SAND2016-2313PE

Exceptional service in the national interest

Sandia National Laboratories

The Reactor Meltdown Accidents At Fukushima Daiichi Nuclear Power Station
What Happened and Lessons Learned

Randall O. Gauntt – Manager, Severe Accident Analysis Department

Sandia Technology Symposium

March 22, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Topics of Discussion……

- What started it all
- Nuclear Reactors – how they work and severe accidents
- What happened at the Fukushima reactors
  - Why did the cores melt?
  - Why did the buildings explode?
- Lessons Learned
- What's happening now?

Sandia National Laboratories

Exceptional service in the national interest

What Started it All

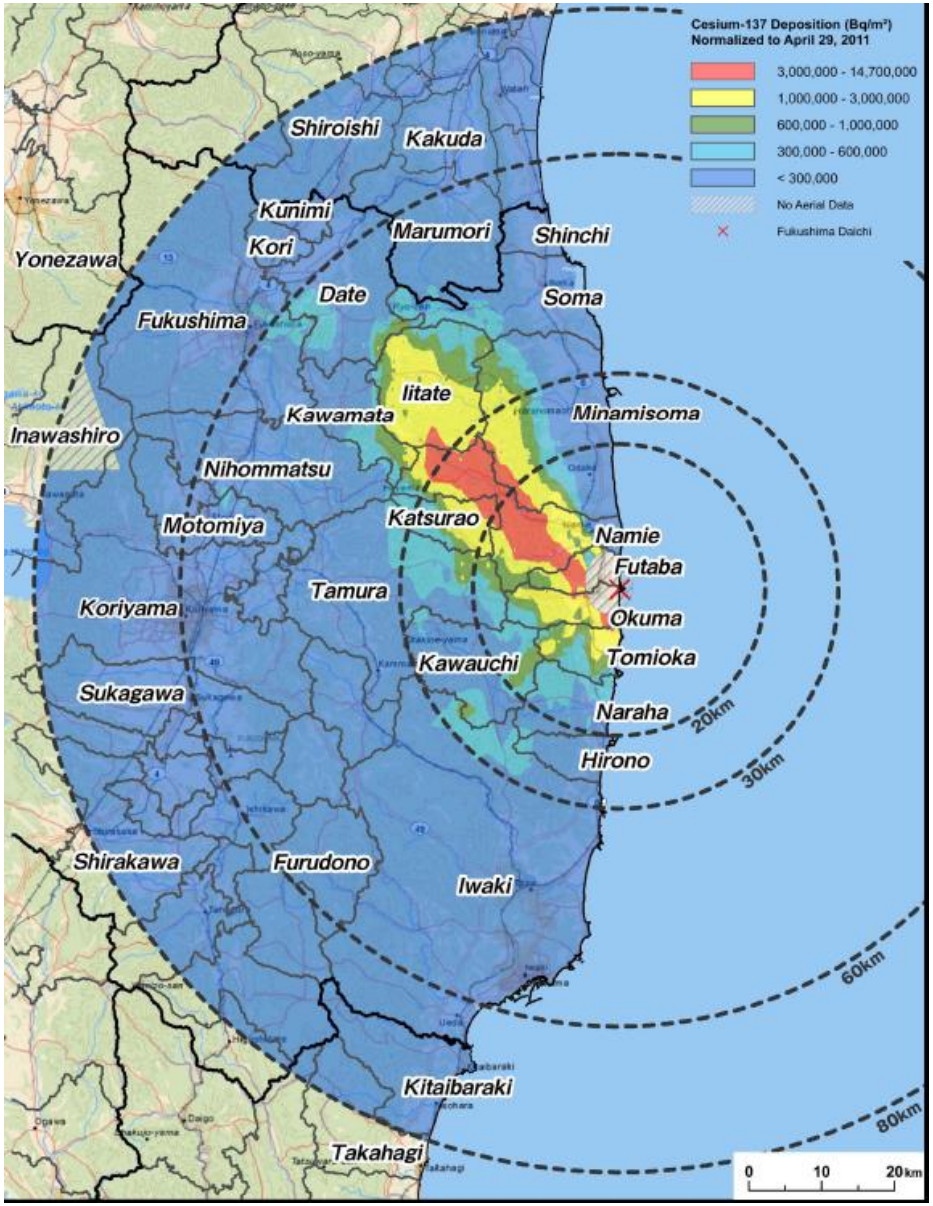
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Perspectives……

- ~20,000 dead or missing from the tsunami
- 2 industrial deaths at Fukushima Nuclear power plant
- No radiation induced fatalities
- 150,000 people displaced from homes
- All 50 nuclear power plants in Japan shut down
- What happened?



Sandia National Laboratories

Exceptional service in the national interest

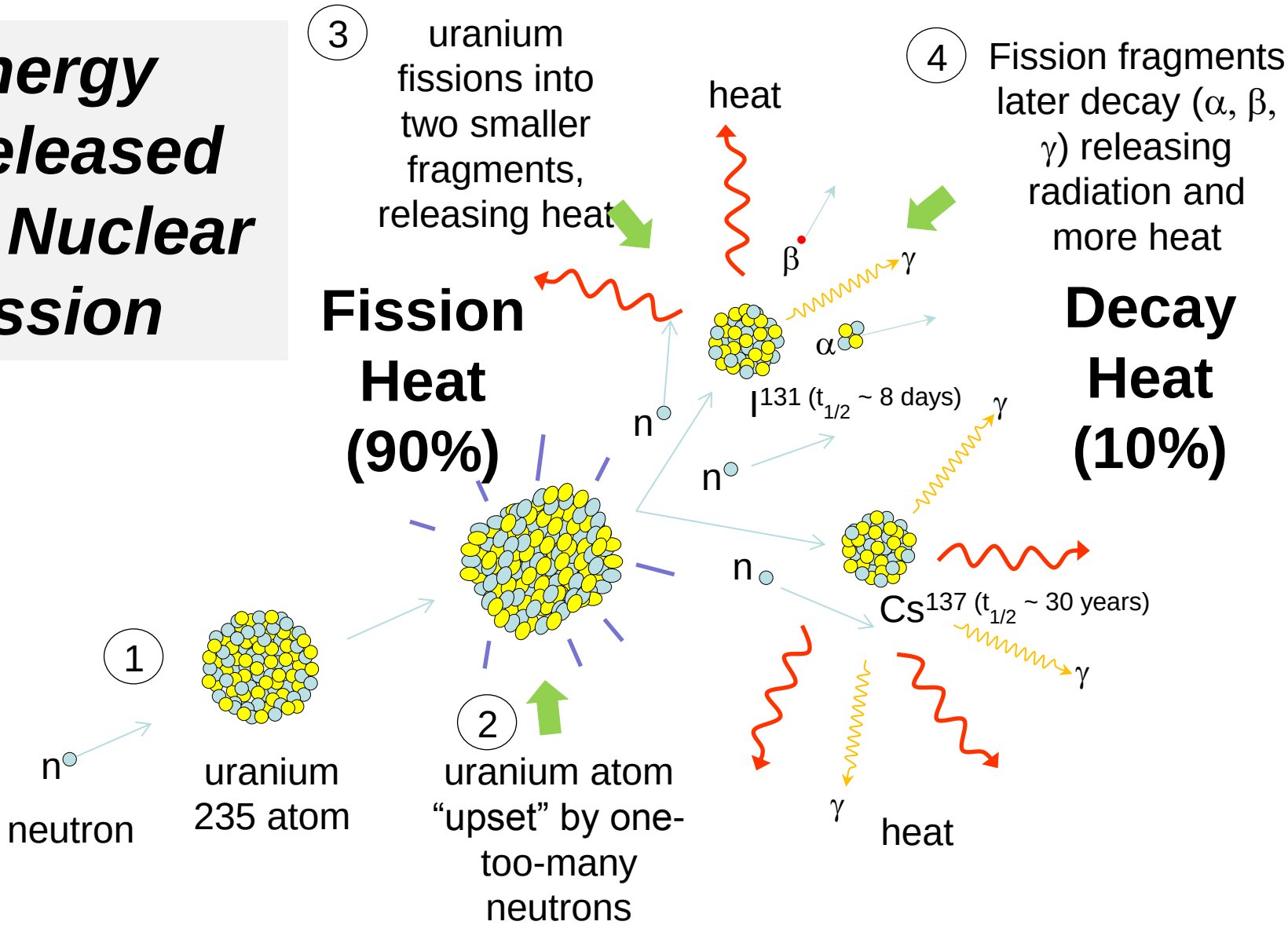
Nuclear Reactors and How They Work

U.S. DEPARTMENT OF ENERGY

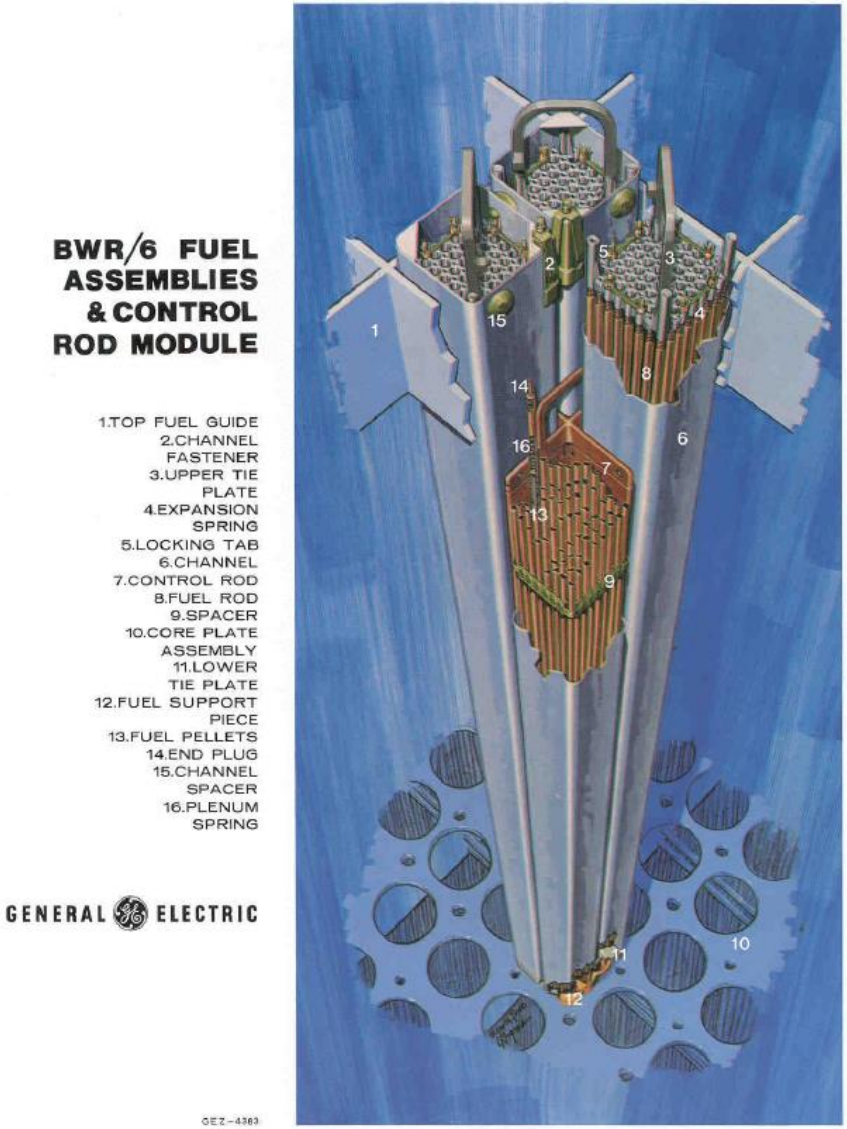
NNSA National Nuclear Security Administration

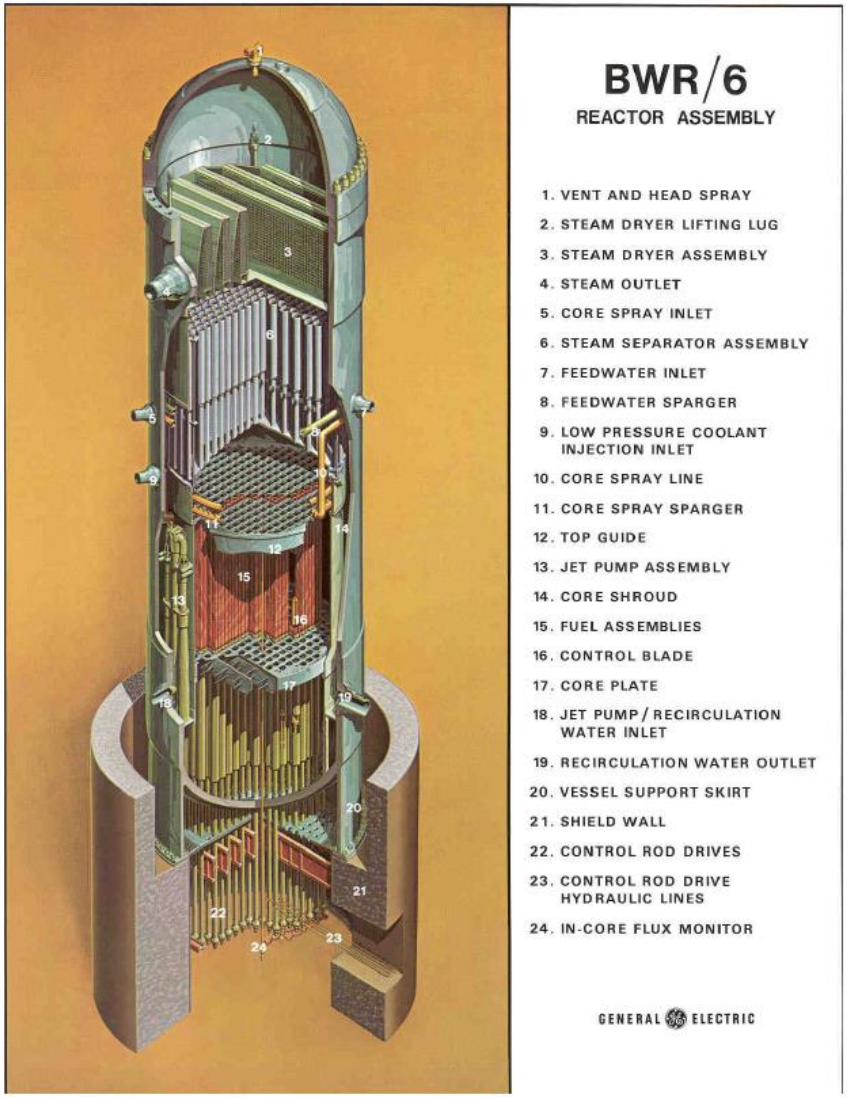
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Energy Released in Nuclear Fission



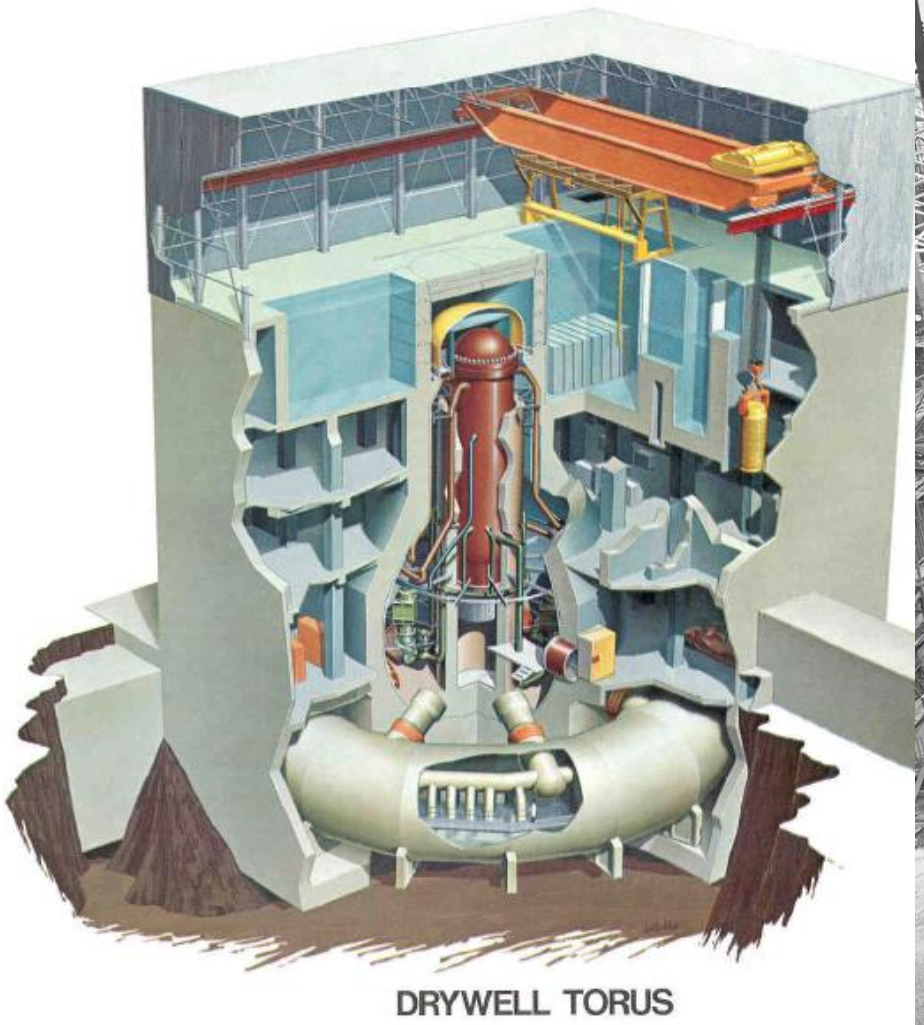
BWR Fuel Assemblies





BWR 6 Reactor Vessel

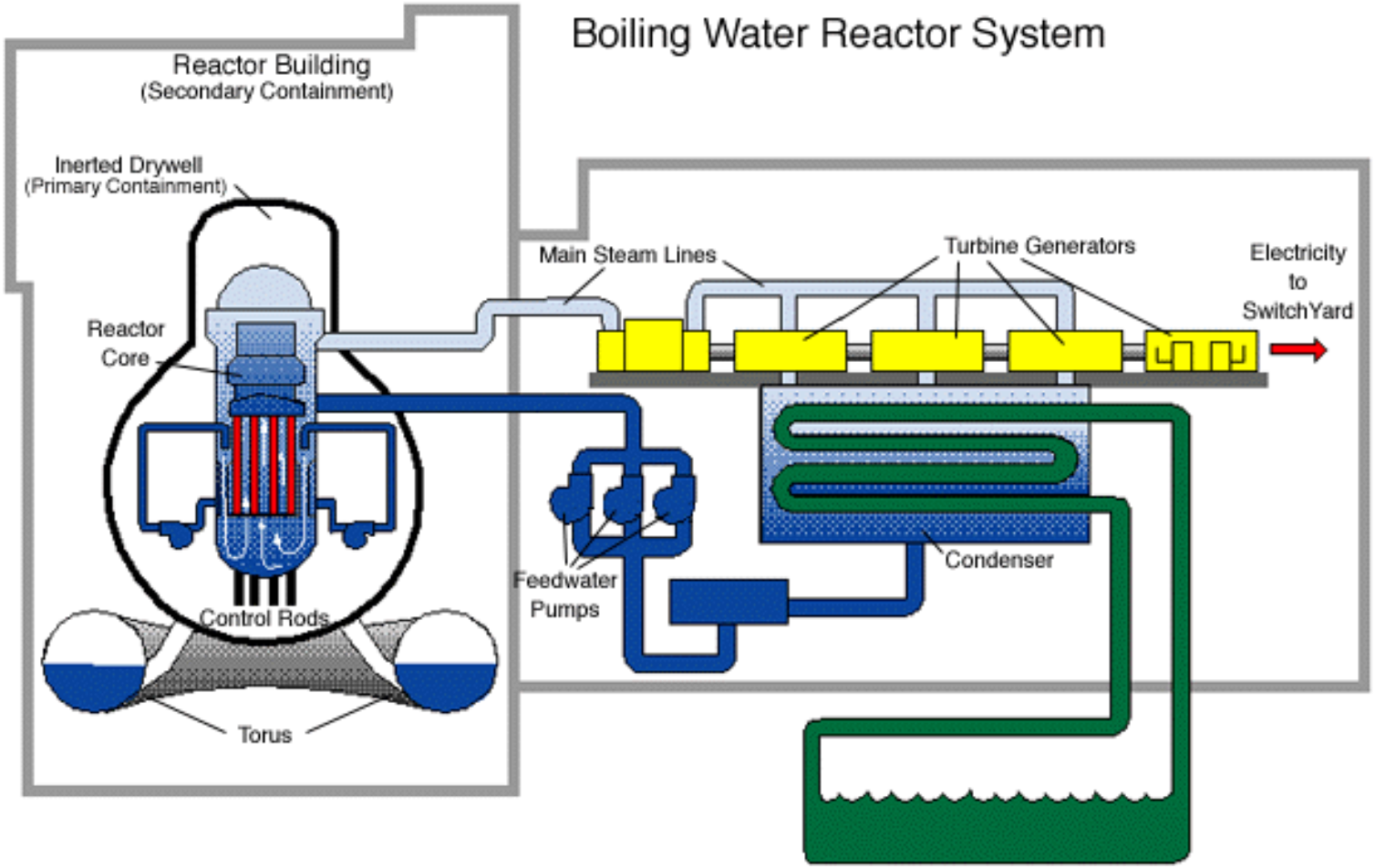
Mark-I Containment



NRC Training Manual

Browns Ferry from Wikipedia

Boiling Water Reactors



The Accidents

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Earthquake Led to Loss of Offsite Power

- Seismic events disrupted roads and power lines
- Regional blackout isolated Fukushima station from power grid
- Reactors shut down
- Site operated by onsite diesel generators

Circuit Breaker damaged

Collapsed tower

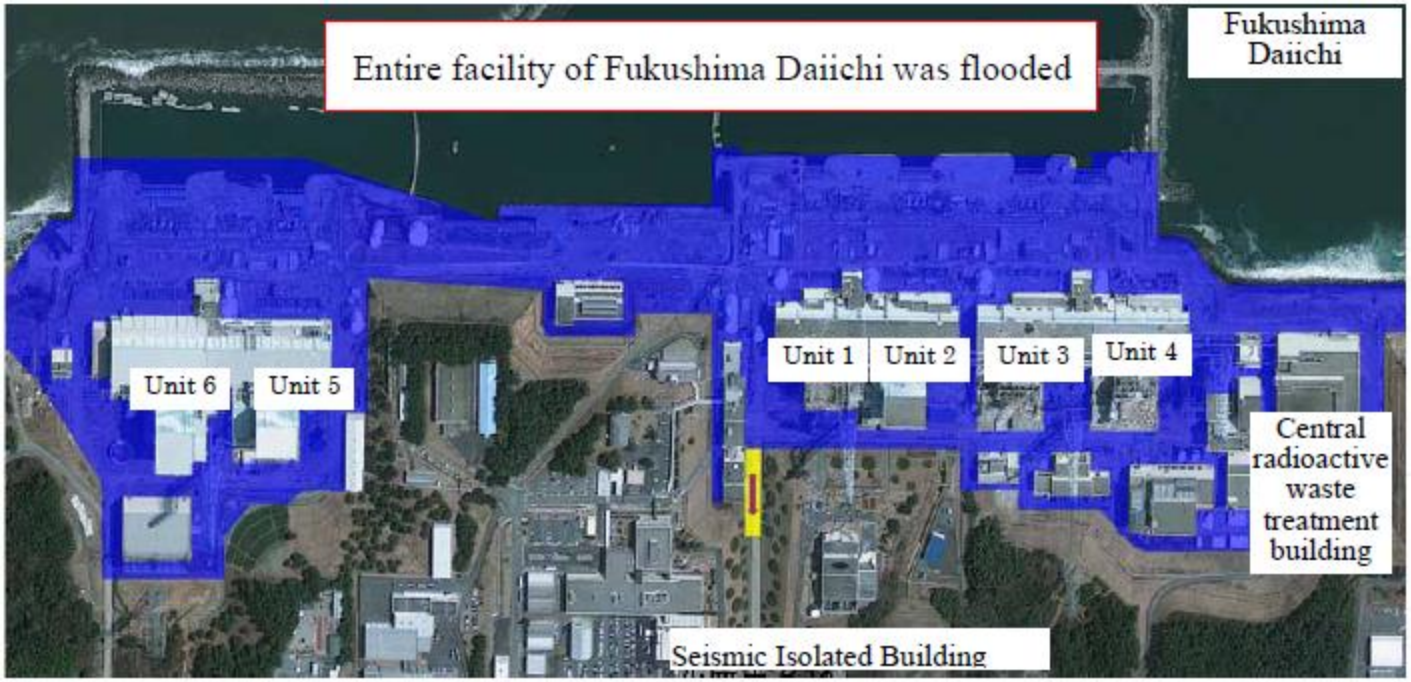
Date : 2011/3/11 15:42

Date : 2011/3/11 15:43

Date : 2011/3/11 15:44

Date : 2011/3/11 15:57

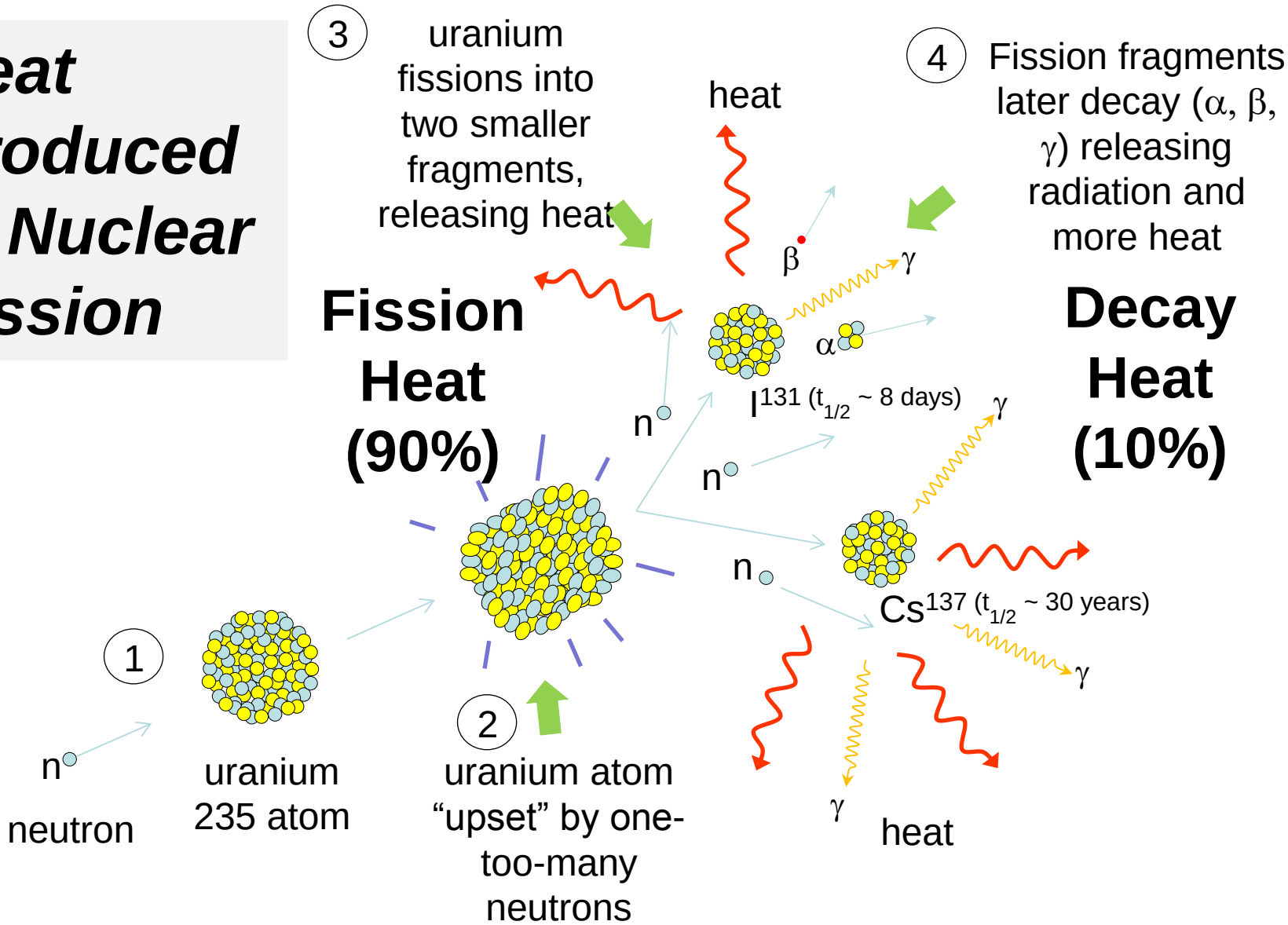
Daiichi Site was Inundated by Tsunami



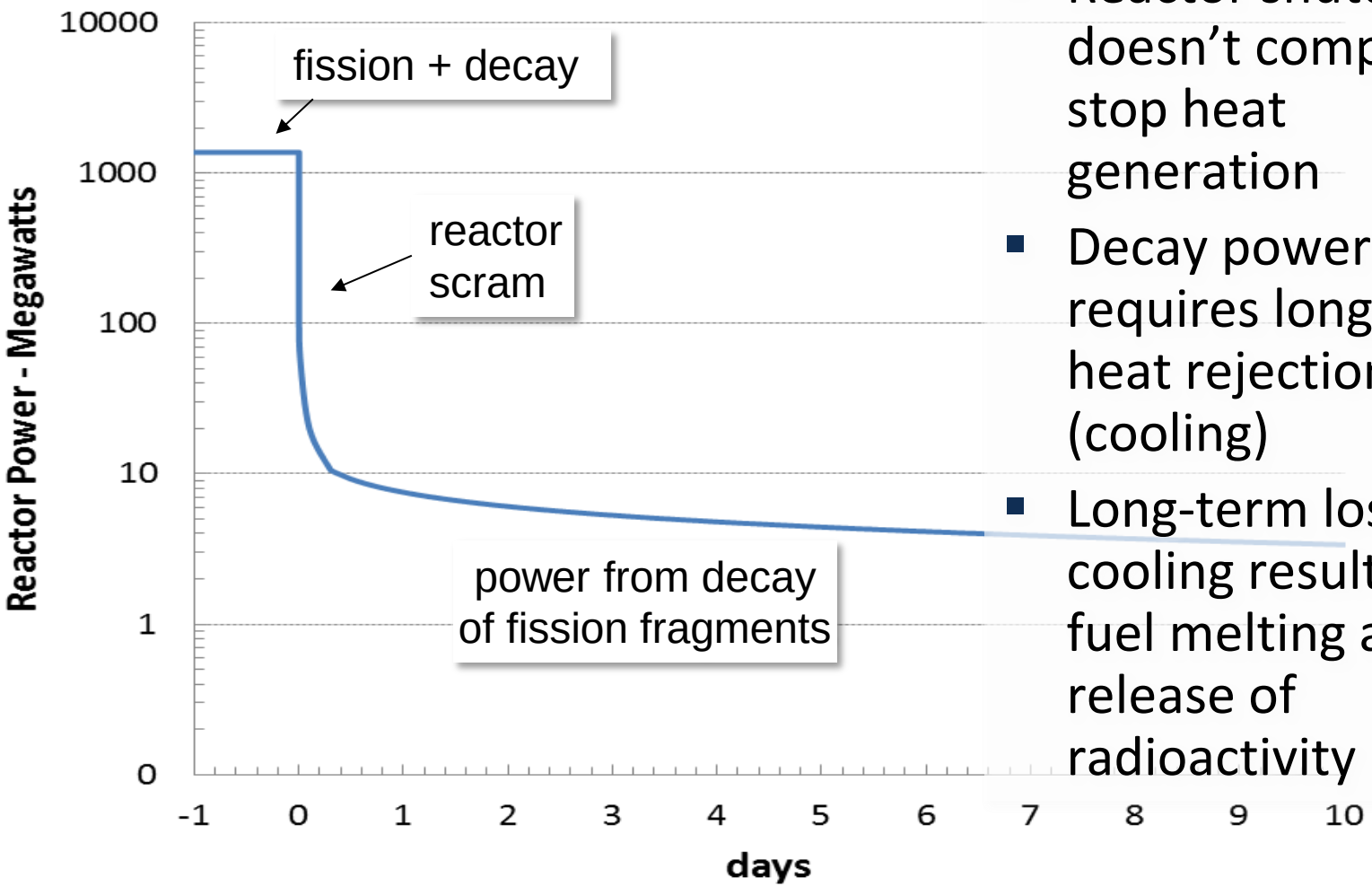
Used by permission from TEPCO

- Site flooding initiated "Station Blackout"
- Unit 1 and Unit 2 lost DC batteries
- Unit 2 maintained uncontrolled "Emergency Core Cooling System"
- Unit 3 retained some DC power and controlled ECCS
- ***All reactors isolated from ultimate heat sink (Ocean)***

Heat Produced in Nuclear Fission



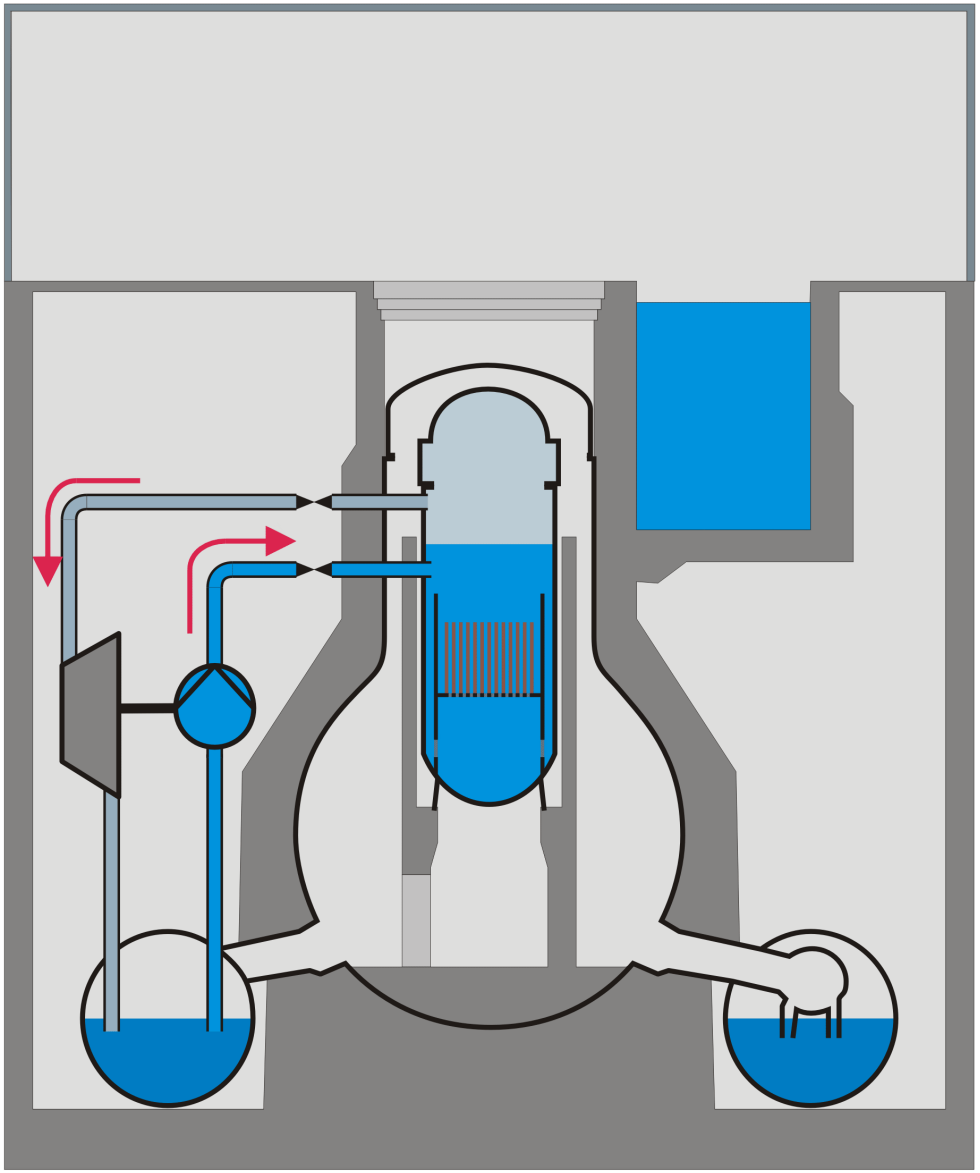
Reactor Power Before and After "Shutdown"



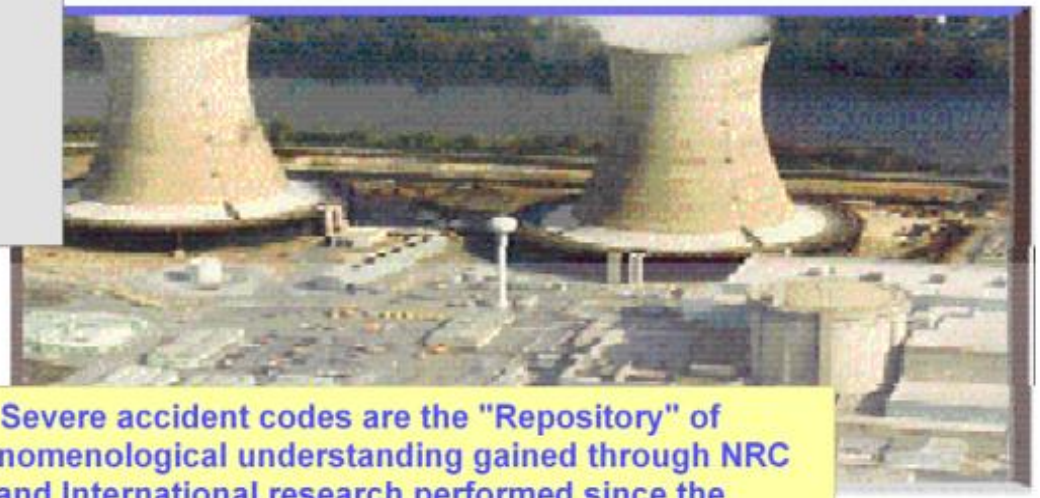
- Reactor shutdown doesn't completely stop heat generation
- Decay power requires long-term heat rejection (cooling)
- Long-term loss of cooling results in fuel melting and release of radioactivity

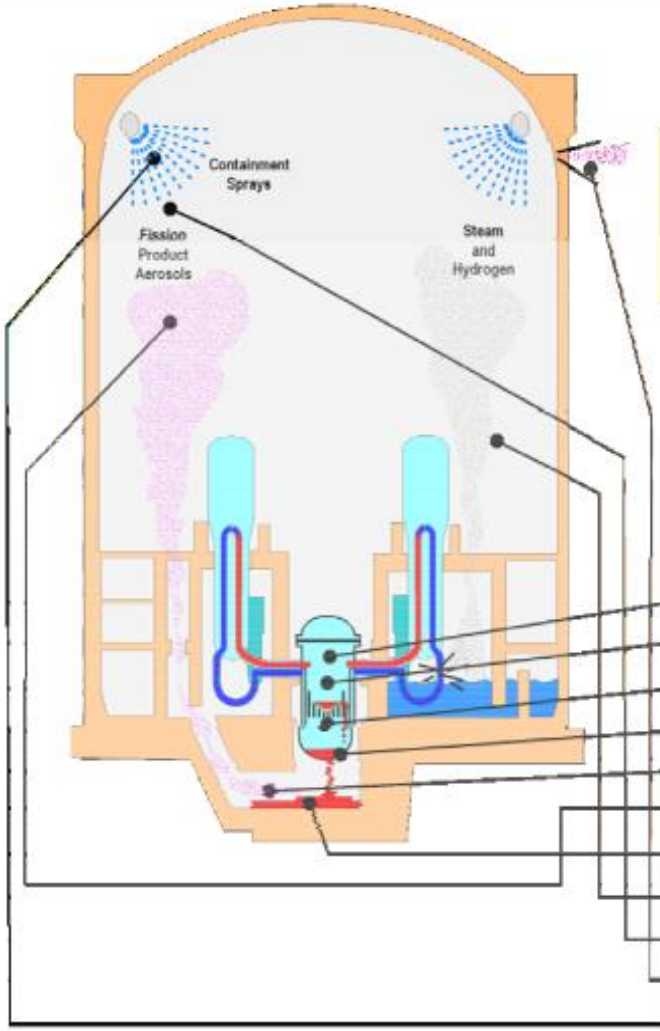
Emergency Cooling System in Boiling Water Reactors

- Steam driven water injection pump maintains water level in reactor
- Decay heat gradually accumulates in suppression pool
  - Water temperature in pool rises until “saturated”
- When pool reaches boiling condition, containment building pressure increases
  - High building pressure can fail containment integrity
- If nuclear fuel is damaged, radioactivity can be released to environment
  - Pool filtering of release significantly reduces environmental release



Modeling and Analysis of Severe Accidents in Nuclear Power Plants





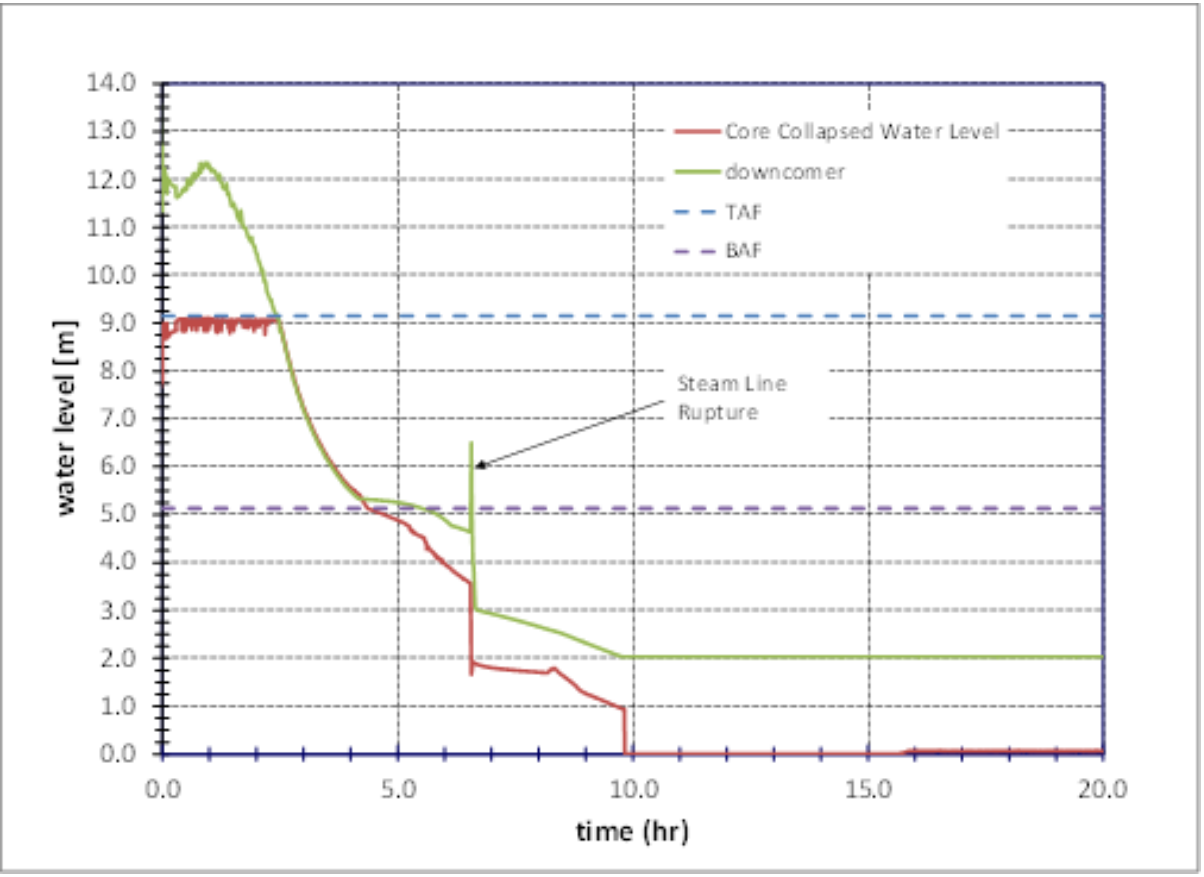
Severe accident codes are the "Repository" of phenomenological understanding gained through NRC and International research performed since the TMI-2 accident in 1979

Integrated models required for self consistent analysis

Important Severe Accident Phenomena

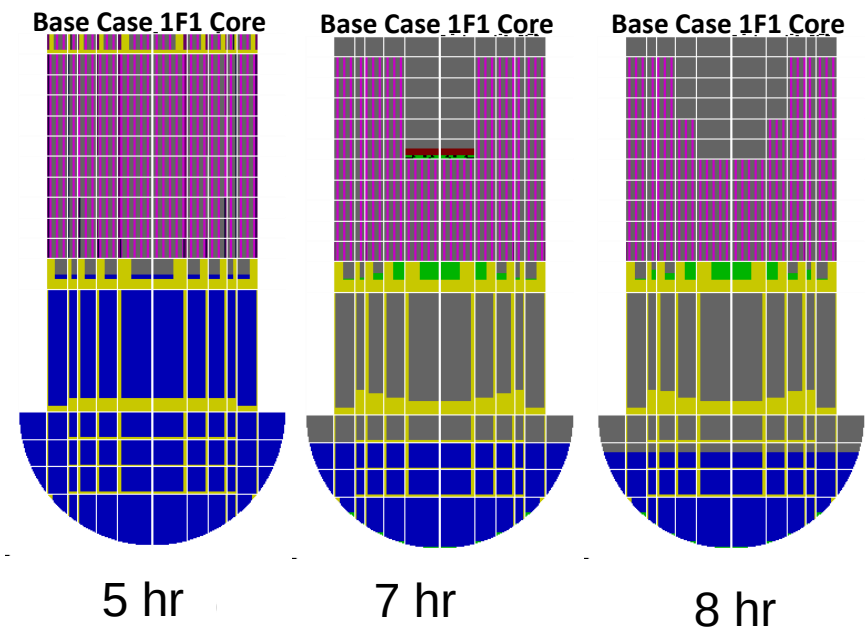
	MELCOR	CONTAIN	VICTORIA	SCDAP RELAP 5
Accident initiation	■			■
Reactor coolant thermal hydraulics	■			■
Loss of core coolant	■			■
Core meltdown and fission product release	■		◢	■
Reactor vessel failure	■			■
Transport of fission products in RCS and Containment	■	■	■	
Fission product aerosol dynamics	■	■	■	
Molten core/basemat interactions	■	■		
Containment thermal hydraulics	■	■		
Fission product removal processes	■	■	■	
Release of fission products to environment	■	■	■	
Engineered safety systems - sprays, fan coolers, etc	■	■		
Iodine chemistry, and more	■			

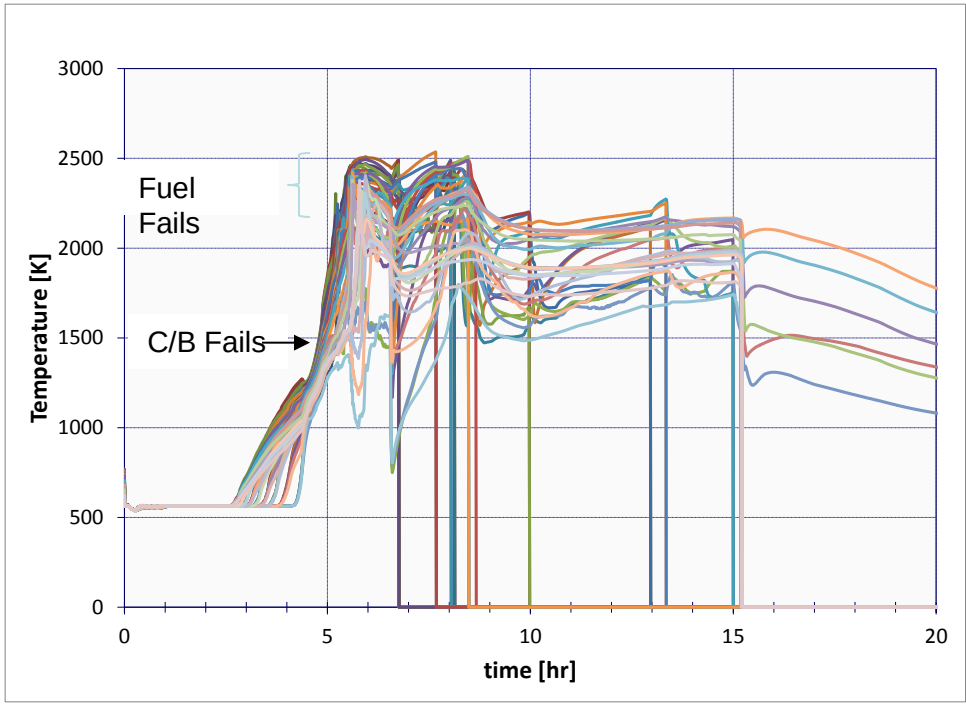
Vessel Water Boil-Down in Unit-1



- MELCOR Code predictions
  - Fuel uncovered at 3 hr
  - Core damage and H_2 generation by 4 hr
  - Steam line rupture at 6.5 hr
  - Reactor Vessel dry at 10 hr
  - Reactor Vessel melt-through between 12 and 14 hr

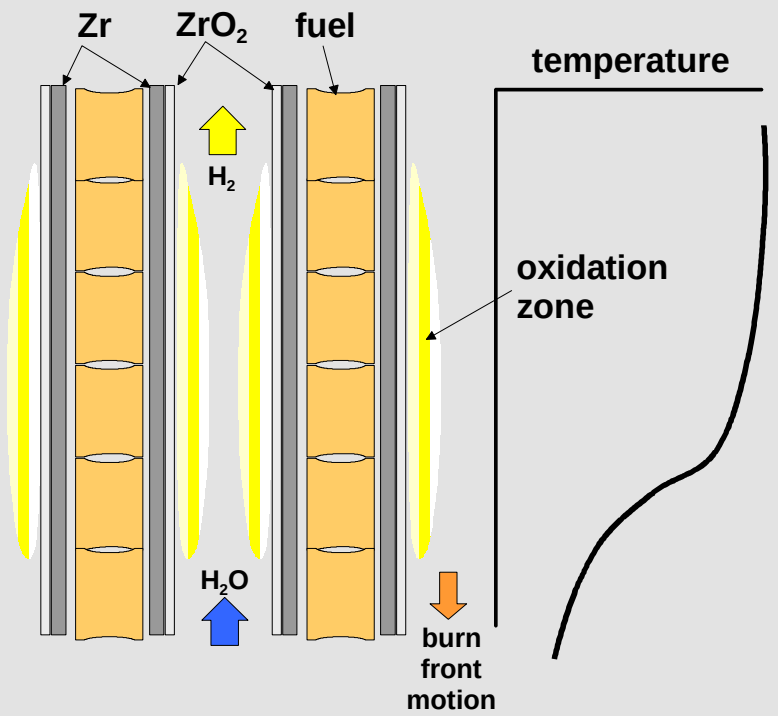
Predicted Degradation of Reactor Core





- Core damage starts at ~ 4 hours – Control Blade fails first
- Progressive fuel melting after 6 hours
- Core exit gas temperatures very high

Steam Oxidation of Fuel Cladding Produces Hydrogen



$$Zr + 2H_2O \longrightarrow ZrO_2 + 2H_2 \quad 5.8\times10^6 \text{ joule/kg}$$

$$\frac{dT}{dt} = \frac{1}{mC_p}\left[Q_{ox}(T) - Q_{loss}(T)\right] \quad \text{heatup rate}$$

- Steam oxidation of Zr tubing produces metal-fire
- Hydrogen is produced in steam-Zr oxidation fire
- Reaction is very exothermic
  - Fire is very hot !!!
- Heat from metal-steam fire drives core melting

Core/Vessel Material Map

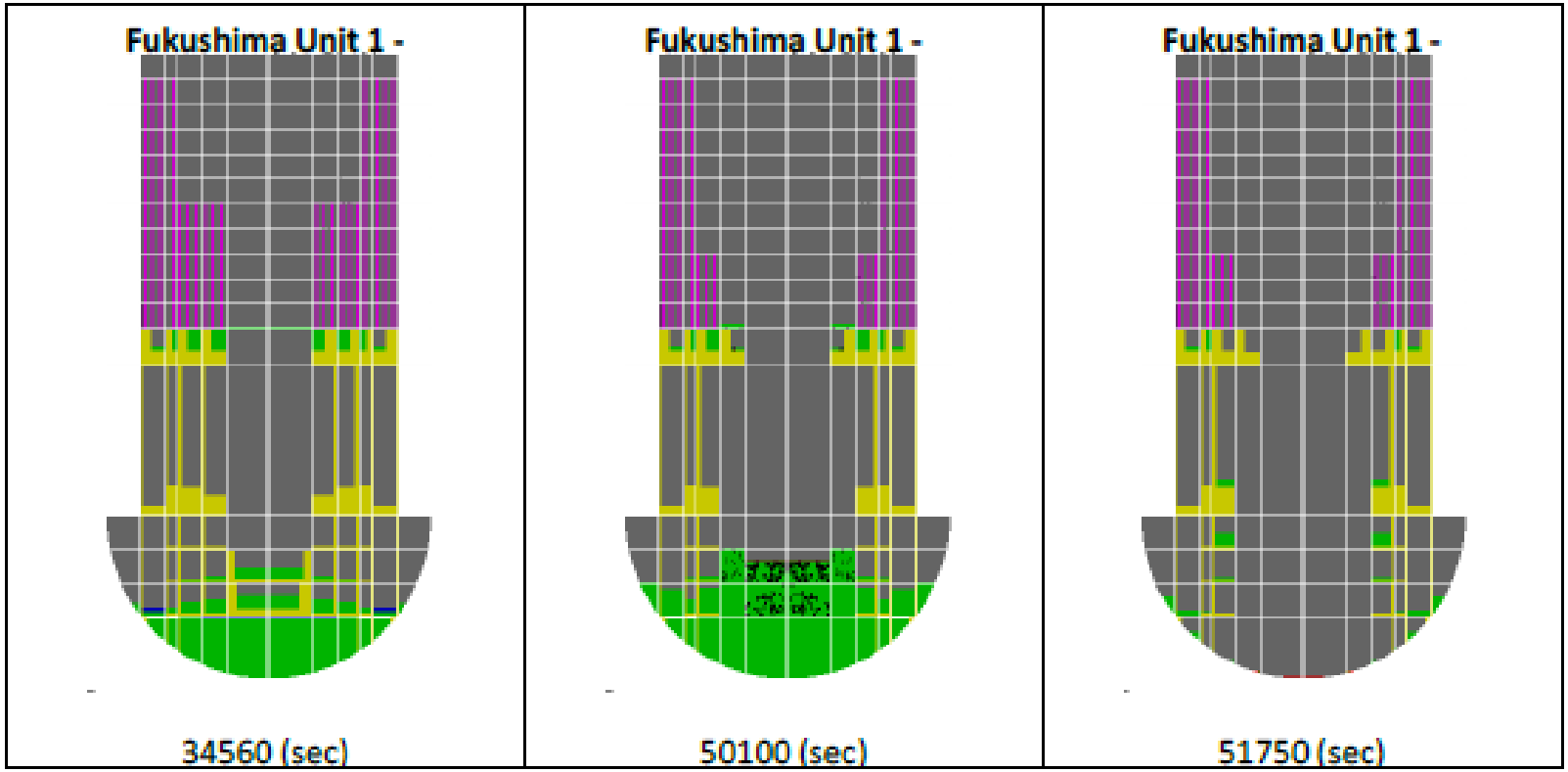


Figure 39 MELCOR-predicted core damage state near time of lower head failure - note some intact fuel assemblies remain in the core region.

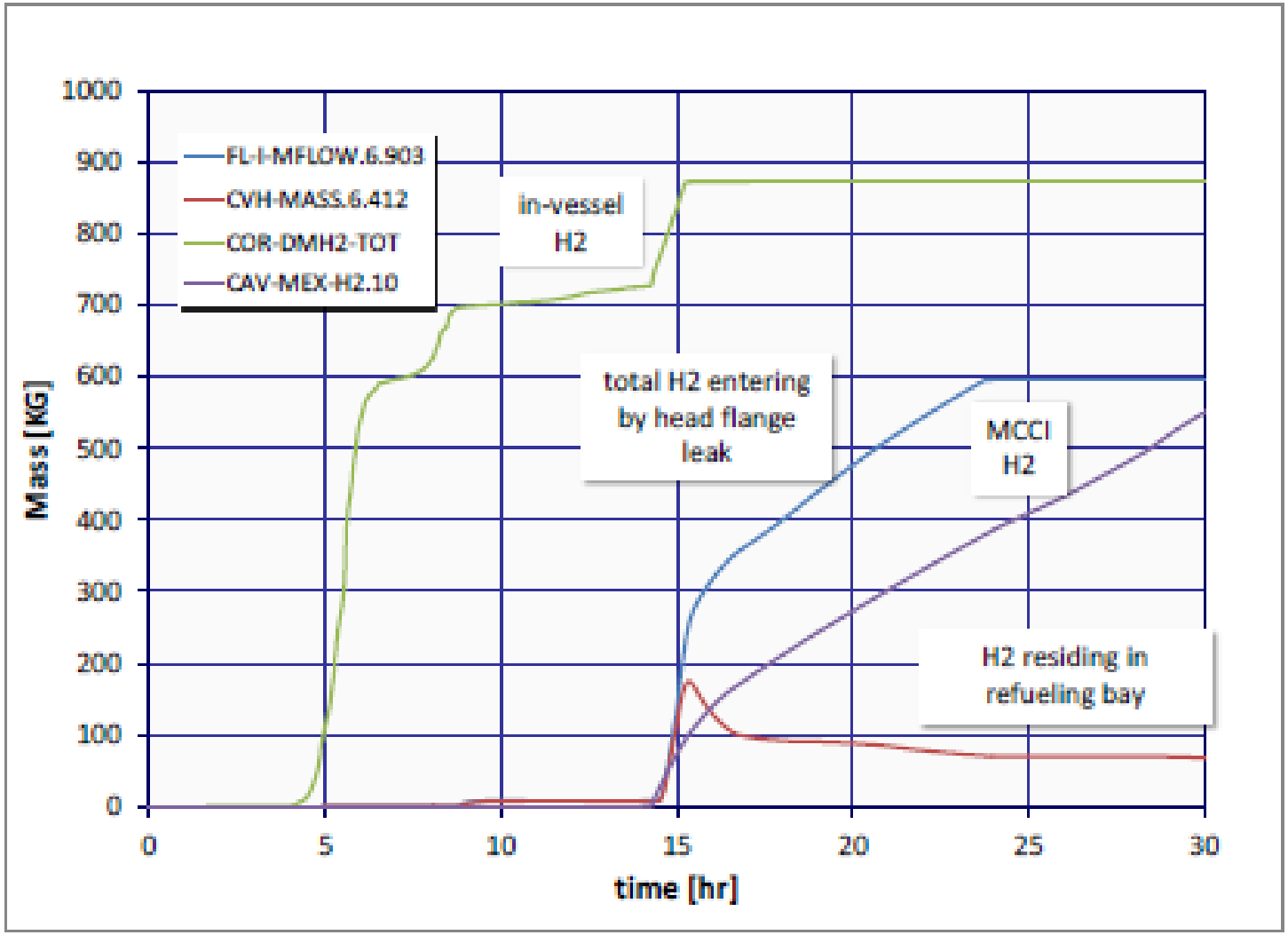
Reactor Vessel Melt-Through

- When fuel-melt burns through lower vessel, molten core materials drop to the concrete floor below the vessel
- Melt attacks the concrete and erodes the floor
- China-Syndrome
- Lots of smoke and radioactive aerosol
- Lots of gas production pressurizes the containment building (CO, CO2 and Hydrogen)
- Concrete erosion can threaten containment integrity

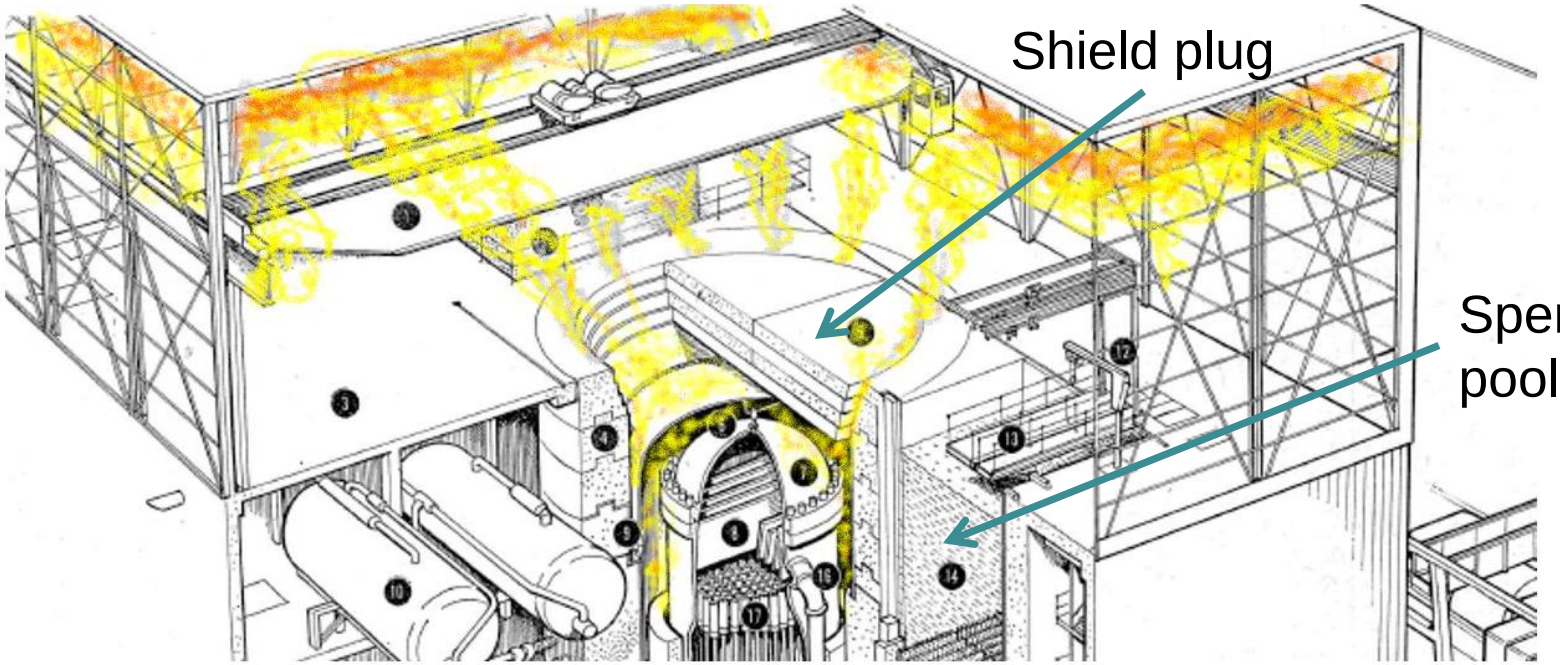
- MCCI experiment
- Decay heat liberates water from concrete
- Metals (Zr and steel) oxidize and produce H_2 and CO
- Exothermic energy from chemical reactions

RSC: 1/02

Hydrogen in 1F1

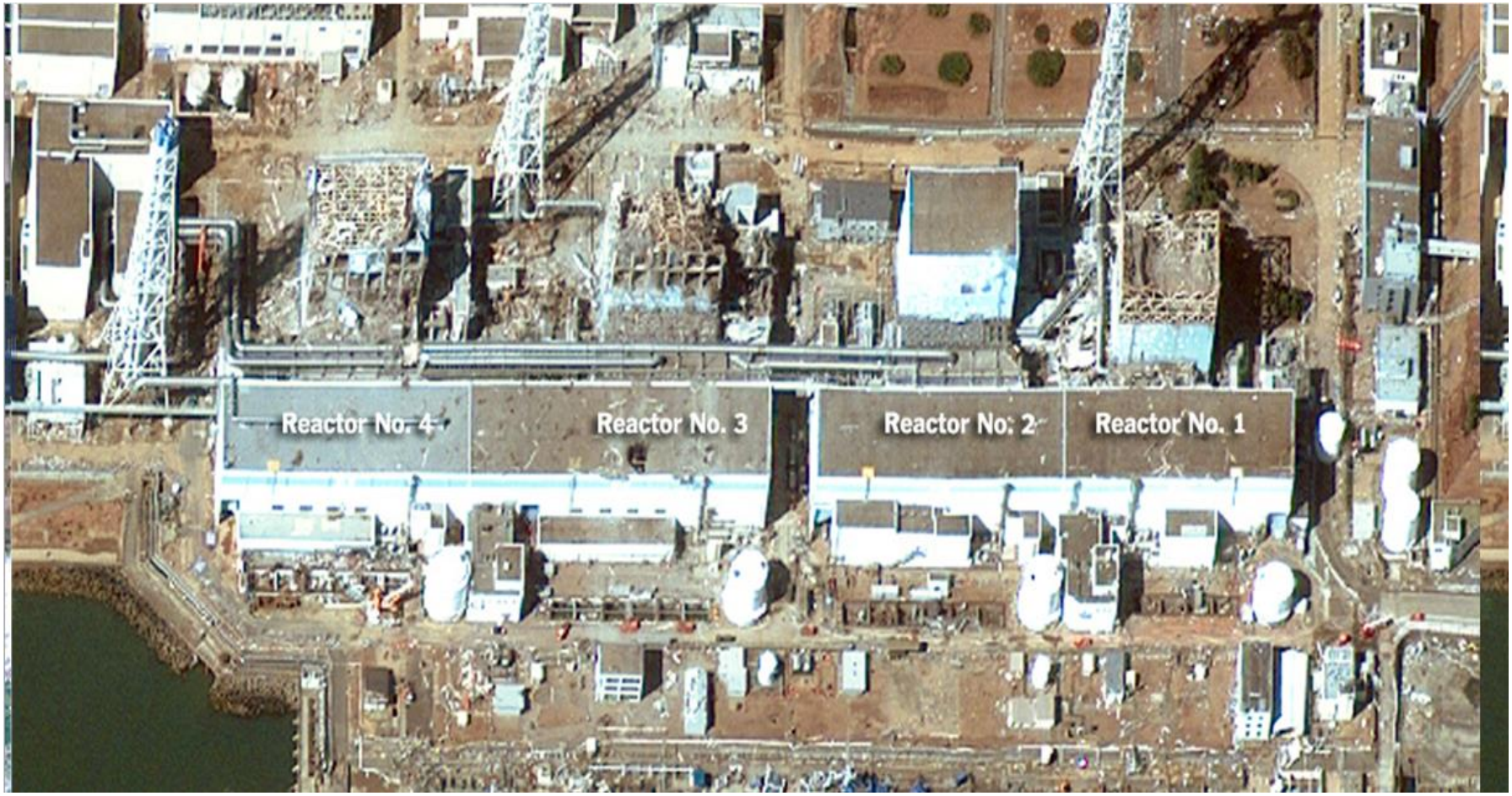


Hydrogen Accumulation in 1F1



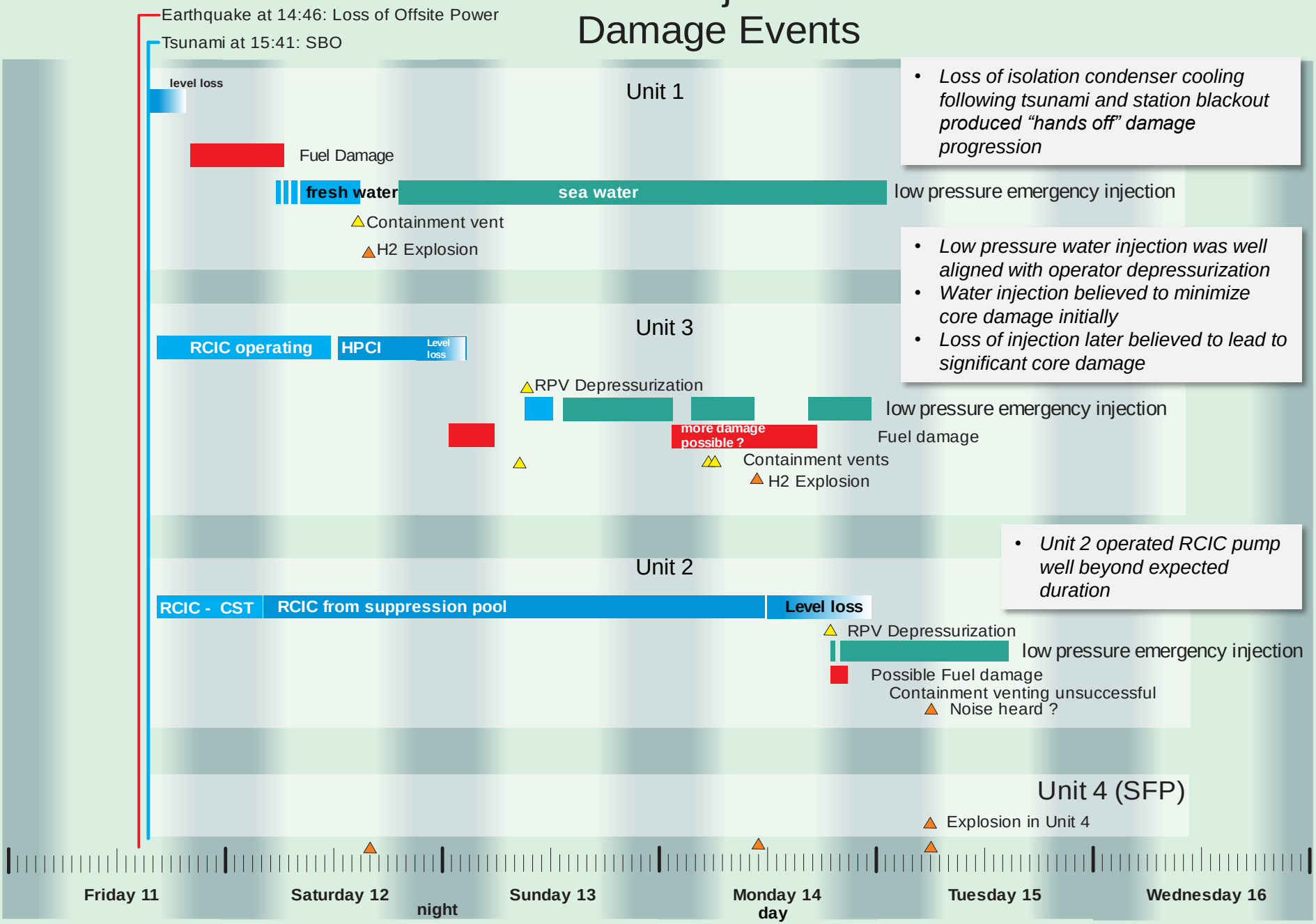
- Between ~12 hours and ~23 hours, steam and hydrogen leaks from drywell head flange and enters RB via shield plug seams
- Hydrogen, CO and steam rises to roof and spreads laterally
- Steam produced in MCCI and from emergency water injection
- Condensation in refueling bay depletes steam in hot layer and enriches hydrogen
- Mixture displaces air from building
- Steam mole fraction exceeds 50% - inert conditions prevent combustion

Hydrogen Explosions



Containment Over-pressurization Led to Release of H2 into Buildings

Timeline of Major Fukushima Damage Events



- *Loss of isolation condenser cooling following tsunami and station blackout produced "hands off" damage progression*

- *Low pressure water injection was well aligned with operator depressurization*
- *Water injection believed to minimize core damage initially*
- *Loss of injection later believed to lead to significant core damage*

- *Unit 2 operated RCIC pump well beyond expected duration*

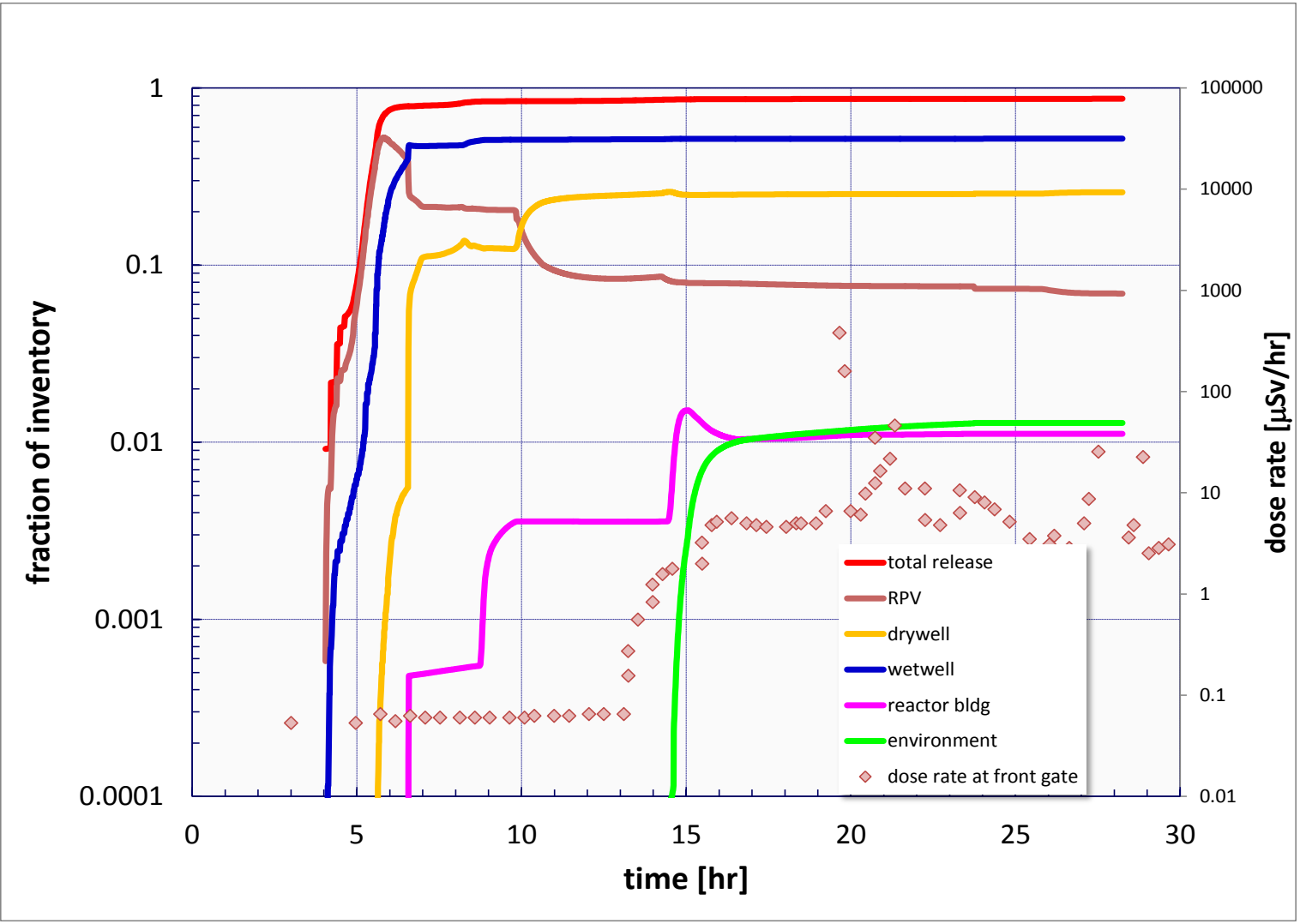
Where's The Radiation?

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Estimated Cs Release from Unit 1

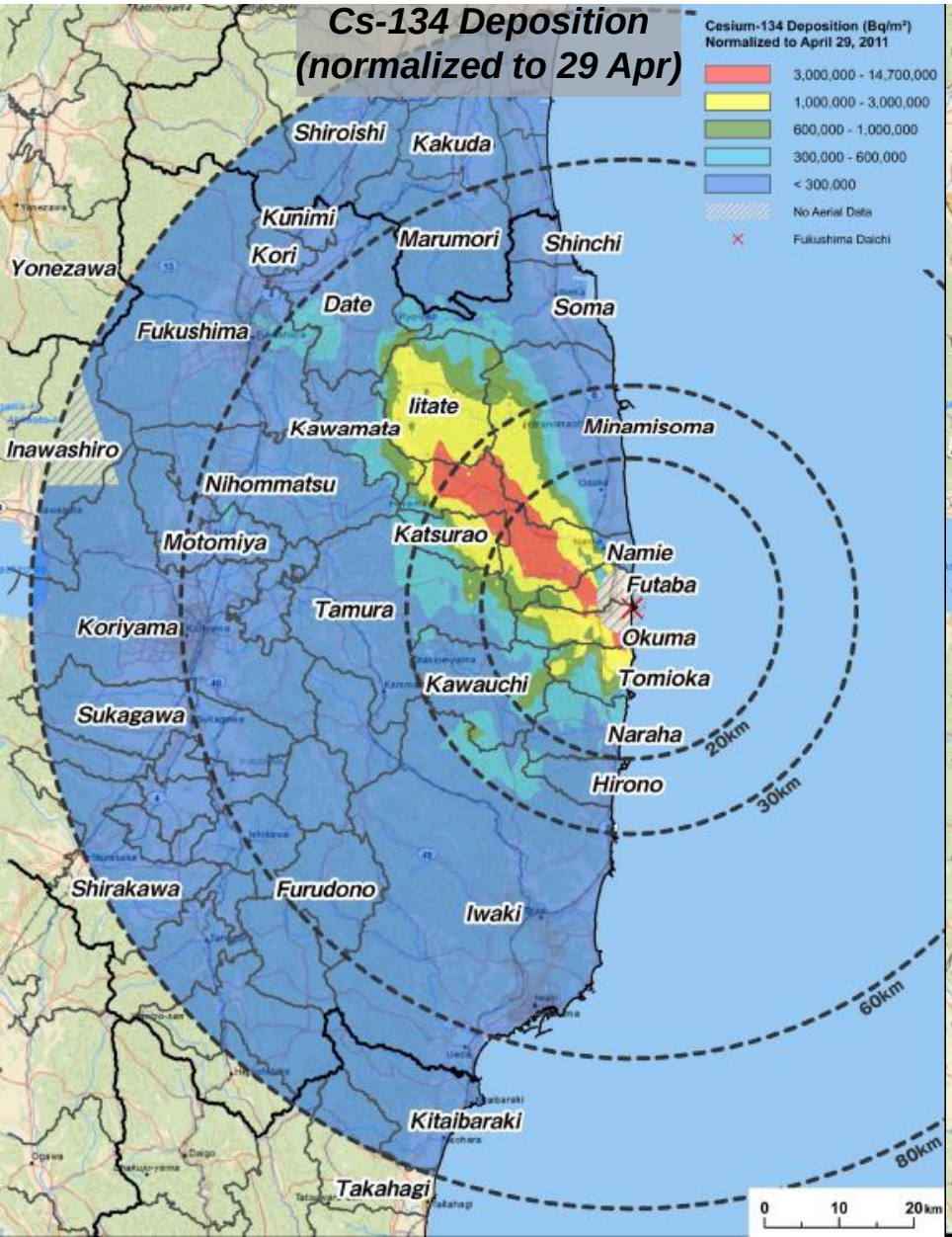


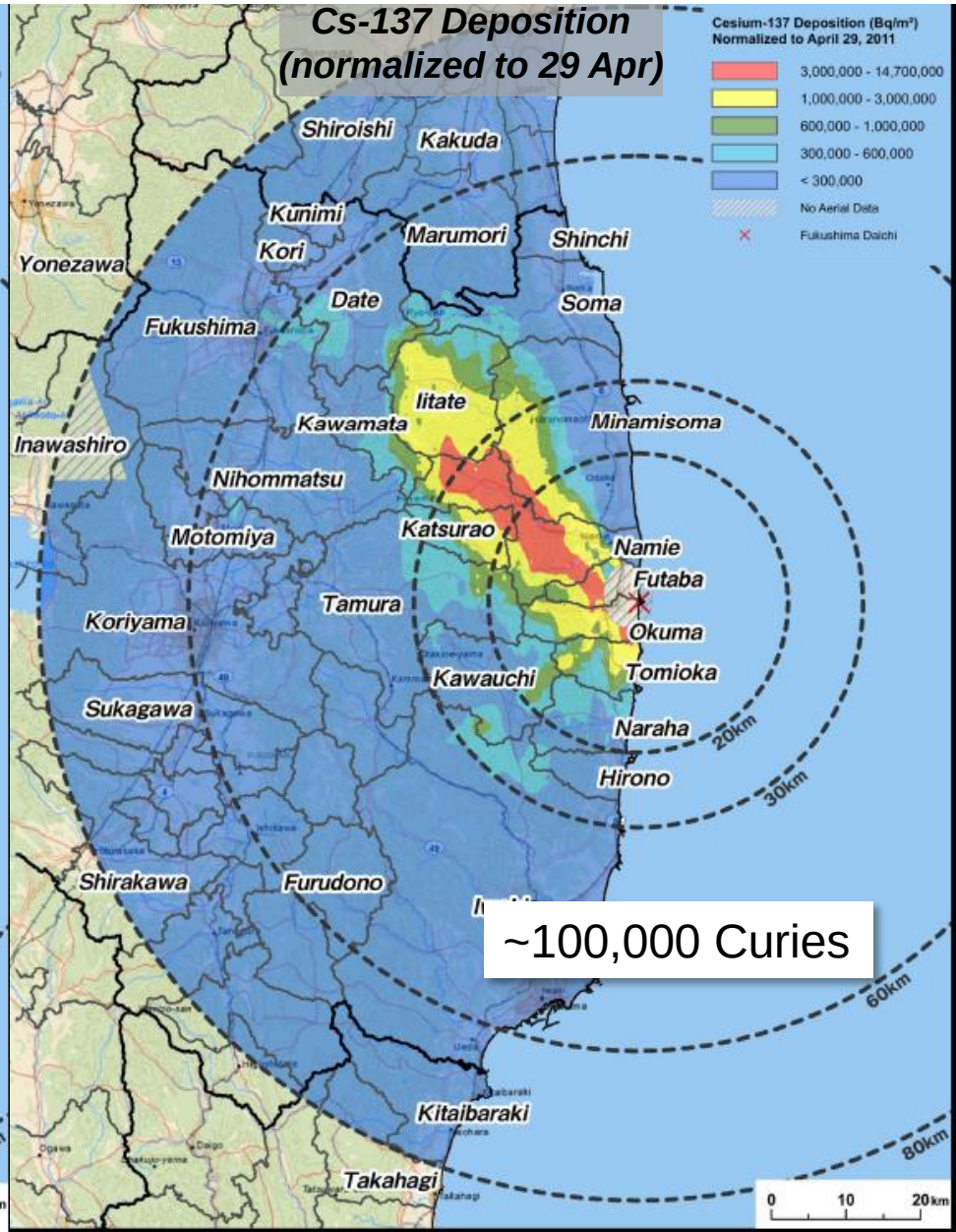
Radiation monitors at front gate jump at ~13 hr

Cs Env release estimated at about 400,000 Ci

Aerial Measuring Results
Joint US/Japan Survey Data

FUKUSHIMA DAIICHI
JAPAN





Things That Went Wrong

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Confounding Problems

- Many calls for evacuation to seismically protected building delayed critical responses
- Site damage from earthquake and dislocated equipment precluded access of fire trucks to places where needed
- Multi-unit disaster created competition and shortage of equipment like fire trucks
- PPE clothing significantly impeded actions
- Unit 1 loss of AC/DC power
  - Disabled a functional cooling system by loss of motor valve control
  - Personnel access to valve impeded by difficult access and radiation levels
- Unit 3 retained DC batteries until depleted
  - Inability for operators to depressurize reactor after loss of DC and building air
  - Loss of steam driven emergency water injection due to loss of valve control
- Unit 2 loss of AC/DC power
  - Steam driven water injection running as loss of DC occurred and system ran unregulated for 3 days
  - Explosion at Unit 1 foiled attempts to rig emergency AC power

Lessons Learned

- Belief that it could never really happen undermines real preparation
  - Preparation for severe accidents outside of thinking
  - Critical equipment below grade and subject to flooding
  - Sea wall too low despite emerging research that higher tsunami possible
- Responders in ad hoc mode from the beginning
  - Disbelief that it's really happening when hours count and clock is ticking
  - Need to locate and operate valves but plan drawings in different building
  - Road destruction prevented bringing in needed equipment and equipment weight exceeded capacity of helecopters

Lessons Learned

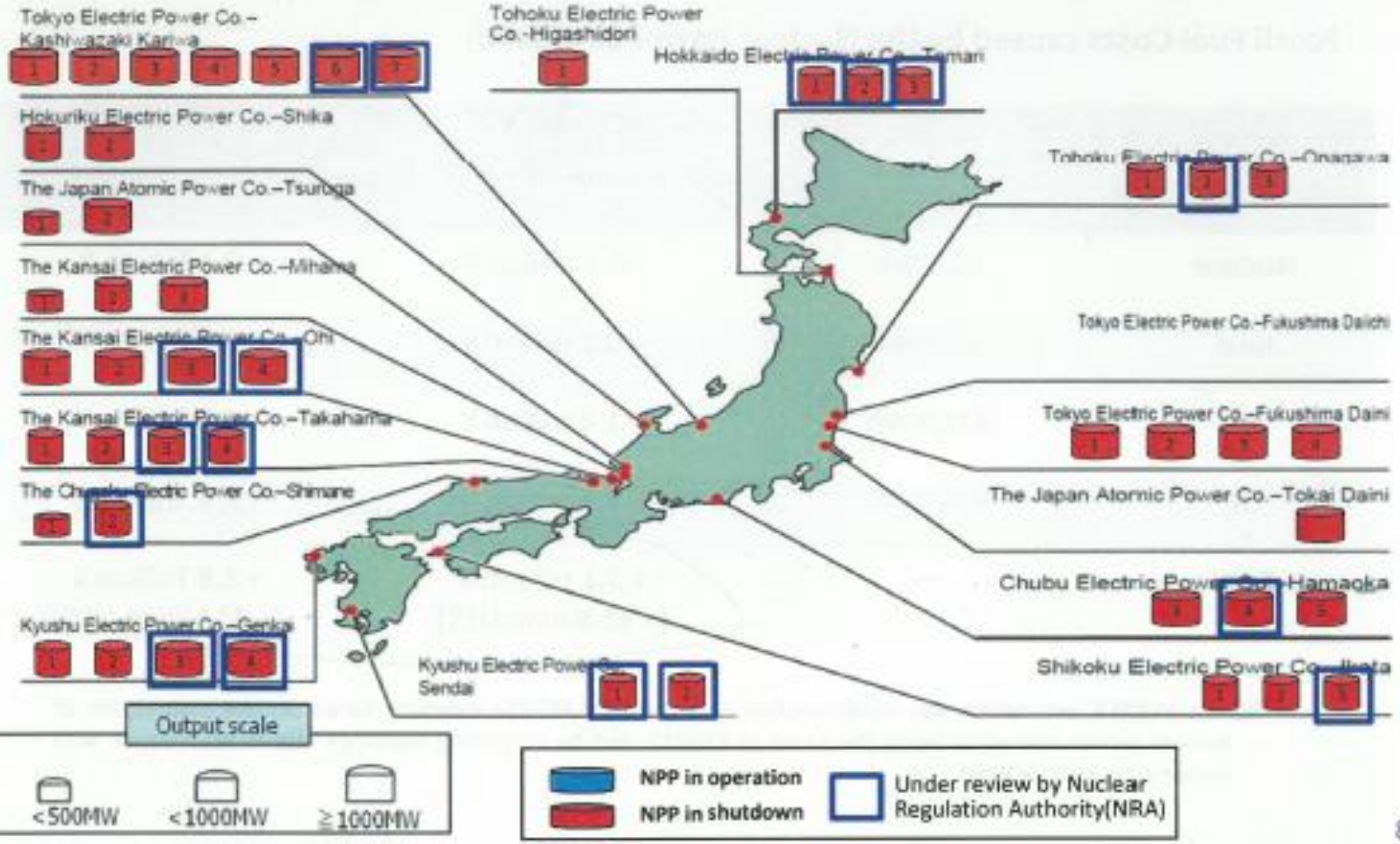
- Chain of Command
  - Imperative to depressurize containments to prevent catastrophic failure meant intentional release of radioactivity to environment
    - Inaction sometimes carries less liability that action
  - Last ditch measure of injecting seawater into reactors meant destroying reactors – they would never restart
  - Communications to corporate decision makers significantly impaired
- Multi-unit accident
  - Could have perhaps managed one accident, but three at once was simply overwhelming
  - Shortage of firetrucks and pumps for three simultaneous accidents and staging impeded by seismic damage to site
- Security versus Safety
  - Locked gates for security impeded emergency equipment access to critical areas

Current Status

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

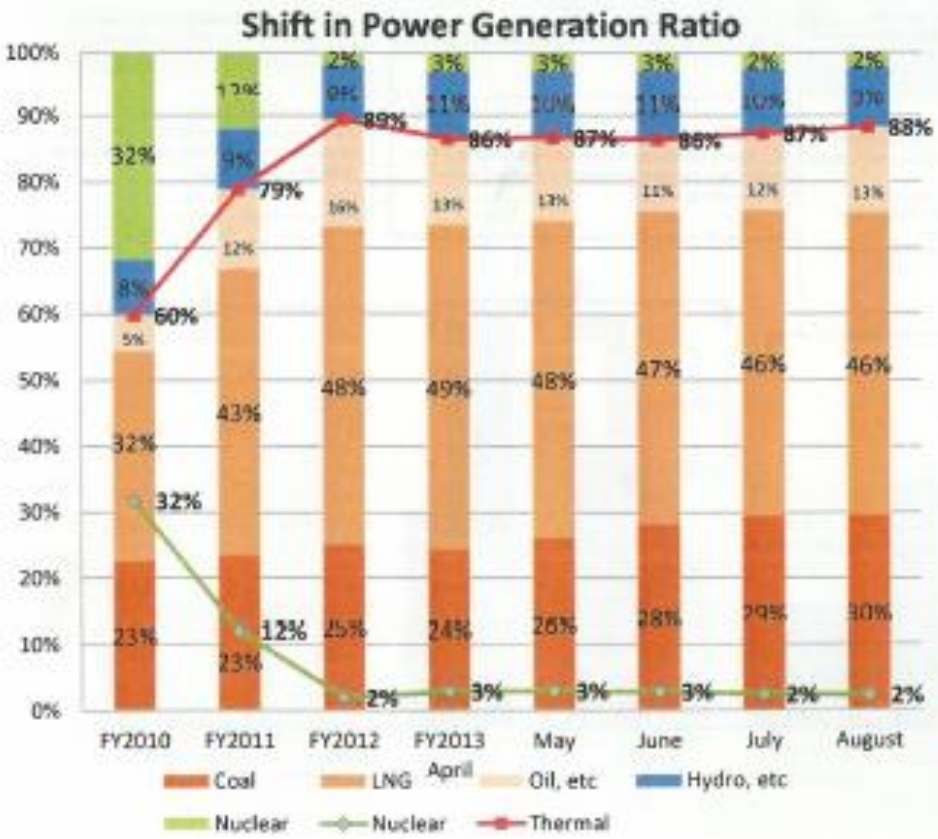
Nuclear Power Plants in Japan

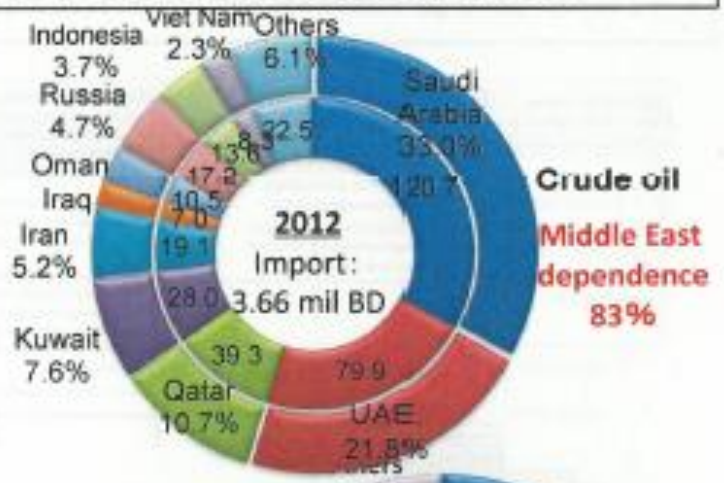
- There are 48 nuclear power plant units in Japan.
- **All units (in red) are in a state of temporary shutdown** as of February 17 2014.
- **17 units (in blue squares)** are under review for restart by the Nuclear Regulation Authority in accordance with its new safety regulations.

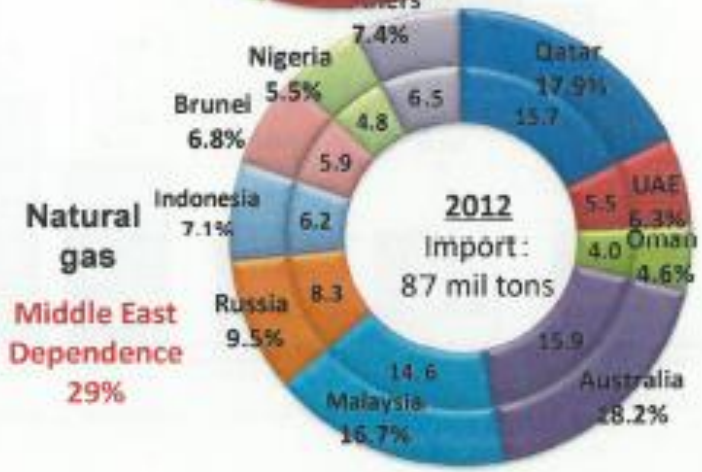


High dependence on thermal power and energy security

- Japan's current dependence on thermal power is higher than that at the time of the oil crisis.
- More than 80% of oil is still imported from the Middle East. If concerns grow, prices may surge or supply of energy and electric power may be jeopardized.



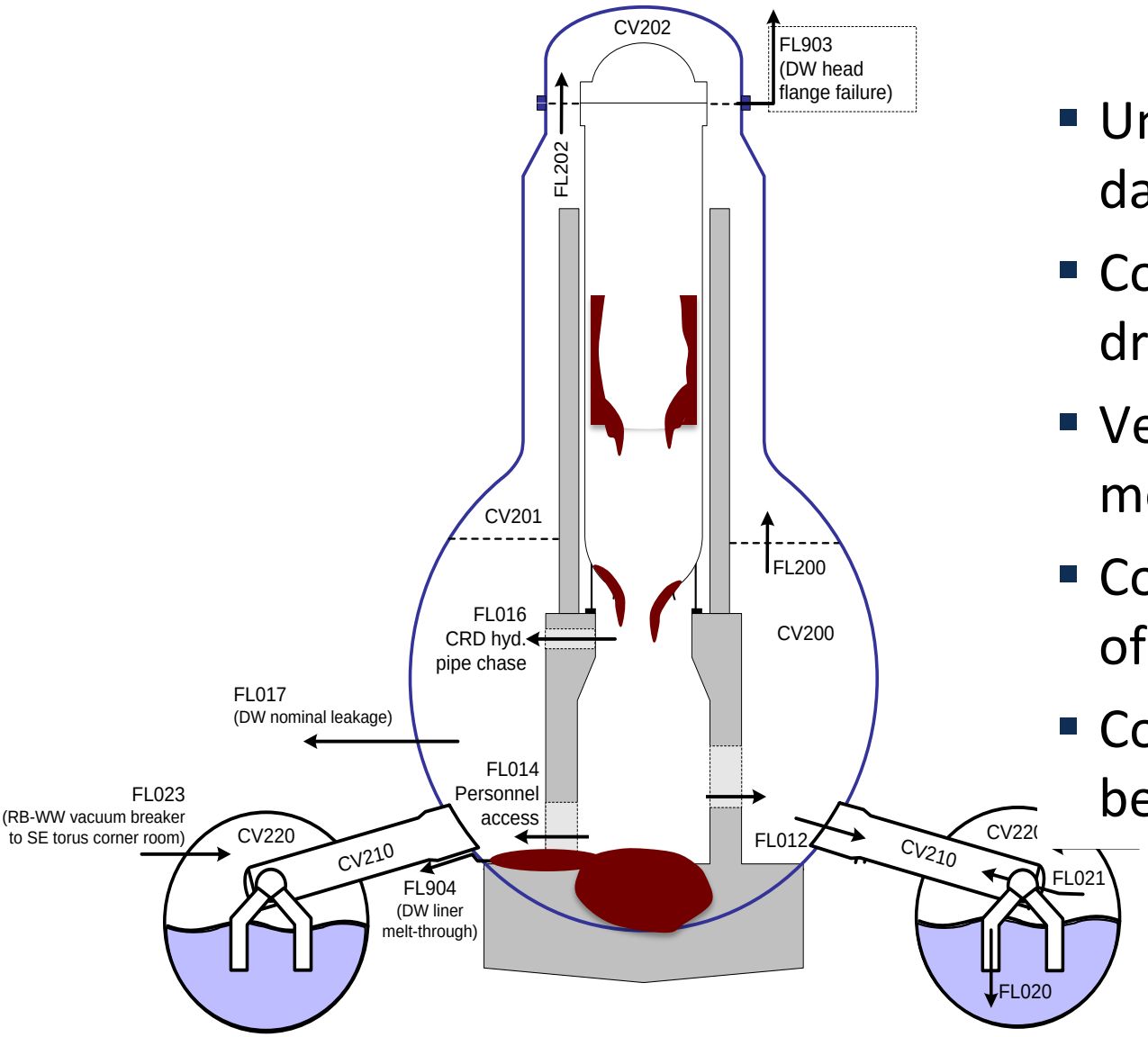




Currently (Dec 2013)…..

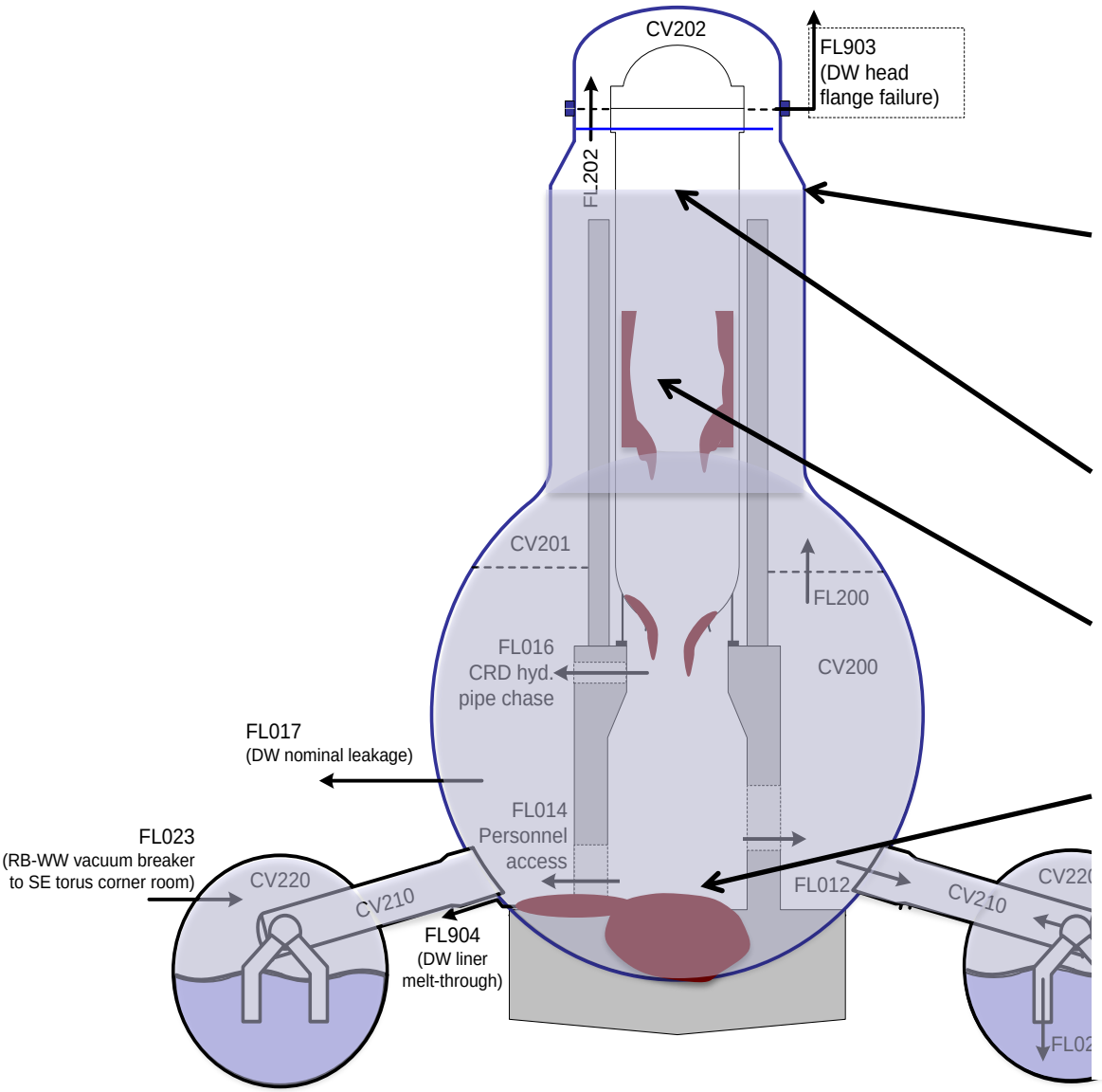
- Still pumping cooling water into damaged reactors
- Containments are leaking and natural ground water entering site and buildings
- Contaminated water is being decontaminated and stored on-site
- Leaks in storage tanks are major P/R problem
  - Not a real problem
- Spent fuel in storage pools being moved into dry casks or safer storage locations
- Decommissioning plans span decades
  - First entry planned for about 8 years from now

Likely Damage States



- Unit 1 likely most damaged
- Core melted and dropped downward
- Vessel lower head melted from the heat
- Core materials on floor of containment
- Containment liner could be penetrated

Fuel Removal and Decommissioning



- Present leaks must be located and repaired
- Containment must be flooded with water
  - Radiation shielding
- Removal of steam separators and dryers
- Removal or core-region fuel remnants
- Excavation of fuel debris in cavity
- 20 to 30 years to completion?

In Country Support

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Activities in U.S. Embassy in Tokyo

- Initial emphasis was on estimating risk potential to returning U.S. citizens that were previously evacuated
- State of reactors and spent fuel pools was vague
  - Communication was slow and cautious (to a fault)
    - Information exchange not flowing freely
  - Confusion over damage condition was frustrating
    - Significant loss of public confidence in both industry and government
  - Accidents were not clearly terminated even weeks after initial events
    - Water flow, nuclear shutdown, secondary seismic, hydrogen concerns
  - Concerns over future secondary seismic events was large
    - Reactors damaged and vulnerable to subsequent earthquakes
- Daily consults with military people based at Yakota
- Daily consultation and assistance to NRC and DOE
  - Severe accident interpretation
  - Source term estimation
  - Explanation of numbers and results
    - Bq/cc, Curies, Sieverts (micro, milli), REMs, numbers, powers of ten 10^3, 10^9, 10^{-6}
  - Exploring mitigation options and success
- Ongoing forensics investigation of events
  - Computer code reconstruction of accidents

NRC War Room At Embassy

- NRC set up mirror site of the Emergency Response Center in Bethesda
  - Reactor safety team
  - Protective measures team
- Evaluated ongoing and emerging issues
  - Flooding, N_2 inerting
- Provided daily reports to Ambassador

NRC Team Led by Chuck Casto Supporting Ambassador John V. Roos

Sandia National Laboratories