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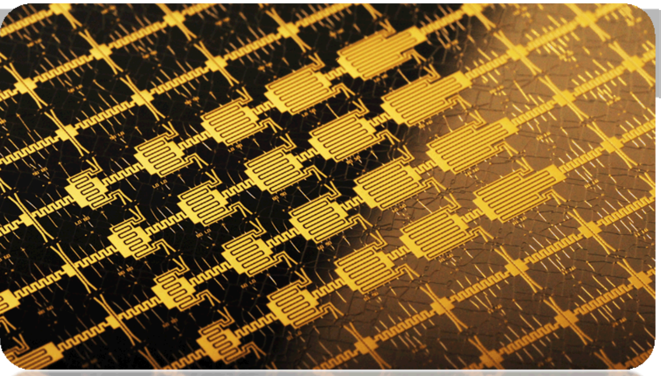
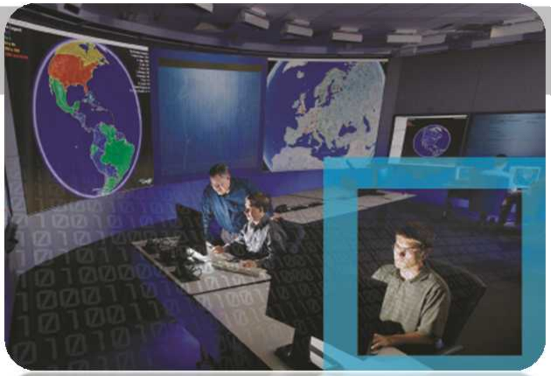


Nuclear Power Plant Severe Accidents

Doug Osborn

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview & Acknowledgements

- Nuclear Power Plants and Systems
- Severe Accident Phenomena
- Fukushima and Severe Accident Scenarios

- Dr. Dana Powers
  - USNRC's R-800 Course
    - Perspectives on Reactor Safety
- Dr. Ron Knief
  - Introduction to Nuclear Engineering
  - Fukushima Lectures

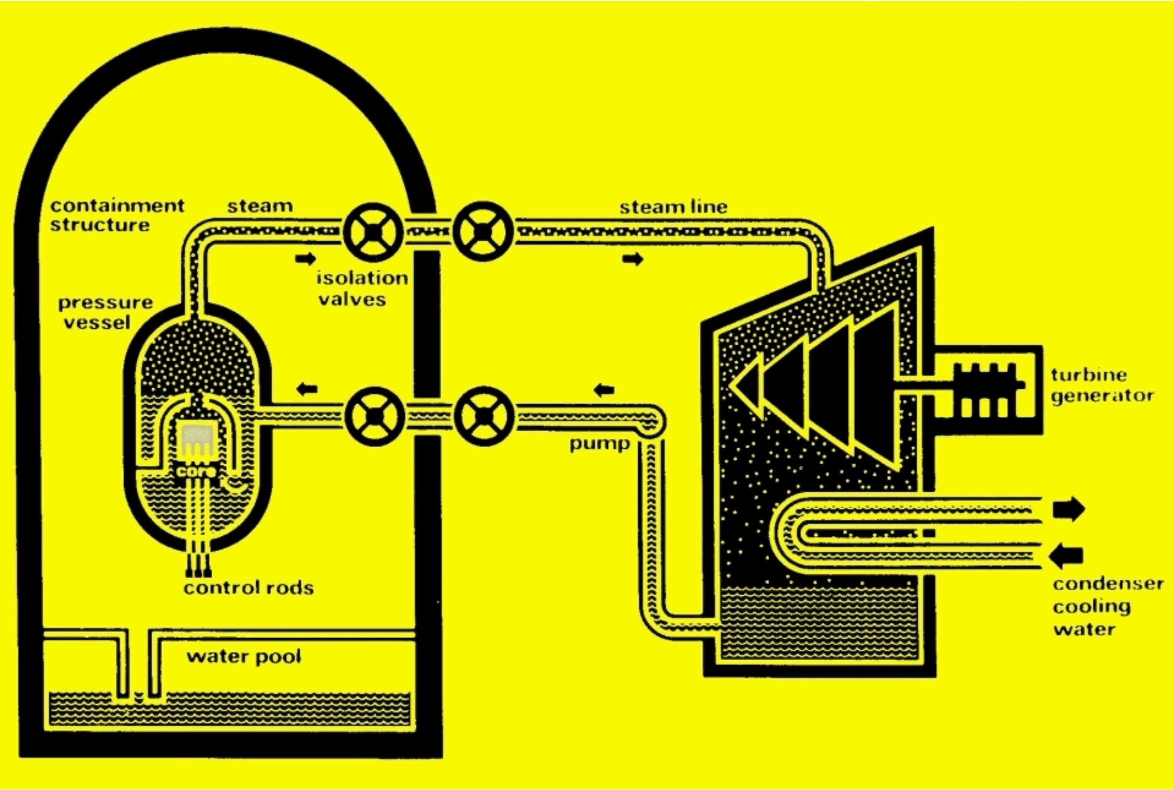
Objectives

- Identify the basic differences in the U.S. commercial nuclear power plant fleet and associated safety systems.
- Describe the principal elements of the defense-in-depth strategy.
- Identify the major phases of a severe accident
- Describe potential environmental release paths from a severe accident.
  - Potential radionuclide chemical & physical mixture forms

Nuclear Power Plants & Systems

Boiler Water Reactor - BWR

- Direct (“1-Loop”) – within reactor
  - Fukushima type of reactor plant
  - 34 within US
  - 600-1420 MWe



Pressurized Water Reactor - PWR

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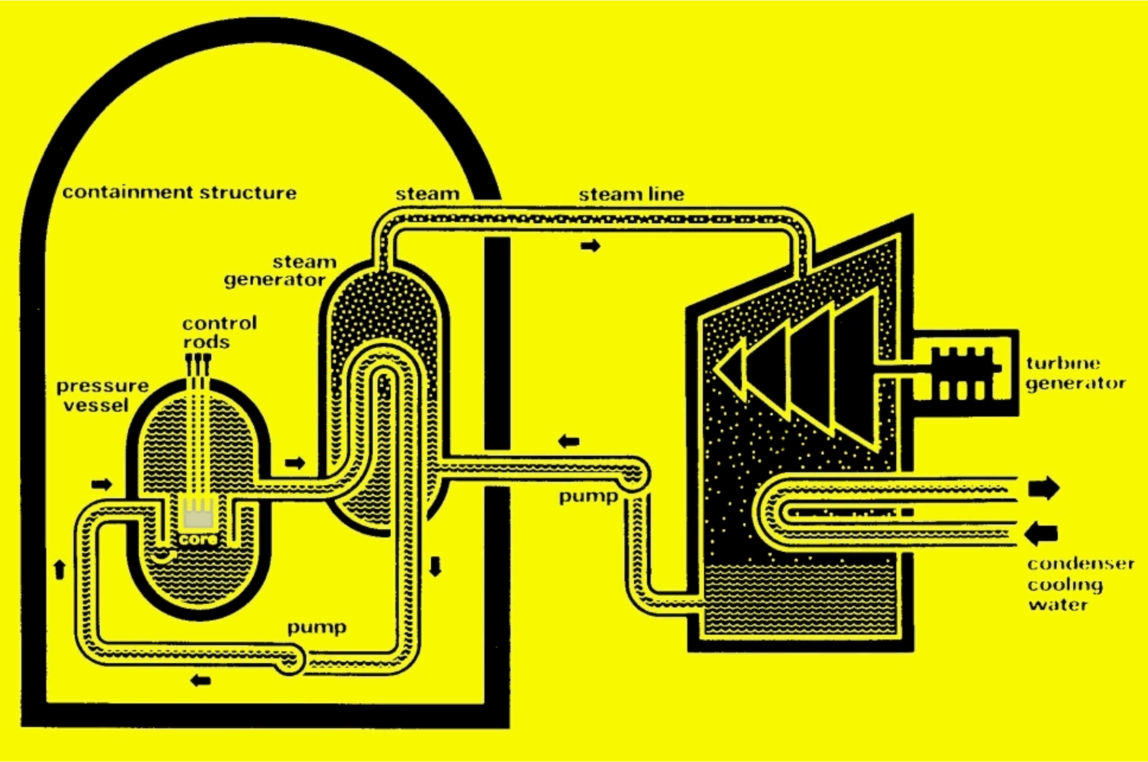
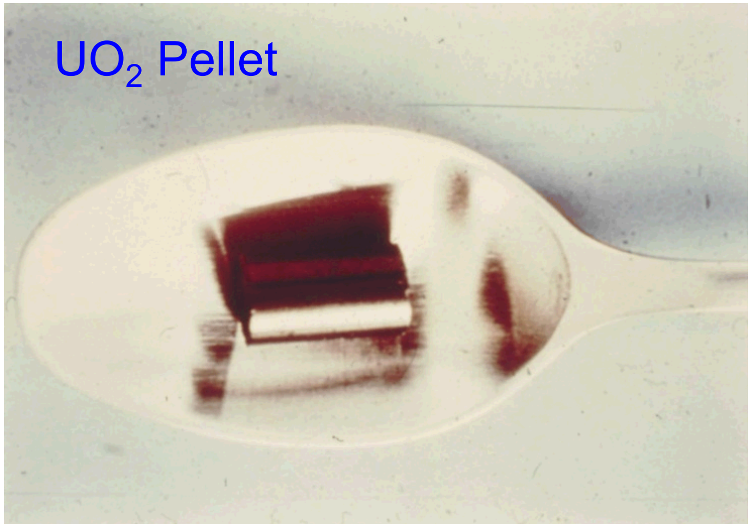
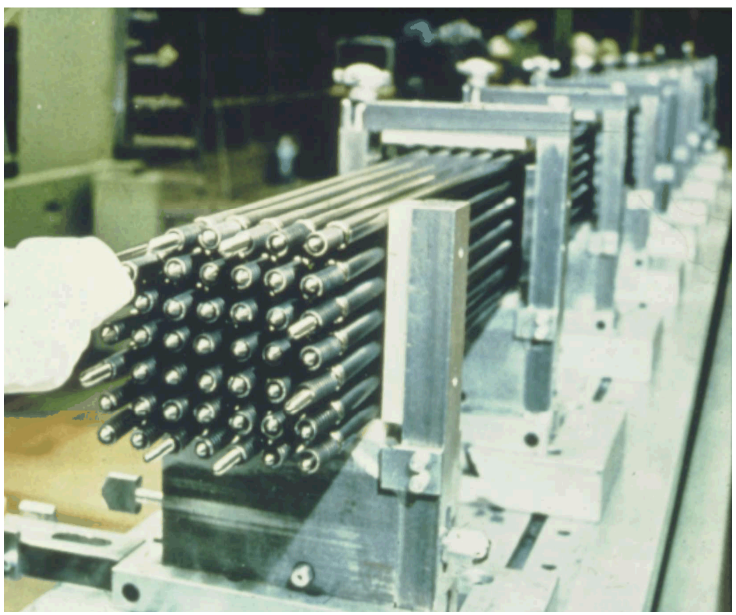
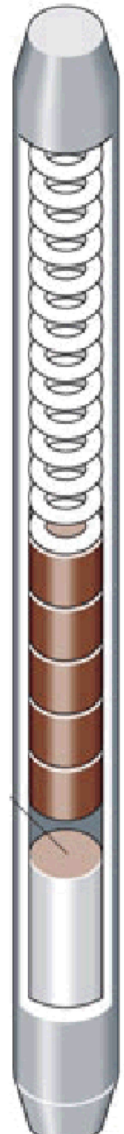
- Indirect ("2-Loop") – outside reactor in heat exchanger
  - Steam generator
  - 65 within US
  - 480 to 1315 MWe

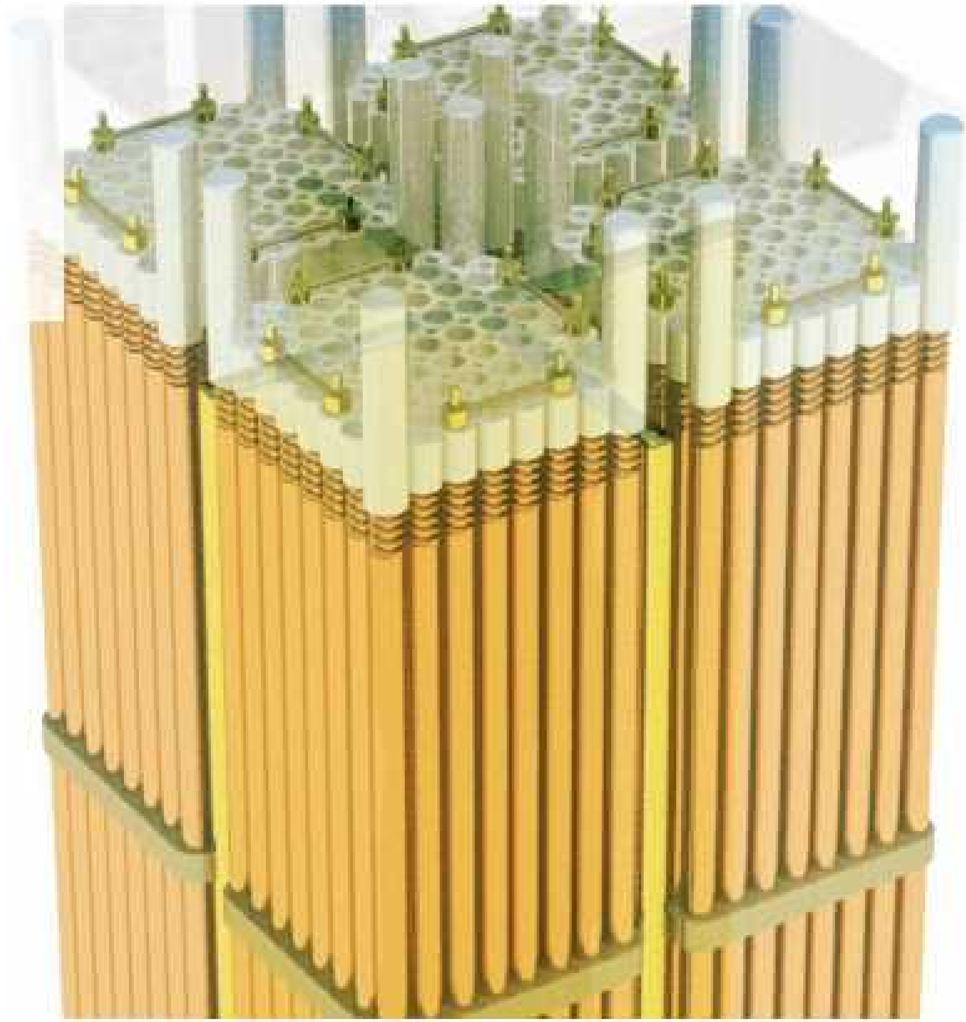


BWR Fuel



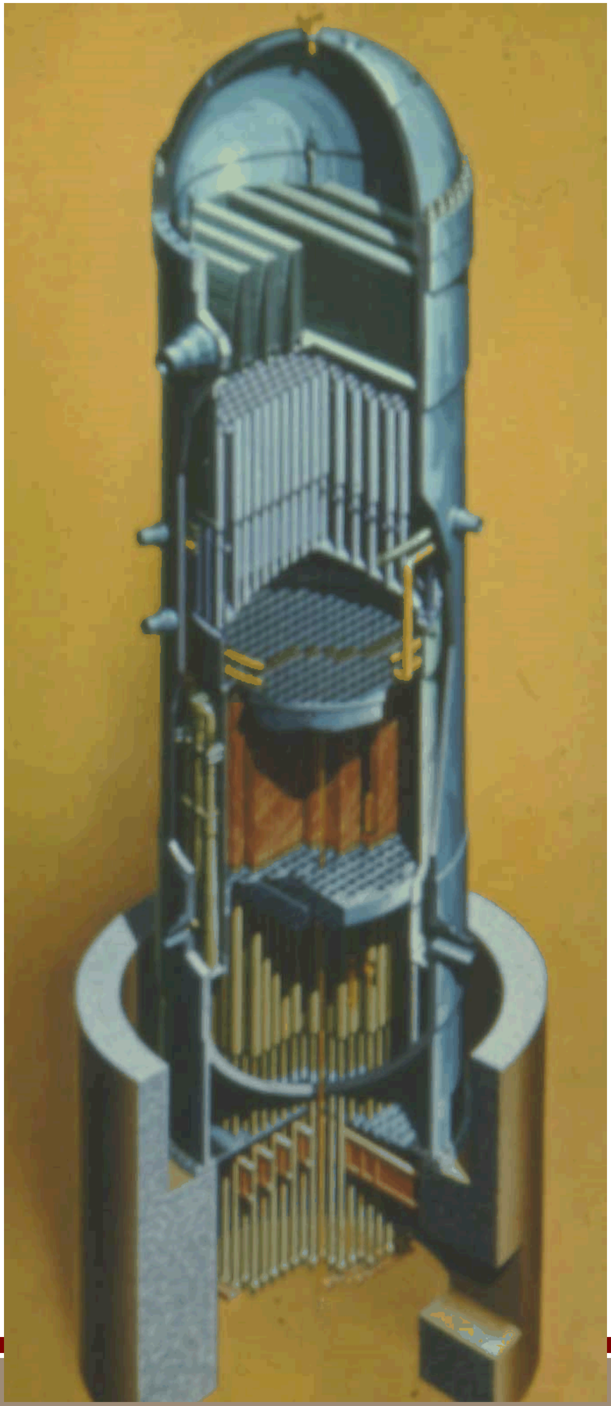






Active Fuel Height ~ 12 ft

BWR Vessel (Primary System)

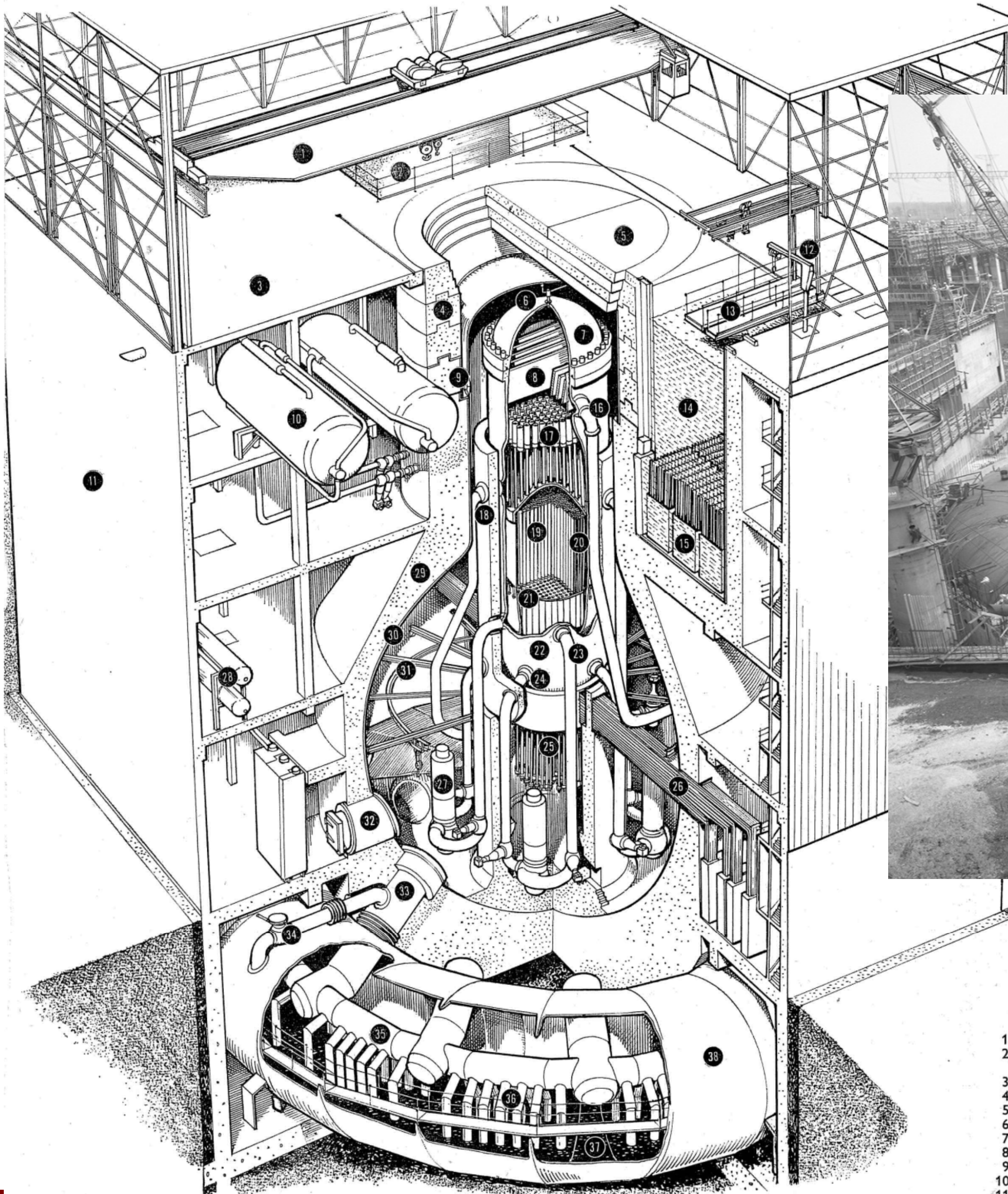


6" Thick Steel

http://econtent.unm.edu/cdm4/browse.php?CISOROOT=/nuceng

OYSTER CREEK

The World's Reactors No. 40



OWNER Jersey Central Power & Light Co.
LOCATION Ocean County, New Jersey, U.S.A.
TYPE Forced circulation, direct cycle,
WR
MW(e) net
0 MW(th)
neral Electric Company

rns & Roe Inc.

7
uivalent diameter: 160·2 in
cumscribed diameter: 170·5 in
at transfer area: 49 200 ft²
annel material: Zircaloy
terial: Enriched UO_2
erage burn-up:
6 500 MWd/t (initial core)
2 000 MWd/t (equilibrium core)
. of assemblies: 560
embly weight (including
hannel): 687 lb
. of rods per assembly: 49
l outside diameter: 0·570 in
tive length: 144 in
dding material: Zircaloy
dding thickness: 0·036 in
. of control blades: 137
ntrol rod poison material:
oron carbide
. of temporary control curtains:
48
rtain material: Boron-stainless
teel
mineralized light water
actor steam output: 5 855 000
b/h
circulation flow rate: 61 × 10^6
b/h
ssure: 1 000 psig
ide diameter: 17 ft 9 in
erall inside height: 63 ft 10 in
ll thickness: 7·125 in
terial: Carbon steel
dding material: Stainless steel
dding thickness: 0·157 in
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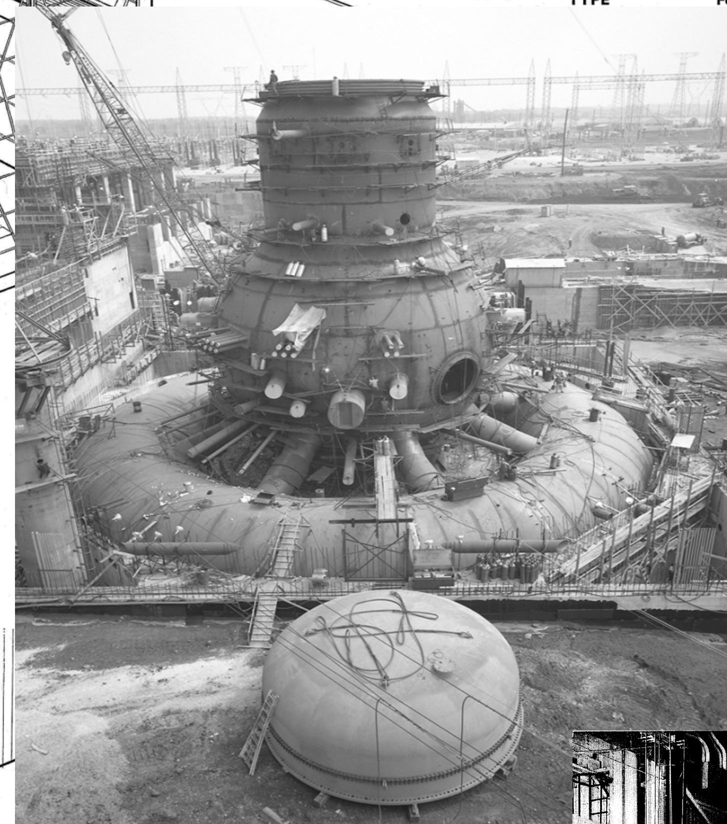
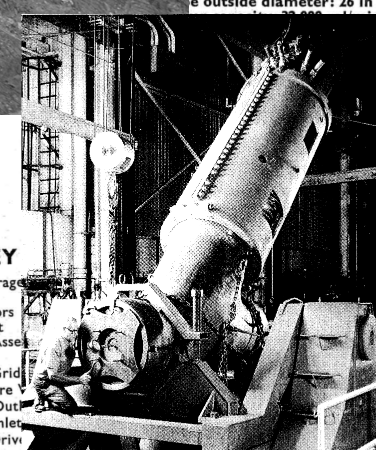




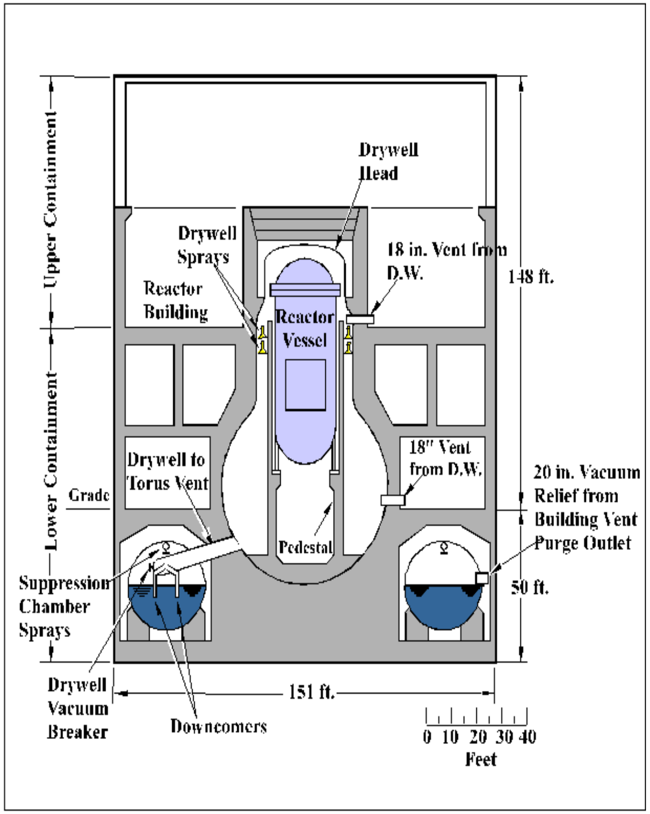
KEY

1. Service Crane and Hoist
2. Equipment Storage Pool (Steam Dryers and Separators)
3. Reactor Service Platform
4. Removable Shield Plugs
5. Removable Top Shields
6. Safety Valve
7. Pressure Vessel Head
8. Steam Dryers
9. Double Seal
10. Isolation Condensers
11. Reactor Building
12. Fuel Handling Grapple
13. Fuel Service Platform
14. Fuel Storage Pool
15. Spent Fuel Storage
16. Steam Outlet
17. Steam Separators
18. Feedwater Inlet
19. Fuel Element Asse
20. Control Blades
21. Fuel Support Grid
22. Reactor Pressure
23. Recirculation Out
24. Recirculation Inlet
25. Control Rod Driv
26. Control Rod Driv
27. Recirculation Pumps
28. Shutdown Heat Exchangers

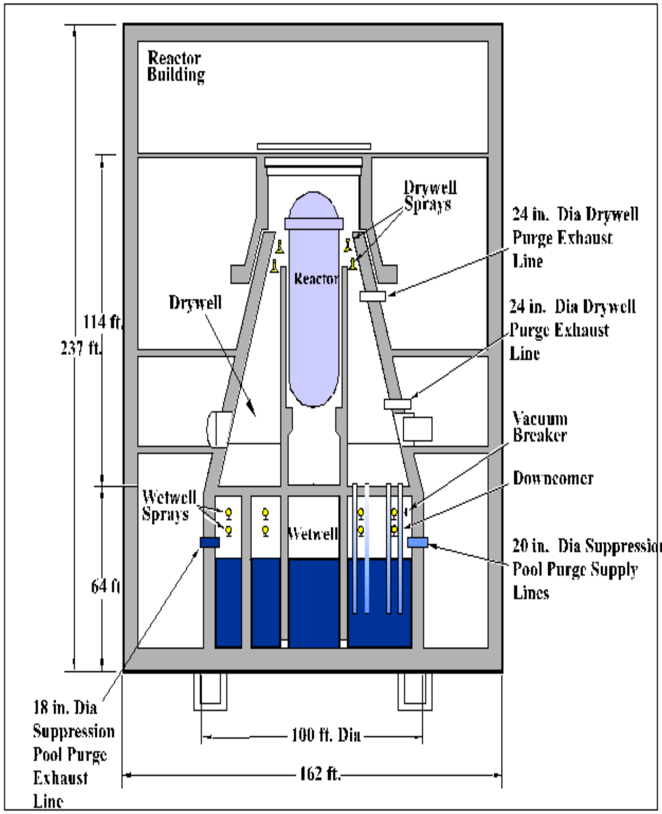
sion

41. Turbine Generator
42. Turbine Service Crane

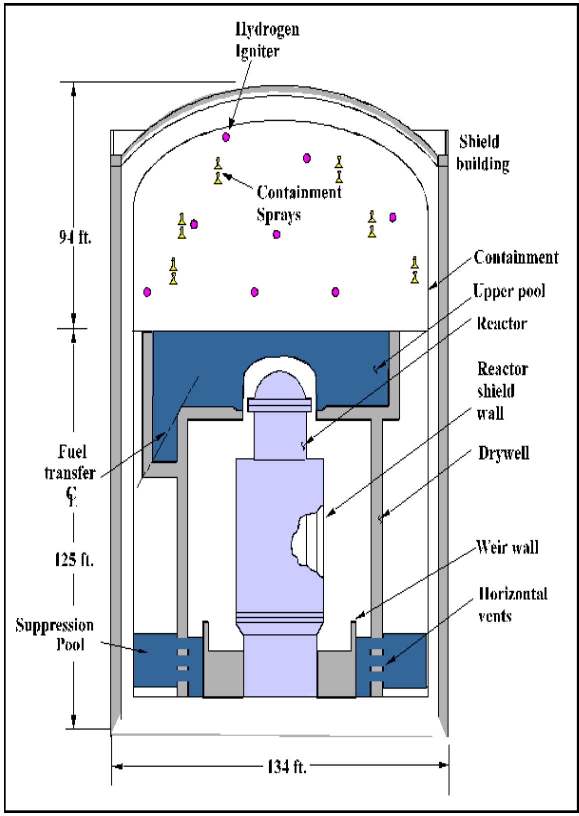
BWR Containments



Mark I
23 in US*



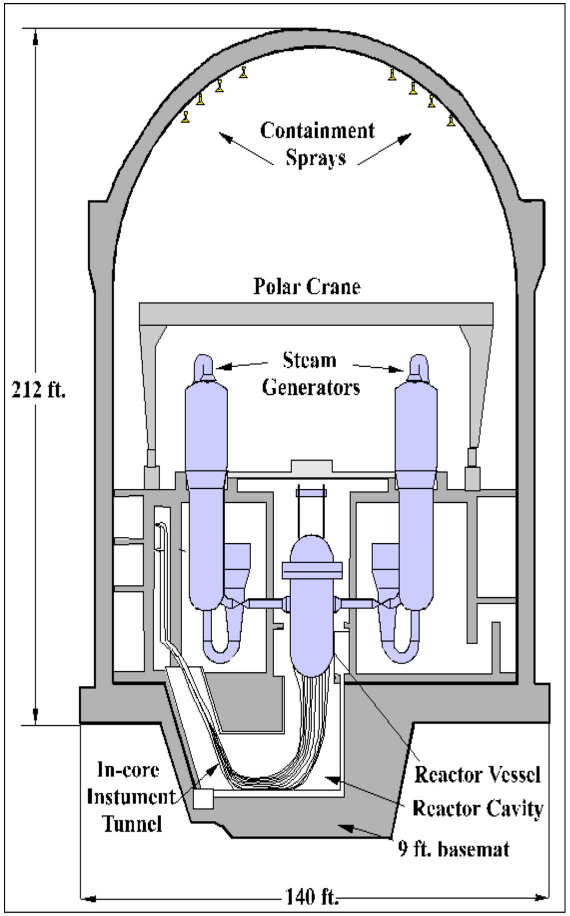
Mark II
8 in US*



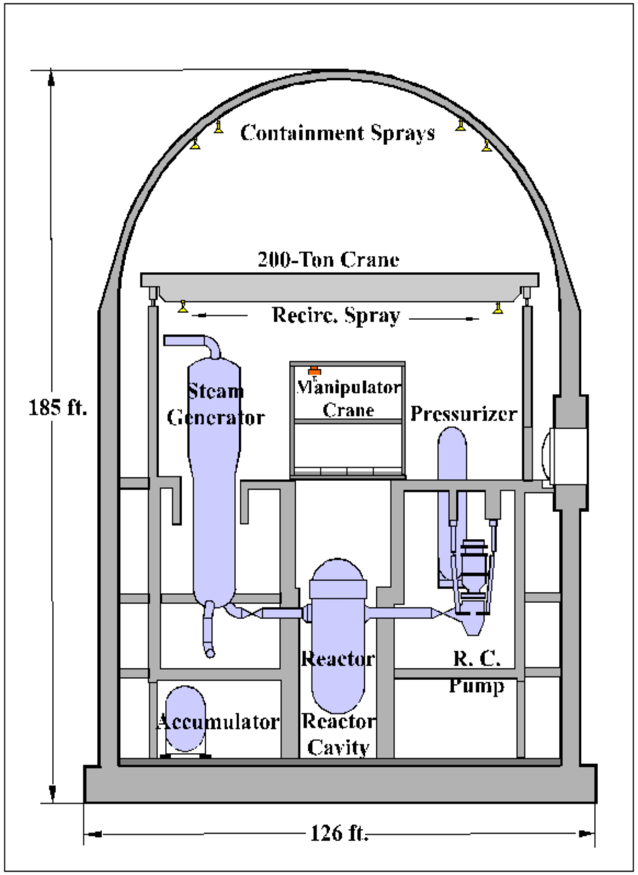
Mark III
4 in US*

* Information as of 2008

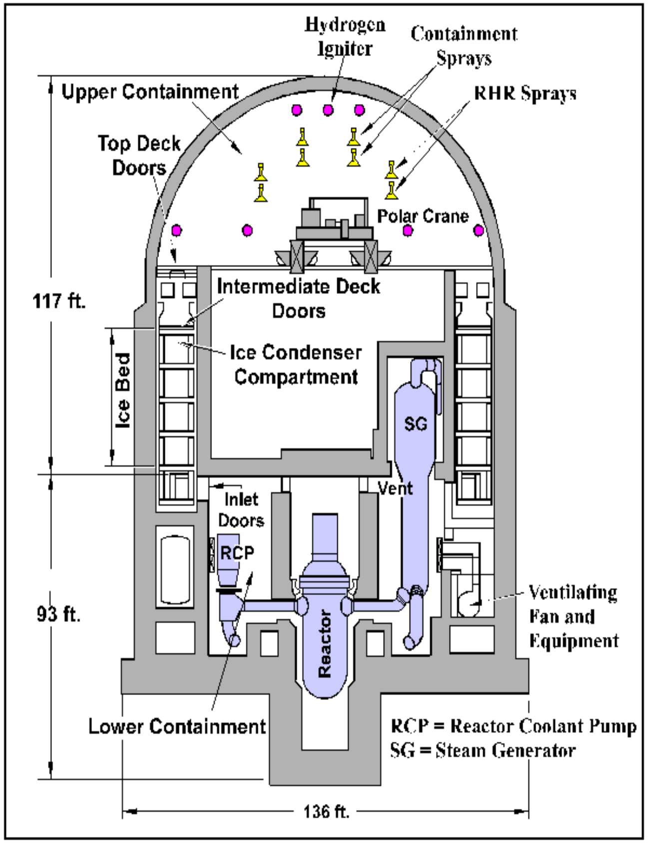
PWR Containments



Large Dry
55 in US*



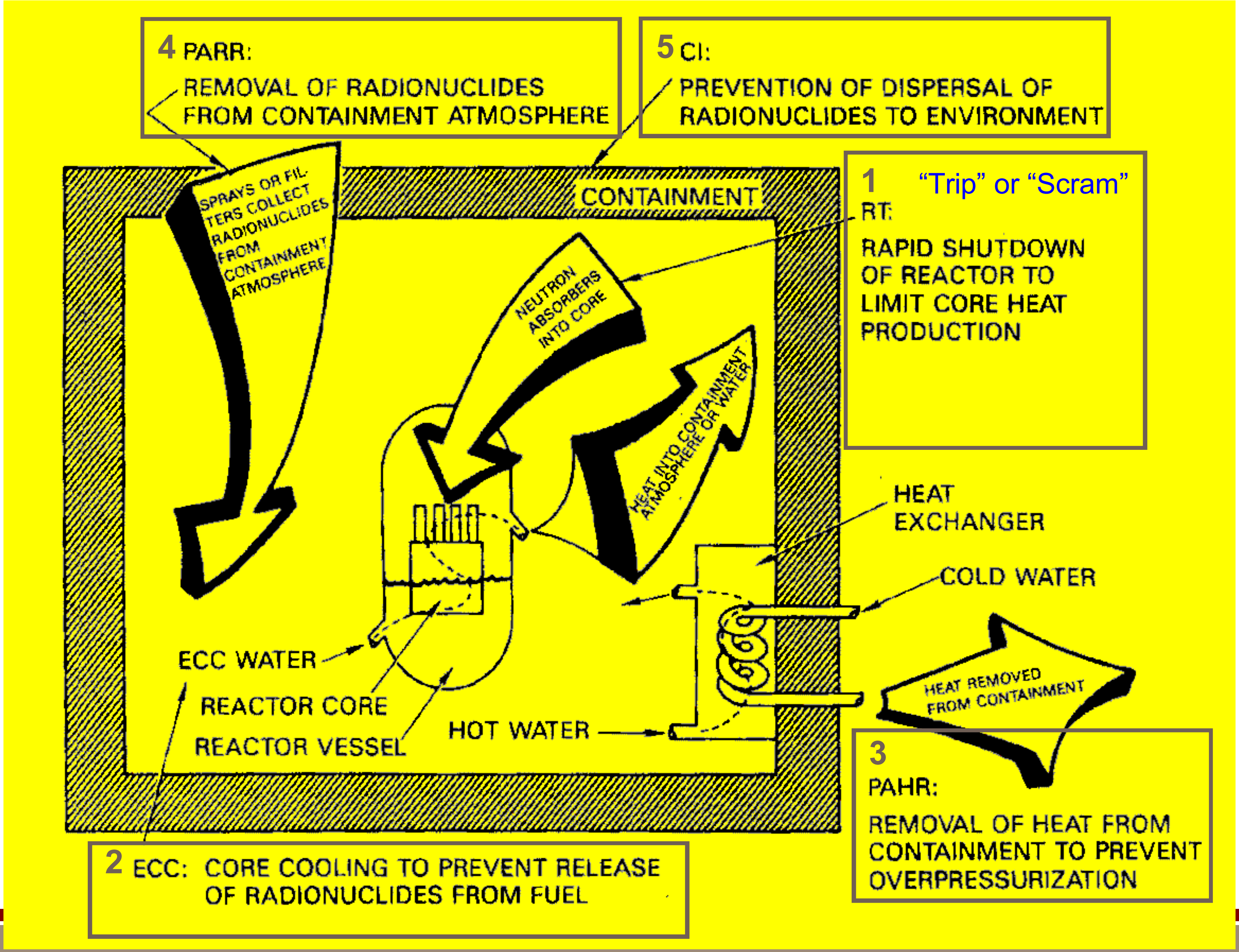
Subatmospheric
5 in US*



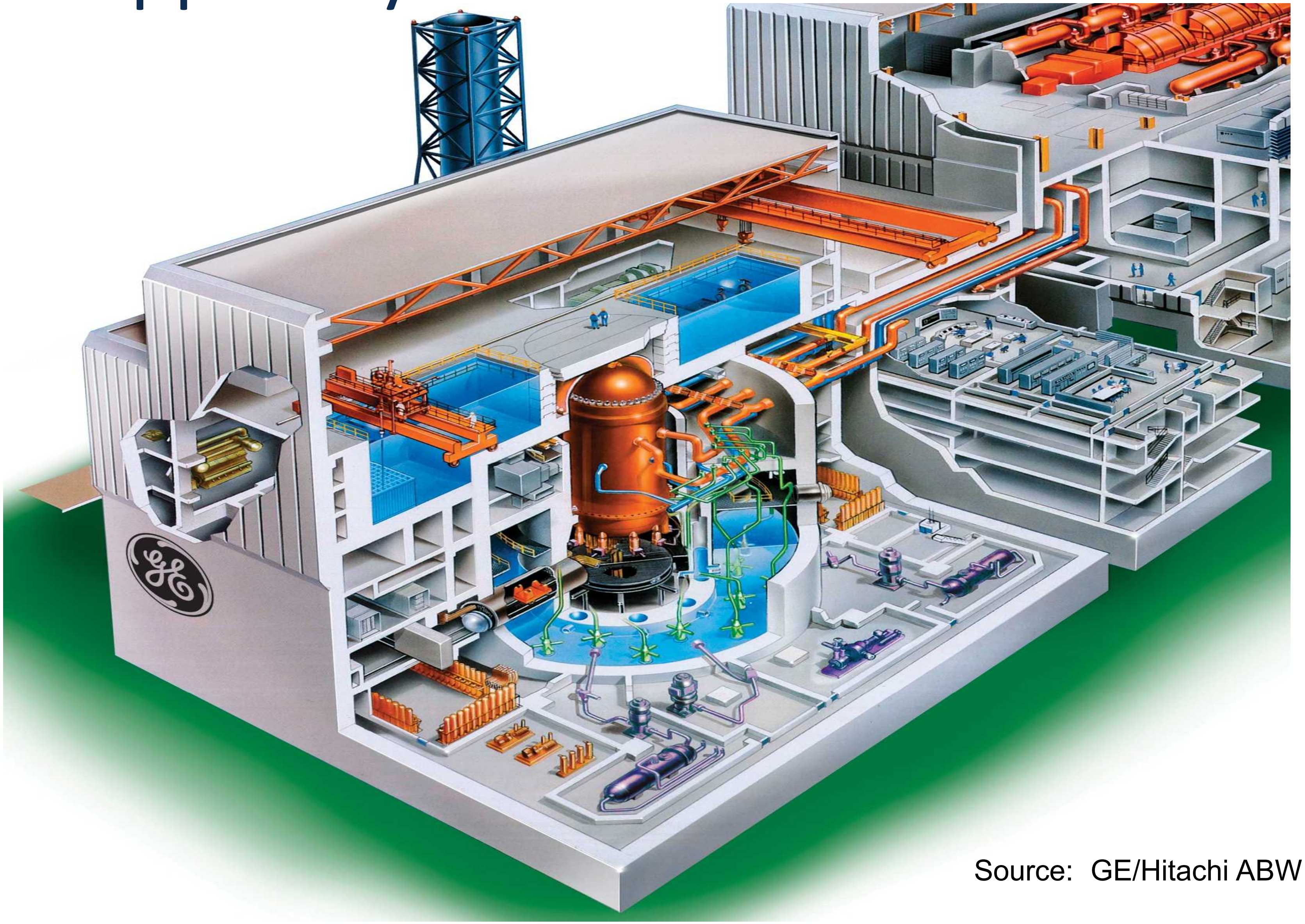
Ice Condenser
9 in US*

* Information as of 2008

Generic Reactor Safety Systems



Support Systems



Source: GE/Hitachi ABWR Design

Emergency Systems

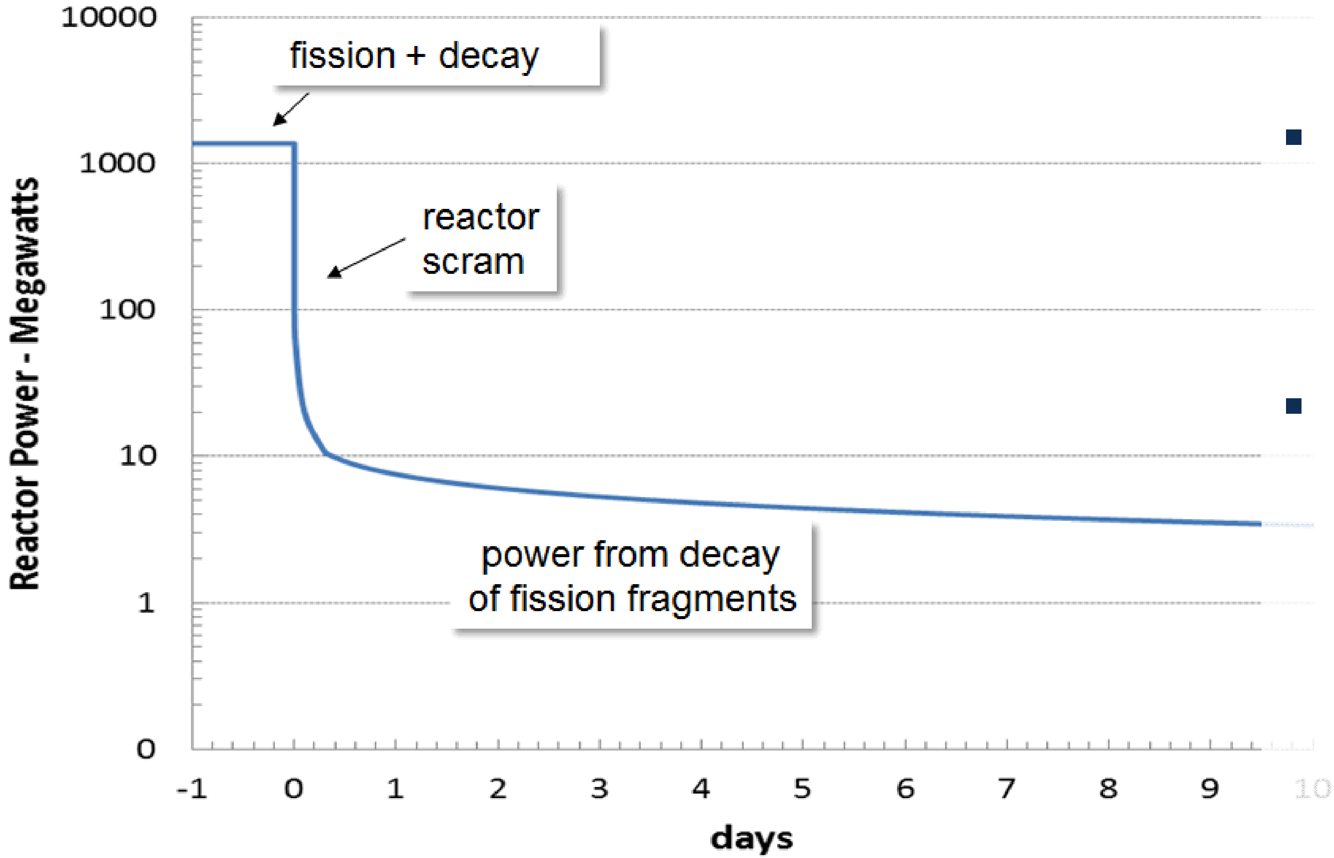
- Automatic shutdown of chain reaction ["scram"/"trip"]
  - Boron-loaded "control rods" inserted into the core
- Injection of cooling water
- Heat removal from cooling water
- Radioactivity removal
- Containment integrity

Energy Sources

- Stored energy in fuel, coolant, and structures - redistribution may result in immediate damage
- Nuclear transients (continuing "criticality")
  - Increased power level
  - Large power pulse
- Decay heat from fission-products
- Chemical reactions among overly hot fuel, cladding, and coolant
- External events
  - Natural (flood, hurricane, tornado, earthquake, &/or tsunami)
  - Man-made (aircraft impact & industrial explosion)

Severe Accident Phenomena

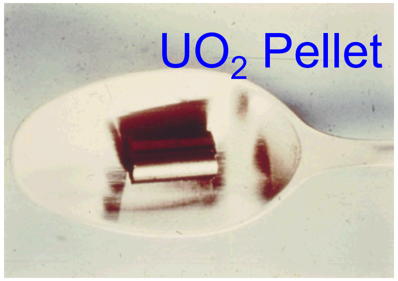
A nuclear power plant vs. your car



- Reactor shutdown doesn't completely stop heat generation
- Decay power requires long-term heat rejection (cooling)
- Long-term loss of cooling results in fuel melting and release of radioactivity

Defense-in-Depth

- Reactor Safety is realized through defense-in-depth
  - Fuel Pellet
  - Metal Cladding
  - Reactor System
  - Containment
  - Evacuation



- A design-basis accident (DBA) is a postulated set of failure events that a facility is designed and built to withstand without exceeding the offsite exposure guidelines of the NRC's siting regulation
  - Loss of flow & Loss of coolant
  - Overcooling & undercooling
  - Reactivity & anticipated transient without scram
  - External events – natural & human caused
  - Spent fuel systems – radioactivity release

Early Stages of Reactor Accidents

In-vessel

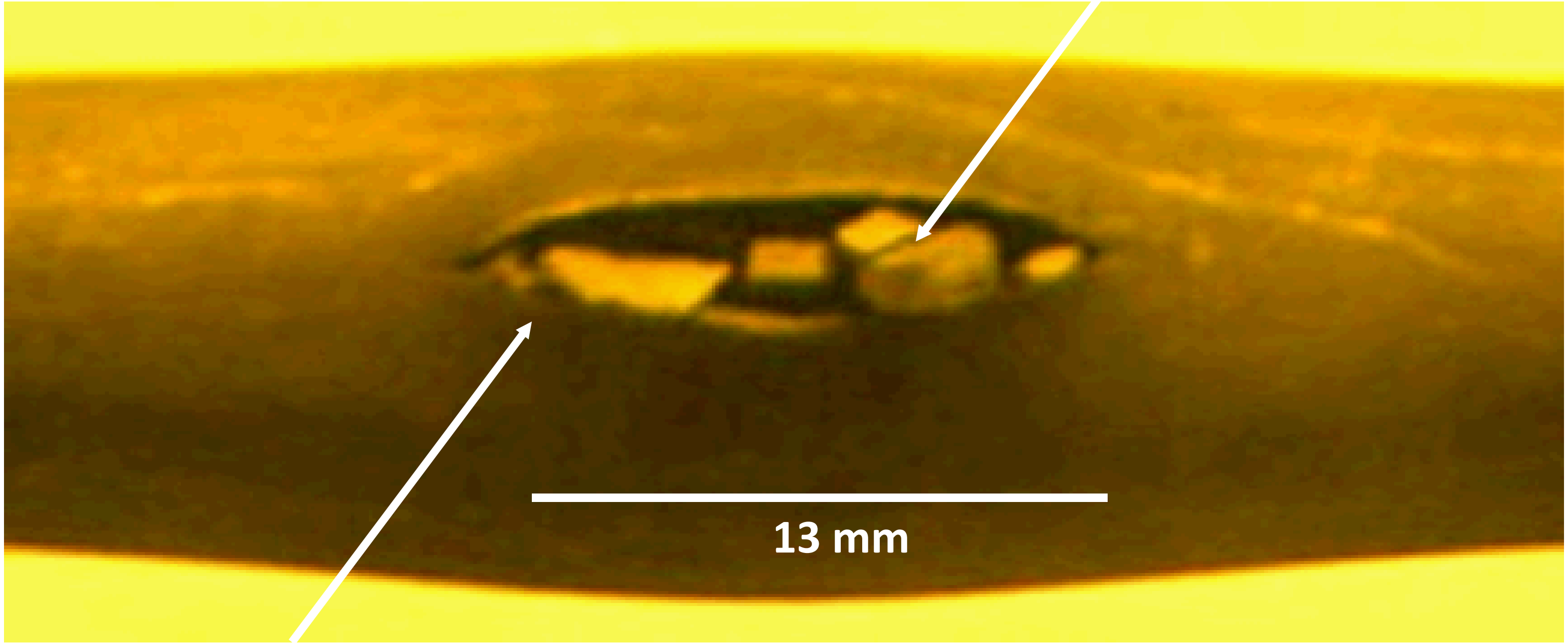
- **Accident initiation and discharge of coolant to 'top of active fuel'**
- **Stages:**
  - **1. boildown of coolant and fuel heatup**
  - **2. clad balloon and rupture**
  - **3. clad oxidation and temp. transient**

DBA & SA

  - 4. clad melting and fuel liquefaction
  - 5. candling and accumulation of core debris
  - 6. relocation of debris from core region
  - 7. debris interactions with vessel

SA

Fuel Rod Balloon



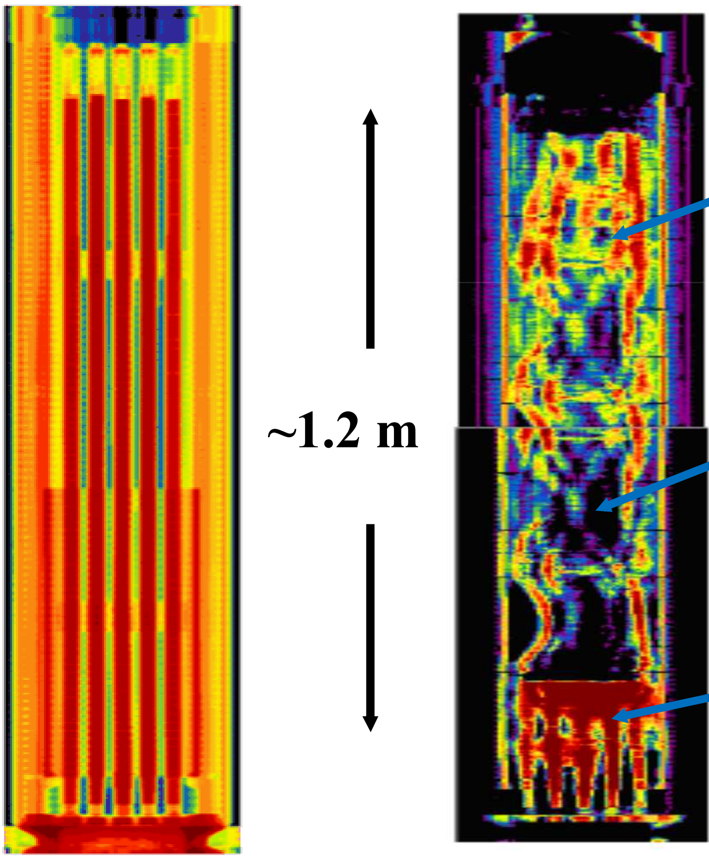
Cladding Oxidation

- Becomes significant when peak fuel temperature reaches about 1832 ^oF (1000^oC)
- Reaction:

$$Zr + 2H_2O \Rightarrow ZrO_2 + 2H_2 + heat$$

- $\Delta H_{rxn} = 2.8 \times 10^3$ Btu/lb$_{Zr}$ (6.5 MJ/kg$_{Zr}$) (Exothermic)
  - TNT = 4.6 MJ/kg
- Reaction rate increases rapidly with temperature
- Next stage begins when cladding melts, but oxidation continues

Cladding Melt

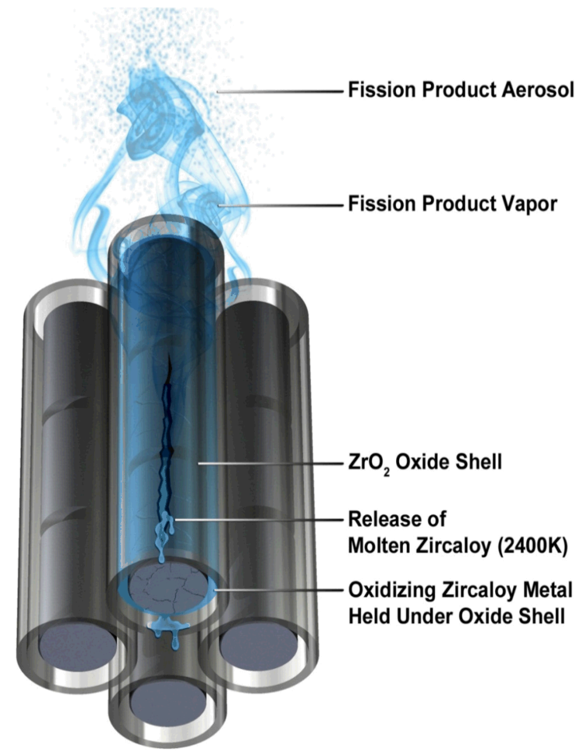


~1.2 m

Deformed and damaged rods

Void left by molten fuel relocation

Accumulated molten pool



Note: *Molten lava is 700 to 1200 C (1300-2200 ^{o}F)*
Molten zircaloy is ~2125 C (3860 ^{o}F)

Hypothesized TMI-2 core configuration after relocation

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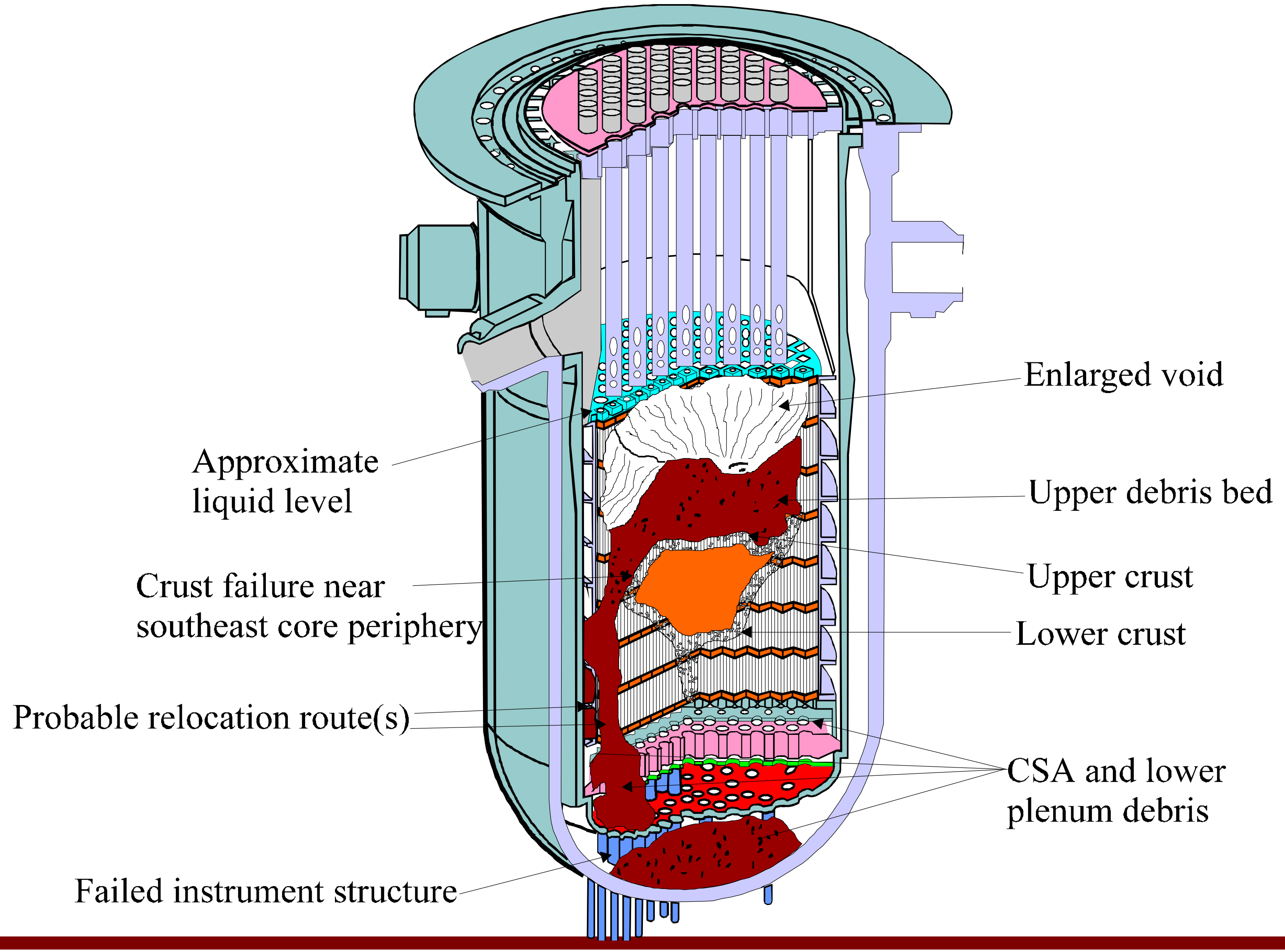


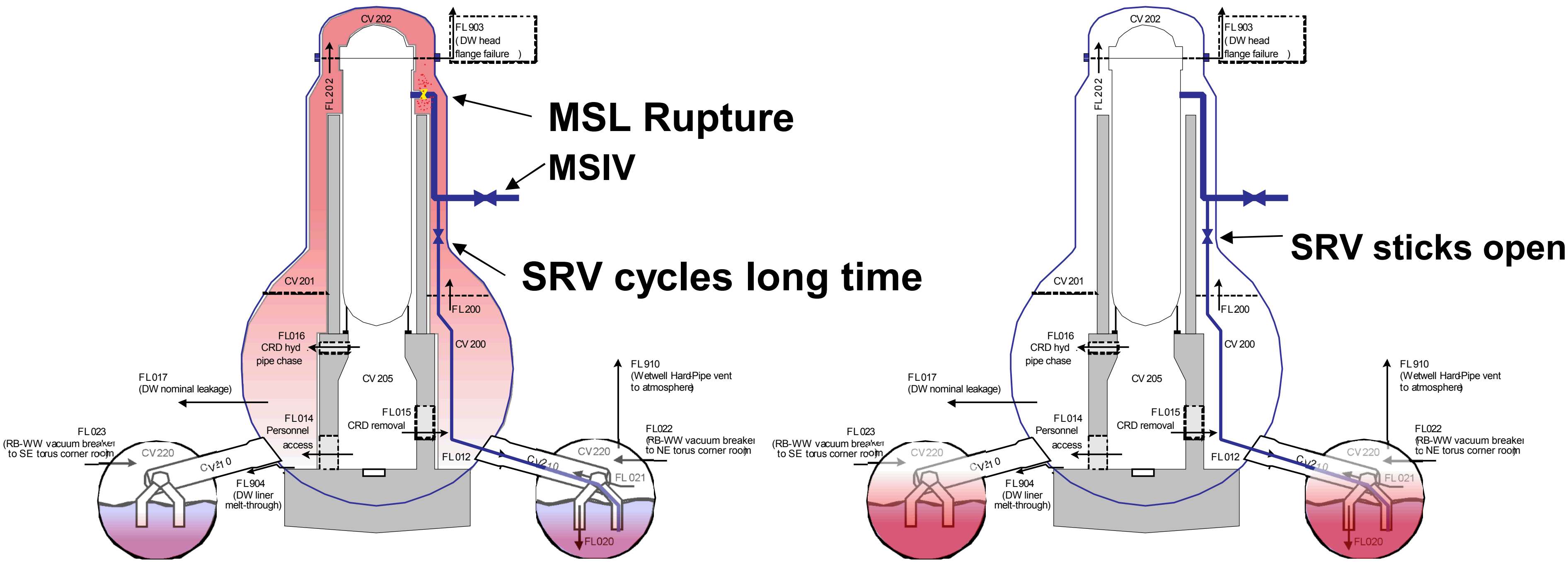
Late Stages of Reactor Accidents

Ex-vessel

- Reactor Coolant System Failure / Depressurization
- Lower Vessel Head Failure
- Molten Core / Concrete Interactions
- Hydrogen Combustion
- Containment Failure

RCS Failure Example

SRV failure vs. MSL failure



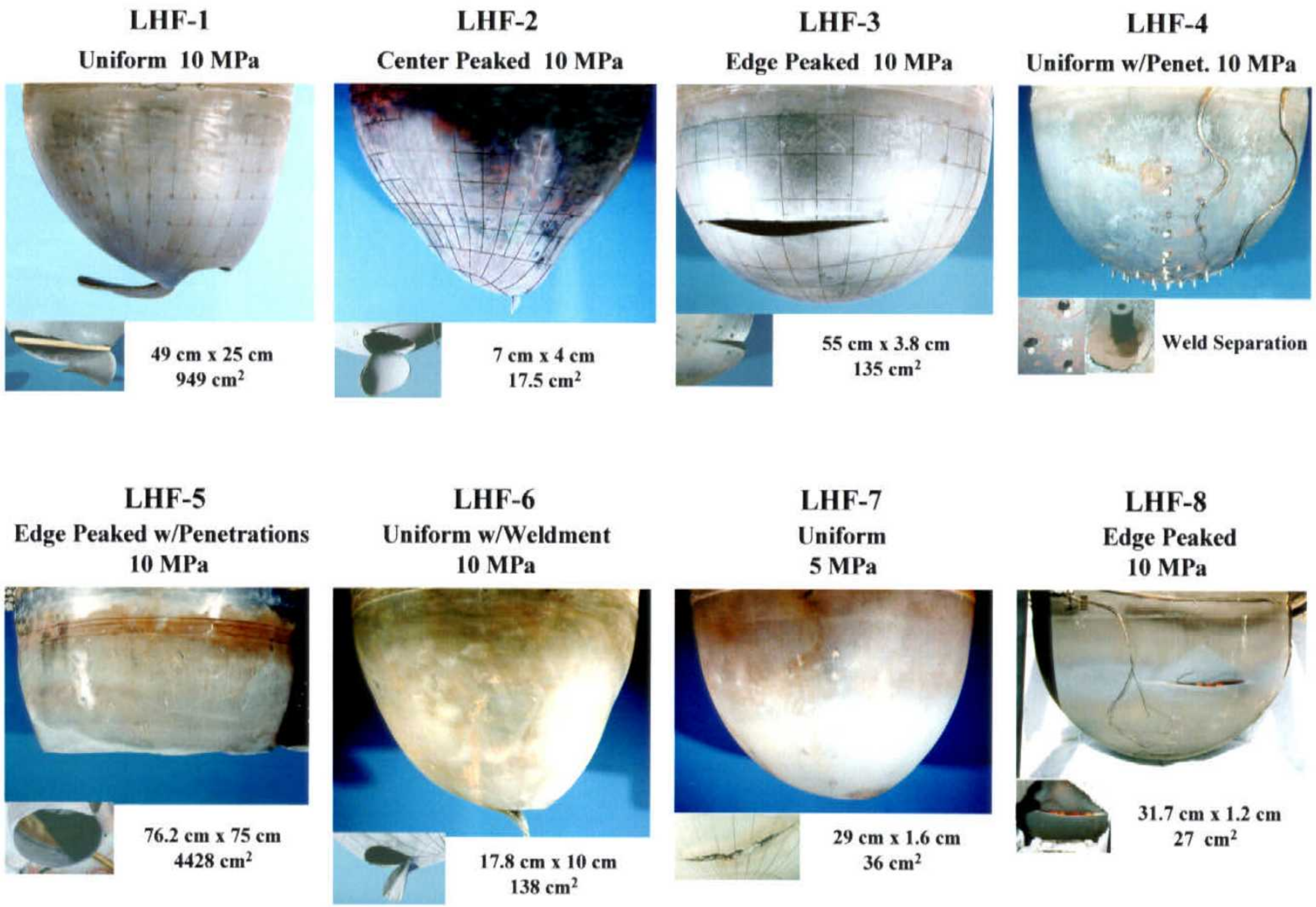
Main steam line failure vents fission products to drywell

Release to environment via drywell head flange or drywell liner melt through

SRV failure vents fission products into wetwell

Wetwell scrubbing minimizes release to the environment

Lower Head Failure



Pictoral summary of the LHF tests sponsored by the USNRC

Molten Core / Concrete Interactions

- *Concrete attack*
- *Gas generation*
  - *Combustible*
  - *Noncombustible*
- *Aerosol releases*

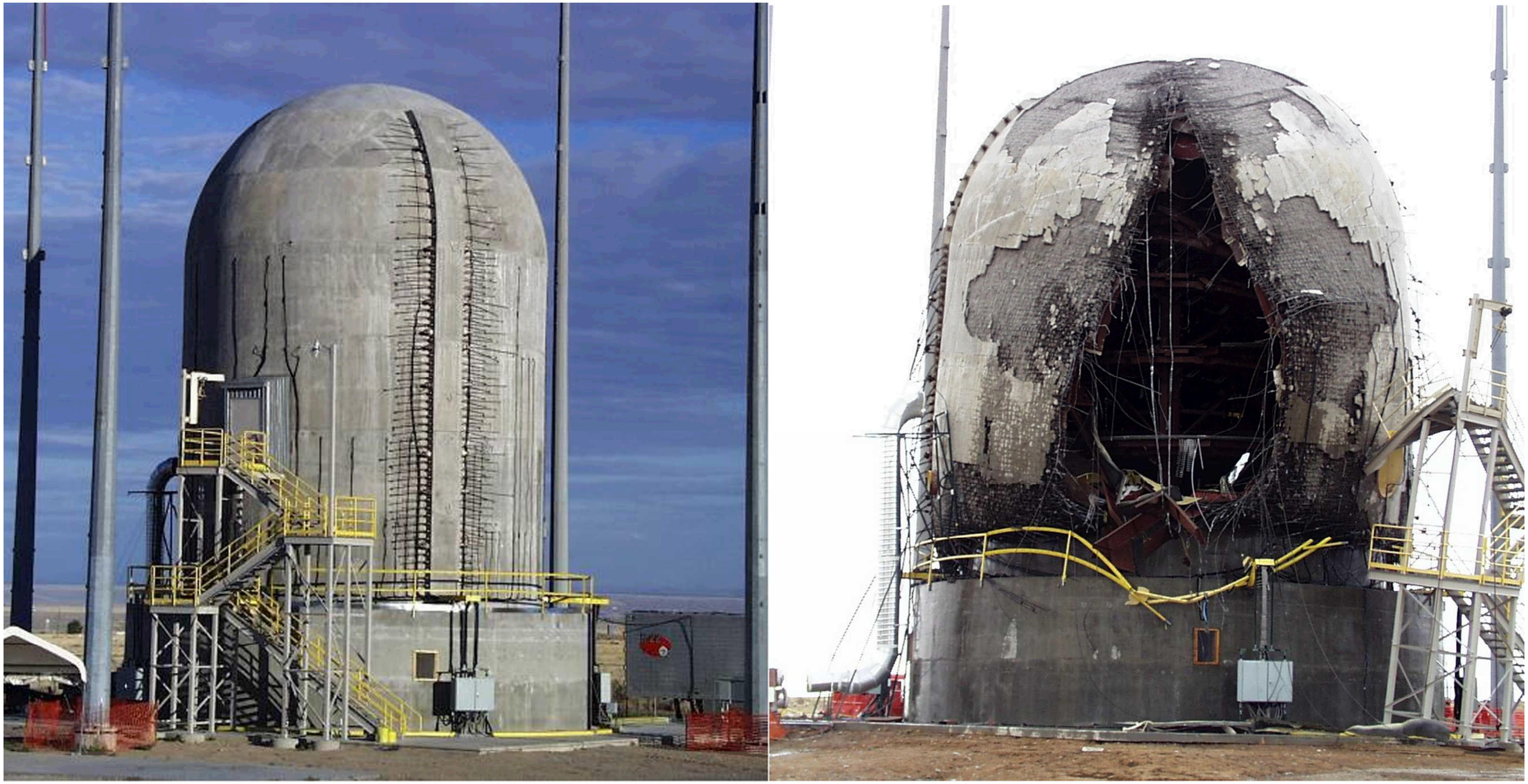
Hydrogen Combustion

	Deflagration	Detonation
Ignition	milliJoules empirical flammability limits	kiloJoules (or deflagration to detonation transition)
Propagation	Conduction Subsonic 1-1000 m/s	Shock Heating Supersonic 1500-3000 m/s
Loads & Structural Response	Static, Thermodynamic Bound	Dynamic Shock Waves Hard to Model (3D)

Deflagrations

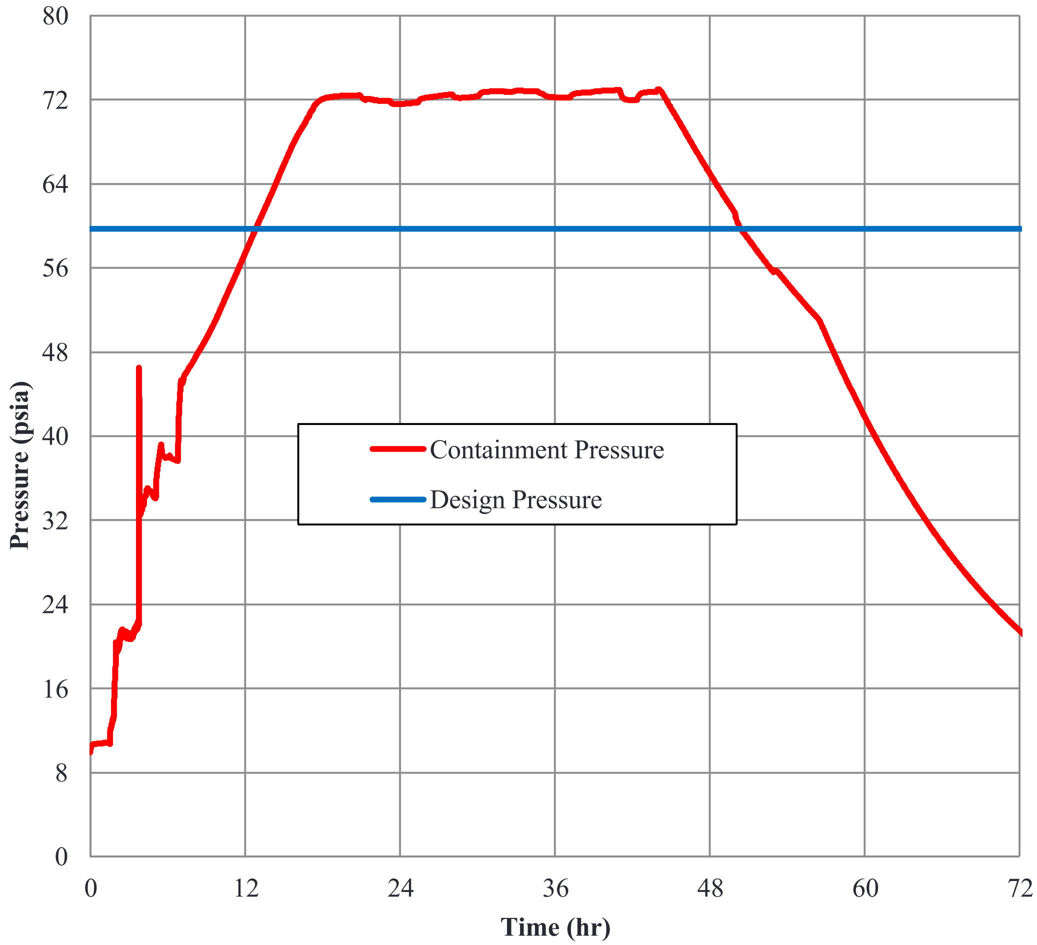
- Conditions required for ignition are understood
- Propagate by conduction from burned to unburned gas
- Burn front is subsonic relative to unburned gas
- Static loading, peak pressure
  - Depends on combustion completeness and heat transfer during burn, which are affected by:
    - Flame speed
      - Initial gas composition and state
      - Geometry and location of ignition source
      - Turbulence
    - Heat sinks
  - Bounded by complete, adiabatic, constant-volume combustion pressure
- The TMI-2 combustion event was a deflagration
- Deflagration to detonation transition Fukushima?

Containment Failure

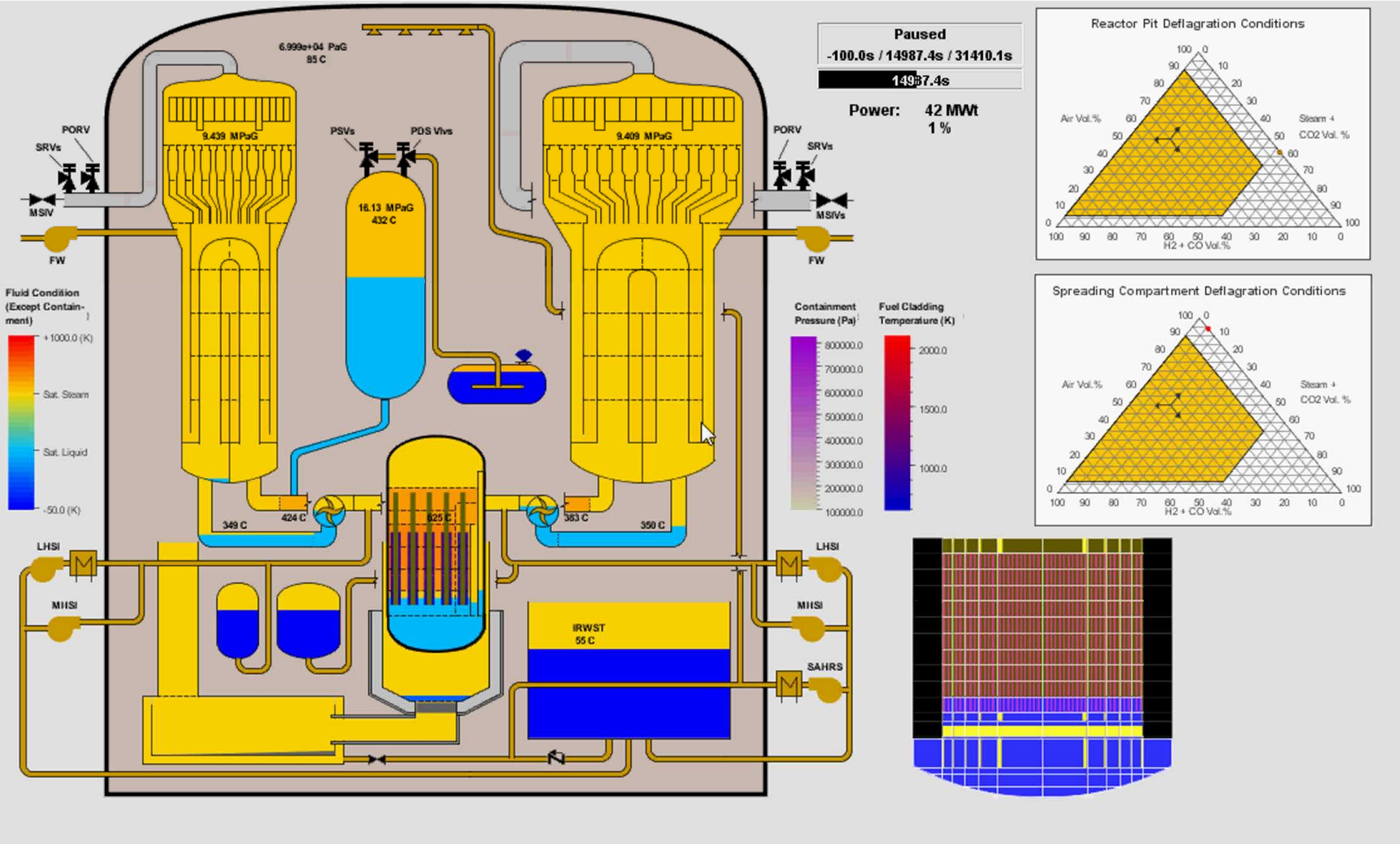


At 70-feet tall and 35-feet in diameter, this ¼ scale containment is the largest nuclear reactor containment vessel model ever tested to failure.

Containment Failure – cont.



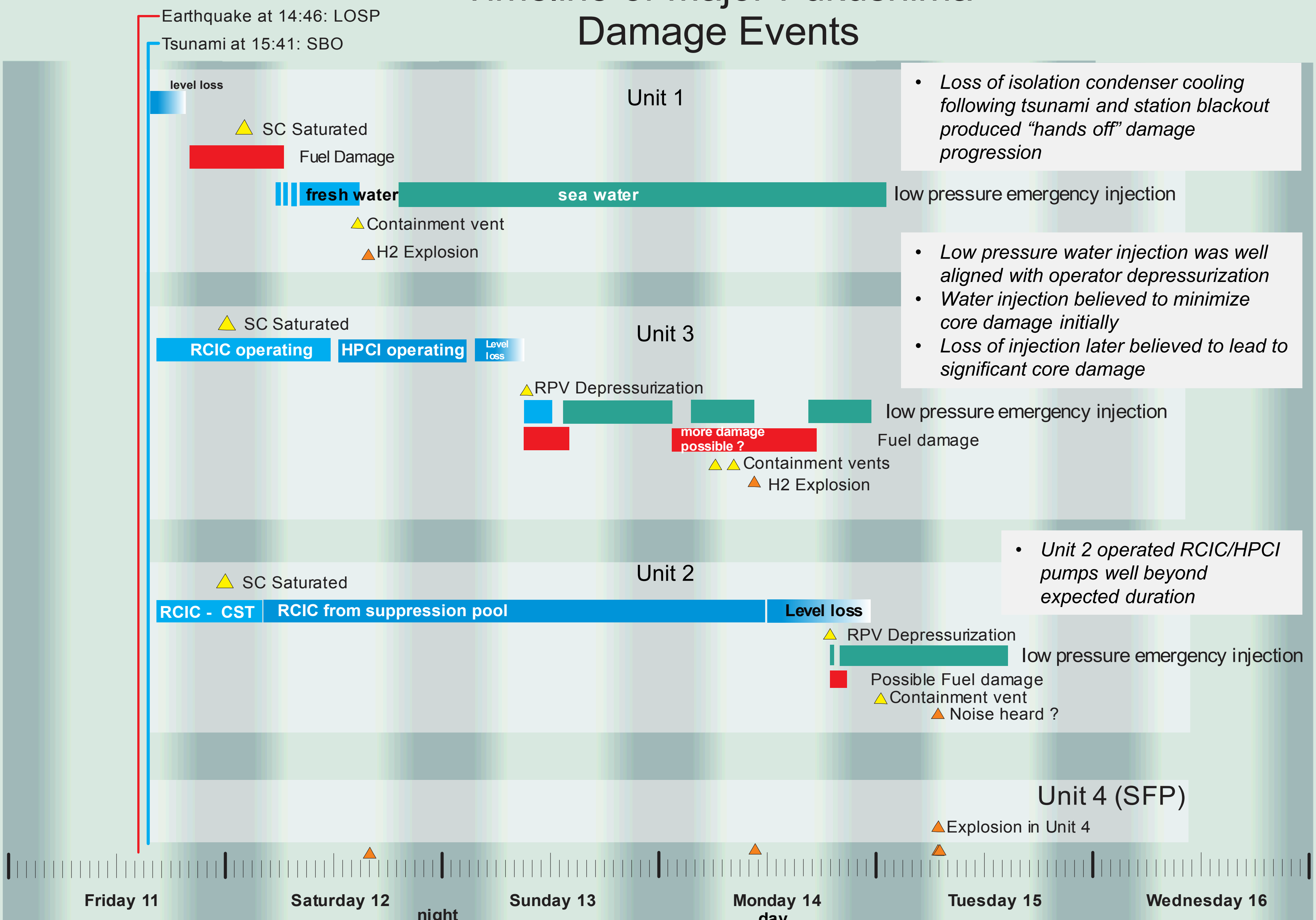
MELCOR – SNAP Video



Fukushima & Severe Accident Scenarios

Fukushima - Before

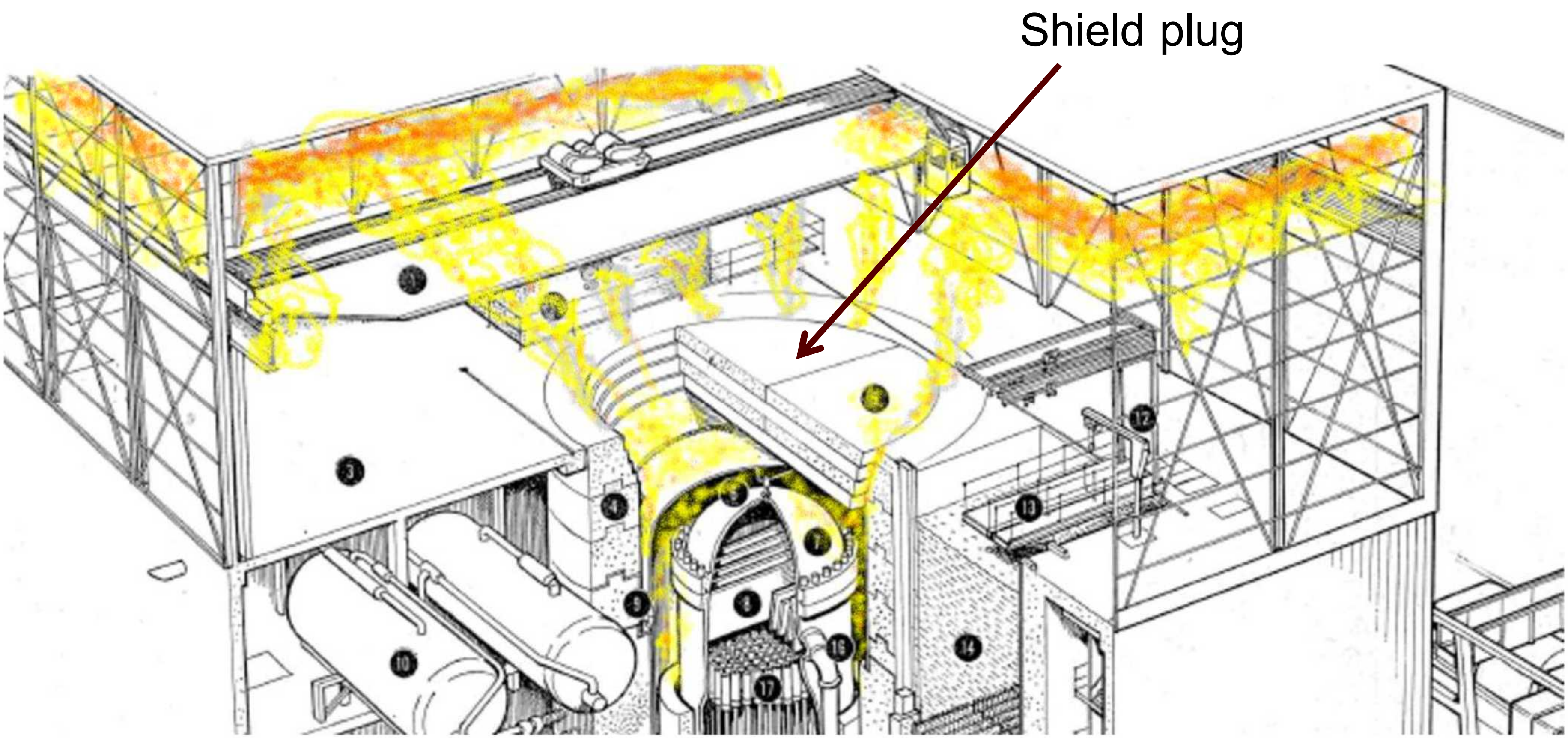
Timeline of Major Fukushima Damage Events



Fukushima - After

Used by permission from TEPCO
Kenji Tetawa

Hydrogen Accumulation in 1F1



Environmental Release Paths

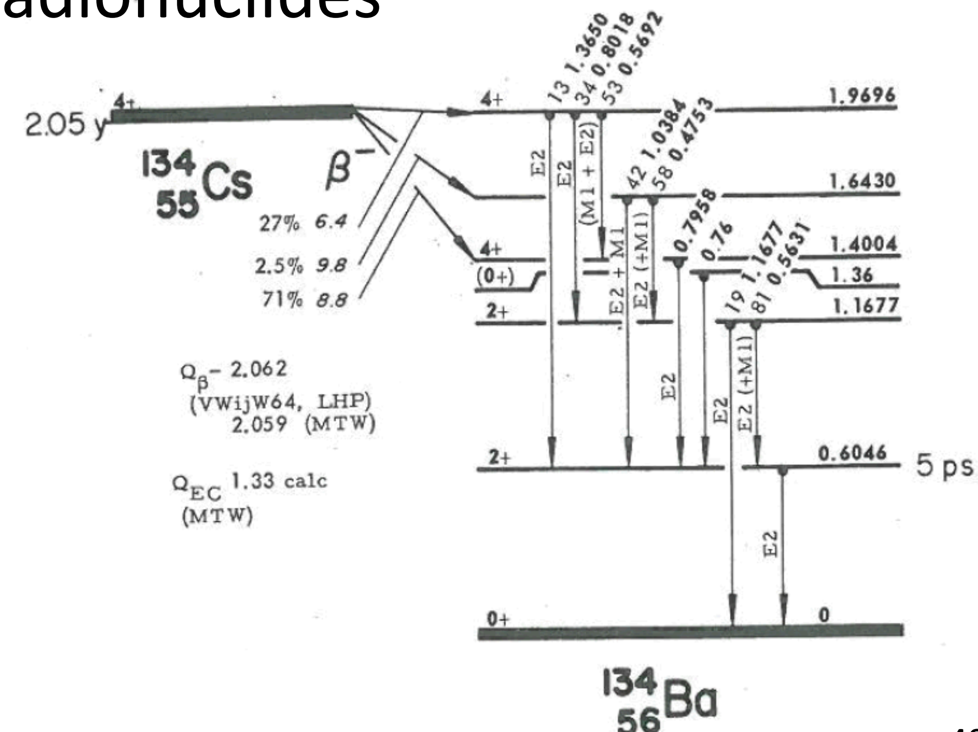
- Each accident sequence is unique
  - Short-term vs. long-term
  - Containment bypass event
  - Multi-unit and spent fuel pools
- Each reactor type and containment type is unique
  - BWR vs. PWR
  - Mark I & II vs. Mark III containments (BWR)
  - Large Dry vs. Ice Condenser containments (PWR)
- Multiple release paths
  - Leakage vs. Containment functional failure
  - Drywell liner melt through vs. Drywell head lifting (BWR)
  - Mitigated vs. Unmitigated pathways

Radionuclide Chemical/Physical Forms

- NUREG-1940 (RASCAL)
  - Iodine (25% particle, 30% reactive gases, and 45% organic gases)
  - Tritium water vapor (HTO) ICRP-60 DCFs
  - FRMAC Assessment Manual Appendix F Supplement 4
    - *DRAFT*
- Cesium
  - CsI, CsOH, Cs_2MoO_4
  - Late phase revaporization
- Particle Size Distributions
  - 1 μm AMED assumption
  - State-of-the-Art Reactor Consequence Analysis (NUREG-1935)
    - 10 particle size bins

Fukushima Lessons Learned

- Beta emitters
  - Sr-90, Ru-106, and other pure beta emitters
- Cascade summing of Cs-134
- Shielded vs Unshielded Radionuclides
  - Cs-137 to Cs-134 ratio
  - Cs-136
  - Br-82, Br-82m
  - Rb-86
  - Sb-124, Sb-124m
  - Pm-150
  - Eu-154



PWR Scenarios

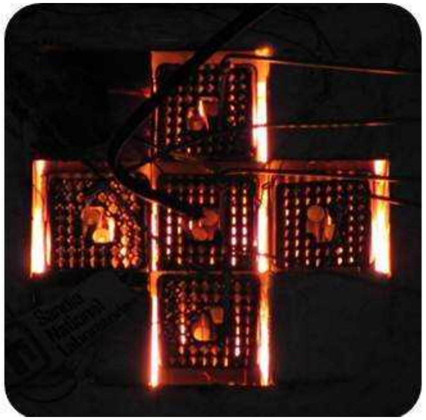
- Station Blackout with Extended loss of AC power
  - SBO/ELAP
- Containment bypass sequence
  - Steam generator tube rupture
  - Failed emergency support system outside containment
    - ISLOCA
- Anticipated transient without Scram (ATWS)
- Full power loss of feedwater
  - TMI-2

BWR Scenarios

- Station Blackout with Extended loss of AC power
  - SBO/ELAP – Fukushima
- In-core flow oscillations which progress to power oscillations
  - Fuel failure
- Failure of the main steam line into the drywell
  - Bypassing the wetwell for capturing the source term
- Containment bypass sequence
  - Main steam line rupture outside containment with failure of the main steam isolation valve
  - Control rod guide tube failure
- Anticipated transient without Scram (ATWS)

Other Scenarios

- SBO during an outage
- Events involving spent fuel pools



Path Forward

- NPP Exercise
- Training Course - Webinar
  - Manual
  - Software

Questions

Q&A

AS400

- *Assume you have validated beta and gamma spec results, and you cannot account for all the beta results. What additional considerations should you take into account and what actions should you take?*
- *Discuss the differences in a radionuclide mixture from a reactor failure vs a spent fuel pool fire.*
- *Discuss which radionuclides are modeled differently from standard FRMAC assumptions and their associated alternate assumptions.*

AS401

- *Discuss reasons why Cs-134 results might be biased low and how can you fix this?*
- *Discuss the potential radionuclide environmental release pathways for a BWR SBO/ELAP scenario.*
- *Where would you find a NPP source term regardless of the pathway?*

Q&A

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- *AS400*
  - *List and discuss in detail three energy sources that would be of concern in a severe accident.*
  - *Discuss the five generic safety systems to prevent or mitigate a severe accident.*
- *AS401*
  - *Discuss in detail the progression of the two major phases of a severe accident.*
  - *Discuss the potential environmental release pathways for a BWR SBO/ELAP scenario.*