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Technical Basis for Severe Accident Mitigating Strategies

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ABSTRACT

This report describes a risk-informed technical investigation of severe accident mitigating strategies for boiling water reactors (BWRs) with Mark I containments. This report focuses on measures that could protect containment integrity and reduce radionuclide releases following a severe reactor accident.

The severe reactor accidents at the Fukushima Daiichi Nuclear Power Plant in March 2011 showed the significant challenges that an unmitigated station blackout (SBO) condition can present to steel BWR containments with relatively small volumes (e.g., Mark I & II containments). Past severe accident studies (e.g., State-of-the-Art Reactor Consequence Analyses (SOARCA)) have estimated a high conditional probability of containment failure in these containments if certain conditions (i.e., high containment pressure and temperatures) cannot be controlled for prolonged periods of time. The operational response at the Fukushima Daini site during this same time period highlighted the benefit of effective operator intervention in preventing a severe reactor accident.

Maintaining the integrity of Mark I containments and reducing the impact of radionuclide releases following a severe reactor accident is the focus of a recent Nuclear Regulatory Commission (NRC) rulemaking activity on Containment Performance and Release Reduction (CPRR). The work described in this report provides the technical basis for responding to the rulemaking. It also provides further technical perspective regarding severe accidents for all BWRs with Mark I containments.

This Electric Power Research Institute (EPRI) technical analysis provides a quantitative and qualitative assessment of a broad spectrum of containment performance and radionuclide release reduction strategy alternatives for a severe reactor accident. Twenty-four unique alternative strategies were evaluated using probabilistic risk assessment (PRA) and severe accident modeling tools.

One of the key insights highlighted in this report is the need for operator actions to facilitate enhanced mitigation of severe reactor accidents. Such actions are described, for example, in the Boiling Water Reactor Owners Group (BWROG) Severe Accident Management Guidelines (SAMGs). These SAMGs address the deployment and use of mitigation features such as those detailed in Nuclear Energy Institute (NEI) 13-02, which proposes guidance for implementing USNRC Order EA 13-109.

The analyses described in this report show that actions to vent containment via the wetwell airspace and to add water to provide cooling of in-vessel and ex-vessel core debris can be effective in preserving containment integrity and reducing releases. Additional hardware (e.g., external engineered filtration) can further reduce radionuclide releases in certain scenarios. Wihout strategies to vent the wetwell and add water to cool core debris, these additional engineered features are generally of benefit to a limited set of scenarios.

EXECUTIVE SUMMARY

This report describes a risk-informed technical investigation of severe accident mitigating strategies for BWR reactors with Mark I containments. This report focuses on measures that could protect containment integrity and reduce radionuclide releases following a severe reactor accident.

Background

The severe reactor accidents at Fukushima Daiichi Nuclear Power Plant in March 2011 showed the significant challenges that an unmitigated station blackout (SBO) condition can present to steel BWR containments with relatively small volumes (e.g., Mark I & II containments). Past severe accident studies (e.g., SOARCA) have estimated a high conditional probability of containment failure in these containments if certain conditions (i.e., high containment pressure and temperatures) cannot be controlled for prolonged periods of time. The operational response at the Fukushima Daini site during this same time period highlighted the benefit of effective operator interventions in preventing a severe reactor accident.

Maintaining the integrity of Mark I containments and reducing the impact of radionuclide releases following a severe reactor accident is the focus of a recent NRC rulemaking activity on Containment Performance and Release Reduction (CPRR). In parallel with this activity, the work described in this report provides further technical perspective regarding severe accidents for BWRs with Mark I containments.

Purpose

The purpose of this research is to evaluate the technical basis for implementing equipment and defining actions that may be taken by nuclear plant operators to protect containment integrity and reduce radionuclide releases following a severe reactor accident.Approach

This EPRI technical analysis provides a quantitative and qualitative assessment of a broad spectrum of alternative strategies for managing containment performance and reducing potential radionuclide releases following a severe reactor accident. Twenty-four unique alternative strategies were evaluated using PRA and severe accident modeling tools. These evaluations were performed in the context of extended loss of AC power (ELAP) events and the challenges they present.

General Insights

One of the key insights highlighted in this report is the need for and the benefit of operator actions to enhance the mitigation of severe reactor accidents. This analysis demonstrates that timely operator actions are needed to manage severe reactor accidents effectively. Operator actions can strongly influence the course of an accident, the ultimate damage state of the plant, and the resulting radionuclide source terms. These influences may be positive or negative, depending on the nature and timing of the actions.

The evaluations in this report consider the effectiveness of proposed guidance in NEI 13-02 for implementing USNRC Order EA 13-109, which identifies the hardware capabilities and plant controls to enhance severe accident management. Guidance for directing the deployment and use of these hardware capabilities is provided in the BWROG SAMGs.

The analyses described in this report show that actions to vent containment via the wetwell airspace and add water to provide cooling of core debris, whether in-vessel or ex-vessel, can be effective in protecting the containment and reducing releases. For certain scenarios, additional hardware features (e.g., external engineered filtration) may be able to reduce radionuclide releases. Without the actions to vent containment and add water, however, the benefit of these additional features may be very limited.

Technical Insights

Providing the capability to flood containment and vent the wetwell of Mark I containments during severe reactor accident conditions has multiple safety benefits (e.g., radionuclide retention in containment water inventory, thermal protection of the containment structures, etc.). Severe accident water addition (SAWA) has the largest benefit of any individual strategy studied in this report. In particular, SAWA to the reactor pressure vessel (RPV) has some advantages over water addition directly to the drywell. However, both are effective strategies in mitigating a severe reactor accident. Additional strategies were found to provide minimal benefit. While additional strategies could provide benefit in individual scenarios, these scenarios were not contained in the set of dominant risk contributing scenarios thereby making those strategies of little benefit.

Severe accident water management (SAWM) and containment (wetwell) vent operation can be viable severe reactor accident management strategies that can maintain the operability of the wetwell vent while maintaining suppression pool radionuclide scrubbing. The SAWM strategy can avoid the need for a severe accident capable drywell vent by preventing overfill of the wetwell during containment flooding.

Conclusions

A range of severe reactor accident management strategies was studied in this report. Of these strategies, the SAWA and SAWM strategies were found to be the most effective in terms of maintaining containment integrity, increasing public safety, and reducing radionuclide releases. Other strategies, including installation of an engineered containment filtration system, were found to be marginally effective at reducing the potential for significant radionuclide releases.

ACRONYMS

APET	Accident Progression Event Tree
BWR	Boiling Water Reactor
BWROG	Boiling Water Reactor Owners Group
CCFP	Conditional Containment Failure Probability
CDET	Core Damage Event Tree
CDF	Core Damage Frequency
CPRR	Containment Protection and Release Reduction
DW	Drywell
DWV	Drywell Vent
ELAP	Extended Loss of AC Power
EPG/SAGs	Emergency Procedure Guidelines/Severe Accident Guidelines
HPC	High Performance Computer
IEF	Individual Early Fatality
LCF	Latent Cancer Fatality
LMT	Liner Melt-Through
MAAP	Modular Accident Analysis Program
MACCS	MELCOR Accident Consequence Code System
MACR	Maximum Averted Cost Risk
USNRC	United States Nuclear Regulatory Commission
PRA	Probabilistic Risk Assessment
QHO	Quantitative Health Objective
RCIC	Reactor Core Isolation Cooling
RPV	Reactor Pressure Vessel
SACV	Severe Accident Capable Vent
SAMG	Severe Accident Management Guidelines
SAWA	Severe Accident Water Addition

SAWM	Severe Accident Water Management
SBO	Station Blackout
SOARCA	State-of-the-Art Consequence Analysis
SRM	Staff Requirement Memoranda
SRV	Safety Relief Valve
WW	Wetwell

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1 INTRODUCTION

This report summarizes a risk-informed technical investigation of severe accident mitigating strategies for BWR reactors with Mark I containments. This report emphasizes the protection of containment integrity and the reduction of radionuclide releases following a severe reactor accident. This summary report is being released in advance of a more detailed technical basis report in order to support industry interactions on the USNRC's rulemaking on Containment Protection and Release Reduction (CPRR) for Mark I and II containments. The scope of this report is limited to the evaluation of accident management strategies in BWRs with Mark I containments but the insights are anticipated to be applicable to BWRs with Mark II containments.

1.1 Background

The severe reactor accidents at Fukushima Daiichi Nuclear Power Plant site in March 2011 showed the significant challenges that an unmitigated station blackout (SBO) condition presents to small volume, steel BWR containments (e.g., Mark I & II containments). Past severe accident studies (e.g., State-of-the-Art Reactor Consequence Analysis [1]) indicate a high conditional probability of containment failure in these containments if certain conditions (i.e., high containment pressure and temperatures) are uncontrolled for prolonged periods of time. The operational response at Fukushima Daini site during this same time period highlighted the benefit of effective operator interventions in preventing a severe reactor accident.

Maintaining the integrity of Mark I containments and reducing the impact of radionuclide releases following a severe reactor accident is the focus of a recent NRC rulemaking activity on CPRR. In tandem with this activity the US nuclear industry is pursuing a similar, separate analysis.

In many ways, this analysis builds on prior industry and USNRC studies [2, 3, 4]. However, the analysis framework utilized in this report has been independently developed in order to effectively evaluate the current/as-planned capabilities of Mark I BWRs in the U.S. following implementation of the Tier 1 post-Fukushima recommendations. This evaluation includes accounting for capabilities outlined in the US nuclear industry's FLEX strategy (see USNRC Order EA 12-049 [5]) for preventing core damage and installing a severe accident capable (SAC) wetwell vent as required for Phase 1 of Order EA 13-109 [6]. The analysis also incorporates alternatives described in NEI 13-02 [7] for Phase 2 of EA 13-109 for Severe Accident Water Addition (SAWA) and Severe Accident Water Management (SAWM). These concepts provide a reliable water source to cool the core debris post core damage and a means to preserve the wetwell venting pathway to reduce radionuclide release.

To this end, EPRI has brought to bear some unique analytical capabilities to support this work, promoting a deeper level of understanding of benefits and ramifications of specific severe accident strategies. The integrated risk model used to support this effort makes use of EPRI's

multi-core, high-performance computer (HPC), named Phoebe, to perform automated accident analyses. This includes automatically generating, evaluating, and extracting results for the unique Modular Accident Analysis Program (MAAP) [8] and MELCOR Accident Consequence Code System (MACCS) [9] scenarios required to quantify and characterize a myriad of accident sequences that are typically analyzed in a probabilistic model. Thus, rather than rely on a limited set of stylized severe accident calculations as has been done in the past, this analysis utilizes a "large-scale" MAAP and MACCS integrated model that is capable of analyzing tens of thousands of severe accident sequences and corresponding consequence analyses in less than a day.

1.2 Purpose of Report

The purpose of this EPRI research is to support nuclear industry decision-makers with technical information, provide insights on severe accident management, and provide a comparative basis to the NRC's CPRR rulemaking activities.

1.3 Organization of Report

An overview of the technical approach employed in this analysis and a description of the severe accident strategies considered in this report is provided in Section 2.

Section 3 describes the quantitative results and other insights for each of the severe accident mitigating strategies explored in this report.

Section 4 summarizes the investigation of sensitivities to the analysis in Section 3, including plant-to-plant variability, modeling assumptions (including public safety effects), and severe accident phenomenological effects.

An overall summary and collection of key insights developed in this analysis is provided in Section 5.

This report represents Volume 1 of the analysis. It provides a summary of the analyses and the insights gained from the analyses. Volume 2[1] contains the appendices that document the details of the risk analysis quantification, MAAP analysis, and corresponding MACCS analysis. A roadmap in Volume 2 cross-references the Volume 2 appendices to relevant sections in Volume 1.

[1] Volume 2 is being released as EPRI Report 3002005300.

2
OVERVIEW OF TECHNICAL APPROACH

2.1 Technical Background

In late 2012, the USNRC staff issued SECY 12-0157 [4], a simplified analysis of a limited set of severe reactor accident scenarios that provided a characterization of the benefit of hardened containment vents and engineered vent filters. The USNRC Commission Staff Requirement Memoranda (SRM) on SECY 12-0157 ultimately directed the staff to undertake a detailed technical analysis to meet the following criteria:

- Consider both engineered filters and filtering strategies,
- Address the "dominant severe accident sequences"
- Credit the installation of the severe accident capable vent (SACV)

Identifying and addressing the dominant severe accident sequences typical to Mark I BWRs as requested by the Commission was determined to require a much more detailed analysis than was performed in SECY 12-0157. Further, this approach required updating the SECY 12-0157 analysis to credit other post-Fukushima enhancements required by the Commission, which include:

- Order EA 12-049 [5] – Post-Fukushima Severe Accident Mitigating Strategies
- Order EA 13-109 [6] – Installation of SACVs
- Emergency Operating Procedure (EOP) and Severe Accident Guidelines (SAGs) enhancement developed by the BWROG

Order EA-12-049 had a significant impact on the typical risk spectrum of a nuclear power plant because the requirements of the order (additional severe accident mitigating strategies) reduced the likelihood of many of the dominant severe accident scenarios.

The requirements of EA 13-109 enhanced plant severe accident mitigation capabilities by requiring the installation of a reliable venting system that can be used in accordance with the new EOP/SAGs developed by the BWROG. The BWROG EOP/SAGs directly incorporate the lessons learned from the accidents at Fukushima and support the implementation of both EA 12-049 and EA 13-109.

Numerous public meetings were held through which the USNRC staff defined the details of EA 13-109 and gained additional insights from the BWROG into the manner in which the post-Fukushima enhancements have influenced the severe accident mitigation capabilities of US plants. The industry performed its own technical analysis in parallel with the USNRCs in order to facilitate a common understanding of plant severe accident mitigation capabilities and their influence on the health and safety of the public.

The technical analysis described in this report has been designed to provide a tractable and flexible, yet detailed, analysis framework. While not a full-scale, plant-specific PRA, the analysis relies upon PRA methods and approaches to characterize the dominant severe accident sequences of interest. The following general principles were used in developing the analysis:

- Expand the simplified analysis presented in SECY 12-0157 where applicable to allow delineation of dominant accident scenarios.
- Focus on extended loss of AC power (ELAP) scenarios as the primary challenge to containment.
- Utilize USNRC references and methodologies wherever practical, including the analysis of the same reference site.
- Rely upon Rev 3 of the BWROG Emergency Procedure Guidelines/Severe Accident Guidelines (EPG/SAGs), except where an alternative mitigation strategy is being evaluated.
- Account for the fact that there are significant uncertainties in both the probability of occurrence and the phenomenological progression of any severe accident.

2.2 Accident Management/Filtering Strategy Alternatives

Previous industry and NRC work on filtering strategies [2,4], identified various approaches to managing the progression of severe accidents. Through a series of public meeting interactions with the NRC staff, a variety of severe accident management alternatives were identified for consideration individually, and in combination, as appropriate:

- Severe Accident Capable (SAC) Wetwell (WW) Vent – per Phase 1 of EA 13-109.
- Drywell vent (DWV) – a severe accident capable vent pathway from the drywell airspace capable of controlling containment pressure during severe accident conditions.
- Severe accident water addition (SAWA) - water addition capability to either the reactor pressure vessel (RPV) or the Drywell (DW) that can be effectively implemented under severe accident conditions.
- Severe accident water management (SAWM) - the management of wetwell water level such that the use of the wetwell vent path is preserved until such time that off-site equipment is available to rapidly flood up the containment to achieve minimum debris submergence level as directed by the EPG/SAGs and until alternate heat removal is established.
- Vent control – control of containment pressure within a specified pressure band during the severe accident by opening and closing a vent pathway.
- Large engineered filter – an engineered filtration system and appurtenances installed on the vent pathway that is designed to trap radionuclide aerosols during a severe core damage event. The large engineered filter is of sufficient capacity to retain efficiency whether installed on the wetwell or drywell vent path and is capable of large aerosol loadings.
- Small engineered filter – an engineered filtration system and appurtenances installed on the vent pathway that is designed to trap radionuclide aerosols during a severe core damage event. The smaller filter is differentiated from the large filter by a reduced capacity for aerosol loading.

A total of 24 alternatives and combinations were identified for consideration in the analysis. Table 2-1 provides a summary of the features of the alternative strategies considered. The strategy color coding in Table 2-1 is maintained throughout the graphics in this report (e.g., results summaries in Section 5 have the same color coding). The color coding is defined as follows:

- Pink alternatives have no severe accident water addition capability.
- Green alternatives credit severe accident water addition capability to the reactor pressure vessel (RPV).
- Blue alternatives credit severe accident water addition capability directly to the drywell (DW).

Table 2-1
Summary of Alternative Cases Considered

Alternative	SAC WW Vent	DW Vent	SAWA	SAWM	Vent Control	Filter	Filter Path
New Base	Yes	None	No	No	No	None	Manual
1A	Yes	SACV	No	No	No	None	Manual
2A	Yes	None	RPV	No	No	None	Manual
2B	Yes	None	RPV	**Yes**	No	None	Manual
2C	Yes	None	RPV	No	**Yes**	None	Manual
2D	Yes	None	RPV	**Yes**	**Yes**	None	Manual
2E	Yes	SACV	RPV	No	No	None	Manual
2F	Yes	SACV	RPV	**Yes**	No	None	Manual
2G	Yes	SACV	RPV	No	**Yes**	None	Manual
2H	Yes	SACV	RPV	**Yes**	**Yes**	None	Manual
3A	Yes	None	DW	No	No	None	Manual
3B	Yes	None	DW	**Yes**	No	None	Manual
3C	Yes	None	DW	No	**Yes**	None	Manual
3D	Yes	None	DW	**Yes**	**Yes**	None	Manual
3E	Yes	SACV	DW	No	No	None	Manual
3F	Yes	SACV	DW	**Yes**	No	None	Manual
3G	Yes	SACV	DW	No	**Yes**	None	Manual
3H	Yes	SACV	DW	**Yes**	**Yes**	None	Manual
4A	Yes	SACV	RPV	No	No	**Small**	Manual
4B	Yes	SACV	DW	No	No	**Small**	Manual
5A	Yes	SACV	RPV	No	No	**Large**	Manual
5B	Yes	SACV	DW	No	No	**Large**	Manual
6A	Yes	SACV	DW	No	No	**Large**	**All Passive**
6B	Yes	SACV	DW	No	No	**Large**	**Manual Pre-CD**

Legend
No SAWA
RPV SAWA
DW SAWA

2.3 Quantitative Figures of Merit

In developing any quantitative risk model, it is important to define the quantitative figures of merit that should be of interest to decision-makers. In a deterministic report by EPRI [2] that explored several severe accident mitigation strategies, including the effects of an engineered containment filter system, an overall decontamination factor (DF) was used to identify potentially effective strategies. Use of this simplified DF is not effective for considering a broad range of potential accident scenarios. This is due to the fact that the DF is highly correlated to the scenario and subject to a number of unresolvable phenomenological uncertainties.

A risk framework offers the opportunity to have a more holistic view of the spectrum of severe accident scenarios by focusing on metrics such as core damage and containment failure probability and metrics that typically support regulatory decisions, such the USNRC's Quantitative Health Objectives (QHOs) and financial consequence risks.

Four quantitative figures of merit are considered for each of the alternative cases:

- Core Damage Frequency (CDF) – the annual probability of core damage events. In this analysis, the focus on core damage events initiated by an extended loss of AC power (ELAP).
- Conditional Containment Failure Probability (CCFP)
  This metric represents the fraction of all core damage scenarios that lead to uncontrolled releases from containment:

  $CCFP = F_{Uncontrolled}/CDF$

  Where,
  $F_{Uncontrolled}$ = Frequency of uncontrolled releases from containment
  CDF = Core damage frequency applicable to the alternative
- Latent Cancer Fatality Risk
  The annual probability of a latent cancer fatality for an individual located within 10 miles of the plant. This metric is used for comparison with the latent cancer fatality Quantitative Health Objective (QHO) from the USNRC Safety Goal Policy Statement.
- Financial Consequence Risk
  Financial consequences reflect the "benefit" aspect of a cost-benefit evaluation. That is, it is the present value of the consequence risk expressed in terms of dollars, which includes the cost associated with both onsite and offsite dose and cleanup costs. For each alternative, the residual Maximum Averted Cost Risk (MACR) is calculated. The MACR represents the dollar value of the residual risk. In considering the net benefit of an alternative, a ΔMACR is calculated based on the change in MACR from the applicable base case to each alternative scenario.

Other metrics such as offsite population dose, offsite land contamination, and population requiring relocation were considered, but these metrics are already included in the financial consequence models. Individual metric analysis in addition to the financial consequence analysis would effectively be double-counting these metrics.

2.4 Integrated Risk Analysis Framework

Effectively evaluating the risks and benefits associated with various alternatives requires an integrated risk analysis framework that supports the quantification of the variety of quantitative figures of merit described in Section 2.3 across the large spectrum of alternatives defined in Table 2-2. The overall analysis framework utilized in this analysis is depicted in Figure 2-1.

The probabilistic portion of risk analysis is quantified using a core damage event tree (CDET) and accident progression event tree (APET)[2]. The essential elements of these tools are summarized in Appendix A. The CDET begins with an ELAP condition and evaluates the important contributors to avoiding core damage. This includes the core damage prevention capabilities being implemented under USNRC Orders EA 12-049 and EA 13-109. Since a number of the alternatives considered in this analysis rely upon equipment implemented under these orders it was important to clearly identify the nature of the resulting core damage scenarios, and the credible severe accident progression sequences associated with each of these core damage scenarios.

The CDET structure, as illustrated in Figure 2-2, contains a total of 20 sequences. Seven of these sequences are "success" sequences, meaning that core damage is avoided. The other 13 sequences are core damage sequences of different types. Each sequence is briefly described below:

<u>CD-001 - FLEX Success as planned</u>

In this success sequence, the reference plant FLEX implementation functions as planned. RCIC starts and runs for the duration of the event, the plant operators take the appropriate actions to vent containment to maintain low suppression pool temperatures to keep RCIC running and control RPV pressure. FLEX is implemented as planned to provide power to instruments and key equipment and a portable pump is used to makeup to the suppression pool.

<u>CD-002 - RCIC & Early WW Venting Succeed, FLEX fails late, Cont. Re-isolated</u>

This core damage sequence involves early success of RCIC and FLEX, followed by failures occurring later in the 72 hour time window. This includes scenarios with failures of RCIC to run long-term, followed by failure of the FLEX equipment to maintain core cooling. The WW vent is initially opened to support RCIC operation, but is closed by the operators when core cooling is lost and the transition is made from the EOPs to the SAGs.

<u>CD-003 - RCIC & Early WW Venting Succeed, FLEX fails late, WW Vent Open</u>

This core damage sequence proceeds like CD-002, but the plant operators do not isolate the WW vent pathway when core cooling is lost.

<u>CD-004 –WW Vent with Late FLEX Success</u>

In this success sequence, plant operators fail to control RPV pressure sufficiently high to maintain a sufficient steam supply for the RCIC turbine. Thus, the RPV is depressurized. However, FLEX is successfully deployed to maintain core cooling.

[2] The APET described here is identical to a typical containment event tree (CET)

CD-005 - RCIC Lost on ED, FLEX Fails, WW Vent Re-Isolated

In this core damage sequence, plant operators fail to control RPV pressure sufficiently high to maintain a sufficient steam supply for the RCIC turbine. Thus, the RPV is depressurized. FLEX is not successfully deployed, either due to human or equipment failures. As with sequence 2, the operators do isolate the open WW vent upon entry into the SAGs.

CD-006 - RCIC Lost on ED, FLEX Fails, WW Vent Not Re-Isolated

This core damage sequence proceeds like CD-005, but the plant operators do not isolate the WW vent pathway when core cooling is lost.

CD-007 – DW Vent & FLEX Success

This success sequence involves a failure to utilize the WW vent to maintain the SP temperature sufficiently low to maintain RCIC in operation. Thus, RCIC is eventually lost, but in this sequence FLEX equipment is successfully deployed to maintain core cooling.

CD-008 - RCIC & Early DW Venting Succeed, FLEX fails late, Cont. Re-isolated

This core damage sequence involves a failure to utilize the WW vent to maintain the SP temperature sufficiently low to maintain RCIC in operation. Thus, RCIC is eventually lost, but in this sequence FLEX equipment is not successfully deployed so core damage occurs. However, operators successfully isolate the DW vent upon entry into the SAGs.

CD-009 - RCIC & Early DW Venting Succeed, FLEX fails late, DW Vent Open

This core damage sequence proceeds like CD-008, but the plant operators do not isolate the DW vent pathway when core cooling is lost.

CD-010 - DW Vent with Late FLEX Success

This success sequence is similar to CD-004, except the DW is used for containment heat removal. FLEX is successfully deployed when RCIC is lost due to operators failing to maintain RPV pressure.

CD-011 - RCIC Lost on ED, FLEX Fails, DW Vent Re-Isolated

In this core damage sequence, plant operators fail to control RPV pressure sufficiently high to maintain a sufficient steam supply for the RCIC turbine. Thus, the RPV is depressurized. FLEX is not successfully deployed, either due to human or equipment failures. As with sequence 5, the operators do isolate the open DW vent upon entry into the SAGs.

CD-012 - RCIC Lost on ED, FLEX Fails, DW Vent Not Re-Isolated

This core damage sequence proceeds like CD-011, but the plant operators do not isolate the DW vent pathway when core cooling is lost.

CD-013 – No Early Vent with Late FLEX Success

This success sequence involves early operation of RCIC but no successful containment venting. As a result, the SP temperature eventually exceeds the limits for successful RCIC operation. However, since this failure occurs late, there is sufficient time for the operators to establish core cooling with FLEX and vent the containment for heat removal.

CD-014 - RCIC Early, Cont. Not Vented, RCIC Lost on SP-T

This core damage sequence involves failure to vent containment maintain the SP temperature low enough to support RCIC operation. This leads to a need for FLEX to provide core cooling. In this sequence, deployment of FLEX and restoration of a containment vent pathway was unsuccessful.

CD-015 - No Early Vent, RPV at Low Pressure with Late FLEX Success

This success sequence is similar to CD-013 except RCIC is lost earlier due to failure of the operators to maintain RPV pressure. However, the transition to FLEX occurs successfully to avoid core damage.

CD-016 - RCIC Succeeds Early (0-6 hrs), FLEX Succeeds, No Venting, ED

This core damage sequence involves the initial success of RCIC and intial deployment of FLEX, but the failure to vent containment leads to loss of RCIC due to high SP temperatures. A transition to FLEX equipment for core cooling is unsuccessful, leading to core damage.

CD-017 - RCIC Succeeds Early (0-6 hrs), FLEX Late/Unavail

This core damage sequence is a typical long-term station blackout scenario where RCIC initially operates and runs until battery depletion. The transition to FLEX fails, either due to delays in deployment or equipment problems, leading to loss of core cooling.

CD-018 – RCIC Fails Early but FLEX Succeeds

This success sequence involves failure of RCIC to successfully operate until FLEX can be fully deployed. Very early failures of RCIC cannot be mitigated by portable FLEX equipment due to insufficient time, but later failures of RCIC (e.g., after ~4 hours) can be. This sequence represents those scenarios.

CD-019 - RCIC Fails Early, Operator ED, FLEX Late/Unavail

This core damage sequence involves failure of RCIC to operate until the FLEX portable equipment can be deployed. In this sequence, power is available and operators successfully depressurize the RPV, but the FLEX equipment is not deployed in time to prevent core damage. This could either be due to the timing of RCIC failures or failures to deploy the equipment in a timely manner.

CD-020 - RCIC Fails Early, No ED, FLEX Ineffective

This core damage sequence involves early loss of RCIC core cooling followed by failure to depressurize the RPV for FLEX deployment. These scenarios are most often characterized by infrastructure damage that prevents successful operator actions.

Given that core damage has occurred as described in the CDET, the next step in the analysis is to evaluate the containment response through the development of an Accident Progression Event Tree (APET). The purpose of the APET, as illustrated in Figure 2-3, is to describe the progression of the event by identifying all appropriate system functions, operator actions, and phenomena that have an impact on the outcome of the event. The outcome, or end state, looks at defining the timing and magnitude for a potential radionuclide release.

The following describes the top events of the APET. These top events have been selected as they have the strongest influence on the prediction of the timing and magnitude of the release.

<u>RPV Depressurization During Core Melt (RPV-PRESS)</u>

The CDET will transfer information relating to the success or failure of RPV depressurization up to the point of core damage. This top event addresses the phenomena associated with causing the vessel to depressurize from the onset of core damage to the time of vessel breach. This top event has three possible outcomes. First is the potential for an induced failure of the main steam line. As discussed in SECY-12-0157, failure of the main steam line (MSL) can occur under conditions of elevated temperatures within the RPV. Creep rupture of the MSL would result in rapid depressurization of the RPV and release of steam, hydrogen and fission products directly into the drywell atmosphere.

The second possible branch in this top event is seizure of an SRV in the open position, also a result of elevated RPV gas temperatures. This failure will result in opening a single SRV with discharge directly into the suppression pool. In addition to seizure of the SRV, this branch will also be taken for cases from the CDET that already had successful depressurization of the RPV.

If neither of these failures occur, the sequence will proceed to a failure of the reactor vessel at high pressure.

<u>In-Vessel Retention (IVR)</u>

If water injection to the RPV can be established prior to vessel breach, it is possible that vessel breach can be prevented with the core debris maintained within the RPV. An example of this could be if a low pressure source of water is available (e.g. FLEX), however, is unable to inject due to elevated pressure in the RPV. If an SRV fails after the onset of core damage, the pressure will be reduced allowing the low pressure pump to inject. Typically it is assumed that an injection source established with sufficient flow at or before core slump into the lower plenum can result in retention of the core material within the RPV. Success of this branch will reduce the challenges to containment due by core debris and typically results in a reduction in the release of radionuclides from containment.

<u>Water Injection Provided to Cool Debris (WTR-INJECT)</u>

This top event branch simply evaluates the potential for establishing a water addition source either to the RPV or directly into the drywell post core damage. For the evaluation of release mitigation, it is assumed that this source of water is available at the time of vessel breach and will successfully cover the core debris ex-vessel. Water addition will serve to limit the drywell temperatures and protect the liner from melting, thereby preserving the venting capability by avoiding the creation of leakage pathways out of containment.

<u>Early Containment Failure Avoided (ECF)</u>

At the time of vessel breach, core debris will be discharged from the RPV into the reactor pedestal region. The core debris can then flow into the drywell, posing a threat to the liner if sufficient cooling is not provided. The top event ECF is used to estimate the likelihood that containment failure could occur coincident with vessel breach. Other than liner melt through, there are other less likely energetic events that could occur at the time of vessel breach such as steam explosions, high pressure melt ejection and direct containment heating. These other

prompt failure modes have been investigated and found to have a low probability, however, they are considered in this event tree structure.

Degree of Molten Core-Concrete Interactions (MCCI)

The next top event addresses the potential uncertainty in the amount of core-concrete attack that could occur, in the presence of a water pool. Recent analysis [ORNL 2013] motivated by the events at Fukushima have shown that even after water is poured onto core debris ex-vessel, core-concrete attack may continue for a period of time. This insight along with known differences in core melt progression between analyses with MELCOR and MAAP [EPRI 2014] have led to this branch point in the event tree. The success path for this event assumes minimal MCCI due to successful water migration into the core debris. The downward or failure path assumes much limited debris cooling and sustained concrete attack.

Wetwell Vent Used for Initial Control (WW-VENT)

As stated previously, the CPRR technical analysis assumes implementation of the BWROG EPG/SAG Revision 3. The procedures and guidelines call for venting of the wetwell as the preferred pathway. The CDET previously addressed anticipatory venting as a FLEX strategy to extend the use of RCIC. The CDET also addressed the possibility that the vent path remained open despite guidance to close the path upon entry into the SAG or when it becomes unnecessary to maintain RCIC operation. This top event looks at venting post core damage. The SAGs will call for venting to maintain containment pressure below the Pressure Suppression Pressure (PSP). Should the PSP be exceeded, then venting will be performed to maintain pressure below the Primary Containment Pressure Limit (PCPL). In addition, once the vessel has been breached, venting to stay below the PCPL is the governing guidance.

After vessel breach, venting through the wetwell will provide filtration of the radionuclide release due to suppression pool scrubbing. Following vessel breach, the current SAGs call for increasing the containment water level, which at some point will result in isolation of the wetwell vent pathway. Assumed in this top event is that as a result of the increased suppression pool water level, the wetwell vent path will be isolated and subsequent venting demands will be satisfied using a drywell vent path.

Drywell Vent Used for Initial Control (DW-VENT)

As stated above, the WW-VENT branch point also addresses the late use of the drywell vent as a result of increasing wetwell water level. This top event does not address that function, but rather addresses the low likelihood that the wetwell vent path is not available. In this situation, the top event DW-VENT is modelled as a back up to the failed wetwell pathway.

Endstate Descriptions

There are 39 unique end states developed in the APET. As a way to describe these, major categories will be discussed with like characteristics.

APET-001,015: These end states both represent scenarios where the core material is retained within the reactor vessel. The only difference is the mode of RPV depressurization; main steam line failure for APET-001 and SRV seizure for APET-015. Both of these end states credit injection into the RPV after the onset of core damage, but before vessel breach. With low pressure injection available and low RPV pressure, there is some likelihood that the damaged

core material will be cooled and maintained within the vessel. Both of these end states include successful venting of the wetwell as a means to remove decay heat from containment.

APET-002, 016: These end states are identical to APET-001 with the exception that the wetwell vent path is unavailable and decay heat removal is provided using a drywell vent.

APET-003, 017: These end states are identical to APET-001 with the exception that neither the wetwell nor drywell vent paths are available for decay heat removal. These scenarios result in overpressure failure of the drywell.

APET-004,018,029: These end states represent scenarios that progress to core damage, vessel breach and release of core material into the containment. Water addition is successfully initiated into either the RPV or drywell, depending on the alternative being evaluated. Due to water addition, early containment breach (i.e. liner melt through) is avoided. All of these scenarios also assume minimal molten core-concrete interaction and successful implementation of wetwell venting. The only difference is the RPV pressure; APET-004 is depressurized due to main steam line rupture, APET-018 is depressurized due to SRV seizure, and APET-029 remains at high pressure.

APET-005,019,030: Identical to the APET-004 cases described above, the only difference is that the wetwell vent path is unavailable and drywell venting occurs to remove decay heat from containment.

APET-006,020,031: Identical to the APET-004 cases described above, the only difference is that neither the wetwell nor drywell vent paths are available for decay heat removal. These scenarios result in overpressure failure of the drywell.

APET-007,021,032: These end states represent scenarios that progress to core damage, vessel breach and release of core material into the containment. Water addition is successfully initiated into either the RPV or drywell, depending on the alternative being evaluated. Due to water addition, early containment breach (i.e. liner melt through) is avoided. These scenarios also assume extensive molten core-concrete interaction and successful implementation of wetwell venting. The only difference is the RPV pressure; APET-007 is depressurized due to main steam line rupture, APET-021 is depressurized due to SRV seizure, and APET-032 remains at high pressure.

APET-008,022,033: Identical to the APET-007 cases described above, the only difference is that the wetwell vent path is unavailable and drywell venting occurs to remove decay heat from containment.

APET-009,023,034: Identical to the APET-007 cases described above, the only difference is that neither the wetwell nor drywell vent paths are available for decay heat removal. These scenarios result in overpressure failure of the drywell.

APET-010,024,035: These end states represent scenarios that progress to core damage, vessel breach and release of core material into the containment. Water addition is successfully initiated into either the RPV or drywell, depending on the alternative being evaluated. In the rare situation where water addition is unable to avoid liner melt through or in cases where other phenomena energetic occurs (e.g. steam explosions, direct containment heating, etc.), early containment breach is assumed. The only difference is the RPV pressure; APET-010 is

depressurized due to main steam line rupture, APET-024 is depressurized due to SRV seizure, and APET-035 remains at high pressure.

APET-011,025,036: These end states represent scenarios that progress to core damage, vessel breach and release of core material into the containment. For these scenarios, water addition is not available, however early containment failure does not occur. The wetwell vent is available, however, without core debris cooling, the drywell integrity will be challenged due to elevated temperatures. The only difference in these 3 end states is the RPV pressure; APET-011 is depressurized due to main steam line rupture, APET-025 is depressurized due to SRV seizure, and APET-036 remains at high pressure.

APET-012,026,037: Identical to the APET-011 cases described above, the only difference is that the wetwell vent path is unavailable and drywell venting occurs to remove decay heat from containment.

APET-013,027,038: Identical to the APET-011 cases described above, the only difference is that neither the wetwell nor drywell vent paths are available for decay heat removal.

APET-014,028,039: These end states represent scenarios that progress to core damage, vessel breach and release of core material into the containment. For these scenarios, water addition is not available and early containment failure occurs as a result of liner melt through. The only difference in these 3 end states is the RPV pressure; APET-014 is depressurized due to main steam line rupture, APET-028 is depressurized due to SRV seizure, and APET-039 remains at high pressure.

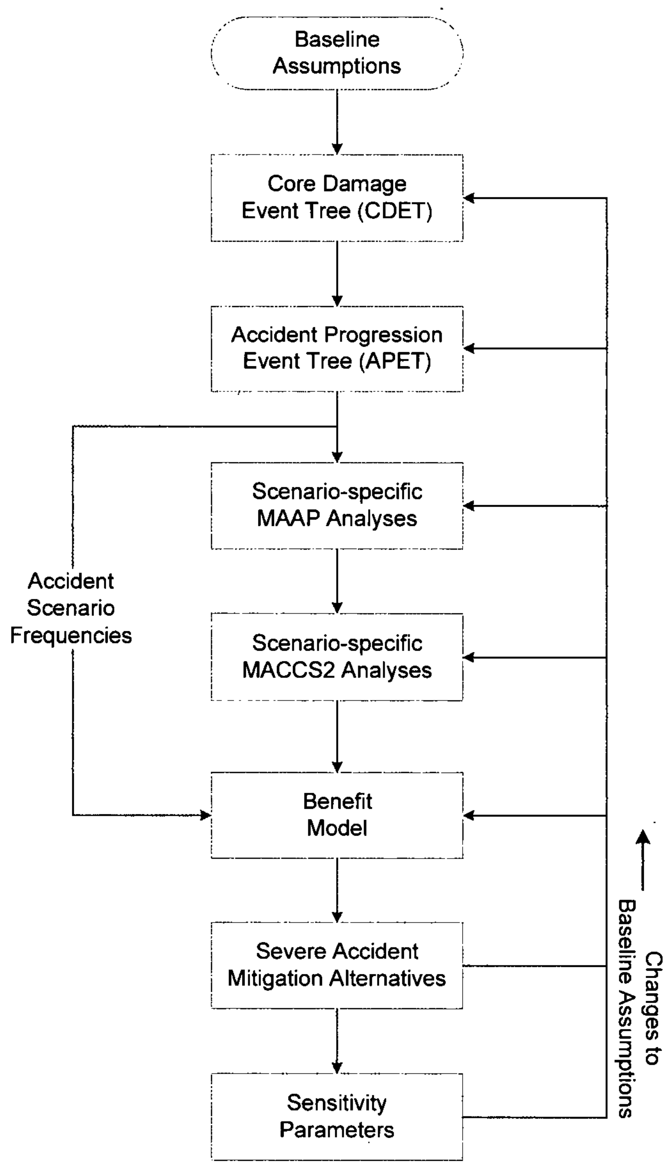

Figure 2-1
Analysis Framework

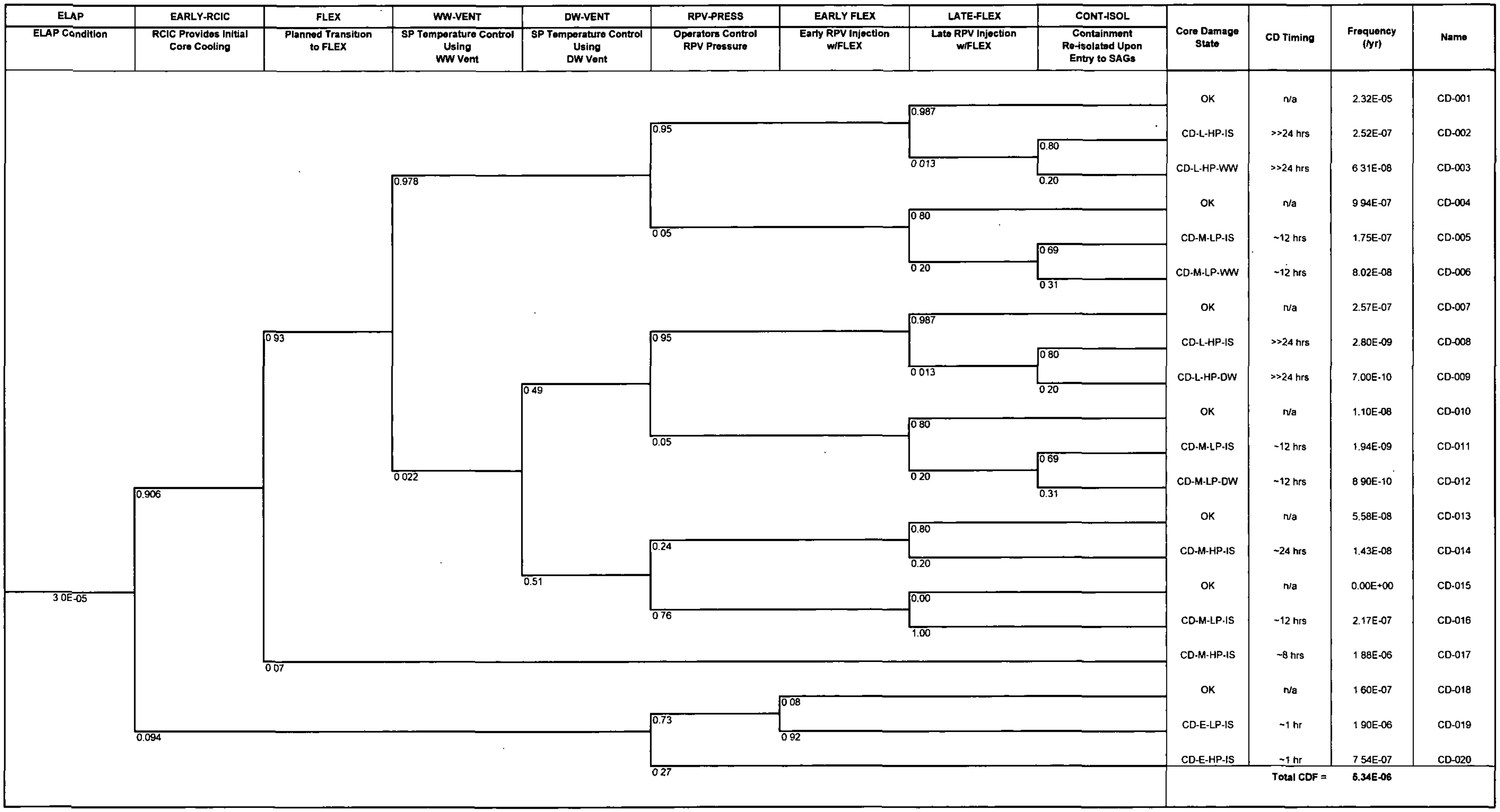

Figure 2-2
Core Damage Event Tree (Example)

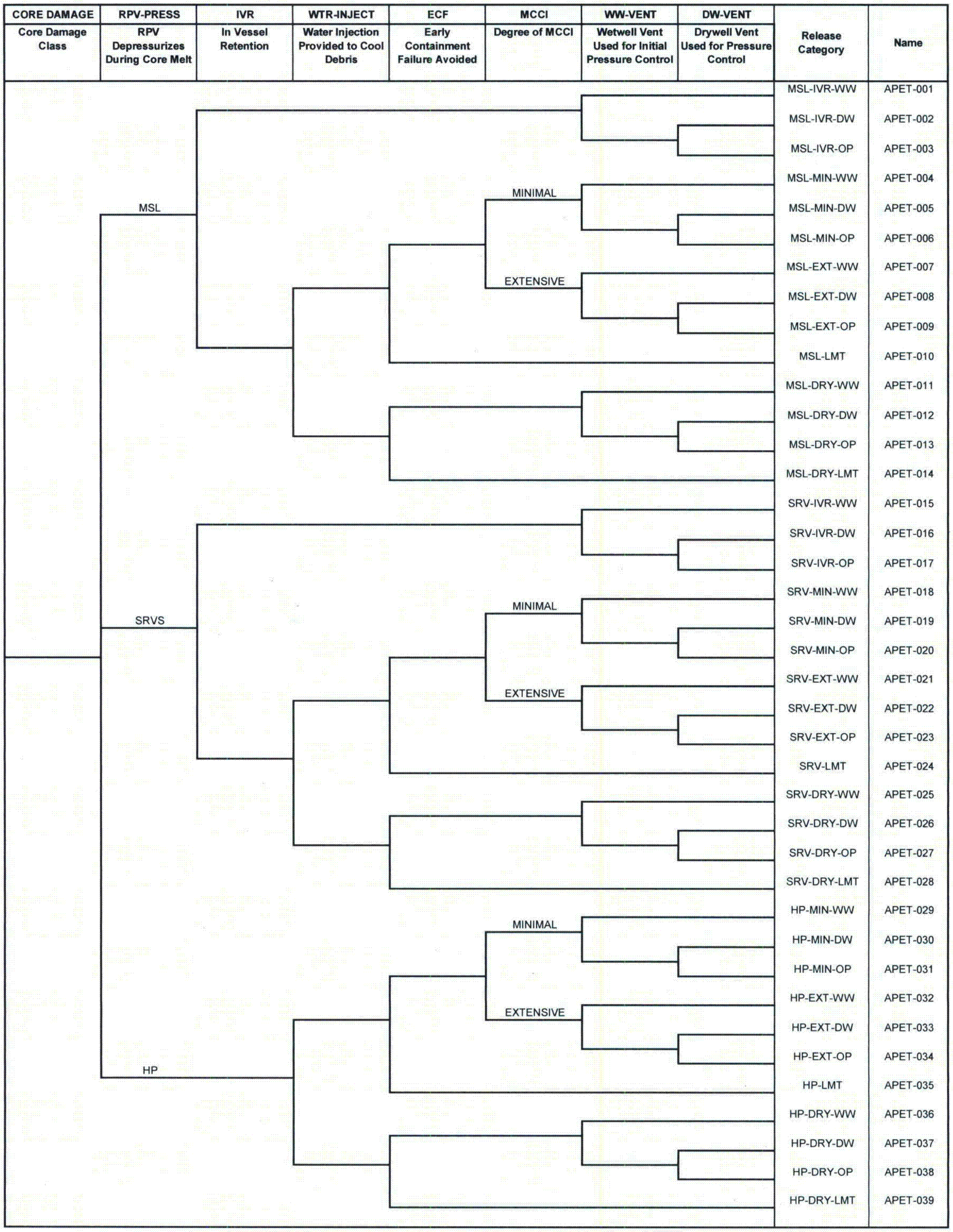

Figure 2-3
Accident Progression Event Tree

A total of 13 CDET endstates involving core damage were identified and 39 APET endstates define the key progression scenarios for each of these core damage scenarios. This branching results in a total of 507 unique radionuclide release scenario endstates for each of the 24 accident management strategy alternatives (13 CDET endstates * 39 APET endstates = 507 unique sequence end states). In total, there were 12,168 release scenarios analyzed for this project (507 unique end states * 24 alternatives = 12,168 release scenarios).

Unique MAAP analyses were performed to characterize each of the over 12,000 release scenarios. The MAAP results provided the release characterization necessary to allow a unique offsite consequence analysis to be performed using MACCS for each release scenario. The MACCS results and the probabilistic results of the CDET/APET analysis provide the information necessary to evaluate the latent cancer risks and financial consequence risks associated with each alternative via offsite dose and economic cost calculations.

The evaluation of the specified alternatives involved the modification of CDET/APET event probabilities (e.g., probability of successful water addition) and/or new boundary conditions for the associated MAAP analysis (e.g., vent cycling vs. remain-open vent operation).

Table 2-2 depicts the alternative designations developed to describe the probabilistic (CDET/APET) and deterministic (MAAP/MACCS) analyses to address the spectrum of alternatives.

Table 2-2
Summary of Alternative Treatments in Integrated Analysis Framework

Alternative	CDET	APET	APET Probabilistic Treatment	MAAP/MACCS Cases
New Base	No DW Vent	Base_Case	No SAWA, No DWV	ALT2A
1A	With DW Vent	ALT1A	No SAWA, with DWV	ALT2A
2A	No DW Vent	ALT2A	SAWA, No DWV	ALT2A
2B	No DW Vent	ALT2B	SAWA, No DWV	ALT2B
2C	No DW Vent	ALT2C	SAWA, No DWV	ALT2C
2D	No DW Vent	ALT2D	SAWA, No DWV	ALT2D
2E	With DW Vent	ALT2E	SAWA with DWV	ALT2E
2F	With DW Vent	ALT2F	SAWA with DWV	ALT2F
2G	With DW Vent	ALT2G	SAWA with DWV	ALT2G
2H	With DW Vent	ALT2H	SAWA with DWV	ALT2H
3A	No DW Vent	ALT3A	SAWA, No DWV, No IVR	ALT3A
3B	No DW Vent	ALT3B	SAWA, No DWV, No IVR	ALT3B
3C	No DW Vent	ALT3C	SAWA, No DWV, No IVR	ALT3C
3D	No DW Vent	ALT3D	SAWA, No DWV, No IVR	ALT3D
3E	With DW Vent	ALT3E	SAWA, No DWV, No IVR	ALT3E
3F	With DW Vent	ALT3F	SAWA, No DWV, No IVR	ALT3F
3G	With DW Vent	ALT3G	SAWA, No DWV, No IVR	ALT3G
3H	With DW Vent	ALT3H	SAWA, No DWV, No IVR	ALT3H
4A	With DW Vent	ALT4A	SAWA with DWV	ALT4A
4B	With DW Vent	ALT4B	SAWA, No DWV, No IVR	ALT4B
5A	With DW Vent	ALT5A	SAWA with DWV	ALT5A
5B	With DW Vent	ALT5B	SAWA, No DWV, No IVR	ALT5B
6A	Passive Only Vent	ALT6A	No Anticipatory Venting, Passive Vent @ PCPL, No IVR	ALT6A
6B	With DW Vent	ALT6B	SAWA with DWV, Passive Vent Post-Core Damage, No IVR	ALT6B

Legend
No SAWA
RPV SAWA
DW SAWA

The generic analysis of severe accident risks is subject to significant uncertainties. A single point estimate solution for a representative plant does not necessarily provide a robust result. In order to understand the sensitivity of the results across the fleet and address the substantial model uncertainties that exist in severe accident analysis, uncertainties were investigated in the following areas:

- Plant to Plant Variability – containment design, siting, etc.
- Model Uncertainties – probabilistic inputs to the risk model
- Phenomenological Uncertainties – key severe accident phenomena as modeled by the MAAP code
- Consequence Model Sensitivities – known areas of uncertainty in the computation of financial impacts using the MACCS code

2.5 Integrated MAAP/MACCS Analysis

Core damage assessment and containment response are evaluated for a number of scenarios and severe accident strategy alternatives. The CDET and APET are quantified for each alternative to allow for the determination of fission product release timing and magnitude. For traditional PRA analysis, the core damage sequences would be binned into plant damage states (PDS) based on sequence similarity and then each of the PDSs would be transferred into the containment analysis. In addition, for the APET end states, binning would be performed with the unique bins representing variations in radionuclide release magnitude and timing. This process allows for limiting the number of discrete severe accident calculations (e.g. using MAAP or MELCOR) needed to represent the various release end states. As a way to increase the fidelity of the CPRR analysis and eliminate issues associated with defining representative cases, this EPRI technical assessment carried out unique MAAP and MACCS calculations for every sequence. Specifically, MAAP 5.02 [8] was used to generate a source term and MAACS 3.7.0 [9] was used for the consequence analysis.

There are a total of 13 core damage end states developed in the CDET and 39 APET end states. This results in a total of 507 unique fission product release end states for each filtering strategy alternative. Of the 24 alternatives identified, only 22 of them require unique sets of MAAP and MACCS calculations. The MAAP and MACCS results for the Base Case and Case 1A are easily derived from alternative 2A and 2E by simply modifying the split fractions representing the success of SAWA and the severe accident drywell vent in the risk model. Therefore, a total of 11,154 unique MAAP and MACCS calculations are needed in support of the technical assessment to address the over 12,000 unique scenarios.

In order to facilitate the rather large demand for computing power, the EPRI High Performance Computer (HPC), "Phoebe", was utilized. This computer utilizes Intel® Xeon® Processors with 784 compute cores. Both Linux and Windows applications are supported on the HPC.

Python, an object-oriented high level programming language, was used to support the development of the MAAP input files, execution of the individual runs, along with extraction and compilation of the results. Output data from each of the MAAP runs was then automatically transferred to MACCS for calculation of the offsite consequences. The compilation process is diagramed in Figure 2-4.

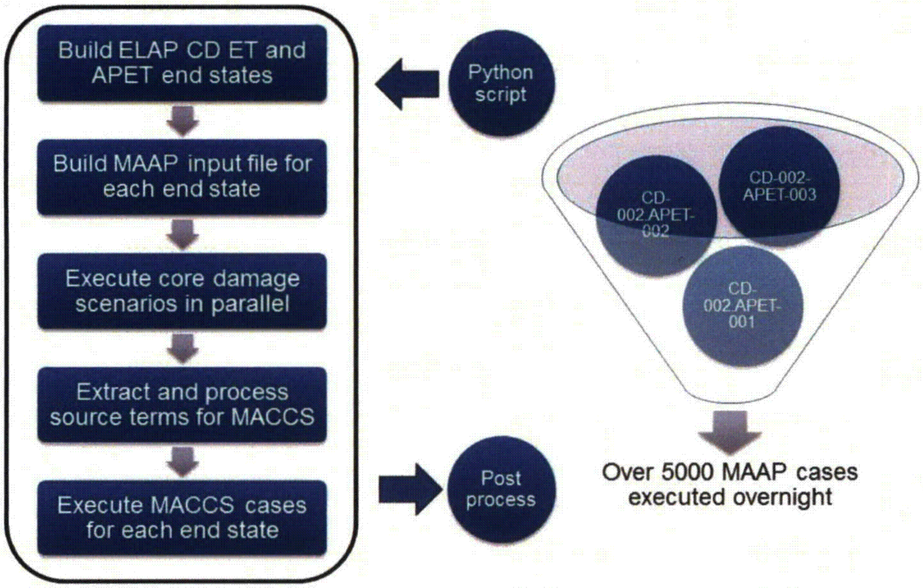

Figure 2-4
MAAP/MACCS Execution Process

2.6 Other Considerations

The following factors are also considered in evaluating the results of the different alternatives:

- Defense-in-depth – The focus here is with the potential improvement in defense-in-depth achieved by the alternative being evaluated.
- Containment temperature control – This involves consideration of the potential benefits of the alternative in controlling drywell temperatures during a severe accident.
- Reliance on human actions – This considers the role of human actions in managing the accident and minimizing releases including the nature, complexity, and timeliness required.
- Instrumentation requirements – Human actions will generally be triggered by instrument indications. This factor considers the nature and availability of any required instrumentation.
- Release reduction – This considers the qualitative impact on any controlled radionuclide releases.
- Hydrogen control – Severe accidents generate hydrogen that can ignite when exposed to air. This factor considers the degree to which the alternative addresses control of hydrogen, with specific emphasis on avoiding hydrogen burns in the Reactor Building.

3
EVALUATION OF ALTERNATIVES

As described in Section 2, a total of 24 alternatives are considered (see Table 2-1). These alternatives consider different hardware and procedural configurations supporting the management of a severe accident in a BWR with a Mark I containment. For the purposes of discussing this large number of alternatives, the cases have been grouped into 6 categories, based on the general nature of the primary accident management strategy:

- Baseline Cases
- Cases with Reactor Pressure Vessel (RPV) Water Addition
- Cases with Drywell (DW) Water Addition
- Cases with Small Engineered Filters
- Cases with Large Engineered Filters
- Cases with Large Engineered Filters & Rupture Disc

3.1 Baseline Cases

Two "Baseline" cases are considered in this analysis. These two cases represent the potential endpoint of plant implementation of Phase 1 of USNRC Order EA 13-109 [6]:

- Base Case - No SAWA - No Drywell Vent
- Case 1A - No SAWA - with a severe accident capable (SAC) Drywell Vent

Figure 3-1 provides a simplified characterization of these two vent configurations. Actual plant configurations will vary considerably.

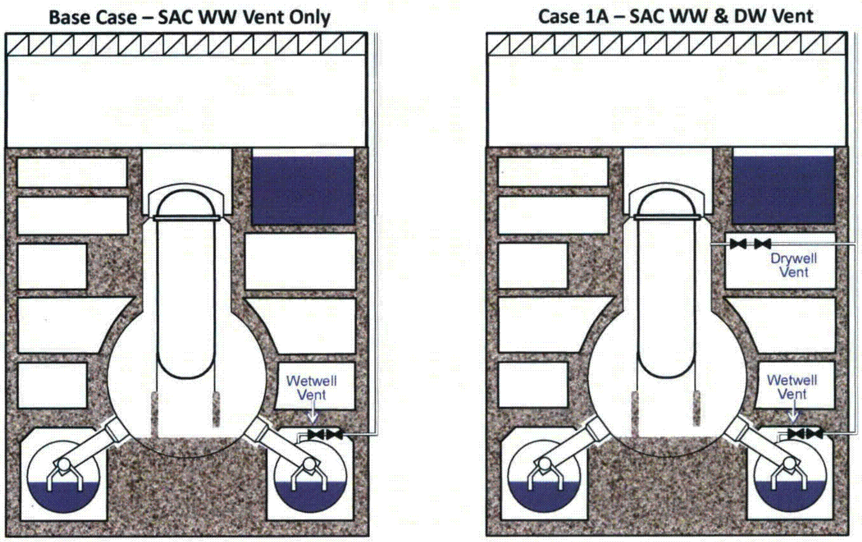

Figure 3-1
General Configuration of Severe Accident Capable Wetwell Vent Concepts

3.1.1 Base Case - No SAWA - No Drywell Vent

The Base Case analysis assumes that the plant has installed a severe accident capable (SAC) wetwell vent for containment pressure control, consistent with Phase 1 of EA 13-109. No additional accident management capabilities are considered.

Quantitative Results – Base Case

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For the Base Case, the CDET associated with a plant without a severe accident capable drywell vent (SACDV) are used. This corresponds with the APET quantification that also assumes that a SACDV is not available.

Table 3-1 provides a summary of the key quantitative results for this case.

Table 3-1
Summary Quantitative Results for Base Case

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.99	3.7E-09/yr	$1,912,926

Figure 3-2 provides a graphical representation of the frequency contributions of various figures of merit within the analysis in a format called a Sankey diagram. The width of bars at each point in the graphic show the relative fraction of the frequency associated with each figure of merit. Since all core damage scenarios lead to an endstate in the APET, this visualization assists in understanding the relative contribution of different types of scenarios and releases contributing to the dominant APET endstates.

The first metric displays the relative contribution core damage event tree (CDET) sequences. The next column associates each of the CDET sequences with a FLEX failure timing, which is next associated with the timing of core damage. Each of those core damage endstates are then shown

contributing to different APET endstates. The Sankey diagram includes all APET scenario endstates that contribute greater than 0.5% to the sum of all endstates for a particular alternative strategy. Finally, each of the APET endstates is correlated with the associated release scenario in the final column.

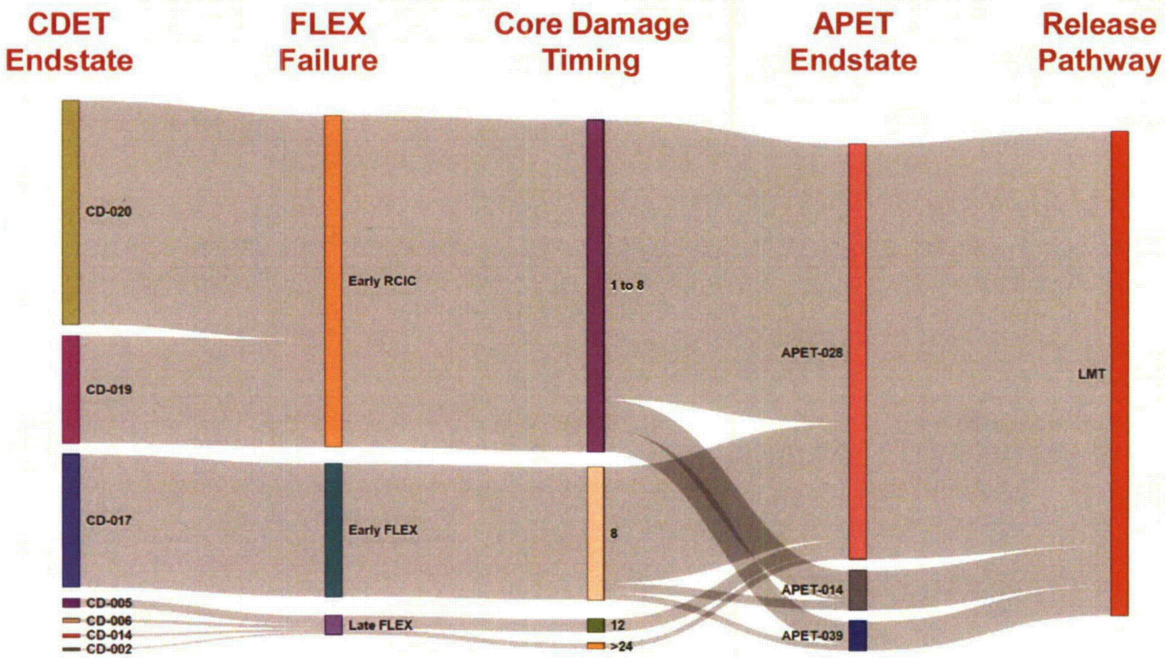

Figure 3-2
Sankey Diagram – Results Visualization for Base Case

Other Considerations – Base Case

While quantitative metrics provide useful, objective characterization of the results, several other considerations are addressed for the Base Case in the table below.

Table 3-2
Summary Assessment of Other Considerations for Base Case

Consideration	Base Case Implications
Defense-in-depth	• The SACV helps protect the containment from over-pressure challenges, but containment integrity can only be preserved with water addition to cool core debris and reduce drywell temperatures.
Containment temperature control	• Without water addition, the drywell will heat up and the drywell shell will be attacked by core debris, increasing the potential for containment failure.
Reliance on human actions	• Operator action is required to open the wetwell vent in accordance with plant EOP/SAGs
Instrumentation requirements	• Containment pressure is the only instrument required to support operator venting actions.
Release reduction	• Without water addition, releases will not be mitigated due to drywell failure.
Hydrogen control	• Venting of the wetwell reduces containment pressure and releases hydrogen from the containment • Lack of water addition capability leads to containment failure due to high temperatures and release of hydrogen into the Reactor Building. Hydrogen burns in the Reactor Building would be expected.

3.1.2 Case 1A - No SAWA - with Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell venting.

No additional accident management capabilities are considered.

Quantitative Results – Case 1A

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available. Table 3-3 provides a summary of the key quantitative results for this case.

Table 3-3
Summary Quantitative Results for Case 1A

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.99	3.7E-09/yr	$1,919,659

Figure 3-3 provides a graphical representation of the frequency contributions of various figures of merit within the analysis in a format called a Sankey diagram. The width of bars at each point in the graphic show the relative fraction of the frequency associated with each figure of merit.

Since all core damage scenarios lead to an endstate in the APET, this visualization assists in understanding the relative contribution of different types of scenarios and releases contributing to the dominant APET endstates.

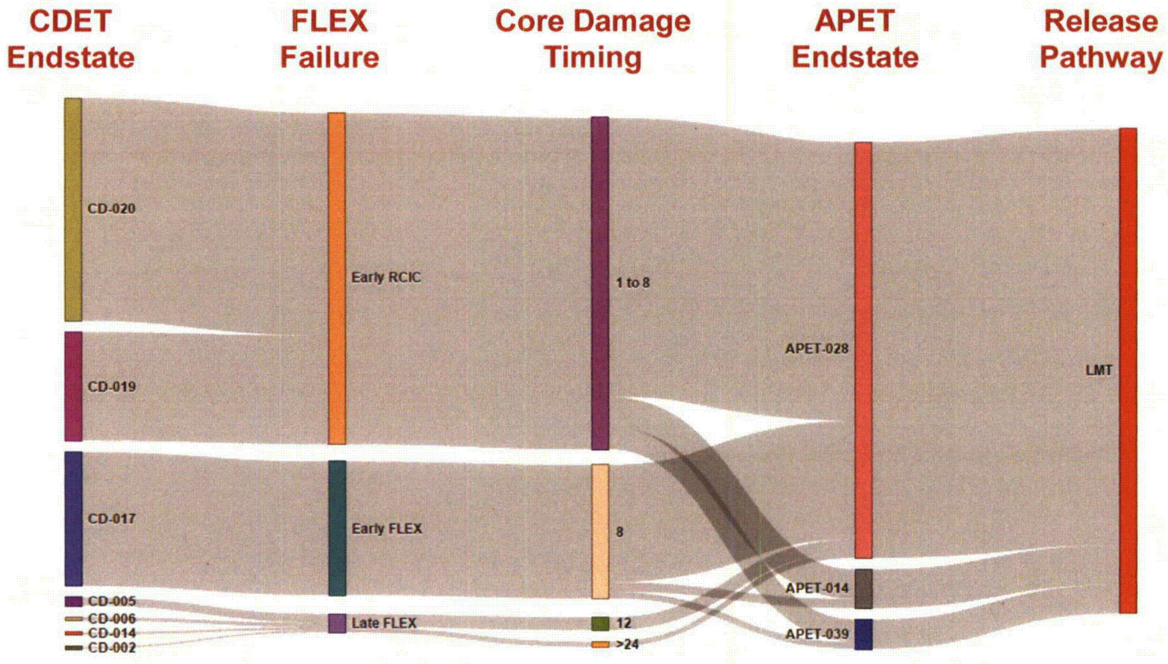

Figure 3-3
Sankey Diagram – Results Visualization for Case 1A

Other Considerations – Case 1A

While quantitative metrics provide useful, objective characterization of the results, several other considerations are addressed for the Case 1A in the table below.

Table 3-4
Summary Assessment of Other Considerations for Case 1A

Consideration	Case 1A Implications
Defense-in-depth	• The addition of the SAC drywell vent provides another vent pathway to protect the containment from over-pressure challenges, but the SAC wetwell vent reliability is already relatively high and containment integrity can only be assured with water addition to cool core debris and reduce drywell temperatures.
Containment temperature control	• No change from Base Case
Reliance on human actions	• Operator action is required to open the wetwell or drywell vent in accordance with plant EOP/SAGs
Instrumentation requirements	• Containment pressure is the only instrument required to support operator venting actions, regardless of vent pathway.

Consideration	Case 1A Implications
Release reduction	• Without water addition, releases will not be mitigated. The use of a SAC drywell vent will significantly reduce the amount of radionuclides and hydrogen released to the RB.
Hydrogen control	• Venting of the wetwell or drywell is effective in reducing containment pressure and releases hydrogen from the containment • Regardless of the number of vent paths, the lack of water will result in containment failure and release of hydrogen into the Reactor Building.

3.2 Cases with RPV Water Addition

The first set of accident management strategy alternatives considered involve strategies that include severe accident water addition (SAWA) directly to the RPV. The SAWA concept has been outlined in detail in NEI 13-02 [7], the industry guidance document for implementation of USNRC Order EA 13-109. The basic concept of SAWA involves the use of a portable pump to provide water addition during severe accident conditions, as depicted in Figure 3-4 below.

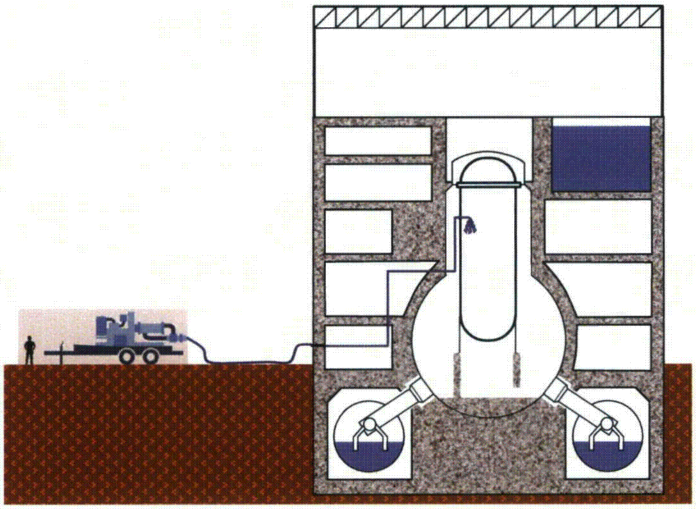

Figure 3-4
SAWA to RPV Concept

A total of 8 SAWA to the RPV cases are evaluated involving different combinations of accident management strategies:

- Case 2A - SAWA to RPV-No Drywell Vent
- Case 2B - RPV SAWM-No Drywell Vent
- Case 2C - SAWA to RPV-Vent Cycling-No Drywell Vent
- Case 2D - RPV SAWM-Vent Cycling-No Drywell Vent
- Case 2E - SAWA to RPV- with Drywell Vent
- Case 2F - RPV SAWM- with Drywell Vent

- Case 2G - SAWA to RPV-Vent Cycling- with Drywell Vent
- Case 2H - RPV SAWM-Vent Cycling- with Drywell Vent

3.2.1 Case 2A - SAWA to RPV-No Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident water addition (SAWA) to the RPV

A severe accident capable drywell vent is not available.

Quantitative Results – Case 2A

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 2A, the CDET associated with a plant without a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-5 provides a summary of the key quantitative results for this case.

Table 3-5
Summary Quantitative Results for Case 2A

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.3E-09/yr	$1,185,467

Figure 3-5 provides a graphical representation of the frequency contributions of various figures of merit within the analysis in a format called a Sankey diagram. The relative length of bars at each point in the graphic show the relative fraction of the frequency associated with each figure of merit. Since all core damage scenarios lead to an endstate in the APET, this visualization assists in understanding the relative contribution of different types of scenarios and releases contributing to the dominant APET endstates. This Sankey applies to Alternatives 2A through 2D and Alternatives 3A through 3D.

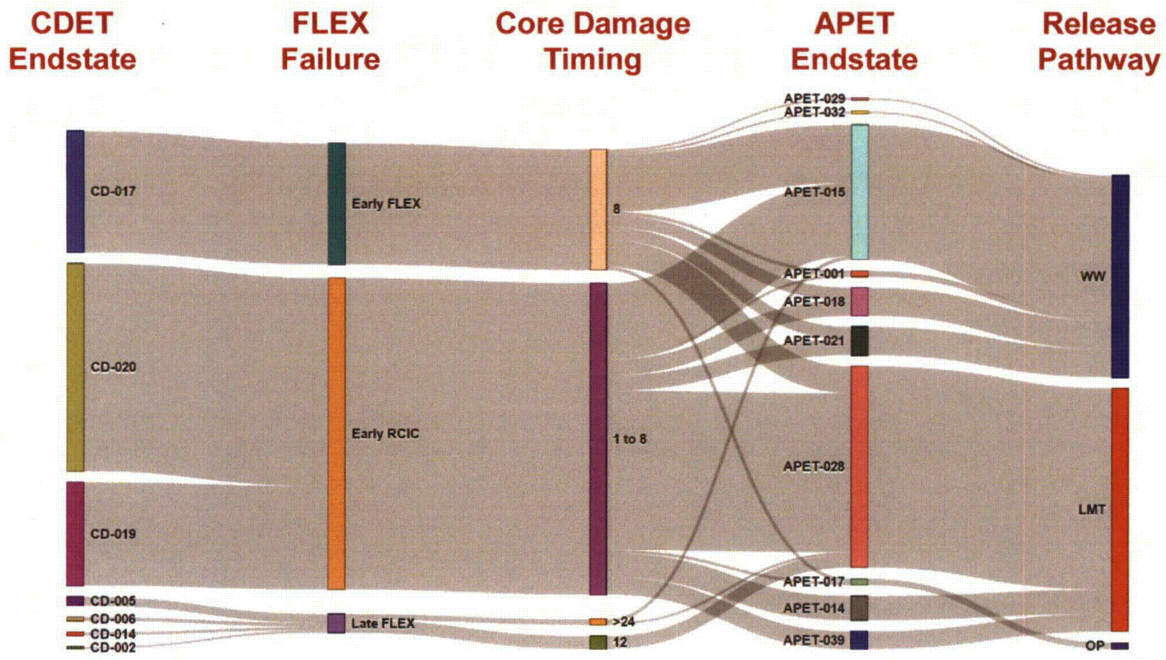

Figure 3-5
Sankey Diagram – Results Visualization for Alternatives 2A-2D and 3A-3D

Other Considerations – Case 2A

While quantitative metrics provide useful, objective characterization of the results, several other considerations are addressed for the Case 2A in the table below.

Table 3-6
Summary Assessment of Other Considerations for Case 2A

Consideration	Case 2A Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for cooling a damaged core within the RPV, thereby protecting the RPV as a fission product barrier.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the RPV. These actions will be taken in accordance with plant EOP/SAGs.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV and suppression pool water level indication are required for SAWA to the RPV.

Consideration	Case 2A Implications
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.
Hydrogen control	• Venting of the wetwell reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen.

3.2.2 Case 2B - RPV SAWM-No Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident water addition (SAWA) to the RPV
- Severe accident water management (SAWM) to maintain the wetwell vent path

A severe accident capable drywell vent is not available.

Quantitative Results – Case 2B

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 2B, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes a severe accident capable drywell vent is available.

Table 3-7 provides a summary of the key quantitative results for this case.

Table 3-7
Summary Quantitative Results for Case 2B

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.1E-09/yr	$1,139,870

Other Considerations – Case 2B

While quantitative metrics provide useful, objective characterization of the results, several other considerations are addressed for the Case 2B in the table below.

Table 3-8
Summary Assessment of Other Considerations for Case 2B

Consideration	Case 2B Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for cooling a damaged core within the RPV, thereby protecting the RPV as a fission product barrier.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell as well as attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent, align and control SAWA to the RPV, and limit suppression pool water level to maintain the WW vent. These actions will be taken in accordance with plant EOP/SAGs. • SAWM does not significantly impact operator work load since actions to reduce water addition rates are not required for many hours after SAWA initiation.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV level and suppression pool level are required for SAWA to the RPV. • SAWM does not require any additional instrumentation.
Release reduction	• Water addition reduces release magnitudes by cooling core debris as well as containment heat sinks. The reduced temperatures of containment heat sinks enhance natural deposition mechanisms. • SAWM avoids the need to open the drywell vent path which results in a small reduction in overall source terms.
Hydrogen control	• Venting of the wetwell reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing the extent of core concrete interaction and minimizing hydrogen and carbon monoxide generation.

3.2.3 Case 2C - SAWA to RPV-Vent Cycling-No Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident water addition (SAWA) to the RPV
- Cycling of the SAC wetwell vent.

A severe accident capable drywell vent is not available.

Quantitative Results – Case 2C

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-9 provides a summary of the key quantitative results for this case.

Table 3-9
Summary Quantitative Results for Case 2C

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.0E-09/yr	$1,117,028

Other Considerations – Case 2C

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 2C in the table below.

Table 3-10
Summary Assessment of Other Considerations for Case 2C

Consideration	Case 2C Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for cooling a damaged core within the RPV, thereby protecting the RPV as a fission product barrier.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell as well as attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the RPV. These actions will be taken in accordance with plant EOP/SAGs. • Operator action is required to open/close the WW vent in order to maintain containment pressure within the desired pressure control band.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV and suppression pool level indication are required for SAWA to the RPV.
Release reduction	• Water addition reduces release magnitudes by cooling core debris as well as containment heat sinks. The reduced temperatures of containment heat sinks enhance natural deposition mechanisms.

Consideration	Case 2C Implications
Hydrogen control	• Venting of the wetwell reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing the extent of core-concrete interaction and minimizing hydrogen and carbon monoxide generation. • Vent control maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal.

3.2.4 Case 2D - RPV SAWM-Vent Cycling-No Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident water addition (SAWA) to the RPV
- Severe accident water management (SAWM)
- Cycling of the SAC wetwell vent.

A severe accident capable drywell vent is not available.

Quantitative Results – Case 2D

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-11 provides a summary of the key quantitative results for this case.

Table 3-11
Summary Quantitative Results for Case 2D

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.1E-09/yr	$1,118,578

Other Considerations – Case 2D

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 2D in the table below.

Table 3-12
Summary Assessment of Other Considerations for Case 2D

Consideration	Case 2D Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for cooling a damaged core within the RPV, thereby protecting the RPV as a fission product barrier.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell as well as attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align, to control SAWA to the RPV, and to limit suppression pool water level to maintain the WW vent. These actions with be taken in accordance with plant EOP/SAGs. • SAWM does not significantly impact operator work load since actions to reduce water addition rates are not required for many hours after SAWA initiation. • Operator action is required to open/close the WW vent in order to maintain containment pressure within the desired pressure control band.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV and suppression pool water levels are required for SAWA to the RPV.SAWM does not require any additional instrumentation.
Release Reduction	• Water addition reduces release magnitudes by cooling core debris as well as containment heat sinks. The reduced temperatures of containment heat sinks enhance natural deposition mechanisms. • SAWM avoids the need to open the drywell vent path which results in a small reduction in overall source terms.
Hydrogen control	• Venting of the wetwell reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing the extent of core-concrete interaction and minimizing hydrogen and carbon monoxide generation. • Vent control maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal.

3.2.5 Case 2E - SAWA to RPV- with Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the RPV

Quantitative Results – Case 2E

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-13 provides a summary of the key quantitative results for this case.

Table 3-13
Summary Quantitative Results for Case 2E

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.1E-09/yr	$1,148,997

Figure 3-6 provides a graphical representation of the frequency contributions of various figures of merit within the analysis in a format called a Sankey diagram. The relative length of bars at each point in the graphic show the relative fraction of the frequency associated with each figure of merit. Since all core damage scenarios lead to an endstate in the APET, this visualization assists in understanding the relative contribution of different types of scenarios and releases contributing to the dominant APET endstates. This Sankey applies to Alternatives 2E through 2H and Alternatives 3E through 3H.

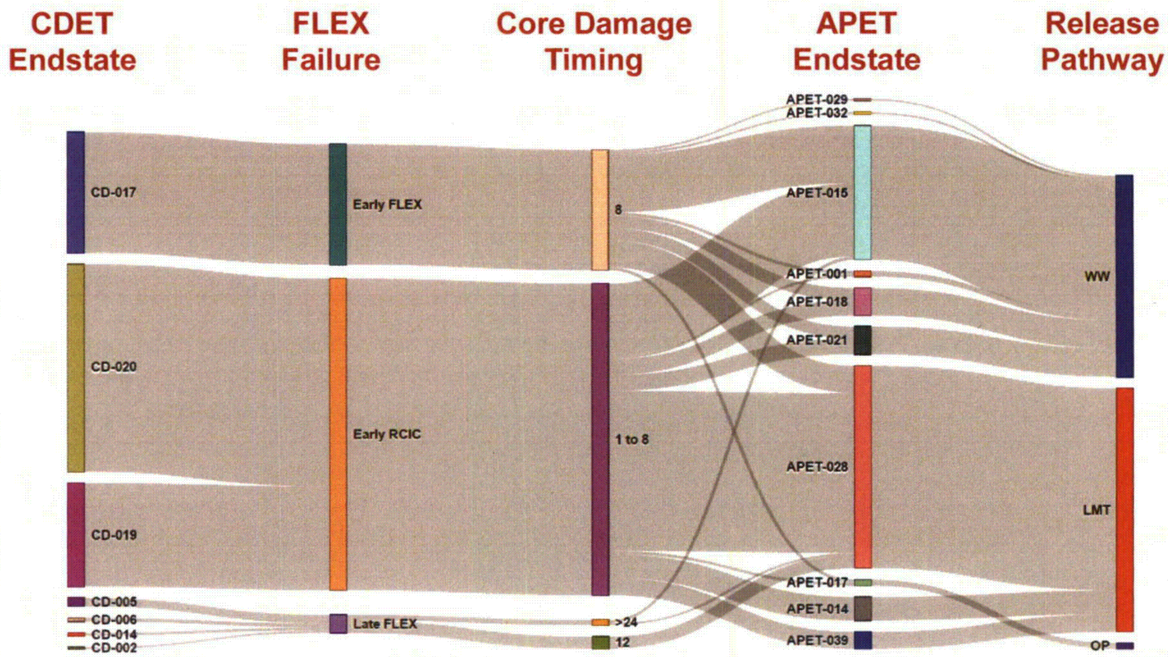

Figure 3-6
Sankey Diagram – Results Visualization for Alternatives 2E-2H and 3E-3H

Other Considerations – Case 2E

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 1A in the table below.

Table 3-14
Summary Assessment of Other Considerations for Case 2E

Consideration	Case 2E Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for addressing core damage in in-vessel, thereby protecting the RPV as a fission product barrier. • The availability of a SAC DW vent has a small incremental benefit in preventing containment overpressure failures. However, the reliability of the SAC WW vent is already quite high.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell/drywell vent and to align and control SAWA to the RPV. These actions with be taken in accordance with plant EOP/SAGs.

Consideration	Case 2E Implications
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV level and suppression pool water level are required for SAWA to the RPV.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment. • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • In this alternative, the DW vent has the following benefits for hydrogen control: o Avoiding exceedance of containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit may be gained from venting hydrogen directly from the drywell, although this benefit is beyond resolution of the analysis codes.

3.2.6 Case 2F - RPV SAWM- with Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the RPV
- Severe accident water management (SAWM) to maintain the wetwell vent path.

Quantitative Results – Case 2F

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-15 provides a summary of the key quantitative results for this case.

Table 3-15
Summary Quantitative Results for Case 2F

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.1E-09/yr	$1,149,640

Other Considerations – Case 2F

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 2F in the table below.

Table 3-16
Summary Assessment of Other Considerations for Case 2F

Consideration	Case 2F Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for addressing core damage in in-vessel, thereby protecting the RPV as a fission product barrier.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align, to control SAWA to the RPV, and to limit suppression pool water level to maintain the WW vent. These actions with be taken in accordance with plant EOP/SAGs. • SAWM does not significantly impact operator work load since actions to reduce water addition rates are not required for many hours after SAWA initiation.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV level and suppression pool level are required for SAWA to the RPV. • SAWM does not require any additional instrumentation.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms. • SAWM avoids the need to open the drywell vent path which results in a small reduction in overall source terms.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.2.7 Case 2G - SAWA to RPV-Vent Cycling- with Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the RPV
- Cycling of the SAC wetwell & drywell vent.

Quantitative Results – Case 2G

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-17 provides a summary of the key quantitative results for this case.

Table 3-17
Summary Quantitative Results for Case 2G

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.1E-09/yr	$1,131,161

Other Considerations – Case 2G

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 2G in the table below.

Table 3-18
Summary Assessment of Other Considerations for Case 2G

Consideration	Case 2G Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for addressing core damage in in-vessel, thereby protecting the RPV as a fission product barrier.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the RPV. These actions with be taken in accordance with plant EOP/SAGs. • Operator action is required to open/close the WW vent in order to maintain containment pressure within the desired pressure control band.

Consideration	Case 2G Implications
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV level and suppression pool water level are required for SAWA to the RPV.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • Vent control maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal. • In this alternative, there two hydrogen related benefits of the DW vent: o Avoiding exceeding containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.2.8 Case 2H - RPV SAWM-Vent Cycling- with Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the RPV
- Severe accident water management (SAWM)
- Cycling of the SAC wetwell & drywell vent.

A severe accident capable drywell vent is not available.

Quantitative Results – Case 2H

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-19 provides a summary of the key quantitative results for this case.

Table 3-19
Summary Quantitative Results for Case 2H

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.1E-09/yr	$1,131,911

Other Considerations – Case 2H

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 2H in the table below.

Table 3-20
Summary Assessment of Other Considerations for Case 2H

Consideration	Case 2H Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for addressing core damage in in-vessel, thereby protecting the RPV as a fission product barrier.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align, to control SAWA to the RPV, and to limit suppression pool water level to maintain the WW vent. These actions with be taken in accordance with plant EOP/SAGs. • SAWM does not significantly impact operator work load since actions to reduce water addition rates are not required for many hours after SAWA initiation. • Operator action is required to open/close the WW vent in order to maintain containment pressure within the desired pressure control band.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV level and suppression pool water level are required for SAWA to the RPV. • SAWM does not require any additional instrumentation.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms. • SAWM avoids the need to open the drywell vent path which results in a small reduction in overall source terms.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen.

Consideration	Case 2H Implications
	• Vent control maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal. • A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.3 Cases with DW Water Addition

The next set of accident management strategy alternatives considered involve strategies that include severe accident water addition (SAWA) to the drywell. The SAWA concept has been outlined in detail in NEI 13-02, the industry guidance document for implementation of USNRC Order EA 13-109. The basic concept of SAWA involves the use of a portable pump to provide water addition directly to the drywell during severe accident conditions, as depicted in Figure 3-7 below.

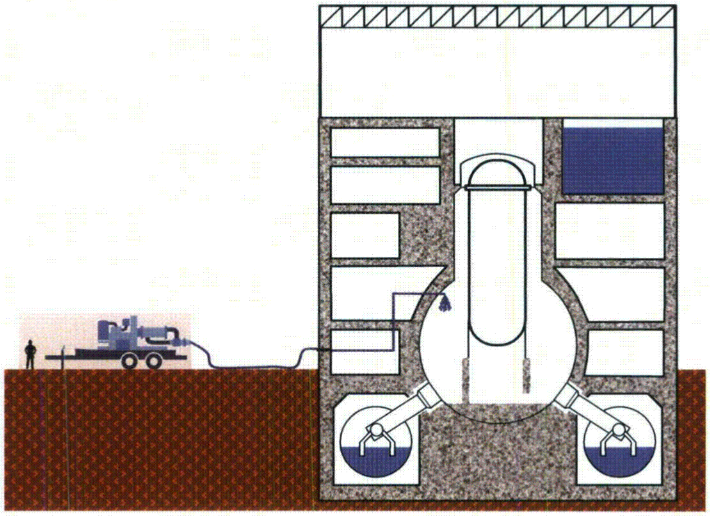

Figure 3-7
SAWA to Drywell Concept

A total of 8 SAWA to the RPV cases are evaluated involving different combinations of accident management strategies:

- Case 3A - SAWA to DW-No Drywell Vent
- Case 3B - DW SAWM-No Drywell Vent
- Case 3C - SAWA to DW-Vent Cycling-No Drywell Vent
- Case 3D - DW SAWM-Vent Cycling-No Drywell Vent
- Case 3E - SAWA to DW- with Drywell Vent
- Case 3F- DW SAWM- with Drywell Vent

- Case 3G - SAWA to DW-Vent Cycling- with Drywell Vent
- Case 3H - DW SAWM-Vent Cycling- with Drywell Vent

3.3.1 Case 3A - SAWA to DW-No Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident water addition (SAWA) to the drywell (DW)

A severe accident capable drywell vent is not available.

Quantitative Results – Case 3A

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available. Table 3-21 provides a summary of the key quantitative results for this case.

Table 3-21
Summary Quantitative Results for Case 3A

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.2E-09/yr	$1,149,492

Figure 3-8 provides a graphical representation of the frequency contributions of various figures of merit within the analysis in a format called a Sankey diagram. The relative length of bars at each point in the graphic show the relative fraction of the frequency associated with each figure of merit. Since all core damage scenarios lead to an endstate in the APET, this visualization assists in understanding the relative contribution of different types of scenarios and releases contributing to the dominant APET endstates.

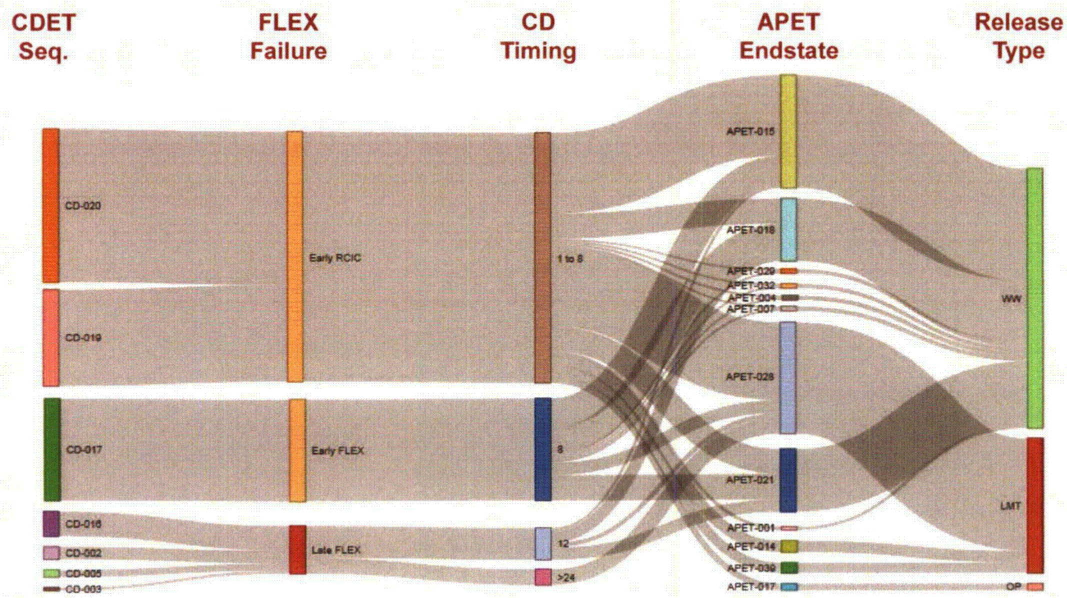

Figure 3-8
Sankey Diagram – Results Visualization for Case 3A

Other Considerations – Case 3A

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 3A in the table below.

Table 3-22
Summary Assessment of Other Considerations for Case 3A

Consideration	Case 3A Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Containment water level is required for SAWA to the DW.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.

Consideration	Case 3A Implications
Hydrogen control	• Venting of the wetwell reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen.

3.3.2 Case 3B - DW SAWM-No Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident water addition (SAWA) to the drywell (DW)
- Severe accident water management (SAWM) to maintain the wetwell vent path

A severe accident capable drywell vent is not available.

Quantitative Results – Case 3B

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-23 provides a summary of the key quantitative results for this case.

Table 3-23
Summary Quantitative Results for Case 3B

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.0E-09/yr	$1,106,782

Other Considerations – Case 3B

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 3B in the table below.

Table 3-24
Summary Assessment of Other Considerations for Case 3B

Consideration	Case 3B Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.

Consideration	Case 3B Implications
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs. • SAWM does not significantly impact operator work load since actions to reduce water addition rates are not required for many hours after SAWA initiation.
Instrumentation requirements	• Containment pressure is required to support operator. venting actions. • Containment water level is required for SAWA to the DW. • SAWM does not require any additional instrumentation.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.
Hydrogen control	• Venting of the wetwell reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen.

3.3.3 Case 3C - SAWA to DW-Vent Cycling-No Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident water addition (SAWA) to the drywell (DW)
- Cycling of the SAC wetwell vent.

A severe accident capable drywell vent is not available.

Quantitative Results – Case 3C

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-25 provides a summary of the key quantitative results for this case.

Table 3-25
Summary Quantitative Results for Case 3C

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.0E-09/yr	$1,097,325

Other Considerations – Case 3C

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 3C in the table below.

Table 3-26
Summary Assessment of Other Considerations for Case 3C

Consideration	Case 3C Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs. • Operator action is required to open/close the WW vent in order to maintain containment pressure within the desired pressure control band.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Suppression pool water level is required for SAWA to the DW.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.
Hydrogen control	• Venting of the wetwell reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • Vent control maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal.

3.3.4 Case 3D - DW SAWM-Vent Cycling-No Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident water addition (SAWA) to the drywell (DW)
- Severe accident water management (SAWM)
- Cycling of the SAC wetwell vent.

A severe accident capable drywell vent is not available.

Quantitative Results – Case 3D

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-27 provides a summary of the key quantitative results for this case.

Table 3-27
Summary Quantitative Results for Case 3D

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.0E-09/yr	$1,098,251

Other Considerations – Case 3D

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 3D in the table below.

Table 3-28
Summary Assessment of Other Considerations for Case 3D

Consideration	Case 3D Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs. • SAWM does not significantly impact operator work load since actions to reduce water addition rates are not required for many hours after SAWA initiation. • Operator action is required to open/close the WW vent in order to maintain containment pressure within the desired pressure control band.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Suppression pool level is required for SAWA to the DW. • SAWM does not require any additional instrumentation.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.

Consideration	Case 3D Implications
Hydrogen control	• Venting of the wetwell reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • Vent control maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal.

3.3.5 Case 3E - SAWA to DW- with Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the drywell (DW)

Quantitative Results – Case 3E

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-29 provides a summary of the key quantitative results for this case.

Table 3-29
Summary Quantitative Results for Case 3E

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.54	2.1E-09/yr	$1,123,236

Other Considerations – Case 3E

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 3E in the table below.

Table 3-30
Summary Assessment of Other Considerations for Case 3E

Consideration	Case 3E Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • The availability of a SAC DW vent has a small incremental benefit in preventing containment overpressure failures. However, the reliability of the SAC WW vent is already quite high.

Consideration	Case 3E Implications
Containment temperature control	• Although not as effective as water addition to the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell/drywell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Suppression pool level is required for SAWA to the DW.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment. • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • In this alternative, there two hydrogen related benefits of the DW vent: o Avoiding exceeding containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.3.6 Case 3F- DW SAWM- with Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the drywell (DW)
- Severe accident water management (SAWM) to maintain the wetwell vent path.

Quantitative Results – Case 3F

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-31 provides a summary of the key quantitative results for this case.

Table 3-31
Summary Quantitative Results for Case 3F

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.54	2.1E-09/yr	$1,111,227

Other Considerations – Case 3F

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 3F in the table below.

Table 3-32
Summary Assessment of Other Considerations for Case EF

Consideration	Case 3F Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs. • SAWM does not significantly impact operator work load since actions to reduce water addition rates are not required for many hours after SAWA initiation.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Containment water level is required for SAWA to the DW. • SAWM does not require any additional instrumentation.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment. • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.3.7 Case 3G - SAWA to DW-Vent Cycling- with Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the drywell (DW)
- Cycling of the SAC wetwell & drywell vent.

Quantitative Results – Case 3G

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-33 provides a summary of the key quantitative results for this case.

Table 3-33
Summary Quantitative Results for Case 3G

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.54	2.0E-09/yr	$1,101,272

Other Considerations – Case 3G

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 3G in the table below.

Table 3-34
Summary Assessment of Other Considerations for Case 3G

Consideration	Case 3G Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs. • Operator action is required to open/close the WW vent in order to maintain containment pressure within the desired pressure control band.

Consideration	Case 3G Implications
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Suppression pool water level is required for SAWA to the DW.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment. • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • Vent control maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal. • In this alternative, there two hydrogen related benefits of the DW vent: o Avoiding exceeding containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.3.8 Case 3H - DW SAWM-Vent Cycling- with Drywell Vent

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the drywell (DW)
- Severe accident water management (SAWM)
- Cycling of the SAC wetwell & drywell vent.

Quantitative Results – Case 3H

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-35 provides a summary of the key quantitative results for this case.

Table 3-35
Summary Quantitative Results for Case 3H

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.54	2.0E-09/yr	$1,100,909

Other Considerations – Case 3H

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 3H in the table below.

Table 3-36
Summary Assessment of Other Considerations for Case 3H

Consideration	Case 3H Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs. • SAWM does not significantly impact operator work load since actions to reduce water addition rates are not required for many hours after SAWA initiation. • Operator action is required to open/close the WW vent in order to maintain containment pressure within the desired pressure control band.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Suppression pool level is required for SAWA to the DW. • SAWM does not require any additional instrumentation.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment. • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.4 Cases with Small Engineered Filters

The next set of accident management strategy alternatives considered involve strategies that include a small engineered filter. A small engineered filter has the advantage of requiring a smaller engineering footprint for the filter building while providing comparable fission product retention effectiveness as the larger filters. The tradeoff is that the small filter has a limited capacity for aerosol loadings and decay heat that, in some scenarios, can be exceeded. The basic concept for the small filter is depicted in Figure 3-9 below.

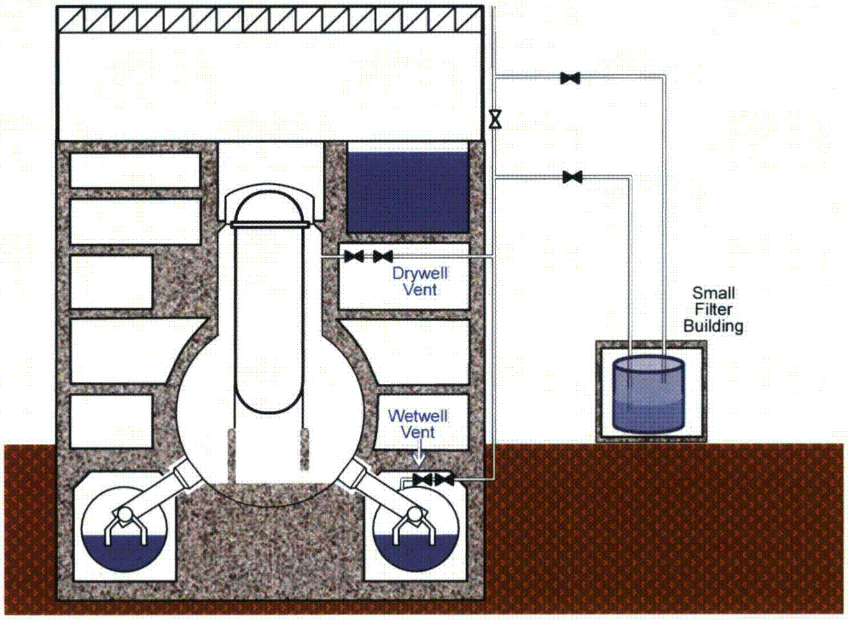

Figure 3-9
Vent Configuration with Small Engineered Filter

Two small engineered filter alternatives were investigated:

- Case 4A - SAWA to RPV-Small Filter
- Case 4B - SAWA to Drywell-Small Filter

3.4.1 Case 4A - SAWA to RPV-Small Filter

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the RPV
- Small engineered filter capable of being manually aligned to the wetwell or drywell vent path

Quantitative Results – Case 4A

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a

plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-37 provides a summary of the key quantitative results for this case.

Table 3-37
Summary Quantitative Results for Case 4A

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.0E-09/yr	$1,105,137

Other Considerations – Case 4A

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 4A in the table below.

Table 3-38
Summary Assessment of Other Considerations for Case 4A

Consideration	Case 4A Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for addressing core damage in in-vessel, thereby protecting the RPV as a fission product barrier.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the RPV. These actions with be taken in accordance with plant EOP/SAGs. • Operator action is required prior to use of the filter and after many hours after initiation to maintain filter effectiveness
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV level and suppression pool water level are required for SAWA to the RPV.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms. • The small filter is sufficiently large to capture radionuclides, except in the unlikely scenarios where the wetwell vent is not initially available.

Consideration	Case 4A Implications
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • The presence of a filter on the vent pathways maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal. • In this alternative, there two hydrogen related benefits of the DW vent: o Avoiding exceeding containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.4.2 Case 4B - SAWA to DW-Small Filter

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the drywell (DW)
- Small engineered filter capable of being manually aligned to the wetwell or drywell vent path

Quantitative Results – Case 4B

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-39 provides a summary of the key quantitative results for this case.

Table 3-39
Summary Quantitative Results for Case 4B

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.54	2.0E-09/yr	$1,102,548

Other Considerations – Case 4B

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 4B in the table below.

Table 3-40
Summary Assessment of Other Considerations for Case 4B

Consideration	Case 4B Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Containment water level is required for SAWA to the DW.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms. • The small filter is sufficiently large to capture radionuclides, except in the unlikely scenarios where the wetwell vent is not initially available.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • The presence of a filter on the vent pathways maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal. • In this alternative, there two hydrogen related benefits of the DW vent: o Avoiding exceeding containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.5 Cases with Large Engineered Filters

The next set of accident management strategy alternatives considered involve strategies that include a large engineered filter. The large engineered filter has the advantage of being designed for a larger aerosol loading and decay heat load. It does, however, require a substantially larger

engineering footprint for the filter building. The basic concept for the large filter is depicted in Figure 3-10 below.

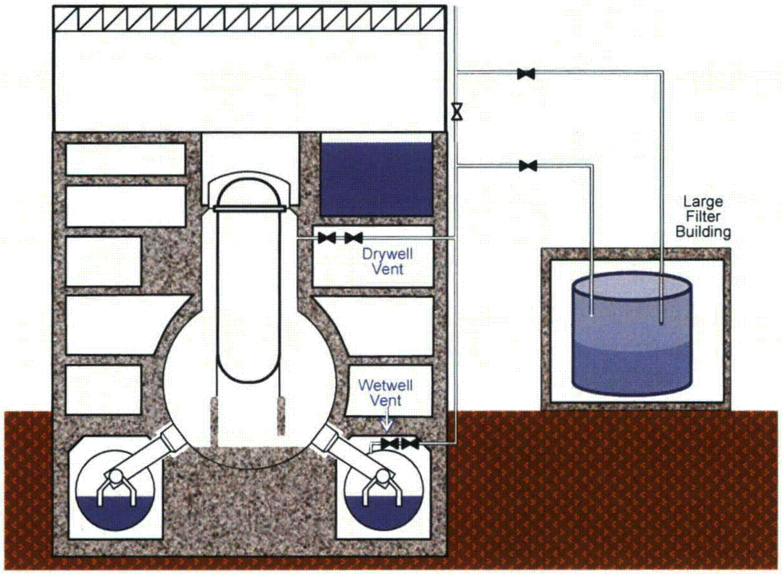

Figure 3-10
Vent Configuration with Large Engineered Filter

Consistent with the small filter alternatives, two large engineered filter alternatives were investigated:

- Case 5A - SAWA to RPV-Large Filter
- Case 5B - SAWA to Drywell-Large Filter

3.5.1 Case 5A - SAWA to RPV-Large Filter

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the RPV
- Large engineered filter capable of being manually aligned to the wetwell or drywell vent path

Quantitative Results – Case 5A

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is.

Table 3-41 provides a summary of the key quantitative results for this case.

Table 3-41
Summary Quantitative Results for Case 5A

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.55	2.0E-09/yr	$1,103,683

Other Considerations – Case 5A

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 5A in the table below.

Table 3-42
Summary Assessment of Other Considerations for Case 5A

Consideration	Case 5A Implications
Defense-in-depth	• Water addition to the RPV, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth. • Water addition to the RPV also increases the potential for addressing core damage in in-vessel, thereby protecting the RPV as a fission product barrier.
Containment temperature control	• Water addition via the RPV, prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the RPV. These actions with be taken in accordance with plant EOP/SAGs. • Operator action is required prior to use of the filter and after many hours after initiation to maintain filter effectiveness
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • RPV level and suppression pool water level are required for SAWA to the RPV.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms. • The large filter is sufficiently large to capture radionuclides in all scenarios where the vent pathway is the containment release pathway.

Consideration	Case 5A Implications
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • The presence of a filter on the vent pathways maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal. • In this alternative, there two hydrogen related benefits of the DW vent: o Avoiding exceeding containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.5.2 Case 5B - SAWA to DW-Large Filter

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the drywell (DW)
- Large engineered filter capable of being manually aligned to the wetwell or drywell vent path

Quantitative Results – Case 5B

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-43 provides a summary of the key quantitative results for this case.

Table 3-43
Summary Quantitative Results for Case 5B

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.54	2.0E-09/yr	$1,096,719

Other Considerations – Case 5B

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 5B in the table below.

Table 3-44
Summary Assessment of Other Considerations for Case 5B

Consideration	Case 5B Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent and to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs.
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Containment water level is required for SAWA to the DW.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms. • The large filter is sufficiently large to capture radionuclides in all scenarios where the vent pathway is the containment release pathway.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • The presence of a filter on the vent pathways maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal. • In this alternative, there two hydrogen related benefits of the DW vent: o Avoiding exceeding containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.6 Cases with Large Engineered Filters & Rupture Disc

The next set of accident management strategy alternatives considered involve strategies that include a large engineered filter with passive features. These cases involve a large engineered filter that has a rupture disc in the vent pathway, rather than just valves. Two "passive" configurations were evaluated. The first is a totally passive filter pathway, shown in Figure 3-11,

that would not require operator action to align. This alternative, Case 6A, was investigated to characterize the potential benefits of a passive containment venting system. Consequently, no operator actions were credited for opening any vent pathway, prior to or after core damage.

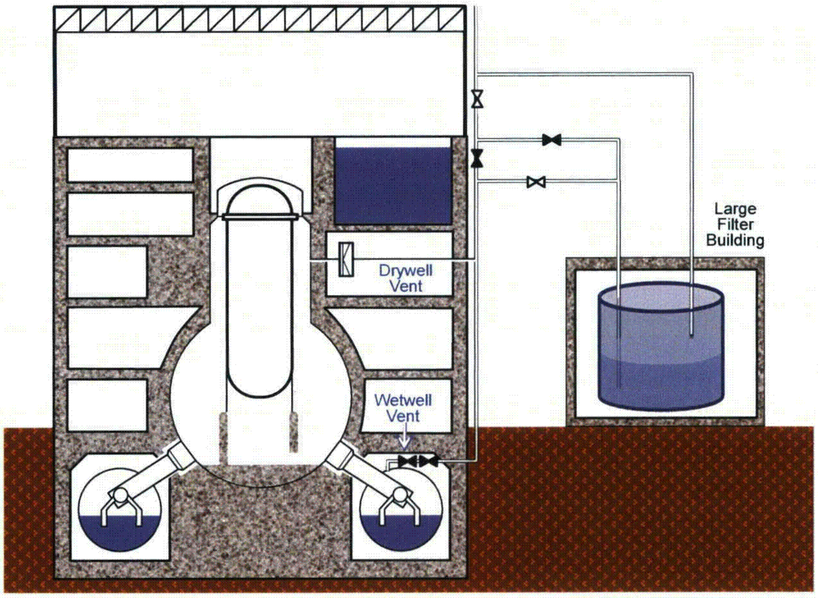

Figure 3-11
Vent Configuration with Large Engineered Passive Filter and Rupture Disc

The second involves a passive filter pathway that can be manually aligned by plant operators, as shown in Figure 3-12. This alternative, Case 6B, credits operator actions for opening any vent pathway prior to core damage but relies upon the passive vent pathway after core damage.

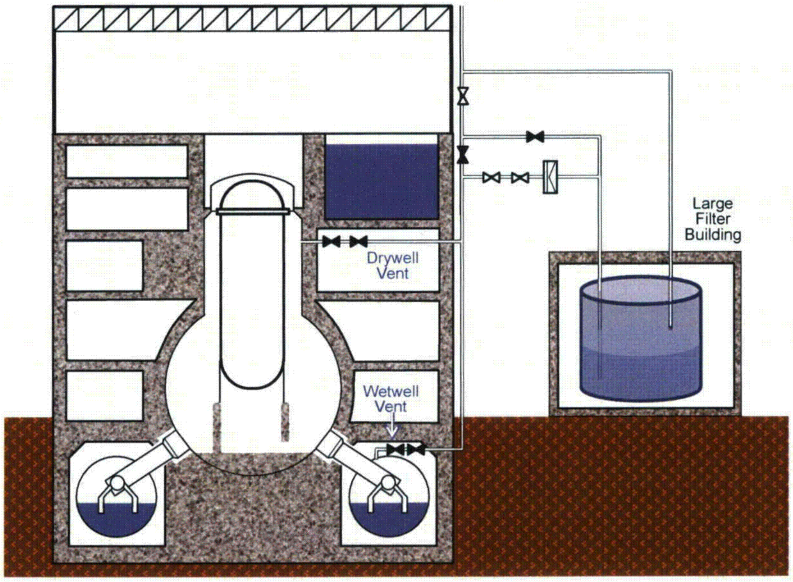

Figure 3-12
Vent Configuration with Manual Vent Large Engineered Filter and Rupture Disc

3.6.1 Case 6A - SAWA to DW-Passive Filter

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the RPV
- Large engineered filter that is passively actuated on vent path

Quantitative Results – Case 6A

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-45 provides a summary of the key quantitative results for this case.

Table 3-45
Summary Quantitative Results for Case 6A

CDF	CCFP	LCF Risk	MACR
7.6E-06/yr	0.48	1.9E-09/yr	$1,071,405

Other Considerations – Case 6A

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 6A in the table below.

Table 3-46
Summary Assessment of Other Considerations for Case 6A

Consideration	Case 6A Implications
Defense-in-depth	• The totally passive nature of the vent pathway precludes anticipatory venting to preserve RCIC operation. This leads to an increase in core damage frequency. • Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• No operator action is required to open the containment vent. • Operator action is required to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs.

Consideration	Case 6A Implications
	• Operator action is required prior to use of the filter and after many hours after initiation to maintain filter effectiveness
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Suppression pool water level is required for SAWA to the DW.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms. • The large filter is sufficiently large to capture radionuclides in all scenarios where the vent pathway is the containment release pathway.
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • The presence of a filter on the vent pathways maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal. • In this alternative, there two hydrogen related benefits of the DW vent: o Avoiding exceeding containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.6.2 Case 6B - SAWA to DW-Pre-CD Manual Filter

This alternative assumes that the hardware and procedures are available to support implementation of the following capabilities beyond the Base Case:

- Severe accident capable drywell vent
- Severe accident water addition (SAWA) to the drywell (DW)

Large engineered filter that is passively actuated on vent path following core damage. Prior to core damage, operators manually align a filter bypass pathway. This bypass pathway must be isolated prior to core damage in order for the large filter to passively actuate.

Quantitative Results – Case 6B

The quantitative APET results are predicated on the results of the core damage event tree (CDET) for the corresponding core damage state. For Case 1A, the CDET associated with a

plant with a severe accident capable drywell vent are used. This corresponds with the APET quantification that also assumes that a severe accident capable drywell vent is available.

Table 3-47 provides a summary of the key quantitative results for this case.

Table 3-47
Summary Quantitative Results for Case 6B

CDF	CCFP	LCF Risk	MACR
7.3E-06/yr	0.52	2.0E-09/yr	$1,093,421

Other Considerations – Case 6B

While quantitative metrics provide a useful, objective characterization of the results, several other considerations are addressed for the Case 6B in the table below.

Table 3-48
Summary Assessment of Other Considerations for Case 6B

Consideration	Case 6B Implications
Defense-in-depth	• Water addition to the DW, in combination with the SACV, helps protect the containment from over-pressure and over-temperature challenges, thereby increasing defense in depth.
Containment temperature control	• Although not as effective as water addition via the RPV, water addition to the DW prevents heat up of the drywell and prevents attack of the drywell shell by core debris. • Drywell temperatures are maintained below 545°F.
Reliance on human actions	• Operator action is required to open the wetwell vent prior to core damage and to isolate any open vent pathways in order to enable the passive vent post-core damage. • No operator action is required to open the containment vent. • Operator action is required to align and control SAWA to the DW. These actions with be taken in accordance with plant EOP/SAGs. • Operator action is required prior to use of the filter and after many hours after initiation to maintain filter effectiveness
Instrumentation requirements	• Containment pressure is required to support operator venting actions. • Containment water level is required for SAWA to the DW.
Release reduction	• Water addition reduces release magnitudes by cooling core debris and by reducing the temperatures of containment heat sinks thereby enhancing natural deposition mechanisms. • The large filter is sufficiently large to capture radionuclides in all scenarios where the vent pathway is the containment release pathway.

Consideration	Case 6B Implications
Hydrogen control	• Venting of the containment reduces containment pressure and releases hydrogen from the containment • Water addition can quench core debris, thereby reducing core concrete interaction and minimizing hydrogen. • The presence of a filter on the vent pathways maintains containment pressure at a slightly more elevated pressure, thus increasing the potential for hydrogen leakage into the Reactor Building. However, the containment is maintained well below design pressure so leakage should be minimal. • In this alternative, there two hydrogen related benefits of the DW vent: o Avoiding exceeding containment pressure limits once the WW vent is lost. This prevents leakage from the drywell head or other containment seals directly into the Reactor Building. o A small benefit is probably gained from venting hydrogen directly from the drywell, although this benefit is beyond the level of detail of the analysis codes.

3.7 Summary of Results

The quantitative results of the 24 alternatives are summarized in Table 3-49. This table also includes the calculation of the change in Maximum Averted Cost Risk (ΔMACR). The ΔMACR would be used to compare the cost of implementation in order to judge the cost-benefit of an alternative. Such a comparison is beyond the scope of this report.

A summary of the insights on the other considerations identified in the evaluation is provided in Table 3-50 in terms of the incremental changes in the considerations between strategies.

Table 3-49
Summary of CDET/APET

Description of Alternative	CDF (/yr)	CCFP	LCF Risk (/yr)	MACR	ΔMACR
Base Case - No SAWA-No DWV	7.3E-06/yr	0.99	3.71E-09	$1,912,926	n/a
Case 1A - No SAWA-DWV	7.3E-06/yr	0.99	3.71E-09	$1,919,659	n/a
Case 2A - RPV SAWA-No DWV	7.3E-06/yr	0.55	2.26E-09	$1,185,467	$727,459
Case 2B - RPV SAWM-No DWV	7.3E-06/yr	0.55	2.09E-09	$1,139,870	$773,057
Case 2C - RPV SAWA-VC-No DWV	7.3E-06/yr	0.55	2.05E-09	$1,117,028	$795,898
Case 2D - RPV SAWM-VC-No DWV	7.3E-06/yr	0.55	2.05E-09	$1,118,578	$794,348
Case 2E - RPV SAWA-DWV	7.3E-06/yr	0.55	2.11E-09	$1,148,997	$770,662
Case 2F - RPV SAWM-DWV	7.3E-06/yr	0.55	2.11E-09	$1,149,640	$770,019
Case 2G - RPV SAWA-VC-DWV	7.3E-06/yr	0.55	2.07E-09	$1,131,161	$788,498
Case 2H - RPV SAWM-VC-DWV	7.3E-06/yr	0.55	2.07E-09	$1,131,911	$787,748
Case 3A - DW SAWA-No DWV	7.3E-06/yr	0.55	2.21E-09	$1,149,492	$763,434
Case 3B - DW SAWM-No DWV	7.3E-06/yr	0.55	2.05E-09	$1,106,782	$806,144
Case 3C - DW SAWA-VC-No DWV	7.3E-06/yr	0.55	2.00E-09	$1,097,325	$815,602
Case 3D - DW SAWM-VC-No DWV	7.3E-06/yr	0.55	2.01E-09	$1,098,251	$814,675
Case 3E - DW SAWA-DWV	7.3E-06/yr	0.54	2.08E-09	$1,123,236	$796,424
Case 3F - DW SAWM-DWV	7.3E-06/yr	0.54	2.06E-09	$1,111,227	$808,432
Case 3G - DW SAWA-VC-DWV	7.3E-06/yr	0.54	2.04E-09	$1,101,272	$818,387
Case 3H - DW SAWM-VC-DWV	7.3E-06/yr	0.54	2.02E-09	$1,100,909	$818,750
Case 4A - RPV SAWA-Small Filter	7.3E-06/yr	0.55	1.97E-09	$1,105,137	$807,790
Case 4B - DW SAWA-Small Filter	7.3E-06/yr	0.54	1.99E-09	$1,102,548	$810,378
Case 5A - RPV SAWA-Large Filter	7.3E-06/yr	0.55	1.96E-09	$1,103,683	$809,243
Case 5B - DW SAWA-Large Filter	7.3E-06/yr	0.54	1.97E-09	$1,096,719	$816,208
Case 6A - DW SAWA-Passive Filter	7.6E-06/yr	0.48	1.93E-09	$1,071,405	$841,521
Case 6B - DW SAWA-Manual Filter	7.3E-06/yr	0.52	1.97E-09	$1,093,421	$819,505

Table 3-50
Incremental Impact of Strategies on Other Considerations

Consideration	SAWA	SAWM	Vent Cycling	Large Eng. Filter	Small Eng. Filter
Defense-in-Depth	Preserves containment boundary SAWA to RPV can preserve RPV barrier	None	None	Fully passive vent increases core damage risk	None
Containment Temperature Control	SAWA to RPV greatest benefit SAWA to DW also effective	None	None	None	None
Reliance on Human Actions	Operator action required to align and initiate SAWA	Operator monitoring and control required after many hours	Operator monitoring and valve control required	Filter operation requires operator actions prior to use and after many hours	Filter operation requires operator actions prior to use and after many hours
Instrumentation Requirements	Containment pressure Suppression pool level RPV level for SAWA to RPV	No additional	No additional	Filter monitoring instrumentation	Filter monitoring instrumentation
Release Reduction	Cools heat sinks and captures radionuclides	Avoids need for DW vent	Increases residence time to allow natural filtering mechanisms to be effective	Effective for specific scenarios already benefiting from other strategies	Effective for specific scenarios already benefiting from other strategies Effectiveness reduced for DW vent only scenarios
Hydrogen Control	Quenches core debris	None	Slightly increased containment pressure	Slightly increased containment pressure due to filter	Slightly increased containment pressure due to filter

4 INVESTIGATION OF RESULTS SENSITIVITIES

Severe accident scenario risks are known to be subject to significant model uncertainties. Quantitative uncertainty propagation was not performed due to the large model uncertainties that overwhelm the parametric uncertainties. Instead, sensitivity investigations were performed to investigate robustness of the baseline analysis with respect to the following areas of model uncertainty:

- Plant-to-plant variability across the Mark I Fleet
- Risk model uncertainties
- Severe accident phenomenological uncertainties
- Consequence Model Assumptions

Some of these sensitivities were considered qualitatively. Others were investigated through the requantification of the baseline model with different input assumptions. In cases where there are quantitative evaluations made, the focus is on four representative cases:

- Base Case - No Severe Accident Water Addition (SAWA)
- Case 2A – SAWA to the RPV
- Case 3A - SAWA to the DW SAWA
- Case 5B - SAWA to the DW with Large Engineered Filter

In general, quantitative impacts are considered in sensitivity studies and are focused on three primary metrics, listed below:

- Latent Cancer Fatality Risk
- Maximum Averted Cost Risk (MACR)
- Change in MACR versus the Base Case (ΔMACR)

4.1 Plant-to-plant Variability

While the use of a reference plant is effective and efficient to limit the number of analyses required, it raises the question of the applicability of the results to the rest of the fleet of BWR Mark Is. At the request of the NRC, the BWROG performed a survey to collect plant-specific parameters that could influence the severe accident behavior of U.S. Mark I plants. As stated previously, Peach Bottom was selected as the reference Mark I plant for the EPRI technical analysis. The survey data included information in the following general categories:

- Containment Design Parameters (e.g. design pressure/temperature, free volumes, floor area)
- Containment Elevations and Volume (e.g. drywell spillover height to vents, torus freeboard volume up to isolation of vent)
- Containment Vent Design (e.g. diameter, loss coefficient)
- Containment Spray System Information (not used in EPRI technical analysis)
- Drywell Head Seal Details (EPRI analysis assumed SOARCA leakage model)
- Pedestal/Drywell Sump Geometry (e.g. volume)
- SRV Capacities

The plant data was reviewed to determine if there could be variations that would influence the overall conclusions from the CPRR technical analysis. Based on the results presented in Section 5 of this report, there is considerable margin in the calculated maximum averted cost risk, and plant-to-plant variations would not be expected to significantly influence the overall conclusion. Some of the potential plant variations were investigated further to confirm that the overall conclusions using the reference plant would be applicable to the other Mark I plants. The following sections outline the data review and its potential impact on the CPRR technical analysis:

- Section 4.1.1 – Containment Heat Capacity
- Section 4.1.2 – Torus Freeboard Volume
- Section 4.1.3 – DW to WW Spillover Height
- Section 4.1.4 – Surrounding Population

4.1.1 Containment Heat Capacity

The ratio of the core power to the containment free volume is a standard indication of the capacity of the plant to cope with an accident involving loss of containment heat removal. Reviewing the containment free volume data for the Mark I plants from the survey data and using the licensed power from www.nrc.gov yields a range of approximately 6 to 13 kilowatts/cubic feet. A smaller value would tend to indicate that accidents with loss of containment heat removal, such as an ELAP, would progress more slowly compared to plants with a higher power to volume ratio. The reference plant selected for the EPRI technical analysis represents the upper end of the range at 13 kilowatts/cubic feet and should provide for margin when compared to all other Mark I plants.

4.1.2 Torus Freeboard Volume

Based on the current severe accident guidance, the wetwell is the preferred venting pathway. Following the instructions in the guidance, containment flooding to the minimum debris submergence level (MDSL) commences after vessel breach has been detected. The MDSL is 4 feet above the drywell floor, which would eventually result in filling the torus with water.

As the water level is increased in the torus, the operator will be required to close the wetwell vent prior to water entering the vent pipe. For some plants, the isolation elevation is based on the physical location of the vent, but for others it is based on the limiting operating range for the torus level instrumentation. Reviewing the plant specific data, the elevation that requires isolation of the wertwell vent varies from 16 to 30 feet above the bottom of the torus. This equates to an additional water volume ranging from 300,000 to almost 1,000,000 gallons. At a flooding of rate of 500 gpm, the time to reach a water elevation requiring isolation of the wetwell vent would vary from 11 to 32 hours. These results indicate the following with regard to wetwell vent isolation:

- There is a significant amount of time before the operator would be required to isolate the wetwell vent
- Water level is changing slowly, providing the operator with ample time to realize that an action needs to be taken
- The torus freeboard volume to require wetwell vent isolation varies from 300,000 to almost 1,000,000 gallons of water

4.1.3 DW to WW Spillover Height

As water is added either to the RPV or directly to the drywell after core debris is discharged onto the containment floor, the water will accumulate up until it begins to spill over into the drywell-to-wetwell vents. The available plant specific data reveals that this spillover height ranges from 0.62 to 3 feet (7.4 - 36 inches) above the drywell floor. Figure 4-1 displays a histogram of the available spillover heights.

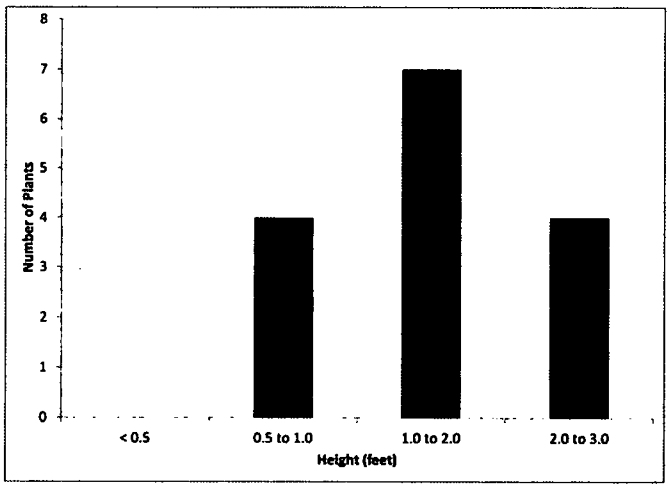

Figure 4-1
Histogram of Spillover Heights

With core debris on the drywell floor, the objective of water addition (SAWA) is to limit the thermal challenges to the drywell due to either liner melt through or direct thermal radiation. These spillover heights are judged to allow sufficient wetting of the debris surface to develop a crust on the upper surface of the debris, thereby limiting the potential for either of these challenges. In addition, any steam generated at the core debris-water interface combined with any airborne aerosols above the debris will significantly reduce thermal radiation from the debris surface and limit the thermal challenge to the drywell.

4.1.4 Surrounding Population

An important input into the off-site consequence analysis is the population within 50 miles of the site. Cumulative population data for all Mark I plant sites was compiled and plotted in Figure 4-2[3]. Note that the CPRR reference plant (i.e., SOARCA BWR plant) represents the upper range for population and is shown as the second largest population site among all Mark I plants. As a way to investigate the sensitivity to a larger surrounding population, an increase in the reference plant population of 30% was chosen to bound the Mark I BWR with the largest 50-mile total population. All other consequence parameters remained the same for this sensitivity.

Alternative 2A was selected to represent this sensitivity which includes severe accident water addition to the RPV. Two of the dominant APET end states were selected as defined by:

> CDET019APET018: RCIC fails early, Operator depressurized RPV, FLEX unavailable late, water addition to RPV, wetwell venting
>
> CDET019APET028: RCIC fails early, Operator depressurizes RPV, FLEX unavailable late, no water addition and LMT at the time of vessel breach

Exercising MACCS for these 2 sequences and assuming a 30% increase in the 50 mile population yields a less than 1% increase in the 10 mile latent cancer fatality risk.

[3] Population values based on SECPOP 4.2 calculations using 2010 US Census data.

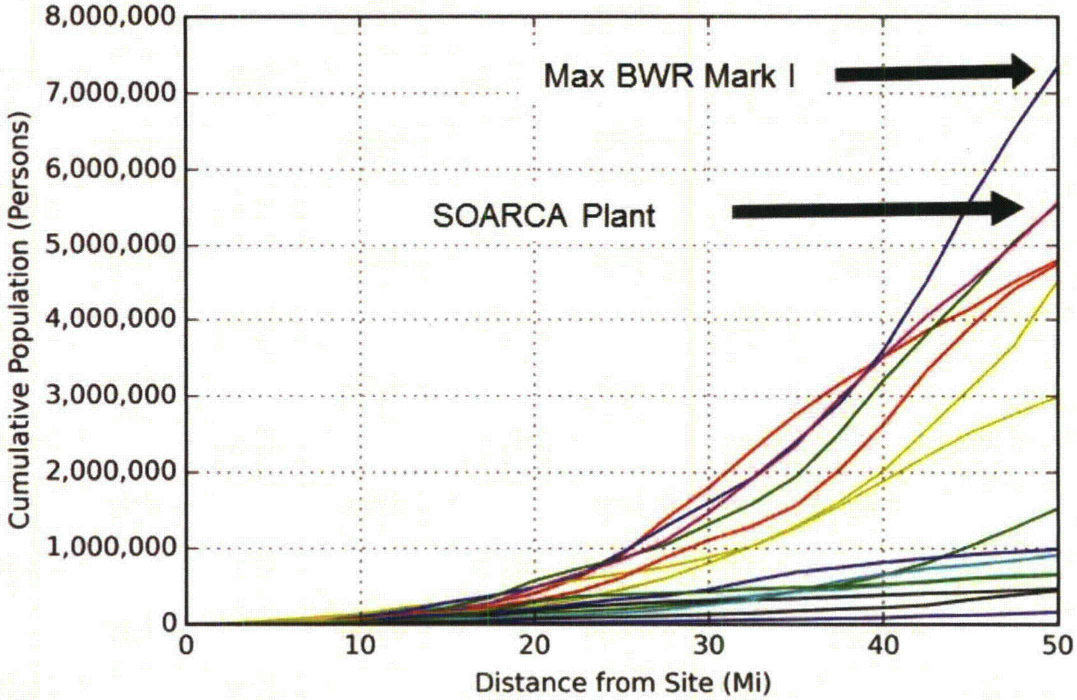

Figure 4-2
Mark I Site Population vs. Distance

4.2 Logic Model Uncertainties

4.2.1 ELAP Frequency

The frequency of an extended loss of AC power (ELAP) is an important input into the risk model since it is the starting point for the analysis. The relationship between assumed ELAP frequency and risk results was investigated for the four primary cases (Base Case and Alternatives 2A, 3A, and 5B) and for the LCF, MACR and ΔMACR risk metrics. The sensitivity of the analysis to ELAP frequency variability was evaluated for each of these cases assuming a factor of 3 increase and decrease in the initiating event frequency.

As shown in Figures 4-3, 4-4, and 4-5, the risk results vary linearly with the assumed ELAP frequency and the LCF results remain far below the QHO level. The maximum credible change is on the order of a factor of 3, given that there is no evidence that ELAP core damage frequencies are greater than the CDF quantitative objective of 1E-4/yr.

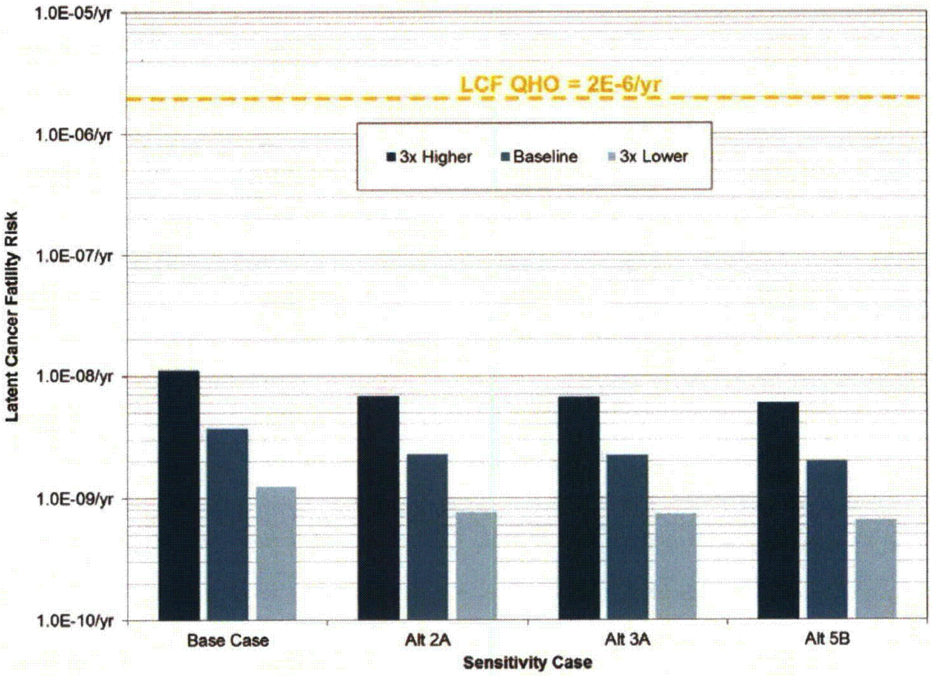

Figure 4-3
Latent Cancer Risk Sensitivity to ELAP Frequency

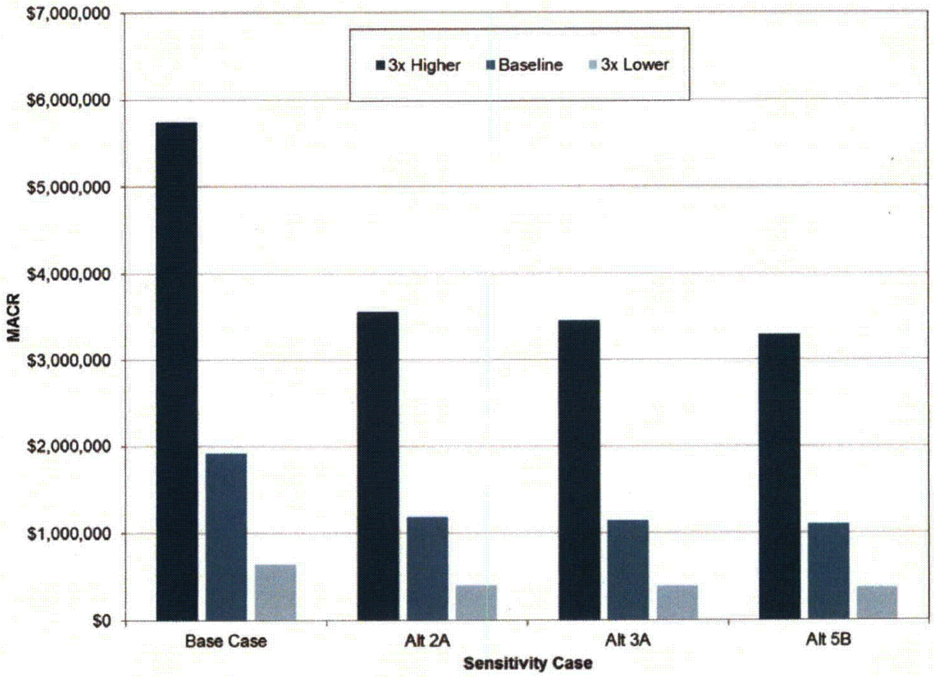

Figure 4-4
MACR Sensitivity to ELAP Frequency

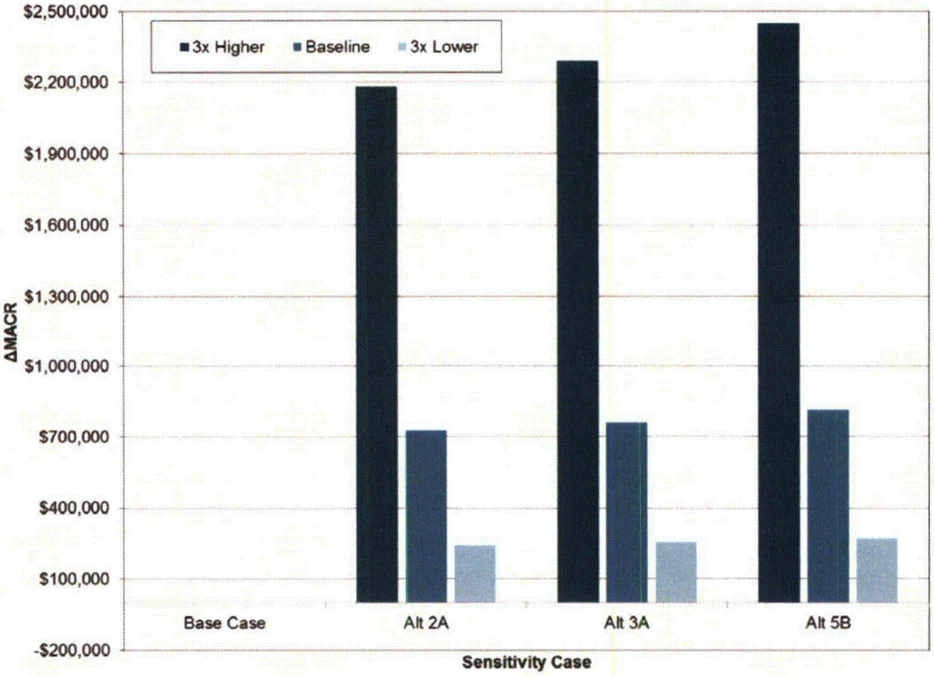

Figure 4-5
ΔMACR Sensitivity to ELAP Frequency

4.2.2 Human Error Rates

Human performance is always an area of uncertainty in risk models. In this case, where operator manual actions are being credited under severe accident conditions, the uncertainties are directly relevant.

For this sensitivity, the risk models for Case 3A (SAWA to DW) and Case 5B (SAWA to DW with Large Engineered Filter) were used to investigate the sensitivity of the risk results to assumed human reliability values. The human error probability for SAWA deployment was varied over the range from 0.01 to 0.99 and the latent cancer risk values were compared. The results of these sensitivities are shown in Figure 4-6. These results show that the latent cancer risk is influenced by the assumed human reliability. As the assumed human error rate increases, the risk levels between the SAWA cases with and without engineered filters converge. This is because the engineered filter is bypassed when SAWA is unavailable. As the failure probability of SAWA increases an increasing faction of scenarios bypass the filter, leading to less benefit from the filter. Conversely, as the assumed human error probability is reduced, the risk benefit of the filter is shown to increase slightly as compared to the SAWA without filter case. However, even in the case with an assumed human error probability of 0.01, this difference is still small (on the order of 5%).

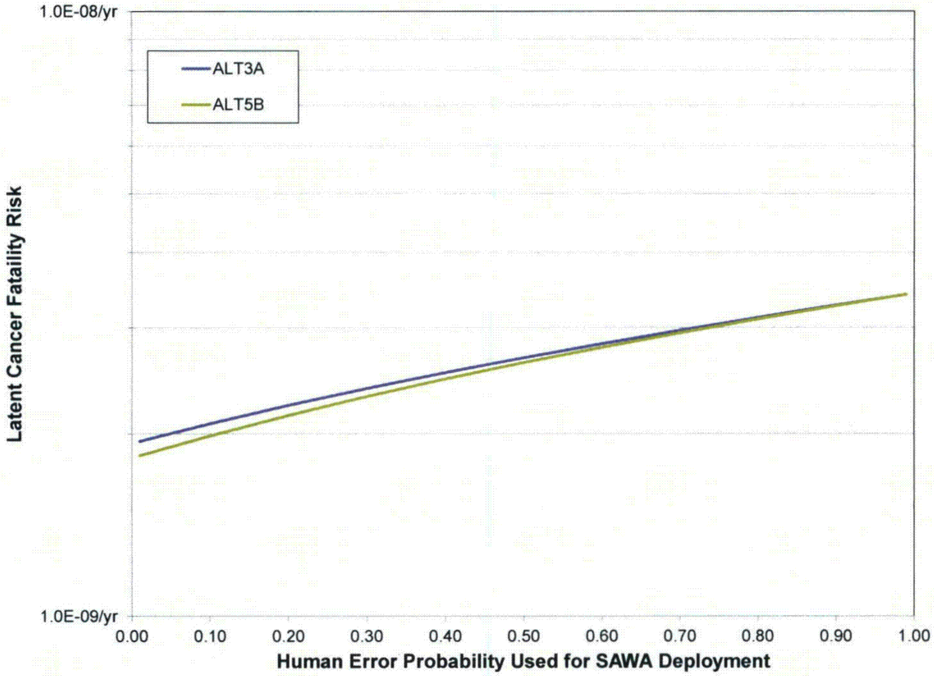

Figure 4-6
Relationship Between Assume Human Error Probability and Latent Cancer Risks

This analysis also provides insights with regard to assumed SAWA equipment reliability where a similar effect would be expected. That is, if a more pessimistic view of SAWA equipment reliability is used, the difference between the cases with and without engineered filters would decrease.

4.3 Phenomenological Uncertainties

4.3.1 Likelihood of SRV Seizure

One insight from the NRC's SOARCA [1] analysis was the likely occurrence of SRV seizure during core melt progression. In performing this analysis, it was recognized that assuming SRV seizure could be a non-conservative assumption since a stuck open SRV depressurizes the vessel and direct a significant fraction of the radioactive aerosols generated during core melt into the suppression pool. The baseline analysis assumes that SRV seizure occurs 85% of the time based on the SOARCA uncertainty analysis. In order to better understand the quantitative impact of this assumption, a sensitivity case was evaluated assuming no SRV seizure for the four primary cases (Base Case and Alternatives 2A, 3A, and 5B) and for the LCF and MACR risk metrics.

As shown in Figures 4-7 and 4-8, the baseline SRV seizure assumptions from SOARCA reduce the overall risks by ~20% versus a case where no SRV seizure occurs for all cases except the filtered case (Alternative 5B), where no change was observed. This sensitivity is well within the uncertainties of the severe accident progression behavior and has no significant impact on the overall results or conclusions of this study.

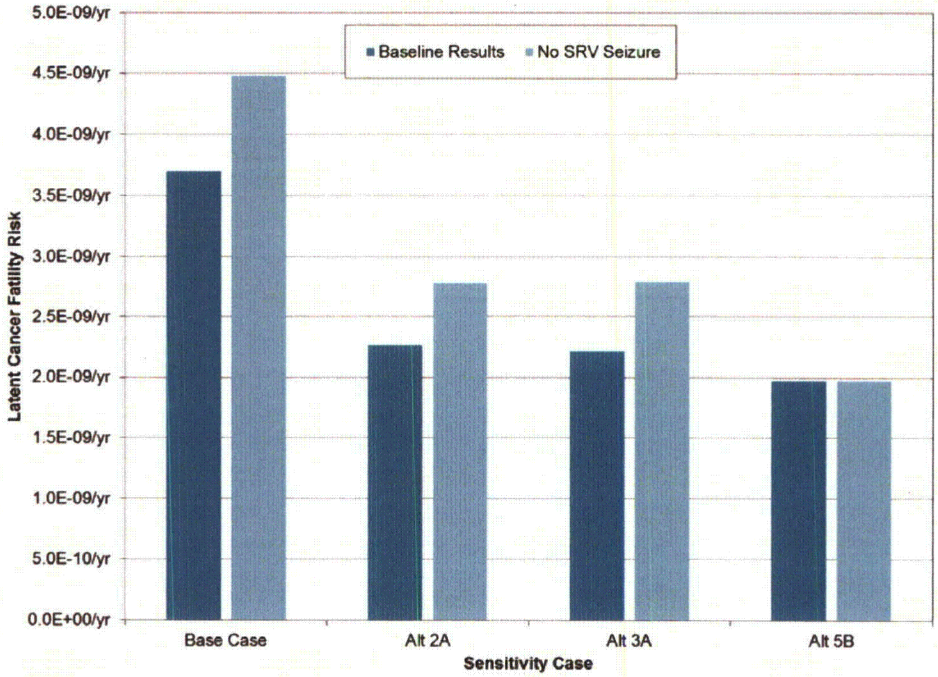

Figure 4-7
Latent Cancer Risk Sensitivity to SRV Seizure Assumption

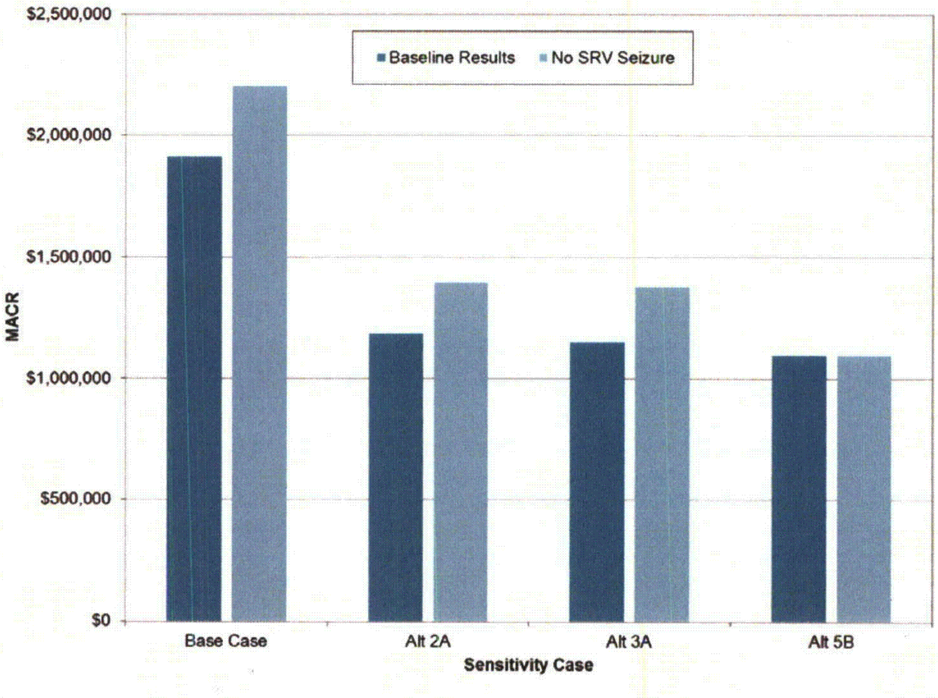

Figure 4-8
MACR Sensitivity to SRV Seizure Assumption

4.3.2 Likelihood of In-Vessel Retention

The baseline analysis assumes a probability that the damaged core can be retained in the vessel, if water addition to the RPV is initiated prior to core relocation into the lower head. In performing this analysis, it was recognized that this assumption might overstate the benefit of in-vessel retention in Alternatives 2A through 2H. In order to better understand the quantitative impact of this assumption, a sensitivity case was evaluated assuming no in-vessel retention for Alternative 2A for comparison to the three other primary cases (Base Case and Alternatives 3A, and 5B) and for the LCF and MACR risk metrics.

As shown in Figures 4-9 and 4-10, the baseline in-vessel retention assumption has a very small impact on the overall consequences for Alternative 2A. This is mainly due to the fact that fission product releases for the in-vessel retention cases are similar to cases with ex-vessel debris and water addition. Again, this sensitivity is well within the uncertainties of the severe accident progression behavior and has no significant impact on the overall results or conclusions of this study. Also, as discussed in Section 3, water addition to the RPV, even after vessel breach has the additional benefit of reducing overall containment temperatures, which supports maintaining containment integrity.

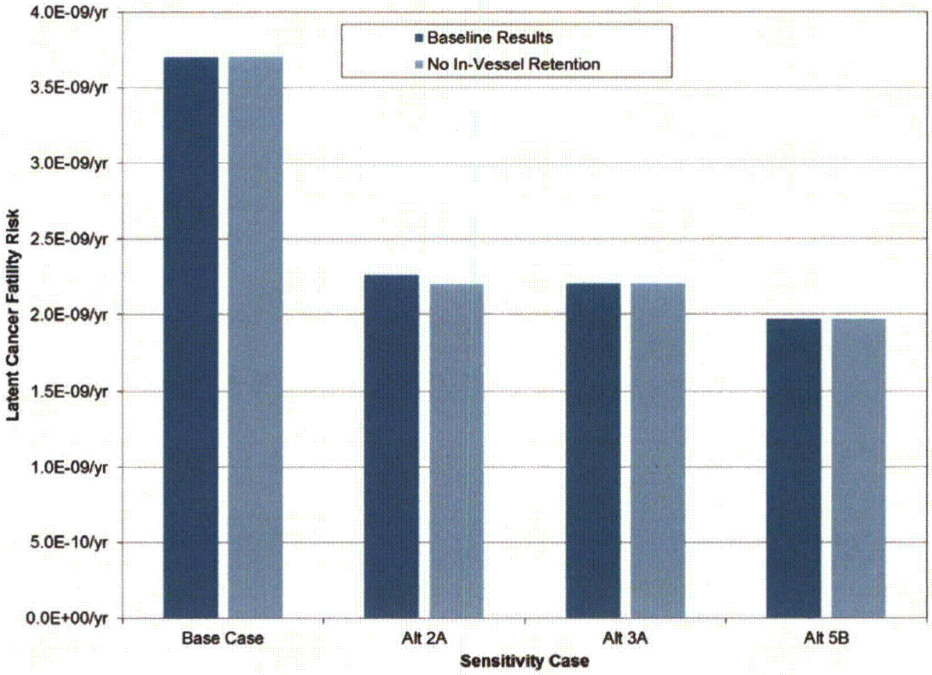

Figure 4-9
Latent Cancer Risk Sensitivity to In-Vessel Retention Assumptions

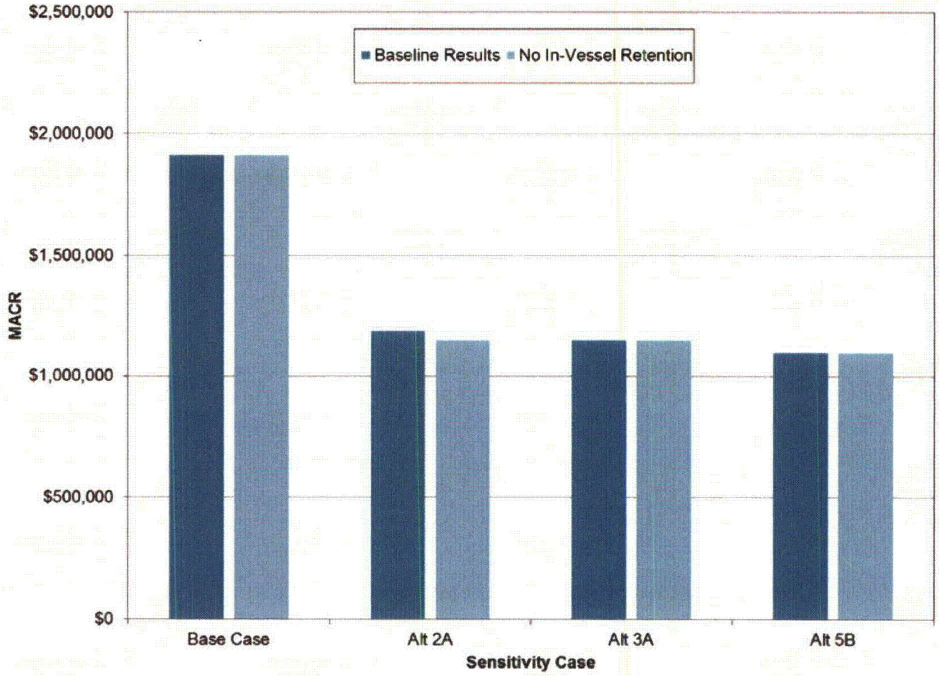

Figure 4-10
MACR Sensitivity to In-Vessel Retention Assumption

4.3.3 Timing of Liner Melt-through

Without water provided to the core debris on the containment floor, there is a high likelihood that core material will spread and contact the drywell shell, resulting in melting and failure of the shell near the floor elevation. This was studied in detail by Theofanous [10]. Liner melt through has the consequence of creating a release pathway that can bypass the designed venting path. For alternative strategies that include an installed external filter, this bypass can significantly reduce the overall benefit of the filter.

The APET described in Section 4.2 assumes that without water supplied to the containment floor, either by injection into the failed RPV or directly to the drywell, liner melt through occurs with a failure probability of 1.0. The MAAP analyses for these scenarios assume that drywell failure occurs 15 minutes following vessel breach. To study the importance of this assumption, a sensitivity analysis was performed that assumed an extended delay between vessel breach and liner melt through for scenarios that do not have water addition to the core debris ex-vessel. The alternative selected was 4A which assumed the presence of a small capacity external filter. The sensitivity analysis was performed for CDET end state 019 and APET end state 028. This scenario is defined as an ELAP with failure of RCIC at t=0 and with successful depressurization of the RPV when the water level drops below the minimum steam cooling water level limit. Vessel breach occurs at approximately 5.5 hours into the event. APET end state 028 is represented as:

- SRV seizure
- No water addition

- Liner melt through

As described above, the base analysis assumes that under these conditions, liner melt through occurs 15 minutes following vessel breach. The sensitivity case performed assumed that liner melt through was delayed for 10 hours following vessel breach. This delay time was selected to maximize the benefit from the external filter. SOARCA analysis assumed that liner melt-through occurred immediately following vessel breach. SECY-12-0157 [4] assumes liner melt through times ranging from 0.4 to a maximum of 3 hours following vessel breach. This extended time should allow for transport of fission products from the drywell into the suppression pool and allow for natural deposition mechanisms to reduce the fission product concentration in the drywell prior to release. Since the APET quantification always assumes liner melt through for this scenario, the sensitivity analysis was modified to allow for operation of the wetwell vent with an external filter, actuated when pressure in the containment exceeded PCPL, or 60 psig.

Figure 4-11 compares the total cesium release fraction between the base case and the delayed LMT sensitivity case. The base case resulted in a Cs release of 3.5%, compared to 1.8% for the delayed liner melt through case. As can be shown, even with the installed filter connected to the vent path, liner melt through creates a release that bypasses the filter, even with a considerable delay time. The primary reason for there being a significant release even in the delayed case is that a large fraction of the Cs release comes from long term revaporization of previously deposited fission products. Without water addition, temperatures in the RPV and containment increase to a point where the deposited fission products return to a vapor state.

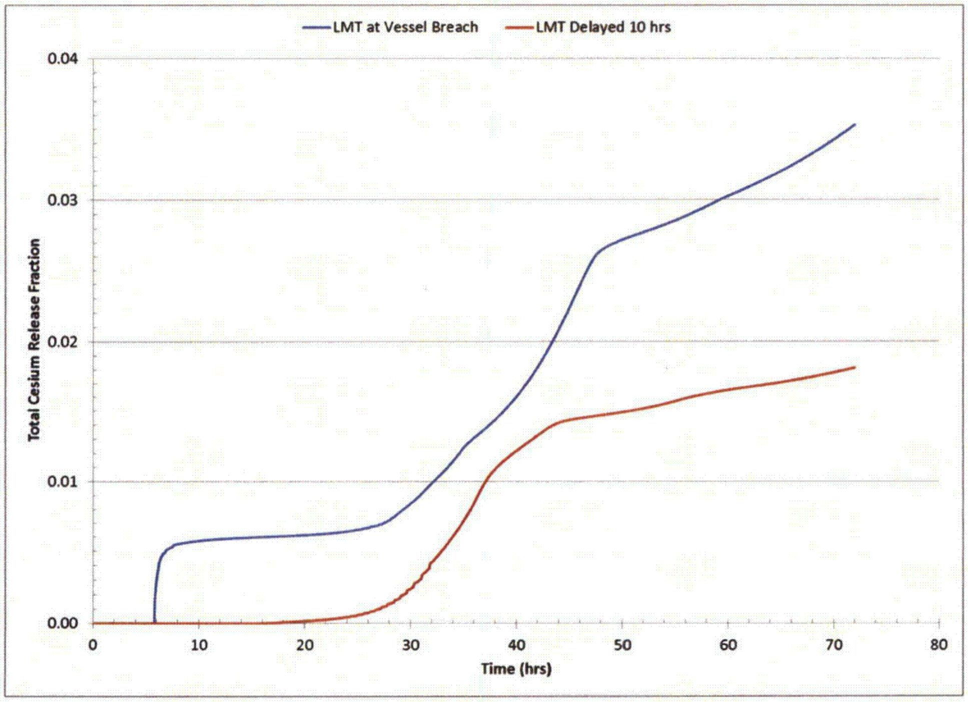

Figure 4-11
Cesium Release vs Time for LMT Sensitivity

Should liner melt through be delayed even further or assumed not to occur, heat up of the drywell will eventually result in leakage through various penetrations, also reducing the benefit

of an external filter. Figure 4-12 shows a calculation included in the Peach Bottom SOARCA analysis. The figure was based on an analysis in which natural convection between the lower and upper drywell regions was modelled. The gas temperatures following vessel breach are plotted and can be seen to very rapidly rise due to the exposed core debris on the floor. It has been estimated that penetration leakage can occur starting at 700 °F (644 K). The MELCOR results clearly show drywell temperatures in excess of that threshold immediately following vessel breach.

The conclusion drawn from this sensitivity analysis is that without water addition, liner melt through and drywell leakage will significantly reduce the benefit of an external filter.

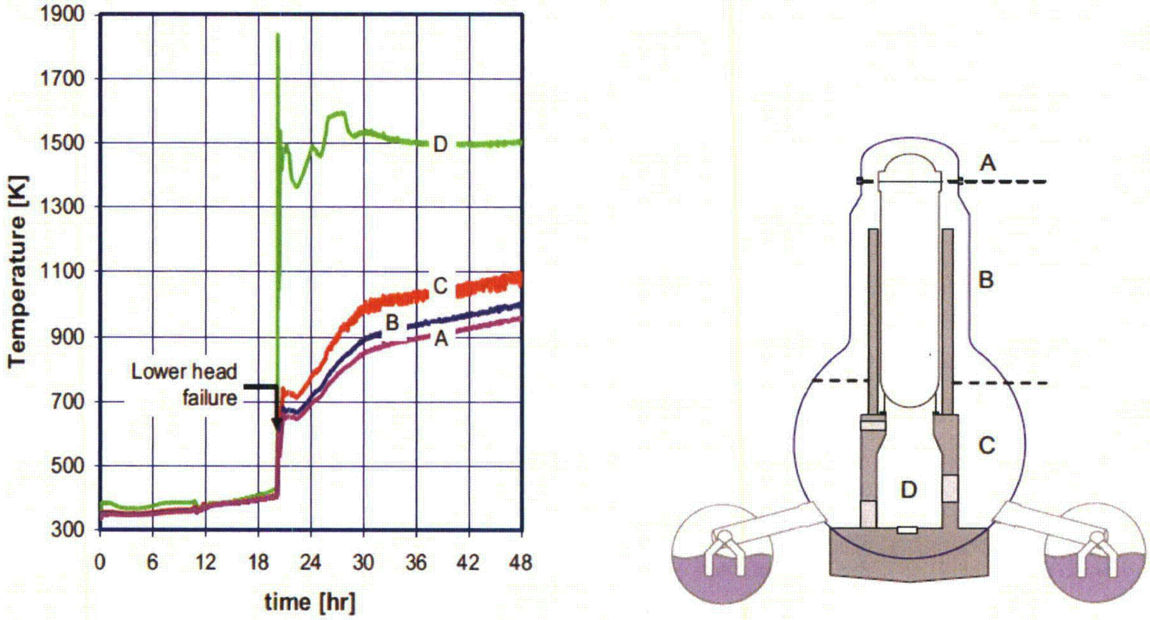

Figure 4-12
Drywell Temperature Results from SOARCA

4.4 Consequence Model Assumptions

4.4.1 Radionuclide Aerosol Deposition Rate

One insight from the USNRC's SOARCA analysis was that the modeled aerosol deposition rate for radioactive particles released from containment following a severe accident is lower than assumed in past consequence analyses like NUREG-1150 [11] and WASH-1400 [12]. In order to better understand the quantitative impact of this assumption, a sensitivity case was evaluated assuming no SRV seizure for the four primary cases (Base Case and Alternatives 2A, 3A, and 5B) and for the LCF and MACR risk metrics.

This sensitivity examines the impact of an increase in deposition velocity to 0.01 m/s. The base scenario reflects a distributed deposition velocity based on release group and particle size that results in an average deposition velocity of less than 0.005 m/s. This sensitivity adjusts all

particles to have a constant deposition velocity of 0.01 m/s regardless of the particle size. This deposition velocity reflects the suggested value used in NUREG-1150.

As shown in Figures 4-13 and 4-14, the deposition rates from SOARCA reduces the overall risks by ~20% in the Base case versus cases that use the old NUREG-1150 assumptions, but has a much smaller impact on the cases with severe accident water addition due to the reduced release of aerosols in those cases. This sensitivity is well within the uncertainties of the severe accident progression behavior and has no significant impact on the overall results or conclusions of this study.

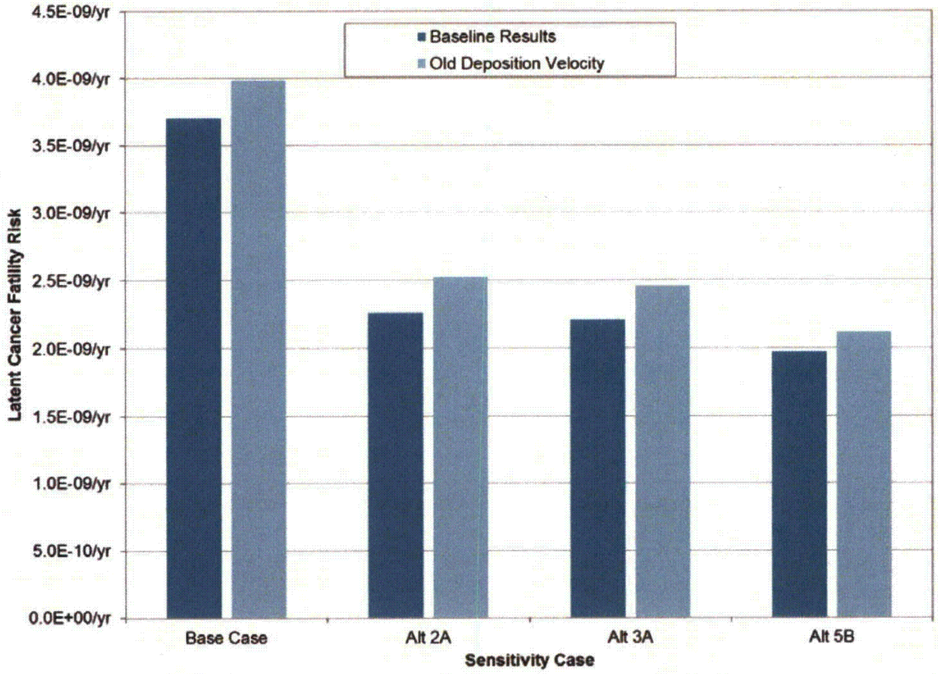

Figure 4-13
Latent Cancer Risk Sensitivity to Deposition Velocity Assumption

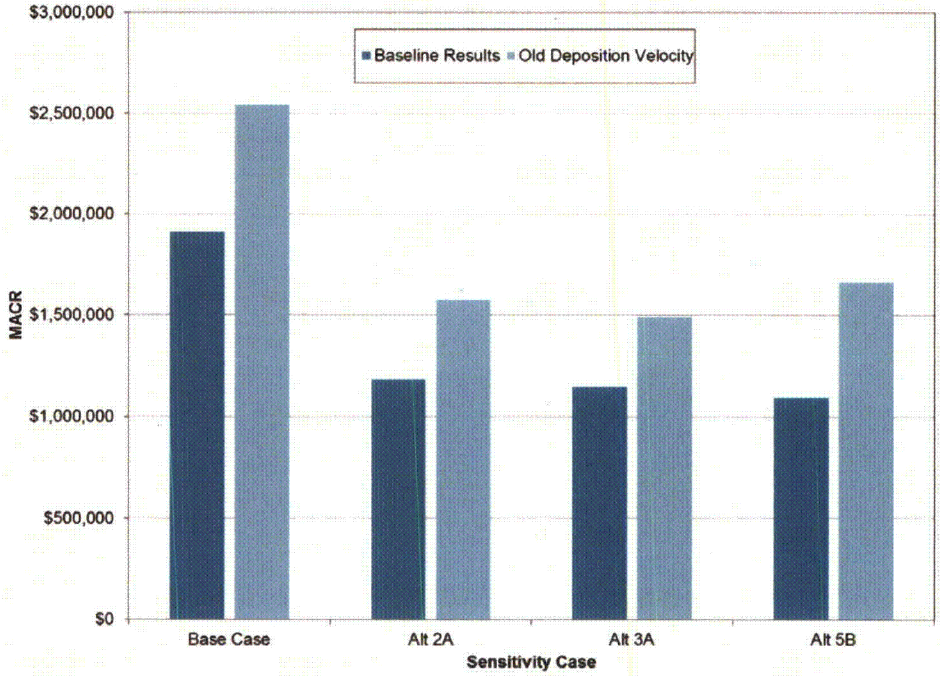

Figure 4-14
MACR Sensitivity to Deposition Velocity Assumption

4.4.2 Evacuation Effectiveness

Evacuation of nearby population is an important element of site emergency planning. Given the interest in the risks from postulated severe natural phenomena where evacuation may be impeded by environmental conditions, a set of sensitivity analyses were performed to consider a range of potential evacuation effectiveness ranging from 100% effective evacuation to no evacuation:

- 99.5% Population Evacuation (Baseline Case)

  The Baseline model for all cases assumed that 99.5% of the population within 10 miles of the site is evacuated consistent with the plant Emergency Plan. This baseline assumption is consistent with the SOARCA study.

- 100% Population Evacuation

  This sensitivity models the evacuation of 100% of the population within 10 miles of the site following accident initiation (base case models 99.5% evacuation). Normal and hot spot relocation criteria were not altered for this sensitivity; intermediate and long-term dose relocation criteria are also consistent with the baseline cases discussed in Section 3.

- 95% Population Evacuation

  This sensitivity models the evacuation of 95% of the population within 10 miles of the site following accident initiation. This sensitivity assumes that 5% of the population within 10 miles of the plant does not evacuate. Normal and hot spot relocation criteria were not altered

for this sensitivity; intermediate and long-term dose relocation criteria are also consistent with the baseline cases discussed in Section 3.

- No Population Evacuation

  This sensitivity case assumes that no evacuation or relocation of the population surrounding the site occurs during the 7 day emergency phase. The normal and hotspot relocation criteria are adjusted to prevent high doses triggering any population relocation (i.e., population within and beyond 10 miles) during the week long emergency phase. Population relocation is allowed to occur following the emergency phase consistent with the base scenario.

The impact of these alternative evacuation effectiveness assumptions were assessed for the four primary cases (Base Case and Alternatives 2A, 3A, and 5B) in terms of the LCF, MACR and ΔMACR risk metrics.

As shown in Figure 4-15, the latent cancer risks are relatively insensitive to 10-mile evacuation percentages above 95%. However, the no evacuation cases show much higher latent cancer risks due to the additional exposures that occur for the un-evacuated population. This demonstrates the known benefit of utility emergency planning in protecting the public health and safety. In the context of extreme external events that may impede evacuation, the no evacuation results must be considered in light of the other probable impacts on public health and safety from the extreme external hazards. However, this analysis indicates that even without evacuation, the consequence results for LCF are still below the USNRC's QHOs.

As shown in Figures 4-16 and 4-17, the computed financial risks are also relatively insensitive to evacuation effectiveness from 95% to 100%. In contrast to the latent cancer risks, the no evacuation case showed negligible impact on overall financial risks.

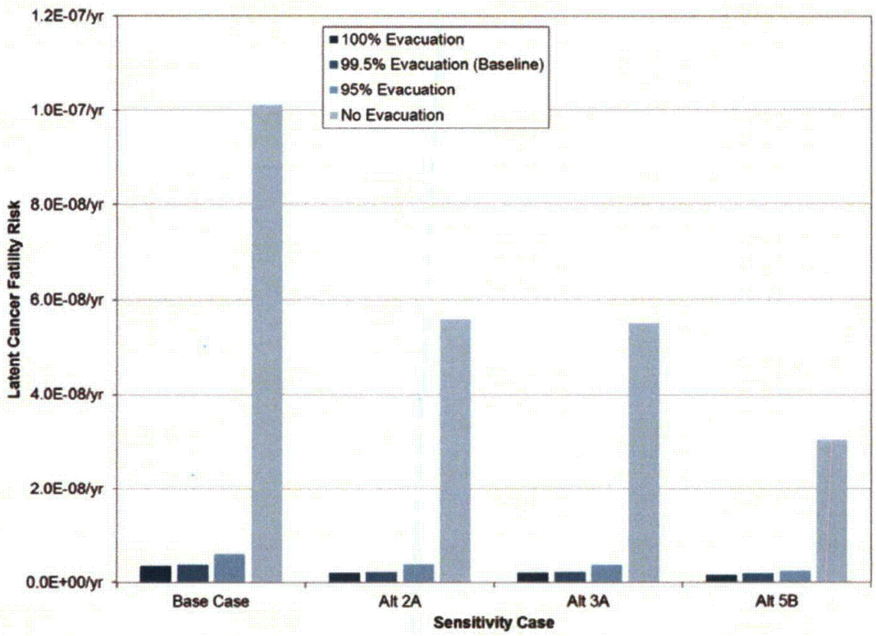

Figure 4-15
Latent Cancer Risk Sensitivity to Evacuation Assumptions

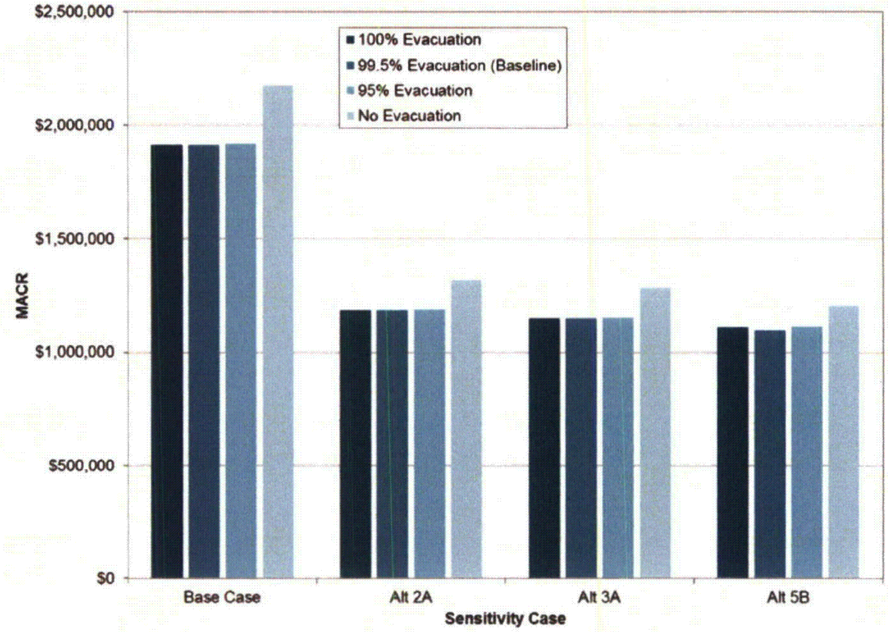

Figure 4-16
MACR Sensitivity to Evacuation Assumptions

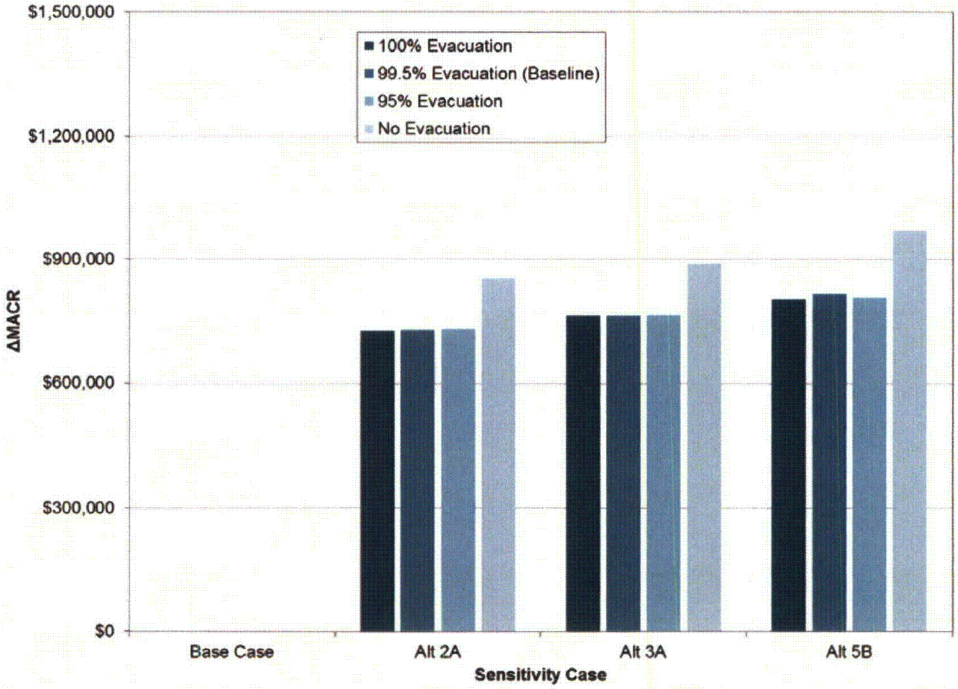

Figure 4-17
ΔMACR Sensitivity to Evacuation Assumptions

4.4.3 Dollar Value of Person-rem

One key factor used in translating the consequences of a release into financial terms is the conversion from dose to economic cost. Typically, this has been done by multiplying the total population dose over a 50 mile radius from the plant by a conversion rate of $2,000 per person-rem. The USNRC is in the process of reviewing this conversion rate and there is some indication that this value may increase in the future. In order to better understand the quantitative impact of this assumption, sensitivity cases were evaluated using $5,200 per person-rem for the four primary cases (Base Case and Alternatives 2A, 3A, and 5B) and for the LCF, MACR and ΔMACR risk metrics.

As shown in Figure 4-18, the dose conversion factor has no impact on LCF risk, which is a health metric, not a financial metric.

As shown in Figures 4-19 and 4-20, changing the value of a person-rem from $2,000 to $5,200 does increase the overall financial consequences. However, the factor of 2.5 change in conversion rate, only translates to a ~30% increase in the financial risks which still results in a relatively low financial risk. Thus, the dose conversion rate does not have a significant impact on the overall results or conclusions of this study.

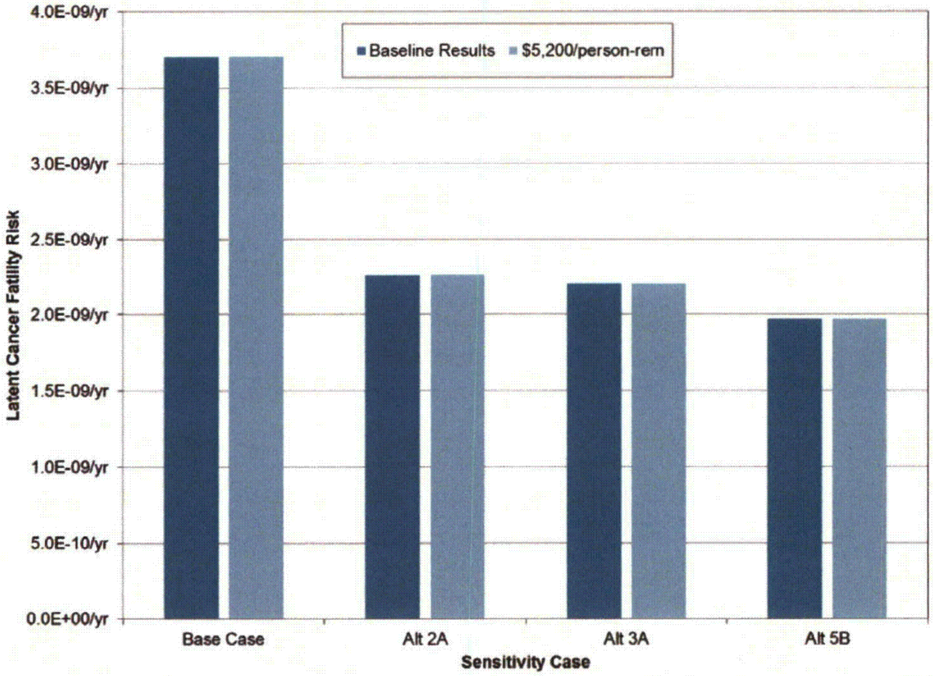

Figure 4-18
Latent Cancer Risk Sensitivity to Dollar-per-person-rem Value Assumption

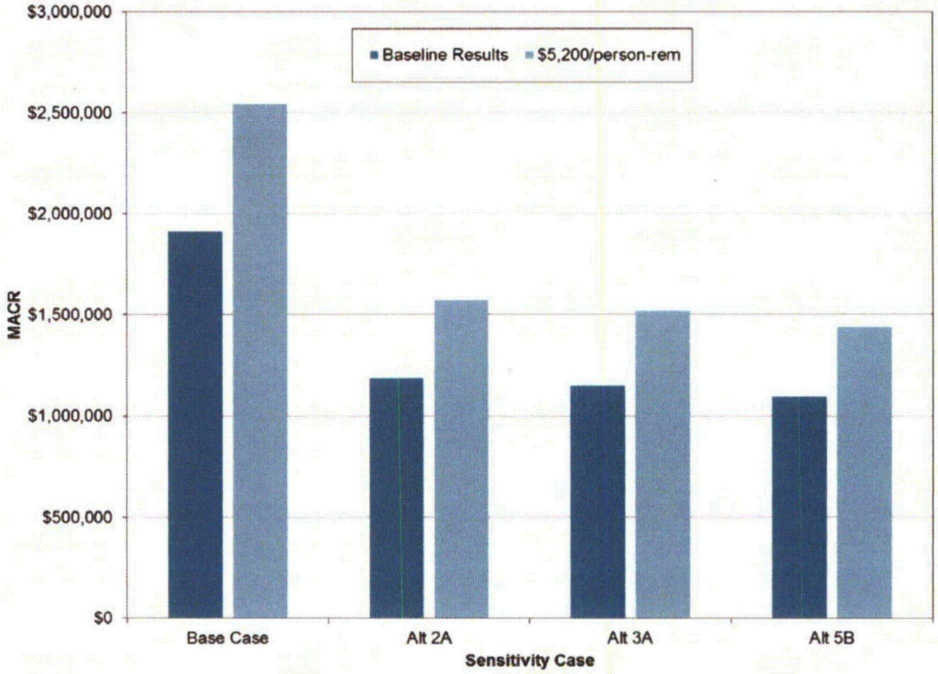

Figure 4-19
MACR Sensitivity to Dollar-per-person-rem Value Assumption

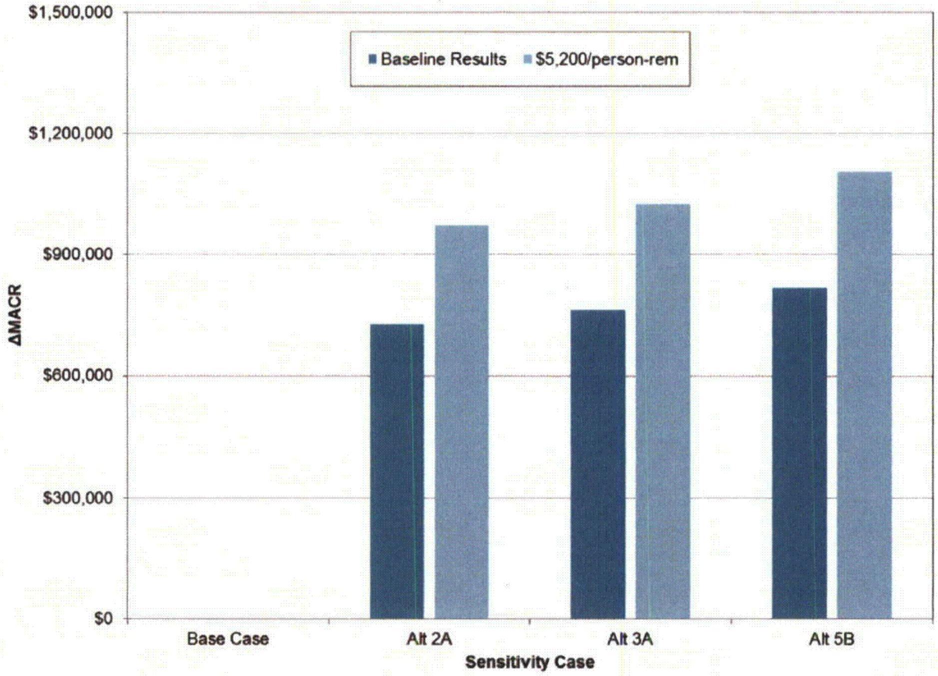

Figure 4-20
ΔMACR Sensitivity to Dollar-per-person-rem Value Assumption

4.4.4 Discount Rate

Another factor used in translating the consequences of a release into financial terms is the discount rate used to compute the present value of the MACR. Typically, a discount rate of 7% has been used by the USNRC. In order to bound the quantitative impact of this assumption, sensitivity cases were performed using a discount rate of 0%. These sensitivities were based on comparison of the four primary cases (Base Case and Alternatives 2A, 3A, and 5B) using the LCF, MACR and ΔMACR risk metrics. Of course, a discount rate of 0% is not realistic, but it allows computation of a bounding MACR value. A discount rate of 0% correlates to a higher offsite economic cost since depreciation of property value is not considered for the consequence calculation.

As shown in Figures 4-21 and 4-22, dropping the discount rate from 7% to zero does increase the overall financial risk results by approximately a factor of 2.

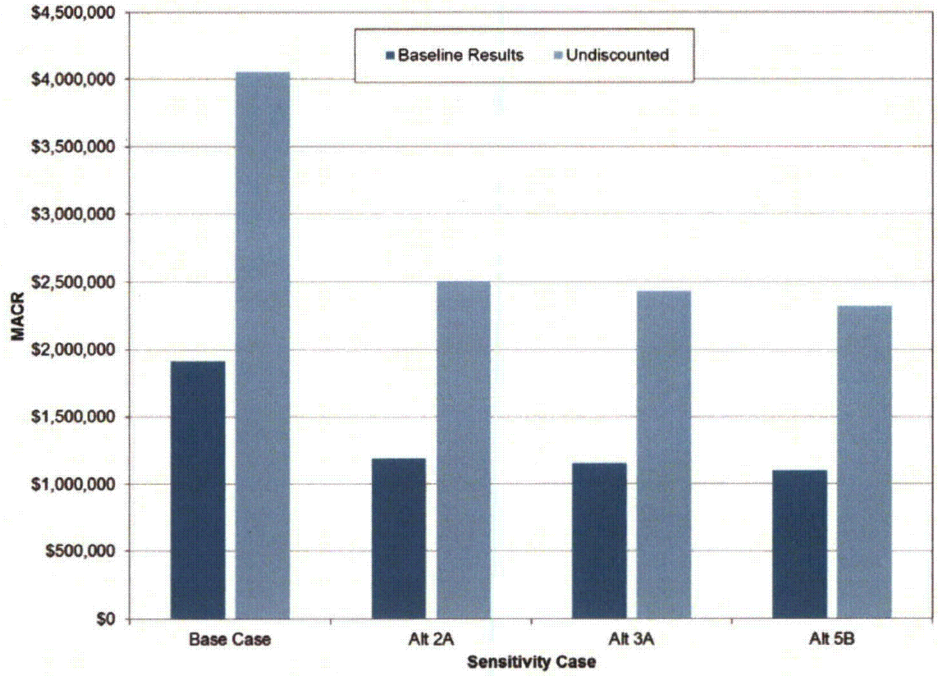

Figure 4-21
MACR Sensitivity to Discount Rate Assumption

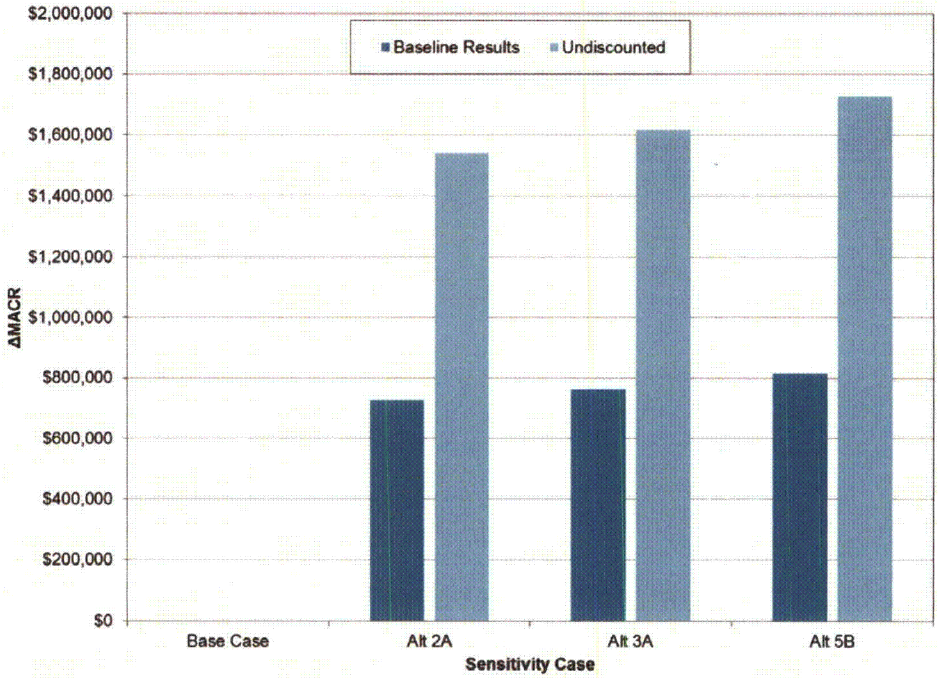

Figure 4-22
ΔMACR Sensitivity to Discount Rate Assumption

4.4.5 Combination Person-rem and Discount Rate Sensitivity

In the financial sensitivity studies above, both dose conversion rate and discount rate have a direct impact on the financial risk estimates. Each of these input assumptions are subject to challenge, so a combined sensitivity study was performed to simultaneously adopt alternative assumptions. In this sensitivity study, a dose conversion rate of $5,200 per person-rem and a discount of 3% are assumed. The impact of this combined variation is evaluated for each of the four primary cases (Base Case and Alternatives 2A, 3A, and 5B), using the MACR and ΔMACR risk metrics. These results are compared to the baseline results that were based on $2,000 per person-rem for dose conversion rate and a 7% discount.

As shown in Figures 4-23 and 4-24, the combined impact of a lower discount rate (3%) and a higher value of a person-rem ($5,200) increases the overall financial risks by approximately a factor of 2.

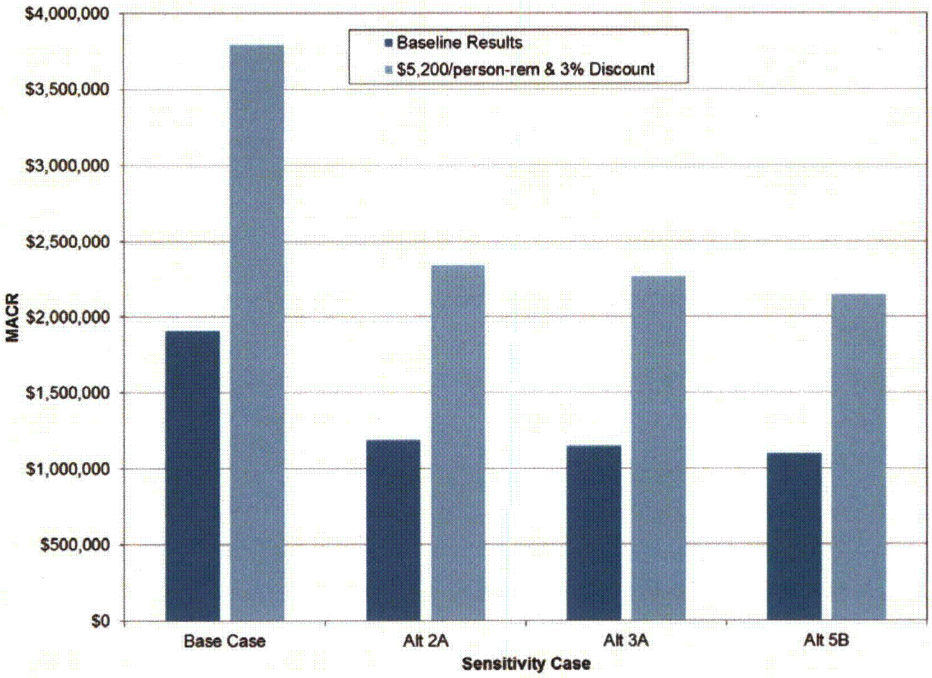

Figure 4-23
MACR Sensitivity to Combined Person-rem Value and Discount Rate Assumption

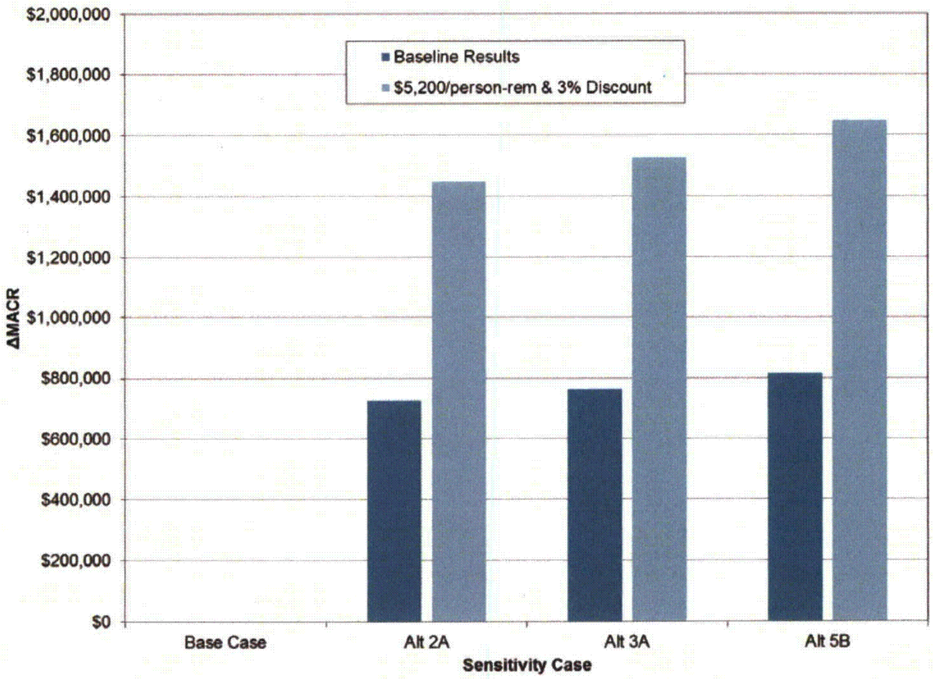

Figure 4-24
ΔMACR Sensitivity to Combined Person-rem Value and Discount Rate Assumption

4.5 Conclusions from Sensitivity Analyses

The above sensitivity analyses consider the impacts on the latent cancer and financial risk results due to

- Plant-to-plant variability across the Mark I Fleet
- Logic model uncertainties
- Phenomenological uncertainties
- Consequence model assumptions

These analyses provide insight into the sensitivity of key inputs to the baseline analysis. Table 4-1 provides a summary of these analyses and the conclusions drawn from each. In general, these sensitivities confirm that the assumptions, uncertainties and parameter variability had minimal to modest impacts on the baseline quantitative results and insights and strengthen the overall conclusions of this report.

Table 4-1
Summary of Conclusions from Sensitivity Investigations

Sensitivity Parameter	Approach	Alternatives	Metrics	Conclusions
Plant to Plant Variability				
Containment Heat Capacity	Qualitative	N/A	N/A	• Reference plant has most limiting containment heat capacity of US fleet
Torus Freeboard Volume	Qualitative	N/A	N/A	• Reference plant is one of the most limiting with respect to torus freeboard volume. • Ample time exists for operating staff and emergency response organization to implement SAWM.
DW to WW Spillover Height	Qualitative	N/A	N/A	• Water addition is the most significant factor in providing debris cooling and controlling drywell temperatures.
Population	Qualitative	2A	0-10 mi	• Reference plant represents the second largest population site. Sensitivity to address largest population site reveals no significant impact.

Table 4-1 (continued)
Summary of Conclusions from Sensitivity Investigations

Sensitivity Parameter	Approach	Alternatives	Metrics	Conclusions
Probabilistic Logic Model				
ELAP frequency	Qualitative	Base, 2A, 3A, 5B	LCF, MACR, ΔMACR	• Risk results vary linearly with the assumed ELAP frequency. • The maximum credible change is on the order of a factor of 3, given that there is no evidence that ELAP core damage frequencies are greater than the CDF quantitative objective of 1E-4/yr.
Human error rates for severe accident water addition	Quantitative	2A	LCF, MACR, ΔMACR	• Risk results are not highly sensitive to the human error probabilities assumed over a broad range of probabilities
Phenomenological				
SRV Seizure During Core Melt	Quantitative	Base, 2A, 3A, 5B	LCF, MACR, ΔMACR	• The baseline SRV seizure assumptions from SORCA reduce the overall risks by ~20% versus a case where no SRV seizure occurs for all cases except the filtered case (Alternative 5B), where no change was observed.
In-Vessel Retention	Quantitative	Base, 2A, 3A, 5B	LCF, MACR, ΔMACR	• Assuming that water addition during the core melt process does not prevent vessel breach results in a small increase in risks from Alternative 2A.
LMT Timing	Qualitative	N/A	Cesium Release	• Due to revaporization of deposited radionuclides, delay in LMT does not show a significant impact on source term.

Table 4-1 (continued)
Summary of Conclusions from Sensitivity Investigations

Sensitivity Parameter	Approach	Alternatives	Metrics	Conclusions
Benefit Model				
Deposition Rate	Quantitative	Base, 2A, 3A, 5B	LCF, MACR, ΔMACR	• Adopting the aerosol deposition rate from NUREG-1150 increases the economic risk in the Base Case by over 20%, but has only a very small impact (<10%) on the alternatives that provide severe accident water addition.
Evacuation Effectiveness	Quantitative	Base, 2A, 3A, 5B	LCF, MACR, ΔMACR	• Computed risks are relatively insensitive to evacuation effectiveness from 95% to 100%. • Cases with no evacuation showed much higher latent cancer risks than cases with relatively effective evacuation, but negligible impact on overall financial risks.
$/Person-rem	Quantitative	Base, 2A, 3A, 5B	MACR, ΔMACR	• Changing the value of a person-rem from $2,000 to $5,200 increases the overall financial consequences. However, this change only translates to a ~30%increase in the financial risks.
Discount Rate	Quantitative	Base, 2A, 3A, 5B	MACR, ΔMACR	• A bounding assumption of no discount on the present value of property (i.e., no property depreciation) increased the overall financial results by approximately a factor of 2.
Combination – Discount Rate & $/Person-rem	Quantitative	Base, 2A, 3A, 5B	MACR, ΔMACR	• The combined impact of a lower discount rate (3%) and a higher value of a person-rem ($5,200) increases the overall financial risks by approximately a factor of 2.

5
SUMMARY TECHNICAL INSIGHTS

5.1 Comparison of Overall Quantitative Results for Alternatives

A total of 24 alternatives were analyzed to evaluate the potential benefits that could be obtained from plant modifications and by implementing various accident management strategies. The quantitative results have been calculated for the following figures of merit:

- Conditional Containment Failure Probability (CCFP)
- Latent Cancer Fatality Risk (LCF)
- Maximum Averted Cost Risk (MACR)

These three figures of merit provide a suitable reference for investigating the benefits from implementing the various strategies.

5.1.1 Influence on Containment Integrity

The first set of quantitative results addresses the containment integrity given a core damage event through the calculation of the conditional containment failure probability (CCFP). Figure 5-1 provides the calculated CCFP for the base cases and all of the alternatives. The results displayed represent the CCFP for:

- Base cases representing the plant without any additional changes
- Severe Accident Water Addition (SAWA) to the RPV
- Severe Accident Water Addition (SAWA) to the Drywell
- Engineered external filters, in addition to SAWA

As shown in Figure 5-1, without any additional changes, the calculated CCFP is 99%. It is important to recall that this analysis has assumed an extended loss of AC power (ELAP) and, that without the addition of water to the core debris ex-vessel, liner melt-through is always assumed to occur. A CCFP less than 100% simply addresses some cases where existing capabilities (e.g. FLEX) were successful in cooling the core debris post core damage.

For all alternatives analyzed, SAWA provides for core debris cooling and results in a significant reduction in CCFP. The residual CCFP (approximately 55%) is found to come from scenarios where SAWA was not available or cases where the containment venting system failed to operate. Note that there is little variation in CCFP among the alternatives beyond the addition of SAWA, including the addition of an external filter. Alternative Case 6A represents a passive vent/filter design, in addition to SAWA, and shows the greatest reduction in CCFP. However, since the passive design could not accommodate anticipatory venting, a key FLEX strategy for several plants, the core damage frequency actually increased for this alternative.

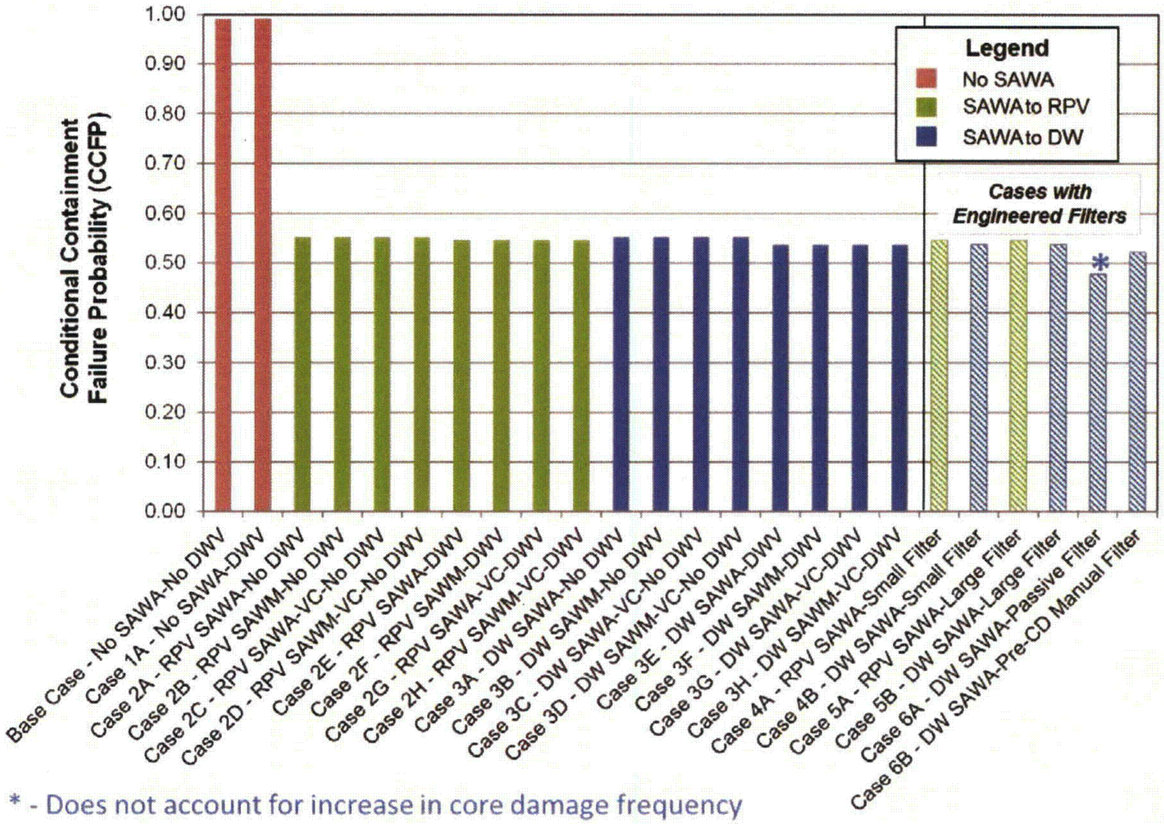

Figure 5-1
Conditional Containment Failure Probability Results

5.1.2 Comparison to Quantitative Health Objectives

The next figure of merit calculated was the latent cancer fatality risk for individuals within 10 miles of the plant. This metric is used for comparison to the Quantitative Health Objective (QHO) from the USNRC Safety Goal Policy Statement. When compared against the QHO for latent cancer fatality risk, Figure 5-2 shows that all alternatives have a margin of 3 orders of magnitude to the QHO limit of approximately 2E-6/yr. The base cases without SAWA are shown to have a LCF risk of approximately 3E-9/yr, compared to all other alternatives with SAWA of 2E-9/yr. On Figure 5-2, there is little variation in LCF observed beyond the implementation of SAWA.To further investigate the LCF risk, Figure 5-3 is provided to show the relative benefits of several potential plant modifications. The LCF value is normalized to a pre-Fukushima value and first plots the reduction in LCF that is obtained as a result of the implementation of FLEX under Order EA-12-049. The “FLEX” bar shows a 75% reduction in the LCF risk from implementation of EA-12-049. The next bar, “SAWA & SACV”, shows the further reduction in LCF risk as a result of severe accident water addition (SAWA) and a severe accident capable vent being implemented under Order EA-13-109. Finally, the incremental reduction in LCF risk is provided for an alternative that includes both SAWA and the addition of an engineered external filter.

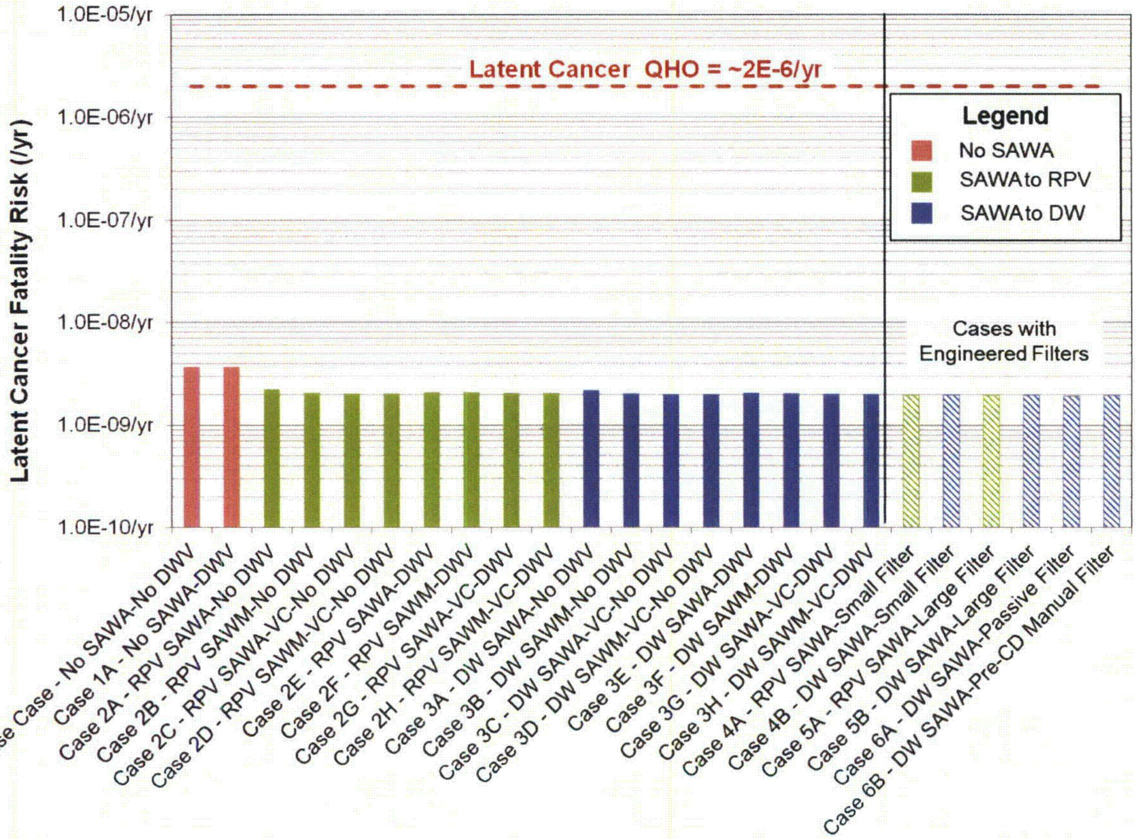

Figure 5-2
Latent Cancer Risk Results

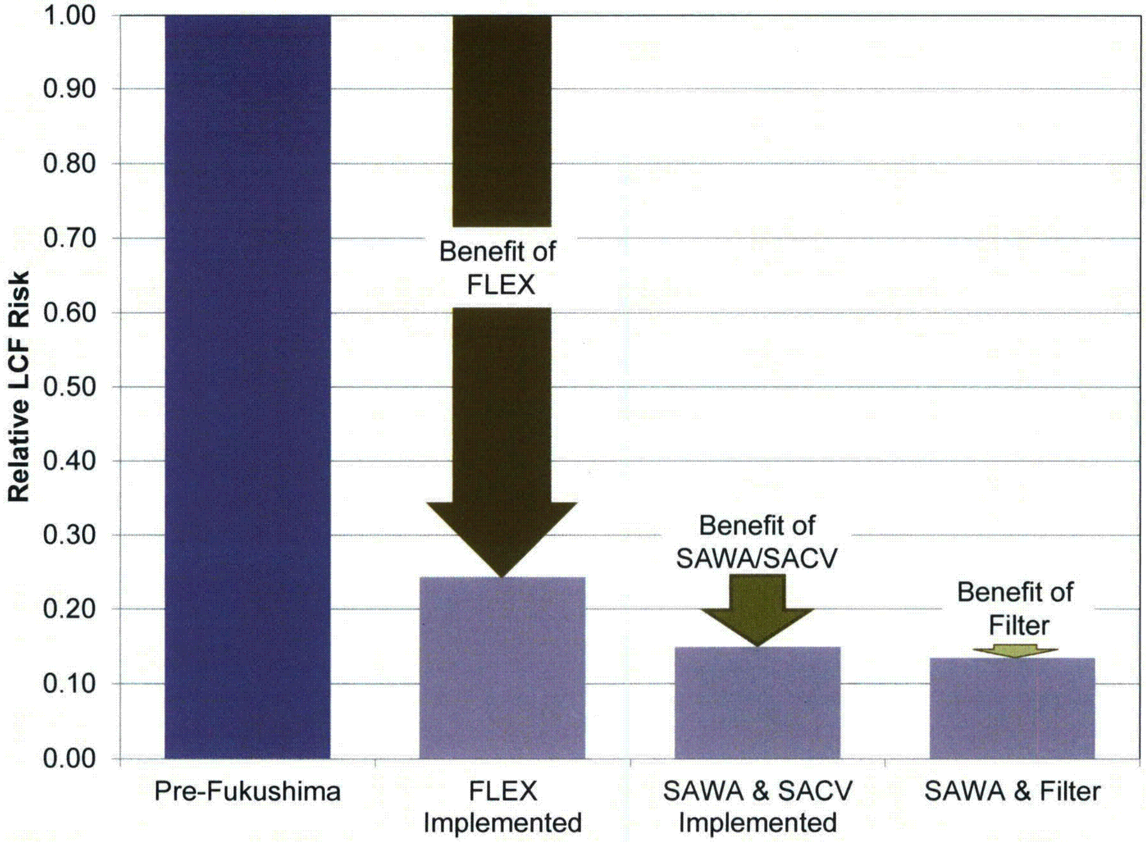

Figure 5-3
Benefit of Various Post-Fukushima Enhancements

5.1.3 Comparison of Maximum Averted Cost Risks (MACR)

In support of a future cost-benefit calculation for each alternative, the next figure of merit is the maximum averted cost risk (MACR). The MACR represents the total cost risk associated with eliminating all potential releases from the plant as computed for each alternative. The dollar value of the risk is based on established NRC methods and includes both the cost of onsite and offsite consequences. Figure 5-4 shows that the MACR for the base cases is approximately $2,700,000. The risk reduction from SAWA can be shown to have the most significant impact on the MACR and all alternatives are found to have a MACR on the order of $1,600,000.

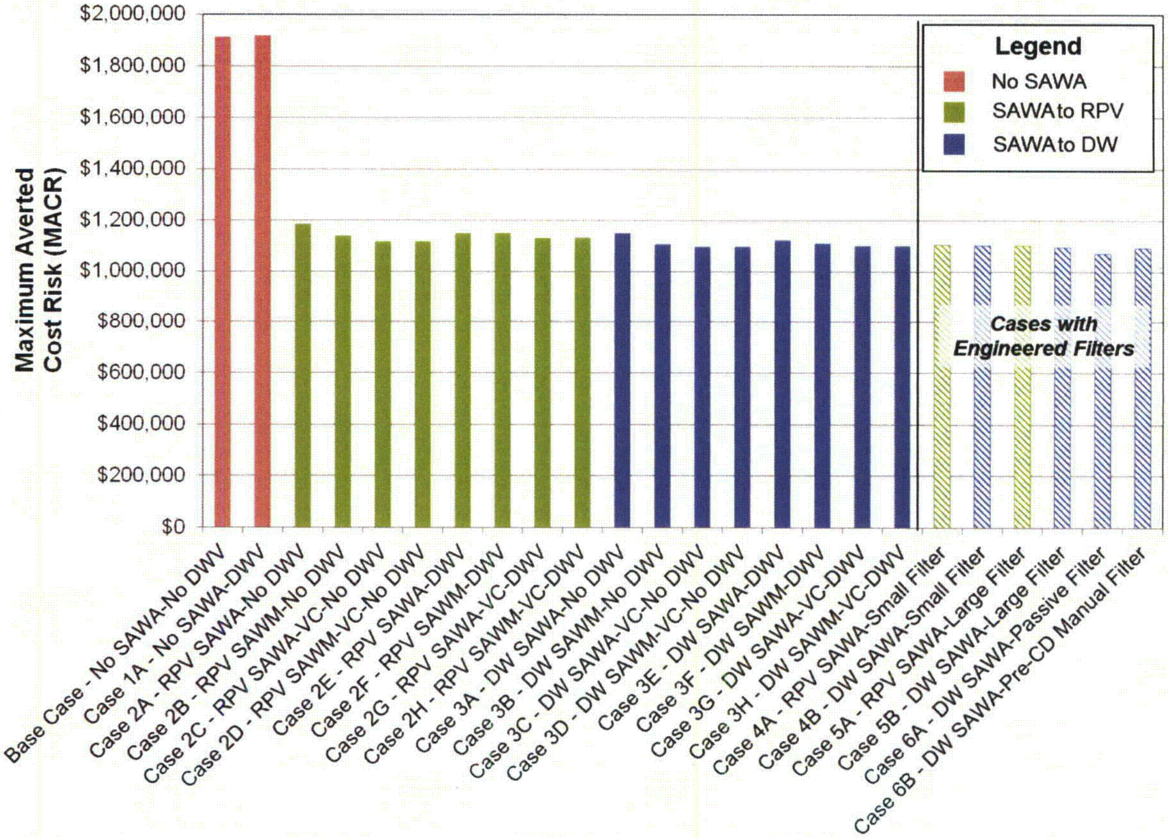

Figure 5-4
Maximum Averted Cost Risk Results

5.1.4 Net Benefit of Alternatives

When comparing the different alternatives, reference to the base case should be established. That is, the change in the MACR is important as it shows the relative cost benefit of implementing the various strategies. Figure 5-5 plots the reduction in MACR (i.e. ΔMACR) for each alternative when compared to the base case. Note that the ΔMACR for the alternatives fall into the range from $1,000,000 to $1,200,000.

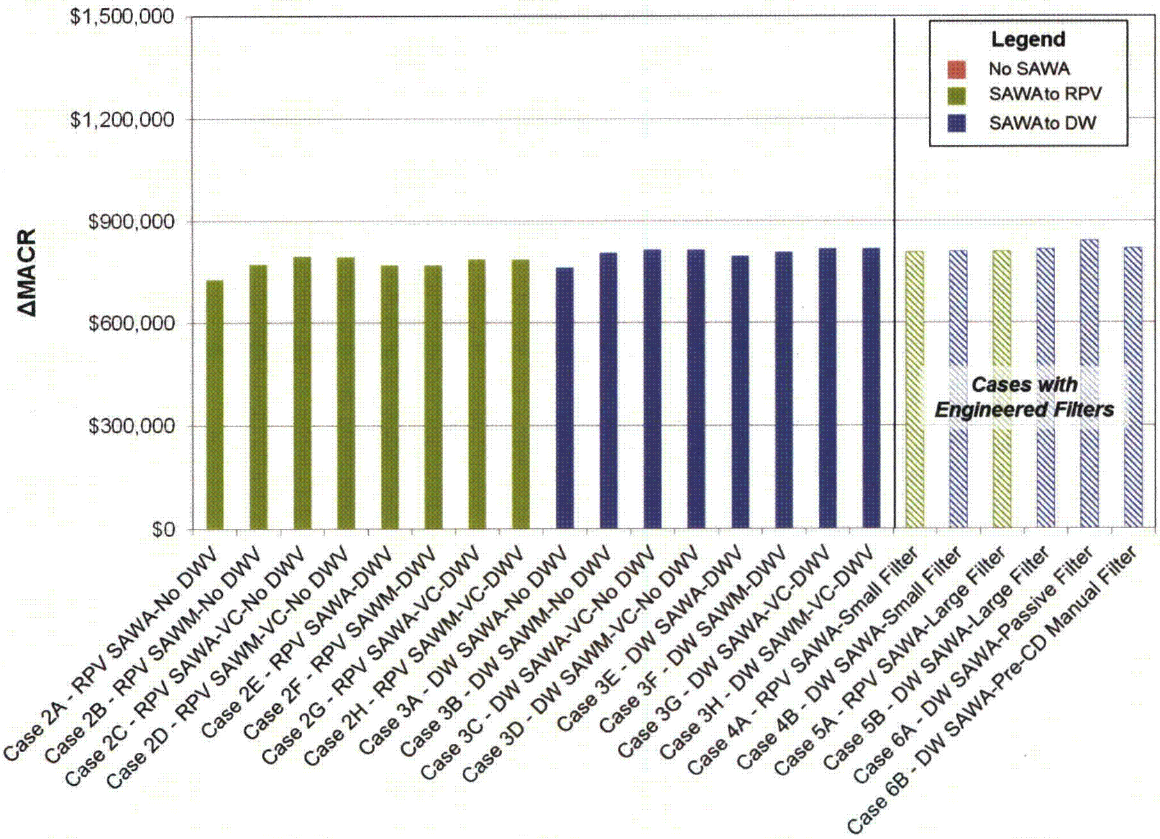

Figure 5-5
Change in Maximum Averted Cost Risk (MACR) Results

5.2 Other Insights

5.2.1 The Essential Role of Operators

The safe operation of any nuclear plant benefits from well-trained, experienced operators. From abnormal conditions to possible post-core damage situations, operator diagnosis and mitigation is essential to stabilize conditions within the plant following an accident. As implemented under order EA-12-049, deployment of portable equipment to maintain adequate core cooling and containment integrity will be performed by trained operators and plant staff.

As described for the alternatives outlined in this report, a set of operator actions are identified to effectively manage a severe accident and reduce any possible radionuclide releases. Where almost all of these actions are currently addressed in existing severe accident management guidance, they involve the following.

- Initiate severe accident water addition as described in the guidance for implementing Order EA-13-109 [6] Phase 2
- Maintain containment integrity through venting under Order EA-13-109

These two actions show the greatest benefit relative to containment protection and release reduction. Additional actions discussed in this report that show a smaller relative margin to safety include:

- Control of containment pressure within a defined range by cycling the vent
- Control of water addition rate to preserve the wetwell vent path

Overall, operator actions are essential to diagnosing and mitigating the potential consequences of a severe core damage event.

5.2.2 The Importance of Water Addition

As shown in the results section of this report, severe accident water addition provides the greatest benefit to containment protection and release reduction. Much as FLEX has been shown to reduce the likelihood of a core damage event, the consequences of a core damage event can be significantly reduced by the addition of a water to cool the ex-vessel core debris and mitigate the releases. This study has also shown that water can be added either to the RPV or directly to the drywell and result in a similar benefit to release reduction.

5.2.3 The Incremental Benefit of Engineered Filters

The incremental benefit from an engineered filter is shown to be small. The main reason for this is that an external filter is only successful in scenarios where effective release reduction has already occurred due to severe accident water addition and successful venting of containment. That is, the engineered filter is shown to reduce the releases from scenarios already benefiting from filtering in containment (i.e. pool scrubbing and natural aerosol removal mechanisms) and is ineffective in cases such as liner melt-through or containment overpressure failure.

5.2.4 "Passive" Vent Capability

As stated earlier, accident mitigation will benefit from a variety of operator actions. A totally passive system for venting has been shown to have some drawbacks in that anticipatory venting, as a way to maintain core injection systems, may not be possible in conjunction with a passive system, and as a result, the core damage frequency has been shown to actually increase for such an alternative. In addition, information provided on most of the filtered venting systems requires numerous operator actions to utilize the system such as,

- Purging of the filter prior to use,
- Preheating the filter material,
- Transport of deposited radionuclides back into containment

The two actions defined in this report, SAWA and venting under Order EA-13-109, are currently within the scope of existing BWR severe accident management guidance and do not pose any additional burden on the staff. In addition, severe accident water management, as a way to preserve the wetwell venting pathway, has been shown to require mitigation very late in the event providing the operators with significant time to initiate control of the water addition source.

5.3 Summary and Conclusions

5.3.1 General Insights

The following general insights have accrued from this analysis:

- Manual actions are needed to manage severe accidents given the broad range of plant conditions that can evolve across the spectrum of beyond design basis scenarios
- Proposed guidance in NEI 13-02 [7] for implementing Order EA 13-109 contains the essential hardware capabilities and controls for effective accident management
- BWROG SAMGs are the appropriate vehicle for directing the deployment and use of these hardware capabilities
- Effective actions can strongly influence the course of an accident, the ultimate damage state of the plant, and the resulting source terms
- Without intervention, containment failure, hydrogen explosions in reactor buildings, and substantial radiological releases can occur
- Specific actions can preserve the integrity of fission product boundaries and greatly reduce the magnitude of radiological releases well below USNRC safety goals
- Actions to vent containment via the wetwell airspace and add water to provide cooling of core debris are effective in reducing releases
- Additional hardware (e.g., external filtration) can further reduce radiological releases, but provides minimal safety benefit and is far from cost effective.

5.3.2 Technical Insights

The following technical insights have been gleaned from this analysis:

- Providing the capability to add water and vent the wetwell of Mark I containments during severe accident conditions has multiple safety benefits:
  - Preserves containment integrity due to over-temperature and over-pressure challenges
  - Cools core debris and reduces the airborne fission products
  - Avoids uncontrolled release of hydrogen to the reactor building which could result in deflagrations
  - Reduces the magnitude of radiological releases from containment
- Severe accident water addition (SAWA) has the largest benefit of any individual strategy
- SAWA with a SAC WW vent impacts key safety metrics:
  - Prevents containment failure
  - Increases margin to the USNRC Safety Goal
  - Reduces release magnitude by enhancing containment DF
  - Reduces doses to the public

  - Reduces longer-term offsite impacts
- SAWA to the RPV has some advantages over water addition to the drywell:
  - Increases the potential to preserve the reactor pressure vessel (RPV) as a fission product barrier
  - Cools core debris and fission products retained in the RPV thereby reducing releases and minimizing long-term thermal challenges to the drywell
  - Provides ex-vessel debris cooling, if needed, via the debris flow path from the RPV
- Addition of an engineered filtration system can reduce the magnitude of controlled (vented) releases from the containment, but the incremental benefit is quite small
  - Filter not effective for uncontrolled releases from containment (i.e., bypass of vent)
- Addition of an engineered filtration system to the containment vent line increases the actions required to manage the accident
  - SAWA is still required
  - Manual operation of the vent is still required
  - Filter management and maintenance
  - Actions will likely be impacted by external source term
- Severe accident water management (SAWM) and vent operation are viable severe accident management strategies that can reduce releases of fission products from containment
  - SAWM can avoid the need to directly vent the drywell, preserving suppression pool scrubbing
  - The results of this analysis are relatively insensitive to variability in consequence metrics.

5.3.3 Conclusions

Manual actions are required to manage the severe accident for all strategies. The adoption of severe accident water addition strategies provides the greatest overall safety benefit, both in terms of protecting containment and reducing releases. Other alternatives, including installation of engineered filters, provide a minimal additional benefit to public health and safety.

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