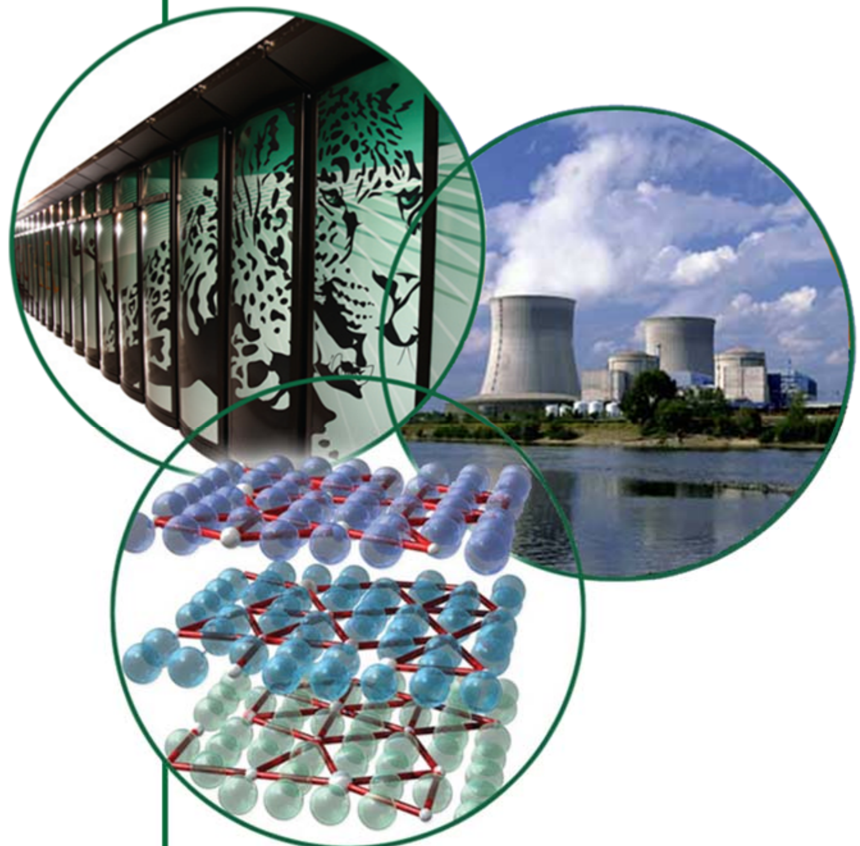
Response of the Fukushima Dai-ichi Nuclear Plant to the March 11, 2011 Earthquake in Japan



Dr. George Flanagan

Oak Ridge National Laboratory

Presented to the EERI/NEC Meeting

April 12, 2012

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

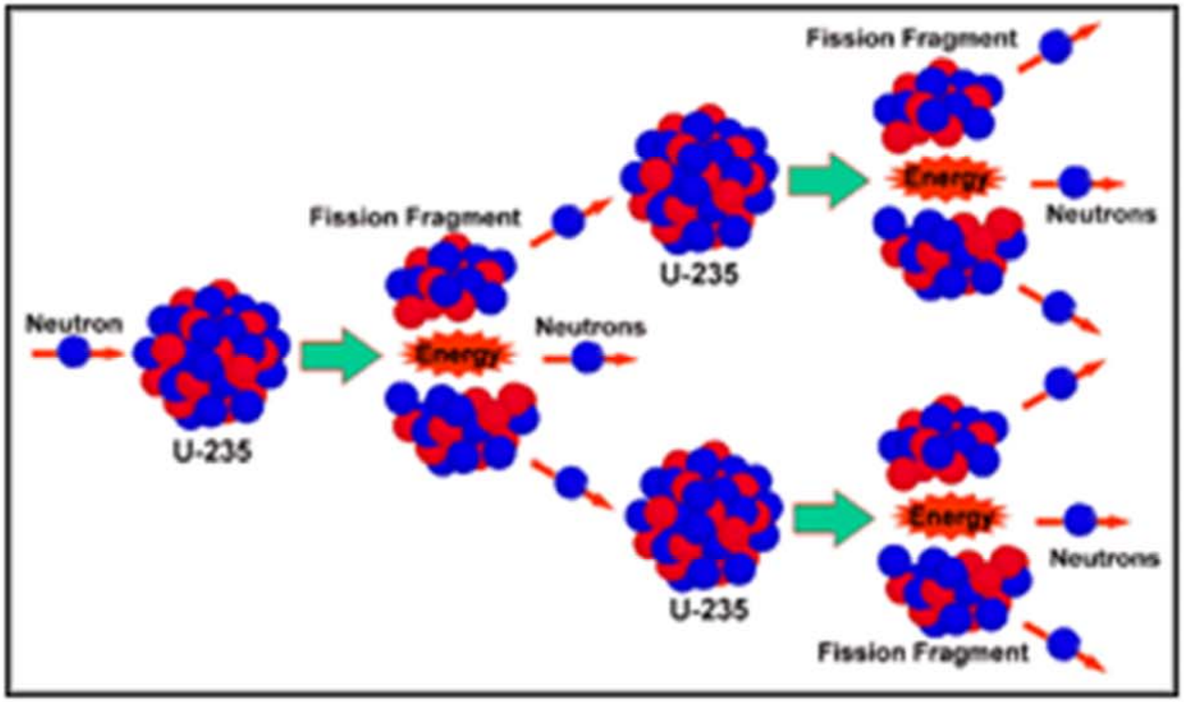
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Presentation Outline

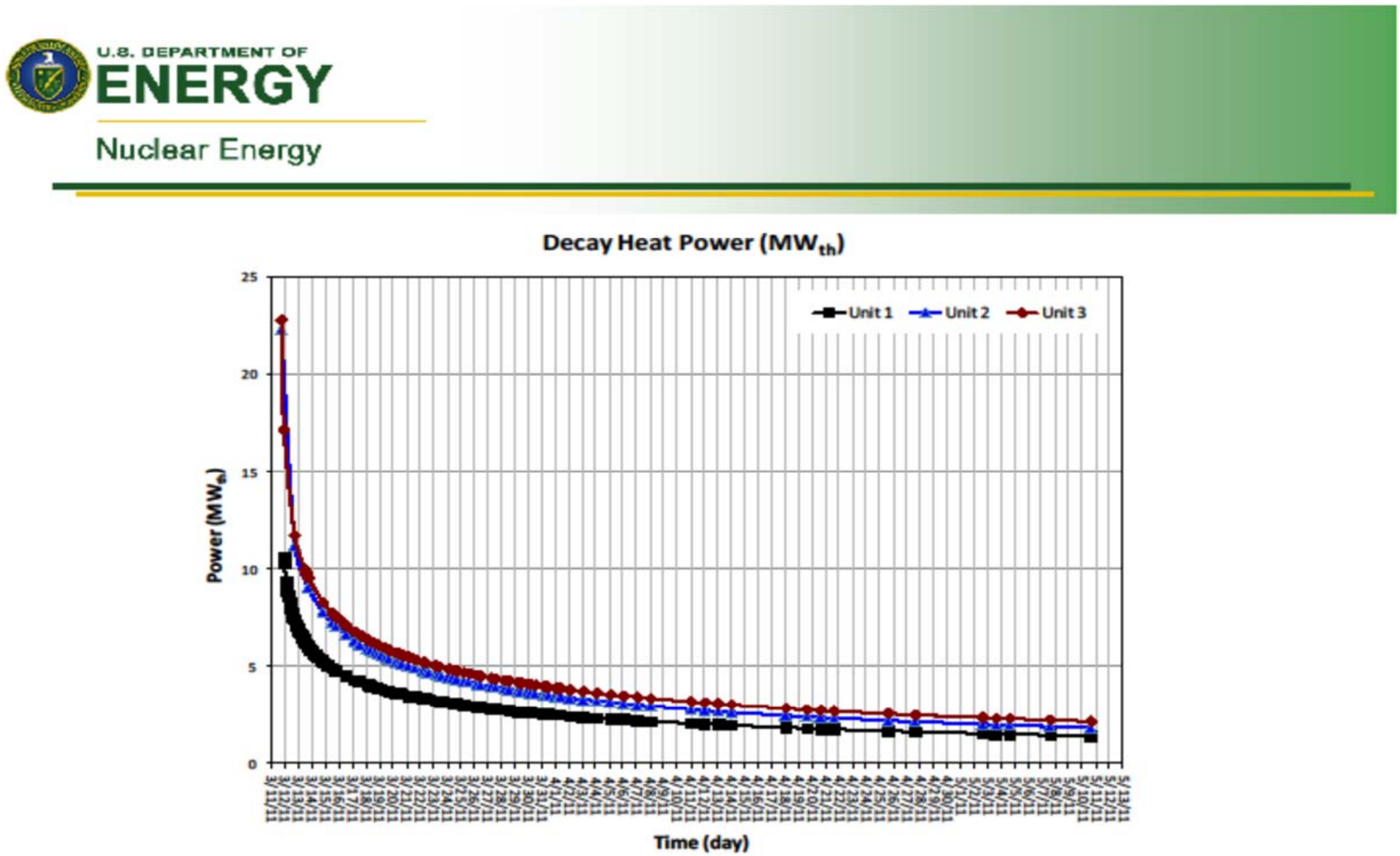
- Basic Reactor Physics and Boiling-Water Design
- Sequence of Events
- Consequences and Mitigation
- Conclusions and Lessons Learned

Basic Reactor Physics
and
Boiling-Water Reactor (BWR) Design

Fission Results in the Production of Energy, Neutrons, and Fission Fragments (Products) — Which are Highly Radioactive

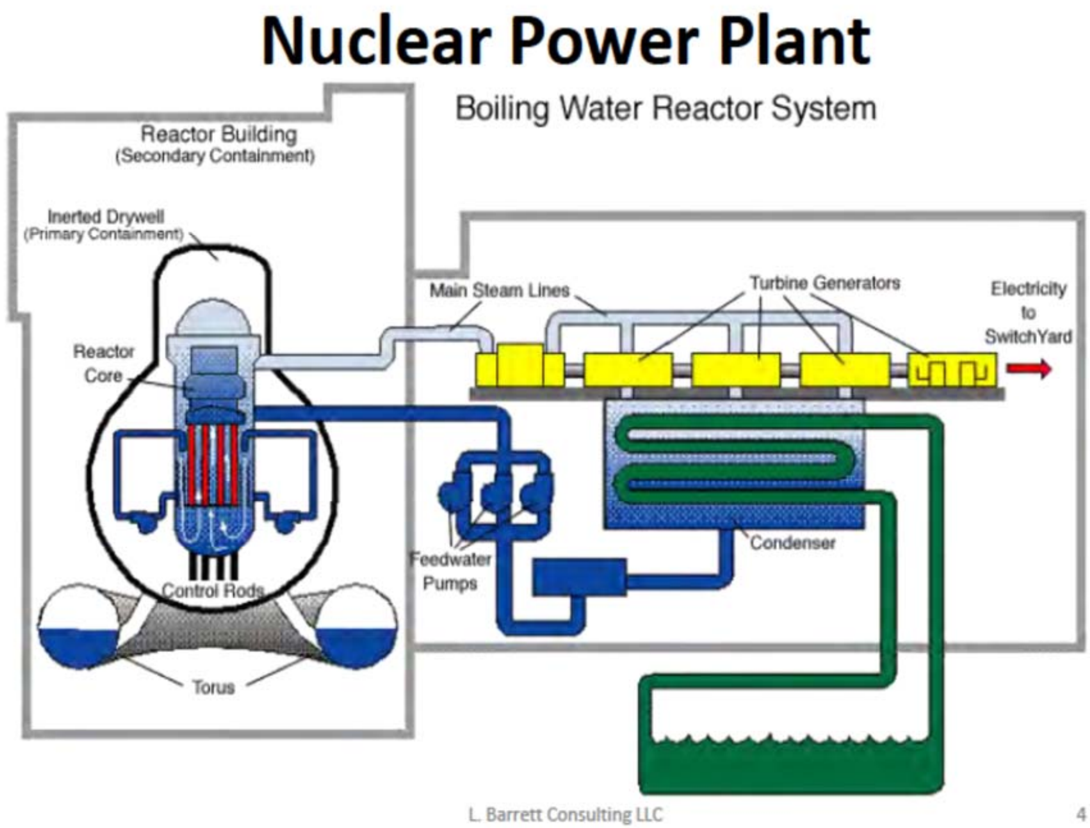


After a Reactor is Shutdown — Heat is Still Generated Because of the Decay of the Radioactive Fission Products (Fragments)

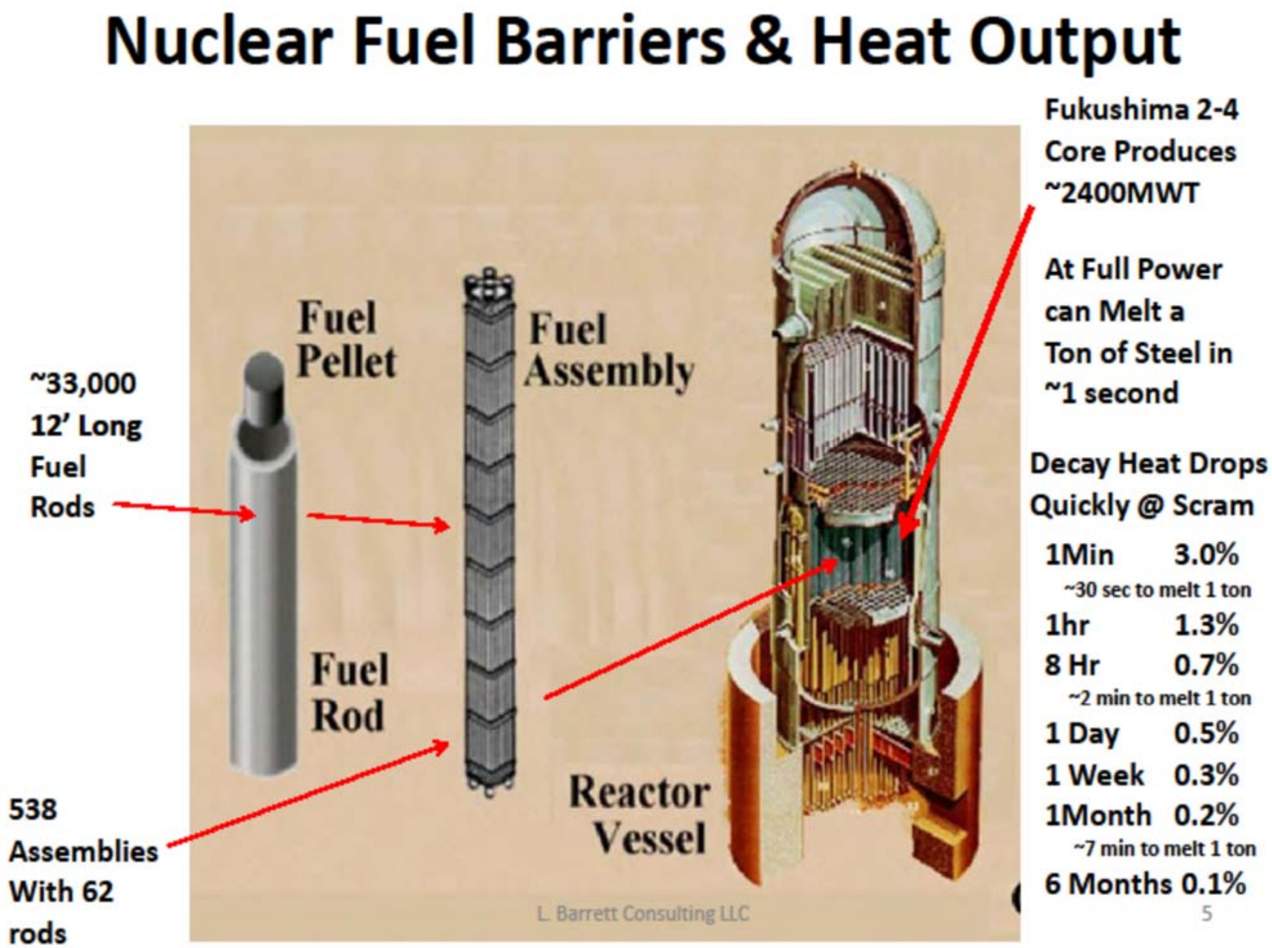


Boiling-Water Reactor (BWR) Uses Nuclear Heat to Boil Water to Create Steam to Produce Electricity

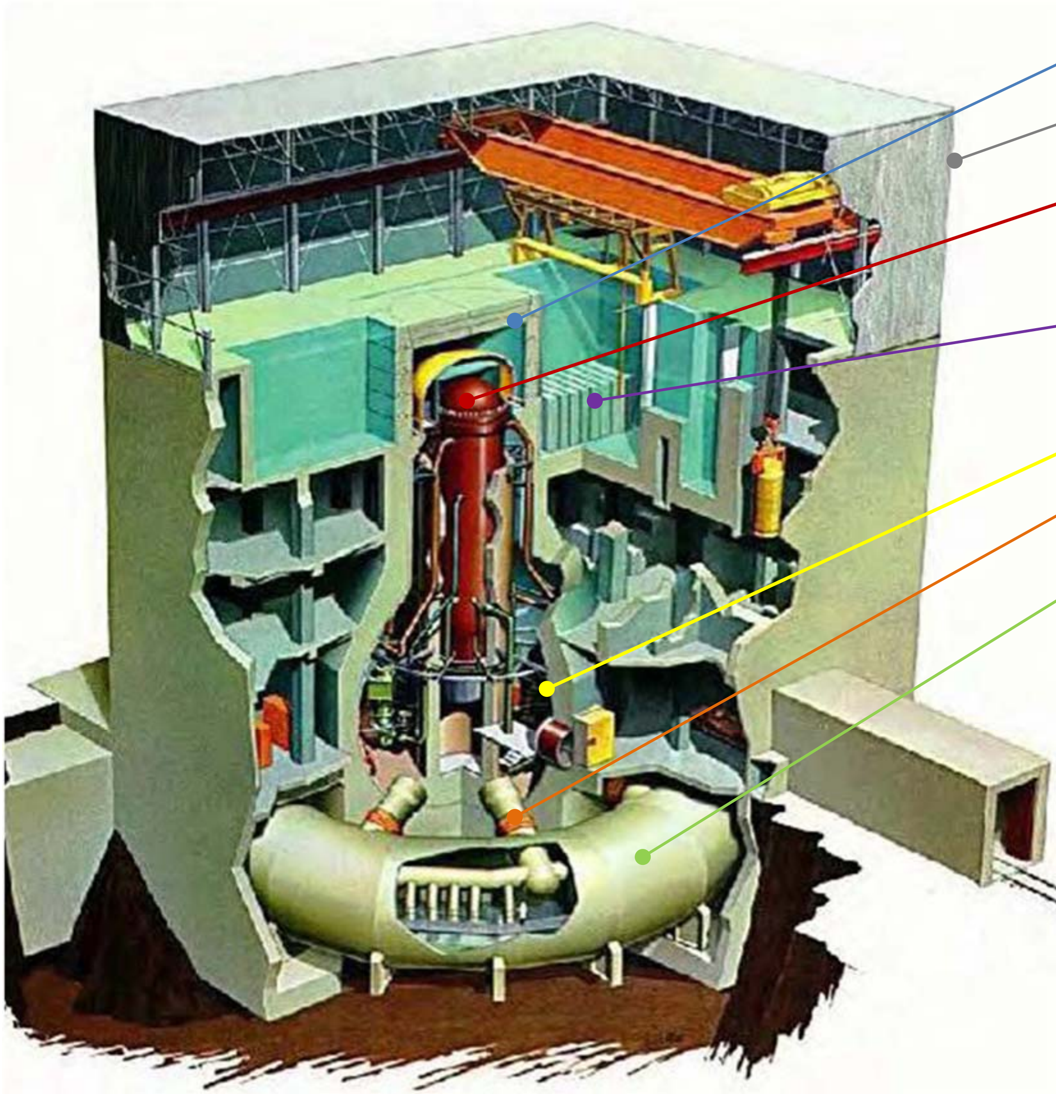
Courtesy of NEXTERA Energy



Nuclear Plants are Designed With Many Barriers to Prevent Release of Radioactive Material Resulting from Fission



Mark 1 Boiling-Water Reactor Containment Design



Courtesy of TVA

GE BWR Mark 1 Containment

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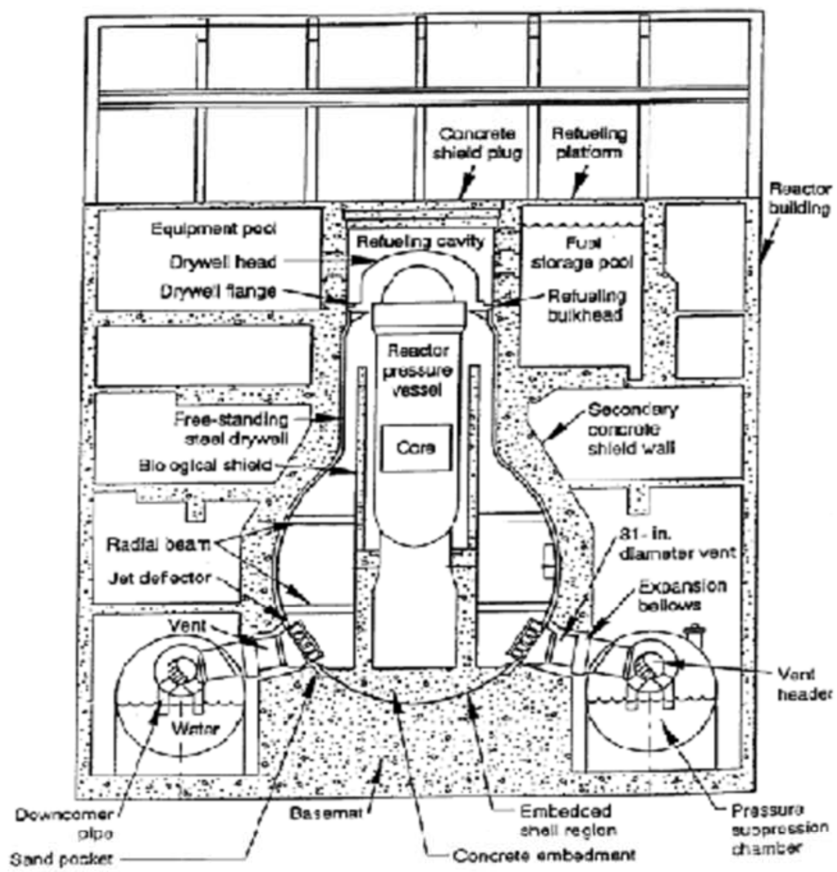


Briefing on Fukus

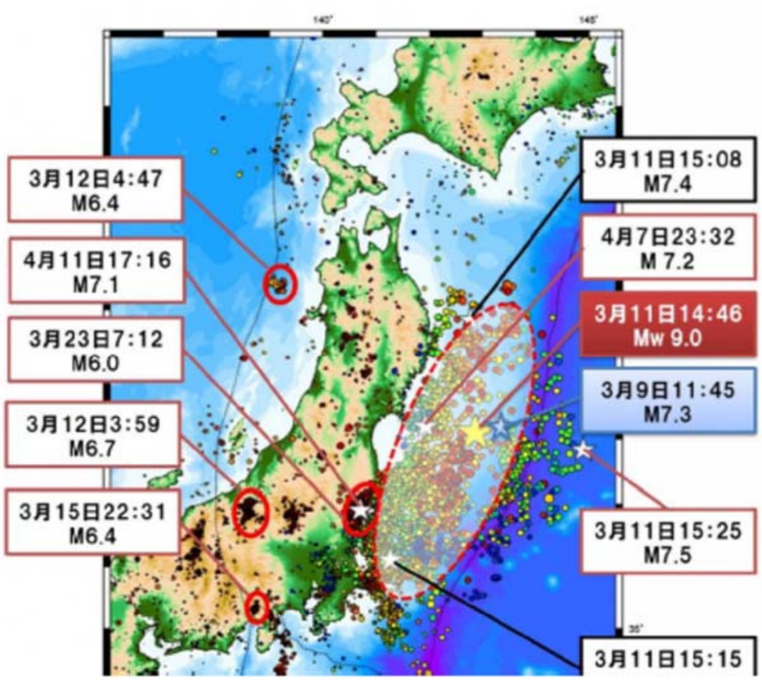
Figure 20. Mark I General Electric,GE BWR Containment.

Myung-Hyun Kim

Sequence of Events

9.0 Earthquake Occurs off the Coast of Japan at 2:46 P.M., March 11, 2011

3.11 Earthquake and aftershocks



Statement by the Headquarter for Earthquake Research, *11March2011*

The Earthquake Research Committee evaluated earthquake motion and tsunami for the individual region off-shore of Miyagi prefecture, to the east off-shore south of Sanriku along the trench, and to the south off-shore of Ibaraki prefecture, but occurrence of the earthquake that is linked to all of these regions is "out of hypothesis".

[SOURCE] http://www.jishin.go.jp/main/index-e.html The 2011 off the Pacific Coast of Tohoku Earthquake

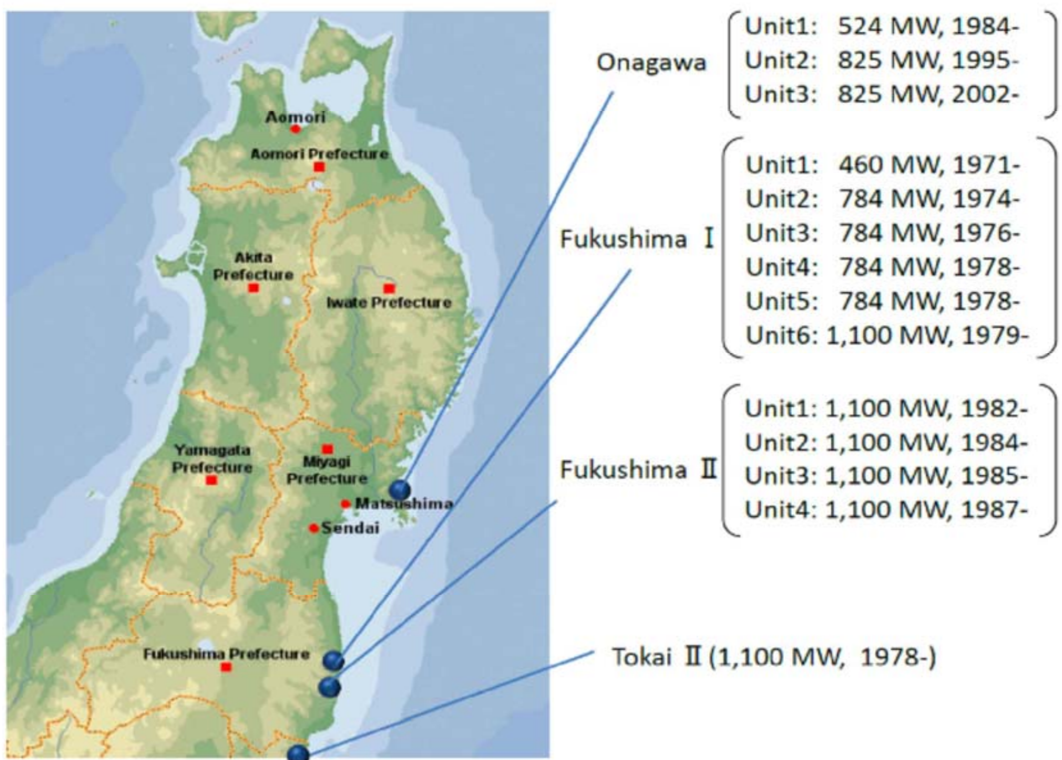
http://outreach.eri.u-tokyo.ac.jp/eqvolc/201103_tohoku/eng/#mesonet

"Earthquake Research Institute, University of Tokyo, Prof. Takashi Furumura and Project Researcher Takuto Maeda"

3

Earthquake/Tsunami Affected 14 Plants on the Eastern Coast of Japan

14 NPPs along the coastal line affected by Tsunami



Courtesy of TEPCO

Some Units of Fukushima 1 (Dai-ichi) were in Operation at the Time of Earthquake

- Units 1–3 were operating at full power
- Unit 4 was defueled (entire core stored in spent fuel pool)
- Units 5–6 in a refueling outage

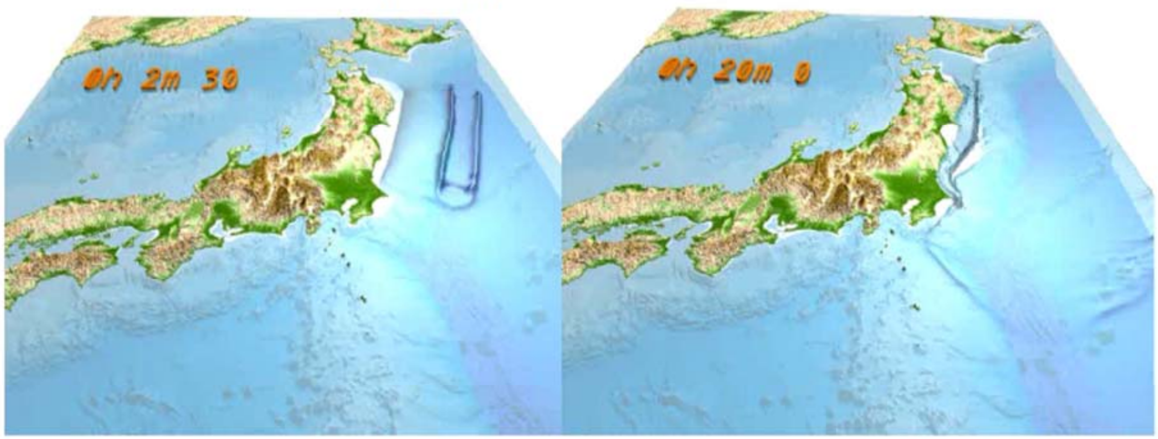
Nuclear Plant Safety Features Perform as Designed Until the Tsunami Hits

3.11 Tsunami

1F1-3 Plant response immediately after the earthquake

14.46 Earthquake followed by Reactor SCRAM,
LOOP, EDGs start, IC/RCIC in operation

15.38-41 Tsunami followed by complete (AC/DC) blackout
and (mostly) isolation from the Ultimate Heat Sink



http://outreach.eri.u-tokyo.ac.jp/eqvolc/201103_tohoku/eng/#mesonet

"Earthquake Research Institute, University of Tokyo, Prof. Takashi Furumura and Project Researcher Takuto Maeda"

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Horizontal E-W Acceleration Exceeded the Seismic Design on Units 2, 3, and 5

Seismic Observed Data

Comparison between Basic Earthquake Ground Motion and the record of intensity

Observation Point (The lowest basement of reactor buildings)		Observed data (*interim) Maximum Response Acceleration (gal)			Maximum Response Acceleration against Basic Earthquake Ground Motion (Gal)		
		Horizontal (N-S)	Horizontal (E-W)	Vertical	Horizontal (N-S)	Horizontal (E-W)	Vertical
Fukushima Daiichi	Unit 1	460※2	447※2	258※2	487	489	412
	Unit 2	348※2	550※2	302※2	441	438	420
	Unit 3	322※2	507※2	231※2	449	441	429
	Unit 4	281※2	319※2	200※2	447	445	422
	Unit 5	311※2	548※2	256※2	452	452	427
	Unit 6	298※2	444※2	244	445	448	415
Fukushima Daini	Unit 1	254	230※2	305	434	434	512
	Unit 2	243	196※2	232※2	428	429	504
	Unit 3	277※2	216※2	208※2	428	430	504
	Unit 4	210※2	205※2	288※2	415	415	504

*1: The data above is interim and is subject to change.
*2: The recording time was about 130-150 seconds

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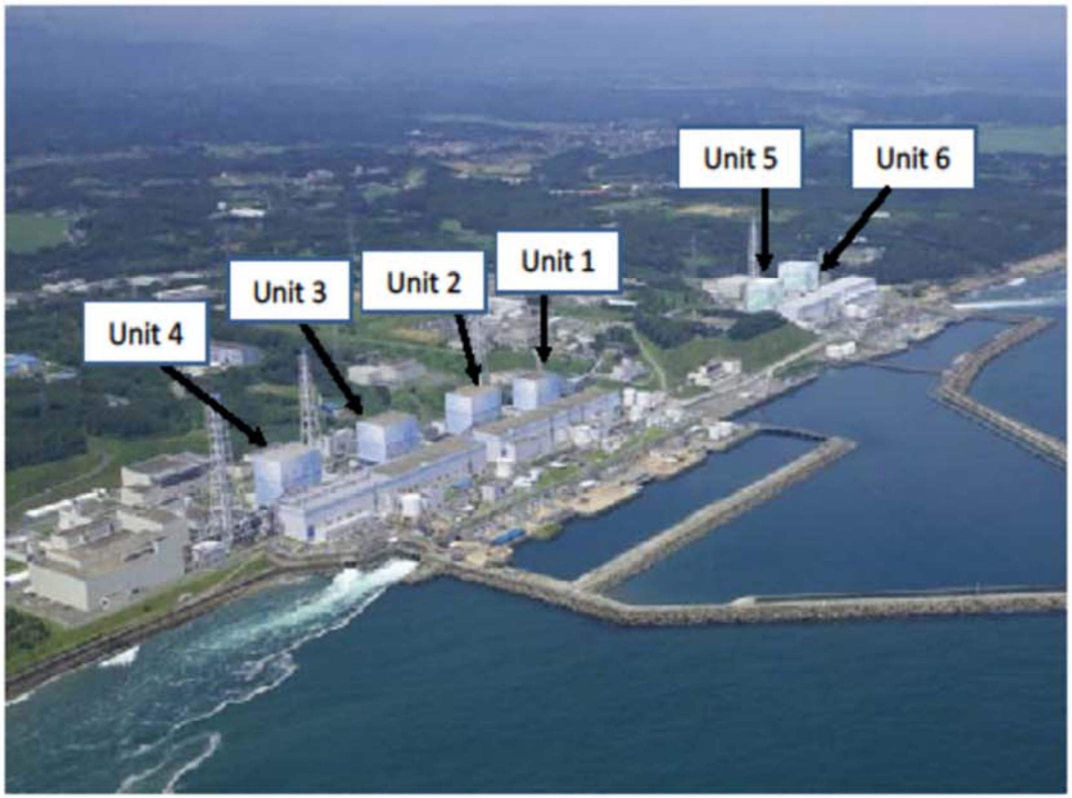
Damage at Switchyard at Fukushima Dai-ichi NPS

[275kV air blast breaker: completely destroyed]

2. Outline of Fukushima Dai-ichi NPS



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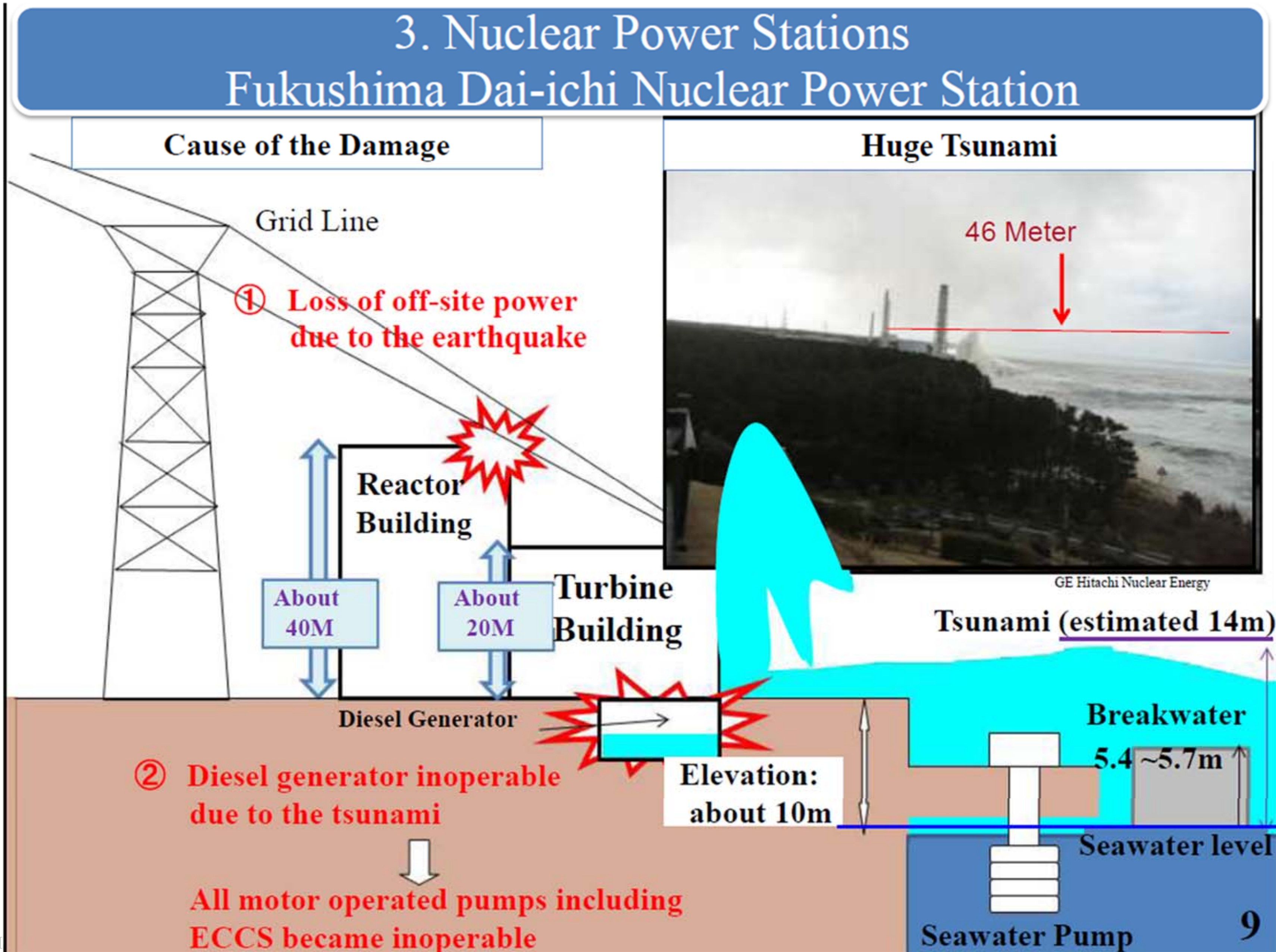
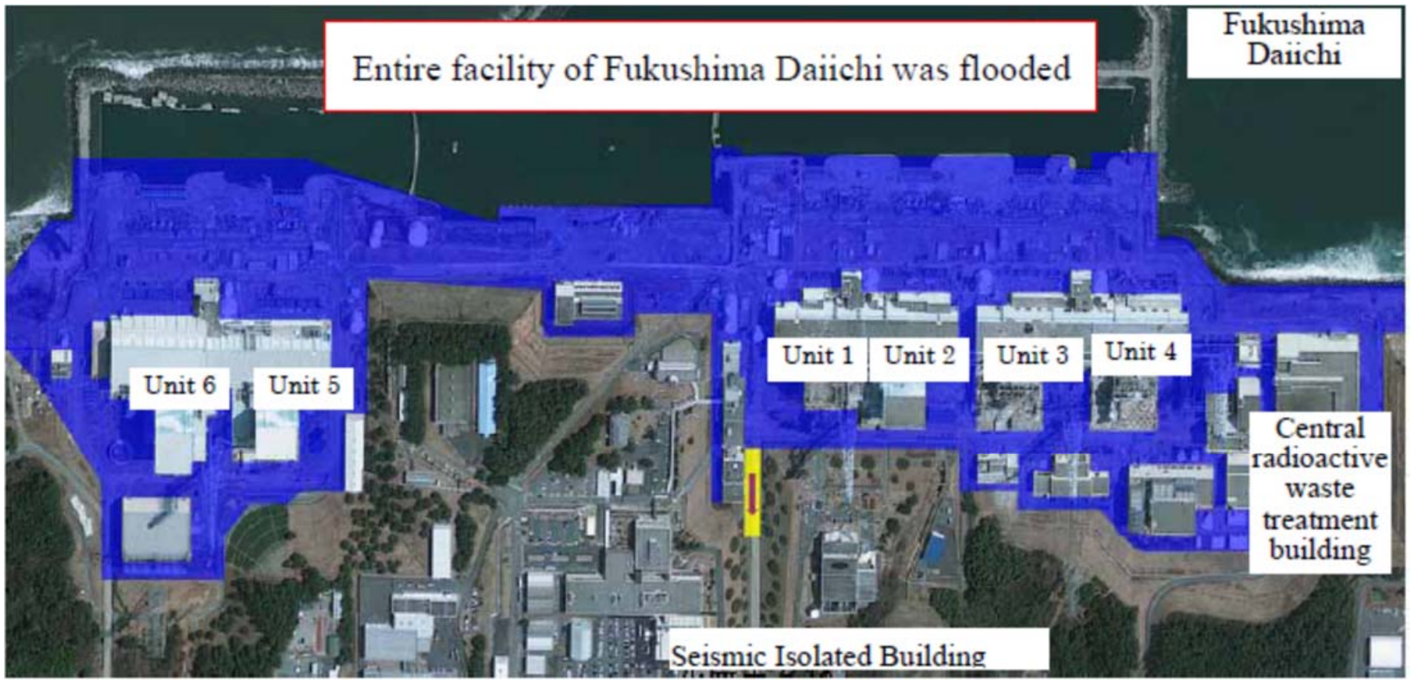
Courtesy of TEPCO

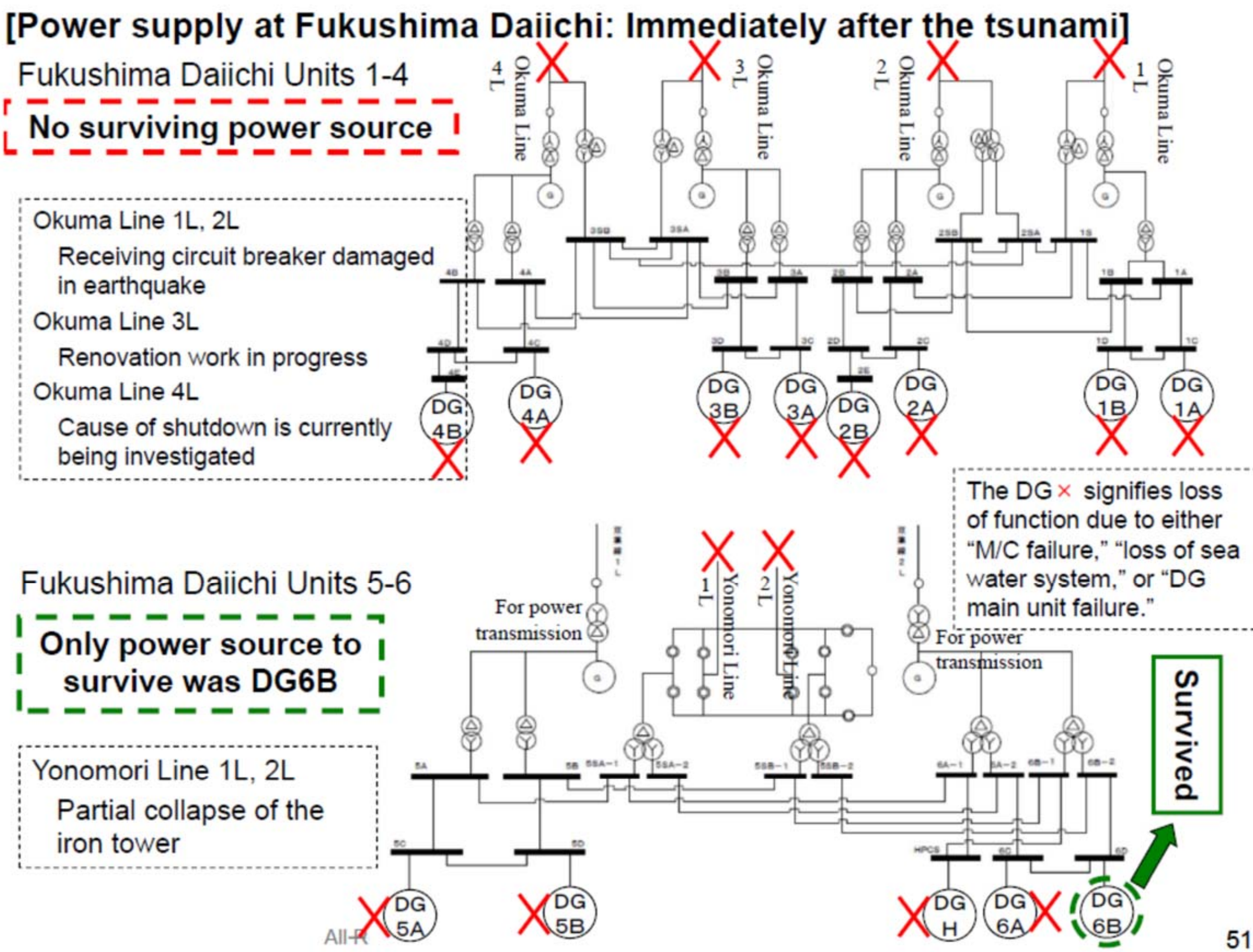
Tsunami Waves (47 feet) Hit Fukushima 1 Plant About 1 Hour After the Earthquake


3. Nuclear Power Stations
Fukushima Dai-ichi Nuclear Power Station
Cause of the Damage
Huge Tsunami
Grid Line
① Loss of off-site power
due to the earthquake
46 Meter
Reactor
Building
About
40M
About
20M
Turbine
Building
GE Hitachi Nuclear Energy
Tsunami (estimated 14m)
Diesel Generator
Breakwater
5.4 ~5.7m
② Diesel generator inoperable
due to the tsunami
Elevation:
about 10m
Seawater level
All motor operated pumps including
ECCS became inoperable
Seawater Pump
9

Nearly all the Dai-ichi Site was Flooded



Only One Diesel Generator Survived at Dai-ichi



for the U.S. Department of Energy

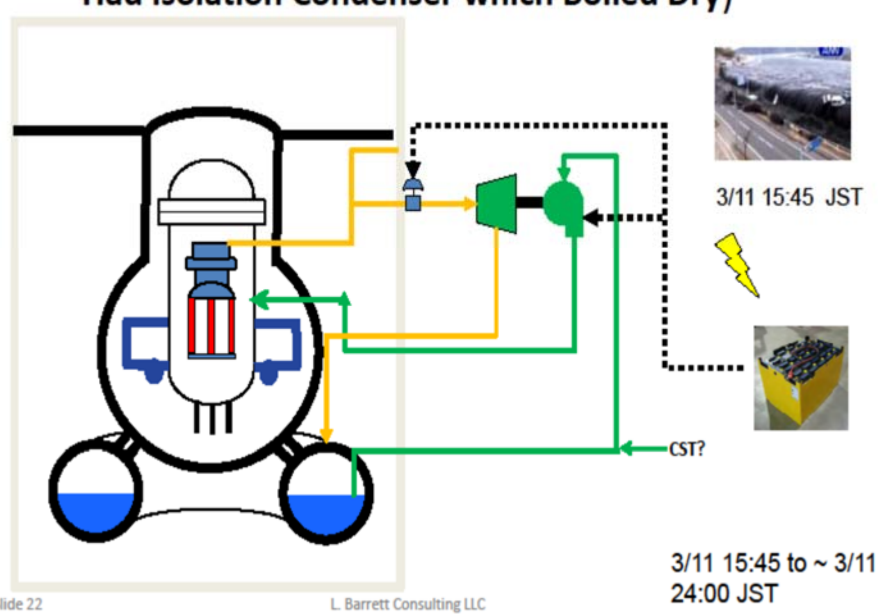
EERI/NEC April 12,2012

OAK RIDGE National Laboratory

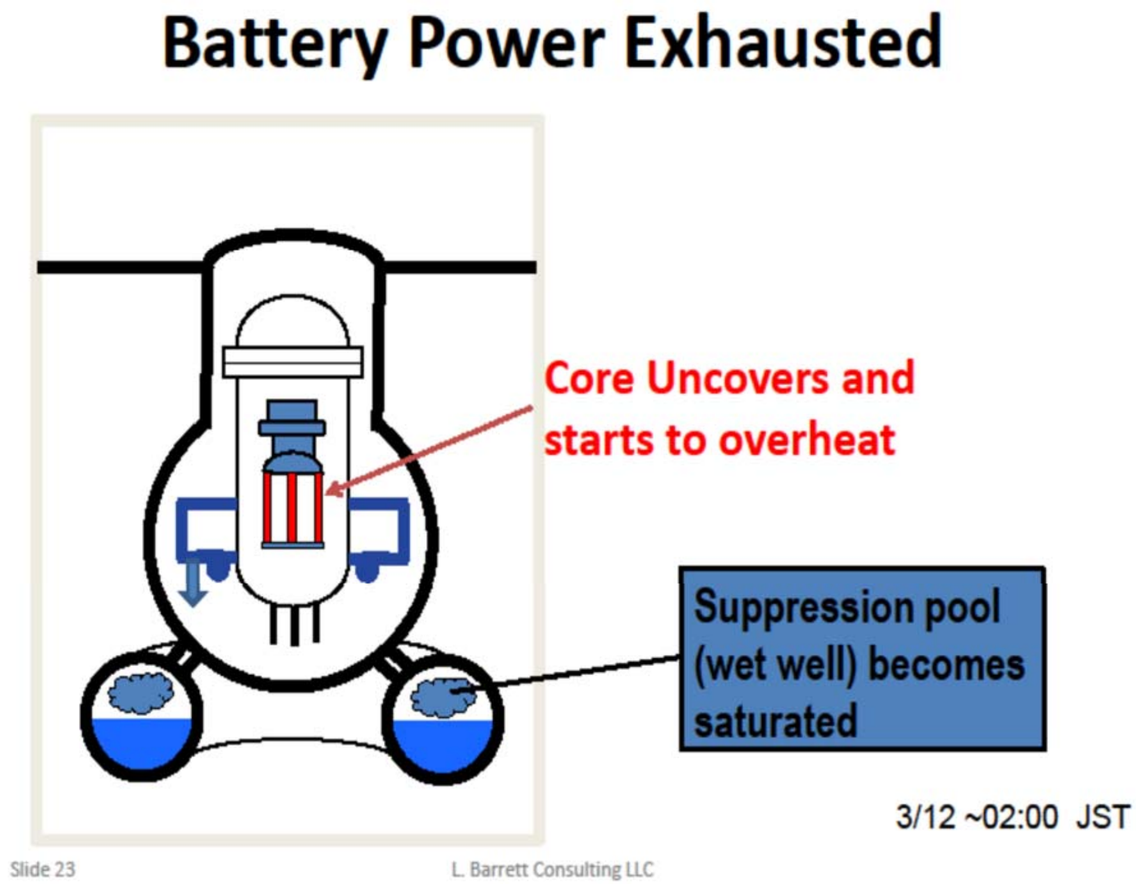
Earthquake Resulted in Loss of Offsite Power/Tsunami Resulted in Loss of All Onsite AC Power (Except Unit 6)

- Emergency plant systems work as designed after earthquake
- Diesel generators were submerged by tsunami (Unit 1 batteries were submerged)
- Backup batteries were depleted after 8–10 hours

Battery Power Control of Steam-Driven Reactor Core Isolation Cooling System In Units 2 &3 (Unit 1 Had Isolation Condenser which Boiled Dry)



Loss of Battery Power Results in Loss of Ability to Remove Decay Heat From the Core



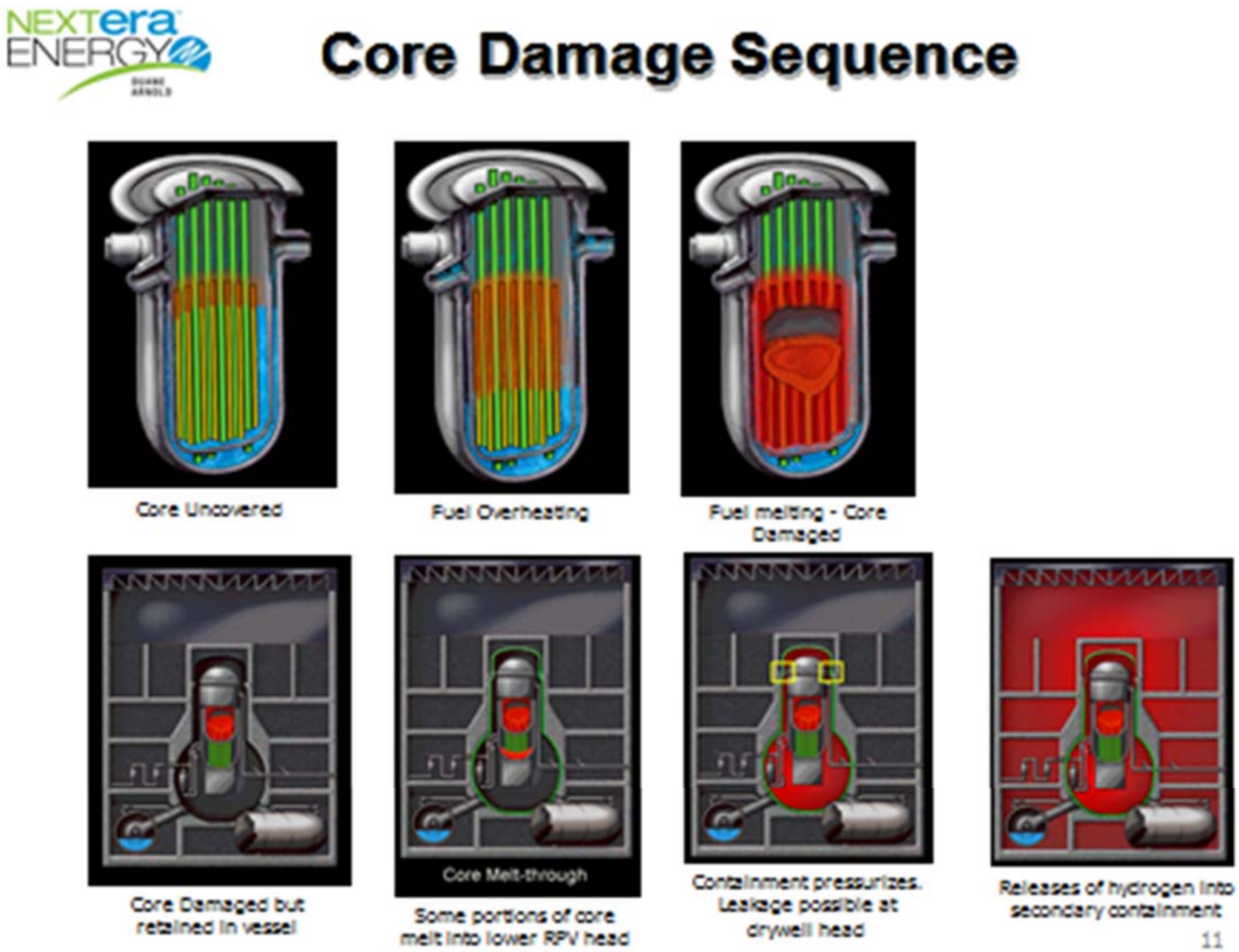
Loss of All AC/DC Power Prevented Use of Cooling and Venting Systems

1F1 Equipment status after the tsunami (equipment used for water injection to the reactor and PCV venting)

	Equipment name	Status	Damage status	Applied operations	Remarks (2F1)
Water injection equipment	High Pressure Coolant Injection system (HPCI)	×	Loss of power (oil pump)	–	O Timely water injection is possible using the MUWC
	Condensate and Feed Water System (FDW)	×	Water injection not possible due to isolation signal	–	
	Core Spray System (CS)	×	Power and sea water system loss	–	
	Shut down Cooling system (SHC)	×	Power and sea water system loss	–	
	Make Up Water Condensate (MUWC)	×	Loss of power, motor water damage	–	
	Fire Protection System (FP)	×	D/D FP* startup not possible	Fire engine used	
PCV Venting equipment	S/C vent valve Valve number: AO-1601-72	×	DC power loss/low air pressure	Temporary battery Temporary air compressor	O Valves can be operated when necessary
	S/C vent bypass valve Valve number: AO-1601-90	×	DC power loss/low air pressure		
	D/W vent valve Valve number: AO-1601-1	×	DC power loss/low air pressure		
	D/W vent bypass valve Valve number: AO-1601-83	×	DC power loss/low air pressure		
	PCV vent valve Valve number: MO-1601-210	×	Power loss	Manual operation	

Applied operations were required as the above-mentioned equipment could not immediately be used after the tsunami.

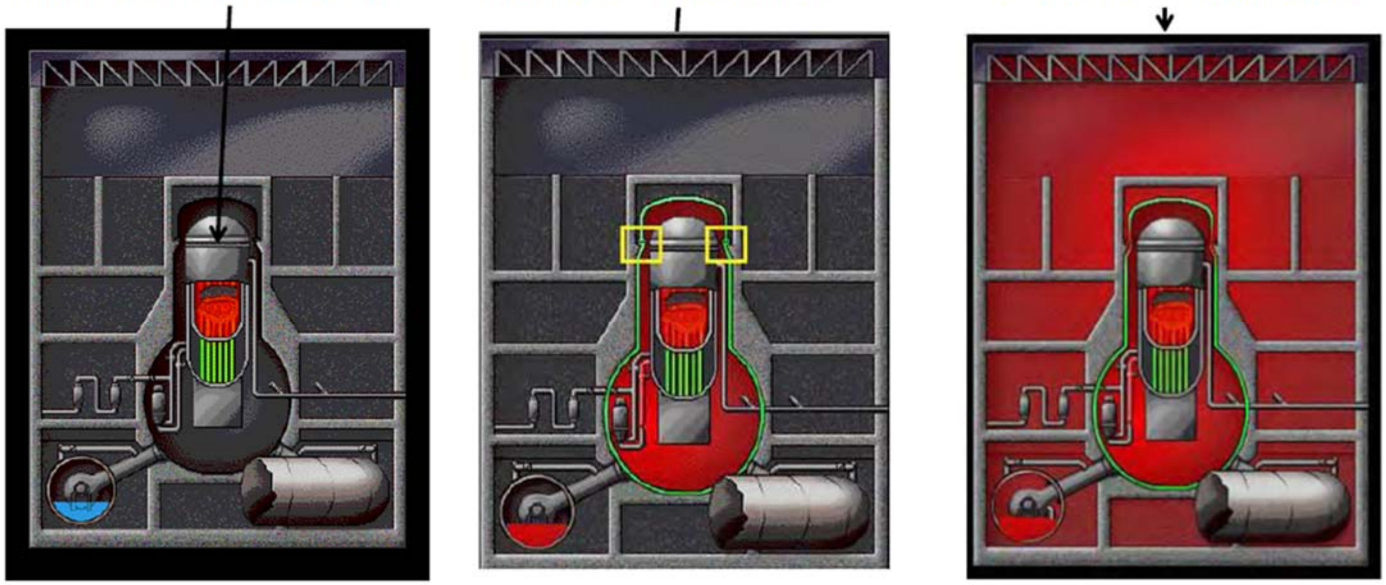
Possible Sequence Leading to Core Damage and Release of Hydrogen



Hydrogen Produced by Zr Clad Interacting with the Steam

Fukushima: Reactor Vessel-Primary-Secondary Containment Sequence

Primary Coolant System | Primary Containment | Secondary Containment



Core Over Heat
-Clad Burst ~900C
-Clad Oxidize ~1200C
-H2 Release
-Partial Melt~1800C-2700C
-Primary Coolant System Overpressure

Vent from Primary Coolant Sys to Primary Containment- H2, Steam, & Fission Products (Xe, Kr, I, Cs etc)

No Primary Containment Cooling therefore Primary Containment Overpressure-Vent to Secondary Containment

L. Barrett Consulting LLC 27

Overpressure of the Containment Resulted in Opening Leakage Pathways for Some Steam and Hydrogen to Enter the Reactor Building—Bypassing the Vent Lines

- Resulted in explosive mixture of hydrogen gas to accumulate in the reactor buildings of Units 1 and 3
- A panel was removed from Unit 2 to vent the building
- A fire and explosion occurred in Unit 4 (reactor was defueled)
  - Thought to be a result of uncovering of the spent fuel
    - Appears this was not the case
    - Cause of Unit 4 explosion is now thought to be from hydrogen generated in Unit 3 being carried into Unit 4 through a shared vent line

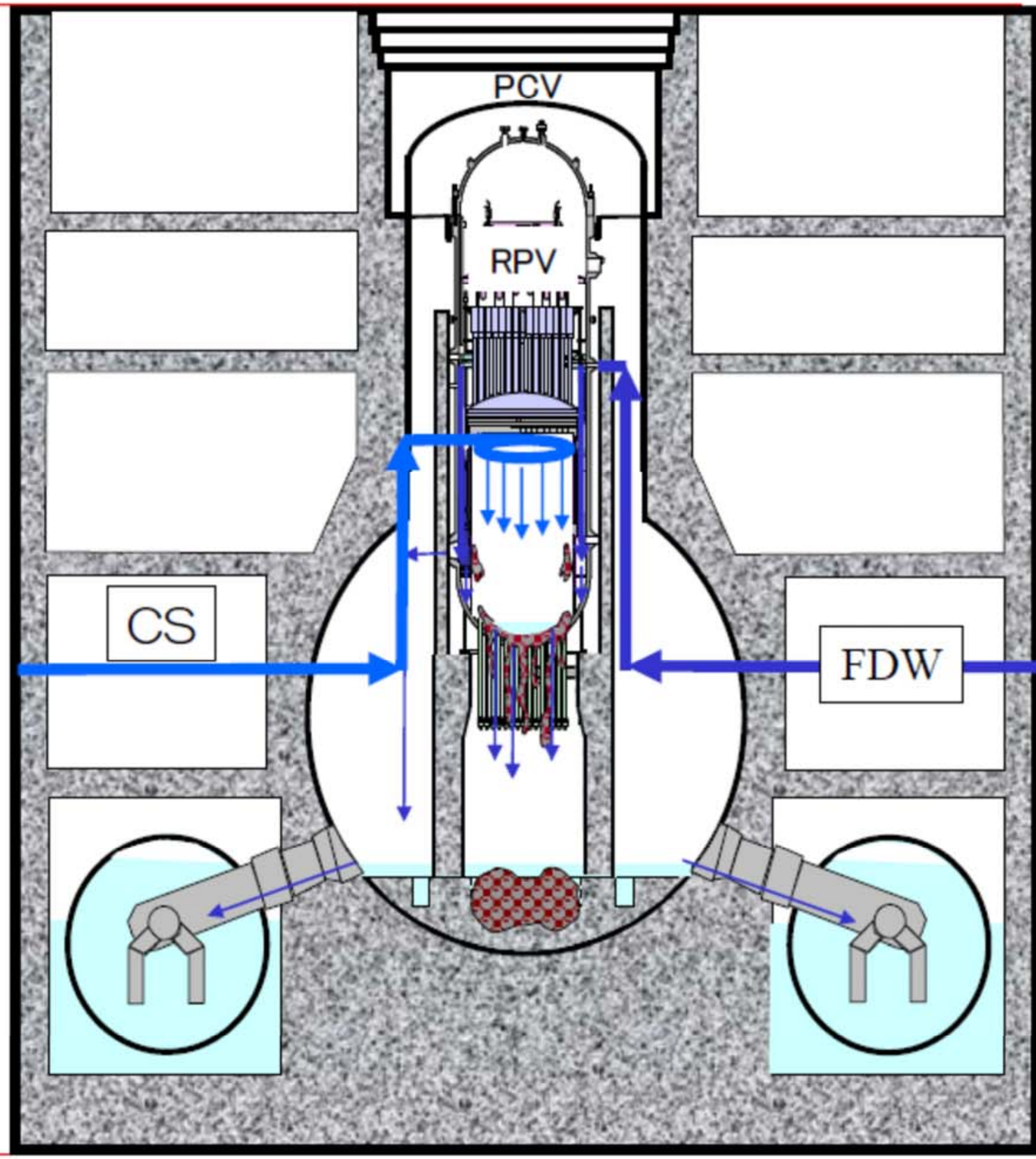
Result was an Explosion in Units 1 and 3 Destroying Parts of the Reactor Buildings

Unit 1 **Unit 3**

Aftermath Destroyed the Secondary Containment, Some Vent Lines — Allowed Uncontrolled Release of Radioactivity to the Atmosphere, to the Site, and to Areas Surrounding the Site—Resulting in an Evacuation (20 km)

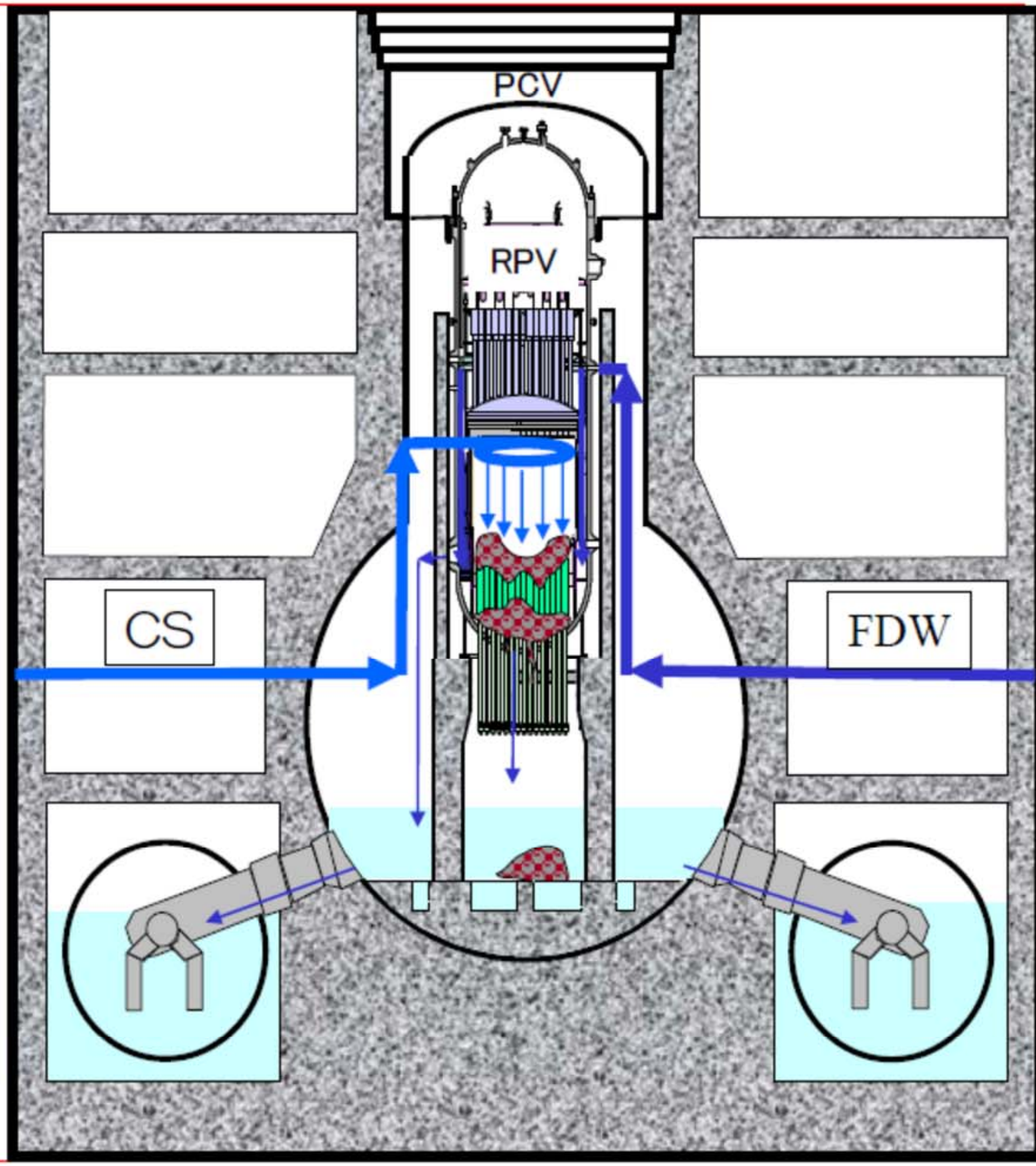
Presumption of reactor core statement (Unit 1)

- Almost no fuel was left at the original position, and completely moved downward after it melted.
- The moved fuel likely damaged PCV and assumed that most of it had dropped to the bottom. (Details for dropped fuel is unknown)
- Dropped fuel is assumed to have caused core concrete reaction.
- Therefore, it is evaluated that all the moved fuel is expected to be cooled directly by water injection. It is also evaluated that the core concrete reaction has been stopped.



Presumption of reactor core statement (Unit 2 and 3)

- There is a range in the evaluation result from "damaged fuel dropped to part of the bottom of PCV" to "Almost all the fuel is left inside RPV".
- If the part of damaged fuel were to have dropped to the bottom of PCV, it can be assumed that core concrete reaction was caused.
- Therefore, it is evaluated that all the moved fuel is expected to be cooled directly by water injection. It is also evaluated that the core concrete reaction has been stopped.



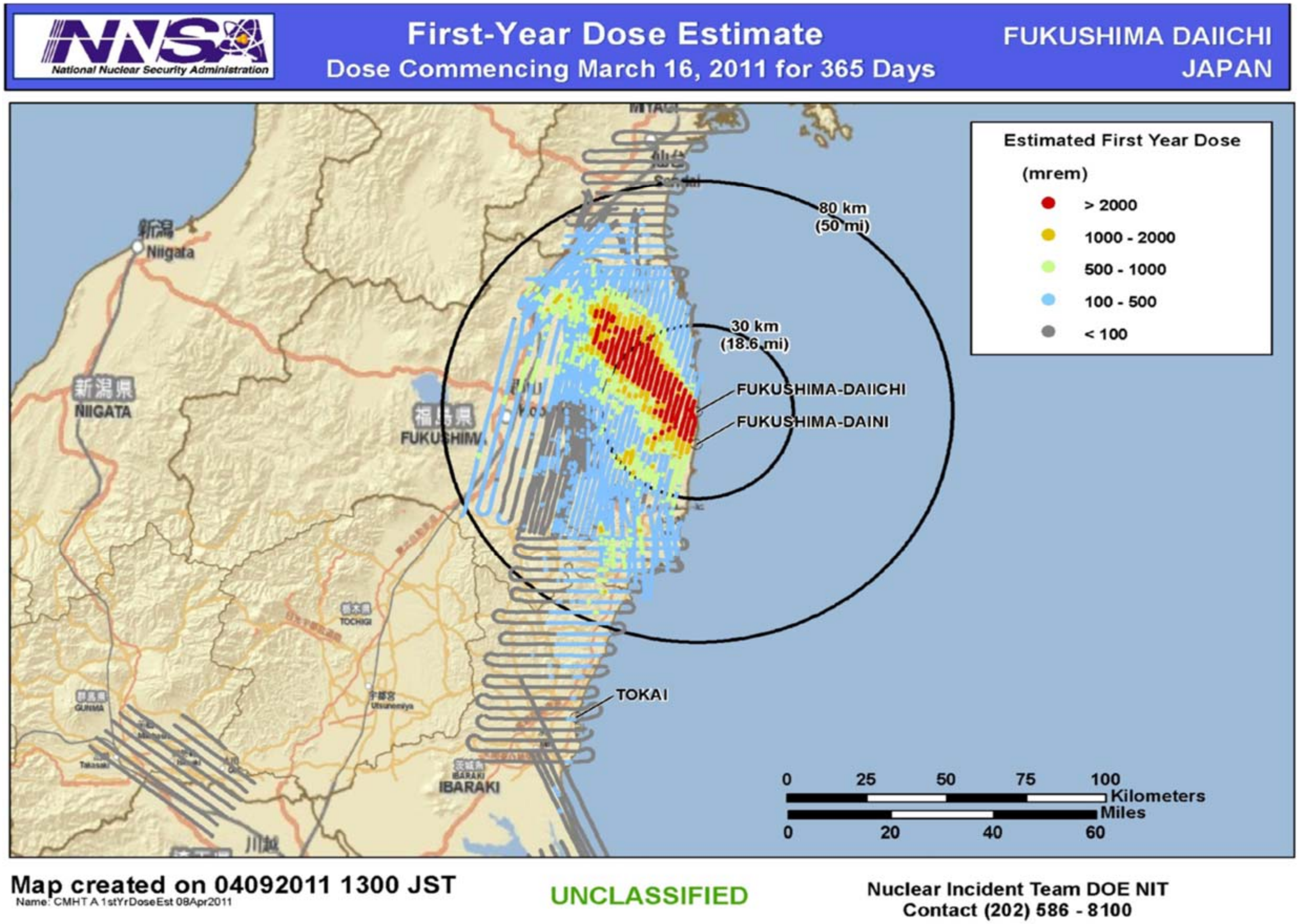
Consequences and Mitigation

Most of the Time Following the Accident the Wind was Blowing Toward the Se wpp3; However, There Were Times When the Winds Blew Toward the Northwest

- Resulted in a plume carrying radiation to drift inland
  - Mandatory evacuation ordered for 20 km around the plant
  - Area between 20–30 km asked to shelter in place and later advised to evacuate
    - Some areas in path of plume affected beyond 30 km
  - Over 70,000 inhabitants affected by evacuation

wpp3 On this slide, I would not try to make CAP each word--just make it read like a sentence
W. P. (Mike) Poore, 4/4/2012

Estimated Dose is About 10 Times Average Background (240 mrem)



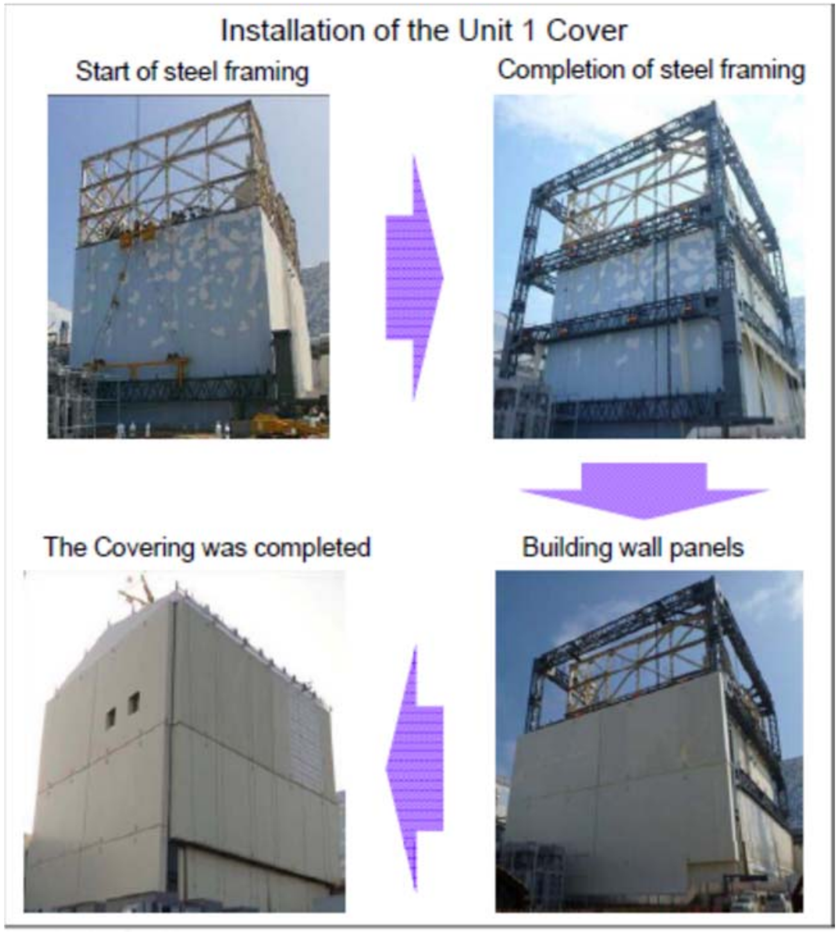
With the Successful Evacuation There was No Significant Radiation Dose to the General Public

- Currently there are no acute radiation effects (even to workers onsite)
- Estimated cancer increase is expected to be below statistical measurement threshold
- Economic impacts enormous
  - Evacuees only allowed limited access within 30 km radius in March 2012
    - Some limited access allowed to some areas within 20 km radius in early April 2012
  - Loss of productivity (manufacturing, agricultural, fishing)
  - Decontamination activities have begun (estimates in 10–250 billion of dollars)
  - Radioactive waste volumes are very large and pose a problem finding appropriate disposal sites in a country with limited land mass

Reactor Cores are Being Cooled and are Stabilized

- All reactors declared to be in cold shutdown in December 2011
  - Temperatures inside the reactors are below 100˚C
  - Cooling water leaking out of reactors is collected
    - Treated to remove radioactive materials
    - Recirculated back into the reactor
  - Radioactive water accumulated on-site immediately following accident is being collected and treated as well
  - Water has been prevented from entering the ocean by use of dikes and dams
  - Decontamination of areas surrounding the reactors (on-site) is ongoing—surfaces have been treated to prevent dust

Cover has been Installed Around Unit 1 Debris is Being Removed Before Covering Units 3 and 4



Mid-to-Long-Term Roadmap towards the Decommissioning of Fukushima Nuclear Power Units 1-4

Present (Step 2 Completed)	Within 2 Years	Within 10 Years	After 30-40 Years
Step 1, 2	**Phase 1**	**Phase 2**	**Phase 3**
<Achieved Stable Conditions> · Reactors: A condition equivalent to Cold Shutdown · Spent Fuel Pools: More stable cooling · Radioactive Contaminated Water: Reduction	**Period to the commencement of the fuel removal from the Spent Fuel Pools (Within 2 years)**	**Period to the commencement of the removal of fuel debris (Within 10 years)**	**Period to the end of the decommissioning (In 30-40 years)**
	-Commence the removal of fuels from the spent fuel pools (Unit 4 in 2 years) -Reduce the radiation impact due to additional emissions from the whole site and radioactive waste generated after the accident (secondary waste materials via water processing and debris etc.) Thus maintain an effective radiation dose of less than 1 mSv/yr at the site boundaries caused by the aforementioned. -Maintain stable reactor cooling and accumulated water processing and improve their credibility. -Commence R&D and decontamination towards the removal of fuel debris -Commence R&D of radioactive waste processing and disposal	-Complete the fuel removal from the spent fuel pools at all Units -Complete preparations for the removal of fuel debris such as decontaminating the insides of the buildings, restoring the PCVs and filling the PCVs with water Then commence the removal of fuel debris (Target: within 10 years) -Continue stable reactor cooling -Complete the processing of accumulated water -Continue R&D on radioactive waste processing and disposal, and commence R&D on the reactor facilities decommission	-Complete the fuel debris removal (in 20-25 years) -Complete the decommission (in 30-40 years) -Implement radioactive waste processing and disposal

Actions towards systematic staff training and allocation, improving motivation, and securing worker safety will be continuously implemented.

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Social/Political Impacts in Japan and Worldwide

- Resignation of Japan's Prime Minister
- Reorganization of Japanese Nuclear Regulatory Structure
- Lack of confidence in TEPCO and the government
- Shutdown of 50+ reactors in Japan (electricity shortage predicted this summer)
- Germany and Switzerland will shutdown their existing plants, and Italy has chosen not to restart their nuclear program
- U.S. NRC just issued orders to nuclear plant owners to reexamine all existing nuclear reactors regarding seismic design, AC power sources, and venting
- Some delay of new reactor builds worldwide

Conclusions and Lessons Learned

- External events may pose the greatest threat to nuclear plants
  - Multiple system failures can lead to significant plant damage
  - Loss of infrastructure (roads, bridges, water, power) prevented assistance
- Planning/training is essential to prevent injury and death (emergency planning, severe accident plans)
- Communication during and following an event is crucial
  - Significant delays in transmission of information between onsite and centralized locations probably contributed to the event
  - Instrumentation used to transmit plant status was lost
- Public relations during an event is very important
  - Information was difficult to obtain both within Japan and clearly in other countries
  - Contradictions led to lack of trust by the public and media
  - Lack of information prevented early assistance from outside sources