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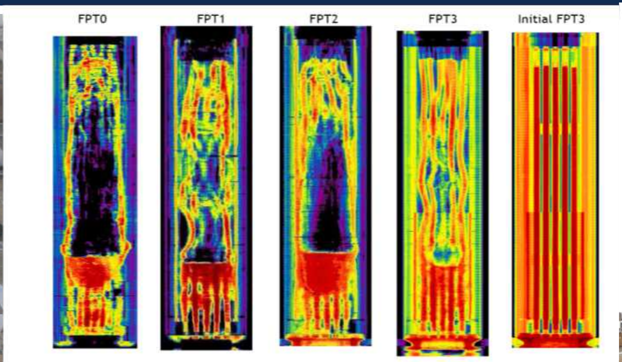

Severe Accident Phenomena

TSG Skill Set

Containment Performance

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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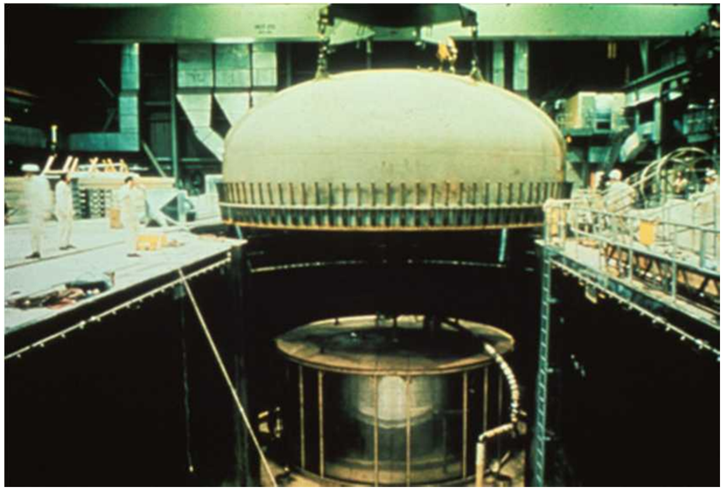
CONTAINMENT CHARACTERISTICS

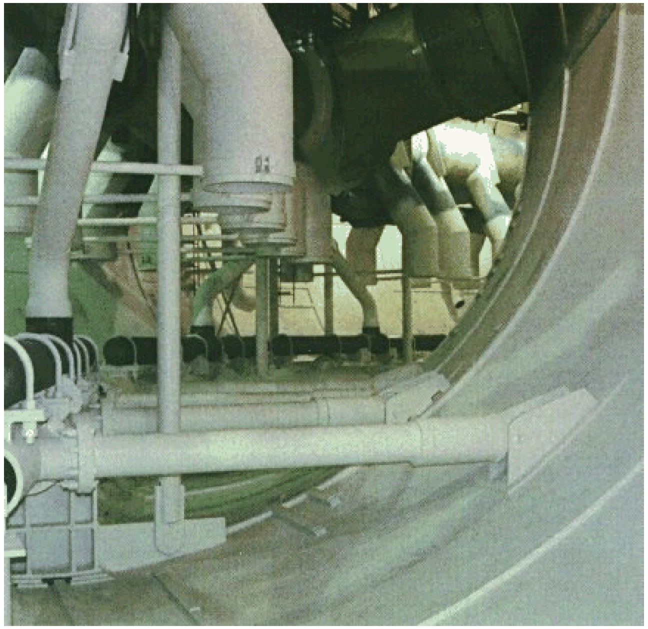
BWR Reactors

- In the United States there are:
  - 23 BWR Mark I
  - 8 BWR Mark II
  - 4 BWR Mark III



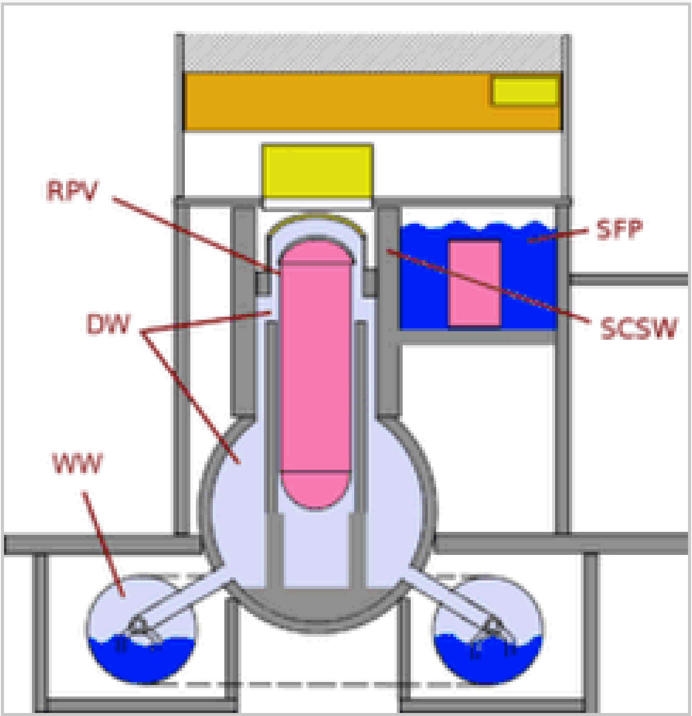
Drywell Head

- Outside the U.S. there are 91 BWR's in operation, undergoing maintenance, or under construction



Inside the Wetwell

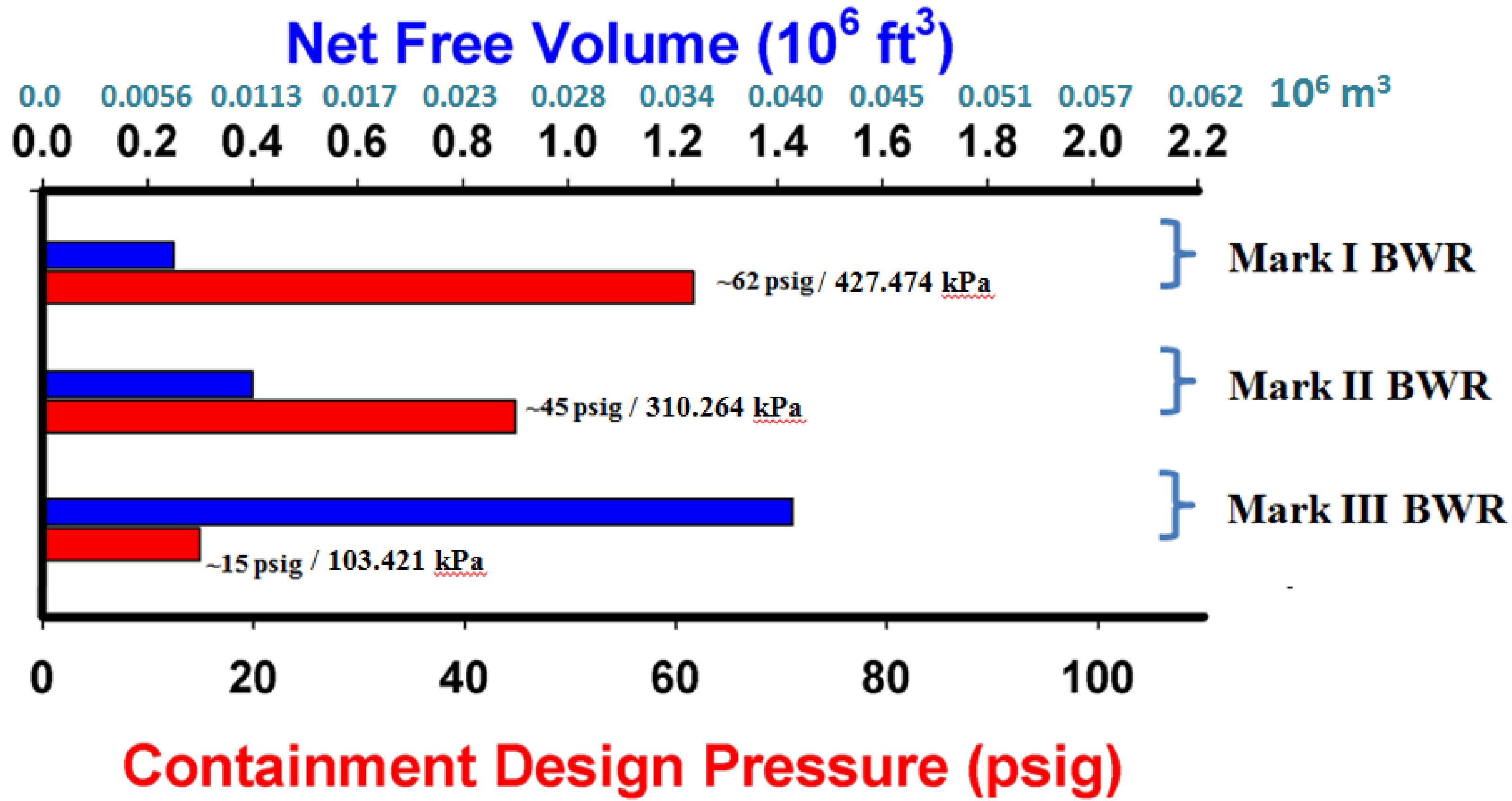
Containment Characteristics



Cross-section sketch of a typical BWR Mark I containment. DW = drywell, WW = wetwell, SF = spent fuel area

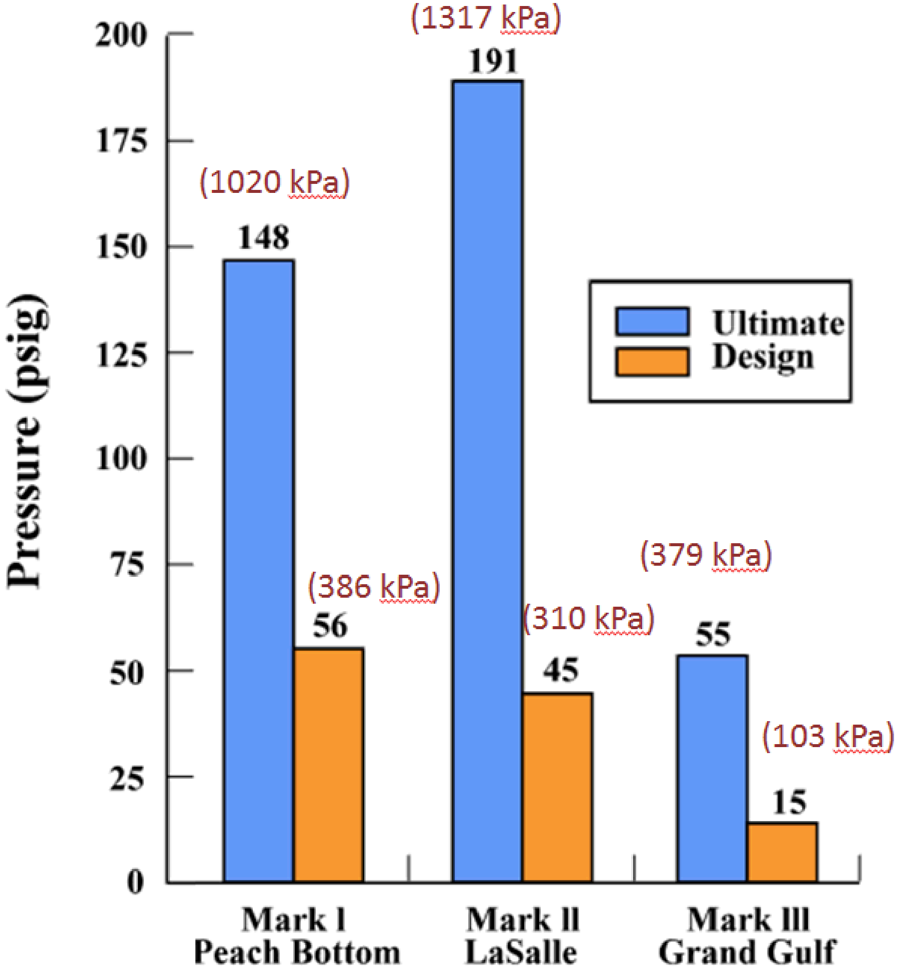
- A drywell is the containment structure enclosing the vessel and recirculation system of a BWR. It provides a pressure suppression system and a fission product barrier.
- A wetwell, or suppression pool, is designed to condense the steam released from the RPV

Typical BWR Containment Characteristics



Containment Design Strengths Vs. Failure Pressures

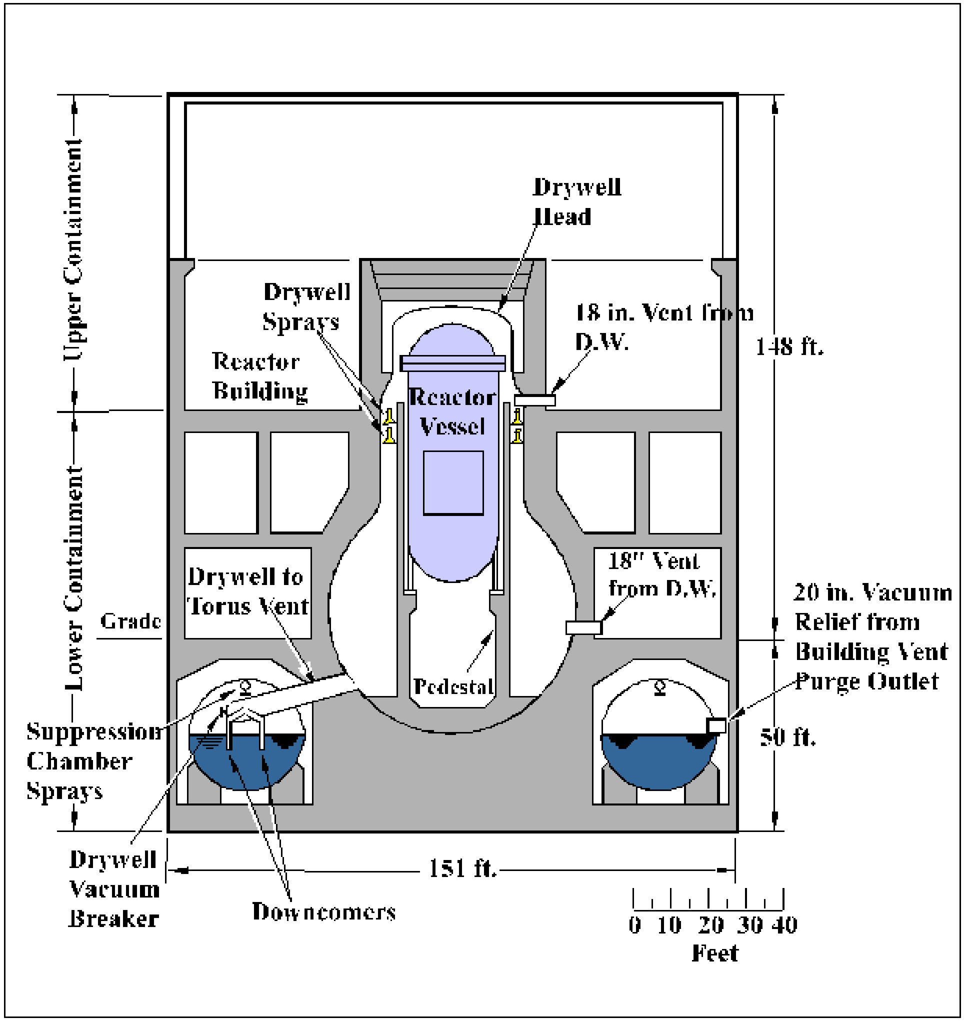
- *Design is generally very conservative*
- *Ultimate failure pressures may be two to five times design pressure if:*
  - *Proper construction*
  - *Proper materials*
  - *Penetrations hold*



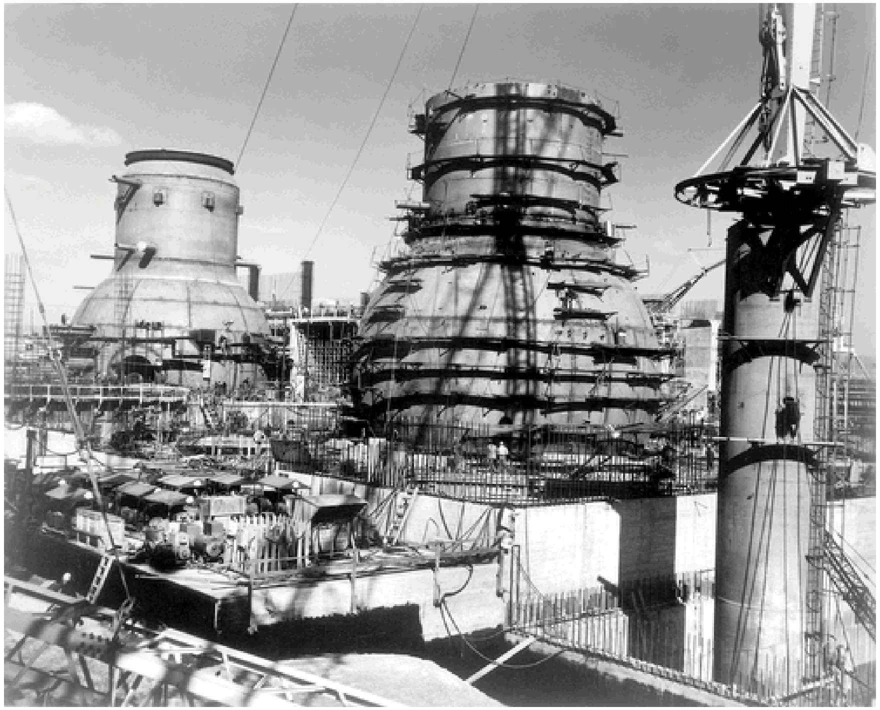
Mark I Containments

- *23 BWRs*
- *Basic strategy:*
  - *Drywell - wetwell concept*
  - *Suppression pool absorbs blowdown energy*
  - *Suppression pool provides water source*
  - *Small volume*
- *Long-term heat removal:*
  - *Suppression pool cooling*
  - *Sprays*
  - *Venting (at most plants)*
- *Inert drywell to preclude combustion*

Typical Mark I BWR Containment



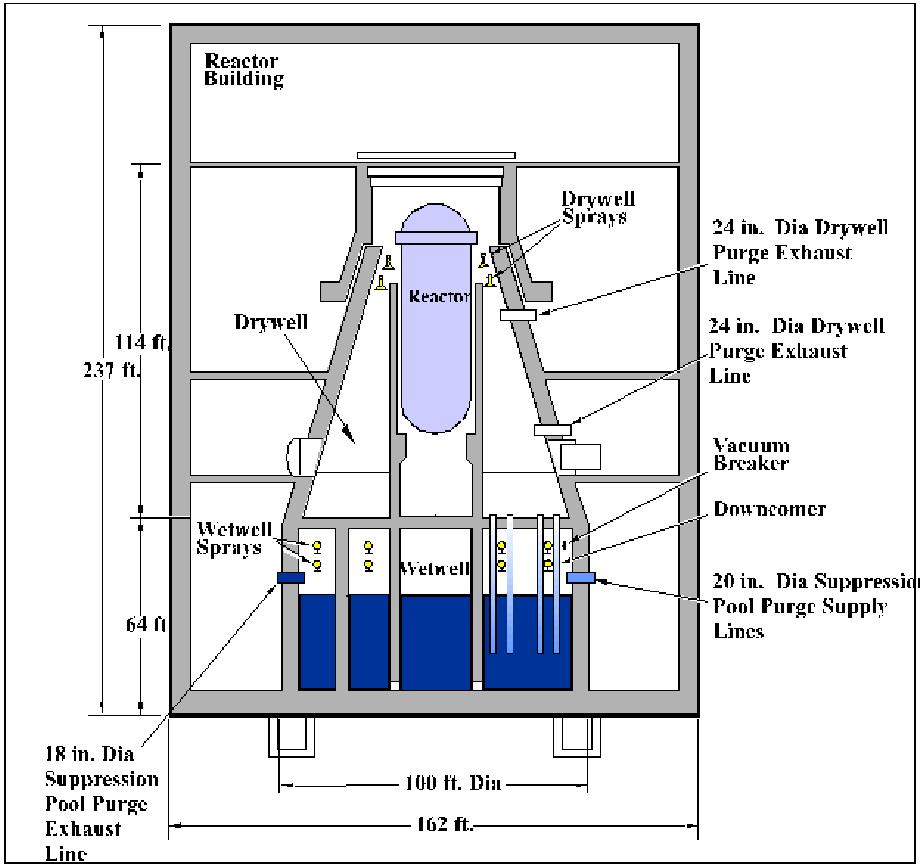
Browns Ferry Under Construction

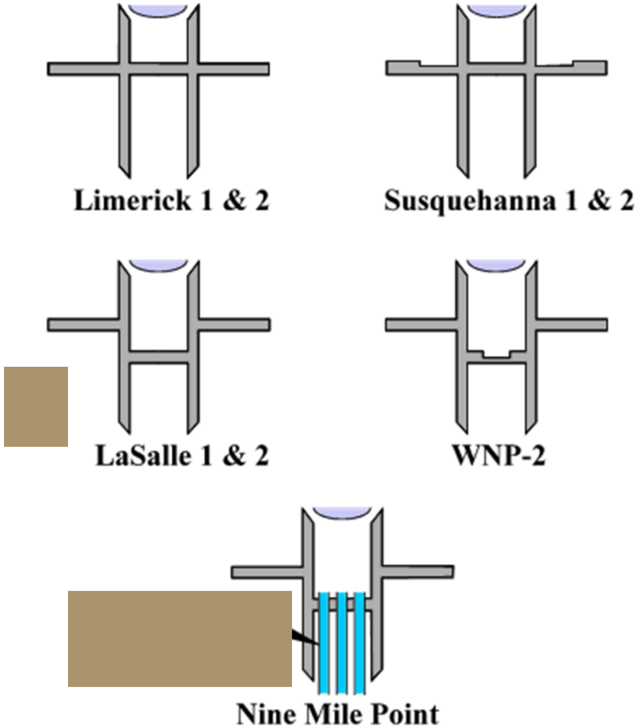


Mark II Containments

- *8 BWRs*
- *Basic strategy - same as Mark I's*
- *Improved suppression pool design - lower design pressure*
- *Long-term heat removal - same as Mark I's*
- *Inert drywell to preclude combustion*

Typical Mark II BWR Containment



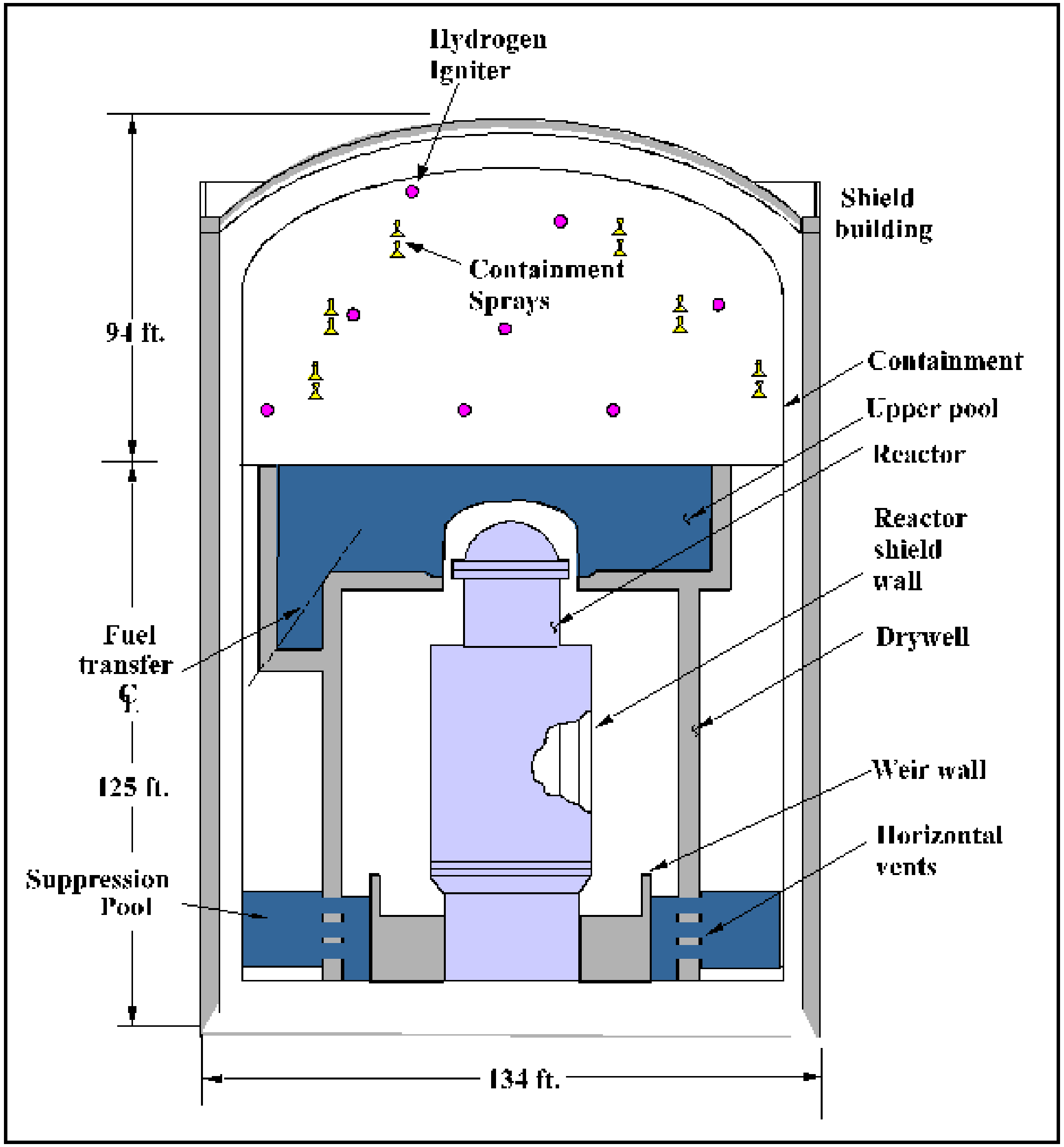


Mark II Cavity Variations

Mark III Containments

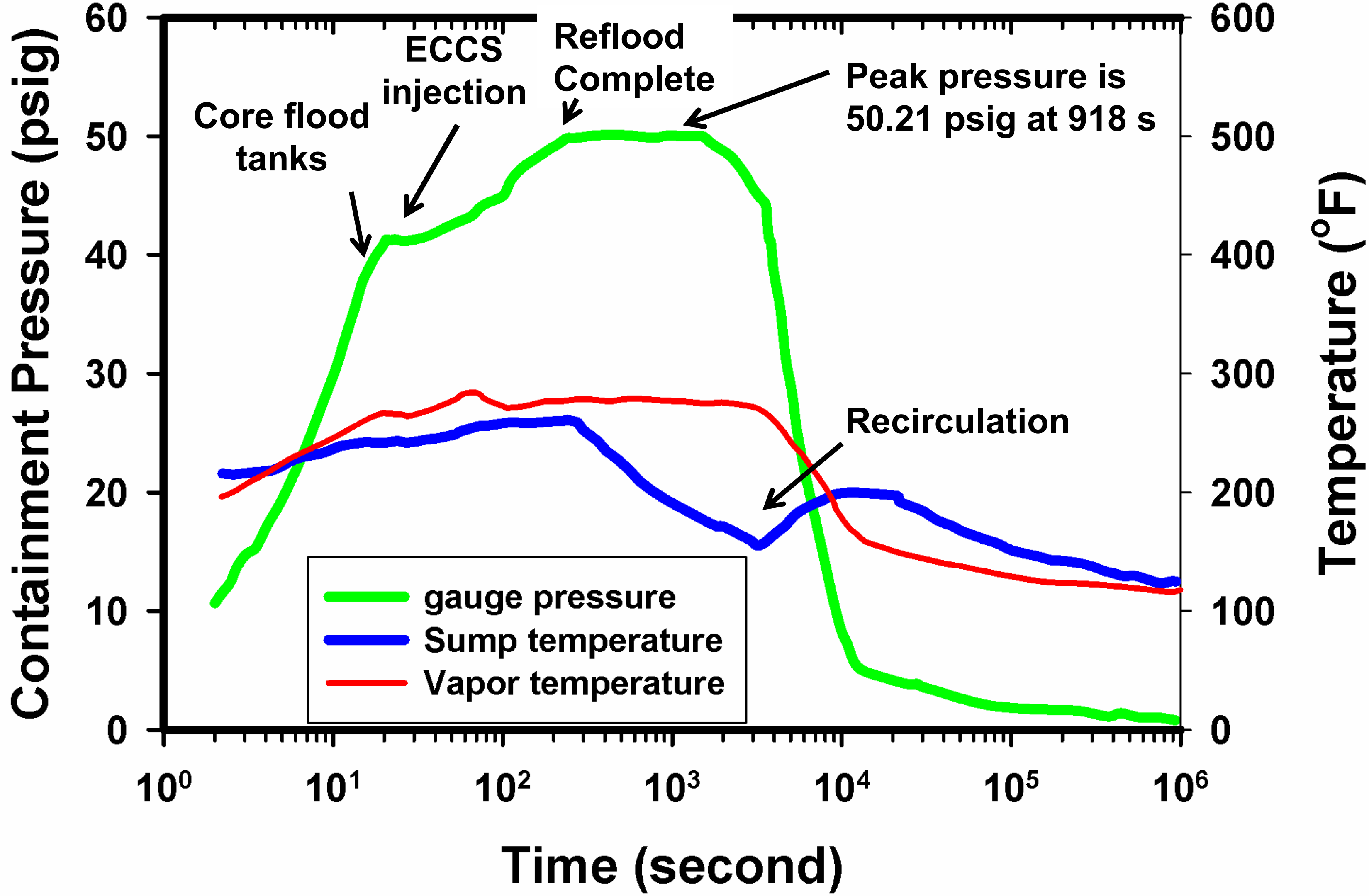
- *4 BWRs*
- *Basic strategy:*
  - *Similar in theory to Mark I's and II's*
  - *Containment structure around drywell*
  - *Large volume*
  - *Upper pool*
  - *Reactor building equipment less vulnerable*
- *Long-term heat removal*
  - *Suppression pool cooling*
  - *Sprays*
- *Igniters for hydrogen control*

Typical Mark III BWR Containment



Containment Design Criteria

- *Basic criteria is to withstand design-basis accidents without exceeding the exposure guidelines of 10 CFR Part 100*
- *Typically:*
  - *Large break LOCA for pressure limit*
  - *Main steam line break for temperature limit*
  - *1% metal-water reaction producing hydrogen*
- *Based on conservative calculations*
- *Assumes*
  - *Successful emergency core cooling (with single failure)*
  - *Success of containment heat removal (with single failure)*



Containment pressure-temperature response for 8.55ft^2 pump discharge break

Additional Containment Design Loads

- *Temperature transients and gradients*
- *Safe shutdown earthquake loads*
- *Internal and external missiles*
- *Loads from pipe rupture*
- *External pressures*
- *Winds and tornadoes*

Containment Leakage

- *Around penetrations*
  - *Piping*
  - *Electrical*
  - *Hatches*
  - *Airlocks*
- *Through isolation valves*
  - *Redundant valves required, locked closed or automatic*
  - *10 CFR 50, Appendix A, GDC 54-57*

Design Leakage

- *Plant-specific*
- *Based on 10 CFR 100 guidelines*
- *Testing required per 10 CFR 50, Appendix J*
  - *Integrated leak rate tests (Type A)*
  - *Penetration tests (Type B)*
  - *Isolation valve tests (Type C)*
- *Two options available for leakage testing*
  - *Option A - Based on conservative design basis*
  - *Option B - Performance based*

Plant	Containment Type	Peak Design-basis accident pressure (psig)	Maximum allowable leakage (weight % per day)
Peach Bottom	BWR Mark I	49.1	0.5
La Salle	BWR Mark II	39.6	0.635
Grand Gulf	BWR Mark III	11.5	0.437

*** The maximum allowable under Option B is 1.0 weight % / day.**

Containment Heat Removal

- *Required per 10 CFR 50, Appendix A, GDC 38.*
- *Containment heat removal systems*
  - *Spray recirculation systems*
  - *Fan coolers*
  - *Suppression pool cooling*
  - *ECC recirculation*
- *Must meet single failure criterion*

Containment Failure Modes And Causes
(including beyond-design basis)

- *Breach*
  - *Rupture (pressure capability lost) or*
  - *Leakage (some pressure maintained)*
  - *Static overpressure*
  - *Dynamic overpressure*
  - *Missile penetration*
  - *Temperature/meltthrough*
  - *Penetration failure*
  - *Pre-existing leakage*
  - *Containment isolation failure*
- *Bypass*
  - *Interfacing systems failure*
  - *Steam generator tube rupture*

Plant-Specific Design Differences

- *Rupture, leakage, or bypass is possible for all containment types*
- *Steel containments more likely to rupture than concrete containments*
- *BWR Mark I and some BWR Mark II containments susceptible to shell (liner) melt-through*
- *BWR drywell coolers not likely to operate under severe accident conditions*
- *Rapid heating of drywell atmosphere*
- *Early high drywell pressure signals*
- *Threat to integrity of head flange seals*
  - *Seal degradation demonstrated at 700 ^{o}F (644K)*
  - *Plant-specific considerations*
- *New designs (Mark III and advanced) have water cooling of drywell head*

CONTAINMENT RESPONSE TO BEYOND DBA'S

Containment threats according to time regime

TIME REGIME	CHALLENGE
Start of the Accident	Pre-existing leak Containment isolation failure Containment bypass
Prior to vessel breach	Reactor coolant system blowdown Insufficient containment heat removal Hydrogen combustion Induced bypass of containment
At or soon after vessel breach	Steam spike; Steam explosion Combustion; Direct containment heating Debris contacts the containment boundary
Late (>2 hrs) after vessel breach	Failure of containment heat removal Combustion; Non-condensible gas generation; Basemat melt-through

Challenges Prior To Vessel Breach

1. *Blowdown loads*
   - *LOCAs*
   - *Vessel rupture*
   - *Steam generator rupture*
2. *Inadequate containment heat removal*
   - *Slow pressurization, hours or days*
   - *Containment failure can cause system failures leading to core damage*
     - *Loss of NPSH*
     - *Piping failure*
     - *Steam effects*
3. *Hydrogen combustion*
   - *Released after onset of core damage*
4. *Late bypass from high RCS temperatures*

Challenges At Or Soon After Vessel Breach

- *Often most threatening time regime*
- *Phenomena can occur simultaneously*
- *Steam spikes and explosions*
  - *With water present in reactor cavity (pedestal region)*
- *Direct containment heating*
  - *High pressure ejection of melt into the containment atmosphere*
- *Hydrogen combustion*
  - *Additional hydrogen generation and release at vessel breach*
- *Mark I shell (liner) melt-through*
  - *Debris contact with steel shell*
- *Mark II downcomer failure*

Late Containment Challenges

1. *High temperatures - especially BWR drywell*
2. *Basemat melt-through*
3. *Long term overpressure*
   - *Steam*
   - *Noncondensible gases*
4. *Combustion*
   - *Additional combustible gases*
   - *Power recovery*

Radionuclide Retention In Containment

- *Scrubbing in suppression pools or overlying water*
- *Washout by sprays*
- *Natural combination and deposition processes*
  - *Agglomeration*
  - *Gravitational Deposition*
  - *Brownian Diffusion*
  - *Thermophoresis*
  - *Diffusiophoresis*
- *Trapping along tortuous release paths and filters*

CONTAINMENT STRATEGIES

Containment Venting

- *No safety relief valves on containments*
- *Penetrations available for venting*
- *Plants would prefer not to make use of these vents during an accident*
  - *Guaranteed release*
  - *Power requirements*
  - *Hazards to personnel*
- *However, BWR Mark I and II plants include venting in their emergency procedures*

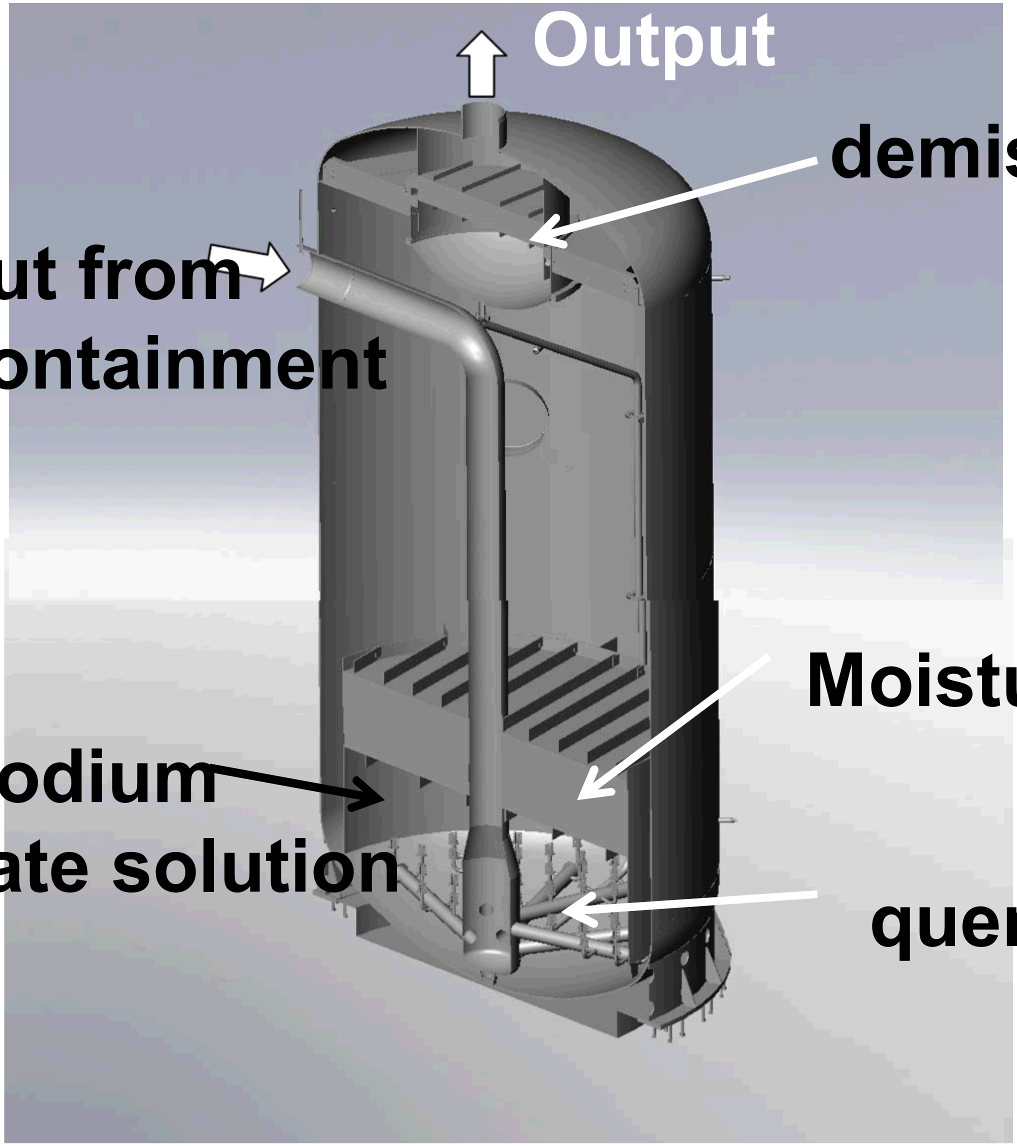
BWR Mark I And Mark II Venting

- *Very plant specific*
  - *Venting pressure*
  - *Lines used (wetwell and drywell)*
- *Effective for long term loss of containment heat removal*
  - *Core cooling initially successful*
  - *Core cooling fails due to high containment pressure or after containment failure*
- *Venting not effective for all sequences*
  - *Vents too small for energetic events and ATWS*
  - *AC power required*
- *Wetwell venting results in scrubbed releases*

Venting Benefits and Concerns

- *Benefits*
  - *Prevent loss of ADS valves*
  - *Prevents RCIC failure*
  - *Prevents unmanaged release*
  - *Reduces core damage frequency*
- *Concerns*
  - *Pump NPSH (net positive suction head) problems*
  - *Venting through ductwork*
    - *Steam in reactor building*
    - *Equipment failures*
    - *Hardened vents now required for Mark I containments*
  - *Need to coordinate venting with evacuation*

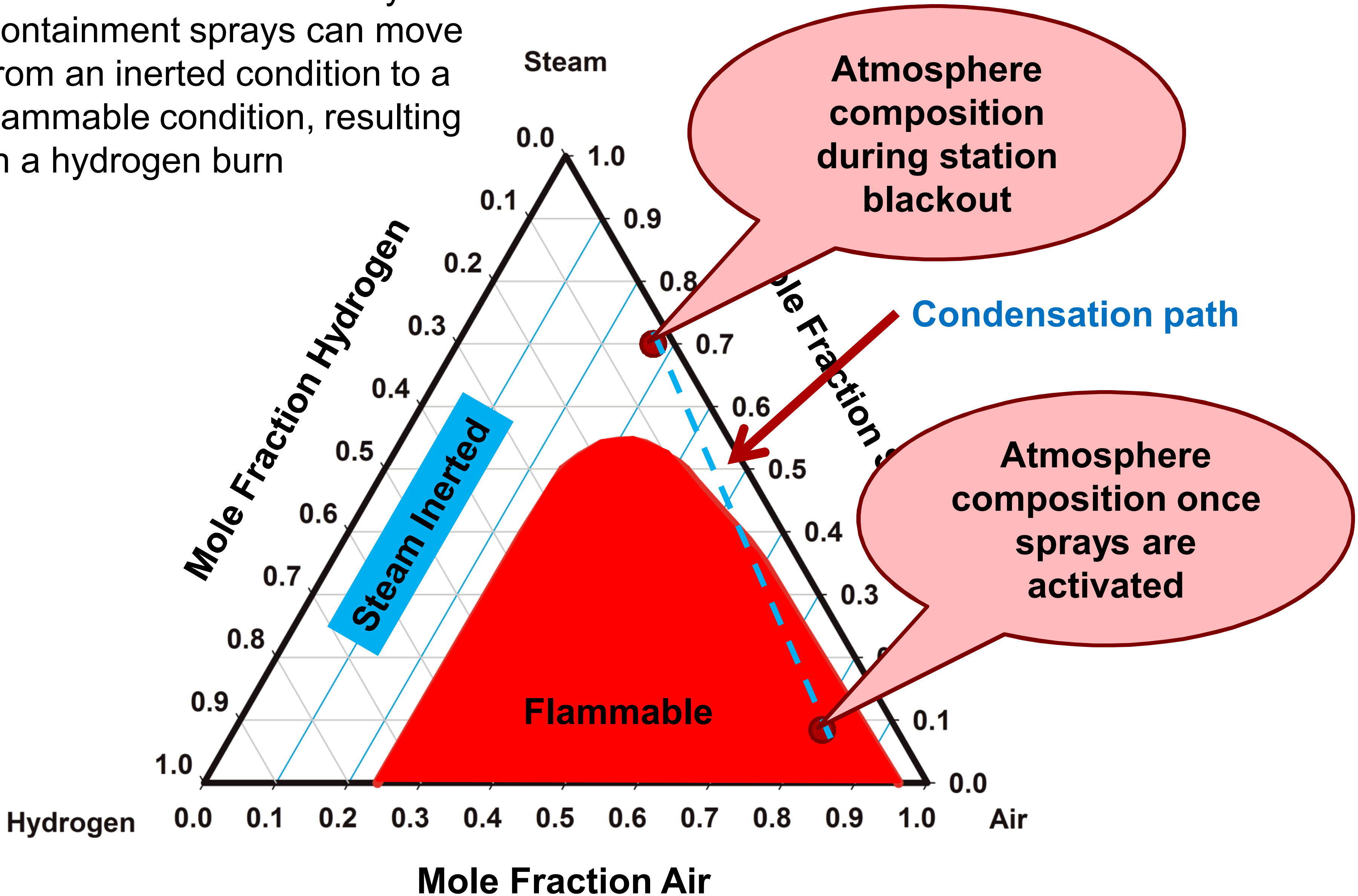
Filter for Containment post-Fukushima



Containment Sprays

- Containment sprays are designed so that the majority of free volume in containment in which steam may escape may be sprayed with water
  - Usually designed to operate in either a feed mode from a storage tank, or in recirculation
- Containment sprays serve two functions during a severe accident
  - Mitigation of high pressure and temperature excursions by removing thermal energy from the containment atmosphere
  - Reduction of airborne radioactive particles by washout and retention in the containment sump or suppression pool
- However, use of containment sprays may result in adverse conditions…

Condensation of steam by containment sprays can move from an inerted condition to a flammable condition, resulting in a hydrogen burn



Summary

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- All BWR designs have generally the same containment characteristics, but there are key differences between the Mark I, II, & III
- Containments were originally designed to mitigate DBA accident conditions
- There are a number of additional challenges during a severe accident, which can result in containment leakage or failure
- Mitigation strategies during accidents can include containment sprays and venting
- However, these strategies can have adverse consequences, both expected and unexpected