SAND2012-3822C

4. Case Study

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administrationunder contract DE-AC04-94AL85000.

The Fukushima Dai-ichi Nuclear Power Station Accident Chronology

Source: Tokyo Electric Power Company

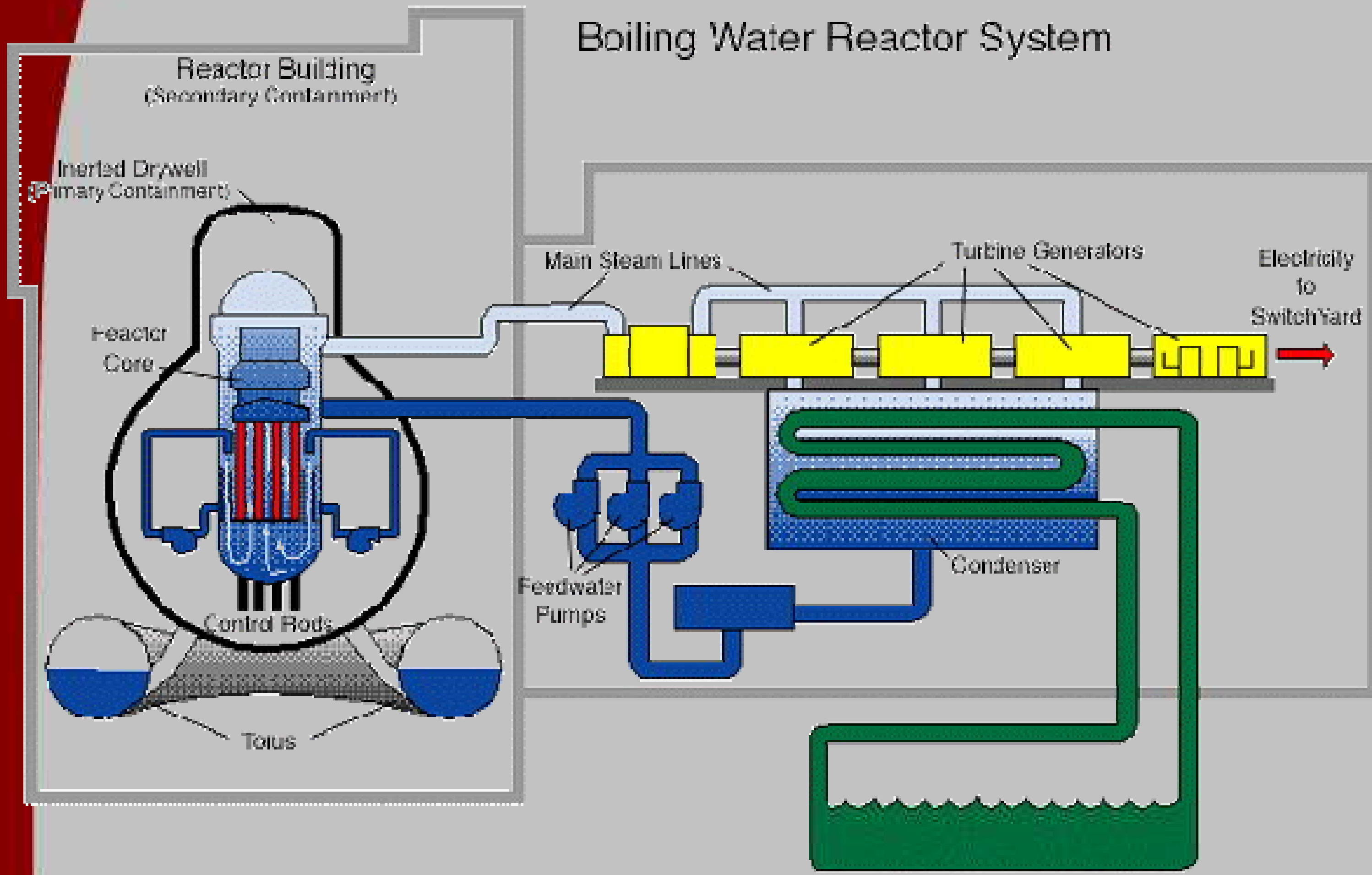
Outline of Presentation

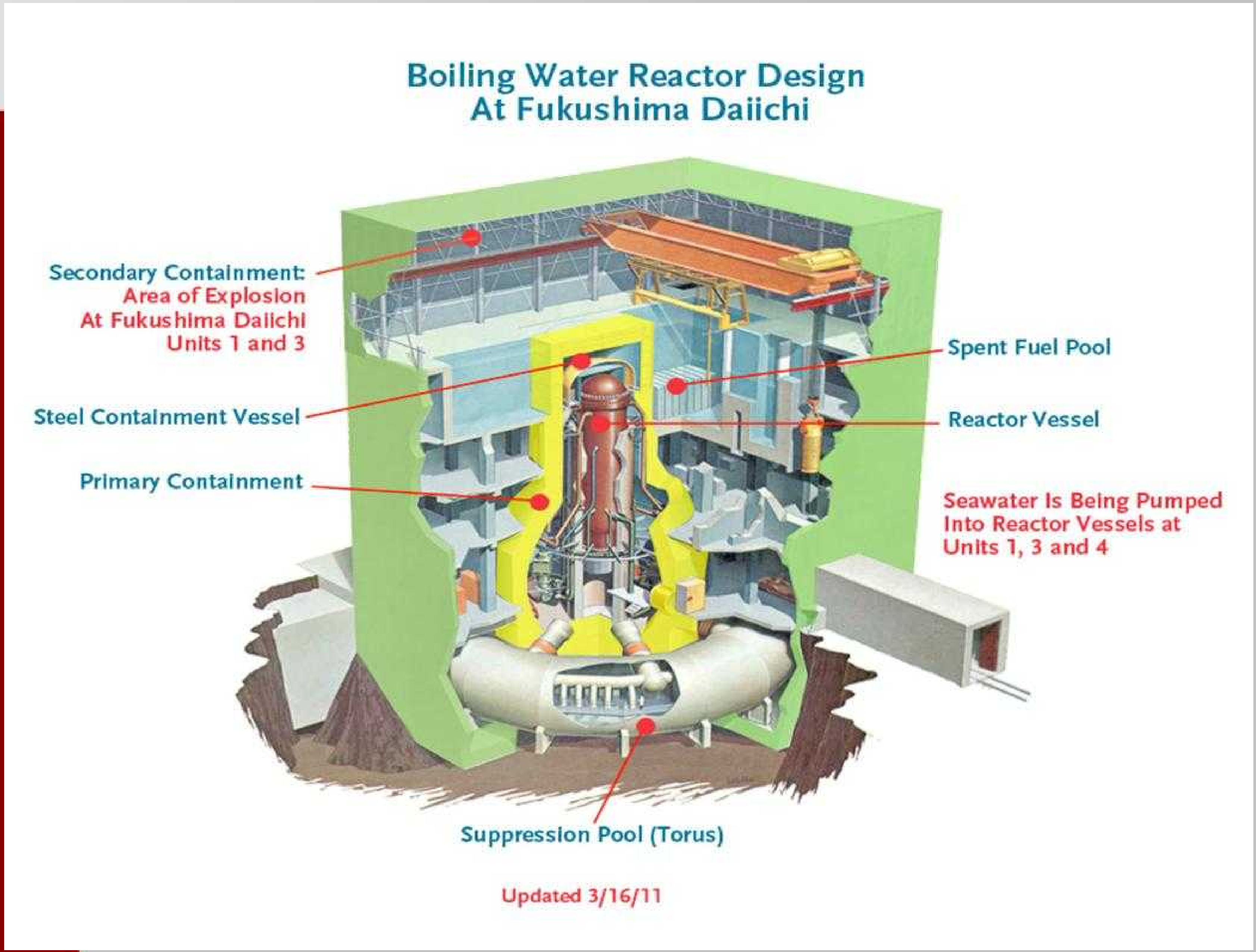
- Plant Information
- Boiling Water Reactor Basics
- Units 1-3 Accident Chronology
- Units 3 and 4 Spent Fuel Pool
- Consequence Management
- Recovery and Countermeasures

Plant Information

- Six BWR units at the Fukushima Nuclear Station:
  - Unit 1: ~460 MWe BWR3 1971 (in operation prior to event)
  - Unit 2: 760 MWe BWR4 1974 (in operation prior to event)
  - Unit 3: 760 MWe BWR4 1976 (in operation prior to event)
  - Unit 4: 760 MWe BWR4 1978 (in outage prior to event)
  - Unit 5: 760 MWe BWR4 1978 (in outage prior to event)
  - Unit 6: 1067 MWe BWR5 1979 (in outage prior to event)

Boiling Water Reactors



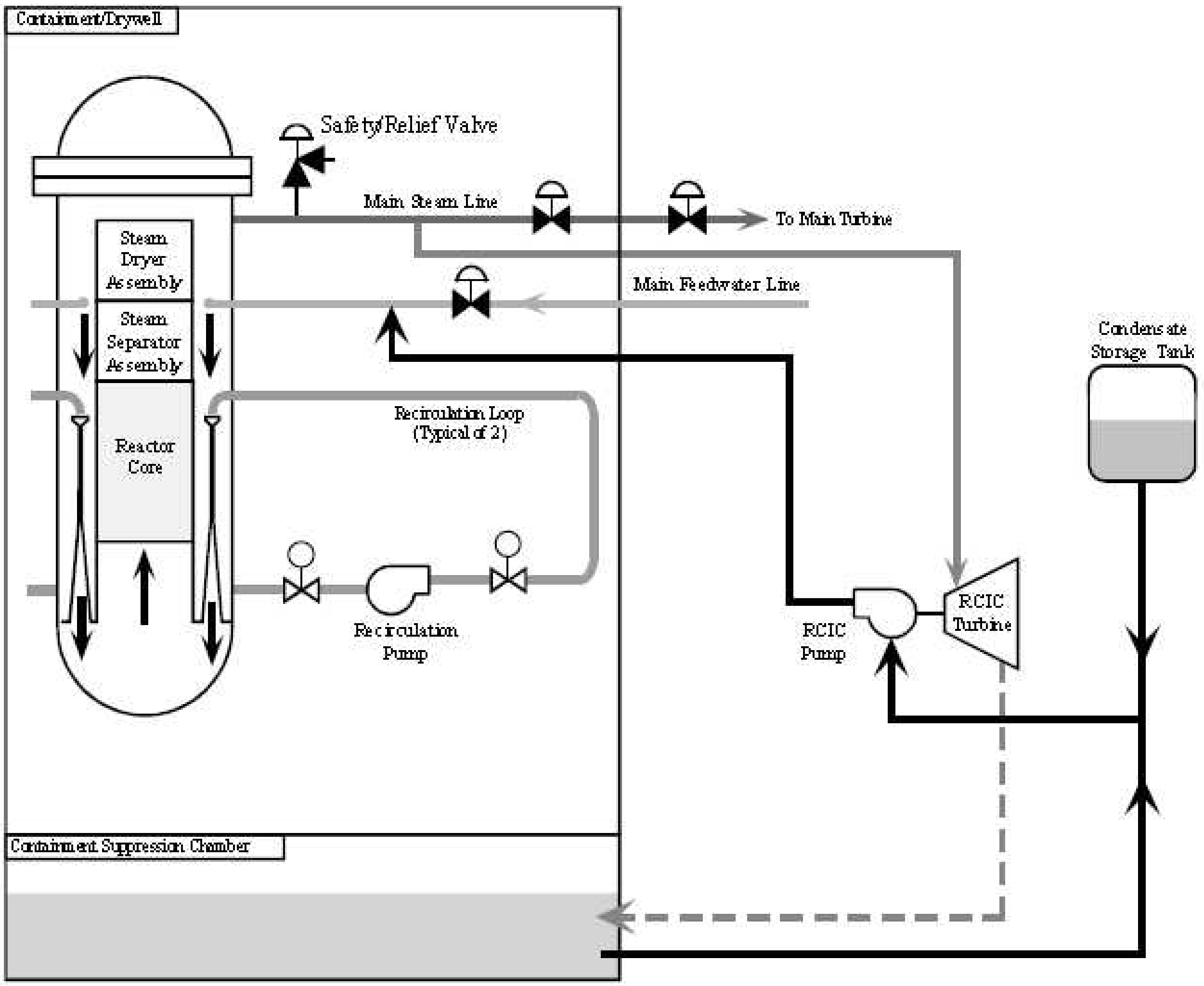

Boiling Water Reactor Design
At Fukushima Daiichi
Secondary Containment:
Area of Explosion
At Fukushima Daiichi
Units 1 and 3
Steel Containment Vessel
Primary Containment
Spent Fuel Pool
Reactor Vessel
Seawater Is Being Pumped
Into Reactor Vessels at
Units 1, 3 and 4
Suppression Pool (Torus)
Updated 3/16/11

Secondary Containment Where Hydrogen Explosions Occurred

Safety Systems to Mitigate Accident Progression

- Many important safety systems are used to mitigate an accident in a BWR
- Systems that rely on AC Power were not available after power was lost
  - Motor operated pumps
  - Motor operated valves
- Other systems are available if power is lost
  - Reactor Core Isolation Cooling (RCIC) System
  - High Pressure Coolant Injection (HPCI) System
  - Isolation Condenser (IC) on Unit 1
  - Containment Venting System

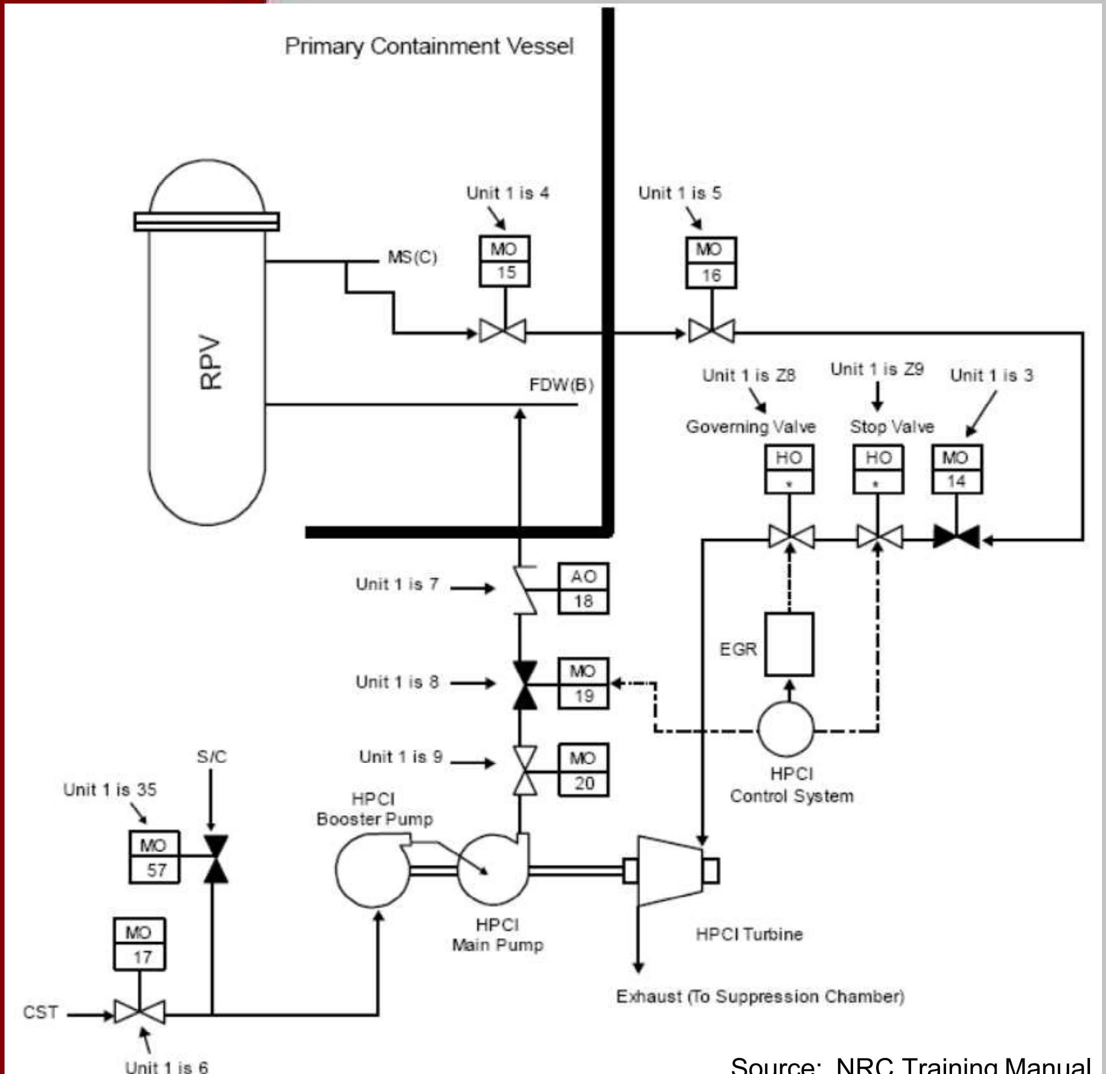
Reactor Core Isolation Cooling (RCIC) System



Source: NRC Training Manual

- Steam driven system
- Used when main steam lines are isolated
- Pump draws from external condensate storage tank or suppression pool
- Adds heat load to suppression pool inside containment
- Activates on low water level or by operator action

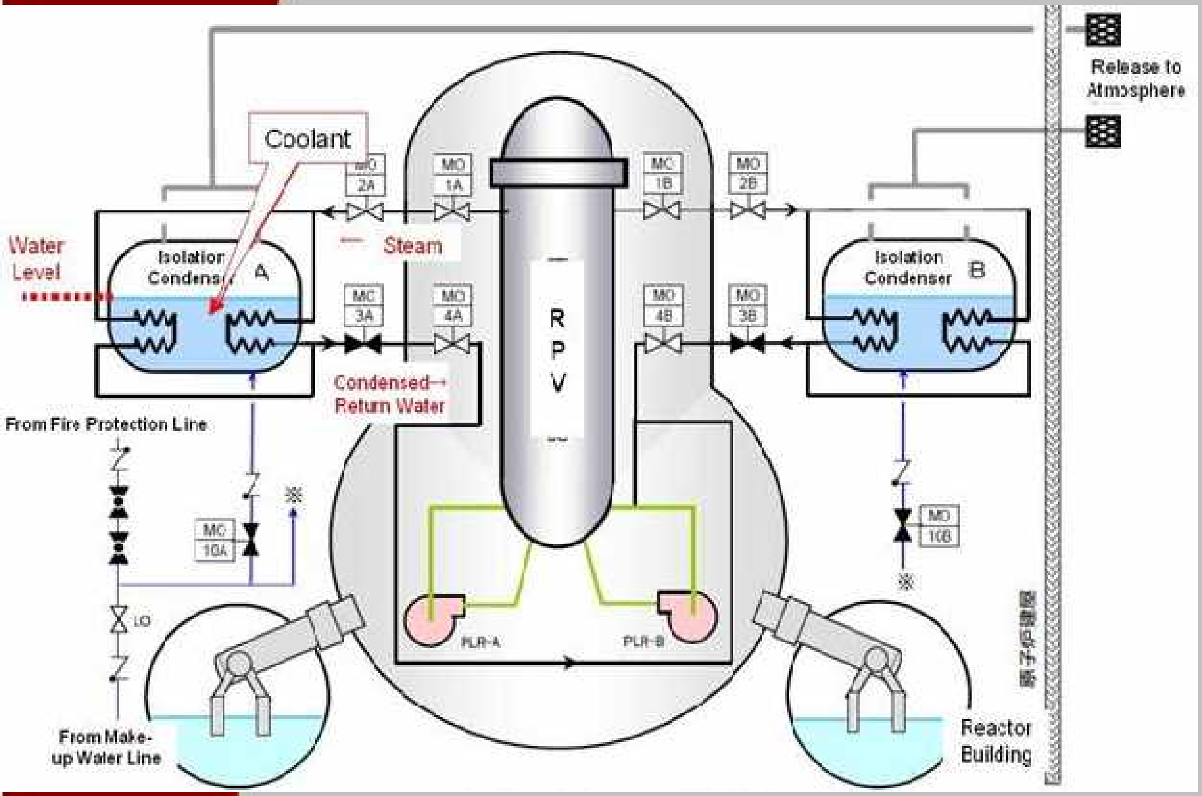
High Pressure Coolant Injection (HPCI) System



Source: NRC Training Manual

- Similar to RCIC
- Also steam driven, but much larger with a bigger pump
- Accepts more steam from the reactor pressure vessel
- Can depressurize the reactor pressure vessel very rapidly

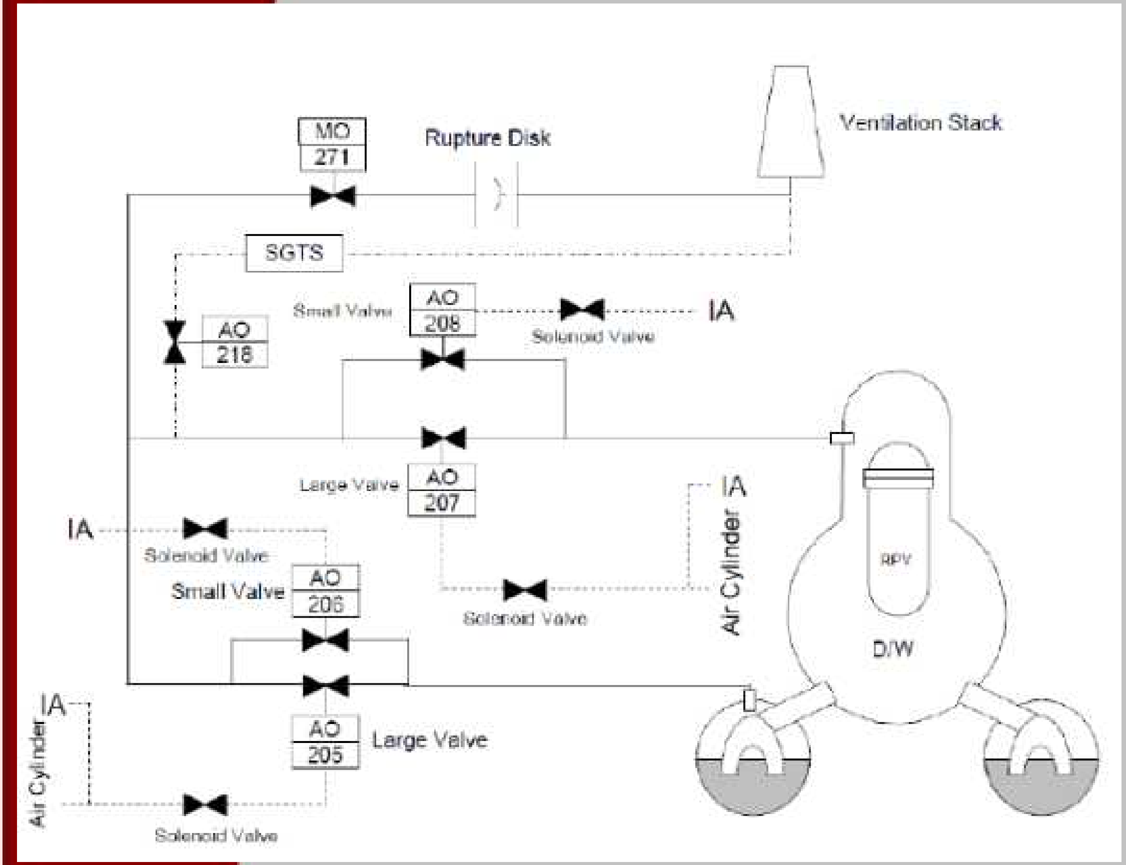
Isolation Condensers (ICs)



Source: NRC Training Manual

- Large heat exchanger that accepts steam from the reactor pressure vessel, quenches it and returns by gravity to the vessel
- Operated by opening valves and providing make up water
- Make up provided by diesel driven fire water system fire during station blackout

Containment Venting System



Source: NRC Training Manual

- Heat in containment raises pressure
- To maintain containment integrity, it is important to vent off steam to reduce vessel pressure
- Can vent from two locations – wet well and dry well
- To operate open MOV, air operated valve, and rupture disk

Accident Chronology – Event Initiation

- A magnitude 9.0 earthquake occurred on March 11 (Japan time), centered offshore of the Sendai region, which contains the capital Tokyo with peak ground horizontal acceleration of 0.561 g
  - Plant design basis was a magnitude 8.2 earthquake and a peak ground horizontal acceleration of (0.447 g)
- Serious secondary effects followed – a significant tsunami and aftershocks.
- Estimated frequency of this earthquake 1E-6 to 1E-4 per reactor year (Japanese government)

The Tsunamis at Dai-ichi

- Seven tsunamis hit the plant
- Maximum height was 14 to 15 m
- Exceeded design basis of 5.7 m (original design basis was 3 m)
- Site grade is 10 m (Units 1-4) and 14 m (Units 5-6)

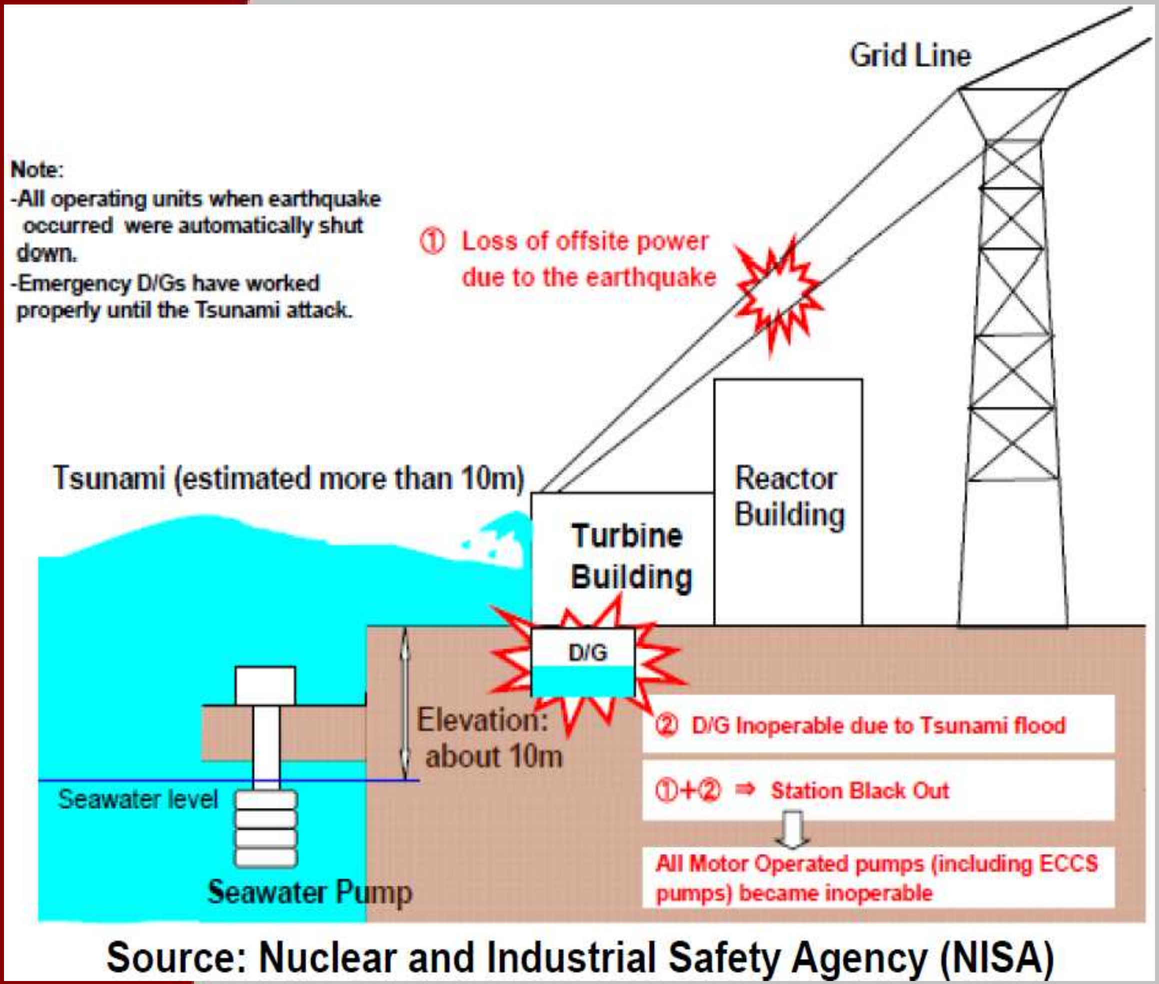
Accident Chronology – Station Blackout

- Earthquake caused reactor/turbine trip and loss of offsite power
- Emergency diesel generators (DGs) started and provided power to emergency systems
- Tsunami waves hit plant resulting in:
  - Flooded water-cooled DGs
  - Shorted emergency seawater pumps required for watered-cooled DGs (two air-cooled DGs survived)
  - Flooded AC buses (all Units)and some DC buses (Units 1 and 2)
  - Flooded switchgear so air-cooled DG for Unit 2 not able to provide power due to switchgear flooding; DG for Unit 6 operable
- Some power buses were not shorted by flooding (SLC & CRD)
- Although some air-cooled DGs were not damaged, loss of AC buses prevented distribution of power to emergency systems

Accident Chronology – Mitigation

- Focused on providing core cooling
  - IC in Unit 1 (HPCI unavailable due to loss of DC bus)
  - RCIC in Unit 2 (HPCI unavailable due to loss of DC)
  - RCIC and HPCI in Unit 3
  - Freshwater and seawater injection using diesel fire water pumps/engines
- And containment pressure control
  - Wetwell and drywell venting
- Neither function was performed in time

Accident Summary



- Off-site power to site lost due to earthquake
- All emergency diesel generators were disabled by flooding from tsunami (generators were 10 – 13 m above sea level)
- Emergency battery power was depleted after 8 hours
- Unable to cool fuel in reactors and spent fuel pools

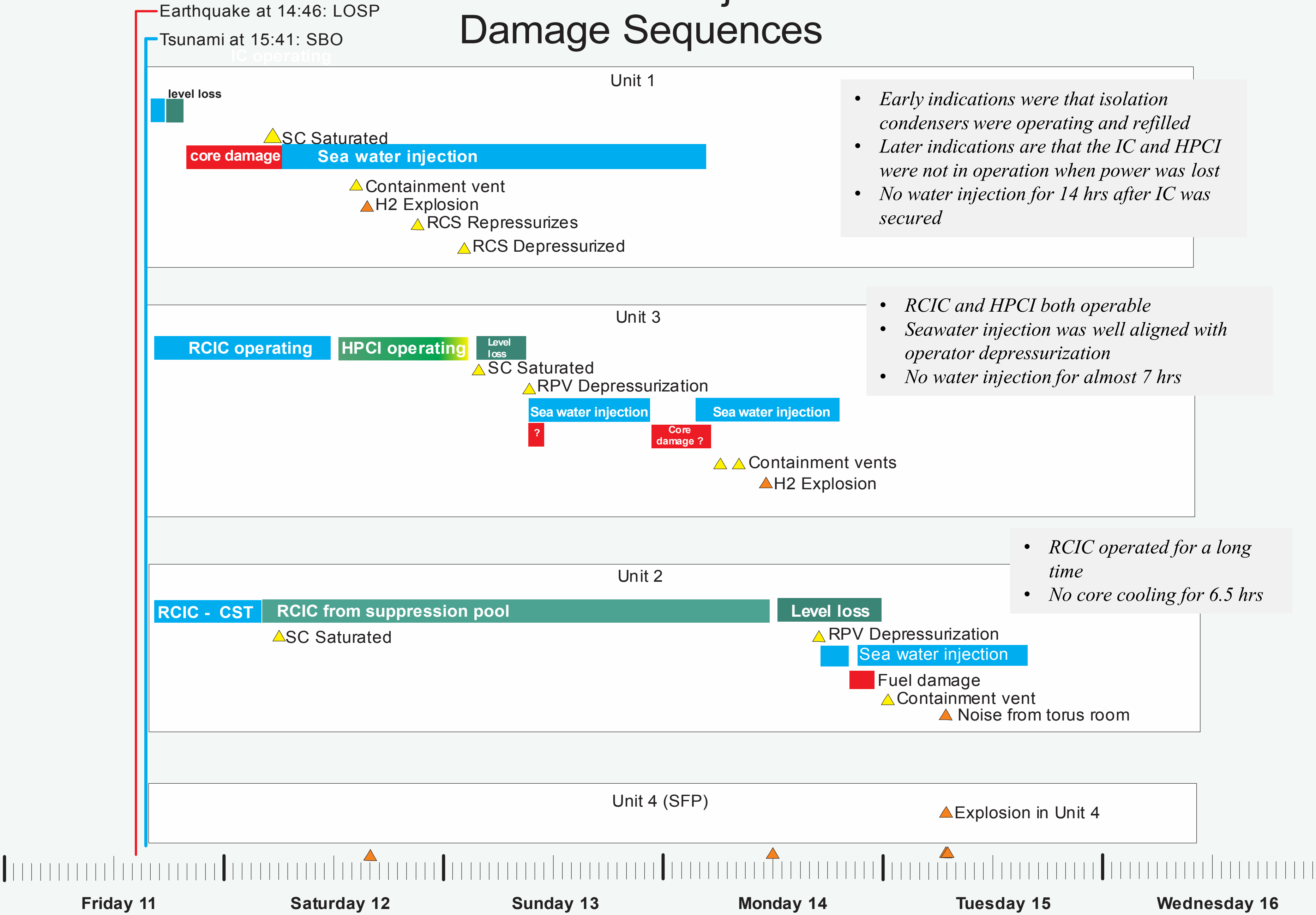
Challenges to Operators

- Much of the work was completed in darkness and flooded area
- Radioactivity levels were elevated
- After shocks and explosions defeated several efforts at aligning power and coolant injection
- Mitigation efforts used unconventional and unique methods – not based on training or procedures but on their fundamental knowledge
- Some had lost families in the tsunami but continued working
- Food was in initially in short supply

Testimonies from Workers

- *"In an attempt to check the status of Unit 4 diesel generator, I was trapped inside the security gate compartment. Soon the tsunami came and I was a few minutes before drowning, when my colleague smash opened the window and saved my life."*
- *"In total darkness, I could hear the unearthly sound of the safety relief valve dumping steam into the torus. I stepped on the torus to open the S/C spray valve, and my rubber boot melted."*
- *"The radiation level in the main control room was increasing 0.01 mSv (1 mrem) every 3 seconds but I couldn't leave—I felt this was the end of my life."*
- *"I asked for volunteers to manually open the vent valves. Young operators raised their hands as well; I was overwhelmed."*
- *"Unit 3 could explode anytime soon, but it was my turn to go to the main control room. I called my dad and asked him to take good care of my wife and kids should I die."*

Timeline of Major Fukushima Damage Sequences

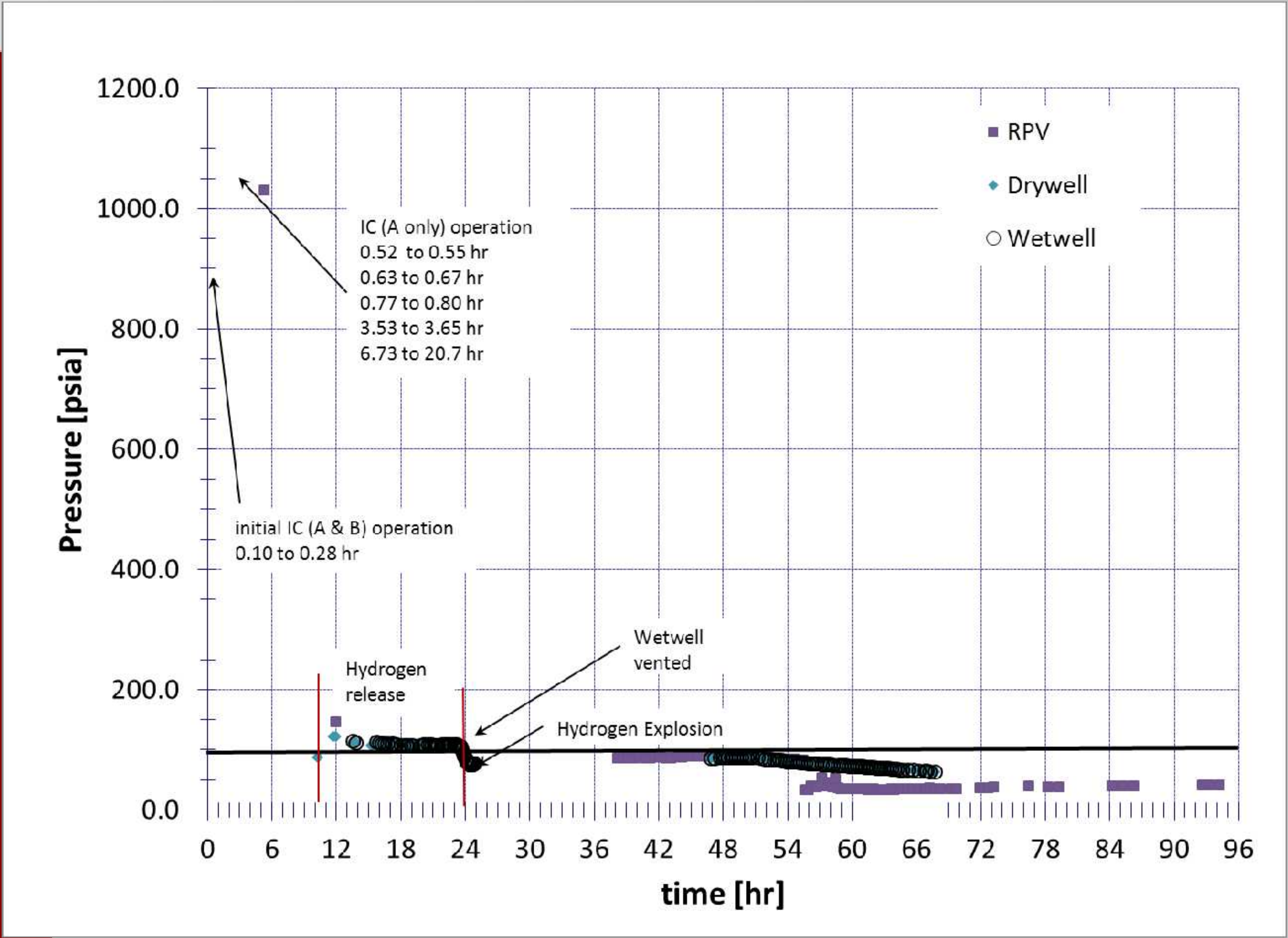


- *Early indications were that isolation condensers were operating and refilled*
- *Later indications are that the IC and HPCI were not in operation when power was lost*
- *No water injection for 14 hrs after IC was secured*

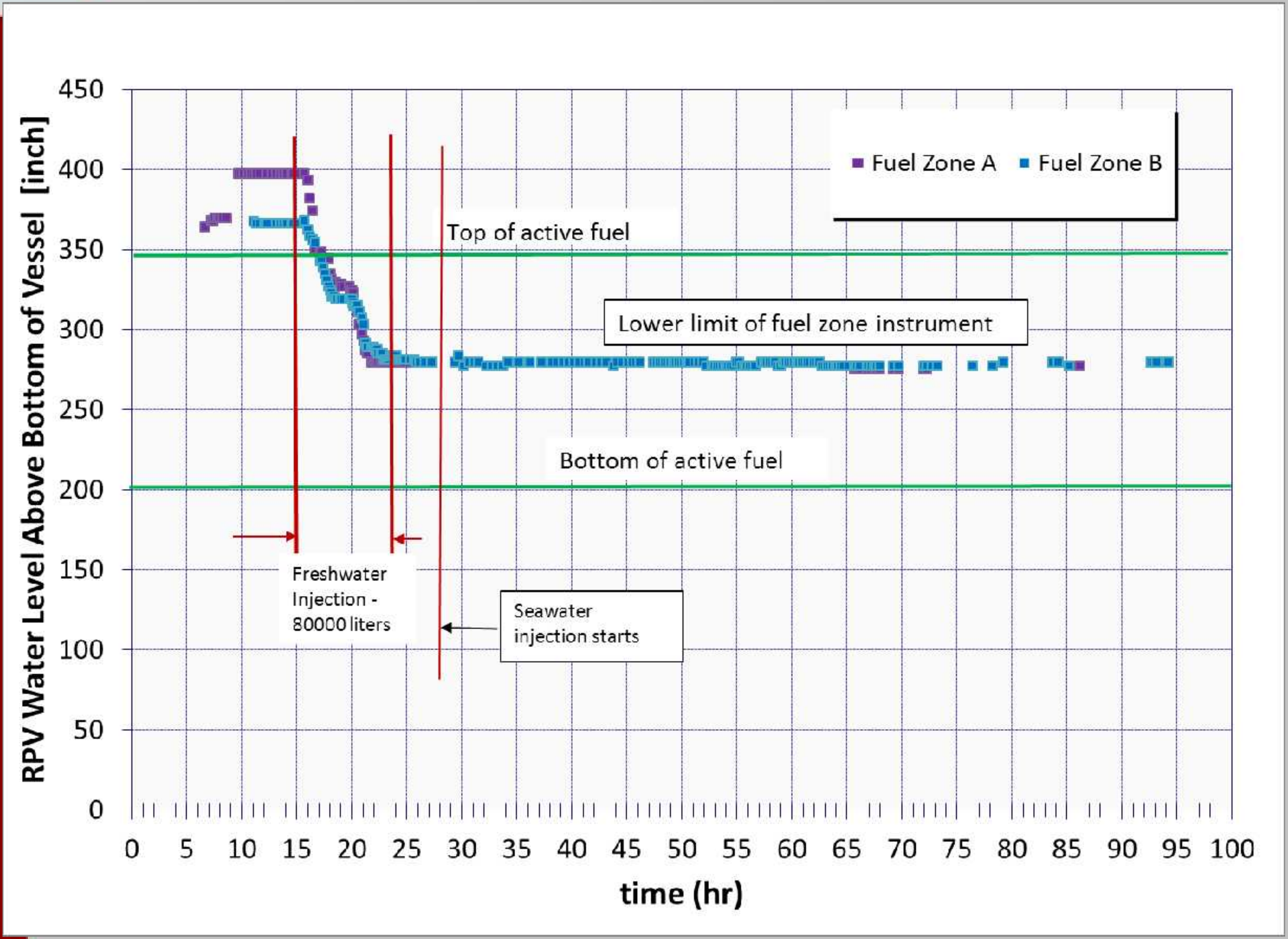
- *RCIC and HPCI both operable*
- *Seawater injection was well aligned with operator depressurization*
- *No water injection for almost 7 hrs*

- *RCIC operated for a long time*
- *No core cooling for 6.5 hrs*

Fukushima Unit 1 Data (1 of 2)



Fukushima Unit 1 Data (2 of 2)



Hydrogen Detonation at Unit 1

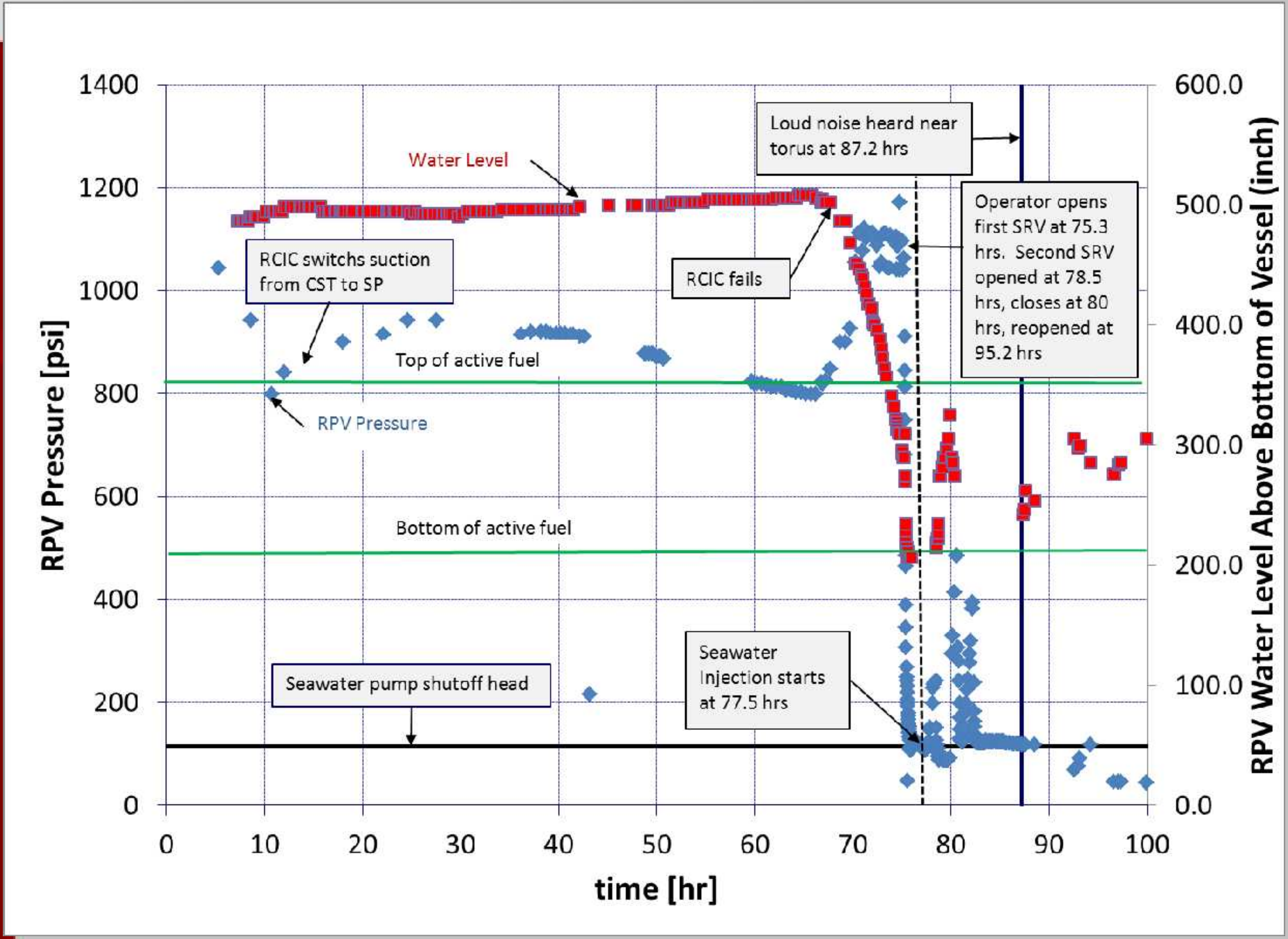
Refueling Floor

Reactor Building

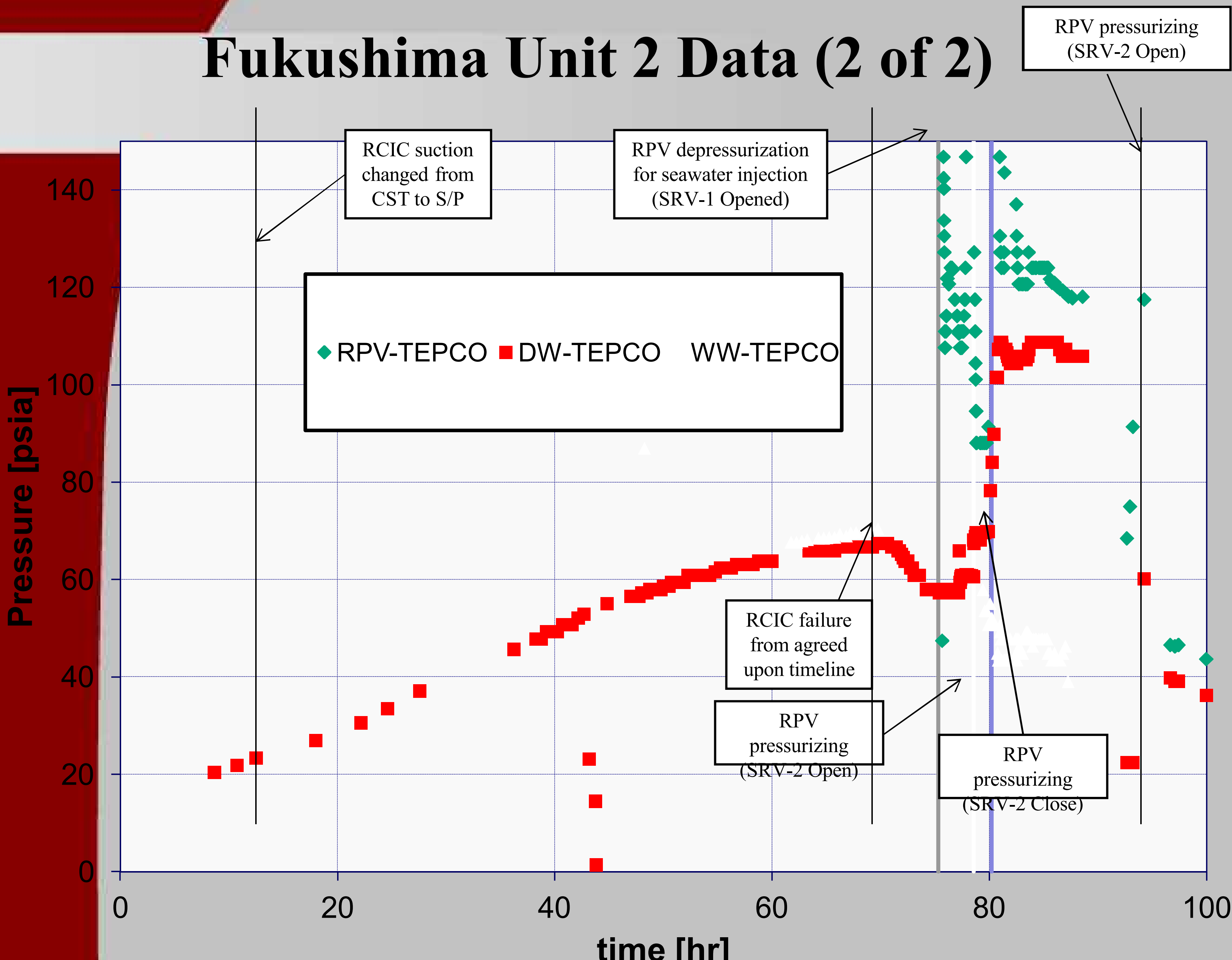
Unit 2 Events

Date and time	Time after scram (hr)	Event
3/11 14:46	-0.05	Earthquake
3/11 14:47	0.00	Scram
3/11 14:50	0.05	RCIC starts
3/11 14:51	0.06	RCIC stops
3/11 15:00	0.22	RHR starts wetwell cooling
3/11 15:02	0.25	RCIC starts
3/11 15:27	0.67	Tsunami wave
3/11 15:28	0.68	RCIC stops
3/11 15:27	0.80	Tsunami wave
3/11 15:36	0.82	RHR stops
3/11 15:39	0.87	RCIC starts
3/11 15:41	0.90	Station blackout
3/12 4:20	13.55	RCIC suction – wetwell
3/14 13:25	70.63	RCIC stops (assumed)
3/14 16:34	73.78	Seawater injection ready
3/14 18:06	75.32	RPV depressurizes via SRV 1
3/14 19:20	76.55	Seawater injection stops
3/14 19:54	77.12	Seawater injection starts
3/14 21:20	78.55	SRV 2 opens
3/14 23:00	80.22	SRV 2 closes
3/15 14:00	95.22	SRV 2 opens

Fukushima Unit 2 Data (1 of 2)



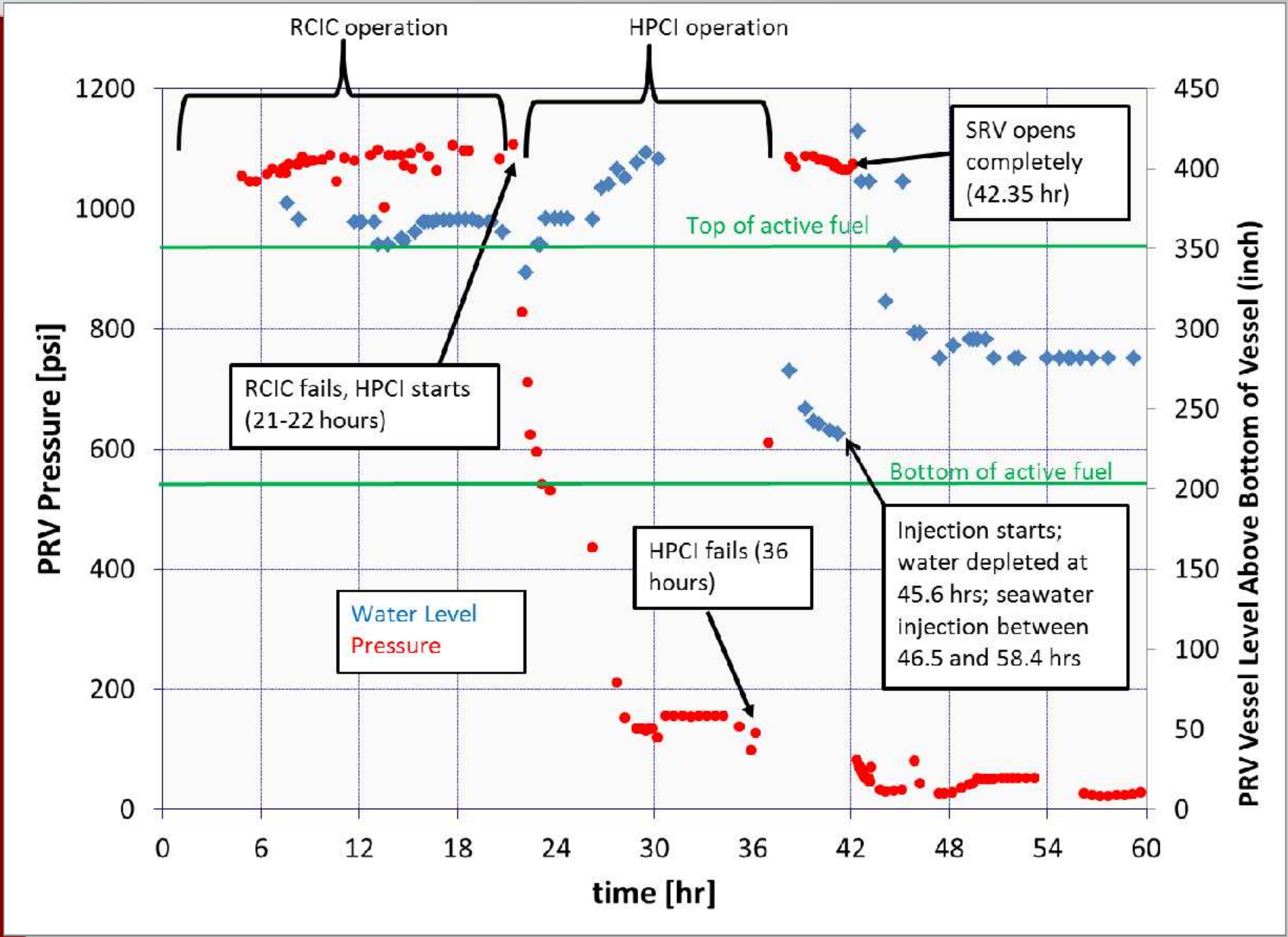
Fukushima Unit 2 Data (2 of 2)



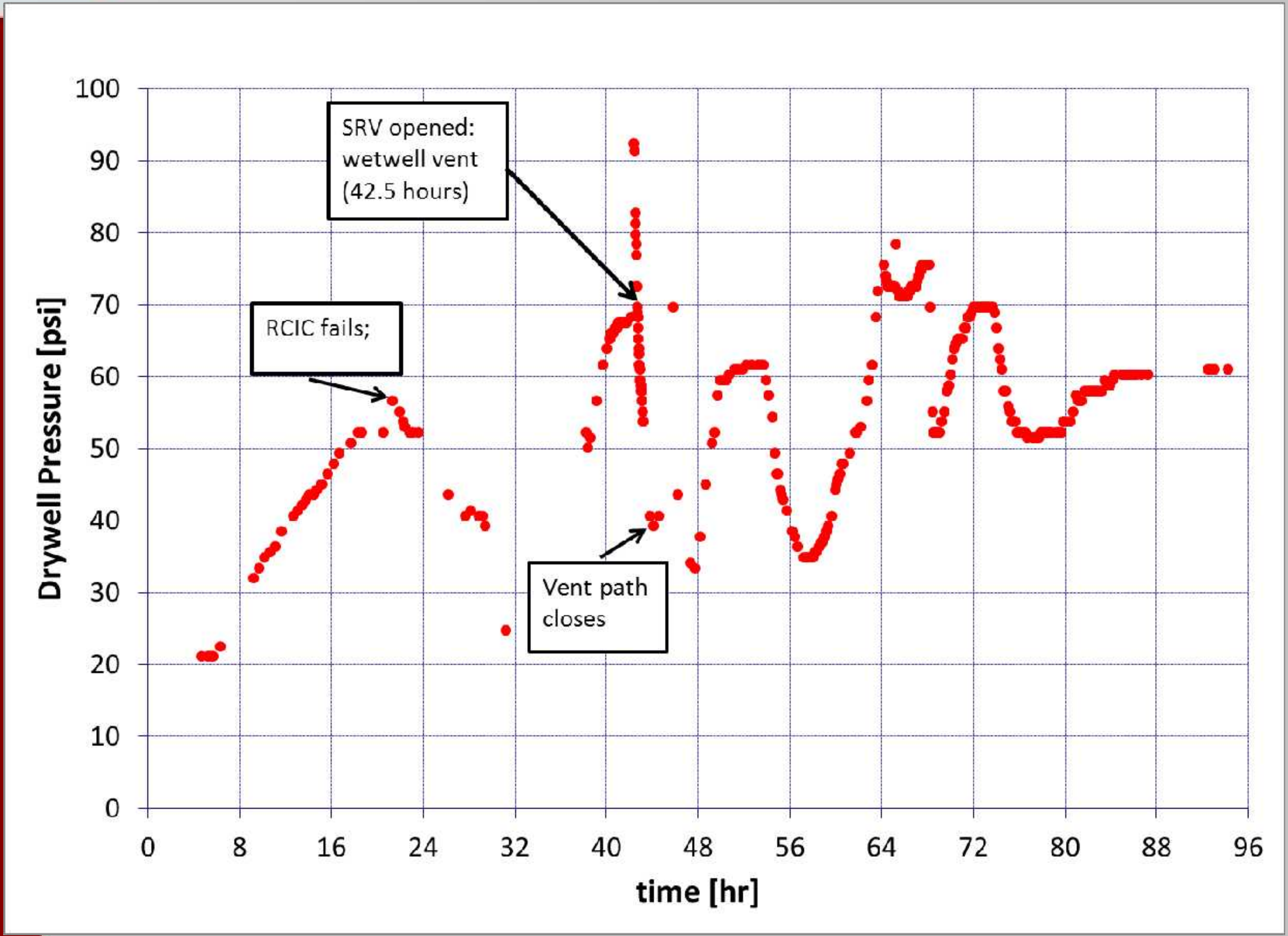
Unit 3 Events

Time after scram (hr)	Event
0.0	**Reactor scram (quake 1 min. before)**
0.30	**RCIC starts**
0.63	**RCIC stops**
0.67, 0.80	**1st and 2nd tsunami waves**
0.85	**Loss of AC power**
1.27	**RCIC starts**
20.82	**RCIC stops**
21.80	**HPCI starts**
30.7 – 35.9	**DC battery depletion**
35.92	**HPCI stops**
42.13 **– 42.35**	**RPV depressurizes via SRV**
41.8 – 42.5	**First S/C vent open**
42.6	**Injection starts**
44.5	**S/C vent close**

Fukushima Unit 3 Data



Unit 3 Containment Pressure



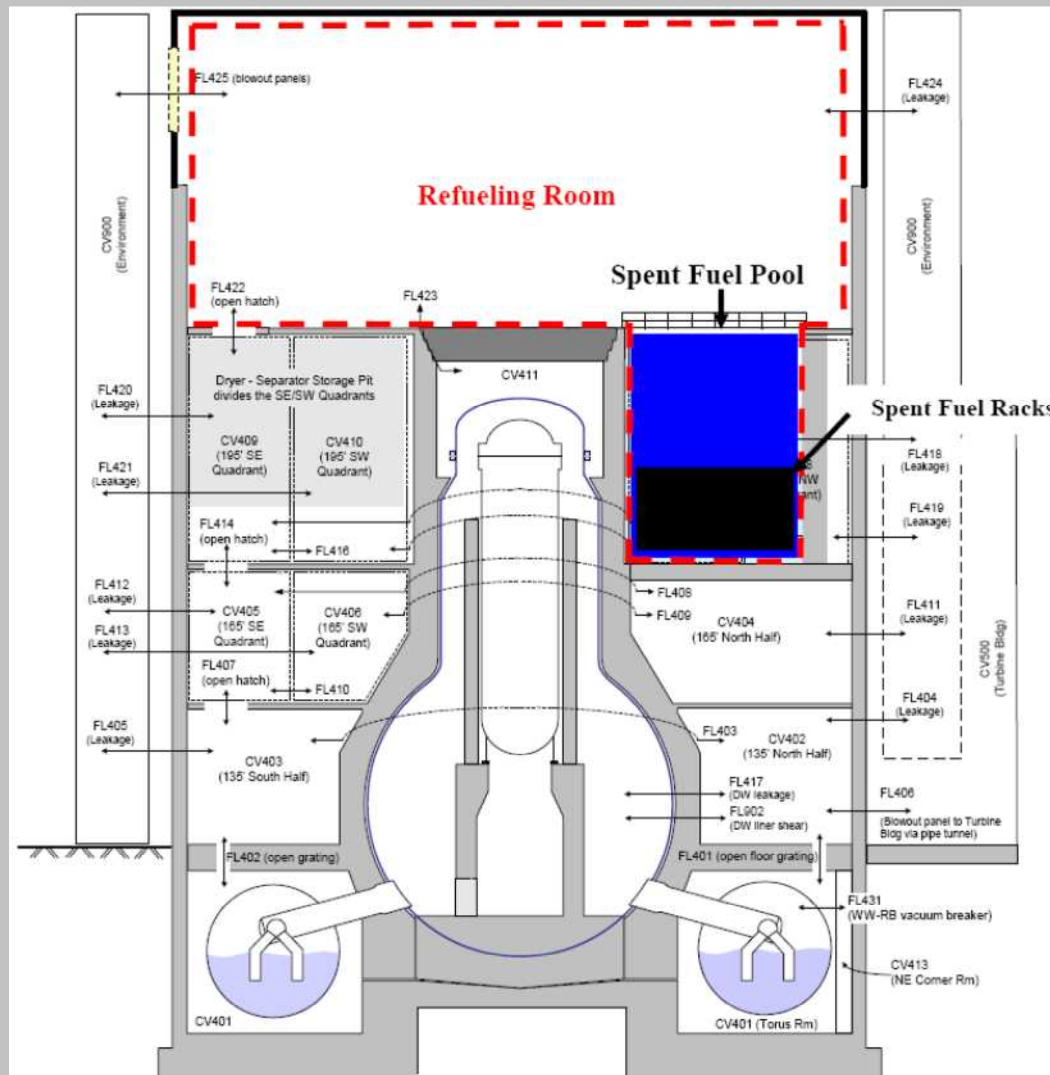
Unit 3 Hydrogen Explosion in Reactor Building at 68 hours

Original source NHK News Japan

Unit 3 Reactor Building

Water Spray/Injection into Spent Fuel Pools

BWR Spent Fuel Pool



Unit 4 Spent Fuel Pool (1 of 2)

- Reactor in Unit 4 was completely de-fueled for maintenance
- All fuel offloaded to spent fuel pool
  - Youngest (hottest fuel was 105 days)
  - Decay heat level was ~2 to 2.5 MW
- Reactor building was devastated by violent explosion on Tuesday March 15 at ~6:10 am after Unit 2 reports loud noise from torus room (events assumed unrelated)
  - Unlike Units 1 and 3, there is no actual video of Unit 4 explosion
  - Explosion was 3.5 days after earthquake

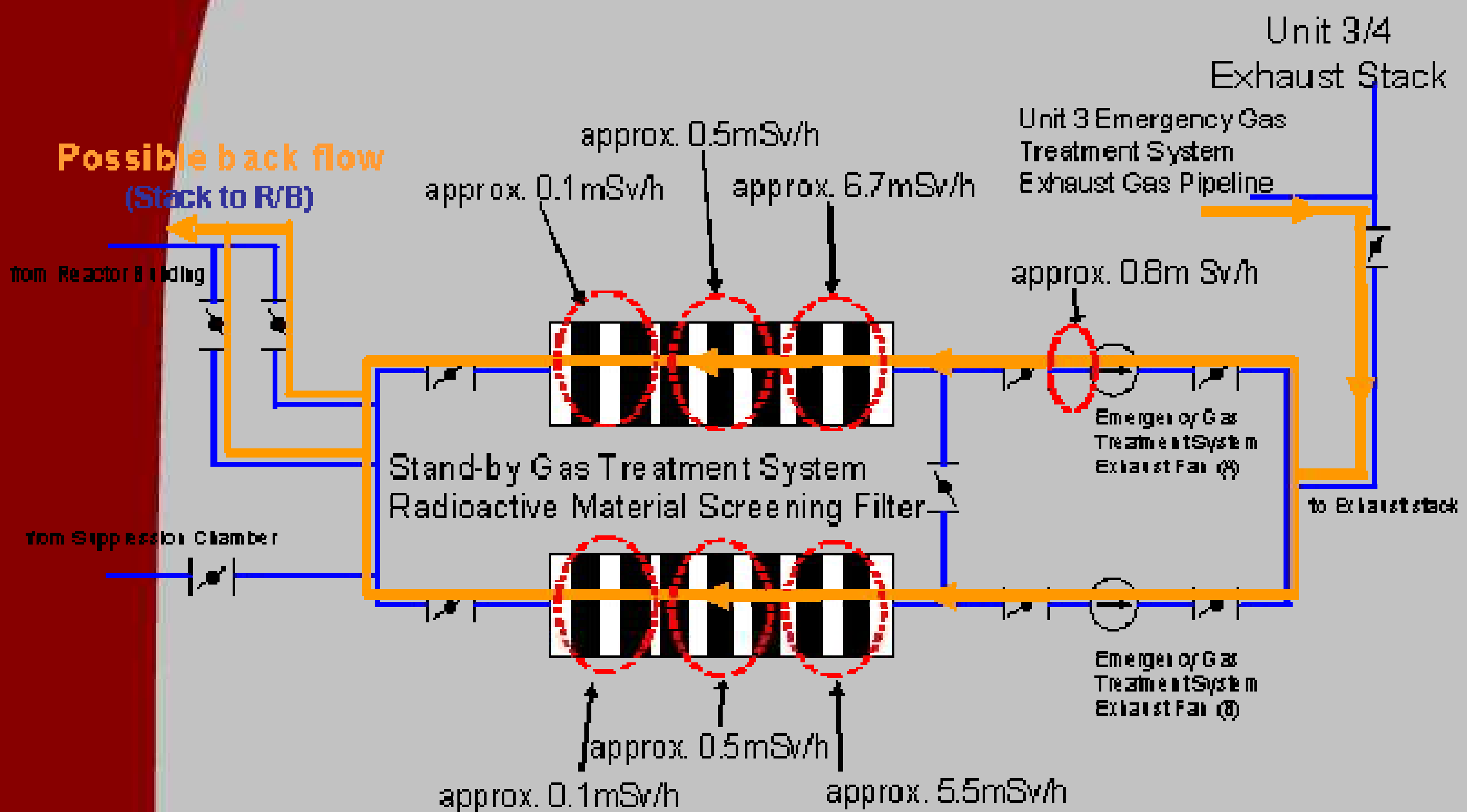
Unit 4 Spent Fuel Pool (2 of 2)

- It was feared that the pool had boiled dry and Zr-steam reaction produced H_2 that subsequently exploded
- Such conditions seemed difficult to imagine without significant water loss
- MELCOR analyses employed to evaluate draindown scenario
- Release of large amount of Cs-137 (little I-131) would have occurred

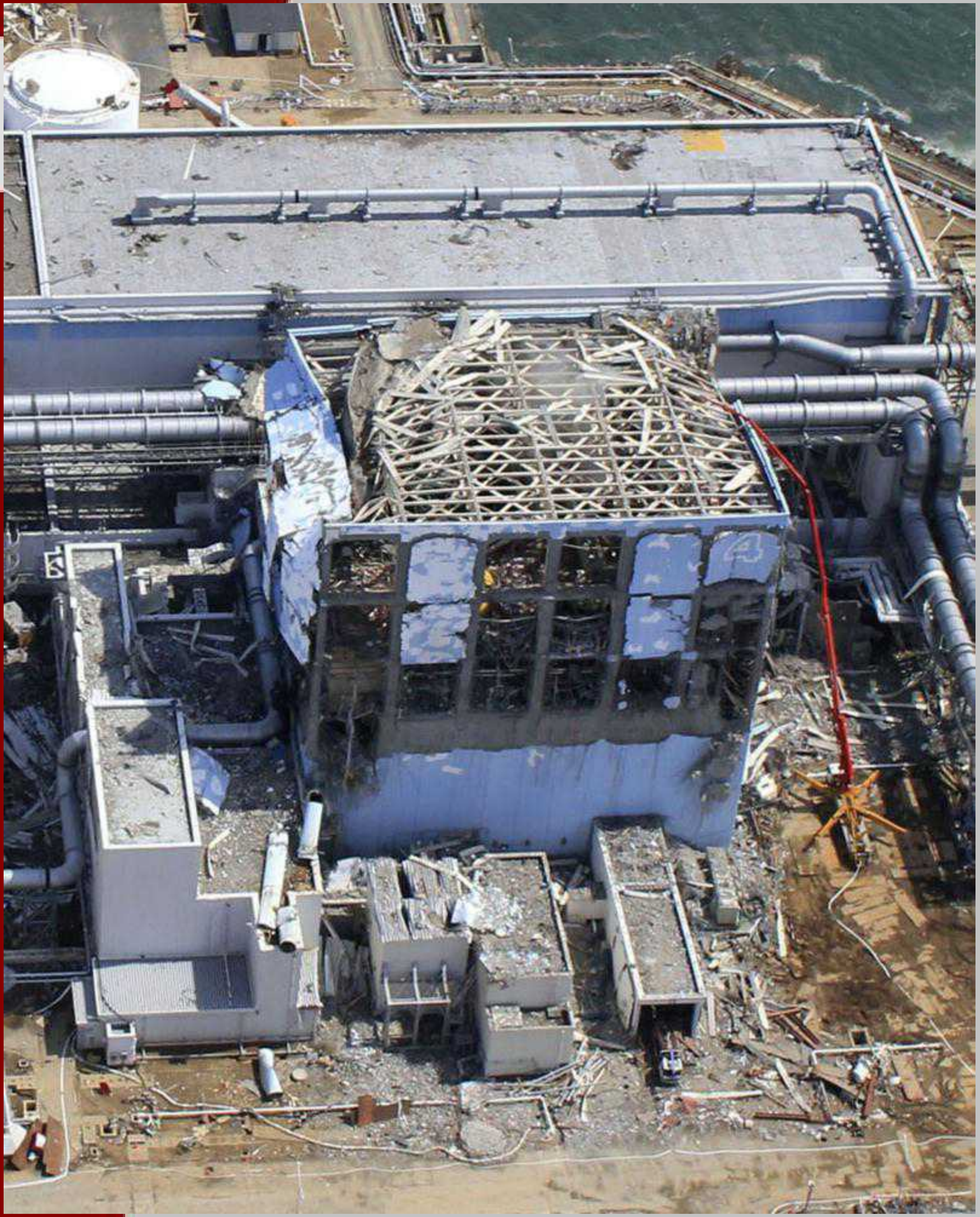
Video from Unit 4 Spent Fuel Pool

Common Off-gas Ducts 1F3-1F4
Source of H2 from Unit 3 Accident?

Evidence of Hydrogen Flow from Unit 3 to Unit 4



Damage to Unit 4



Unit 3 Spent Fuel Pool Damage

- Concrete and steel from building destruction fell onto pool
- Radioactivity level in Unit 3 pool much higher than Unit 2
- Isotopic measurement of Cs-137, I-131 and Cs-134 suggests
  - Some damage to stored fuel (Cs-134/Cs137)
  - Some contamination from the reactor accident(s) (Cs/I)

Video from Unit 3 Spent Fuel Pool

Accident Chronology – Summary (1 of 2)

- Isolated from external heat sink with internal sinks depleted, Emergency Operation Procedures (EOPs) for depressurization and low pressure injection was not successful
  - Response time for lost power, water or cooling was too long to help
  - Low pressure injection inadequate to recover cores
  - Fire trucks in use at unit 1 when needed at another unit
- Severe accidents were not avoided in any case
  - Mitigation not so successful – Effectiveness of Emergency Operation Procedures (EOPs) and Severe Accident Mitigation Guidelines (SAMGs) should be evaluated
  - Traditional SAMG recommendations to add water aggravate fission produce release from damaged containments
  - Nevertheless, releases are believed to be not massive (~1% per reactor)

Accident Chronology – Summary (2 of 2)

- Plant data measurements were inadequate to manage post accident controls
  - Few pressures and temperatures and unreliable, unreliable water levels measurements for vessel, containment and wetwell, degrading instruments
- Response to accident was at times ad hoc
- Responders at times were unfamiliar with severe accidents
- Systems and responses invented on the fly as needed
  - Sometimes no good solutions are available
- Much to be learned – more vigilance and advanced planning is needed

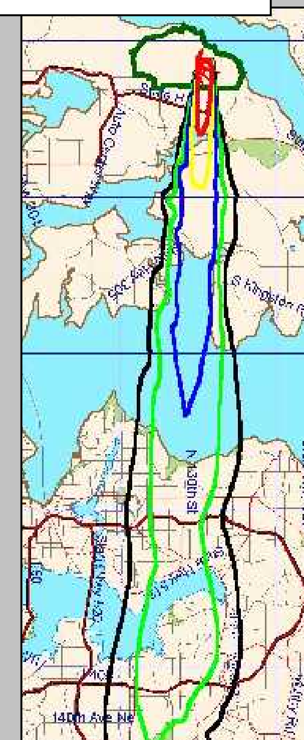
U.S. Department of Energy (U.S. DOE) Consequence Management Support

- Assist the Federal, State, Local, Tribal and foreign governments in protecting the health and well being of their citizens:
  - Estimate/determine the radionuclide source term
  - Provide initial predictions (data products) using atmospheric dispersion models and source term estimates
  - Verify, validate and update predictions based on ground monitoring data, fixed wing surveys and laboratory analysis data
  - Provide comprehensive characterization of environmental and public impacts based on models and data
  - Predict radiation dose impacts over various time phases
  - Predict food contamination impacts
  - Comprehensive characterization of environmental and public impacts based on this data
  - Provide centralized point of contact for federal assets
  - Provide data to Decision Makers for public protection decisions

Consequence Management Assets

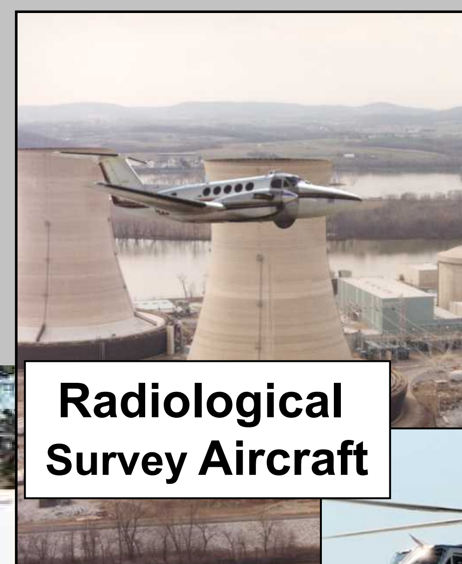
Data Analysis/ Management

Field Personnel



SNL & LLNL Models

Laboratory Personnel



Radiological Survey Aircraft

Mobile Laboratories

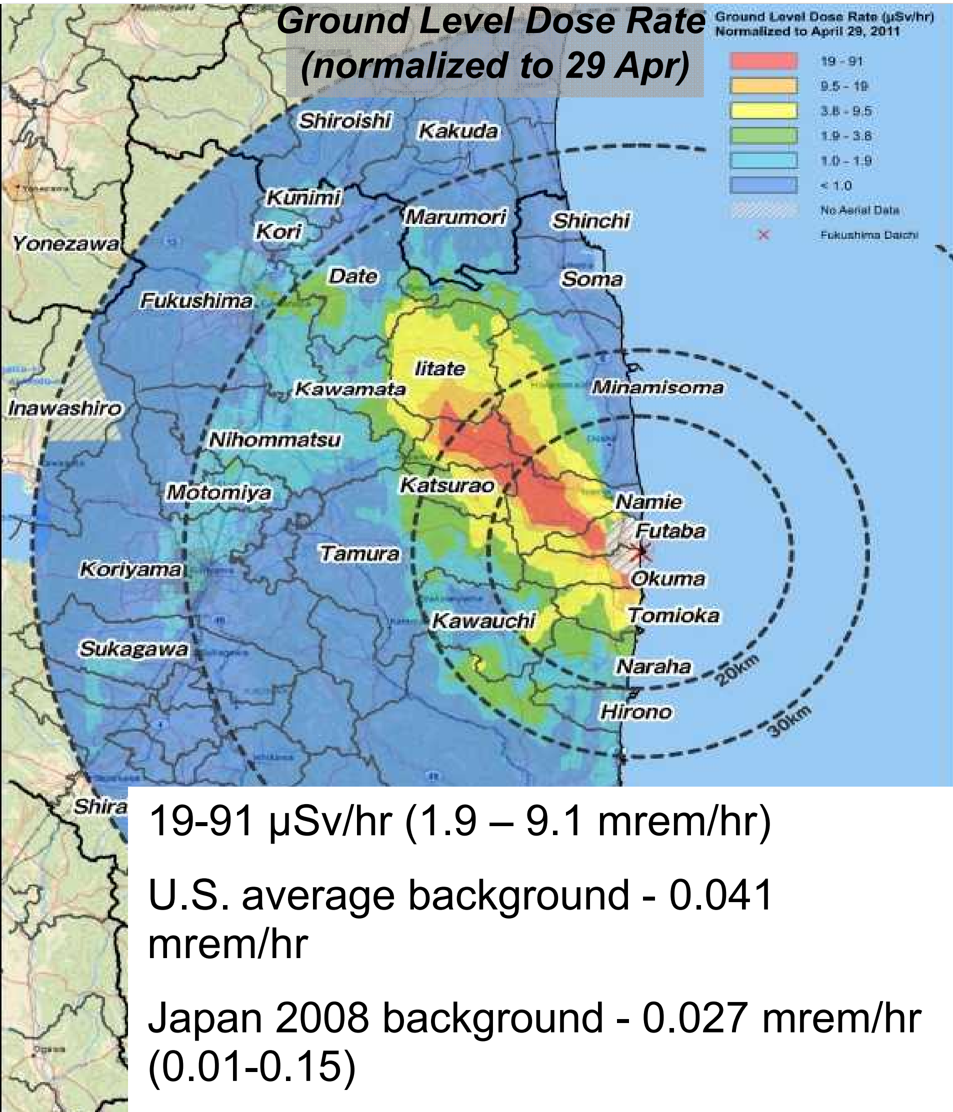
What Radionuclides and How Much Radioactivity was Released?

- Potential Source Terms
- 4 Boiling Water Reactors at risk
- 4 Spent Fuel Pools, holding spent fuel of various age, at risk
- Fuel
  - Low Enriched Uranium
  - Mixed Oxide (< 6% in Unit 3)
- Many different species of radionuclides produced by nuclear fission
  - Different half-lives (seconds to thousands of years)
  - Different radiations (alpha, beta, gamma)
- Difficult to determine the exact condition of reactors and spent fuel pools

Aerial Measuring Results
Joint US/Japan Survey Data

NNSA National Nuclear Security Administration

FUKUSHIMA DAIICHI
JAPAN

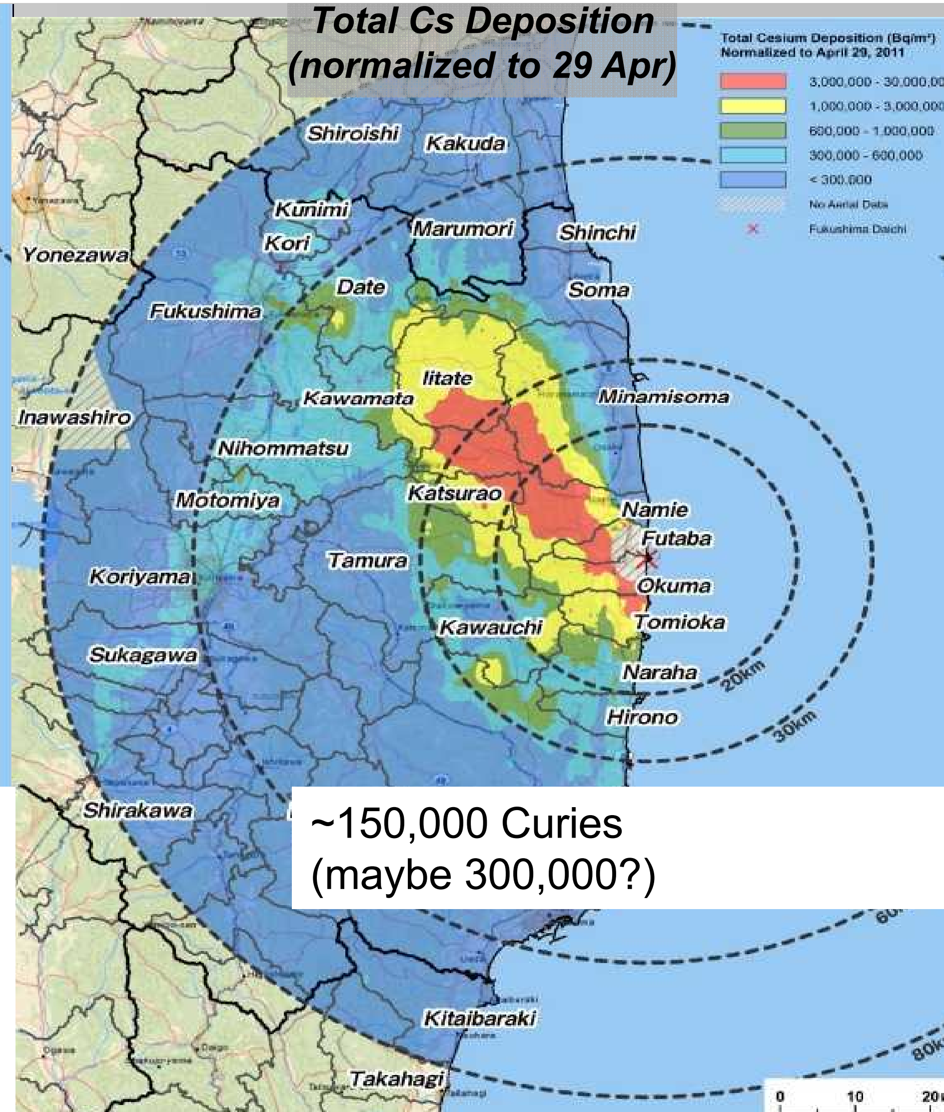


19-91 µSv/hr (1.9 – 9.1 mrem/hr)

U.S. average background - 0.041 mrem/hr

Japan 2008 background - 0.027 mrem/hr (0.01-0.15)

(UNSCEAR, 2008)



~150,000 Curies
(maybe 300,000?)

Field Monitoring Activities

What Was Done?

- Mobile monitoring
- In-situ measurements
- Exposure/dose rate measurements
- Air sampling
- Soil samples
- Swipe samples

Why?

- Calibrate Aerial Measurement System measurements
- Define radionuclide mixture
- Support radiological assessments
- Assess resuspension of deposited materials
- Assess migration of radionuclides

Summary of Activities

- > 620 air samples
- > 117 in-situ spectra
- > 141 soil samples

Confounding Factors (1 of 2)

- 15 hour time difference between teams in Japan and New Mexico.
- Japanese regulations were not understood
- Insufficient staffing led to burnout
- Massive amounts of data were available for review and assessment
- Management of data flow and communication (email) was very difficult
- It was difficult to get current data on the actual status (health) of the reactors
- Multiple releases occurred under varying weather (snow, rain, sunshine) and wind conditions
- Difficult to perform accurate radiological assessments for quite some time because the radionuclide mixture and released activities were not known

Confounding Factors (2 of 2)

- Command and Control was overwhelmed, everything was given top priority
- Leadership struggled to coordinate taskings and current status of Consequence Management assets at multiple laboratories in the U.S. and multiple locations in Japan
- The Consequence Management Home Team was put under a lot of pressure to produce assessments and data products too quickly, and therefore, Quality Assurance and Quality Control measures were not always adequate
- Rapidly changing wind and precipitation created complex dispersion patterns
- Complex terrain challenged models to predict and explain deposition patterns
- Rain and snow created complex deposition patterns
- Many different individuals and agencies were making their own predictions

Continuing Consequence Management Activities

- U.S. Air Force Japan and Japanese governments to continue monitoring activities as needed
- Japanese trained and equipped to fly U.S. DOE Aerial Measurement System
- Japanese equipped with an enhanced laboratory analysis capability
- U.S. Air Force Japan trained and equipped to fly contingency Aerial Management System
- U.S. DOE continues to support Japanese and U.S. Air Force Japan from Home Team
- Additional radiological assessments

Countermeasures for Japanese Nuclear Power Stations (1 of 4)

- Make stations safer against a tsunami by preventing flooding at the site and inside buildings
- Take multiple and diverse measures to protect the cooling function
- Lead reactors to cold shutdown reliably and safely even under conditions similar to those that occurred at Fukushima

Countermeasures for Japanese Nuclear Power Stations (2 of 4)

- Measures to prevent to flooding on site
  - New and higher reinforced concrete sea walls to withstand earthquakes and tsunamis
  - Intake water ponds for sea water overflow
  - Protection walls inside the sea walls to protect pumps outdoors ponds
  - Emergency Sea Water Cooling System with pump installed inside a water tight building
  - Intake water ponds connected by sea water tunnel to provide multiple sources of cooling water for emergency pump

Countermeasures for Japanese Nuclear Power Stations (3 of 4)

- Measures to prevent flooding inside reactor buildings
  - Double structures for large cargo receiving docks
  - New structures with waterproof doors in outside walls of reactor buildings that enhance pressure resistance and waterproofing
  - Install new water-tight doors, reinforce existing ones for basement equipment rooms
  - Other measures to further enhance waterproofing

Countermeasures for Japanese Nuclear Power Stations (4 of 4)

- Multiple alternative means for emergency measures to ensure cooling function and lead reactors to cold shutdown
  - Emergency generators on building roof tops, spare storage batteries, multi-power supplies if battery power is depleted
  - Gas turbine generators, fuel tanks, and power equipment with waterproof power cables outside reactor building on high ground
  - Alternative means of water injection by makeup water pumps powered by gas turbine generators and emergency generators
  - Direct injection of water into the reactor by portable power pumps
  - New water tanks on high ground
  - Remote pressure venting and nitrogen cylinders for manual venting
  - Replacement sea water pumps in emergency supply warehouse on high ground
  - Heavy equipment deployed to remove debris on site roads
  - Restoration of external site power and recovery of cooling function

Recovery at Unit-1

After hydrogen burn

Now

Questions?