In addition, much larger phenomenological uncertainties are introduced under severe accident conditions than when the core is undamaged and is in a fixed geometric position. Finally, considerable uncertainty in the availability and functionality of core cooling equipment is also indicated, since major failures must have already occurred to arrive at a severe accident condition.

### Containment

The second defense-in-depth goal is containment of fission products on site in the event of a severe accident. This is a critical threshold because containment of fission products on site results in minimal impact to public health and the environment, while failure to contain radioactive material leads to the potential for widespread health, environmental, and socio-economic consequences. Furthermore, once a large release has occurred, the ability to influence outcomes is limited by uncontrollable factors, such as weather and public response.

Thus, the containment goal provides a reliable backstop against uncertainties in the prevention of severe accidents and protects against the uncertainties associated with uncontrollable releases and the potentially large and varied consequences.

The event at TMI showed the importance of a reliable containment design—the second element of the defense-in-depth strategy. Despite extensive core damage, the containment was successful, limiting fission product release to insignificant levels. The passive attributes of the containment building (i.e., the large volume and inherent strength) were critical to prevent the release of radioactive materials despite the hydrogen burn that ensued. At TMI, the containment barrier provided sufficient time for event diagnoses and recovery from operator errors that occurred earlier in the event. However, the accident at TMI was not complicated by an extended loss of electrical power and heat removal systems, as was the case at Fukushima.

### Mitigation of Release (Emergency Preparedness)

Emergency planning and response is the third and final element of defense in depth. This element provides protection against uncertainties in containment performance under severe accident conditions. Evacuation and sheltering protect against acute doses of radioactive materials. Relocation protects against long-term health effects in the event of containment failure. This element does not, however, protect against environmental or socio-economic consequences.

The containment failures at Fukushima showed the importance of emergency planning for protection against acute doses of radiation. Evacuation, shelter, and relocation were very effective in limiting doses to the public. The Fukushima event also confirmed that when containment fails in a severe accident, the consequences (economic, social, and long-term health) are large, difficult to estimate, and depend upon critical but uncontrollable factors, such as weather and public reaction.

In considering additional requirements for venting systems for BWRs with Mark I or II containments, the deliberations ultimately will need to determine whether those additional protections are reasonable in light of the costs and the benefits, including the desire for effective defense in depth for dominant severe accident sequences. A process to consider in deliberating the containment improvement options is to follow the progression of accidents and determine at what point does the combination of event probability and consequence, with consideration of related uncertainties, warrant regulatory controls. For BWRs, estimates of low core melt frequencies have, in part, justified the NRC's previous acceptance of the estimated high conditional failure probability of the Mark I and II containments. The containments did fail, however, during the accident at the Fukushima Dai-ichi facility, as predicted for those plant conditions. Further, the failure of containments during the Fukushima accident resulted in a large release of radioactive material and greatly complicated the attempts of plant operators to stop conditions from worsening. For example, the loss of the reactor buildings (secondary containments) resulted from hydrogen explosions, which occurred because of difficulties in venting to maintain pressures and hydrogen levels within the containment structures.

### Summary—Defense in Depth

The relatively high likelihood of a failure of Mark I and II containments following a core melt accident questions the level of defense in depth that this intended barrier to the release of radioactive material provides. Improving the chances that the containment venting function is available under severe accident conditions reduces the chances of failure and uncontrolled releases. Providing filters in the venting system significantly reduces release of radioactive materials for the dominant core melt scenarios.

Option 1

Option 2

Option 3

Option 4



## 5.2 Uncertainties

As discussed above, there are significant uncertainties in estimating the frequency of events for which a severe accident capable or filtered venting system would be a useful severe accident design feature. The results of the regulatory analyses are sensitive to the event frequency, and as shown above, a frequency assumption of  $2 \times 10^{-4}$  per reactor-year is sufficient to make the filtered vent marginally cost effective. There are also significant uncertainties in the calculation of event consequences in terms of the dispersion of radioactive material into the site environs. This is due in part to significant uncertainties about the degree to which radioactive materials would be retained within the plant as a result of systems such as sprays and suppression pools. Estimating economic consequences given a large release of radioactive material also includes large uncertainties related to modeling the many different aspects of local economies and their impact on the larger economy. An example of this is the supply chain disruptions that followed the tsunami in Japan or the flooding in Thailand. Just as an increase in event frequency by approximately an order of magnitude was sufficient to change the results of the cost/benefit analyses, so would an increase in consequences by an order of magnitude appear to change the balance between costs and benefits.

### Summary—Uncertainties

Significant uncertainties exist in the estimation of event frequencies and consequences. This factor provides support for taking additional action. The benefits from the proposed changes, in terms of reducing the consequences from severe accidents, would be greatest for Option 3 (filter) while the least would be from Option 2 (unfiltered venting).

Option 1

Option 2

Option 3

Option 4



## 5.3 Severe Accident Management

The Fukushima experience demonstrated that responding to and arresting the accident was complicated by the problems associated with venting containment and the failure of containment. The failure of containments as a result of overpressure conditions creates harsh

environments in the reactor building and other plant locations. In turn, the elevated temperatures and radiation levels can impede operators in their attempts to restore installed equipment or put into service temporary equipment such as what EA-12-049 requires. Severe accident capable vents would not only include equipment that could remain functional and support venting operations during severe accident conditions, but they would also address shielding and equipment operation to ensure personnel could execute needed tasks during a severe accident. Some severe accident capable venting designs include the use of passive features, such as rupture disks, to provide additional confidence that the system would operate and prevent failure of containment structures because of overpressure conditions.

The filtered vent designs would provide the same improvements to the plant to prevent containment failures and help control conditions within the reactor building and other site areas. The filtered system could provide an additional advantage in that decisionmakers could be more confident (or at least less stressed) about ordering the venting operation knowing that the filter would contain the vast majority of radioactive materials. From an accident management perspective, this increased confidence in the venting operation would enable measures to restore installed equipment, connect temporary equipment, or otherwise take measures to arrest the accident.

Summary—Severe Accident Management  
Improving the containment venting systems to support operation under severe accident conditions would enhance the possible management of the accident by allowing operators to focus on other recovery actions. Each proposed option provides some benefit, but filtered systems are the simplest while a performance-based approach could be integrated into other severe accident management activities and procedures.

Option 1

Option 2

Option 3

Option 4



## 5.4 Hydrogen Control

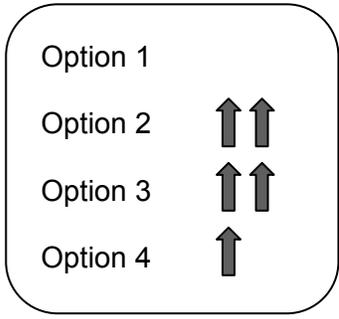
In addition to providing pressure control, severe accident capable or filtered venting systems also can remove hydrogen from the containment spaces and lessen the likelihood of hydrogen deflagration and detonations in the containment structures or the reactor building. The primary consideration for improving the control of hydrogen during a severe accident is associated with the Tier 3 item related to NTF Recommendation 6, “Hydrogen Control and Mitigation Inside Containment or in Other Buildings.” However, the successful venting of containments during severe accidents can help address the potential problems of the buildup of hydrogen in primary and secondary containment systems. Selection of any of the severe accident capable venting options proposed in this paper will therefore influence and potentially help resolve hydrogen control issues for Mark I and II containments.

The benefits of venting hydrogen for BWRs with Mark I or II containments were evident during the Fukushima accident. Hydrogen generated by various mechanisms associated with severe accidents made its way to the reactor buildings and exploded. Those explosions, in turn, increased the amount of radioactive materials escaping from the facility, complicated operators efforts to respond to the event, and increased concerns about the integrity of spent fuel pools.

The location of the spent fuel pools within the BWR reactor buildings is another feature that makes the venting function and control of hydrogen especially important to these reactor designs. Proper venting of hydrogen would alleviate concerns associated with hydrogen burns within the reactor building, possibly affecting the integrity of the spent fuel pool.

**Summary – Hydrogen Control**

The experience at Fukushima Dai-ichi demonstrated the importance of effective control of hydrogen generated during severe accidents. The possible containment venting systems discussed in this paper (Options 2, 3, or 4) could provide a way to improve the control of hydrogen.

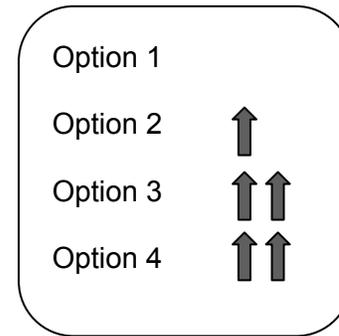


### 5.5 External Events

The technology comparison above may not fully address the influence of external events and the fact that such hazards could be major contributors to the risk profiles for operating nuclear power plants. The estimated core damage frequencies for BWRs from internal events are lower than those for PWRs, in part because of the multiple systems available to add water to the reactor core. However, events such as an extended loss of electrical power renders some of these systems unavailable and potentially reduces the BWR advantage for such events, which are likely to be caused by a major external event (e.g., a beyond-design-basis seismic or flooding event). Provided that the enhanced venting systems, either severe accident capable or filtered, are able to survive the external event and remain available for use if the accident progresses to involve significant core damage, then the system could be a major part of the accident response. As mentioned under the severe accident management factor, the availability of a reliable venting system during severe accident conditions could help prevent conditions from degrading further and enable responders to continue efforts to cool the molten core. The venting system thereby compliments the ability of the portable equipment to help arrest an event even if previous efforts had failed to prevent core damage.

**Summary – External Events**

Beyond design basis external events such as the 2011 earthquake and tsunami in Japan will challenge normal and emergency power and cooling systems at a nuclear power plant. There is a significant advantage to having installed equipment and strategies in place to address such events and conditions and thereby avoid the nuclear power plant compounding the consequences from such events.



## 5.6 Multi-Unit Events

The quantitative evaluations performed in Sections 2 and 3 did not consider potential scenarios involving accidents at more than one unit at a multiple unit site. The tsunami that flooded the Fukushima site initiated a series of events that resulted in core damage accidents at three of the six units sharing the site. The most likely cause of multi-unit accidents is a major beyond-design-basis external event, such as what occurred at Fukushima and discussed above. Although the frequency of such events might be estimated for particular sites, the uncertainties are relatively large given the limited recorded histories and limited knowledge of hazards, such as large (beyond-design-basis) seismic or flooding events. In addition, the possibility of core damage events at multiple units has the potential for larger releases and increased economic damage. By improving severe accident management functions and, especially in the case of the filtered vent, reducing the releases from each unit, the enhanced venting systems could help address concerns about concurrent core damage events at multiple units.

### Summary—Multi-unit Events

Conditions or events (e.g., external hazards) that challenge multiple units at a nuclear facility is a concern that the Fukushima accident highlighted. There is a significant advantage to having installed equipment and strategies in place to address such multi-unit events.

Option 1

Option 2



Option 3



Option 4



## 5.7 Independence of Barriers

The events at Fukushima highlighted the interdependence between the performance of core cooling functions and the pressure suppression containment designs used for BWRs with Mark I or Mark II containment designs. This dependent relationship between what is generally thought of as individual barriers to the release of radioactive materials has been noted in several severe accident studies and during the operating history of BWRs with Mark I or Mark II containments (see Enclosure 2). Although the primary fission product barriers usually are discussed as being largely independent of each other, the NRC has previously recognized and accepted some dependencies, such as the crediting of containment accident pressure for supplying net positive suction head for pumps in the emergency core cooling system. In its SRM for SECY-11-0014, “Staff Requirements—SECY-11-0014—Use of Containment Accident Pressure in Analyzing Emergency Core Cooling System and Containment Heat Removal System Pump Performance in Postulated Accidents,” dated March 15, 2011, the Commission directed the NRC staff to continue to use existing guidance in the standard review plan, which states:

Defense in depth is preserved (for example, system redundancy, diversity, and independence are maintained commensurate with the expected frequency and consequence of challenges to the system; defenses against potential common cause failures are maintained and the introduction of new common cause failure mechanisms is assessed; and defenses against human errors are maintained).

Although the discussion above relates to design-basis functions, previous (pre-Fukushima) evaluations that the NRC performed also found that the expected frequency and consequences of severe accidents involving potential releases through established vent pathways for BWRs did not warrant additional severe accident design features (see SECY-89-017, "Mark I Containment Performance Improvement Program," dated January 23, 1989, and related SRM). However, the Commission could find that the Fukushima accident has changed our understanding of severe accident frequencies and consequences such that measures are needed to address this issue and compensate for the lack of independence between the core cooling and containment functions. The installation of a filtered vent would be a plausible approach to improving the defense-in-depth attributes for BWRs with Mark I or Mark II containments. In its efforts to address lessons learned from Fukushima, the industry, to date, has emphasized additional measures for preventing core damage (e.g., making available portable pumps for injection into the core or drywell) versus the installation of an additional barrier (filters) on a dedicated vent pathway from containment.

A focus on preventing or arresting the progression of core damage is also consistent with EA-12-050, which requires modifications to ensure BWRs with Mark I and II containments have a reliable hardened vent to control containment pressure. The NRC issued EA-12-050 with a finding that the action was needed for adequate protection and included the following explanation:

The events at Fukushima Dai-ichi highlight the possibility that extreme natural phenomena could challenge the prevention, mitigation and emergency preparedness defense-in-depth layers. At Fukushima, limitations in time and unpredictable conditions associated with the accident significantly challenged attempts by the responders to preclude core damage and containment failure. In particular, the operators were unable to successfully operate the containment venting system. The inability to reduce containment pressure inhibited efforts to cool the reactor core. If additional backup or alternate sources of power had been available to operate the containment venting system remotely, or if certain valves had been more accessible for manual operation, the operators at Fukushima may have been able to depressurize the containment earlier. This, in turn, could have allowed operators to implement strategies using low-pressure water sources that may have limited or prevented damage to the reactor core. Thus, the events at Fukushima demonstrate that reliable hardened vents at BWR facilities with Mark I and Mark II containment designs are important to maintain core and containment cooling.

#### Summary—Independence of Barriers

While it may not be necessary or practical to ensure the complete independence of each barrier to the release of radiation, it is desirable to minimize dependencies and address the high conditional failure probability of Mark I and Mark II containments following a compromise of the preceding barriers (fuel and coolant system). The filtered system would provide the most independence while the unfiltered vent could result in large releases in the attempts to reduce containment overpressure conditions.

Option 1

Option 2



Option 3



Option 4



## 5.8 Emergency Planning

The installation of severe accident capable or filtered venting systems can add to existing emergency planning margins (e.g., effective evacuation periods) by controlling the release of radioactive materials as compared to containment failure by overpressurization. The filtered vent system provides additional advantages by dramatically reducing the amount of radioactive material released through containment venting during severe accident conditions. This could allow different protective action recommendations that would reduce the number of evacuees, thereby reducing the stress and risks associated with such emergency measures. In addition to the effects on immediate protective measures to protect public health and safety, the filtered vent option reduces or eliminates concerns about the return of populations following a possible release of radioactive materials and long-term exposures associated with contamination of the countryside through the failure of containment or the release from an unfiltered venting operation. The issue of long-lasting effects from a release also relates to other qualitative factors, such as societal considerations and uncertainties in estimating economic consequences.

#### Summary—Emergency Planning

Improving containment venting functions during severe accidents would reduce uncertainties and releases, thereby enabling improvements in emergency planning or reducing the need to evacuate large numbers of people. The most benefit in reducing the demands on emergency planning would be associated with Option 3 (filter) while the proposed change with the least benefit would be from Option 2 (unfiltered venting).

Option 1

Option 2



Option 3



Option 4



## 5.9 Consistency between Reactor Technologies

NUREG-1150, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," provides a comparison between a Mark I containment and a PWR containment of the conditional containment failure probability given various core damage events. The following figure from NUREG-1150 shows that the conditional failure probability for Mark I containments is relatively high (approximately 0.75 for the plant evaluated in that study).

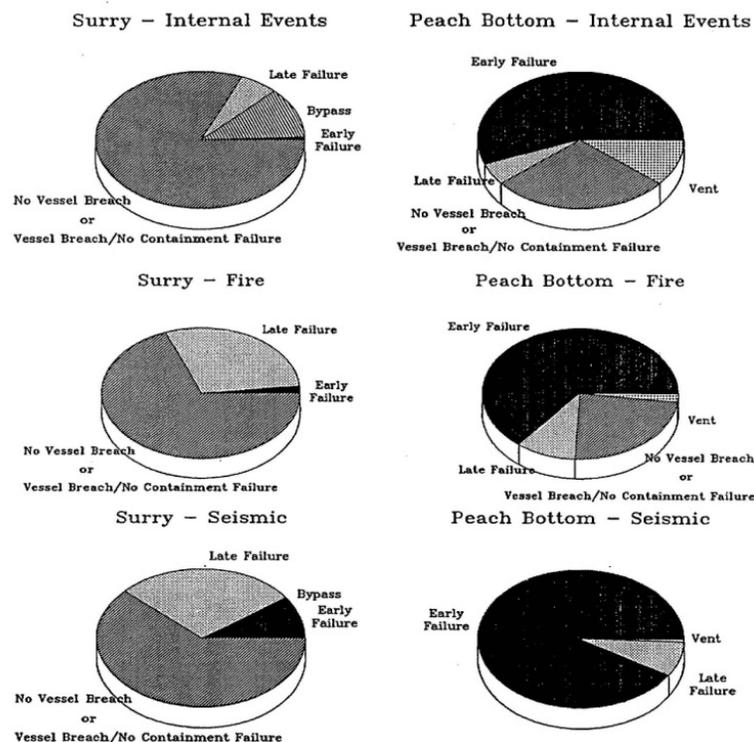


Figure 9.5 Relative probability of containment failure modes (internal and external events, Surry and Peach Bottom).

Figure 4: Comparison of Containment Failure Modes  
Source: NUREG-1150

However, as pointed out in NUREG-1150 and NUREG-1560, and shown in the following figures, when combined with estimated frequencies of core damage events, the risk of large releases from BWRs with Mark I and Mark II containments is comparable to other plant designs. A lower core damage frequency is estimated because of a more diverse set of plant equipment that is able to add water to the reactor core under most plant conditions. The weighting of the defense-in-depth approaches to emphasize minimizing core damage can result in similar overall risk profiles for large releases. However, many of these core-cooling systems would be rendered unavailable for events such as an extended station blackout that occurred at Fukushima Dai-ichi. Thus, given a core damage event, the higher conditional failure probability of containment failure means that a release is more likely than not.

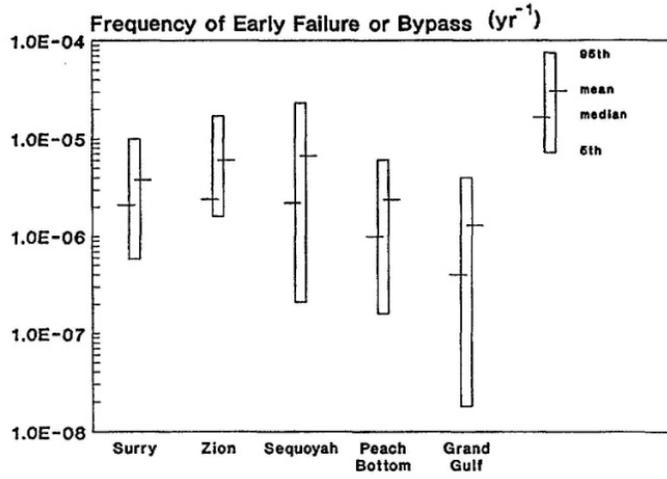


Figure 9.3 Frequency of early containment failure or bypass (all plants).

Figure 5: Frequency of Containment Failure or Bypass  
Source: NUREG-1150

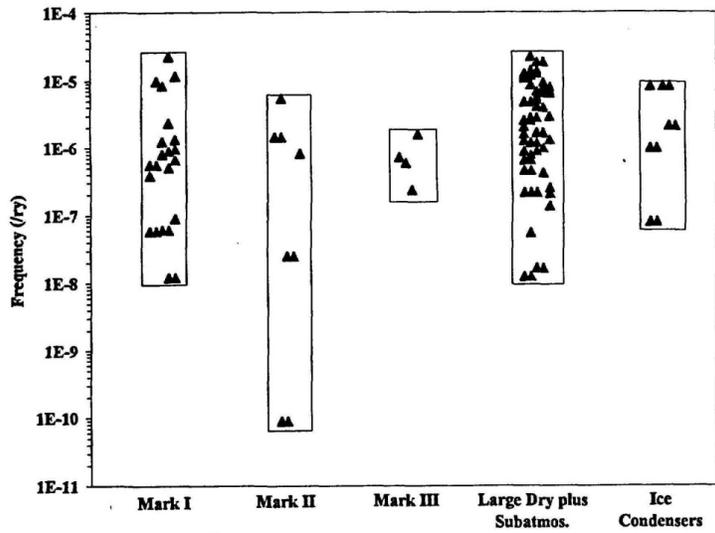


Figure E.3 Frequencies of significant early release (by containment type) as reported in the IPEs.

Figure 6: Frequency of Significant Early Release  
Source: NUREG-1560

**Summary—Consistency with Other Technologies**  
While the proposed improvements to venting systems for BWRs with Mark I and II containments address a known weakness in the severe accident performance for those plants, the pursuit of these improvements without resolving broader issues (e.g., NTF Recommendation 1 and the Severe Accident Policy Statement) introduces the possibility for inconsistent treatment of severe accident capabilities for the various reactor technologies.

Option 1    ↑↑↑  
Option 2  
Option 3  
Option 4    ↑

### 5.10 **Severe Accident Policy Statement**

Following the 1979 accident at TMI, the United States and the international nuclear safety community recognized that severe accidents needed further attention. The NRC evaluated, generically, the capability of existing plants to tolerate a severe accident and found that the design-basis approach contained significant safety margins for the analyzed events. These margins permitted operating plants to accommodate a large spectrum of severe accidents. Based on this information, the Commission, in its “Policy Statement on Severe Accidents Regarding Future Designs and Existing Plants” (50 FR 32138; August 8, 1985), concluded that existing plants posed no undue risk to public health and safety. The Commission also concluded that no basis existed for immediate action on generic rulemaking or other regulatory changes affecting these plants because of the risks that a severe accident posed. To address this issue for operating plants in the long term, the NRC issued SECY-88-147, “Integration Plan for Closure of Severe Accident Issues,” in May 1988. This document identified the following necessary elements for closure of severe accidents:

- performance of an individual plant examination
- assessment of generic containment performance improvements
- improved plant operations
- a severe accident research program
- an external events program
- an accident management program

Each of these programs and the conclusions reached are discussed elsewhere in this paper and its enclosures. The portion of the policy statement that deals with operating plants states:

In light of the above principles and conclusions, the Commission's policy for operating reactors includes the following guidance:

- Operating nuclear power plants require no further regulatory action to deal with severe accident issues unless significant new safety information arises to question whether there is adequate assurance of no undue risk to public health and safety.
- In the latter event, a careful assessment shall be made of the severe accident vulnerability posed by the issue and whether this vulnerability is plant or site specific or of generic importance.
- The most cost-effective options for reducing this vulnerability shall be identified and a decision shall be reached consistent with the cost-effectiveness criteria of the Commission's backfit policy as to which option or set of options (if any) are justifiable and required to be implemented.
- In those instances where the technical issue goes beyond current regulatory requirements, generic rulemaking will be the preferred solution. In other cases, the issue should be disposed of through the conventional practice of issuing Bulletins and Orders or Generic Letters where modifications are justified through backfit policy, or through plant-specific decision making along the lines of the Integrated Safety Assessment Program (ISAP) conception.
- Recognizing that plant-specific PRAs have yielded valuable insight to unique plant vulnerabilities to severe accidents leading to low-cost modifications, licensees of each operating reactor will be expected to perform a limited-scope, accident safety analysis designed to discover instances (i.e., outliers) of particular vulnerability to core melt or to unusually poor containment performance, given core-melt accidents. These plant-specific studies will serve to verify that conclusions developed from intensive severe accident safety analyses of reference or surrogate plants can be applied to each of the individual operating plants. During the next two years, the Commission will formulate a systematic approach, including the development of guidelines and procedural criteria, with an expectation that such an approach will be implemented by licensees of the remaining operating reactors not yet systematically analyzed in an equivalent or superior manner.

For advanced nuclear power plants, including both the evolutionary and passive designs, the NRC concluded that vendors should address severe accidents during the design stage. Designers can take full advantage of the insights gained from such input as probabilistic safety assessments, operating experience, severe accident research, and accident analysis by designing features to reduce the likelihood that severe accidents will occur and, in the unlikely occurrence of a severe accident, to mitigate the consequences of such an accident. Incorporating insights and design features during the design phase is much more cost effective than modifying existing plants.

**Summary—Severe Accident Policy Statement**  
Although the Severe Accident Policy Statement specifies that severe accident design features could be imposed on operating reactors using the established backfit process, the importance of the qualitative factors suggests a need to revisit portions of the current regulatory framework (including the Severe Accident Policy Statement). The status quo option best fits the current policy statement and its traditional application.

Option 1    ↑↑  
Option 2  
Option 3  
Option 4    ↑

### 5.11 International Practices

A description of the staff's collection and assessment of information from various countries related to decisions on filtered venting systems is provided in Enclosure 3. As discussed in that enclosure, the majority of countries with BWRs using Mark I and Mark II containment designs have modified or plan to modify the designs to include filtered containment venting systems. In addition, some countries are requiring filtered venting systems on other reactor containment designs. As previously mentioned, in the discussions on determining whether a proposed change meets the standard of a substantial increase in safety, the Commission stated:

...The approach is also flexible enough to allow for arguments that consistency with national and international standards, or the incorporation of widespread industry practices, contributes either directly or indirectly to a substantial increase in safety. Such arguments concerning consistency with other standards, or incorporation of industry practices, would have to rest on the particulars of a given proposed rule...

Although no particular international standard exists that calls specifically for filtered vents for Mark I and Mark II containments, Option 3 is consistent with the general standards and guides that call for improving the ability of containments to contain radioactive materials during severe accident conditions. Pursuing Option 3 would also place the United States among the majority of countries that have required filtered venting systems, and maintain its stature as a leader in nuclear safety. Another significant benefit from the international experience is the development and installation of various filtering systems. This lessens concerns that requiring filtered vents would necessitate research and development programs to design and test a new technology.

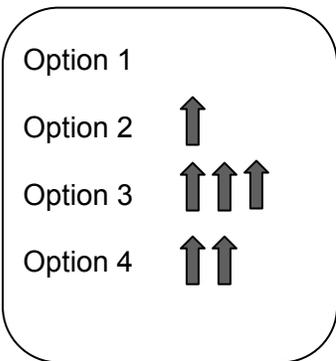
Many countries that have pursued filtered venting systems have done so coincident with the development of the defense-in-depth system described in guidance from the International Atomic Energy Agency (IAEA) and Western European Nuclear Regulators' Association (WENRA). This defense-in-depth logic includes a specific level for dealing with severe accidents and minimizing the need to displace populations near nuclear power plants. The logic is shown below, along with the corresponding regulatory structure in the United States.

International System of Defense In Depth		Corresponding US Considerations	
1	Normal Operations	Normal Operations	
2	Anticipated Operational Occurrences	Anticipated Operational Occurrences	
3	Design Basis Accidents	Design Basis Accidents	
	<b>Design Extension Events</b>	<b>Beyond Design Basis Events (Design Extension considered under Recommendation 1)</b>	
4	<b>Severe Accident</b>	<b>Safety Goal Policy Statement</b> <b>Severe Accident Policy Statement</b> - <b>Operating Plants</b> - <b>New Reactors</b>	
5	Emergency Planning	Emergency Planning	

Figure 3: Comparison of Defense-in-Depth Approaches

As shown above, the regulatory systems are similar in most areas, but they differ in the treatment of beyond-design-basis and severe accidents. The Severe Accident Policy Statement is discussed as a separate qualitative factor.

**Summary—International Practices**  
As discussed in Enclosure 3, most countries that have reactors with Mark I or Mark II containments require or plan to require filtered vent systems. Although not specifically included in an international standard, a desire to maintain consistency with international practices would support taking action (in order of Option 3, Option 4, and then Option 2)



## 6. SUMMARY

Based on the quantitative and qualitative considerations discussed above, some of the more significant positive and negative attributes (i.e., pros and cons) for each of the options are as follows:

**Option 1:** Status Quo: Continue with the implementation of EA-12-050 for reliable Hardened vents to reduce the likelihood of core damage and failure of BWR Mark I and Mark II containments and take no additional action to improve their ability to operate under severe accident conditions or to require the installation of a filtered vent system

### Pros:

- Consistent with Severe Accident Policy Statement that no additional measures are needed for operating reactors
- No additional costs to industry and the NRC
- Consistent with quantitative cost-benefit analysis findings using current framework and assumptions
- Consistent with findings from SAMA analyses

### Cons:

- Maintains defense-in-depth “imbalance” between prevention of core damage and mitigation (i.e., while measures have been taken to reduce chances of core melt, high conditional failure probability remains for containment if core melt does occur)
- Of the four options, results in highest doses and highest economic consequences in the unlikely event of a severe accident
- Inconsistent with international practices that emphasize reliable containment as a critical function

**Option 2:** Severe accident capable vents order: Upgrade or replace the reliable hardened vents that EA-12-050 requires with a containment venting system designed and installed to remain functional during severe accident conditions

### Pros:

- Supports severe accident management by improving hydrogen control, pressure control (supports low-pressure injection), and minimizing radiation releases to reactor building
- Reduces doses to emergency workers (relative to an uncontrolled containment failure)
- Consistent with industry approach in EPRI study (without performance measure)
- Involves limited changes to existing EA-12-050, related guidance, and implementation schedules

Cons:

- Would involve significant release of radioactive materials when venting operations are performed during severe accident conditions
- Uncertainty of decontamination factor is large and highly dependent on the specifics and timing of the accident scenario
- Does not resolve issues about the use of drywell path for venting
- Not supported by quantitative cost benefit analysis using current framework and assumptions
- Could be viewed as inconsistent with both the NRC's Severe Accident Policy Statement and international practices

**Option 3:** Filtered vents order: Design and install an engineered filtered containment venting system that is intended to prevent the release of significant amounts of radioactive material following the dominant severe accident scenarios at BWRs with Mark I and Mark II containments

Pros:

- Supports severe accident management by improving hydrogen control, pressure control (supports low-pressure injection), and minimizing radiation releases to reactor building
- Reduces doses to emergency workers (relative to an uncontrolled containment failure) without increasing offsite releases
- Ensures high decontamination factors that are independent of specifics of the accident sequence (excluding containment bypass sequences)
- Confidence in decontamination factor supports use of system from both wetwell and drywell
- Improves defense-in-depth balance between prevention and mitigation (i.e., addition of filter directly addresses containment performance issues)
- More consistent with international approach to containment reliability

Cons:

- Not supported by quantitative cost benefit analysis using current framework and assumptions (highest cost of proposed options)
- Could be viewed as inconsistent with NRC's Severe Accident Policy Statement

**Option 4:** Severe accident confinement strategies:  
Pursue development of requirements and technical acceptance criteria for confinement strategies and require licensees to justify operator actions and systems, or combinations of systems, such as suppression pools, containment sprays, and separate filters to accomplish the function and meet the requirements.

#### Pros:

- Consistent with Commission policy to encourage use of performance-based requirements
- Possible to integrate with the NRC's resolution of other regulatory policy issues and development of revised guidance on defense in depth and industry's evaluation of strategies and technologies
- Improves defense-in-depth balance between prevention and mitigation

#### Cons:

- Requires development of performance standards and acceptable methods for demonstration of compliance (difficult task given high uncertainties, limited testing, and nature of severe accident conditions)
- Would likely extend the resolution of this issue by several years
- Large uncertainties in both the NRC and industry costs and schedules

### 6.1 Conclusion

Based on its regulatory analyses, the staff concludes that installation of engineered filtered venting systems for Mark I and Mark II containments is the option that would provide the most regulatory certainty and the timeliest implementation. The NRC performed a cost-benefit assessment considering both quantifiable and qualitative factors after NRC senior managers determined that the possible imposition of requirements for severe accident capable or filtered venting systems satisfy the "substantial safety improvement" standard of 10 CFR 50.109. A comparison of only the quantifiable costs and benefits of the proposed modifications, if considered safety enhancements, would not, by themselves, demonstrate that the benefits exceed the associated costs. However, revising assumptions related to event frequencies or event consequences to address the significant uncertainties in modeling severe accident scenarios could lead to a conclusion that the proposed options are at least marginally cost-effective. In addition, the majority of the qualitative factors discussed in Section 5 (1) support pursuing an improved venting system for BWRs with Mark I or Mark II containments to address specific design concerns (e.g., high conditional failure probability for containment failure given core melt); (2) support severe accident management functions by preventing releases of radioactive materials, hydrogen, and steam into the reactor building or other locations on the site; (3) minimize the contamination of the site environs; and (4) reduce the reliance on emergency planning for protection of public safety. The staff concludes that considering both the quantitative and qualitative factors shows the direct and indirect costs associated with Options 2 and 3, and most likely Option 4, are cost-justified in light of the substantial increase in the overall protection of the public health and safety that is provided by addressing severe accident conditions for BWRs with Mark I and Mark II containments. In addition, the NRC staff finds that the combination of quantitative and qualitative factors (e.g., providing improved defense in depth) best supports the installation of engineered filtered venting systems at BWRs with Mark I and II containments.