Filtered Containment Venting Systems

Bob Fretz, Senior Project Manager
Japan Lessons Learned Project Directorate
Office of Nuclear Reactor Regulation

Advisory Committee on Reactor Safeguards
Fukushima Subcommittee
October 3, 2012
Purpose

• To present the staff’s preliminary regulatory analysis of the need for filtered venting systems in BWR Mark I and Mark II containments
Proposed Schedule

• 8:40 – 9:00 Introduction
• 9:00 – 9:45 Design and Regulatory History, and Foreign Experience
• 9:45 – 10:30 FCVS in Severe Accident Management
• 10:30 – 11:00 MELCOR Analysis
• 11:00 – 12:30 MACCS2 Analysis
• 12:30 – 1:30 Break
• 1:30 – 2:30 Risk Evaluation
• 2:30 – 3:30 Regulatory Analysis
• 3:30 – 4:30 Qualitative Arguments
• 4:30 – 5:00 Next Steps
Discussion Outline

• Project Plan
• SECY Paper
  1. Design and Regulatory History
  2. Foreign Experience
  3. Analysis of FCVS in Severe Accident Management
  4. Technical Analyses (MELCOR/MACCS/PRA)
  5. Stakeholder Interactions
  6. Evaluation of Options

• Next Steps
Project Plan - Highlights

- **November 30**: SECY Paper to Commission
- **November 20**: SECY Paper to EDO
- **November 1**: ACRS Full Committee
- **October 31**: ACRS Subcommittee
- **October 30**: Draft Rev. 2 CP to SC
- **October 16**: Draft Rev. 1 CP to SC
- **October 4**: Public Meeting
- **October 3**: ACRS Subcommittee
Purpose of Paper

“The purpose of this paper is to provide the U.S. Nuclear Regulatory Commission (NRC) with information and recommendations from the NRC staff regarding the imposition of new requirements related to containment venting systems for boiling water reactors (BWRs) with Mark I and Mark II containments.”

Options

1. No Change
2. Severe Accident Capable Vent
3. Filtered Vent
4. Performance-Based Approach
SECY Paper Outline

- SECY Paper with Summaries of Enclosures, Options, and Recommendations
  1. Design and Regulatory History
  2. Foreign Experience
  3. Analysis of FCVS in Severe Accident Management
  4. Technical Analyses (MELCOR/MACCS/PRA)
  5. Stakeholder Interactions
  6. Evaluation of Options
Current Status

• Technical and policy assessments and evaluations ongoing

• Preliminary results being shared, subject to change

• Continuing to engage Steering Committee on path forward

• Staff recommendations will be made when technical evaluations and policy assessments are complete
Design and Regulatory History, and Foreign Experience

Bob Dennig
Office of Nuclear Reactor Regulation
Containment and Ventilation Branch
Design and Regulatory History

• Mark I Containments
  – WASH-1400 & NUREG-1150 found that Mark I containments could be severely challenged if a severe accident occurred
  – Relatively small volume
    ▪ Gas and steam buildup affect pressure more dramatically
  – BWR cores have ~3 times the quantity of zirconium as PWRs
    ▪ Potential for hydrogen gas and containment pressurization
Design and Regulatory History

• Mark I Containments
  – Containment Performance Improvement Program
    ▪ Determine what actions, if any, should be taken to reduce the vulnerability to severe accidents
    ▪ Staff recommended
      – Improve hardened vent
      – Improve RPV depressurization system
      – Provide alternate water supply to RPV and drywell sprays
      – Improve emergency procedures and training
    ▪ Commission approved hardened vent
    ▪ Other recommendations evaluated as part of IPE program
Design and Regulatory History

• Mark II Containments
  – Similar to Mark I, the most challenging severe accident sequences are station blackout and anticipated transients without scram
  – Risk profile dominated by early failure with a release that bypasses the suppression pool
  – Hardened venting was considered not beneficial because of unacceptable offsite consequences without an external filter like MVSS
  – Staff did not recommend generic backfit of hardened vent, but recommended a comprehensive evaluation as part of the IPE program
Design and Regulatory History

• Filtered Containment Vents
  – TMI Action Item – 10 CFR 50.34(f) “provide one or more dedicated containment penetrations, equivalent in size to a single 3-foot diameter opening, in order not to preclude future installation of systems to prevent containment failure, such as a filtered vented containment system”
  – Shoreham supplemental containment venting system
  – During the CPIP, possibility of filters for Mark I and Mark II containment vents was raised, but not pursued
  – Significant advancements in containment venting filter technology have occurred over the past 25 years
Design and Regulatory History

• What we have today...Order EA-12-050 requires
  – Reliable hardened vent capable of performing during a prolonged SBO (designed for use prior to the onset of core damage)
  – Severe accident conditions not considered
  – Designed to minimize operator actions
  – Discharges effluent to a release point above main plant structures
Foreign Experience

• Staff visited Sweden, Switzerland, and Canada

• Commission Paper will summarize FCVS regulatory and technical bases, and status of FCVS in other countries

• Insights from visits and public meetings consistent with previous findings
  – 1988 CSNI Report 156, Specialists’ Meeting on Filtered Containment Venting Systems

• Together, FCVS and containment flooding scrub fission products from core debris and remove decay heat
Foreign Experience

• Government decree and/or regulator’s order after TMI, Chernobyl, or Fukushima
  – Some plants installed or committed to install FCVS prior to requirement (e.g., Germany and Japan)
  – Regulator and industry develop guidance following regulatory decision (e.g., Sweden)
  – Some countries have periodic backfit reviews
    ▪ Actual accidents more influential to decision (e.g., Switzerland)
  – Severe accidents were not part of the design basis when the decision was made
Foreign Experience

• Technical Bases Summary
  – Manage severe accident overpressure challenges
  – Defense-in-depth to address uncertainties associated with severe accidents
  – Significantly reduce offsite release and land contamination

• After Barsebäck filter was installed, subsequent filter costs considered low to modest
Foreign Experience

• Quantitative Bases Summary
  – Sweden land contamination goal
  – Require a Level 3 PSA
    ▪ Level 1 frequencies low but not sufficient
    ▪ After the decision, ensure equipment performance is acceptable generically and on plant-specific basis
      – Acceptable not judged quantitatively – “significantly reduce”, “almost eliminate”, etc.
      – Factored into emergency planning
## Status of FCVS Internationally

<table>
<thead>
<tr>
<th>Country</th>
<th>Boiling Water Reactors (BWR) by Containment Types</th>
<th>PWR</th>
<th>PWR/VVER</th>
<th>PHWR</th>
<th>PHWR/Candu</th>
<th>LWGR/RBMK/EGP</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>GE Mark I</td>
<td>GE Mark II</td>
<td>ABB Mark II</td>
<td>GE Mark III</td>
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<td>ABWR</td>
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<td>China</td>
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<td>Czech Republic</td>
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<td>Germany</td>
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<td>Ukraine</td>
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<tr>
<td>United Kingdom</td>
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</tr>
</tbody>
</table>

| #                        | FCVS installed and operational, or Committed to installing FCVS |
| #                        | Considering installing FCVS                                    |
| #                        | No FCVS; has not committed to installing FCVS                  |
| #                        | FCVS Status Unknown                                             |

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# Foreign Experience

## FCVS Status at Non-U.S. BWR Facilities

<table>
<thead>
<tr>
<th>FCVS Status</th>
<th>GE Mark I</th>
<th>GE Mark II</th>
<th>ABB Mark II</th>
<th>GE Mark III</th>
<th>Other</th>
<th>ABWR</th>
<th>Totals</th>
<th>Percentage</th>
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</thead>
<tbody>
<tr>
<td>FCVS Operational</td>
<td>1</td>
<td>0</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>13</td>
<td>30%</td>
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<tr>
<td>Committed</td>
<td>6</td>
<td>7</td>
<td>0</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>25</td>
<td>57%</td>
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<tr>
<td>Considering</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>5%</td>
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<tr>
<td>No FCVS</td>
<td>2</td>
<td>2</td>
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<td>0</td>
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<td>0</td>
<td>4</td>
<td>9%</td>
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<tr>
<td><strong>Non-U.S. Totals</strong></td>
<td><strong>10</strong></td>
<td><strong>9</strong></td>
<td><strong>6</strong></td>
<td><strong>7</strong></td>
<td><strong>9</strong></td>
<td><strong>3</strong></td>
<td><strong>44</strong></td>
<td></td>
</tr>
</tbody>
</table>
FCVS in Severe Accident Management

Jerry Bettle
Office of Nuclear Reactor Regulation
Containment and Ventilation Branch
FCVS in Severe Accident Management

• Reviewed spectrum of plant procedures
• EOPs and SAMGs describe multiple containment vent pathways
• EDMGs provide portable pumps for RPV/DW injection
• Existing guidance provides for containment venting and injecting water to the reactor cavity
• EOPs focus on preventing core damage
• Decision to vent may be complicated with an unfiltered vent
FCVS in Severe Accident Management

- DW Sprays for Decontamination
  - Spray headers designed for DBA purposes (pressure control and heat removal) with flow rates of 1,000’s GPM (provide estimated DFs around 10)
  - Portable pumps with flow rates in low 100’s GPM result in spray nozzle dribble and DFs much less than full flow DFs
    - Good for cavity flooding
    - Not as effective for decontamination
FCVS in Severe Accident Management

• Suppression Pool for Decontamination
  – SRV discharge via T-quencher in bottom of subcooled suppression pool provides an aerosol DF of 100 to 300
  – Downcomer pipes which discharge higher in the suppression pool at or near saturation temperatures provide DFs of 10 or less
FCVS in Severe Accident Management

- EPRI Investigation of Strategies for Mitigating Radiological Releases in Severe Accidents
  - Employs a portable pump to flood drywell cavity and maintain suppression pool subcooling
  - Controls containment pressure near design value for holdup, settling, plate-out, spray effect, and high velocity discharge into suppression pool
  - Cycles containment vent valves to maintain containment pressure band (substantial reliance on instrumentation, valves/actuators, and operator actions)
  - Swap-over from WW to DW vent after 20 hours as containment floods up
FCVS in Severe Accident Management

• Staff preliminary assessment of EPRI investigation
  – Did not address potential increase in penetration leakage due to increased heat, radiation, and pressure
  – Did not address operation of valve, including instrumentation, procedures and human performance
  – Did not address water vapor condensation in vent line and potential for hydrogen buildup
Options Identified by Staff

• No Change (Option 1)
• Severe Accident Capable Vent (Option 2)
• Filtered Vent (Option 3)
• Performance-Based Approach (Option 4)
Option 2 - Severe Accident Capable Vent

• Upgraded reliable hardened vent for severe accident conditions and service
  – Higher temperatures and pressure
  – Hydrogen considerations in the vent line (inerting considerations)
  – Severe accident capable vent valves
  – Shielding for operator actions and personnel access to reactor building and/or remote manual operation of vent valves
Option 2 - Severe Accident Capable Vent

- Capable of safely handling hydrogen – Protect the reactor building and mitigate early hydrogen pressurization
- Capable of safely handling fission products – Maintain reactor building integrity for access to instrumentation and equipment, and facilitate operator actions
- Wetwell vent path only (did not consider consequences of swap-over to drywell vent)
- Protects containment by venting even after core damage
- Success depends on uncertain accident progression, decontamination in the suppression pool, and drywell sprays
- Upgrading existing Mark I vent path may require more work than expected for the reliable hardened vent
Option 3 - Filtered Vent

- Significant enhancement in severe accident containment performance
  - Benefits of Option 2 plus defense in depth enhancements
- No identified technical or safety problems
- Venting with a filter results in a much smaller release compared to without a filter
- Proven, feasible option that has been implemented in several countries
Option 3 - Filtered Vent

- External Filter System
  - Vent line branch from wetwell with normally closed valves are most compatible with early venting
    - May eventually be submerged and unusable due to drywell water injection
  - Vent line from drywell with two branches (one with rupture disk and normally open valve for passive venting, and the other with normally closed valves for early manual venting)
    - Supports drywell floodup and avoids shifting from wetwell to drywell venting and reliance on operator action to preserve containment function for 24+ hrs
Option 3 - Filtered Vent

- External Filter System
  - Staff would develop a technical basis to require a minimum DF or other performance requirement
    - e.g., DF > 1,000 aerosols (including submicron),
    - e.g., DF > 100 elemental Iodine
  - Engage stakeholders to develop appropriate performance criteria
  - May require active and passive features for prolonged SBO under severe accident conditions
Option 3 - Filtered Vent

• External Wet Filter System
Option 4 - Performance Based

• Potential approaches
  – Each plant meets a defined DF for a defined source term
  – Each plant meets criteria defined for combination of event frequencies and DF
  – Each plant performs a site-specific cost/benefit analysis

• Could potentially address forthcoming industry “filtering strategy” proposal (anticipating industry submittal)
Technical Analysis of Options 1, 2, & 3

• NRR identified a number of accident sequences (i.e., cases) to be evaluated by RES in support of conducting a Regulatory Analysis
  – Base cases were intended to be representative of options considered
  – Sensitivity cases also evaluated

• MELCOR calculations
  – Calculations informed by SOARCA and Fukushima
  – Various prevention and mitigation actions

• MACCS calculations
  – Venting with and without filter

• Event sequences and probabilities
• Consequence and frequency estimates
MELCOR Analysis

Sudhamay Basu and Allen Notafrancesco
Office of Nuclear Regulatory Research
Fuel and Source Term Code Development Branch
Insights on BWR Mark I Response

• SOARCA Peach Bottom Analysis
  – Base case SBO sequences with no sprays or venting
  – Primary containment vessel failure modes
    ▪ DW liner shell melt-thru and over-pressure
  – Reactor building accident response
    ▪ Blow-out panels open, local H2 combustion, and roof failure

• Fukushima
  – Long term SBO with protracted RCIC operation
  – Primary containment vessel failure modes
    ▪ Over-pressurization with leakage thru drywell head and containment penetrations?
  – Reactor building accident response
    ▪ Significant combustion events
Filtered Vent MELCOR Analysis

- Based on SOARCA MELCOR modeling
- Accident sequences
  - Informed by SOARCA and Fukushima
  - Long-term SBO (base case 16 hr RCIC)
- Mitigation actions
  - B.5.b and/or FLEX provide core spray or drywell spray (300 gpm)
  - Containment venting
- Sensitivity analysis
  - Spray flow rate and timing, wetwell versus drywell venting, and RCIC duration
Insights from MELCOR Calculations

• Water on the drywell floor is needed to prevent liner melt-through
  – Also scrubs fission products and reduces drywell temperature

• Venting prevents over-pressurization failure
  – Wetwell venting is preferable to drywell venting

• Need combination of venting and drywell flooding
  – More reduction in fission product release
  – Maintain reactor building integrity
MELCOR BWR Nodalization

Reactor Building Nodalization

Containment Nodalization
### Examples of MELCOR Results

<table>
<thead>
<tr>
<th>Event Timing (hr.)</th>
<th>Case 2 RCIC only</th>
<th>Case 3 RCIC + wetwell vent</th>
<th>Case 6 RCIC + core spray</th>
<th>Case 7 RCIC + core spray + wetwell vent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station blackout</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>RCIC flow terminates</td>
<td>17.9</td>
<td>17.9</td>
<td>17.9</td>
<td>18.0</td>
</tr>
<tr>
<td>Core uncovery</td>
<td>22.9</td>
<td>22.9</td>
<td>22.9</td>
<td>22.9</td>
</tr>
<tr>
<td>Relocation of core debris to lower plenum</td>
<td>25.9</td>
<td>25.9</td>
<td>25.9</td>
<td>25.8</td>
</tr>
<tr>
<td>RPV lower head failure</td>
<td>37.3</td>
<td>34.3</td>
<td>36.7</td>
<td>33.8</td>
</tr>
<tr>
<td>Drywell pressure &gt; 60 psig</td>
<td>22.8</td>
<td>22.8</td>
<td>23.3</td>
<td>23.2</td>
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<tr>
<td>Drywell head flange leakage (&gt;80 psig)</td>
<td>25.5</td>
<td>---</td>
<td>25.4</td>
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</tr>
<tr>
<td>Drywell liner melt-through</td>
<td>40.3</td>
<td>36.6</td>
<td>---</td>
<td>---</td>
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<tr>
<td>Calculation terminated</td>
<td>48</td>
<td>48</td>
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</table>
## Examples of MELCOR Results

<table>
<thead>
<tr>
<th>Event Timing (hr.)</th>
<th>Case 12 RCIC + drywell vent</th>
<th>Case 13 RCIC + drywell spray + drywell vent</th>
<th>Case 14 RCIC + drywell spray</th>
<th>Case 15 RCIC + drywell spray + wetwell vent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station blackout</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
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<td>17.9</td>
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<td>28.7</td>
<td>25.7</td>
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<tr>
<td>Calculation terminated</td>
<td>48</td>
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</tbody>
</table>
## Examples of MELCOR Results

<table>
<thead>
<tr>
<th>Selected MELCOR Results</th>
<th>Case 2 RCIC only</th>
<th>Case 3 RCIC + vent</th>
<th>Case 6 RCIC + core spray</th>
<th>Case 7 RCIC + core spray + vent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris mass ejected (1000 kg)</td>
<td>286</td>
<td>270</td>
<td>255</td>
<td>302</td>
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<tr>
<td>In-vessel hydrogen generated (kg-mole)</td>
<td>525</td>
<td>600</td>
<td>500</td>
<td>600</td>
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<tr>
<td>Ex-vessel hydrogen generated (kg-mole)</td>
<td>461</td>
<td>708</td>
<td>276</td>
<td>333</td>
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<tr>
<td>Other non-condensable generated (kg-mole)</td>
<td>541</td>
<td>845</td>
<td>323</td>
<td>390</td>
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<tr>
<td>Cesium release fraction at 48 hrs.</td>
<td>1.32E-02</td>
<td>4.59E-03</td>
<td>3.76E-03</td>
<td>3.40E-03</td>
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<tr>
<td>Iodine release fraction at 48 hrs.</td>
<td>2.00E-02</td>
<td>2.81E-02</td>
<td>1.70E-02</td>
<td>2.37E-02</td>
</tr>
</tbody>
</table>
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<th>Case 15 RCIC + drywell spray + wetwell vent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris mass ejected (1000 kg)</td>
<td>345</td>
<td>351</td>
<td>267</td>
<td>257</td>
</tr>
<tr>
<td>In-vessel hydrogen generated (kg-mole)</td>
<td>714</td>
<td>793</td>
<td>614</td>
<td>650</td>
</tr>
<tr>
<td>Ex-vessel hydrogen generated (kg-mole)</td>
<td>774</td>
<td>410</td>
<td>327</td>
<td>276</td>
</tr>
<tr>
<td>Other non-condensable generated (kg-mole)</td>
<td>922</td>
<td>485</td>
<td>383</td>
<td>270</td>
</tr>
<tr>
<td>Cesium release fraction at 48 hrs.</td>
<td>1.93E-01</td>
<td>1.86E-01</td>
<td>1.12E-03</td>
<td>3.01E-03</td>
</tr>
<tr>
<td>Iodine release fraction at 48 hrs.</td>
<td>4.90E-01</td>
<td>4.84E-01</td>
<td>5.41E-03</td>
<td>1.86E-02</td>
</tr>
</tbody>
</table>
Drywell Pressure

- Pressure (psia)
- Time (hr)

- Red: RCIC (case 2)
- Green: RCIC+vent (case 3)
- Blue: RCIC+CS (case 6)
- Orange: RCIC+CS+vent (case 7)
- Purple: RCIC+DW spray (case 14)
- Black: RCIC+DW spray+vent (case 15)

- Wetwell vent at 60 psig in cases 3, 7, and 15

- Lower head failure in cases 2 and 6
- Case 2: liner melt-thru
- Case 14: beginning of drywell head-flange leak
- Case 3: liner melt-thru
- Case 15: lower head failure
- Beginning of drywell head-flange leakage in cases 2 and 6
MACCS2 Analyses Supporting Filtered Containment Venting Systems Commission Paper

Tina Ghosh
Office of Nuclear Regulatory Research
Nathan Bixler
Sandia National Laboratories
Outline

• Overview of MACCS2
  – MACCS2 Modules
    ▪ ATMOS: Atmospheric Modeling
    ▪ EARLY: Emergency Phase Modeling
    ▪ CHRONC: Long Term Phase Modeling
  – MACCS2 Uses
  – References

• MACCS2 analysis for filtered containment venting systems
  – Scope of analysis
  – Inputs
  – Results of calculations, venting with and without filter
Overview of MACCS2

• MACCS2: MELCOR Accident Consequence Code System 2
  – Level-3 PRA tool to assess the risk and consequence associated with a hypothetical release of radioactive material into the atmosphere
  – First released in 1997
  – Evolved from series of codes: CRAC, CRAC2, MACCS, MACCS2
  – Estimates consequences
    ▪ Health effects – numbers and risks
    ▪ Economic impacts – land areas and costs
  – No equivalent industry code

• WinMACCS Graphical User Interface
  – Assist the user in creating MACCS2 inputs
  – Preprocessor for MACCS2 input
  – Postprocessor for MACCS2 output
  – Allow uncertainty mode sampling

• Use of MACCS2 in State-of-the-Art Reactor Consequences Analyses study peer-reviewed by independent panel of experts
MACCS2 models the radioactive transport through the atmosphere (e.g. plume rise, dispersion, dry and wet deposition)

MACCS2 estimates the health effects from: inhalation, cloudshine, groundshine, skin deposition, and ingestion (e.g. water, milk, meat, crops)
MACCS2 Modules

• ATMOS
  – Not associated with a phase
  – Atmospheric transport and deposition

• EARLY (1 day to 1 week)
  – Emergency-phase
  – Prompt and latent health effects
  – Effects of sheltering, evacuation, and relocation

• CHRONC
  – Intermediate phase (0 to 1 year)
  – Long-term phase (0 to 317 years; 30-50 years typical)
  – Latent health effects
  – Effects of decontamination, interdiction, and condemnation
ATMOS Module

Atmospheric Transport and Dispersion (ATD) Estimates

• Dispersion based on Gaussian plume segment model
  – Provisions for meander and surface roughness effects
  – Phenomena not treated in detail in this model: irregular terrain, spatial variations in wind field, temporal variations in wind direction
  – A study (NUREG/CR-6853) comparing the MACCS2 ATD model with two Gaussian puff codes and a Lagrangian particle tracking code showed that the MACCS2 mean results (over weather) were within a factor of 2 for arc-averages and a factor of 3 at a specific grid location out to 100 miles from the point of release.

• Multiple Plume Segments (up to 200)
• Plume rise from initial release height
• Effects of building wake on initial plume size
• Dry and wet deposition
• Radioactive decay and ingrowth (150 radionuclides, 6 generations)
ATMOS Module (continued)

• MELCOR source term is input via MELMACCS

• Meteorological data required
  – Wind speed and direction
  – Pasquill stability category
  – Precipitation rate
  – Seasonal AM and PM mixing-layer height

• User selectable meteorology sampling options
  – Single weather sequence
  – Multiple weather sequences
    ▪ Statistical sampling to represent uncertain conditions at the time of a hypothetical accident

• Outputs
  – Dispersion parameters, $\chi/Q$, fraction remaining in plume
  – Air and ground concentrations
EARLY Module

• Emergency-phase consequences
  – Acute and lifetime doses for following dose pathways
    ▪ Inhalation (direct and resuspension),
    ▪ Cloudshine
    ▪ Groundshine
    ▪ Skin deposition
  – Associated health effects
    ▪ Early injuries/fatalities from acute doses
    ▪ Latent health effects from lifetime committed doses

• Doses are subject to effects of
  – Sheltering
  – Evacuation
    ▪ Speed can vary by phase, location, precipitation
  – Relocation criteria for individuals
    ▪ Based on projected dose

• Outputs
  – Doses, health effects, land contamination areas
CHRONC Module

• Intermediate Phase (optional, 0 to 1 year)
  – Dose pathways
    ▪ Groundshine
    ▪ Resuspension inhalation
  – Continued relocation is only protective action

• Long-Term Phase (up to 317 years, 30 to 50 typical)
  – Dose pathways
    ▪ Groundshine
    ▪ Resuspension inhalation
    ▪ Ingestion
  – Protective actions
    ▪ Based on habitability and farmability
    ▪ Actions include
      – Decontamination
      – Interdiction
      – Condemnation
Decision logic for long-term protective actions

- Habitability criterion initially met?
  - No actions required
  - Population home at beginning of long-term phase

- Decontamination sufficient to restore habitability?
  - First-level decontamination performed if sufficient
  - Sequentially higher levels of decontamination performed if required
  - Population returns home following decontamination

- Decontamination plus interdiction sufficient to restore habitability?
  - Highest-level decontamination performed
  - Property is interdicted up to 30 years
  - Population returns home following decontamination plus interdiction

- Property is condemned when
  - Habitability cannot be restored within 30 years
  - Cost to restore habitability > value of property
CHRONC Module (continued)

• Economic costs
  – Per diem and lost income for evacuation/relocation
  – Moving expense lost income for interdicted property
  – Decontamination labor and materials
  – Loss of use of property
  – Condemned property
  – Contaminated crops and dairy

• Output
  – Doses by pathway and organ
  – Latent health effects
  – Economic costs
MACCS2 Uses

• PRAs and other severe accident studies (e.g., SOARCA)
  – Risks from operating a facility
  – Relative importance of the risk contributors
  – Insights on potential safety improvements

• NRC Regulatory Analyses
• NEPA Studies (National Environmental Policy Act) such as: License extension and new reactor applications
  – Environmental Impact Statements (EISs)
    ▪ the results of the calculations are typically used to compare the accident risks posed by various alternatives
  – Severe Accident Mitigation Alternatives (SAMAs) and Design Alternative (SAMDAs) analyses required for license renewal and for new licenses

• DOE Applications: Authorization basis analyses performed for DBAs
  – the analyst is interested in conservatively calculated, bounding dose estimates for well-defined DBA and beyond-DBA accident scenarios. The results of this analysis are used to determine if the safety basis of the facility is adequate for operation (DOE 1989, 1992b)

• MACCS2 has an international usership (US plus over 10 other countries)
References

- Consolidated NUREG/CR Manual Under Development
Scope of Analysis for Filtered Vents

MACCS2 used to calculate:

• Offsite population doses
  – Includes doses to public as well as off-site decontamination workers

• Individual latent cancer fatality risk and prompt fatality risk

• Land contamination
  – For different thresholds of Cs-137 concentration in soil (Ci/km²)

• Economic cost

• For 50-mile radius around plant
Inputs

• Work is based on the SOARCA project, which is documented in NUREG-1935 and NUREG/CR-7110 Volume 1
• Started with SOARCA inputs for Peach Bottom Atomic Power Station pilot plant (with exception of source term, and ingestion pathway modeled)
• Habitability (return) criterion used is 500 mrem/year, per Pennsylvania State guideline
• Statistical sampling of weather sequences used to represent uncertain conditions at the time of a hypothetical accident (~1,000 weather trials)
• Linear-no-threshold dose response model
Inputs – Six Emergency Phase Cohorts

• Cohort 1: 0 to 10 Public
• Cohort 2: 10 to 20 Shadow
• Cohort 3: 0 to 10 Schools and 0 to 10 Shadow
• Cohort 4: 0 to 10 Special Facilities
• Cohort 5: 0 to 10 Tail
• Cohort 6: Non-Evacuating Public (assumed to be 0.5%)

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Inputs – Decontamination Factor of Filters

- Neither MELCOR nor MACCS2 models mechanistically the decontamination effect of an external filter
- A prescribed decontamination factor (DF) value is assigned for an external filter
- This DF is applied to only a portion of the total fractional release - the portion which is released through a flow path connected to venting
- For the MACCS2 input, the MELCOR source term from the relevant flow path was reduced by the DF
## MACCS2 Results Per Event

<table>
<thead>
<tr>
<th>Event</th>
<th>Base case Case 2</th>
<th>Base case with WW venting Case 3 Unfiltered Filtered DF = 10</th>
<th>Base case with core spray Case 6</th>
<th>Base case with WW venting and core spray Case 7 Unfiltered Filtered DF = 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population dose 50 mile radius per event (rem)</td>
<td>510,000</td>
<td>400,000&lt;br&gt;180,000</td>
<td>310,000</td>
<td>240,000&lt;br&gt;37,000</td>
</tr>
<tr>
<td>Population weighted latent cancer fatality (LCF) risk 50 mile radius per event</td>
<td>4.8E-05</td>
<td>3.3E-05&lt;br&gt;1.3E-05</td>
<td>2.5E-05</td>
<td>1.6E-05&lt;br&gt;2.2E-06</td>
</tr>
<tr>
<td>Contaminated area (km²) with level exceeding 15 µCi/m² per event</td>
<td>280</td>
<td>54&lt;br&gt;8</td>
<td>72</td>
<td>34&lt;br&gt;0.4</td>
</tr>
<tr>
<td>Total economic cost 50 mile radius per event ($M)</td>
<td>1,900</td>
<td>1,700&lt;br&gt;270</td>
<td>850</td>
<td>480&lt;br&gt;18</td>
</tr>
</tbody>
</table>
## MACCS2 Results Per Event (continued)

<table>
<thead>
<tr>
<th>Event</th>
<th>Base case with drywell venting</th>
<th>Base case with DW venting and DW spray</th>
<th>Base case with drywell spray</th>
<th>Base case with WW venting &amp; drywell spray</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case 12 Unfiltered Filtered 1 DF=1,000 Filtered 2 DF=5,000</td>
<td>Case 13 Unfiltered Filtered DF=1,000</td>
<td>Case 14</td>
<td>Case 15 Unfiltered Filtered DF = 10</td>
</tr>
<tr>
<td>Population dose 50 mile radius <em>per event</em> (rem)</td>
<td>3,800,000 230,000 210,000</td>
<td>3,900,000 60,000</td>
<td>86,000</td>
<td>280,000 43,000</td>
</tr>
<tr>
<td>Population weighted latent cancer fatality (LCF) risk 50 mile radius <em>per event</em></td>
<td>3.2E-04 1.6E-05 1.4E-05</td>
<td>3.3E-04 3.7E-06</td>
<td>6.4E-06</td>
<td>2.1E-05 2.7E-06</td>
</tr>
<tr>
<td>Contaminated area (km²) with level exceeding 15 $\mu$Ci/m² <em>per event</em></td>
<td>9,200 28 25</td>
<td>8,800 2</td>
<td>10</td>
<td>28 0.3</td>
</tr>
<tr>
<td>Total economic cost 50 mile radius <em>per event</em> ($M)</td>
<td>33,000 390 370</td>
<td>33,000 38</td>
<td>116</td>
<td>590 20</td>
</tr>
</tbody>
</table>
Insights from MACCS2 Calculations

• The health effect of interest is latent cancer fatality risk, which is controlled in part by the habitability (return) criterion
  – Essentially no prompt fatality risk
• In terms of long-term radiation, the most important isotope is Cs-137, and most of the doses are from ground shine
• There is a non-linear relationship between decontamination factor and both land contamination area and health effects
Severe Accident Containment Vent Risk Evaluation

Marty Stutzke
Office of Nuclear Regulatory Research
Outline

• Purpose
• Conditional Containment Failure Probability
• Insights from Severe Accident Mitigation Alternatives (SAMA) Analyses
• Technical Approach
• Results
• Uncertainties
Purpose

- To estimate the risk reduction resulting from installation of a severe accident containment vent for use in regulatory analysis
  - 50-mile population dose ($\Delta$person-rem/ry)
  - 50-mile offsite cost ($\Delta$/ry)
  - Onsite worker dose risk ($\Delta$person-rem/ry)
  - Onsite cost risk ($\Delta$/ry)
  - Land contamination ($\Delta$conditional contaminated land area)
Conditional Containment Failure Probability
(BWR Individual Plant Examinations)

Source: NUREG-1560, Figure 12.3
Conditional Containment Failure Probability
(PWR Individual Plant Examinations)

Source: NUREG-1560, Table 12.17
## Conditional Containment Failure Probability
### (ILRT Extension License Amendments)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Type</th>
<th>ILRT Interval</th>
<th>Accident Phenomena</th>
<th>Bypass (ISLOCA)</th>
<th>Isolation Failures</th>
<th>Total CCFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper</td>
<td>Mark I</td>
<td>3 in 10y</td>
<td>94.6%</td>
<td>0.0%</td>
<td>1.0%</td>
<td>95.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 10y</td>
<td>94.6%</td>
<td>0.0%</td>
<td>1.0%</td>
<td>95.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 15y</td>
<td>94.6%</td>
<td>0.0%</td>
<td>1.0%</td>
<td>95.6%</td>
</tr>
<tr>
<td>Nine Mile Point 1</td>
<td>Mark I</td>
<td>3 in 10y</td>
<td>62.4%</td>
<td>2.7%</td>
<td>9.7%</td>
<td>74.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 10y</td>
<td>62.4%</td>
<td>2.7%</td>
<td>9.7%</td>
<td>74.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 15y</td>
<td>62.4%</td>
<td>2.7%</td>
<td>9.8%</td>
<td>74.9%</td>
</tr>
<tr>
<td>Peach Bottom</td>
<td>Mark I</td>
<td>3 in 10y</td>
<td>61.1%</td>
<td>2.4%</td>
<td>2.7%</td>
<td>66.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 10y</td>
<td>61.1%</td>
<td>2.4%</td>
<td>3.4%</td>
<td>67.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 15y</td>
<td>61.1%</td>
<td>2.4%</td>
<td>4.0%</td>
<td>67.5%</td>
</tr>
<tr>
<td>Pilgrim</td>
<td>Mark I</td>
<td>3 in 10y</td>
<td>97.7%</td>
<td>0.6%</td>
<td>0.0%</td>
<td>98.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 10y</td>
<td>97.7%</td>
<td>0.6%</td>
<td>0.1%</td>
<td>98.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 15y</td>
<td>97.7%</td>
<td>0.6%</td>
<td>0.1%</td>
<td>98.4%</td>
</tr>
<tr>
<td>Vermont Yankee</td>
<td>Mark I</td>
<td>1 in 10y</td>
<td>86.8%</td>
<td>1.1%</td>
<td>0.1%</td>
<td>88.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 15y</td>
<td>86.8%</td>
<td>1.1%</td>
<td>0.2%</td>
<td>88.1%</td>
</tr>
<tr>
<td>LaSalle</td>
<td>Mark II</td>
<td>3 in 10y</td>
<td>82.9%</td>
<td>2.4%</td>
<td>0.4%</td>
<td>85.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 10y</td>
<td>82.9%</td>
<td>2.4%</td>
<td>0.6%</td>
<td>85.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 15y</td>
<td>82.9%</td>
<td>2.4%</td>
<td>0.8%</td>
<td>86.1%</td>
</tr>
<tr>
<td>Limerick</td>
<td>Mark II</td>
<td>3 in 10y</td>
<td>62.4%</td>
<td>1.3%</td>
<td>0.7%</td>
<td>64.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 10y</td>
<td>62.4%</td>
<td>1.3%</td>
<td>1.5%</td>
<td>65.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 15y</td>
<td>62.4%</td>
<td>1.3%</td>
<td>2.0%</td>
<td>65.7%</td>
</tr>
</tbody>
</table>
Consideration of Filtered Containment Vents in SAMA Analyses
(As of February 2012)

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Filtered Containment Vent Not Considered</th>
<th>FCV Considered (Screening Analysis)</th>
<th>FCV Considered (Detailed Analysis)</th>
<th>License Renewal Granted, but Limited SAMA</th>
<th>License Renewal Application Not Submitted</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWR Mark I</td>
<td>5</td>
<td>11</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>BWR Mark II</td>
<td>1</td>
<td>3</td>
<td></td>
<td>2</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>BWR Mark III</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>PWR large dry containment</td>
<td>22</td>
<td>10</td>
<td>14</td>
<td></td>
<td>9</td>
<td>55</td>
</tr>
<tr>
<td>PWR subatmospheric containment</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>PWR ice condenser</td>
<td>2</td>
<td>4</td>
<td></td>
<td>3</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>28</td>
<td>26</td>
<td>29</td>
<td>3</td>
<td>18</td>
<td>104</td>
</tr>
</tbody>
</table>

Screening Analysis: cost of implementation > plant-specific maximum possible monetized averted risk
### Detailed SAMA Analyses of Filtered Containment Venting

<table>
<thead>
<tr>
<th>Plant</th>
<th>Offsite Dose Reduction</th>
<th>Estimated Benefit</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FitzPatrick</td>
<td>3.73%</td>
<td>$4,090</td>
<td>Successful torus venting accident progression source terms were reduced by a factor of 2 to reflect the additional filtered capability</td>
</tr>
<tr>
<td>Pilgrim</td>
<td>0.00%</td>
<td>$0</td>
<td>Successful torus venting accident progression source terms were reduced by a factor of 2 to reflect the additional filtered capability</td>
</tr>
<tr>
<td>Vermont Yankee</td>
<td>0.11%</td>
<td>$200</td>
<td>Successful torus venting sequences were binned into the Low-Low release category to conservatively assess the benefit of this SAMA</td>
</tr>
</tbody>
</table>

Not clear if post-core-damage venting to prevent containment overpressurization failure was considered in these analyses
## Core Damage Frequency

<table>
<thead>
<tr>
<th>Source</th>
<th>CDF (/ry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUREG-1150 Peach Bottom (includes internal events, fires, and seismic events based on the LLNL hazard curves)</td>
<td>1E-4</td>
</tr>
<tr>
<td>SPAR Internal and External Event Models (BWR Mark I Plants)</td>
<td>1E-5, 2E-5</td>
</tr>
<tr>
<td>Duane Arnold</td>
<td>2E-5</td>
</tr>
<tr>
<td>Monticello</td>
<td></td>
</tr>
<tr>
<td>Peach Bottom</td>
<td></td>
</tr>
<tr>
<td>SAMA Analyses (Five BWR Mark I and Mark II plants with internal and external event PRAs)</td>
<td>2E-5 to 6E-5</td>
</tr>
<tr>
<td>Global Statistical Value</td>
<td>3E-4</td>
</tr>
</tbody>
</table>
## Economic Consequences

<table>
<thead>
<tr>
<th>Source</th>
<th>cost/event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulatory analysis handbook</td>
<td>$3B*</td>
</tr>
<tr>
<td>(NUREG/BR-0184, Table 5.6, Peach Bottom, 1990 dollars)</td>
<td></td>
</tr>
<tr>
<td>SAMA Analyses</td>
<td></td>
</tr>
<tr>
<td>Peach Bottom</td>
<td>$10B*</td>
</tr>
<tr>
<td>Minimum for BWR Mark I and Mark II plants (Hatch)</td>
<td>$0.6B*</td>
</tr>
<tr>
<td>Maximum for BWR Mark I and Mark II plants (Hope Creek)</td>
<td>$30B*</td>
</tr>
<tr>
<td>Estimated Fukushima offsite costs (3 Units)</td>
<td>$62B</td>
</tr>
<tr>
<td>(Japan Center for Economic Research, June 2011, includes land condemnation for 20 km and compensation for 10 years)</td>
<td></td>
</tr>
<tr>
<td>Deepwater Horizon oil spill</td>
<td>$23B</td>
</tr>
</tbody>
</table>

*Frequency-weighted average of the point estimates for internal events*
Designing a Technical Approach

• Focus on BWR Mark I plants
• Risk modeling
  – No change in CDF
  – Need to use simplified Level 2/3 PRA
    ▪ Not feasible to develop complete Level 3 PRA
    ▪ SOARCA MELCOR and MACCS2 for Peach Bottom

• Eight candidate plant modifications
  – Vent actuation: manual or passive
  – Vent location: wetwell or drywell
  – Filter: no or yes

• Consideration of post-core-damage core spray or drywell spray to prevent liner melt-through

Affects frequency estimation

Affects consequence estimation
Assumptions and Groundrules

• Use existing regulatory analysis guidance
  – Risk evaluation developed on a “per-reactor” basis
  – Multi-unit accidents not addressed
  – Spent fuel pool accidents not addressed

• Release sequence consequences are reasonably approximated by determining the consequences of SBO sequences

• Battery life is 16 hours

• Filter decontamination factor of 10

• No credit for recovering offsite power if core-damage was caused by an external hazard (e.g., seismic, high winds)

• If a sequence involves failure to open the vent or containment bypass (e.g., ISLOCA), then use of a portable pump (B.5.b/FLEX) for core spray or drywell spray following core damage is precluded due to a harsh work environment (high dose rates, high temperatures, etc.)
Release Event Tree

<table>
<thead>
<tr>
<th>CD</th>
<th>Hazard</th>
<th>Sequence Type</th>
<th>Vent</th>
<th>OSP Recovery</th>
<th>Portable Pump</th>
<th>Seq</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>internal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>Vented</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>LMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>OP + LMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>Vented</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>Vented</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>LMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>OP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>OP + LMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9</td>
<td>OP + LMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>Vented</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td>LMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>OP + LMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13</td>
<td>Vented</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>LMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>OP + LMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>OP + LMT</td>
</tr>
</tbody>
</table>

- SBO: System Bus Overload
- LMT: Loss of Main Supply
- OP: Overpressure
# Release Sequence Quantification Data Sources

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core-damage frequency</td>
<td>2E-5/ry</td>
<td>SPAR models</td>
</tr>
<tr>
<td>Fraction of total CDF due to external hazards</td>
<td>0.8</td>
<td>SPAR-EE models</td>
</tr>
<tr>
<td>Breakdown of sequence types for internal hazards</td>
<td>Other (not SBO, bypass, or fast)</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>SBO</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Bypass (ISLOCAs)</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Fast (MLOCAs, LLOCAs, ATWS)</td>
<td>0.01</td>
</tr>
<tr>
<td>Breakdown of sequence types for external hazards</td>
<td>Other (not bypass)</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Bypass</td>
<td>0.05</td>
</tr>
</tbody>
</table>
## Release Sequence

### Quantification Data Sources

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability that severe accident vent fails to open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod 0</td>
<td>1</td>
<td>Current situation (base case)</td>
</tr>
<tr>
<td>Mods 1,3,5,7 – other or SBO</td>
<td>0.3</td>
<td>SPAR-H (manual vent, longer available time)</td>
</tr>
<tr>
<td>Mods 1,3,5,7 - fast</td>
<td>0.5</td>
<td>SPAR-H (manual vent, shorter available time)</td>
</tr>
<tr>
<td>Mods 2,4,6,8</td>
<td>0.001</td>
<td>Engineering judgment (passive vent)</td>
</tr>
<tr>
<td>Conditional probability that offsite power is not recovered by the time of lower head failure given not recovered at the time of core damage (internal hazards)</td>
<td>0.38</td>
<td>NUREG/CR-6890</td>
</tr>
<tr>
<td>Probability that portable pump for core spray or drywell spray fails</td>
<td>0.3</td>
<td>SPAR-H; consistent with B.5.b study done by INL</td>
</tr>
</tbody>
</table>
Mapping Release Sequence End States to MELCOR/MACCS2 Cases

<table>
<thead>
<tr>
<th>Release Sequence End State</th>
<th>Identifier</th>
<th>LMT</th>
<th>OP</th>
<th>OP + LMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vented</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Drywell Status</td>
<td>wet</td>
<td>dry</td>
<td>wet</td>
<td>dry</td>
</tr>
<tr>
<td>Sequences</td>
<td>1,4,5,10,13</td>
<td>2,6,11,14</td>
<td>7</td>
<td>3,8,9,12,15,16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vent Location</th>
<th>Filter</th>
<th>Mod(s)</th>
<th>MELCOR/MACCS2 Case</th>
<th>MELCOR/MACCS2 Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetwell</td>
<td>No</td>
<td>0 - none</td>
<td>Case 7 or 15</td>
<td>Case 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 - manual</td>
<td>(no filter)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 – passive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drywell</td>
<td>No</td>
<td>3 - manual</td>
<td>Case 13</td>
<td>Case 14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 – passive</td>
<td>(no filter)</td>
<td></td>
</tr>
<tr>
<td>Wetwell</td>
<td>Yes</td>
<td>5 - manual</td>
<td>Case 7 or 15</td>
<td>Case 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 – passive</td>
<td>(filter)</td>
<td></td>
</tr>
<tr>
<td>Drywell</td>
<td>Yes</td>
<td>7 - manual</td>
<td>Case 13</td>
<td>Case 14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 - passive</td>
<td>(filter)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Case 7 or 15 refers to cases without a filter; Case 3, 6, 12, 14, and 15 refer to cases with a filter.
## Accident Sequence Frequency Contributions

<table>
<thead>
<tr>
<th>Containment Failure Mode</th>
<th>Manual Vent Mods 1, 3, 5, 7</th>
<th>Passive Vent Mods 2, 4, 6, 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overpressurization (OP)</td>
<td>0.4%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Liner Melt-Through (LMT)</td>
<td>19.6%</td>
<td>28.0%</td>
</tr>
<tr>
<td>Overpressurization and Liner Melt-Through (OP + LMT)</td>
<td>33.1%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Total</td>
<td>53.2%</td>
<td>33.1%</td>
</tr>
</tbody>
</table>
Reduction in Population Dose Risk ($\Delta$person-rem/reactor-year)

<table>
<thead>
<tr>
<th></th>
<th>Unfiltered</th>
<th></th>
<th>Filtered</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wetwell</td>
<td>Drywell</td>
<td>Wetwell</td>
<td>Drywell</td>
</tr>
<tr>
<td>Manual</td>
<td>Mod 1</td>
<td>Passive</td>
<td>Mod 5</td>
<td>Manual</td>
</tr>
<tr>
<td>Mod 2</td>
<td>Manual</td>
<td>Passive</td>
<td>Mod 6</td>
<td>Passive</td>
</tr>
<tr>
<td>Mod 3</td>
<td>Mod 3</td>
<td>Mod 4</td>
<td>Mod 7</td>
<td>Mod 8</td>
</tr>
</tbody>
</table>

| Reduction in Population Dose Risk | 3.0 | 4.3 | -44.3 | 5.7 | 8.2 | 5.3 | 7.6 |

Unfiltered: 3.0 - 4.3 = -44.3
Filtered: 5.7 - 8.2 = -63.3
Reduction in Offsite Cost Risk ($/reactor-year)

<table>
<thead>
<tr>
<th>Unfiltered</th>
<th>Filtered</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wetwell</td>
</tr>
<tr>
<td>Manual</td>
<td>Mod 1</td>
</tr>
<tr>
<td>Passive</td>
<td>Mod 2</td>
</tr>
<tr>
<td>$13,842</td>
<td>$19,767</td>
</tr>
</tbody>
</table>

\(-$414,582\)

\(-$592,117\)
**Reduction in Worker Dose Risk**  
\((\Delta \text{person-rem/reactor-year})\)

<table>
<thead>
<tr>
<th></th>
<th>Unfiltered</th>
<th>Filtered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetwell</td>
<td>Manual</td>
<td>Mod 2</td>
</tr>
<tr>
<td>Drywell</td>
<td>Manual</td>
<td>Mod 3</td>
</tr>
<tr>
<td></td>
<td>Passive</td>
<td>Mod 4</td>
</tr>
</tbody>
</table>

- **Unfiltered**
  - Wetwell: 0.14
  - Drywell: 0.20

- **Filtered**
  - Wetwell: 0.17
  - Drywell: 0.25

- **Manual**
  - Wetwell: 0.14
  - Drywell: 0.20

- **Passive**
  - Wetwell: 0.17
  - Drywell: 0.25
## Reduction in Onsite Cost Risk

(Δ$/reactor-year)

<table>
<thead>
<tr>
<th>Unfiltered</th>
<th></th>
<th>Filtered</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetwell</td>
<td>Manual</td>
<td>Drywell</td>
<td>Manual</td>
</tr>
<tr>
<td>Mod 1</td>
<td>Manual</td>
<td>Mod 2</td>
<td>Mod 3</td>
</tr>
<tr>
<td>Mod 3</td>
<td>Passive</td>
<td>Mod 4</td>
<td>Passive</td>
</tr>
<tr>
<td>Mod 5</td>
<td>Manual</td>
<td>Mod 6</td>
<td>Manual</td>
</tr>
<tr>
<td>Mod 7</td>
<td>Passive</td>
<td>Mod 8</td>
<td>Passive</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unfiltered</th>
<th></th>
<th>Filtered</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetwell</td>
<td>$10,634</td>
<td>Drywell</td>
<td>$24,485</td>
</tr>
<tr>
<td>Mod 1</td>
<td>$15,185</td>
<td>Mod 2</td>
<td></td>
</tr>
<tr>
<td>Mod 3</td>
<td>$10,634</td>
<td>Mod 4</td>
<td>$17,147</td>
</tr>
<tr>
<td>Mod 5</td>
<td>$17,147</td>
<td>Mod 6</td>
<td>$17,147</td>
</tr>
<tr>
<td>Mod 7</td>
<td></td>
<td>Mod 8</td>
<td>$24,485</td>
</tr>
</tbody>
</table>
### Reduction in Conditional Contaminated Land Area (Δsquare kilometers)

<table>
<thead>
<tr>
<th></th>
<th>Unfiltered</th>
<th></th>
<th>Filtered</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wetwell</td>
<td>Drywell</td>
<td>Wetwell</td>
<td>Drywell</td>
</tr>
<tr>
<td>Manual</td>
<td></td>
<td></td>
<td>Manual</td>
<td></td>
</tr>
<tr>
<td>Mod 1</td>
<td>157.4</td>
<td>224.8</td>
<td>Mod 5</td>
<td>182.2</td>
</tr>
<tr>
<td>Mod 2</td>
<td></td>
<td></td>
<td>Mod 6</td>
<td>260.1</td>
</tr>
<tr>
<td>Manual</td>
<td></td>
<td></td>
<td>Manual</td>
<td></td>
</tr>
<tr>
<td>Mod 3</td>
<td></td>
<td></td>
<td>Mod 7</td>
<td>177.8</td>
</tr>
<tr>
<td>Mod 4</td>
<td></td>
<td></td>
<td>Mod 8</td>
<td>253.5</td>
</tr>
<tr>
<td>Manual</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manual</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reduction in Conditional Contaminated Land Area:
- Unfiltered: -5,747.0
- Filtered: -8,207.2
Uncertainty Analysis

• Approximate Monte Carlo analysis performed to gain an appreciation of the uncertainties involved
  – Sequence frequencies
  – Sequence consequences
### Uncertainty Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core-damage frequency</td>
<td>2E-5/ry</td>
<td>Log-normal; EF = 10</td>
</tr>
<tr>
<td>Fraction of total CDF due to external hazards</td>
<td>0.8</td>
<td>Beta; $\alpha = 0.5$, $\beta = 0.125$</td>
</tr>
<tr>
<td><strong>Breakdown of sequence types for internal hazards</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (not SBO, bypass, or fast)</td>
<td>0.83</td>
<td>Dirichlet $\alpha_1 = 41$</td>
</tr>
<tr>
<td>SBO</td>
<td>0.12</td>
<td>$\alpha_2 = 6$</td>
</tr>
<tr>
<td>Bypass (ISLOCAs)</td>
<td>0.05</td>
<td>$\alpha_3 = 2.5$</td>
</tr>
<tr>
<td>Fast (MLOCAs, LLOCAs, ATWS)</td>
<td>0.01</td>
<td>$\alpha_4 = 0.5$</td>
</tr>
<tr>
<td><strong>Breakdown of sequence types for external hazards</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (not bypass)</td>
<td>0.95</td>
<td>Beta; $\alpha = 0.5$, $\beta = 9.5$</td>
</tr>
<tr>
<td>Bypass</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>
# Uncertainty Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability that severe accident vent fails to open</td>
<td>Mod 0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Mods 1,3,5,7 – other or SBO</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Mods 1,3,5,7 - fast</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Mods 2,4,6,8</td>
<td>0.001</td>
</tr>
<tr>
<td>Conditional probability that offsite power is not recovered by the time of lower head failure given not recovered at the time of core damage (internal hazards)</td>
<td>0.38</td>
<td>Beta; $\alpha = 0.5$, $\beta = 0.816$</td>
</tr>
<tr>
<td>Probability that portable pump for core spray or drywell spray fails</td>
<td>0.3</td>
<td>Beta; $\alpha = 0.5$, $\beta = 1.167$</td>
</tr>
<tr>
<td>Consequences</td>
<td>Per MELCOR/MACCS2 results and regulatory analysis assumptions</td>
<td>Log-normal; EF = 10 (correlated)</td>
</tr>
</tbody>
</table>
Uncertainty in Population Dose Risk Reduction
Uncertainty in Offsite Cost Risk Reduction

![Graph showing the reduction in offsite cost risk for different models. The x-axis represents the models (Mod1 to Mod8), and the y-axis shows the reduction in cost risk ($/yr). The graph includes data points for the 5th, mean, point estimate, median, and 95th percentiles.]
Uncertainty in Onsite Worker Dose Risk Reduction
Uncertainty in Onsite Cost Risk Reduction

![Graph showing reduction in onsite cost risk for different models](image)
Uncertainty in Conditional Contaminated Land Area
Regulatory Analysis and Backfitting

Aaron Szabo
Office of Nuclear Reactor Regulation
Rulemaking Branch
Outline

• Regulatory Decision-Making Process
  – Task-specific information
  – Steps for a Regulatory Analysis
• Backfitting
  – Adequate Protection
  – Cost-Justified Substantial Safety Enhancement
• Filtered Vents Regulatory Analysis
  – Assumptions and Sensitivities
  – Quantitative Analysis
    ▪ Current Framework
    ▪ Sensitivity Analysis
  – Qualified Attributes
• Summary
Regulatory Decision-Making Process

• Regulatory Analysis looks at all the costs and all the benefits of the regulatory action to inform decision-makers
  – Quantified and qualified
  – Identify uncertainties with the analysis

• Backfitting determines if we can impose a requirement on licensees (10 CFR 50.109)
Methodology for Regulatory Analysis

- 4 Options
  - 1: No Change (Re-affirm EA-12-050)
  - 2: Severe Accident Capable Vent
  - 3: Filtered Vent
  - 4: Performance-Based Approach

- All attributes dispositioned using current framework
  - NUREG/BR-0058, NUREG/BR-0184, NUREG-1409
  - Any deviations are identified and provided as a sensitivity analysis
Methodology for Regulatory Analysis

• Steps to perform a Regulatory Analysis
  – Identify legitimate alternatives and options
  – Determine if the action is a backfit
  – Evaluate attributes
    ▪ Public Health (Accident)
    ▪ Offsite Property
    ▪ Industry Implementation
    ▪ NRC Implementation
    ▪ Regulatory Efficiency
  • Occupational Health (Accident)
  • Onsite Property
  • Industry Operation
  • NRC Operation

– Develop recommendations
How Information is Provided

• Recommendations are provided using the “best [point] estimate” calculations

• Benefits and costs are determined by multiplying the probability of the event by the change in consequences
  – (e.g. Probability of event times (Alt. 1 consequence – Alt. 2 consequence))

• Sensitivity analyses are provided for decision-makers
• Adequate Protection
  – Severe Accident Capable Vent
  – Filtered Vent
  – Performance-Based Approach
Backfitting - Cost-Justified Substantial Safety Enhancement

• 2 Part Analysis
  – Substantial Safety Enhancement
  – Cost-justified

• SRM-SECY-93-086, “Backfit Considerations”
  – The safety enhancement criterion should be administered with the degree of flexibility the Commission originally intended
  – The standard is not intended to be interpreted in a manner that would result in disapprovals of worthwhile safety or security improvements having costs that are justified in view of the increased protection that would be provided
  – Allows for both quantitative and qualitative arguments
• Substantial Safety Enhancement
  – Attributes included
    ▪ Public Health (accident)
    ▪ Occupational Health (accident)
Backfitting - Cost-Justified Substantial Safety Enhancement

• Cost-Justified
  – Attributes included
    ▪ Public Health (accident)
    ▪ Occupational Health (accident)
    ▪ Industry Implementation and Operation
    ▪ NRC Implementation and Operation
    ▪ Offsite Property and Onsite Property
    ▪ Regulatory Efficiency
Analysis Assumptions (NUREG/BR-0184)

• Onsite Property
  – Option 1 = Upper bound ($2B (1993) or $3.2B (2012))
  – Option 2 = Middle ($1.5B (1993) or $2.4B (2012))
  – Option 3 = TMI ($750M (1981) or $1.9B (2012))

• Occupational Workers (during accident)
  – Does not include decontamination and cleanup
  – Assumes at least 1,000 workers (small dose)
  – Option 1 = Upper bound (14,000 person-rem)
  – Option 2 = Middle (3,300 person-rem)
  – Option 3 = TMI (1,000 person-rem)
### Sensitivity Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current Framework</th>
<th>Sensitivity Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dollar per person-rem</td>
<td>$2,000 (NUREG-1530)</td>
<td>$4,000 (EPA and ICRP No. 103)</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>3% and 7% (OMB Circular A-4)</td>
<td>Undiscounted (Current Market)</td>
</tr>
<tr>
<td>Initial Event Probability</td>
<td>2E-05 PRA based (SPAR Model)</td>
<td>3E-04 Global Statistical Value</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Accidents/Operation)</td>
</tr>
<tr>
<td>Monte Carlo PRA</td>
<td>Point Estimate</td>
<td>5th Percentile and 95th Percentile</td>
</tr>
<tr>
<td>Replacement Energy Costs</td>
<td>$15.4 million/year (NUREG/BR-0184)</td>
<td>$56.3 million/year to $716,000/year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Updated, regional based with</td>
</tr>
<tr>
<td></td>
<td></td>
<td>high and low values)</td>
</tr>
<tr>
<td>Other unit(s) at site shutdown</td>
<td>All Mark I and Mark II reactors shutdown (30 units)</td>
<td></td>
</tr>
</tbody>
</table>
Sensitivity Analysis

- Recommendation will be based on current framework
- Assessed 107 sensitivity cases based on the consequence results for each option, not including the discount values
  - No sensitivity cases for Industry and NRC Implementation and Operation costs
Quantitative Analysis – Option 2, SACV (Current Framework)

- Estimated Costs
  - Industry Costs: $60M
  - NRC Costs: $8M to $12M
  - Total Costs: $68M to $72M
Quantitative Analysis – Option 2, SACV (Current Framework)

• Estimated Benefits (range based on discount factors)
  – Public Health: 112 person-rem averted
    ▪ $4M to $5.7M
  – Occupational Health: 5 person-rem averted
    ▪ $100,000 to $200,000
  – Offsite Property (Cost Offset)
    ▪ $8M to $11M
  – Onsite Property (Cost Offset)
    ▪ $4.4M to $7.5M
  – Total Benefit
    ▪ $16.5M to $24.4M

• Net Value
  – ($55.5M) to ($43.6M)
Quantitative Analysis – Option 3, Filtered Vent (Current Framework)

• Estimated Costs
  – Industry Costs: $465M (based on $15M per unit)
  – NRC Costs: $8M to $12M
  – Total Costs: $473M to $477M
Quantitative Analysis – Option 3, Filtered Vent (Current Framework)

- Estimated Benefits (ranges based on discount factors)
  - Public Health: 212 person-rem averted
    - $6.3M to $9.3M
  - Occupational Health: 7 person-rem averted
    - $300,000 to $400,000
  - Offsite Property (Cost Offset)
    - $14M to $20M
  - Onsite Property (Cost Offset)
    - $104M to $181M
  - Total Benefit
    - $125M to $211M

- Net Value
  - ($352M) to ($262M)
Quantitative Analysis – Option 4, Performance-Based (Current Framework)

- No quantified costs or benefits
- Discussion provided qualitatively
- Amenable to site-specific approaches
Qualitative Arguments

• Will be included in the Regulatory Analysis
• Historically, they have considered safety goal policy qualitative goals, defense-in-depth, uncertainties, consistency with standards (regulatory efficiency), etc.
Summary

• Option 2 (SACV) and Option 3 (filtered vent) do not appear to be cost-beneficial quantitatively in the current framework
  – Sensitivity analysis may provide cases that are cost-beneficial
  – May require qualitative arguments for “substantial safety enhancement”
Qualitative Arguments for Filtered Vents (Option 3)

Tim Collins
Office of Nuclear Reactor Regulation
Division of Safety Systems
Qualitative Arguments

• Defense-in-Depth
• Severe Accident Management Decision Making
  – Operator Response
  – Hydrogen Control
• Consequence Uncertainties
• International Practice
Enhances Defense-in-Depth

• Containment is an essential element of DID – Protects against uncertainties in prevention of severe accidents and potential consequences of a large release
• Filtering compensates for the loss of the containment barrier due to venting
• Filtering improves confidence to depressurize containment to address other severe accident challenges
Enhances Defense-in-Depth

- Filtering extends time for emergency planning implementation
  - Adds margin for uncertainty in weather, public response, collateral damage, communications, etc.
Severe Accident Management Decision Making

- Improves operator confidence in a “clean” release for hydrogen control
  - Allows early operator intervention to vent hydrogen and control containment pressure
  - Sustained lower pressure reduces leakage of hydrogen thru penetration seals
  - Decreased leakage reduces threat from hydrogen explosion to reactor building, spent fuel pool, and emergency responders
Severe Accident Management Decision Making

• Facilitates arrest of in-vessel melt progression and ex-vessel challenge to drywell liner
  – Allows early operator intervention to control pressure
    ▪ Sustained lower pressure facilitates injection from low pressure water sources
      – Increases chances of early melt arrest and protection of liner
    ▪ Sustained lower pressure reduces leakage of fission products thru penetration seals
      – Facilitates operator access to reactor building for recovery
  ▪ Facilitates use of all onsite resources
Operator confidence in “clean” release facilitates use of vent as a mitigation tool

- Supports use of drywell and/or wetwell as vent inlet
  - Alleviates concerns with wetwell floodup strategy
- Supports passive actuation
  - Minimal consequences of inadvertent actuation
Consequence Uncertainties

- Improves protection against uncertainties associated with potential land contamination
  - Fission product release fractions
  - Weather patterns
  - Farm products/food chain impacts
  - Hydrology
  - Economic impacts
Consequence Uncertainties

• Reduces potential for significant social repercussions
  – Public anxiety
  – Impact on energy supply chain
International Practices

• Consistent with recommendation from Extraordinary Meeting of Members of Convention on Nuclear Safety to upgrade “measures to ensure containment integrity, and filtration strategies and hydrogen management for the containment”

• Consistent with decisions of most European countries, Canada, Taiwan, and Japan
Next Steps

• Continue staff assessment and develop recommendations
• Engage Steering Committee
• Present conclusions and recommendations to ACRS on October 31 and November 1