BWROG Fukushima Response Committee

Plant Evaluation of Severe Accident Mitigation Strategies

Provides results of plant tabletop evaluation of potential strategies to mitigate severe accidents resulting from Fukushima-type events

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I. PURPOSE

A. Introduction

The BWROG initiated a “tabletop” pilot evaluation of the filtering strategy options identified by EPRI in Reference 1. The pilot was performed as a “tabletop” because no physical plant changes were made during the effort; rather the assessment was made using available design and procedural information and postulated details in cases where the designs or procedures did not exist.

A BWR plant with a Mark I containment is the volunteer pilot plant. This plant was not the reference plant used by EPRI. This was a conscious decision by the BWROG to allow the strategies identified by EPRI to be tested at another plant. Further, this pilot investigates in much greater detail the plant-specific capabilities that would need to be employed to support the EPRI filtering strategies for representative severe accident scenarios.

B. Objectives of Pilot

1. Implementability

Evaluate the implementability at a specific plant of strategies (outlined in EPRI 2012 Technical Report 1026539, “Investigation of Strategies for Mitigating Radiological Releases in Severe Accidents: BWR Mark I and Mark II Studies” [Reference 1] for mitigating severe accident scenarios initiated by a long-term loss of electric power

a. Required design changes
b. EOP/SAMG/procedural enhancements
c. FLEX equipment design and availability, and proposed FLEX procedure implementation
d. Containment vent filter considerations

2. Plant-Specific impacts

Verify that plant-specific variations of these generic strategies will achieve the desired performance goal(s) of reducing radionuclide releases and therefore provide support for the performance-based filtering option

a. Demonstrate the overall effectiveness of the Mark I containment system in retaining radionuclides in representative plant scenarios
b. Illustrate successful use of Mitigating Strategies (FLEX) to prevent vessel breach
c. Use of FLEX equipment to support the post core damage strategies that maximize Decontamination Factors

d. Investigate control of vent valve cycling through automatic design or operator action

3. Filtration and Containment Integrity

Demonstrate that the optimal strategies provide filtration and protect containment integrity.

4. Process for Implementation

Outline a process for the plant-specific assessment and implementation of effective, performance-based filtering strategies for other BWRs in the US fleet.

C. Generic Strategies Considered (from EPRI Report)

EPRI’s report [Reference 1] investigating strategies for mitigating radiological releases in severe accidents identify a number of specific filtering strategies, including the installation of an engineered filter system. This effort focuses on the implementation of such strategies at a specific plant.

The industry is in the process of implementing fuel damage prevention strategies under NEI 12-06 [Reference 2] that provides an integrated set of diverse and flexible capabilities to prevent fuel damage and maintain containment integrity. This capability, supported by a set of key installed and portable equipment, is referred to by industry as “FLEX”.

One important insight from the EPRI report is that not all severe accidents will benefit from engineered filters. Different modes of containment failure can impact the effectiveness of an engineered filter. In this effort, the pilot plant considers how their planned FLEX capabilities might be supplemented to enhance release filtering. There are two important issues in considering this:

- Which severe accident scenarios would benefit from filtering strategies and/or engineered filters?
  and
- What is the potential for FLEX-type equipment to be used to support implementation of filtering strategies?

A representative logic tree presented in Figure 1 provides a logical binning process for identifying the severe accident scenarios that may benefit from engineered filters.

The starting point for any consideration of severe accidents is that this is beyond design basis condition. This condition can be either due to a beyond design
basis combination of events and failures or the occurrence of a beyond design basis external event. Some of these conditions can be mitigated by existing engineered safety features. In such cases, core damage would be avoided. Severe accident scenarios that involve loss of containment integrity would result in an engineered filter being bypassed and therefore ineffective. If early core cooling is provided by engineered plant features, then the portable FLEX capabilities provide an additional level of defense against core damage. It is only after the engineered features and the FLEX capabilities are ineffective in preventing core damage that engineered filters or filtering strategies may be required. However, as shown in the referenced EPRI report, the same SAMG actions that direct cooling of the core debris also limit release and support filtering strategies. If debris cooling is not successful, the filter will be bypassed and will be ineffective in mitigating a release. Therefore, it is only those scenarios that have effective SAMG actions that have the potential for an engineered filter to be effective. At the same time those same scenarios benefit from implementation of enhanced SAMG actions (refinements to existing SAMG actions indicated by this tabletop) focused on filtering strategies. Thus, engineered filters are only beneficial in severe accident scenarios where enhanced SAMG capabilities will also enable filtering strategies.

Figure 1
Severe Accident Sequence Binning Tree
In demonstrating the effectiveness of FLEX equipment and procedures for mitigating severe accidents, the question has been raised as to how FLEX equipment can be relied on to mitigate a severe accident when it apparently was not available to prevent the severe accident. The Failure Modes and Effects Analysis (FMEA) shown in Table 0 evaluates the impact of failures of FLEX to prevent core damage on its capability to support filtering strategies.

Three functional failure modes for FLEX are considered:

- Early Core Cooling Fails – these involve system or human failures that prevent the installed plant equipment from functioning until the portable FLEX equipment can be deployed.
- FLEX Deployment Ineffective – these involve failures that impact the deployment of the portable FLEX equipment.
- FLEX Equipment Failures – these involve failures of the portable FLEX equipment itself.

Representative failure causes are identified for each functional failure mode. For each of these failure causes, the impact on the effective implementation of filtering strategies is considered. Finally, the relevant provisions of NEI 12-06 that address these failure modes are described.

As can be seen from this FMEA, many FLEX failure causes do not have any impact on the use of FLEX equipment for filtering strategies. In addition, for the majority of those that could potentially impact implementation of filtering strategies, NEI 12-06 has already included contingency actions to minimize the potential for this failure cause to occur.

Thus, it is concluded that there is a very good possibility of FLEX resources being available to support filtering strategies.

Table 0

<table>
<thead>
<tr>
<th>Functional Failure Mode</th>
<th>Failure Cause Leading to Core Damage</th>
<th>Effect on Filtering Strategies Capability</th>
<th>Prevents Use for Filtering?</th>
<th>Relevant FLEX Provisions (NEI 12-06)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Core Cooling Fails</td>
<td>RCIC/IC fails to operate until FLEX can be deployed</td>
<td>None</td>
<td>NO</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>DC control power lost</td>
<td>None</td>
<td>NO</td>
<td>Capability to manually initiate RCIC required</td>
</tr>
<tr>
<td></td>
<td>RCIC/IC water source unavailable</td>
<td>None</td>
<td>NO</td>
<td>Essentially indefinite supply</td>
</tr>
<tr>
<td>Event</td>
<td>Action</td>
<td>Resolution</td>
<td>Reference Source Required</td>
<td>Notes</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>--------</td>
<td>------------</td>
<td>---------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>RPV instrumentation inadequate</td>
<td>None</td>
<td>NO</td>
<td>Reference source required for all available sources for required parameters</td>
<td></td>
</tr>
<tr>
<td>Substantial LOCA occurs</td>
<td>None</td>
<td>NO</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>FLEX Deployment Ineffective</td>
<td>Operators do not diagnose need for FLEX</td>
<td>Could degrade or delay</td>
<td>DEGRADED FLEX interfaced with EOPs. Training and drill requirements</td>
<td></td>
</tr>
<tr>
<td>Operators fail to deploy in a timely manner</td>
<td>None</td>
<td>NO</td>
<td>Training and drill requirements</td>
<td></td>
</tr>
<tr>
<td>Difficulties transporting equipment</td>
<td>Could delay implementation</td>
<td>YES</td>
<td>Transport and debris removal equipment required</td>
<td></td>
</tr>
<tr>
<td>FLEX deployment precluded by initiating event</td>
<td>Unavailable</td>
<td>YES</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>SRVs fail to open to depressurize RPV</td>
<td>None</td>
<td>NO</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>RPV injection paths impaired</td>
<td>None</td>
<td>NO</td>
<td>Primary and alternate injection path required</td>
<td></td>
</tr>
<tr>
<td>Containment pressure instrumentation inadequate</td>
<td>Degraded capability. SAMG should address actions without instrumentation.</td>
<td>DEGRADED Reference source required for all available sources for required parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetwell vent fails to open</td>
<td>Wetwell vent required for SAMG</td>
<td>YES</td>
<td>EA 12-050 requirements</td>
<td></td>
</tr>
<tr>
<td>FLEX Equipment Failures</td>
<td>FLEX pump(s) fail to start</td>
<td>Degraded or fails enhanced SAMG</td>
<td>YES N+1 pumps provided</td>
<td></td>
</tr>
<tr>
<td>FLEX pump(s) fail to operate long-term</td>
<td>Degraded or fails enhanced SAMG</td>
<td>YES</td>
<td>N+1 pumps provided</td>
<td></td>
</tr>
<tr>
<td>Essential supplies not replenished (e.g., fuel, water, etc.)</td>
<td>Long-term loss of enhanced SAMG</td>
<td>DEGRADED Regional response center provides short-term and long-term supplies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLEX hoses fail</td>
<td>None. Separate hoses provided.</td>
<td>NO</td>
<td>---</td>
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The following enhanced SAMG strategies were considered in the tabletop exercise:

1. **Reliable containment spray @ > 300 gpm**

   This strategy uses a portable FLEX pump and alternate water source to cool or quench ex-vessel core debris, reduce containment temperature, and remove aerosol radionuclides from the containment atmosphere.

2. **Reliable severe accident wetwell vent**

   This strategy uses a dedicated hardened pathway to prevent overpressurization of containment, and relies on the suppression pool to scrub radionuclides.

3. **Reliable severe accident drywell vent**

   This strategy also uses a dedicated hardened pathway to prevent overpressurization of containment. It is used when the containment is flooded to a degree when the wetwell vent is no longer available.

4. **Installed containment vent filter**

   This strategy utilizes a commercial vent filter, of either dry or wet design, to provide additional scrubbing of radionuclides vented through the wetwell or drywell vent line.
II. SUMMARY OF RESULTS

A. Introduction

A tabletop exercise was performed at a BWR with a Mark I containment to evaluate the implementability of the severe accident mitigation strategies developed and analyzed by an interdisciplinary project team, and reported in Reference 1. The goals for the evaluation were:


2. Verify that plant-specific variations of these generic strategies will achieve the desired performance goal(s) of reducing radionuclide releases and therefore provide support for the performance-based filtering option.
   a. Demonstrate the overall effectiveness of the Mark I containment system in retaining radionuclides in representative plant-specific scenarios.
   b. Illustrate that successful use of Mitigating Strategies (FLEX) can prevent vessel breach.
   c. Use of FLEX equipment to support the post core damage strategies that maximize Decontamination Factors.
   d. Investigate control of vent valve cycling through automatic design or operator action.

3. Demonstrate that the optimal strategies provide filtration and protect containment integrity.

4. Outline a process for the plant-specific assessment and implementation of effective, performance-based filtering strategies for other BWRs in the US fleet.

B. Generic Conclusions

1. Injecting to the RPV at or before core slump should prevent RPV breach by core debris and result in effective radionuclide retention in containment.

2. Water on the floor of the Mark I drywell prior to RPV breach by core debris can prevent liner failure and improve radionuclide retention.

3. RPV breach by core debris with no water on the Mark I drywell floor will likely result in liner failure in a very short period of time in some cases.

4. Improved guidance and training for operators to determine when core breach occurs is needed. Instrumentation and procedures to determine the RPV core breach condition may also be needed.
5. Evaluations of containment limiting pressure and the ability to raise them by improving limiting component capability may be appropriate. This evaluation should include uncertainties associated with containment structural response.

6. Controlling containment venting should show improved radionuclide retention over opening and leaving the vent path open.

7. Containment spray is beneficial in managing the severe accident.

8. Procedures need improved direction for shifting strategy between RPV injection and containment flooding.

9. The timing of actions or conditions within the RPV and containment is governed by the power level of the reactor and the integrated heat capacity of the containment. Across the BWR fleet these can vary considerably and therefore the above listed generic conclusions should be considered by accounting for plant-specific attributes.

C. Plant-Specific Insights

Although similarities in prevention and mitigation of core damage exist through use of the BWROG EPGs and SAMGs, plant-specific system design and containment features can have an impact on the degree of benefit of the generic strategies. The insights listed below are deemed applicable to the plant evaluated in the tabletop exercise. Those insights in the Generic Conclusions section above are also applicable to this plant.

1. Allowing containment de-inerting could result in a hydrogen burn and containment failure. Installation of a filter would not prevent this from occurring. A LOCA, though not specifically evaluated here, could result in the same concern.

2. Isolation Condenser availability delays core damage and subsequent vessel breach which results in improved radionuclide retention and also increases the amount of time available to connect and use FLEX equipment.

3. Containment spray is beneficial in managing the severe accident. The specific containment spray configuration at this plant hinders effective spray flow under severe accident conditions.

4. FLEX: Need to maintain DC power availability for ERV operation (loss of power results in steam release to the drywell through the reactor head safety valves).

5. FLEX: May need pumps capable of producing higher drywell spray flow.

6. FLEX: Diverse geographic locations for FLEX connection points needed.

7. Procedures – allowance to vent from the drywell to maintain pressure below Pressure Suppression Pressure (PSP) vs. limiting vent path to the wetwell.

8. The use of ICs resulted in no heat addition to containment from injection sources.
9. The location of the RHV piping above the torus allowed for increased water level in the torus during torus flooding.

D. Implications for Severe Accident Management

- Supplemental procedure guidance is needed to provide direction to the operators as to when actions should be shifted from providing injection to the RPV to providing injection for containment flooding. When implementing the SAG into a plant-specific guideline or procedure, words should be added to the chart that reflect the basis discussion.
- Achieving a sufficient volume of water on the containment floor prior to vessel breach is needed to prevent containment failure.
- Controlling the release of non-condensable gases is needed to prevent negative pressure in the containment (containment pressure limit) and to prevent de-inerting the containment.
- Thermal conditions in the drywell head area could be challenging and should be reviewed.

E. Implications for Determining Need for Filters

- Managing the accident by implementing these filtering strategies, including water injection to the RPV or containment, is much more important than adding an external filter.
- Engineered filters are beneficial only in severe accident scenarios where enhanced SAMG capabilities are employed to prevent containment failure modes that effectively bypass the filter. In such cases, this will also enable filtering strategies.
- The value of a filter is dependent, to some degree, on a plant-specific evaluation that accounts for the procedural and design attributes that influence the progression of the severe accident scenario.
F. Filtering Strategy Effectiveness

Implementing alternate strategies is more important to successful severe accident management than filters. The focus on reducing radionuclides to the environment should be on managing the accident through the primary strategies (cooling and venting) using a prevention strategy rather than mitigation approach; adding a second layer of scrubbing (secondary strategy focused on mitigation) provides only marginal improvement. Simply adding a filter in a vent path to the environment does not effectively manage the accident. The range of conditions possible during severe accidents does not lend credence to an engineered solution that focuses on one specific mode of potential release to the environment. Rather, flexibility in implementing alternate strategies given a range of possible accident progression and timing challenges is better suited toward a performance-based approach using severe accident decision-making provided by the BWROG SAMGs and use of alternate equipment strategies being enhanced through utility response to the Fukushima NTTF Tier 1 recommendations.
III. METHODOLOGY

A. Approach

Figure 2 illustrates the methodology by which this tabletop exercise was performed. Explanations of each step follow.

![Figure 2: Pilot Methodology Diagram](image-url)
1. **Assemble a multi-disciplinary team**

The pilot was performed by a multi-disciplinary team with the following composition:

- Plant site project manager
- Plant experts in operations, EOPs and SAMGs, FLEX implementation, Reliable Hardened Vent (RHV) design, filter procurement planning, PRA
- External (BWROG) project manager (not required for similar exercises at other BWRs)
- EPRI MAAP analysis experts (EPRI personnel not required for similar exercises at other BWRs)
- External plant participants with expertise in plant systems and RHV design (not required for similar exercises at other BWRs)

2. **Identify applicable severe accident scenarios and strategies**

Selection of scenarios and strategies was based on two sources:

- Scenarios reviewed in EPRI 2012 Technical Report 1026539 [Reference 1]
- Insights from the plant-specific PRA for the plant evaluated in this tabletop. At this time, the plant PRA includes internal events, internal flooding, and internal fires, but no external events. However, the nature of the core damage scenarios from these internal hazards are expected to be reasonably representative of scenarios caused by external hazards. Based on the current PRA, five classes of accidents contribute over 95% of the total CDF and are candidates to be addressed in the assessment of filtering strategies:
  - Class 1A - Loss of Inventory (high pressure)
  - Class 1B - Loss of Inventory (station blackout)
  - Class 1D - Loss of Inventory (low pressure)
  - Class 2A - Loss of Inventory after Containment failure
  - Class 5 - Break Outside Containment Loss of Inventory

The first three classes involve scenarios with inadequate makeup to the RPV. The difference in these three scenarios is primarily the timing of core damage, the systems available for release mitigation, and the pressure of the RPV at the time of initiation of core damage. The applicability of filtering strategies to these scenarios can be enveloped by various station blackout scenarios and reliance on the more limited capabilities of portable FLEX-type equipment, i.e., if the Containment Spray System (RHR) is available for drywell sprays, then the filtering
benefits would exceed those predicted with lower capacity portable pumps. Finally, a spectrum of station blackout (SBO) scenarios are present in the internal hazards PRAs:

- Fast SBO, e.g., loss of DC/no EC,
- Long-term SBO, e.g., EC initially works, and
- Very long-term SBO, e.g., late loss of the EC.

In the last two classes, 2A and 5, the containment boundary is compromised. As a result, filtering strategies are not likely to be effective. Consequently, these classes are not evaluated in the plant tabletop exercise.

3. **Identify plant capabilities and guidelines**

At the time of the pilot, the plant was still working to define their FLEX implementation strategies consistent with the NRC’s post-Fukushima requirements. The strategies initially selected for mitigating the severe accident scenarios similarly represent those available to plant operators based on their existing and currently planned plant capabilities and guidelines. These include the following:

- FLEX equipment and procedures currently planned to implement NEI 12-06 [Reference 2]. Plant personnel described that the plant FLEX implementation plan will support deployment and use of the portable FLEX pump within 2 hours of the initial plant conditions indicating that the FLEX capabilities are needed.

- HCVS (Hardened Containment Venting System) capabilities currently planned for installation in response to NRC Order EA-12-050 [Reference 3].

- Severe Accident Management Guidance as incorporated in the plant SAPs (Severe Accident Procedures), which are based on BWROG EPG/SAG Rev 2.

It should be noted that there are several significant design differences between the EPRI reference plant and this plant:

- This plant has an Isolation Condenser (IC) that is their primary core heat removal system in station blackout conditions. In scenarios with the IC available containment response is different than the EPRI reference plant because core decay heat is removed directly from the RPV during the coping period, rather than being transferred to the suppression pool.
  - The plant does not have high pressure steam-driven injection systems like RCIC (or HPCI) similar to the EPRI reference plant.
The plant ADS system utilizes electro-mechanical relief valves (ERVs) rather than the safety-relief valves (S/RVs) used at the EPRI reference plant. In the event of loss of DC power, the ERVs do not relieve pressure. Under such conditions, the reactor head safety valves cycle to maintain RPV pressure. These safety valves discharge directly to the upper region of the drywell rather than through tailpipes to the suppression pool.

The design pressure of the plant suppression pool is lower than the drywell. The pressure at which venting is initiated during severe accident scenarios may be different than other BWRs.

Desirable plant capabilities (design, equipment, or procedures) that do not exist or are not expected to be part of the plant FLEX/HCVS implementation plans were identified as “gaps” as part of the pilot evaluation and documented herein.

4. Identify plant-specific gaps and feasible enhancements

a. Select scenarios

As the primary purpose of the tabletop exercise was to evaluate the EPRI strategies on a plant-specific basis, the scenarios from the EPRI report were aligned to fit the plant capabilities and procedures. Specifically, scenarios and sensitivities are evaluated for the following classes of scenarios:

- Total loss of offsite and onsite AC power with the ICs unavailable.
- Total loss of offsite and onsite AC power with 2 of 4 ICs initially available, but no makeup is available to the ICs.
- Total loss of offsite and onsite AC power with 2 of 4 ICs initially available with 36,000 gallons of makeup available to the ICs.

These classes of scenarios provide a spectrum of core damage timings and allow the effectiveness of filtering strategies to be assessed across a range of sensitivities.

b. Evaluate containment system and filtering strategy

Analyses were performed for the selected scenarios using MAAP 4.0. Initial conditions and, assumptions were selected as described in 4a above to evaluate the EPRI scenarios but considering plant capabilities. Equipment capabilities and procedures used are based on existing plant-specific design or planned changes to address the NRC Orders EA-12-049 [Reference 5] and EA-12-050.

One specific gap identified at the initiation of the pilot was the lack of a means to connect a portable FLEX-type pump to the containment spray header. Since FLEX focuses on core damage prevention, this capability is beyond its scope. The plant identified a possible design change that
would allow a connection to the plant raw water system, which has an existing connection to the spray header. The conceptual design outlined by the plant is to provide a connection for a portable FLEX pump outside of the reactor building. The advantage of this design is that it avoids the need to enter the reactor building so the connection can be made, even after core damage has occurred. The FLEX pump selected by the plant has a runout flow of 600 gpm. However, due to head loss in the piping and drywell spray nozzles, the maximum delivered spray flow was computed to be approximately 375 gpm. The plant containment spray system design uses a common header to supply both drywell and wetwell sprays. Based on the design characteristics of the flow path, roughly 300 gpm would be delivered to the drywell spray and the other 75 gpm would flow through the wetwell spray portion of the header.

The specific strategies evaluated in the pilot are outlined in Section III.B.

c. Perform sensitivity analysis

After performing the initial evaluation of each chosen scenario, in most cases additional sensitivity studies were performed for that scenario to evaluate the effect on containment system performance of possible enhancements to equipment or procedures (example: the use of different pressure control strategies to understand the possible benefit of an automatic control valve for venting instead of manual operator action). In addition, different deployment times are assumed for the FLEX pump, but all times are longer than the planned implementation time of 2 hours.

d. Determine reliability and effectiveness of strategies

The reliability and effectiveness of strategies are evaluated for each scenario. Reliability includes the feasibility and reliability of operator actions and the capability of equipment to support the strategies. Effectiveness includes consideration of the ability to maintain containment integrity and retain radionuclides in containment. If the success of the strategies was confirmed, the team proceeded to analyze the next strategy. If not, possible enhancements to equipment or procedures were considered for additional sensitivity studies.

e. Document results and enhancements

Results of each strategy and sensitivity study are captured later in this report, along with conclusions and a discussion of possible enhancements to equipment and procedures. The equipment and procedures subject to enhancement would include existing plant procedures, EOPs, and SAPs; FLEX equipment and procedures; existing or planned HCVS equipment; or changes to permanently installed equipment.
B. Plant-Specific Filtering Strategies Utilized in This Tabletop

1. Containment spray/flooding @ ≥ 300 gpm
   a. General description:
      This strategy is intended to utilize a portable FLEX pump of providing approximately 300 gpm to the drywell spray headers and connected to an external water source (likely a dry hydrant, though other options are being considered). Primary and alternate injection points outside the Reactor Building are provided. At each of these points the external water source can be directed to either RPV Injection or Containment Spray, with no capability of spraying the torus and drywell separately.
   b. Plant-specific enhancement(s) to be considered as a result of this tabletop:
      • Design or FLEX implementation changes:
        (1) Provide a diverse location (from the primary connection points) for the alternate connection points external to the Reactor Building for injection to the RPV or Containment Spray. This will allow for hooking up the FLEX equipment in case the primary connection point is inaccessible.
        (2) Increased sizing of the RHV and design considerations such as temperature.
      • Plant procedural/SAMG changes: Plant specific SAMG changes may include the ability to vent from the drywell or the torus when managing containment pressure below PSP. This would align the plant to the generic BWROG guidelines.
      • Generic EPG/SAG changes: In severe accident procedures, Operators will normally prioritize RPV injection over Containment Spray. Changes may be necessary to clarify the strategies associated with injection to the RPV and drywell (i.e. Containment Sprays). Changes may also be necessary to improve the operator's ability to detect when vessel breach occurs.
      • During the scenario, while in the plant-specific equivalent of SAG RPV and Primary Containment Flooding step RC/F-5, the operators were intent on getting water on the drywell floor (a specific priority is listed in the plant-specific guideline that reflects the strategy of the basis discussion for step RC/F-5). This led them to disregard the evaluation questions and not realize that if a single portable pump is available, the appropriate action is to connect to RPV injection and restore and maintain RPV injection above the Minimum Debris Retention Injection Rate (MDRIR). As reinforced by one of the MAAP scenarios, this action would prevent RPV breach by core debris.

2. Containment spray @ ≥ 300 gpm
a. General description:

This strategy is intended to utilize a portable FLEX pump of 400 gpm capacity connected to an external water source (likely a dry hydrant, though other options are being considered). Primary and alternate injection points outside the Reactor Building are provided. At each of these points the external water source can be directed to either RPV Injection or Containment Spray with no capability of spraying the torus and drywell separately.

b. Enhancement(s) required, if any, for implementation:

- Plant design or FLEX implementation changes: Same as Item 1.b above
- Plant procedural/SAMG changes: Same as item 1.b above
- Generic EPG/SAG changes: In severe accident procedures, operators will normally prioritize RPV injection over Containment Spray. Changes may be necessary to clarify the strategies associated with injection to the RPV and drywell (i.e. Containment Sprays). Changes may also be necessary to improve the operator’s ability to detect when a vessel breach occurs.

3. Reliable severe accident wetwell vent

a. General description:

The existing 24” hardened vent path is routed from the top of the wetwell through an air-operated and a motor-operated isolation valve to a common header (in the Turbine Building) with the drywell vent and then to the Plant Stack. Planned changes to the hardened vent design include:

- Dedicated 12” flowpath
- New seismically qualified vent piping with more direct routing to release point
- New seismically qualified vent chimney whose exit is above the Reactor Building.
- New AO isolation valves with 24 hour air supply
- Remote control/indication panel in the Control Room
- Upgraded instrumentation with 24-hour power supply, to include
  - Dedicated radiation monitor
  - Temperature
  - Pressure
  - Valve position
  - Support system status
b. Potential scope includes:

- Automatic pressure control valve on the common discharge line
- Flanged connection for potential external engineered filter
- Installation of rupture disks in parallel with PCV (SECY-12-157 also would recommend rupture disks in lieu of CIVs for passive operation)

For the first 24 hours, the system will be remotely operable from the Control Room for up to 10 open/closed cycles. After 24 hours it is planned to replenish the pneumatic supply either from an air compressor or new nitrogen bottles, and with power supplied from FLEX equipment.

c. Enhancement(s) required, if any, for implementation:

- Plant design changes: Pipe size larger than the currently planned 12 inches is being considered to permit higher venting capacities required by severe accidents. Add pressure control valves (manual or automatic) sufficient to support up to 10 open/closed cycles in the first 24 hours.
- Plant procedural/SAMG changes: EOPs and SAPs will be revised to support operation of the RHV system.
- Generic EPG/SAG changes: As with the EPRI study, controlling containment pressure in a band was found to be beneficial.

4. Reliable severe accident drywell vent

a. General description:

In general, the discussion in Section III.B.3 above applies. The drywell vent pathway will have its own isolation valves and will tie into the wetwell vent pathway downstream of the wetwell vent isolation valves.

b. Enhancement(s) required, if any, for implementation:

- Plant design changes: Consistent with Section III.B.3.
- Plant procedural/SAMG changes: Consistent with III.B.3 and changes that will permit the use of the drywell vent to maintain pressure below PSP vs. limiting vent path to the wetwell.
- Generic EPG/SAG changes: Once containment vent has swapped from the wetwell to the drywell and containment sprays have been scrubbing the drywell atmosphere, there may be benefit in slowly reducing containment pressure to reduce the driving force for hydrogen leakage.

5. Installed engineered containment vent filter

a. General description:
Allowance for potential filter installation is reflected in routing the hardened vent line. Potential installation of a RHV filter has been considered and the modification for the RHV is intending to contain flanged connection points that could accommodate future installation and routing of the filtered vent option. Consideration of this option is consistent with the EPRI report’s acknowledgement that a low DF engineered filter may be used in a performance-based approach. Based on current plans, the engineered filter would be downstream of the drywell/wetwell connection points where it forms a combined header. Therefore it would filter the drywell and wetwell paths.

b. Enhancement(s) required, if any, for implementation:

- Plant design changes: Installation of an engineered containment vent filter is a significant challenge. A water-based filter requires significant structural design and presents a number of challenges in the layout of the vent pathway. Consequently, a smaller, lighter dry filter is being considered here. Dry filter vendors assert that testing exists to substantiate their claims that even pre-scrubbed effluents (e.g., wetwell vent effluents) can be effectively scrubbed. These claims were not investigated by the BWROG due to vendor proprietary constraints.

- Plant procedural/SAMG changes: Same as generic changes.

- Generic EPG/SAG changes: The filter, if one is required, will be used only in conjunction with the common RHV wetwell/drywell header.

C. Inputs and Boundary Conditions for Plant Response Analysis

A series of MAAP analyses were performed to investigate the response of the plant to selected mitigation strategies. These strategies, based on the original EPRI analysis, were initiated using plant-specific procedures and guidance and reflect planned FLEX implementation equipment and strategies. As applicable to the various scenarios run, the following represent general assumptions employed in the MAAP analysis.

1. Scenarios initiated by long-term Station Blackout (SBO) and Extended Loss of AC Power (ELAP) conditions.
2. DC power is assumed to be available unless otherwise indicated for specific scenarios.
3. When applicable, 2 of the 4 ICs are credited.
4. Makeup to the IC is not credited, unless specified.
5. Upon reaching the Minimum Zero-Injection RPV Water Level (MZIRWL), 4 ERVs are assumed to be manually opened to depressurize the RPV unless otherwise indicated for specific scenarios.
6. ERVs discharge directly to the suppression pool.
7. For total loss of DC power cases, the ERVs do not function and, therefore, the head safety valves lift to relieve vessel pressure. The safety valves discharge directly into the upper drywell.

8. Onset of core damage is assumed when the maximum core temperature exceeds 1800°F.

9. For accident sequences without water injection to the drywell floor prior to the discharge of core debris from the RPV, containment shell failure is assumed to occur within 15 minutes following vessel breach.

10. Per the PCF-5 branch of SAP-1, the wetwell is initially vented as the pressure approaches the PSP. For conditions in which FLEX is aligned to the RPV before a venting requirement is reached, the appropriate step of SAP-1 will be either PCF-4 (injection rate > MDRIR) or PCF-3 (RPV level > BAF) depending on predicted RPV water level height. In either case, venting is done to remain below the Primary Containment Pressure Limit (PCPL).

11. Upon exceeding a torus water level of 13.5 ft, transfer is made to the PCF-6 branch of SAP-1 and subsequent venting will be based on pressure approaching PCPL.

12. Where containment venting is directed by plant specific procedures, a containment pressure band of 5 psid is selected for use for the analyses performed to demonstrate controlled venting per plant procedures.

13. Upon exceeding a high water level in the torus, the wetwell vent is isolated and any subsequent venting occurs through the drywell.

14. Venting actions are based on the pressure measured at the bottom of the torus.

15. For continued injection or drywell flooding from external water sources, the injection is terminated after the containment water level reaches the specific drywell high water level limit.

16. To simulate the plant design and the proposed FLEX pump injecting to the RPV, a total flow rate of 375 gpm at a shutoff head of 350 psia was assumed.

17. To simulate the proposed FLEX pump spraying the containment, 75 gpm is directed to the torus sprays and 300 gpm to the drywell sprays.

18. The torus spray header is located at 16 ft above the bottom of the torus.

19. Based on plant-specific analysis, flow was calculated to be discharged from the two lower drywell spray headers. These headers are approximately 20 and 30 feet above the floor respectively. An average spray drop height of 15 feet is conservatively assumed.
20. Minimal credit is given for heat removal and radionuclide scrubbing by drywell spray droplets due to the design of the pilot plant spray nozzles and the relatively low flow rates assumed. The assumed droplet diameter of 0.5 inch was based on the nozzle diameter thread entering the spray header with no credit given for droplet breakup resulting from impaction on the nozzle deflector. The aerosol capture efficiency of 0.0003 was conservatively selected as the absolute minimum value from Figure 19 of NUREG/CR-5966, “A Simplified Model of Aerosol Removal by Containment Sprays”, Powers and Burson, June 1993 [Reference 4].

21. A total RPV seal leakage at normal pressure is determined that is consistent with the plant’s Station Blackout (SBO) analysis. This is represented by a constant flow area and, therefore, flow will be reduced as the RPV pressure is lowered.

22. The drywell failure pressure is determined that is consistent with the plant-specific containment design. The actual failure assumes a reduction in pressure capability due to elevated gas temperature. In order to address the thermal inertia of the containment structure, elevated gas temperature effects are assumed to be required to exist for at least 5 minutes before containment breach is assumed.

23. Vent valves can be cycled up to 10 times based on the plant HCVS design; vent valves would be opened at a certain torus pressure and closed at 5 psig lower for those scenarios where they are cycled to maintain PCPL. They would be opened at a different torus pressure and closed at 5 psig lower for those scenarios where they are cycled to maintain PSP.

24. For demonstration purposes, it is assumed that the operators would have at least until the time of core relocation into the lower head to initiate drywell sprays. This is meant to represent the SAPs requiring water on the drywell floor prior to vessel breach.

25. Accident simulation time is assumed to be 72 hours from the initiation of the event.

D. Scenario Evaluations

A total of 6 severe accident scenarios were evaluated as part of the pilot. These scenarios were selected based on the representative core damage scenarios seen in the plant-specific PRA and to align with plausible FLEX failure modes. All scenarios assume all onsite and offsite AC power is unavailable for the duration.

Scenario Description

1. Scenario 1 represents a case where the FLEX capability is delayed such that core damage is not avoided, but RPV injection is established prior to vessel breach.
2. Scenario 2 represents a case where the ICs are initially unavailable and FLEX capability is applied to spray the containment to cool the core debris. The containment vent is assumed to be unavailable.

3. Scenario 3 represents a case where the ICs are initially unavailable, but the ERVs are opened to reduce RPV pressure prior to vessel breach.

4. Scenario 4 represents a case where the ECs are initially unavailable and the ERVs cannot be opened to reduce RPV pressure because DC power is assumed to be unavailable. RPV pressure is controlled strictly with the reactor vessel head safety valves.

5. Scenario 5 represents a case where 2 of the 4 ICs are initially available, but makeup to the ECs is unsuccessful.

6. Scenario 6 represents a case where 2 of the 4 ICs are initially available and makeup of 36,000 gallons to the ECs is successful.

1. **Scenario 1: In-Vessel Retention**

   a. Description:

   This accident sequence was initiated with a total loss of offsite and onsite AC power. In addition, the ICs are assumed to be unavailable. Key events and operator actions included the following:

   - Operator assumed to depressurize the RPV using 4 ERVs when the RPV water level lowers to the MZIRWL.
   - FLEX pump was assumed to be initiated injecting to the RPV at 2.9 hours which corresponded to the time of core relocation into the lower plenum.
   - Containment venting per plant procedures.

   b. Results:

   Key results and accident timing are provided in Table 1.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Loss of AC power</td>
</tr>
<tr>
<td>18 min</td>
<td>RPV level at top of active fuel (TAF)</td>
</tr>
<tr>
<td>27 min</td>
<td>RPV level exceeds MZIRWL, 4 ERVs opened</td>
</tr>
<tr>
<td>45 min</td>
<td>Onset of core damage</td>
</tr>
</tbody>
</table>
Due to the timing for initiation of the FLEX pump, vessel breach was not predicted to occur. The cesium release for this case was estimated at 3.3E-5 or an overall DF of 30,000.

c. **Sensitivity Case Scenario 1a:**

To investigate the timing for the initiation of the FLEX pump, a delay of about 1 hour was assumed. This delay in providing RPV injection until 4 hours did not result in a predicted vessel breach. Core debris was retained in-vessel. There was only a slight change in the time to reach PCPL to 21.4 hours. There was little change in the cesium release for this case.

d. **Output:**

The following figures provide the time history plots for the following parameters:

1. RPV pressure
2. RPV water level (above bottom of RPV)
3. Drywell pressure
4. Drywell gas temperature
5. Suppression Pool temperature
6. Cesium release from the Wetwell vent

Results are plotted for the original case assuming initiation of FLEX at 2.9 hours along with the sensitivity case assuming FLEX initiation at 4 hours. These cases demonstrate the successful use of the FLEX pump after the onset of core damage and the ability to retain core material within the reactor vessel, therefore limiting the overall release of radionuclides from containment. Suppression pool scrubbing via the ERV discharge quenchers is effective at reducing the amount of radionuclides released at the time of wetwell venting.

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9</td>
<td>Relocation of core debris to the lower plenum, initiate FLEX makeup to RPV</td>
</tr>
<tr>
<td>22.9</td>
<td>Containment pressure reaches PCPL, Wetwell vent opened</td>
</tr>
</tbody>
</table>
2. **Scenario 2: Debris Cooling and No Vent**

   a. **Description:**

   This accident sequence was initiated with a total loss of offsite and onsite AC power. In addition, the ICs are assumed to be unavailable. This case is different from the previous Scenario 1 in that containment venting was assumed to not be available and that the FLEX pump was aligned to the containment spray headers. Key events and operator actions included the following:

   - Operator assumed to depressurize the RPV using 4 ERVs when the RPV water level exceeded the MZIRWL.
   - FLEX pump was assumed to be initiated at 2.9 hours providing spray flow to the drywell and torus headers.
   - Containment vent assumed unavailable.
   - Drywell shell failure not assumed in order to estimate overpressure failure time.

   b. **Results:**

   Key results and accident timing are provided in Table 2.

   **Table 2 – Scenario 2 Accident Timing**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Loss of AC power</td>
</tr>
<tr>
<td>18 min</td>
<td>RPV level at TAF</td>
</tr>
<tr>
<td>27 min</td>
<td>RPV level exceeds MZIRWL, 4 ERVs opened</td>
</tr>
<tr>
<td>45 min</td>
<td>Onset of core damage</td>
</tr>
<tr>
<td>2.9 hr</td>
<td>Relocation of core debris to the lower plenum, initiate FLEX to spray drywell</td>
</tr>
<tr>
<td>6.3 hr</td>
<td>Reactor vessel breached due CRD tube penetration failure</td>
</tr>
<tr>
<td>19.5 hr</td>
<td>Drywell failure due to over pressure at elevated temperature</td>
</tr>
</tbody>
</table>

   As seen in the attached figures, the peak containment pressure at the time of vessel breach was about 60 psia, below the ultimate failure pressure. However, due to long term heat transfer from the core debris, the containment pressure and temperature conditions resulted in failure at 19.5 hours.

   With failure of the drywell, the cesium release was about 1.0% representing an overall DF of 100.
c. Output:

The following figures provide the time history plots for the following parameters:

1. RPV pressure
2. RPV water level (above bottom of RPV)
3. Drywell pressure
4. Drywell gas temperature
5. Suppression Pool temperature
6. Cesium release from the drywell failure
3. **Scenario 3: ECs Unavailable**

a. **Description:**

This accident sequence was initiated with a total loss of offsite and onsite AC power. In addition, the Emergency Condensers are assumed to be unavailable. Key events and operator actions included the following:

- Operator assumed to depressurize the RPV using 4 ERVs when the RPV water level lowered to the MZIRWL.
- FLEX pump was assumed to be initiated at 2.9 hours providing spray flow to the drywell and torus headers.
- Containment venting per plant procedures for the base case and as indicated for each of the sensitivity cases.
- There is an initial operator delay in opening the wetwell vent of 20 minutes after reaching the PSP. The purpose of this delay is to account for the fact that the operator may not be anticipating the need to vent and some time will be required to diagnose and execute the vent actions. This same time delay is used in other scenarios, as applicable.

b. **Sensitivity Case Scenario 3S1:**

Sensitivity case 3S1 was run assuming that the venting operation was not controlled as defined by plant guidance. The wetwell vent was assumed to remain open after the initial lift due to pressure approaching the PSP. This case was also run assuming that there was an initial delay of 20 minutes for opening the wetwell vent.
c. Sensitivity Case Scenario 3S2:

Sensitivity case 3S2 was run assuming that the venting operation was controlled as defined by plant guidance, however, to simulate the operation of an automatic pressure control valve; there was no initial delay in opening the wetwell vent.

d. Results:

Key results and accident timing are provided in Table 3.

Table 3 – Scenario 3 Accident Timing

<table>
<thead>
<tr>
<th>Event</th>
<th>Base</th>
<th>3S1</th>
<th>3S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of AC power</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RPV level at TAF</td>
<td>18 min</td>
<td>18 min</td>
<td>18 min</td>
</tr>
<tr>
<td>RPV level exceeds MZIRWL, 4 ERVs opened</td>
<td>27 min</td>
<td>27 min</td>
<td>27 min</td>
</tr>
<tr>
<td>Onset of core damage</td>
<td>45 min</td>
<td>45 min</td>
<td>45 min</td>
</tr>
<tr>
<td>Relocation of core debris to the lower plenum</td>
<td>2.9 hr</td>
<td>2.9 hr</td>
<td>2.9 hr</td>
</tr>
<tr>
<td>Initiation of FLEX to containment sprays</td>
<td>2.9 hr</td>
<td>2.9 hr</td>
<td>2.9 hr</td>
</tr>
<tr>
<td>Reactor vessel breached</td>
<td>6.3 hr</td>
<td>6.3 hr</td>
<td>6.3 hr</td>
</tr>
<tr>
<td>Wetwell vent opened initially opened</td>
<td>6.7 hr</td>
<td>6.7 hr</td>
<td>6.3 hr</td>
</tr>
<tr>
<td>Isolate wetwell vent due to high torus water level</td>
<td>44.9 hr</td>
<td>46.4 hr</td>
<td>44.8 hr</td>
</tr>
<tr>
<td>Drywell vent initially opened</td>
<td>47.6 hr</td>
<td>NA</td>
<td>48.5 hr</td>
</tr>
<tr>
<td>Overall DF (1/cesium release)</td>
<td>3156</td>
<td>833</td>
<td>2674</td>
</tr>
</tbody>
</table>

The containment pressure exceeds the PSP at the time of vessel breach, requiring that the containment be vented. After an initial 20 minute delay, the wetwell vent is opened and closed to maintain pressure within a 5 psid band from the PSP. Over the first 40 minutes following the initial opening of the wetwell vent, the vent is cycled 2 times. Due to continued water addition to the drywell and quenching of the core debris, the pressure remains below the venting pressure until almost 24 hours. As a result of increased water addition to the containment and a reduction in containment free volume, venting continues from 24 to almost 45 hours when high torus water level requires isolation of the wetwell vent. During this 21 hour period the wetwell vent is cycled 8 times to maintain pressure within the prescribed band. Once the wetwell vent is isolated, the pressure
continues to increase requiring venting via the drywell starting at about 48 hours. The accident simulation was terminated after 72 hours of accident time. From 48 through 72 hours, an additional 8 cycles were required using the drywell vent to maintain pressure within the prescribed band.

During the period of wetwell venting, the overall cesium release fraction was 2.3E-4. By the time that drywell venting was required; the majority of airborne radionuclides had been removed from the gas space through gravitational settling and other natural mechanisms. Therefore, the overall cesium release fraction via the drywell vent through 72 hours was less than 1.E-4. Combining these 2 release fractions yields an overall release of less than 3.3E-4, representing and overall in-containment filtering DF of over 3000.

The first sensitivity case (3S1) assumes that the wetwell vent is opened after the initial 20 minute delay from the time of vessel breach, but remains open until isolated on high torus water level. With the vent remaining open from 7 until 46 hours, when it was isolated due to high torus water level, the total cesium release fraction was computed to be 1.2E-3. This equates to an overall in-containment DF of about 833. Since the containment pressure had remained low until 46 hours, long term venting of the drywell was not required within the 72 hour simulation period.

The 3S2 sensitivity case assumed operation of an automatic pressure control valve and was assumed to open immediately upon reaching the PSP limit. The benefit of controlling the pressure shows an overall DF similar to the manual control base case assuming a 20 minute delay in first opening the wetwell vent.

e. Output:

The following figures provide the time history plots for the following parameters:

1. RPV pressure
2. Drywell pressure
3. Drywell gas temperature
4. Drywell water level
5. Cesium release from the drywell Vent
6. Cesium release from the Wetwell Vent
4. **Scenario 4: ICs Unavailable and No DC Power**

a. **Description:**
   
   This accident sequence was initiated with a total loss of offsite and onsite AC power. It is assumed that the ICs are unavailable. In addition, DC power was assumed unavailable, which resulted in the unavailability of the ERVs. Without the ERVs, the pressure from the vessel will be relieved directly into the drywell via the head safety valves. Key events and operator actions included the following:
   
   - FLEX pump was assumed to be initiated at 3.5 hours providing spray flow to the drywell and torus headers. In all cases, FLEX pump usage was chosen concurrent with core relocation. Provided the time is greater than the actual time needed to connect the FLEX equipment (2 hours), the results should be conservative.
   
   - Containment venting per plant procedures for the base case and as indicated for each of the sensitivity cases.
   
   - There is an initial operator delay in opening the wetwell vent of 20 minutes after reaching the PSP.

b. **Sensitivity Case Scenario 4S1:**

   Sensitivity case 4S1 was run to investigate the vent control pressure band. As defined in the base case analysis, the operators would control venting within a 5 psid pressure band. Scenario 4S1 assumed that the pressure band was extended to 20 psid. This resulted in larger variations in pressure.

c. **Sensitivity Case Scenario 4S2:**

   Sensitivity 4S2 assumed that there would be no control of the vent. Once the wetwell vent was opened at the time of vessel breach, it remained open until reaching a high torus water level.

d. **Sensitivity Case Scenario 4S3:**

   Case 4S3 was run assuming that a dedicated source of DC power was made available and used to open a single ERV when the RPV water level exceeded MZIRWL. Similar to the base case, pressure control of the vent at 5 psid was assumed.

e. **Results:**

   Key results and accident timing are provided in Table 4.
Table 4 – Scenario 4 Accident Timing

<table>
<thead>
<tr>
<th>Event</th>
<th>Base</th>
<th>4S1</th>
<th>4S2</th>
<th>4S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of AC and DC power</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RPV level at TAF</td>
<td>20 min</td>
<td>20 min</td>
<td>20 min</td>
<td>20 min</td>
</tr>
<tr>
<td>Containment pressure exceeded PSP</td>
<td>15 min</td>
<td>15 min</td>
<td>15 min</td>
<td>15 min</td>
</tr>
<tr>
<td>Wetwell vent initially opened</td>
<td>35 min</td>
<td>35 min</td>
<td>35 min</td>
<td>35 min</td>
</tr>
<tr>
<td>Open single ERV at MZIRWL</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>29 min</td>
</tr>
<tr>
<td>Onset of core damage</td>
<td>57 min</td>
<td>58 min</td>
<td>58 min</td>
<td>51 min</td>
</tr>
<tr>
<td>Relocation of core debris to the lower plenum</td>
<td>3.5 hr</td>
<td>3.3 hr</td>
<td>3.3 hr</td>
<td>2.8 hr</td>
</tr>
<tr>
<td>Initiation of FLEX to containment sprays</td>
<td>3.5 hr</td>
<td>3.3 hr</td>
<td>3.3 hr</td>
<td>2.8 hr</td>
</tr>
<tr>
<td>Reactor vessel breached</td>
<td>3.5 hr</td>
<td>3.3 hr</td>
<td>3.3 hr</td>
<td>7.0 hr</td>
</tr>
<tr>
<td>Isolate wetwell vent due to high torus water level</td>
<td>45.5 hr</td>
<td>45.1 hr</td>
<td>46.9 hr</td>
<td>44.3 hr</td>
</tr>
<tr>
<td>Drywell vent initially opened</td>
<td>48.1 hr</td>
<td>67.8 hr</td>
<td>&gt; 72 hr</td>
<td>46.2 hr</td>
</tr>
<tr>
<td>Overall DF (1/cesium release)</td>
<td>12658</td>
<td>990</td>
<td>667</td>
<td>1105</td>
</tr>
</tbody>
</table>

The base case scenario results in opening the wetwell vent at 35 minutes into the accident due to approaching the PSP. This early containment pressurization was due to the discharge of steam directly into the drywell from the head safety valves. At 3.5 hours into the accident, the FLEX pump was assumed to be started with flow going to both the drywell and torus spray headers. Due to the continued addition of water to the containment, high torus water level is reached and the wetwell vent was isolated at about 45 hours into the event. Continued addition of water reduces the overall containment free volume and the drywell vent is required at about 48 hours. At the end of the simulation (72 hours), the cesium release fraction via the wetwell vent was 3.6E-5 and 4.3E-5 for the drywell vent path. Combined this represents an overall in-containment DF of about 12,000. This is several times larger than in Scenario 3. This interesting result is due to radionuclides being discharged directly into the drywell early rather than into the wetwell via the ERVs in Scenario 3. The aerosol deposition in the drywell benefits from the sprays operating along with natural aerosol removal mechanisms prior to transport into the wetwell. It is important to keep in mind that both Scenarios 3 and 4 resulted in large DFs, indicating very low releases out of containment.
For sensitivity Scenario 4S1, the vent control was assumed to allow the pressure to be reduced further prior to closing the vent. This control scheme was modeled for both the wetwell and drywell vent. The overall release through the wetwell vent was $1.0 \times 10^{-3}$ representing an overall DF of 990. The slight variation in the time for core material relocation into the lower head is due to small changes in the drywell pressure conditions. These differences can feed back to the in-vessel melt progression due to small changes in the vessel-to-drywell heat transfer. The added benefit of vent control is to prevent any negative pressure being created as part of early venting followed by sprays.

For sensitivity Scenario 4S2, vent control was not modeled and the vent remained open after the initial demand. For this scenario, the wetwell vent was isolated due to high torus water level at 46.9 hours into the accident. Once the wetwell vent was isolated, the pressure did not increase to the limit requiring drywell venting within the 72 hour simulation period.

Sensitivity Scenario 4S3 assumed that a dedicated DC power source was made available to power a single ERV. The ERV was assumed to be opened when the RPV water level exceeded the MZIRWL at 29 minutes into the accident. The overall DF was slightly greater than 1000. The higher release from the wetwell vent path was due to a reduction in the radionuclide removal in the drywell due to opening a direct path from the vessel to the torus pool.

f. Output:

The following figures provide the time history plots for the following parameters:

1. RPV pressure
2. Drywell pressure
3. Drywell gas temperature
4. Drywell water level
5. Cesium release from the drywell Vent
6. Cesium release from the Wetwell Vent
5. **Scenario 5: ICs Initially Available – No IC Makeup**

a. **Description:**

This accident sequence was initiated with a total loss of offsite and onsite AC power. In this case, 2 of the 4 ICs were available, however makeup to the EC after the water was depleted was not assumed. Key events and operator actions included the following:

- FLEX pump was assumed to be initiated at 4.8 hours providing spray flow to the drywell and torus headers.
- Containment venting per plant procedures for the base case and as indicated for each of the sensitivity cases.
- There is an initial operator delay in opening the wetwell vent of 20 minutes after reaching the PSP.

b. **Sensitivity Case Scenario 5S1:**

This sensitivity assumed that pressure control occurred using a larger pressure band. As the base case pressure was controlled within a 5 psid range, Scenario 5S2 assumed a larger band of 20 psid. Note that this sensitivity also assumed that the wetwell was initially opened at the time the containment pressure exceeded PSP, without the 20 minute delay modeled in the base case.

c. **Sensitivity Case Scenario 5S2:**

This sensitivity assumed no venting pressure control. Once the wetwell vent was opened, it remaining open until it was isolated due to high torus water level. Note that this sensitivity also assumed that the wetwell was initially opened at the time the containment pressure exceeded PSP, without the 20 minute delay modeled in the base case.

d. **Results:**

Key results and accident timing are provided in Table 5.

### Table 5 – Scenario 5 Accident Timing

<table>
<thead>
<tr>
<th>Event</th>
<th>Base</th>
<th>5S1</th>
<th>5S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of AC power</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RPV level at TAF</td>
<td>1.5 hr</td>
<td>1.5 hr</td>
<td>1.5 hr</td>
</tr>
<tr>
<td>RPV level exceeds MZIRWL, 4 ERVs opened</td>
<td>1.8 hr</td>
<td>1.8 hr</td>
<td>1.8 hr</td>
</tr>
<tr>
<td>Onset of core damage</td>
<td>2.2 hr</td>
<td>2.2 hr</td>
<td>2.2 hr</td>
</tr>
<tr>
<td>Relocation of core debris to the lower plenum</td>
<td>4.8 hr</td>
<td>4.8 hr</td>
<td>4.8 hr</td>
</tr>
<tr>
<td>Initiation of FLEX to containment sprays</td>
<td>4.8 hr</td>
<td>4.8 hr</td>
<td>4.8 hr</td>
</tr>
<tr>
<td>Reactor vessel breached due</td>
<td>9.0 hr</td>
<td>9.0 hr</td>
<td>9.0 hr</td>
</tr>
</tbody>
</table>
CRD tube penetration failure

| Wetwell vent initially opened | 9.3 hr | 9.0 hr | 9.0 hr |
| Isolate wetwell vent due to high torus water level | 46.2 hr | 47.0 hr | 47.4 hr |
| Drywell vent open (pressure at torus bottom > PCPL) | 48.9 hr | 49.1 hr | NA |
| Overall DF (1/cesium release) | 6329 | 1811 | 1299 |

Successful operation of the emergency condensers extends the timing of core damage and shifts the overall timeline out compared to Scenario 3. At 4.8 hours into the accident, the FLEX pump was assumed to be started with flow going to both the drywell and torus spray headers. The base case scenario results in opening the wetwell vent at 9.3 hours into the accident due to approaching the PSP as a result of a pressure spike occurring at the time of vessel breach. Since the pressure increases rapidly at the time of vessel breach, a 20 minute delay is assumed for the operator to respond to the rapidly changing conditions. Due to the continued addition of water to the containment, high torus water level is reached and the wetwell vent was isolated at about 46 hours into the event. Continued addition of water reduces the overall containment free volume and the drywell vent is required at about 49 hours. At the end of the simulation (72 hours), the cesium release fraction via the wetwell vent was 3.6E-5 and 4.3E-5 for the drywell vent path. Combined, this represents an overall in-containment DF of about 6300. This is twice as large as Scenario 3. The extended time prior to core damage provided by the successful operation of the emergency condensers results in lower decay heating and slightly lower radionuclide releases.

Sensitivity Scenario 5S1 shows a higher release and lower overall in-containment DF due to the larger pressure band used for vent control.

Without any vent control, Scenario 5S2 yields an overall DF of about 1300. Note that all sensitivity cases result in substantial in-containment filtering.

e. Output:

The following figures provide the time history plots for the following parameters:

1. RPV pressure
2. Drywell pressure
3. Drywell gas temperature
4. Drywell water level
5. Cesium release from the drywell Vent
6. Cesium release from the Wetwell Vent
Scenario 5

RPV Pressure (psia)

Time (hrs)

Scenario 5

DW Water Level (ft)

Time (hrs)

Scenario 5

DW Pressure (psia)

Time (hrs)

Scenario 5

CsI DW Vent

Time (hrs)

Scenario 5

DW Gas Temp (F)

Time (hrs)

Scenario 5

CsI WW Vent

Time (hrs)
6. Scenario 6: ICs Initially Available – 36,000 Gallons of Makeup

a. Description:

This accident sequence was initiated with a total loss of offsite and onsite AC power. In this case, 2 of the 4 ICs were available with a total of 36,000 gallons of makeup available. Key events and operator actions included the following:

- ERVs assumed unavailable.
- FLEX pump was assumed to be initiated at 9.3 hours providing spray flow to the drywell and torus headers.
- Containment venting per plant procedures for the base case and sensitivity case 6S1, and as indicated for each of the additional sensitivity cases.

b. Sensitivity Scenario 6S1:

This sensitivity investigated the impact of providing DC power to a single ERV to depressurize the reactor vessel.

c. Sensitivity Scenario 6S2:

This sensitivity assumed no vent pressure control.

d. Sensitivity Scenario 6S3:

This sensitivity also assumed no vent pressure control; however, the initial venting as the containment pressure approached PSP was performed using the drywell vent.

e. Results:

Key results and accident timing are provided in Table 8.

<table>
<thead>
<tr>
<th>Event</th>
<th>Base</th>
<th>6S1</th>
<th>6S2</th>
<th>6S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of AC power</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RPV level at TAF</td>
<td>1.9 hr</td>
<td>1.9 hr</td>
<td>1.9 hr</td>
<td>1.9 hr</td>
</tr>
<tr>
<td>Open a single ERV at MZIRWL</td>
<td>NA</td>
<td>3.5 hr</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Onset of core damage</td>
<td>5.0 hr</td>
<td>5.0 hr</td>
<td>5.0 hr</td>
<td>5.0 hr</td>
</tr>
<tr>
<td>Relocation of core debris to the lower plenum</td>
<td>9.3 hr</td>
<td>7.6 hr</td>
<td>9.3 hr</td>
<td>9.3 hr</td>
</tr>
<tr>
<td>Initiation of FLEX to containment sprays</td>
<td>9.3 hr</td>
<td>7.6 hr</td>
<td>9.3 hr</td>
<td>9.3 hr</td>
</tr>
<tr>
<td>Wetwell vent initially opened</td>
<td>9.3 hr</td>
<td>14.2 hr</td>
<td>9.3 hr</td>
<td>11.0 hr</td>
</tr>
<tr>
<td>Reactor vessel breached</td>
<td>11.0 hr</td>
<td>14.2 hr</td>
<td>11.0 hr</td>
<td>11.0 hr</td>
</tr>
<tr>
<td>Containment failure</td>
<td>NA</td>
<td>NA</td>
<td>11.0 hr</td>
<td>20.1 hr</td>
</tr>
<tr>
<td>Isolate wetwell vent due to</td>
<td>51.7 hr</td>
<td>50.1 hr</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Scenario 6 cases are similar to the Scenario 4 cases in that the ERVs are not available. The Scenario 6 cases include the ICs with a limited amount of makeup available. With the assumed RPV leakage, water level drops to TAF in 1.9 hours into the accident. Onset of core damage occurs at 5.0 hours with vessel breach at 11 hours. After the loss of the ICs, steam is discharged directly to the drywell and the containment pressure approaches the PSP requiring the operators to vent the wetwell at 9.3 hours into the event. In fact, the PSP is reached at the time when the core is relocated into the lower plenum. The steam generation causes the head safeties to relieve into the drywell causing the pressure to exceed the PSP. Due to continued containment flooding from an external water source, the wetwell vent is isolated due to a torus high water level at about 52 hours. With the wetwell vent closed, the containment pressure slowly increases until the drywell vent is required at about 60 hours. The radionuclide release begins at about 9.3 hours when the wetwell vent is first opened. Recall that the vent is cycled for the base case. Release through the drywell vent occurs later. The cesium release via the wetwell vent path is 4.1 E-4 and 2.2E-5 through the drywell path. The combined release represents an overall in-containment DF of about 2300.

Sensitivity Scenario 6S1 is identical to the base case, but with the assumption that a single ERV is available to depressurize the RPV. MZIRWL is the trigger for this action that occurs at 3.5 hours into the event. With the additional release of radionuclides to the wetwell, the initial release when the wetwell vent is opened is slightly larger than in the base case. The wetwell release fraction for cesium is 9.6E-4. For this sensitivity case, the pressure did not increase to require venting of the drywell within the 72 hour simulation period.

Sensitivity Scenario 6S2 assumed no vent control. Once the wetwell vent was opened, it remained open until isolated on high torus water level. A result of leaving the vent path open was purging of all of the non-condensable gas from containment. Once the sprays were initiated, cooling of containment reduced the pressure to below one atmosphere allowing outside gas to be drawn into the vent path. This outside gas contains 20% oxygen and can provide for a combustible atmosphere in the wetwell and drywell. At 11 hours into the event, conditions existed for hydrogen combustion. The assumption made in the calculation was that any hydrogen burning in containment would immediately result in failure of the drywell. This may be somewhat conservative, however due to high temperatures combined with elevated pressure, containment integrity is judged to be threatened.
Sensitivity Scenario 6S3 is identical to 6S2 except that the drywell vent is initially used instead of the wetwell path. This was done to see if some of the existing non-condensable gas could be kept in the torus to prevent the negative pressure seen in case 6S2. Where this was not completely the result, Table 6 shows that the potential for hydrogen combustion was not observed until almost 20 hours into the event. As a result of the drywell breach, cesium releases were higher for 6S2 and 6S3 resulting in significantly lower DFs.

It should also be noted that a negative pressure in containment will either be relieved by drawing flow back through the vent path or via the torus room-to-torus vacuum breakers. The introduction of oxygen into the containment during a severe core damage accident can lead to combustion of the existing hydrogen and the potential for containment breach. Consistent with the similar Scenario 4 cases, this can be avoided with vent control per existing plant guidelines.

f. Output:

The following figures provide the time history plots for the following parameters:

1. RPV pressure
2. Drywell pressure
3. Drywell gas temperature
4. Drywell water level
5. Cesium release from the drywell Vent or Failure
6. Cesium release from the Wetwell Vent
E. Influence of Engineered Containment Vent Filters on Scenarios

As noted in Section I, engineered filters are only beneficial in severe accident scenarios where enhanced SAMG capabilities will also enable filtering strategies. The table below provides a summary of the overall containment system DF computed for the base case of each scenario:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>DF</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – In-Vessel Retention</td>
<td>&gt; 30,000</td>
<td>All debris retained in-vessel</td>
</tr>
<tr>
<td>2 – Debris Cooling &amp; No Vent</td>
<td>~100</td>
<td>Containment failed</td>
</tr>
<tr>
<td>3 – ICs Unavailable</td>
<td>&gt; 3,000</td>
<td>Effective radionuclide retention</td>
</tr>
<tr>
<td>4 – ICs Unavailable and No DC Power</td>
<td>&gt; 10,000</td>
<td>Effective radionuclide retention</td>
</tr>
<tr>
<td>5 – ICs Initially Available – No IC Makeup</td>
<td>&gt; 6,000</td>
<td>Effective radionuclide retention</td>
</tr>
<tr>
<td>6 – ICs Initially Available – 36,000 Gallons of Makeup</td>
<td>&gt; 2,000</td>
<td>Effective radionuclide retention</td>
</tr>
</tbody>
</table>
In each case, except Scenario 2 where the containment vent was assumed to be unavailable and the drywell consequentially failed, the plant-specific filtering strategies were successful in retaining radionuclides in containment. Therefore, the addition of engineered filters was not evaluated further.

However, it is worth noting that the SECY-12-0157 [Reference 6] strategy of simply opening the containment vent pathway and allowing the containment to depressurize was found in Scenarios 6S2 and 6S3 to lead to the introduction of oxygen into containment and a hydrogen burn that failed containment. This is due to the displacement of non-condensables from the containment and quenching of the steam in containment leading to a negative pressure differential between the containment and the reactor building. The Scenario 6 base case did not allow the introduction of oxygen because control of the vent retained sufficient non-condensables to preclude development of a negative pressure condition.

F. Summary and Conclusions

1. Generic Conclusions
   a. Injecting to the RPV at or before core slump should prevent RPV breach by core debris and result in effective radionuclide retention in containment
   b. Water on the floor of the Mark I drywell prior to RPV breach by core debris can prevent liner failure and improve radionuclide retention.
   c. RPV breach by core debris with no water on the Mark I drywell floor will likely result in liner failure in a very short period of time in some cases
   d. Improved guidance and training for operators to determine when core breach occurs is needed. Instrumentation and procedures to determine the RPV core breach condition may also be needed.
   e. Evaluations of containment limiting pressure and the ability to raise them by improving limiting component capability may be appropriate. This evaluation should include uncertainties associated with containment structural response.
   f. Controlling containment venting should show improved radionuclide retention over opening and leaving the vent path open.
   g. Containment spray is beneficial in managing the severe accident.
   h. Procedures need improved direction for shifting strategy between RPV injection and containment flooding.
   i. The timing of actions or conditions within the RPV and containment is governed by the power level of the reactor and the integrated heat capacity of the containment. Across the BWR fleet these can vary considerably and therefore the above listed generic conclusions should be considered by accounting for plant-specific attributes.
2. **Key plant-specific insights**

Although similarities in prevention and mitigation of core damage exist through use of the BWROG EPGs and SAMGs, plant-specific system design and containment features can have an impact on the degree of benefit of the generic strategies. The insights listed below are deemed applicable to the plant evaluated in the tabletop exercise. Those insights in the Generic Conclusions section above are also applicable to this plant.

a. Allowing containment de-inerting could result in a hydrogen burn and containment failure. Installation of a filter would not prevent this from occurring. A LOCA, though not specifically evaluated here, could result in the same concern.

b. Isolation Condenser availability delays core damage and subsequent vessel breach which results in improved radionuclide retention and also increases the amount of time available to connect and use FLEX equipment.

c. Containment spray is beneficial in managing the severe accident. The specific containment spray configuration in the plant hinders effective spray flow.

d. FLEX: Need to maintain DC power availability for ERV operation (loss of power results in steam release to the drywell through the reactor head safety valves).

e. FLEX: May need pumps capable of producing higher drywell spray flow.

f. FLEX: Diverse geographic locations for FLEX connection points needed.

g. Procedures: Allowance to vent from the drywell to maintain pressure below PSP vs. limiting vent path to the wetwell.

h. The use of ICs resulted in no heat addition to containment from injection sources.

i. The location of the RHV piping above the torus allowed for increased water level in the torus during torus flooding.

3. **Implications for Severe Accident Management**

a. Supplemental procedure guidance is needed to provide direction to the operators as to when actions should be shifted from providing injection to the RPV to providing injection for containment flooding. When implementing the SAG into a plant-specific guideline or procedure, words should be added to the chart that reflect the basis discussion.

b. Achieving a sufficient volume of water on the containment floor prior to vessel breach is needed to prevent containment failure.
c. Controlling the release of non-condensable gases is needed to prevent negative pressure in the containment (containment pressure limit) and to prevent de-inerting the containment.

d. Thermal conditions in the drywell head area could be challenging and should be reviewed.

4. Implications for Determining Need for Filters

a. The reduction in post accident release rates derived through containment filtering strategies evaluated in this report is expected to exceed the release rate reduction benefits obtained through installation of an external filter on a generic basis and over a broad spectrum of accident scenarios.

b. Engineered filters are beneficial only in severe accident scenarios where enhanced SAMG capabilities are employed to prevent containment failure modes that effectively bypass the filter. In such cases, this will also enable filtering strategies.

c. The value of a filter is dependent, to some degree, on a plant-specific evaluation that accounts for the procedural and design attributes that influence the progression of the severe accident scenario.

5. Filtering strategy effectiveness

Implementing alternate strategies is more important to successful severe accident management than filters. The focus on reducing radionuclides to the environment should be on managing the accident through the primary strategies (cooling and venting) using a prevention strategy rather than mitigation approach; adding a second layer of scrubbing (secondary strategy focused on mitigation) provides only marginal improvement. Simply adding a filter in a vent path to the environment does not effectively manage the accident. The range of conditions possible during severe accidents does not lend credence to an engineered solution that focuses on one specific mode of potential release to the environment. Rather, flexibility in implementing alternate strategies given a range of possible accident progression and timing challenges is better suited toward a performance-based approach using severe accident decision-making provided by the BWROG SAMGs and use of alternate equipment strategies being enhanced through utility response to the Fukushima NTTF Tier 1 recommendations.
IV. IMPLEMENTATION

This implementation process will be useful to the BWR fleet if the NRC allows a performance-based alternative in connection with the vent filtering issue.

The implementation process is intended to demonstrate that plant severe accident management strategies meet performance goals, rather than trying to achieve a threshold Decontamination Factor. The process, intended to be followed by each plant implementing the strategies described in the report, follows the flow chart laid out in Section III, “Methodology” and Figure 2, and is described in more detail in Section II. The only exception is that the BWROG, EPRI, and external utilities need not be involved in every plant evaluation that follows this process.

In general, performance goals for equipment operation and operator actions should meet the twin objectives of being reliable and effective. Consideration of reliability and effectiveness should involve the following:

- Reliable
  - Equipment designed and maintained for expected conditions
  - Operator actions feasible and reliable
  - Actions proceduralized and trained on
- Effective
  - Maintains acceptable pressures and temperatures throughout containment
  - Maximizes in-containment radionuclide removal mechanisms

Performance goals can be established separately for the principal steps involved in implementing the filtration strategies discussed in this report. These steps and their correlative broad performance goals may include:

- RPV injection using permanently installed equipment
  - Performance Goal: Provide sufficient injection to prevent core relocation
- RPV injection using FLEX equipment and procedures
  - Performance Goal: Provide sufficient injection to prevent core relocation
- Containment spray using FLEX equipment and procedures
  - Performance Goal: Provide sufficient containment spray to quench core debris, prevent containment liner breach, and provide filtration of radionuclides
  - Performance Goal: Provide sufficient containment spray to maintain drywell temperature below appropriate levels
- Controlled wetwell venting using a severe accident capable vent
o Performance Goal: Provide sufficient venting capability to relieve containment pressure as required by applicable procedures

o Performance Goal: Provide capability to maintain containment pressure within a controlled band to minimize oxygen influx into containment

o Performance Goal: Provide capability to open and close the vent as many time as is necessary to vent the wetwell using applicable procedures

- Controlled drywell venting using a severe accident capable vent
  
o Performance Goal: Once wetwell venting is no longer possible due to containment flooding, provide sufficient venting capability to relieve containment pressure as required by applicable procedures
  
o Performance Goal: Provide capability to maintain containment pressure within a controlled band to minimize oxygen influx into containment
  
o Performance Goal: Provide capability to open and close the vent as many time as is necessary to vent the drywell using applicable procedures

- External filtration, if deemed necessary to supplement other strategies
  
o Performance Goal: Provide capability to further reduce radionuclide releases, in addition to reductions from in-containment filtration, if deemed necessary

- Operator actions in carrying out EOPs and SAMGs.
  
o Performance Goal: Provide training on governing EOPs, SAMGs, and FLEX procedures
  
o Performance Goal: Periodically demonstrate capability to effectively utilize EOPs, SAMGs, and FLEX procedures

Achievement of these performance goals will minimize the potential releases from a severe accident at any plant.

As noted above, further development of appropriate performance goals can be carried out separately from this tabletop activity. It is anticipated that an NRC Order, perhaps a revision to Order EA-12-050, will be utilized to implement SECY-12-0157. The development of performance goals should be performed on a generic basis as part of the industry response to this possible Order revision. These performance goals should be coordinated with NRC to assure an appropriate degree of regulatory acceptance before utility planning and implementation begins.
V. REFERENCES


5. EA-12-049, USNRC, “Issuance of Order to Modify Licenses With Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events,” ML12054A735, March 2012

6. SECY-12-0157, USNRC, “Consideration of Additional Requirements for Containment Venting Systems for Boiling Water Reactors With Mark I and Mark II Containments”, ML12325A704, November 2012