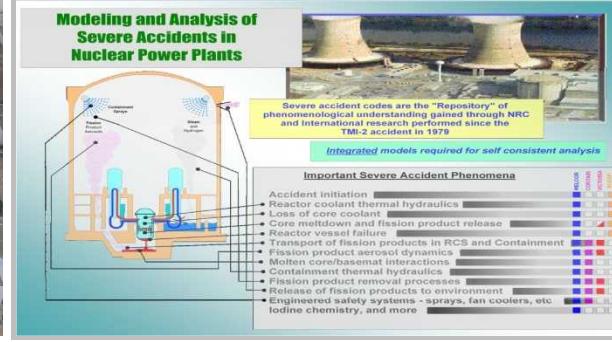


Exceptional service in the national interest



Source: Tokyo Electric Power Company



The Fukushima Dai-ichi Accidents

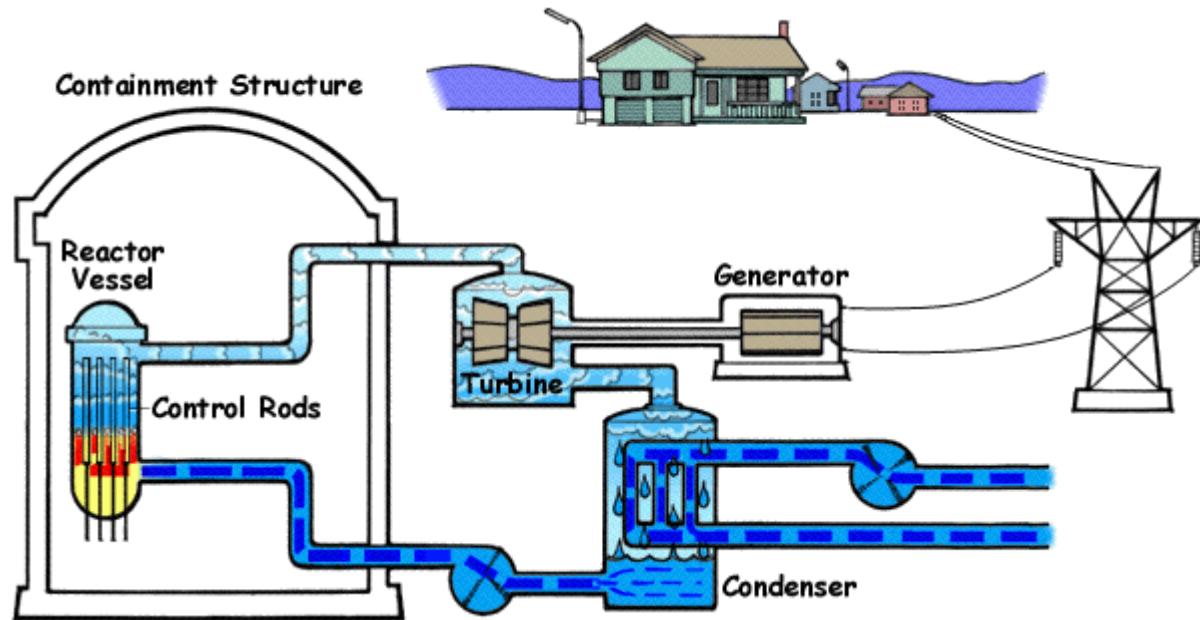
**Presented at IG Training Session
Albuquerque, NM; August 19, 2013**

**Susan Y. Pickering, Senior Manager
Nuclear Energy Safety Technologies
Sandia National Laboratories**

Outline

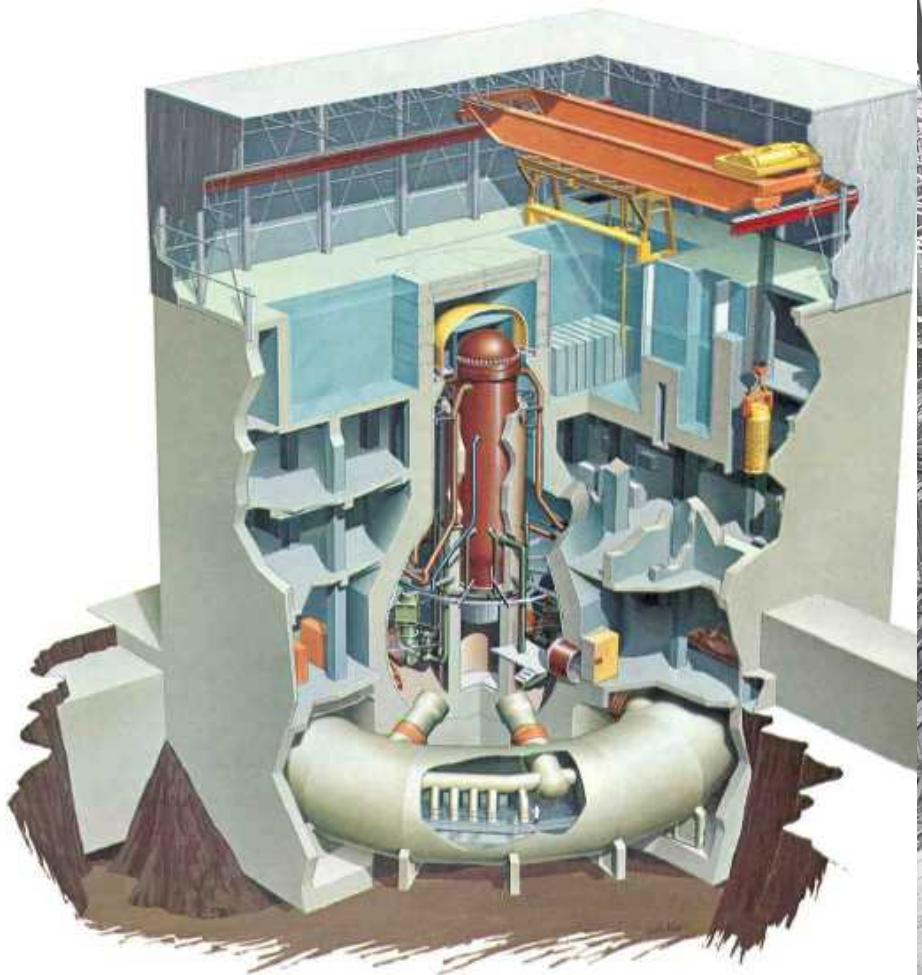
- Nuclear Energy Basics
- The Accident
- In-Country Support
- Accident Reconstruction
- Summary & US Actions
- Questions?

Nuclear Energy Basics



From www.nrc.gov

Mark-I Containment



DRYWELL TORUS

NRC Training Manual



Browns Ferry from Wikipedia

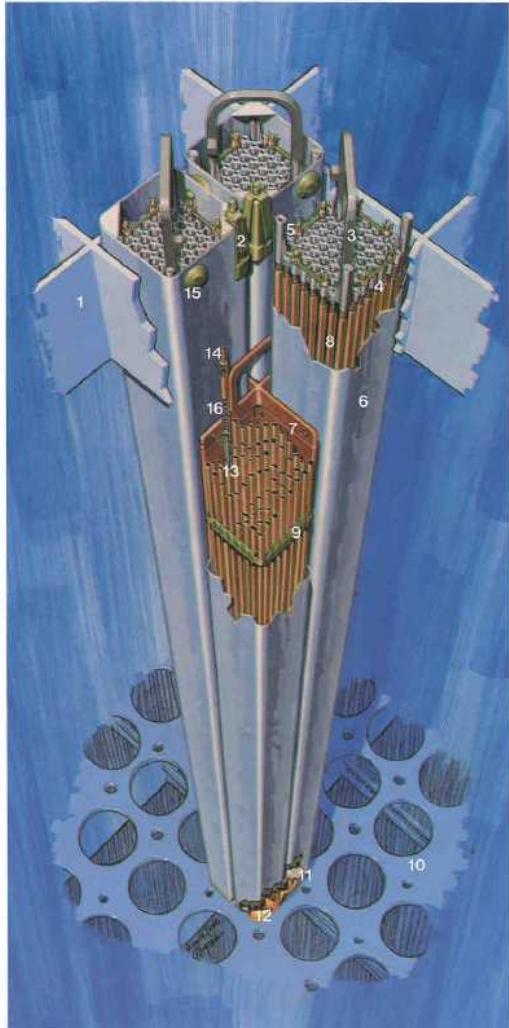
BWR Fuel Assemblies

BWR/6 FUEL ASSEMBLIES & CONTROL ROD MODULE

1. TOP FUEL GUIDE
2. CHANNEL FASTENER
3. UPPER TIE PLATE
4. EXPANSION SPRING
5. LOCKING TAB
6. CHANNEL
7. CONTROL ROD
8. FUEL ROD
9. SPACER
10. CORE PLATE ASSEMBLY
11. LOWER TIE PLATE
12. FUEL SUPPORT PIECE
13. FUEL PELLETS
14. END PLUG
15. CHANNEL SPACER
16. PLENUM SPRING

GENERAL  ELECTRIC

GEZ-4363

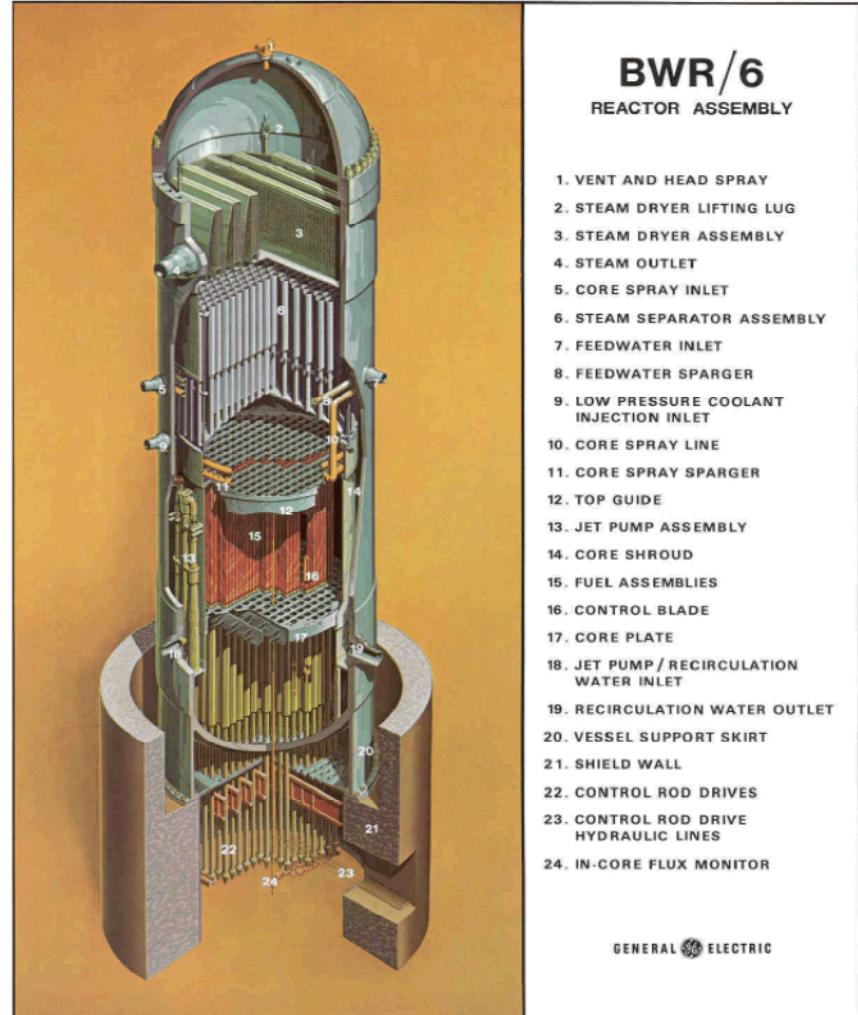


NRC Training Manual

BWR/6 REACTOR ASSEMBLY

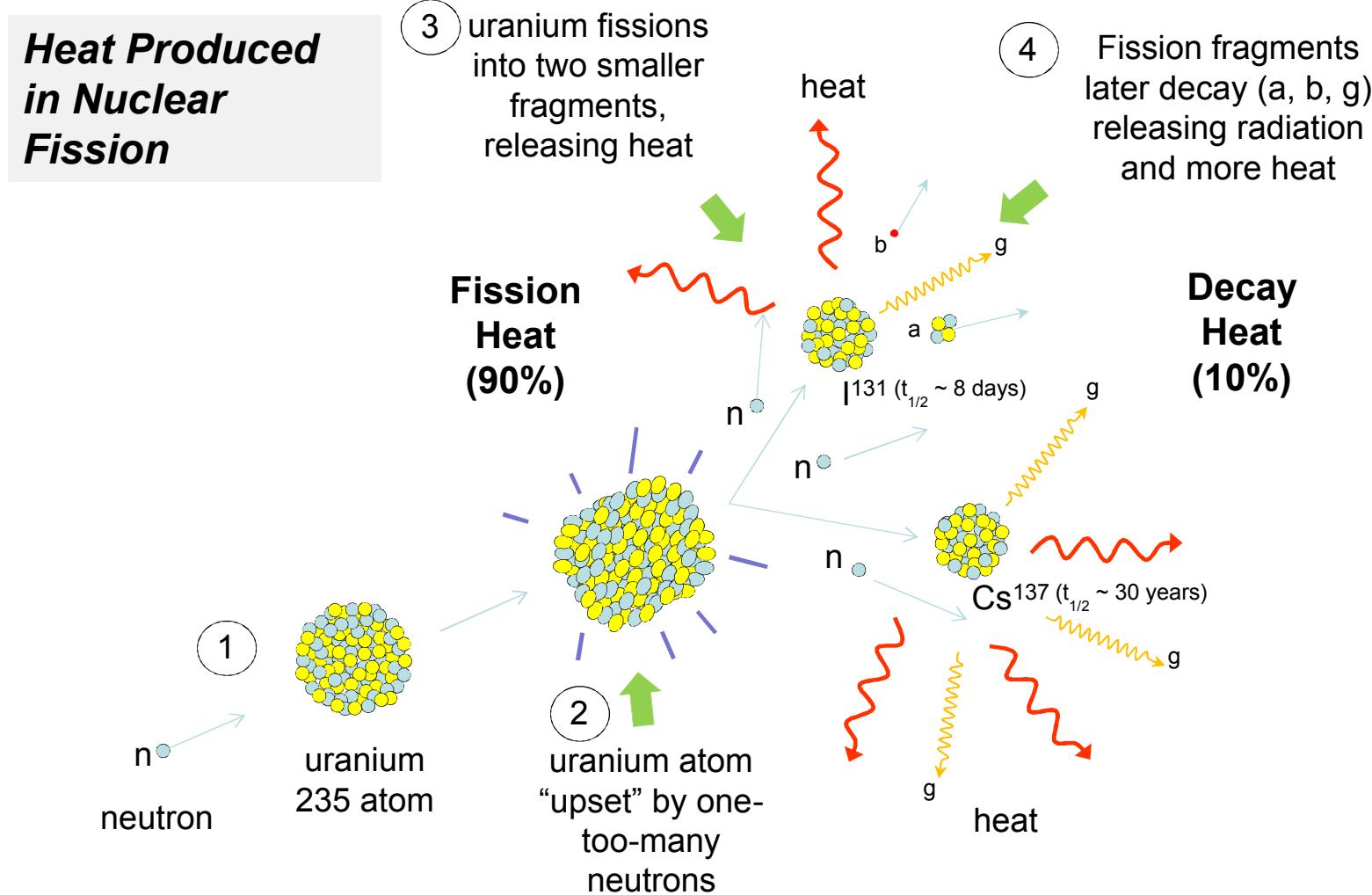
1. VENT AND HEAD SPRAY
2. STEAM DRYER LIFTING LUG
3. STEAM DRYER ASSEMBLY
4. STEAM OUTLET
5. CORE SPRAY INLET
6. STEAM SEPARATOR ASSEMBLY
7. FEEDWATER INLET
8. FEEDWATER SPARGER
9. LOW PRESSURE COOLANT INJECTION INLET
10. CORE SPRAY LINE
11. CORE SPRAY SPARGER
12. TOP GUIDE
13. JET PUMP ASSEMBLY
14. CORE SHROUD
15. FUEL ASSEMBLIES
16. CONTROL BLADE
17. CORE PLATE
18. JET PUMP / RECIRCULATION WATER INLET
19. RECIRCULATION WATER OUTLET
20. VESSEL SUPPORT SKIRT
21. SHIELD WALL
22. CONTROL ROD DRIVES
23. CONTROL ROD DRIVE HYDRAULIC LINES
24. IN-CORE FLUX MONITOR

GENERAL  ELECTRIC

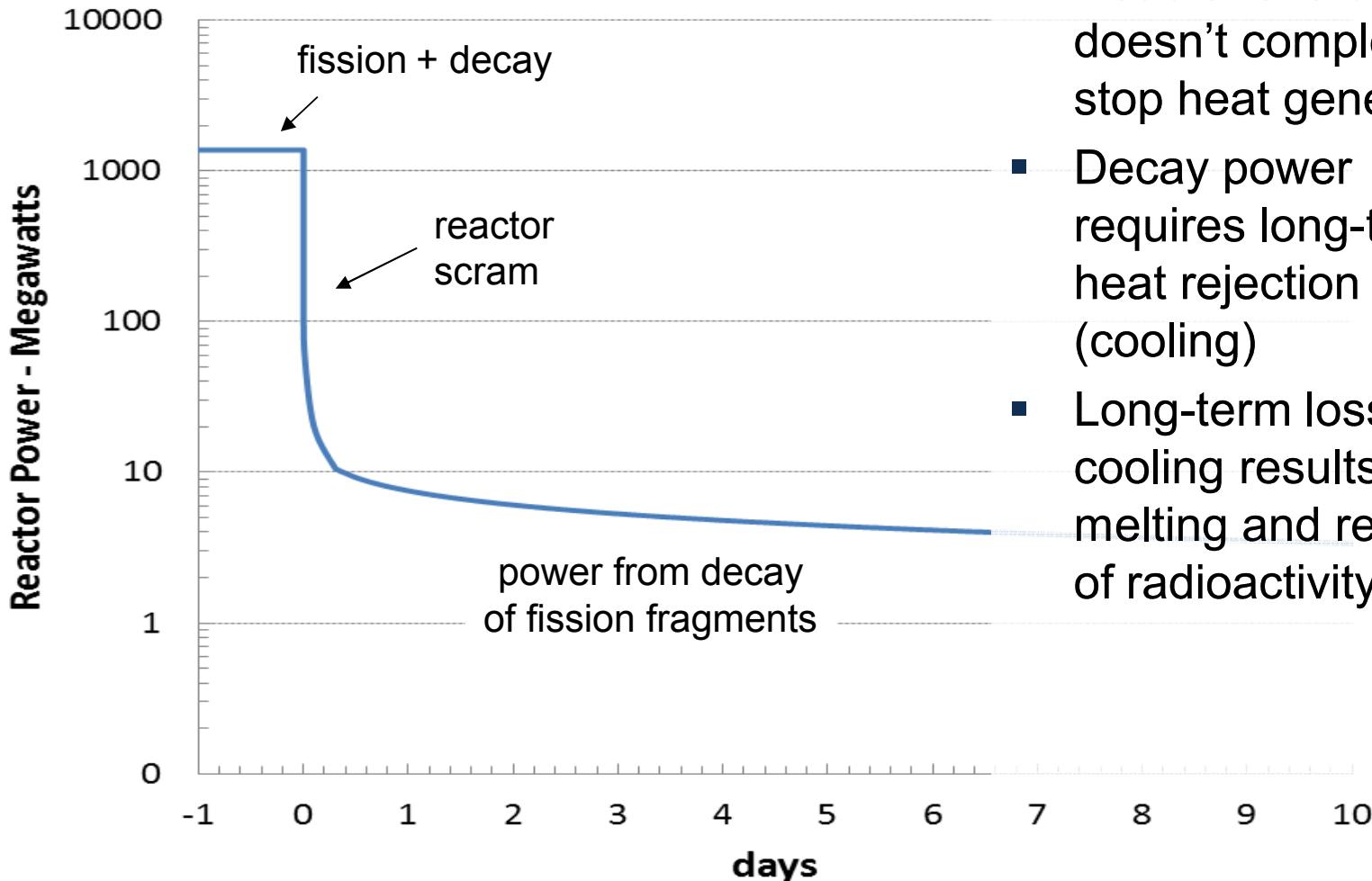


BWR 6 Reactor Vessel

Decay Heat is the Problem

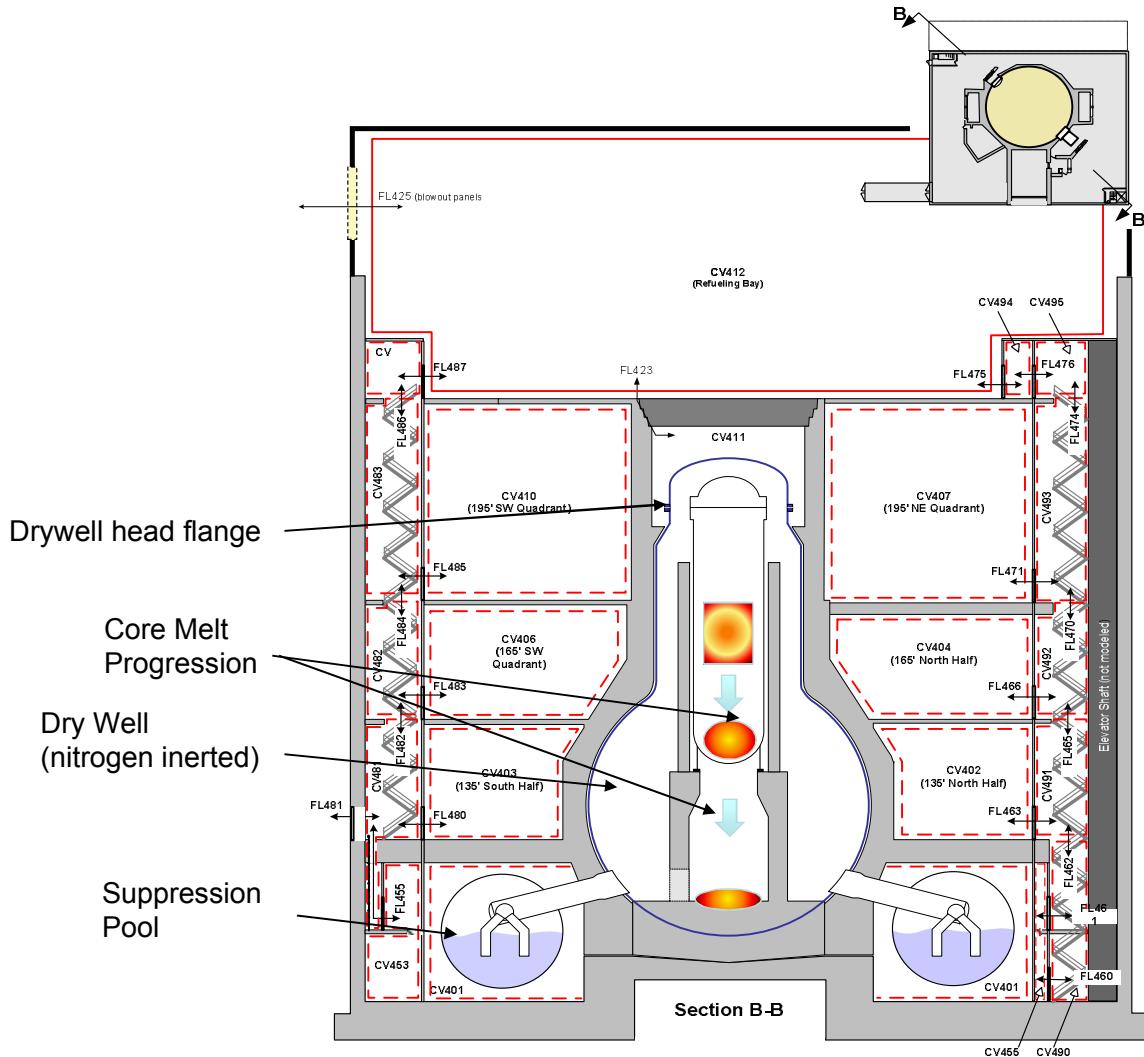


Reactor Power Before and After “Shutdown”



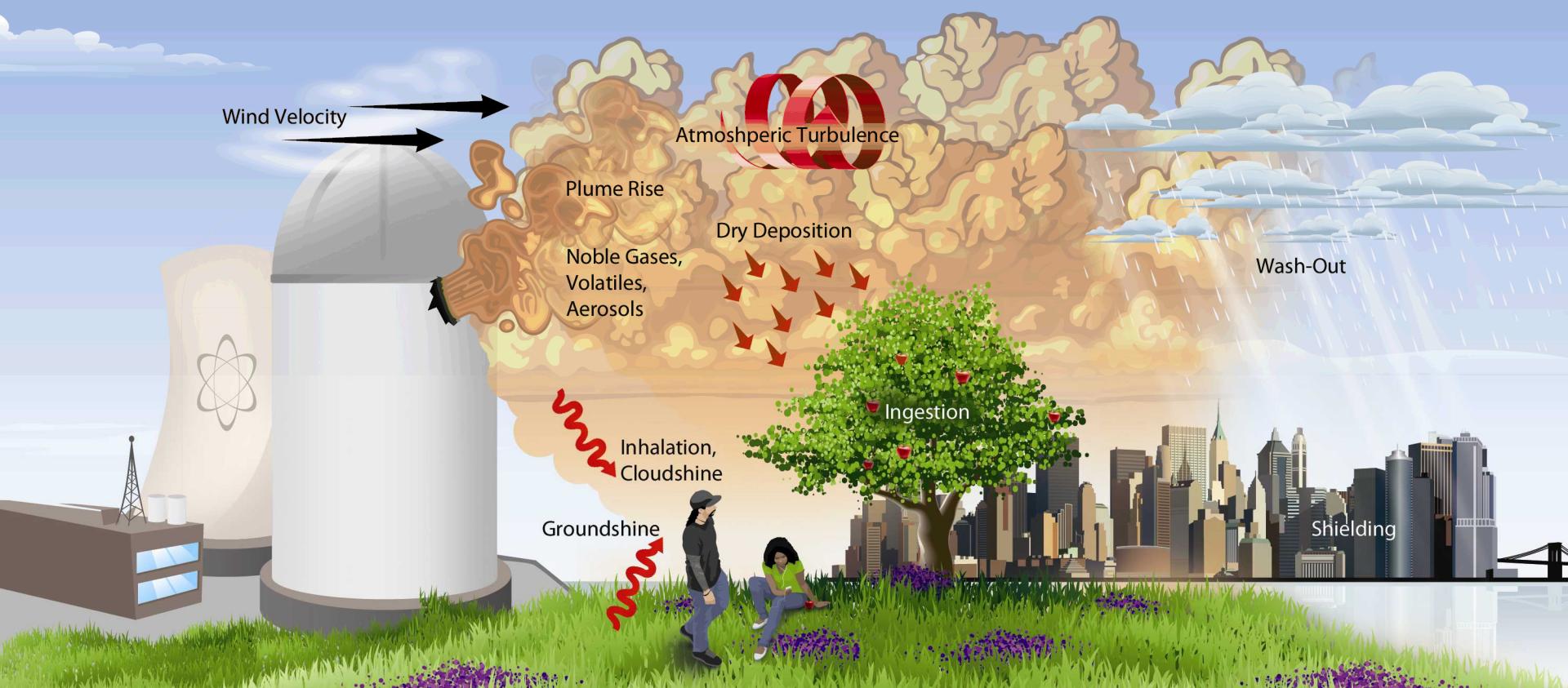
- Reactor shutdown doesn't completely stop heat generation
- Decay power requires long-term heat rejection (cooling)
- Long-term loss of cooling results in fuel melting and release of radioactivity

Core Melt Progression in Mark-I



- Uncovering of core
 - Fuel overheating
 - Zr-fire and H_2 gen.
 - Core meltdown
- Slumping to lower head of reactor pressure vessel
 - Melt relocation to containment floor
- Core-concrete interaction
 - Erosion of concrete
 - CO_2/CO gas generation
 - Containment over-pressurization
- Release of radioactivity to environment

MACCS Atmospheric Transport and Consequence Estimation



Design Basis for Seismic Events

Deterministic Considerations

- OBE – operational basis earthquake
 - The largest earthquake that could “reasonably” be expected to be encountered during the lifetime of the plant
 - Design of plant should be such that no shutdown or interruption of plant function should be experienced
 - No subsequent examination is required
 - If OBE exceeded, plant must be shutdown for inspection to demonstrate it is safe to restart
- SSE – Safe Shutdown Earthquake
 - The largest earthquake for which key plant safety function must be maintained
 - Pressure vessel and RCS integrity
 - Ability to shutdown the reactor
 - Ability to prevent or mitigate releases consistent with 10CFR100 requirements

OBE and SSE, Continued

- SSE is the largest earthquake magnitude considered possible for the site, considering known geological features, faults, and historical data
 - May never have been observed to occur historically
 - Critical equipment that must survive classified as Category 1
 - Other equipment may be damaged
 - Category 1 equipment qualifications determined by
 - Physical tests, perhaps to destruction (shaker table or explosive simulation)
 - Detailed analyses
- OBE Operating Basis Earthquake – must be at least $\frac{1}{2}$ SSE
 - OBE requirements could dominate design (e.g.. Pipe restraints)

The Accident

Earthquake Led to Loss of Offsite Power

- Seismic events disrupted roads and power lines
- Local offsite blackout isolated Fukushima Dai-ichi station from power grid
- Reactors shut down and emergency core cooling systems operated as designed
- Site powered and operated by onsite diesel generators



Circuit Breaker damaged

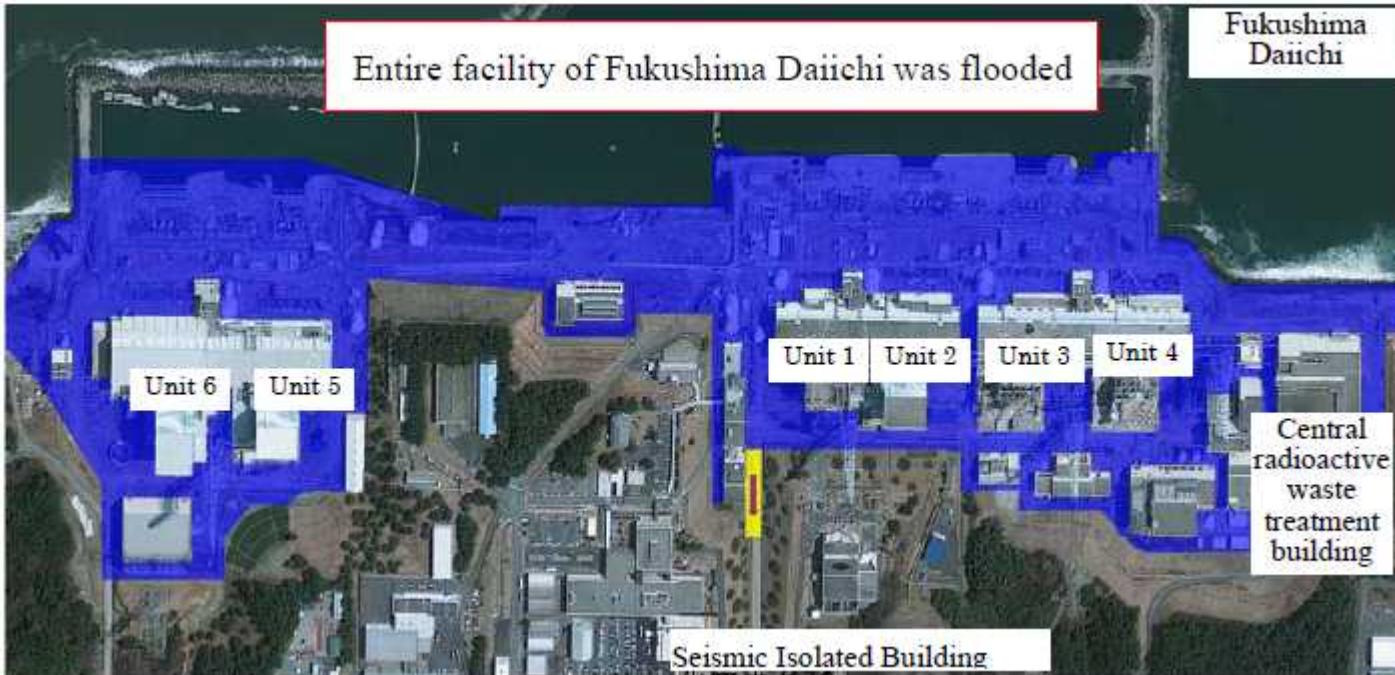


Collapsed tower

Used by permission from TEPCO



Dai-ichi Site was Inundated



- Site flooding initiated “Station Blackout”
 - Diesel generators flooded and fuel tanks swept away
- Unit 1 and 2 lost DC batteries
 - blind to what was happening and No ECCS
 - DC power available
- Unit 2 and 3 maintained “Emergency Core Cooling System”
- All reactors isolated from ultimate heat sink (Ocean)

Used by permission from TEPCO

Damage from Explosions



Damage to 1F4

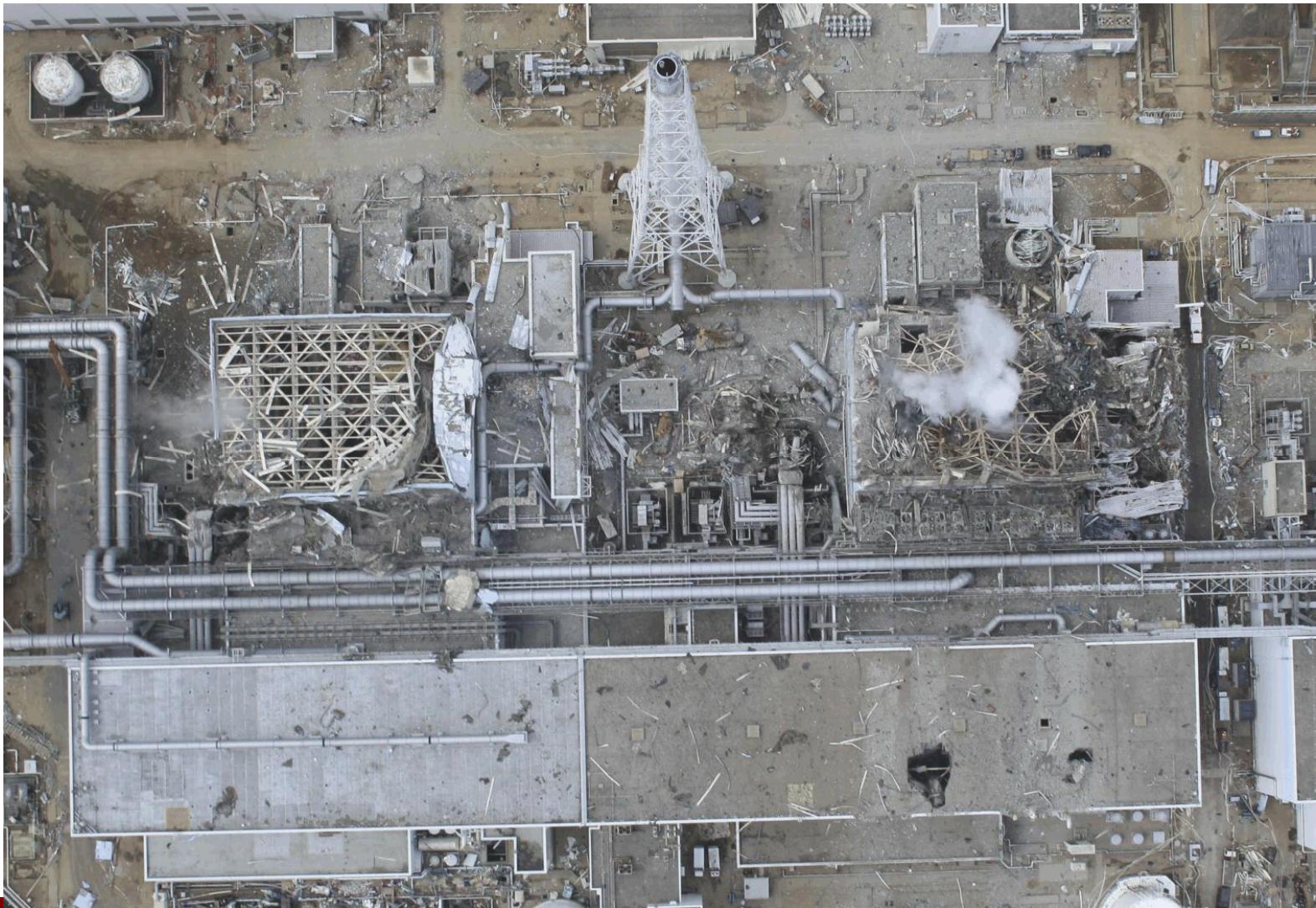


Spent Fuel Pool-4 Status

- TEPCO says was never uncovered
- Water level being maintained
- Water isotopic measurements
 - Very low activity (less than a fraction of one rod)
 - Source is not from pool as iodine fraction is too high
 - Source is from adjacent reactors, possibly contaminated sea water injection
- Pool images indicate very little damage
 - But not absolutely conclusive in my mind
- Resolution is important because if H₂ came from fuel in pool, then cladding is highly embrittled and will greatly complicate fuel removal

Common Off-gas Ducts 1F3-1F4

Source of H₂ from Unit 3 Accident?



In-Country Support

Activities in U.S. Embassy

- Initial emphasis was on estimating risk potential to returning U.S. citizens that were previously evacuated
- Sandia team developed baseline MELCOR models for predicted reactor damage states
 - Fraction core damage
 - Source term released
 - Forecasting tool for potential future events
- Daily consults from military people based at Yakota Air Base
- Daily consultation and assistance to NRC, DOE, DoS
 - Severe accident interpretation
 - Explanation of numbers and results
 - Exploring mitigation options and success
- Technical discussions and data/information requests with INPO/TEPCO
- Technical support to the Consortium partners
- Consultation with Japanese engineers on severe accident modeling
- Ongoing forensics investigation of events

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, N2 inerting
- Provided daily reports to Ambassador

NRC Team Led by Chuck Casto

Supporting Ambassador John V. Roos

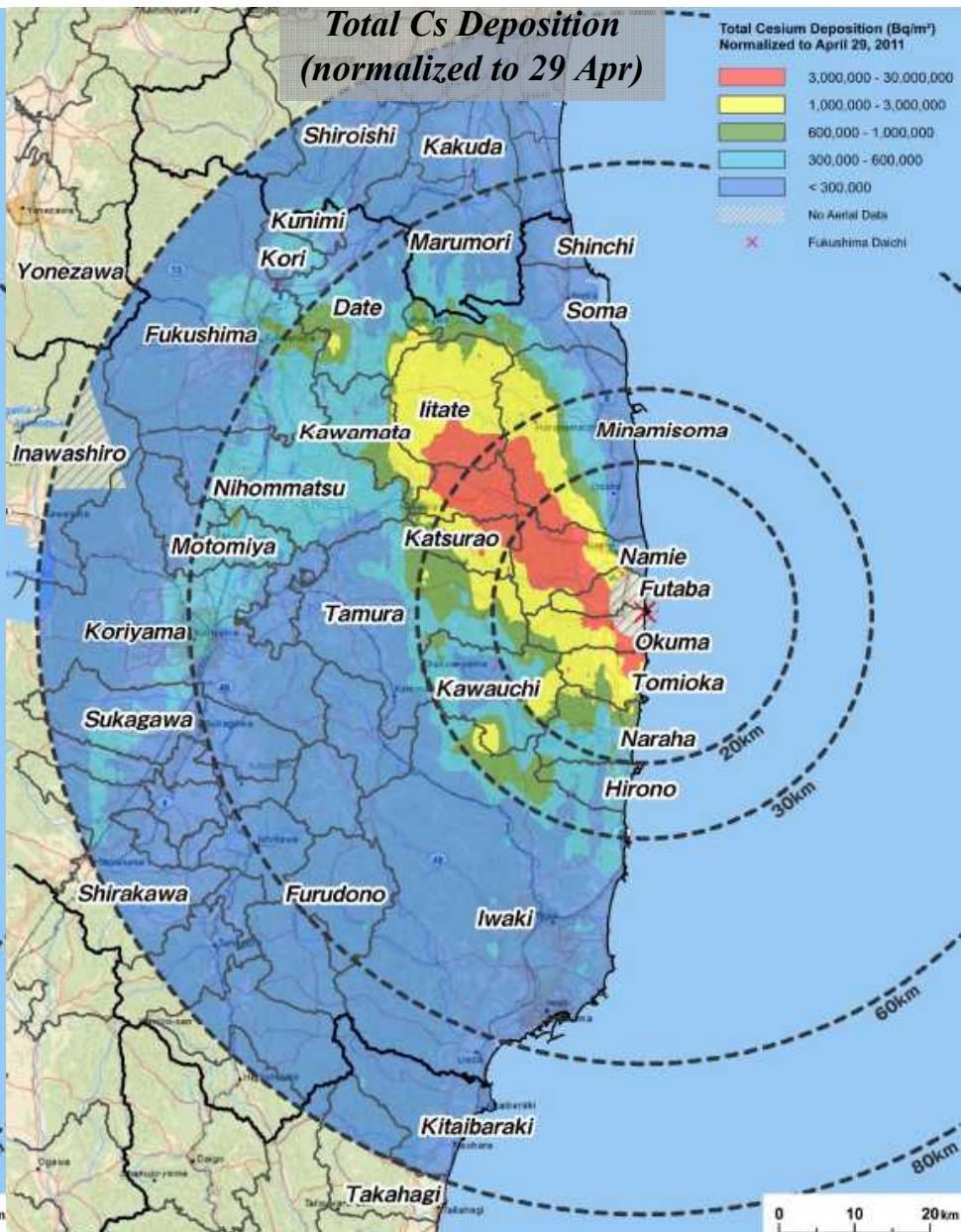
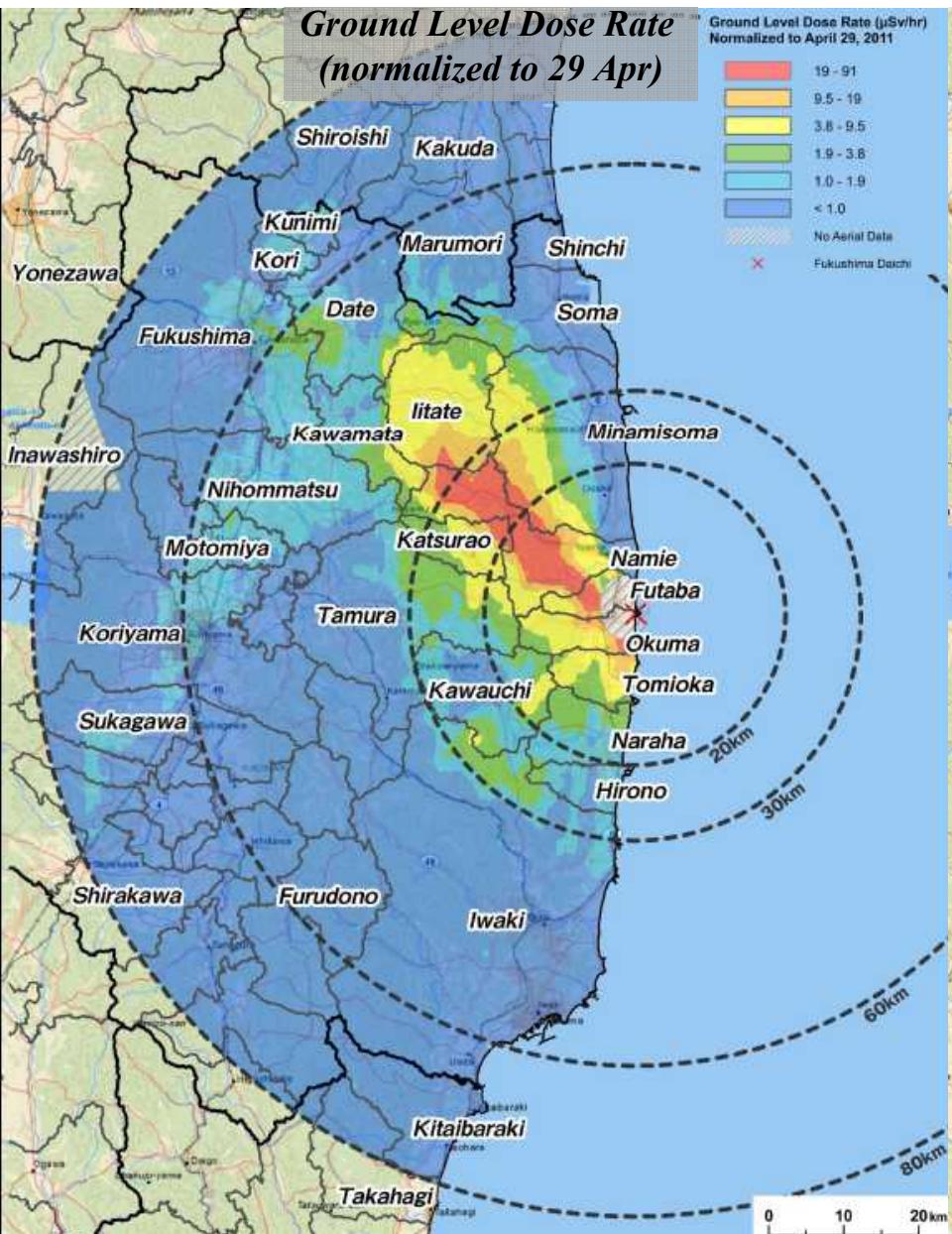


During the Accident

- Activated NNSA Consequence Management Home Team
 - 24/7 support for field operations
 - Dose Assessment
 - Analyzed rad doses based on modeled releases and actual rad measurements
 - Helped define evacuation zones
 - Analyzed food, soil, air
 - Laboratory Analyses
 - Received samples from Government of Japan
 - Managed laboratories across the US
 - Validated results
 - Uploaded over 10,000 sample results
- Conducted research on decontamination technology
 - Cs capture from seawater
- Provided information on multiple capabilities
 - Robotics, drones, decontamination, emergency response

Aerial Measuring Results Joint US/Japan Survey Data

FUKUSHIMA DAIICHI
JAPAN



Decontamination Technology

- Crystalline Silicotitanates remove Cs through ion exchange
 - Started as LDRD in 1993
 - Commercialized through CRADA in 1995, licensed to UOP
 - Won R&D 100 Award in 1996
- Deployed at Fukushima Dai-ichi in June 2011
- Decontaminated 100+ million gallons of contaminated seawater



Accident Reconstruction



SNL Fukushima Dai-ichi MELCOR Reactor Models



State-of-the-Art Reactor Consequence Analyses Project

Volume 1: Peach Bottom Integrated Analysis

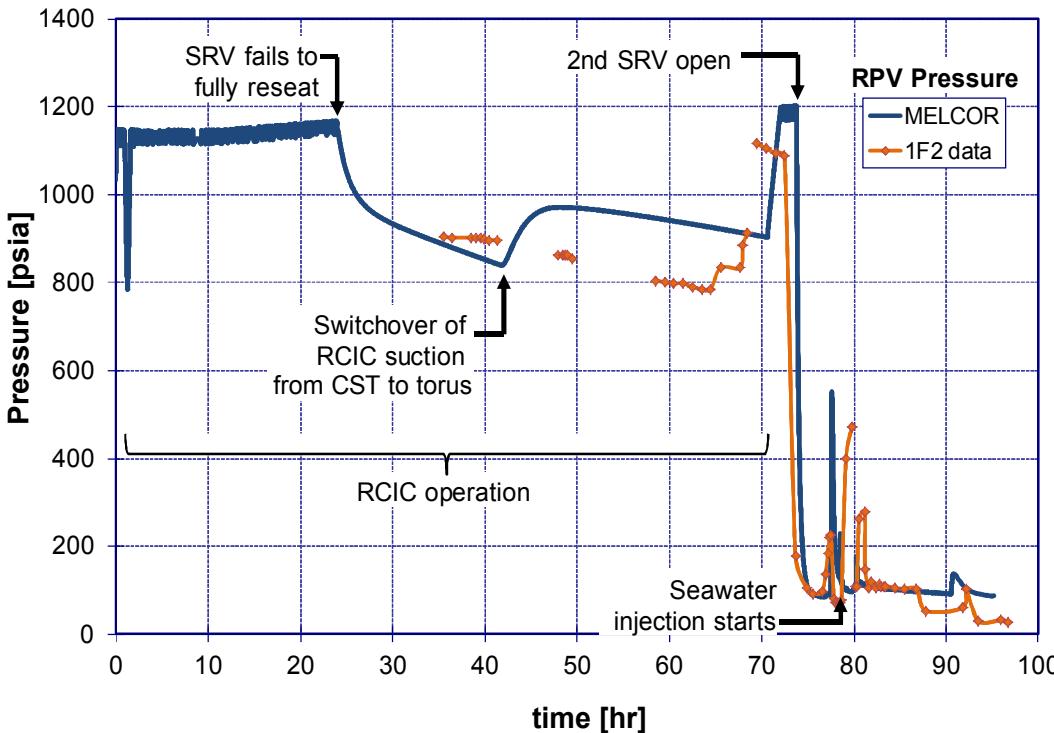
Manuscript Completed: January 2012
Date Published: January 2012

Prepared by:
Sandia National Laboratories
Albuquerque, New Mexico 87185
Operated for the U.S. Department of Energy

NUREG/CR-7110, Vol. 1

- BWR Mk-I model from the NRC's State-of-the-Art Consequence Analysis (SOARCA) project used as a template
 - 20+ years of BWR model R&D
 - Current state-of-the-art/best practices
- Incorporated reactor-specific information into the template to create Fukushima Dai-ichi reactor models
- Developed surrogate information for unavailable Fukushima Dai-ichi information
- Analyses performed using MELCOR 2.1

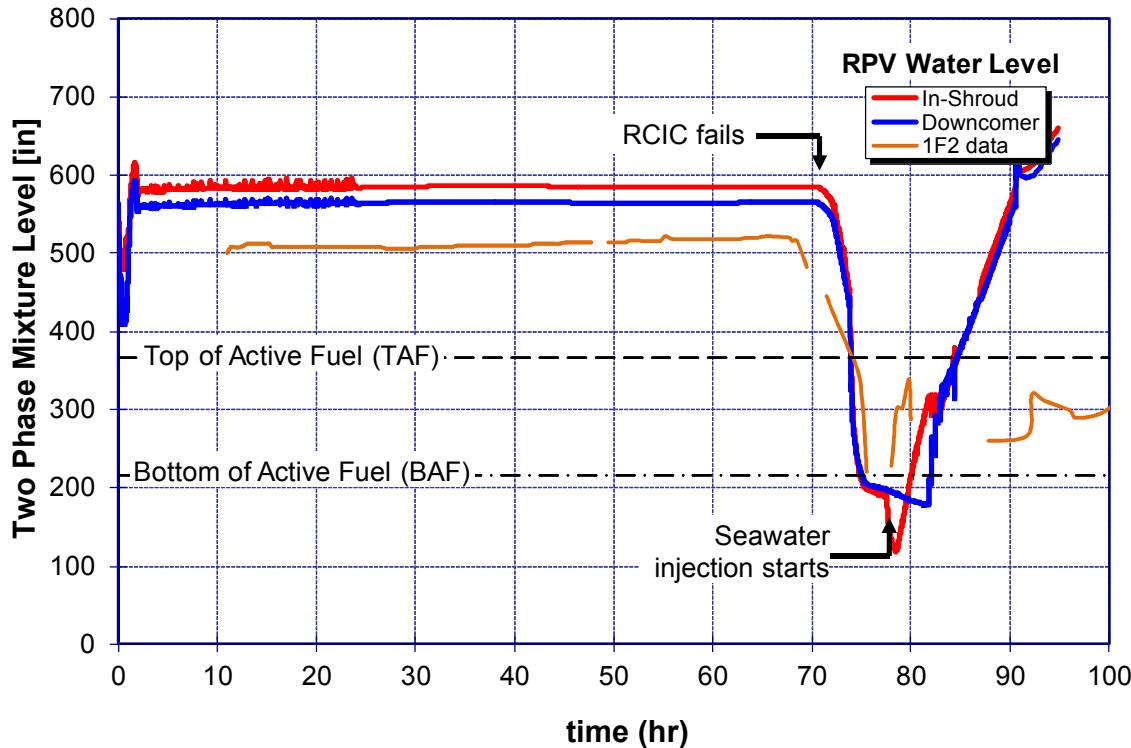
MELCOR Analysis of 1F2 Reactor Pressure



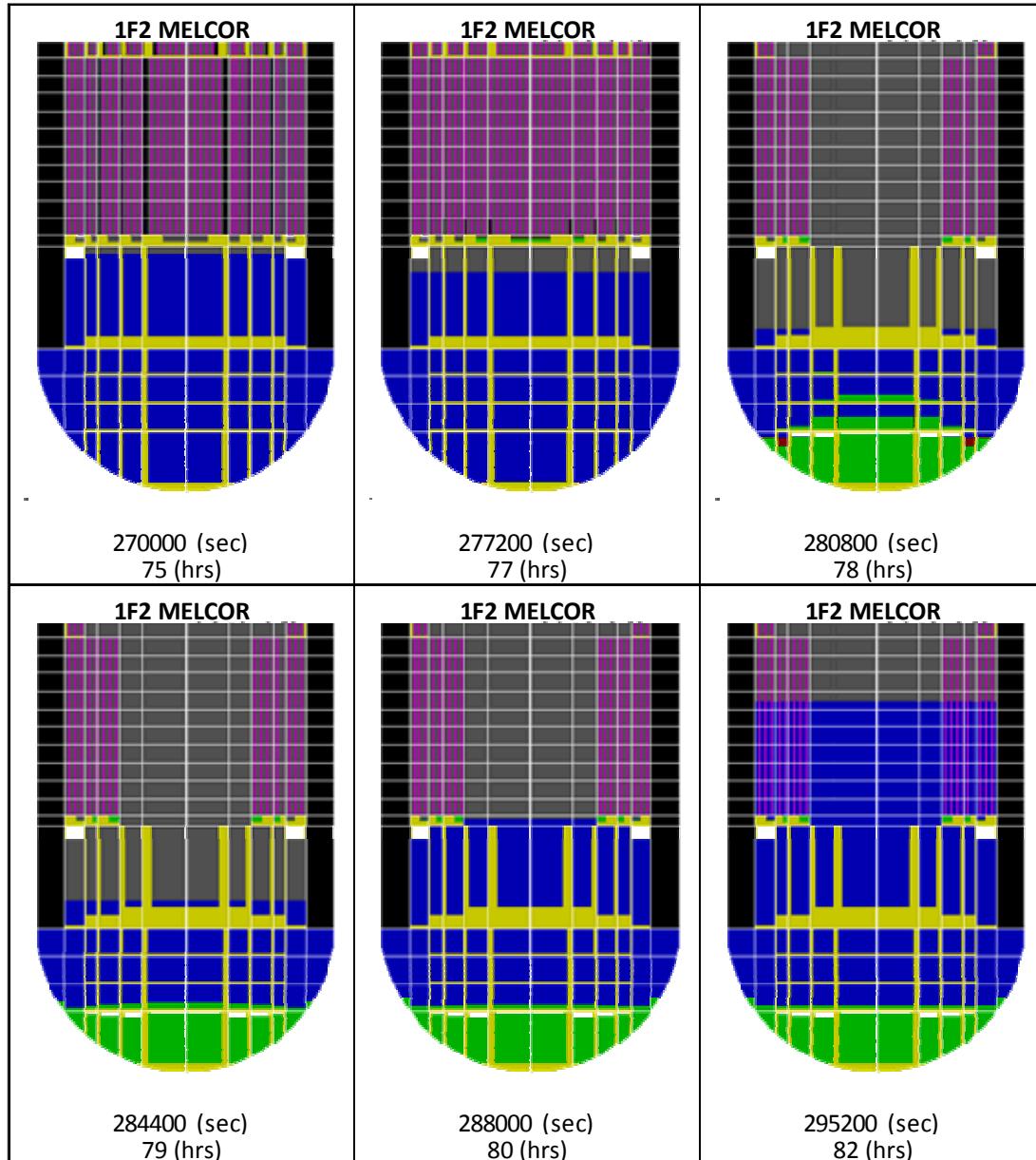
- Analysis assumes 2 inch effective hole in torus after earthquake
- RCIC operates for very long time
 - It is believed that CST was refilled several times
- After saturation in torus, steam escapes via torus hole
- As vessel water level drops, operators depressurize vessel to enable sea water injection

MELCOR Analysis of 1F2

Reactor Water Level



- RCIC fails finally and injection to vessel ceases
- Vessel water level drops
- Operators depressurize reactor and start sea water injection
- Water level recovers but whole core has been uncovered



MELCOR Predicted Core Damage

US Actions & Summary



Summary

- Persistent and significant decay heat must be removed for months following reactor “shutdown”
- Loss of heat rejection causes coolant boilover and core overheating
 - Fuel rod cladding (Zr) burns at high temperature
 - Core meltdown and release of radiation
- Earthquake and Tsunami at Fukushima
 - Reactors “shut down” following earthquake – loss of offsite power
 - Tsunami flooded site – station blackout and loss of heat rejection
 - Reactors isolated from ultimate heat sink
- Heat storage on-site exhausted
 - Suppression pools boiling
 - Injection pumps failed
 - Reactor cores uncovered and cores melted down
 - Radioactivity released to environment
 - Population evacuated and land contaminated
- Prolonged SBO conditions and multi-unit accidents prevented accident recovery actions from succeeding

Summary

- Response to accident was ad hoc
- Severe accidents were not avoided
 - Some were mitigated more than others – effectiveness of responses not clear
 - Traditional recommendations to add water aggravate release from damaged containments
 - Releases are believed to be small (~1% per reactor)
- Reactors were doomed by lack of fresh water and loss of heat sink
 - Response time to replace lost power, water or cooling was too long to help
- Data from plant inadequate to manage post accident controls
 - Few pressures and temperatures and unreliable, unreliable water levels measurements, degraded instruments
- Much to be learned – more vigilance and advanced planning is needed
- Policy & decision makers do not always understand the science
- Tools provide useful real-time information and long-term understanding
- Results can be counterintuitive
- Ability to reduce probability is diminishing
- Capabilities need to be maintained

US Actions (www.nrc.gov)

- Mitigation and Station Blackout strategies – enhancing capability to maintain safety during prolonged loss of electrical power, e.g., installed, portable on-site, flown or trucked in equipment
- Containment venting – all plants of similar design required to install reliable, hardened vents to remove heat and pressure before damage
- Filtration & confinement strategies – to confine or filter rad material
- Spent fuel instrumentation – all plants to install water level instrumentation
- Seismic & flooding reevaluations & walk-downs – using present-day information
- Emergency preparedness, communication, on-site emergency capabilities - improvements – effectively respond to an event affecting multiple reactors, large-scale events
- Plant specific actions and progress can be accessed on the NRC website

Questions?

