BWROG Tabletop: Plant Evaluation of EPRI SAM Strategies

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Generic plant insights

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Summary

Overview

Performance-based approach found to be reliable and effective

Managing containment through debris cooling and reliable venting is the most important strategy

Effective reduction in radionuclides achievable by plant-specific filtration strategies

External filters may be useful for some scenarios as identified on a plant-specific basis

A performance-based approach maximizes the retention of radionuclides within containment to a greater degree than an external filter system alone

Tabletop Goals

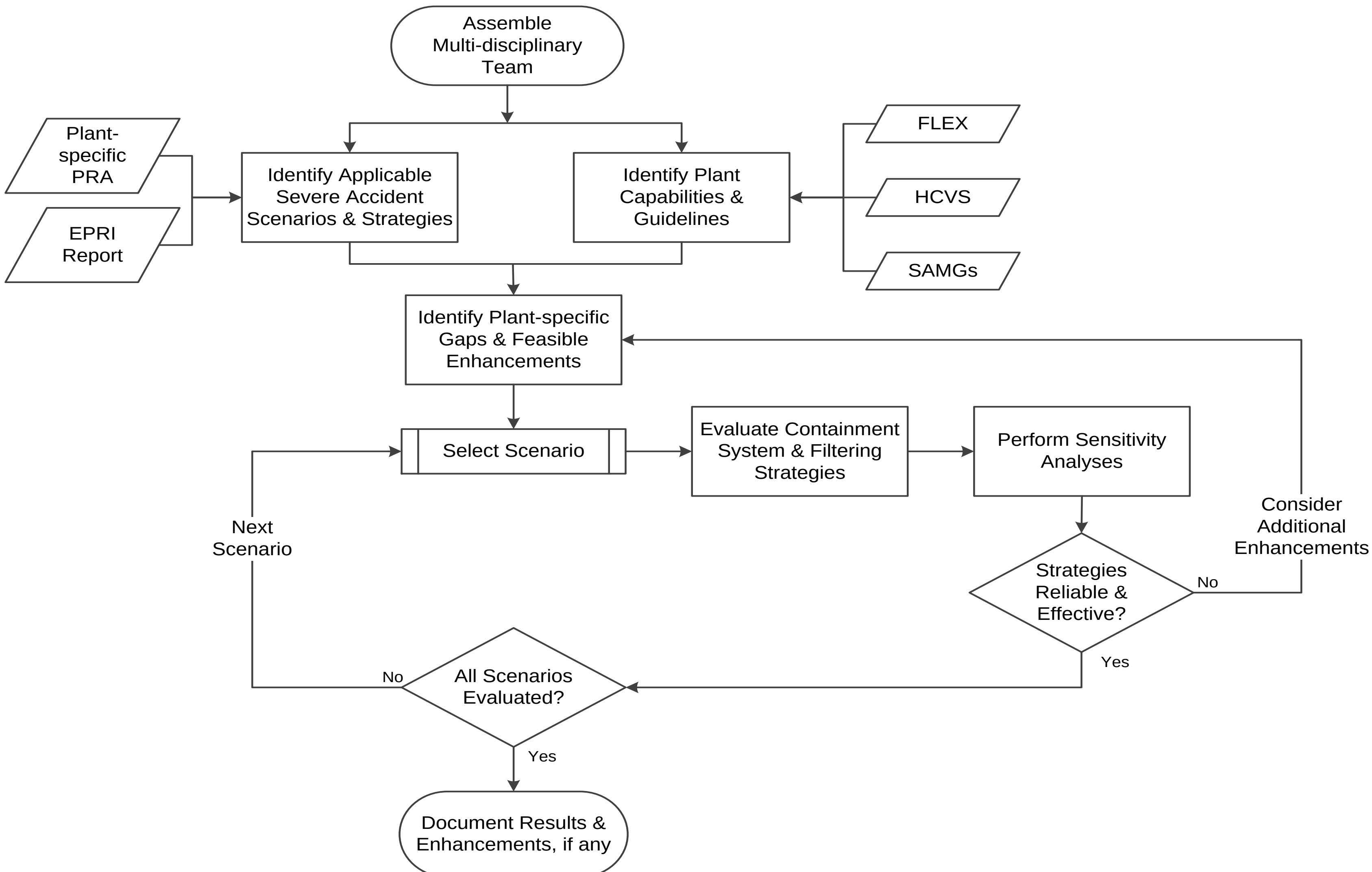
Evaluate the implementation of filtration strategies outlined in EPRI 2012 Technical Report 1026539 at a specific plant

Verify that plant-specific implementation of the generic strategies will achieve the desired performance goal(s) of reducing radionuclide releases

Demonstrate that the strategies provide filtration and protect containment integrity

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

Tabletop Methodology



Methodology: Team Selection

Plant site project manager

Plant experts in operations, EOPs and SAMGs, FLEX implementation, Hardened Containment Vent System (HCVS) design, PRA

External (BWROG) project manager (not required for similar exercises at other BWRs)

MAAP analysis experts

External plant participants with expertise in plant systems and RHV design (not required for similar exercises at other BWRs)

The evaluation benefited from the broad background of individuals knowledgeable in plant operations, design, and risk

Methodology: Strategy Selection (1)

2 sources were used to focus evaluation of plant-specific filtration strategies:

- EPRI report (generic strategies)
- Plant-specific PRA for determining the spectrum of accident sequences of interest

Methodology: Strategy Selection (1) (Cont'd)

EPRI report generic strategies:

- Reliable containment spray @ > 300 gpm
- Reliable severe accident wetwell vent
- Reliable severe accident drywell vent
- Installed containment vent filter

Methodology: Strategy Selection (1) (Cont'd)

Plant PRA: 95% of plant CDF from:

- 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

First 3 can be summarized in 3 SBO scenarios

- Fast SBO
- Long-term SBO
- Very long-term SBO

Last 2 – containment compromised, external filtering strategy ineffective

A **plant-specific PRA provides insight into the dominant core damage scenarios reflecting unique plant features**

Methodology: Plant Capabilities

The evaluation assumed the following plant capabilities:

- FLEX equipment and procedures in response to Order EA-12-049 and NEI 12-06
- HCVS design in response to Order EA-12-050
- EOPs and SAMGs (based on existing plant design)

Methodology: Plant-Specific Gaps and Feasible Enhancements

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

Methodology: Plant-Specific Gaps and Feasible Enhancements (Cont'd)

Select scenarios

Evaluate containment system and filtering strategy

Perform sensitivity analysis

Determine reliability and effectiveness of strategies

Document results and enhancements

Methodology: Plant-Specific Gaps and Feasible Enhancements (Cont'd)

Select scenarios

- Scenarios and sensitivities are evaluated for the following classes of scenarios:
  - Loss of all AC power, ICs unavailable
  - Loss of all AC power, 2 ICs initially available, but no makeup to the ICs
  - Loss of all AC power, 2 of 4 ICs initially available with makeup available to the ICs
- These classes of scenarios provide a spectrum of core damage timings

Methodology: Plant-Specific Gaps and Feasible Enhancements (Cont'd)

Evaluate containment system and filtering strategy

- Scenario analysis using MAAP 4
  - Specific scenario results to follow
- Equipment capabilities based on existing design and procedures or planned changes to address orders
- One identified gap: Lack of means to connect port-able FLEX pump to the containment spray header
  - Design change identified to address this gap

Methodology: Plant-Specific Gaps and Feasible Enhancements (Cont'd)

Perform sensitivity analysis

- Additional sensitivity studies performed for most scenarios to evaluate effect on containment system performance of possible enhancements, such as:
  - Automatically controlled venting
  - Different deployment times for FLEX pumps

Methodology: Plant-Specific Gaps and Feasible Enhancements (Cont'd)

Determine reliability and effectiveness of strategies

- Reliability:
  - Feasibility and reliability of operator actions
  - Capability of equipment to support the strategies
- Effectiveness:
  - Ability to maintain containment integrity
  - Ability to retain radionuclides in containment
- If the success of the strategies was confirmed, the team analyzed the next strategy
- If not, possible enhancements to equipment or procedures were considered for additional sensitivity studies

Methodology: Plant-Specific Gaps and Feasible Enhancements (Cont'd)

Document results and enhancements in report

- Equipment and procedures subject to enhancement:
  - Existing plant procedures, EOPs, and SAPs
  - FLEX equipment and procedures
  - Existing or planned HCVS equipment
  - Permanently installed equipment

Methodology: Strategy Selection (2)

Containment spray/flooding @ $\geq$ 300 gpm

- FLEX pump provides ~ 300 gpm to drywell spray headers
- Possible enhancements:
  - Diverse locations for FLEX pump hookup
  - Increased size of HCVS piping and valves
  - SAMG changes to vent from torus or drywell
  - Generic EPG/SAMG changes to
    - Enhance selection of RPV injection vs drywell spray
    - Enhance RPV breach detection

Methodology: Strategy Selection (2) (Cont'd)

Reliable severe accident wetwell vent

- Implement planned changes to HCVS (EA-12-050)
- Possible enhancements:
  - Automatic pressure control valve (PCV) on vent line
  - Installation of rupture disks in parallel with PCV
  - Flanged connection for potential external filter
  - Additional pneumatic supply beyond 24 hours
  - Increased size of HCVS piping and valves
  - EOP/SAMG changes to support HCVS use
  - Generic EPG/SAMG changes to utilize a pressure control band

Methodology: Strategy Selection (2) (Cont'd)

Reliable severe accident drywell vent

- Implement planned changes to HCVS (EA-12-050)
- Possible enhancements same as for wetwell vent, except
  - EOP/SAMG changes that will permit the use of the drywell vent to maintain pressure below PSP vs. limiting vent path to the wetwell
  - Generic EPG/SAMG changes for slowly reducing containment pressure to reduce the driving force for hydrogen leakage

Methodology: Strategy Selection (2) (Cont'd)

External containment vent filter

- Assumes low DF engineered filter may be used in a performance-based approach
- Water-based filter imposes significant installation challenges in layout of vent pathway
- Dry filter would be considered, if filter required
- Generic and plant-specific EPG/SAMG changes would be needed for filter use in conjunction with HCVS

Methodology: Scenario Analysis

Methodology: Plant-Specific Features

BWR 2 with Mark 1 Containment – 1850 MWth

- Isolation Condensers for decay heat removal, 4 subsystems
- Isolation Condenser makeup tanks – 36,000 gallons
- Four Electromatic Relief Valves (ERVs) for reactor depressurization
- DC power is needed for ERV operation
- Reactor vessel head safeties provide backup pressure protection. No pneumatic or power required for operation but discharge to drywell head region
- No steam driven pumps
- Existing hardened vent path not available during SBO
- B.5.b containment injection path requires Reactor Building entry

Methodology: Analysis Inputs and Assumptions

- When applicable, 2 of the 4 Emergency Condensers (EC) are credited
- Makeup to the EC is normally not credited, unless specified
- Upon reaching the Minimum Zero-Injection RPV Water Level, 4 ERVs are assumed to be manually opened to depressurize the RPV if DC power is available
- ERVs discharge directly to the suppression pool
- For a 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 drywell

Methodology: Analysis Inputs and Assumptions (Cont'd)

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

Per the PCF-5 branch of SAP-1, the wetwell is initially vented as the pressure approaches the Pressure Suppression Pressure (PSP)

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 the Primary Containment Pressure Limit (PCPL)

Venting operations, as defined by plant-specific guidance, recommends controlling the pressure within a defined 5 psid pressure band

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

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

Methodology: Analysis Inputs and Assumptions (Cont'd)

To simulate the proposed FLEX pump injecting to the RPV, a total flow rate of 400 gpm at a shutoff head of 350 psia was assumed

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

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

The average drywell spray fall height is 15 ft

Total RPV seal leakage at normal pressure is assumed to be 115 gpm. This is represented by a constant flow area and, therefore, flow will be reduced as the pressure is lowered

Methodology: Analysis Results

FLEX Recovers Damaged Core In-Vessel

Case	DC Avail	IC Avail	IC makeup	Flex Avail	ERVs	Vent Control	Delay in Vent	DF	Comments
1	Yes	No	NA	Injection @ 3 hr	4	As needed per existing procedure guidance	No	> 10,000	Vessel breach prevented
1a	Yes	No	NA	Injection @ 4 hr	4	As needed per existing procedure guidance	No	> 10,000	Vessel breach prevented with additional delay in Flex

Insights: Flex initiation post core damage but prior to core slump can maintain fuel within the RPV and reduce overall release significantly

Methodology: Analysis Results (Cont'd)

Ex-Vessel Core Debris Cooling without Vent

Case	DC Avail	IC Avail	IC makeup	Flex Avail	ERVs	Vent Control	Delay in Vent	DF	Comments
2	Yes	No	NA	Spray @ 3 hr	4	No Vent	NA	100	W/o vent, Drywell Overpressure failure
Insights: Without successful vent, containment failure results in larger radionuclide release									

Methodology: Analysis Results (Cont'd)

Isolation Condensers Unavailable

Case	DC Avail	IC Avail	IC makeup	Flex Avail	ERVs	Vent Control	Delay in Vent	DF	Comments
3	Yes	No	NA	Spray @ 3 hr	4	Controlled 5 psid	20 min	3,100	Simulates operator vent control
3s1	Yes	No	NA	Spray @ 3 hr	4	Remains Open	20 min	800	Higher release w/o vent control
3s2	Yes	No	NA	Spray @ 3 hr	4	Controlled 5 psid	No	2,600	Simulates auto control
Insights: Vent control results in reduction in radionuclide release									

Methodology: Analysis Results (Cont’d)

Isolation Condensers Unavailable and no DC Power

Case	DC Avail	IC Avail	IC makeup	Flex Avail	ERVs	Vent Control	Delay in Vent	DF	Comments
4	No	No	NA	Spray @ 3 hr	Head Safeties	Controlled 5 psid	20 min	> 10,000	Effective vent control
4s1	No	No	NA	Spray @ 3 hr	Head Safeties	Controlled 20 psid	20 min	≈1000	Larger control band increases release
4s2	No	No	NA	Spray @ 3 hr	Head Safeties	Remains Open	20 min	660	No vent control increases release
4s3	For 1 ERV	No	NA	Spray @ 3 hr	1 ERV @ 30 min	Controlled 5 psid	20 min	1,100	Portable DC to 1 ERV

Insights: Lifting head safeties challenges drywell head due to increased local temperatures, however lower radionuclide release

Methodology: Analysis Results (Cont'd)

Isolation Condensers Initially Available without Makeup

Case	DC Avail	IC Avail	IC makeup	Flex Avail	ERVs	Vent Control	Delay in Vent	DF	Comments
5	Yes	Yes	No	Spray @ 5 hr	4	Controlled 5 psid	20 min	6,300	Effective vent control
5s1	Yes	Yes	No	Spray @ 5 hr	4	Controlled 20 psid	No	1,800	Larger control band increases release
5s2	Yes	Yes	No	Spray @ 5 hr	4	Remains Open	N0	1,300	No vent control increases release
Insights: ICs delay core damage and vent control results in lower radionuclide releases									

Methodology: Analysis Results (Cont'd)

Isolation Condensers Initially Available with 36,000 Gallons Makeup

Case	DC Avail	IC Avail	IC makeup	Flex Avail	ERVs	Vent Control	Delay in Vent	DF	Comments
6	No	Yes	Yes	Spray @ 3 hr	Head Safeties	Controlled 5 psid	No	2,300	Vent control prevents introduction of oxygen into containment
6s1	For 1 ERV only	Yes	Yes	Spray @ 3 hr	1 ERV @ 30 min	Controlled 5 psid	No	1,000	Vent control prevents introduction of oxygen into containment
6s2	No	Yes	Yes	Spray @ 3 hr	Head Safeties	Remains Open	No	30	Introduction of oxygen resulting in hydrogen burn
6s3	No	Yes	Yes	Spray @ 3 hr	Head Safeties	Open Drywell Vent	No	80	Introduction of oxygen resulting in hydrogen burn (delayed)

Insights: Enhancements identified for Flex strategy to power CRD pumps to provide RPV makeup and battery chargers for DC power, also negative impact on vent remaining open IC makeup is on the secondary side of the heat exchanger.

Methodology: Results Summary

Scenario	DF	Comments
1 – In-Vessel Retention	> 30,000	All debris retained in-vessel
2 – Debris Cooling & No Vent	~100	Containment failed
3 – ICs Unavailable	> 3,000	Effective radionuclide retention
4 – ICs Unavailable and No DC Power	> 10,000	Effective radionuclide retention
5 – ICs Initially Available – No IC Makeup	> 6,000	Effective radionuclide retention
6 – ICs Initially Available – 36,000 Gallons of Makeup	> 2,000	Effective radionuclide retention

Methodology: Scenario Analysis Conclusions

1. Core debris cooling is essential for accident management and effective filtering whether performed in containment or using an external filter
2. Controlled venting improves in containment filtering efficiency and prevents hydrogen burn
3. Containment filtering strategies are effective under a variety of assumed plant conditions and equipment availability
4. Maintaining DC power availability using either installed or FLEX sources is needed to ensure ERV operation
5. Increased containment spray capability will improve containment temperature control and containment filtering

Generic Insights

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

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

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

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

Generic Insights (Cont'd)

Evaluations of containment limiting pressure and the ability to raise it by improving limiting component capability may be appropriate. This evaluation should include uncertainties associated with containment structural response

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

Containment spray is beneficial in managing the severe accident

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

Generic Insights (Cont'd)

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

Plant-unique features can influence the benefit of a particular strategy. Prevention of core damage or retention of core debris within the vessel represent the best strategy for retaining radionuclides

Plant-Specific Insights

Generic insights also apply to this plant

Allowing containment de-inerting could result in a hydrogen burn and containment failure. Installation of a filter would not prevent this from occurring

Isolation Condenser availability delays core damage and subsequent vessel breach which results in improved radionuclide retention

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

Plant-Specific Insights (Cont'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)
- May need pumps capable of producing higher drywell spray flow
- Diverse geographic locations for FLEX connection points needed

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

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Plant-Specific Insights (Cont'd)

The use of ICs resulted in no heat addition to containment

The location of the HCVS piping above the torus allowed for increased water level in the torus during torus flooding

Other Insights

Supplemental procedure guidance is needed to provide direction to the operators for shifting from providing injection to the RPV to providing injection for containment flooding

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

Other Insights (Cont'd)

Insights related to use of external filters

- Containment filtering strategies evaluated in this report are expected to provide lower release rates, achieved through reliable ex-vessel debris cooling and over a broad spectrum of accident scenarios, than those obtained through installation of an external filter on a generic basis
- External filters are only marginally beneficial when strategies have been employed to prevent containment failure modes that effectively bypass the filter
- The value of a filter and filtration strategies are 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

Implementation

Focus on performance goals for equipment and operation of mitigation systems rather than DF

Performance goals should be reliable and effective

General performance goals recommended for all equipment and operator actions used in the generic strategies for severe accident mitigation

- Specific performance goals can be developed separately

Implementation (Cont’d)

Possible performance goals for

- RPV injection by permanently installed or FLEX Equipment:
  - Prevent core relocation
- Containment spray via FLEX:
  - Provide sufficient containment spray to quench core debris, prevent containment liner breach, and provide filtration of radionuclides
  - Provide sufficient containment spray to maintain drywell temperature below appropriate levels

Implementation (Cont'd)

Possible performance goals for

- Controlled wetwell venting using a severe accident capable vent:
  - Provide sufficient venting capability to relieve containment pressure as required by applicable procedures
  - Provide capability to maintain containment pressure within a controlled band to minimize oxygen influx into containment
  - Provide capability to open and close the vent as many times as is necessary to vent the wetwell using applicable procedures

Implementation (Cont'd)

Possible performance goals for

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

Implementation (Cont'd)

Possible performance goals for

- External filtration, if deemed necessary to supplement other strategies
  - 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
  - Provide training on governing EOPs, SAMGs, and FLEX procedures
  - Periodically demonstrate capability to effectively utilize EOPs, SAMGs, and FLEX procedures

Summary

Performance-based approach found to be reliable and effective

Managing containment through debris cooling and reliable venting is the most important strategy

Effective reduction in radionuclides achievable by plant-specific filtration strategies

External filters may be useful for some scenarios as identified on a plant-specific basis

A performance-based approach maximizes the retention of radionuclides within containment to a greater degree than an external filter system alone