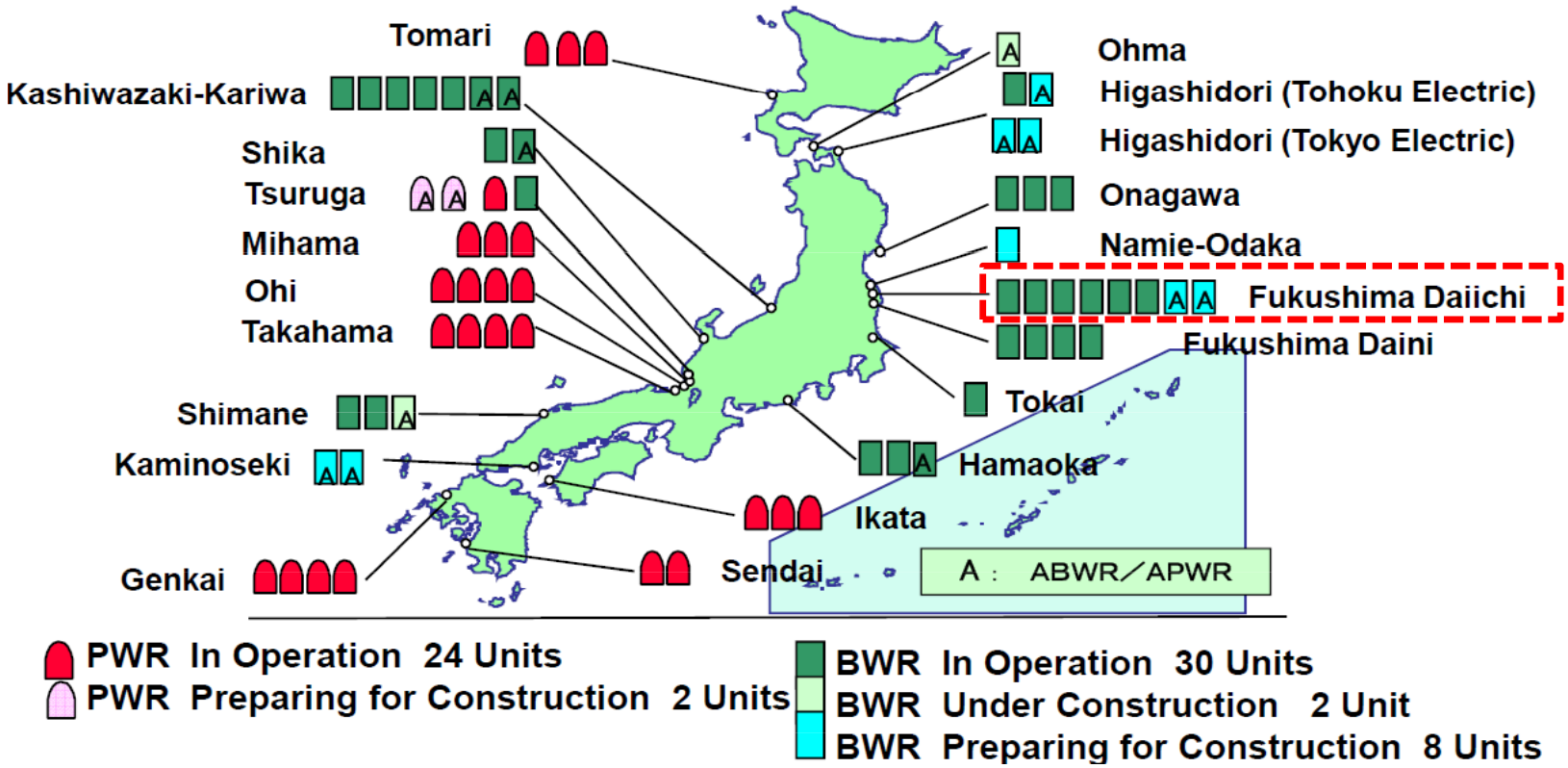
NUCLEAR POWER PLANTS IN JAPAN



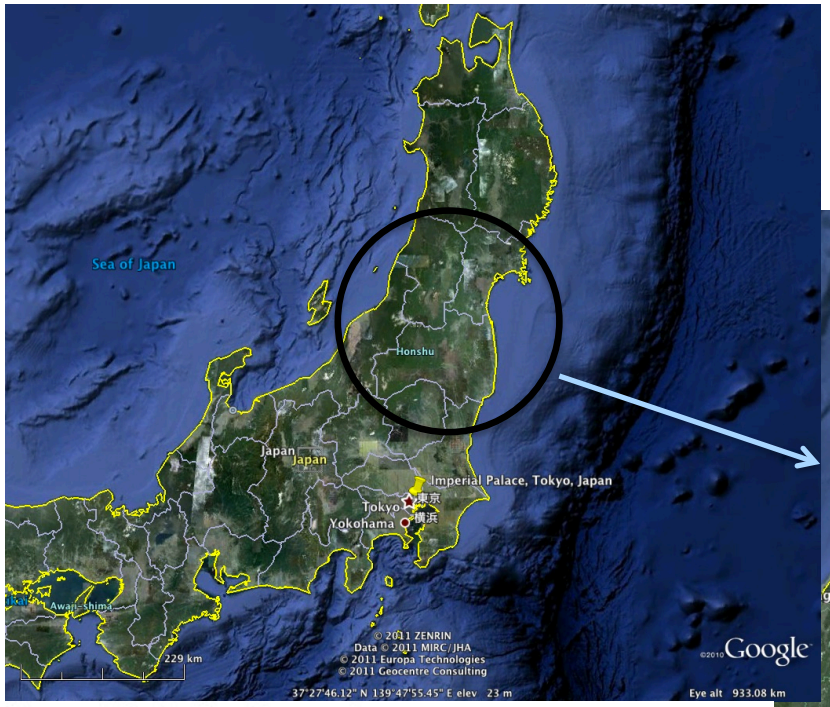
WHAT HAPPENED AT FUKUSHIMA DAIICHI/DAINI (11 MARCH 2011)

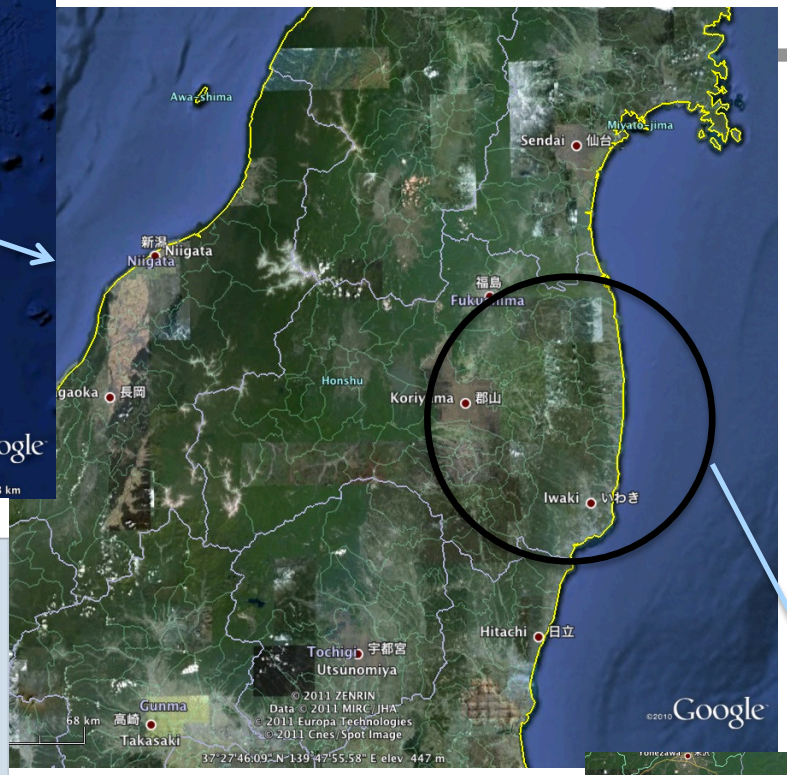
- Rarity of Earthquake (last similar one 1200 years previously) and Tsunami
- Natural vs. Human Causes
- MIT Study of Nuclear and Direct Seismic Risks Consistent with What Happened
- Direct Earthquake and Tsunami Consequences: > 20,000 dead, broad coastal devastation to 5 km inland, tsunami barriers overwhelmed
- Large-Scale Evacuation to Hotels and Emergency Facilities
- No Electricity, Gridlock, Fuel Shortages
- Cold Snowy Weather, Many Strong Aftershocks

NOTABLE EARTHQUAKES

PGA (max recorded)	Magnitude	Depth	Fatalities	Earthquake
2.2g	6.3	5 km	166	2011 Christchurch
1.7g	6.7	19 km	57	1994 California
1.26g	7.1	10 km	0	2010 Canterbury
1.01g	6.6	10 km	11	2007 Chūetsu offshore
0.8g	6.8	16 km	6,434	1995 Kobe
0.78g	8.8	35 km	521	2010 Chile
0.51g	6.4		612	2005 Zarand
0.5g	**9.0**	**32 km**	**Unknown**	**2011 Sendai (& tsunami)**
0.5g	7.0	13 km	92,000	2010 Haiti
0.24g	6.4		628	2004 Morocco
0.18	9.2	23 km	143	1964 Alaska
0.125	7.7	44 km	27	1978 Miyagi (Sendai)

http://en.wikipedia.org/wiki/Peak_ground_acceleration#PGA_hazard_risks_worldwide


Sea of Japan
Honshu
Japan
Imperial Palace, Tokyo, Japan
Tokyo
東京
Yokohama
横浜
© 2011 ZENRIN
Data © 2011 MIRC/JHA
© 2011 Europa Technologies
© 2011 Geocentre Consulting
Google
37°27'46.12" N 139°47'55.45" E elev 23 m
Eye alt 933.08 km


Niigata
新潟
Sendai
仙台
Honshu
長岡
Koriyama
郡山
Iwaki
いわき
Hitachi
日立
Tochigi
宇都宮
Utsunomiya
Gunma
高崎
Takasaki
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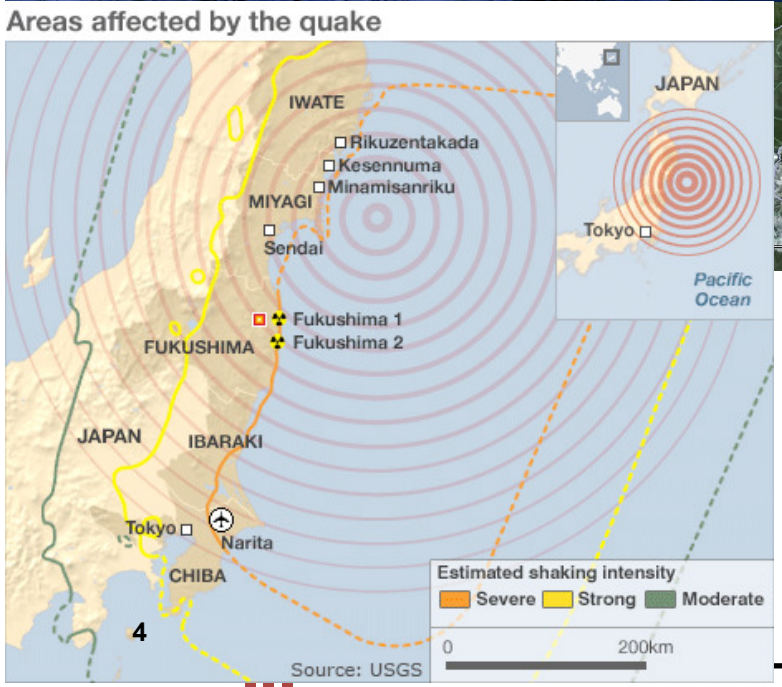
Data © 2011 MIRC/JHA
© 2011 Europa Technologies
© 2011 Cnes / Spot Image
Google
37°27'46.09" N 139°47'55.58" E elev 447 m

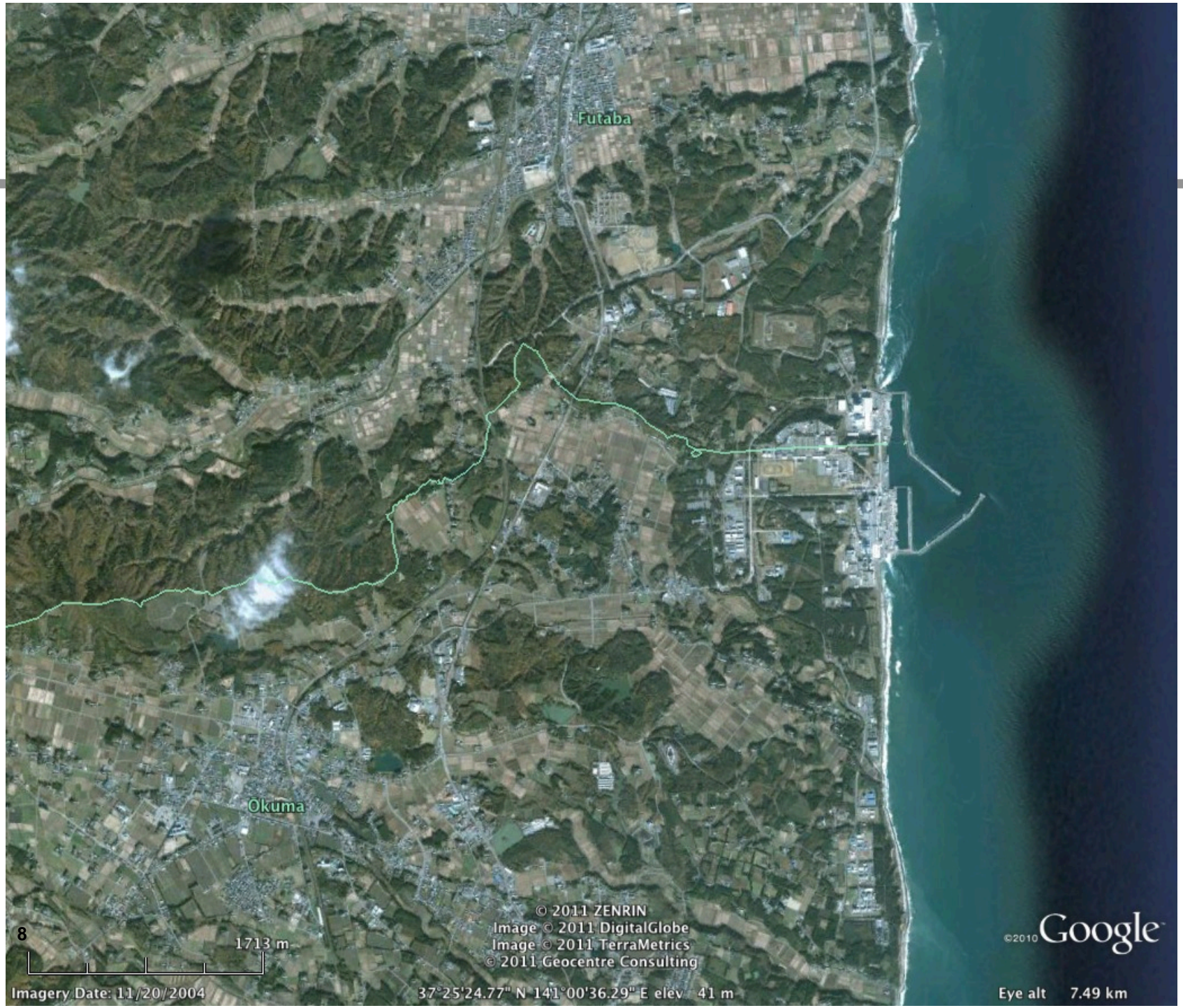

Areas affected by the quake
JAPAN
IWATE
Rikuzentakada
Kesennuma
Minamisanriku
MIYAGI
Sendai
Tokyo
Pacific Ocean
Fukushima 1
Fukushima 2
FUKUSHIMA
JAPAN
IBARAKI
Tokyo
Narita
CHIBA
Estimated shaking intensity
Severe
Strong
Moderate
0
200km
Source: USGS


~ 15 km radius
Fukushima
Soma
Minamisoma
Koriyama
Shirakawa
Iwaki
Google


Soma
相馬
福島
Fukushima
Fukushima
南相馬
Minamisoma
会津若松
Koriyama
郡山
~ 15 km radius
Shirakawa
白河
Iwaki
いわき
Nasushiobara
那須塩原
27 km
© 2011 ZENRIN
© 2011 Cnes / Spot Image
© 2011 Europa Technologies
Data © 2011 MIRC / JHA
37°24'19.82" N 140°35'04.73" E elev 414 m
©2010 Google
Eye alt 116.68 km


Namie
Futaba
Okuma
~ 8 km radius
6
3.75 km
©2011 ZENRIN
Image © 2011 DigitalGlobe
Data © 2011 MIRC/JHA
© 2011 Geocentre Consulting
©2010 Google
Imagery Date: 12/11/2005
37°25'33.19" N 140°58'09.55" E elev 58 m
Eye alt 17.15 km


Katsurao
120
114
253
288
6
Kawauchi
Joban Expy
Fukushima Daiichi
~10 km
Fukushima Daini
©2011 ZENRIN
Image © 2011 DigitalGlobe
© 2011 Geocentre Consulting
Data © 2011 MIRC/JHA
8.43 km
Imagery Date: 12/11/2005
37°23'58.70" N 140°55'20.00" E elev 388 m
©2010 Google
Eye alt 36.83 km


Futaba
Okuma
8
1713 m
© 2011 ZENRIN
Image © 2011 DigitalGlobe
Image © 2011 TerraMetrics
© 2011 Geocentre Consulting
©2010 Google
Imagery Date: 11/20/2004
37°25'24.77" N 141°00'36.29" E elev 41 m
Eye alt 7.49 km


9
405 m
© 2011 ZENRIN
Image © 2011 DigitalGlobe
© 2011 Geocentre Consulting
©2010 Google
Imagery Date: 11/20/2004
37°25'24.86" N 141°02'00.18" E elev 13 m
Eye alt 1.76 km

12 March 2011

14 March 2011

Satellite images of Fukushima Daiichi.
Copyright DigitalGlobe


Image Credit: DigitalGlobe
Image Annotation: ISIS
Image Date: March 14, 2011
Smoke or dust plume from the explosion
After the explosion at Unit 3, damage to the reactor building can be seen. Steam can be seen venting out of the reactor building
Steam venting out of the building
After the explosion at Unit 1, the top of the reactor building is damaged

THE NATURE OF THE POWER PLANT

- Six Reactors (Mark 1 BWRs, most 780 Mwe) and Fuel Pools
  - Units 1 – 4 grouped together, Units 5 and 6 separated and higher
- Units 1 – 3 Operating at Full Power
  - Units 4 – 6 shutdown since November 2010
- One Common Spent Fuel Pool
- Siting on Seaside, 10 m Elevation, 6 m Tsunami Barrier, 0.5 g SSE PGA
- Surroundings
  - Moderate population density along coast and inland valleys
  - Among low mountains, nearest population centers: Fukushima (30 km, population = 295,000), Sendai (60 km, population = 1 million)

COMMERCIAL OPERATION OF FUKUSHIMA-1 UNIT 1

Unit	Type	Containment Type	First criticality	Electric power	Scheduled Shutdown	Constructors
Fukushima I – 1	BWR/3	**Mk-1**	Oct. 1970	460 MW	**26 Mar '11**	GE
Fukushima I – 2	BWR/4	Mk-1	July 18, 1974	784 MW	18 Jul '14	GE
Fukushima I – 3	BWR/4	Mk-1	Mar. 27, 1976	**784 MW**	26 Mar '16	Toshiba
Fukushima I – 4	BWR/4	Mk-1	Oct. 12, 1978	784 MW	12 Oct '18	Hitachi
Fukushima I – 5	BWR/4	Mk-1	Apr. 18, 1978	784 MW	18 Apr '18	Toshiba
Fukushima I – 6	BWR/5	Mk-2	Oct. 24, 1979	1,100 MW	24 Oct '19	GE
Fukushima I – 7 (planned)	ABWR	ABWR	Oct. 2016	1,380 MW		
Fukushima I – 8 (planned)	ABWR	ABWR	Oct. 2017	1,380 MW		

Commercial operation of Fukushima-1 Unit 1 : March 26, 1971
It is ready to decommissioning at this month.
It is one of the oldest NPP in Japan.

DAMAGE TO FUKUSHIM DAIICHI NUCLEAR POWER PLANT

- Earthquake Magnitude 9 (0.5 g PGA), Tsunami (height = 14 m)
- Automatic Shutdown of All Operating Reactors and Start of Shutdown Coolant and Emergency Power Systems

STATION BLACKOUT TO ENTIRE SITE (TSUNAMI-CAUSED 55 MINUTES AFTER EARTHQUAKE)

- Loss of Grid Due to Earthquake
- Loss of Emergency Backup AC Power Due to Tsunami
- Flooding of13 onsite Emergency Diesel Generators (EDGs), one survived at units 5 & 6
- No Mobile Backup Generators Were Available
- Flooding of Emergency Switchgear Sites
- Destruction of EDG Fuel Tanks
- Site Immediately Inaccessible Except via Sea
- Communication to TEPCO HQ Cut Off
- Governmental Units Preoccupied with Direct Emergency Effects
- Damage to Surrounding Civil, Communication, Travel Infrastructure Prevented Help from Outside

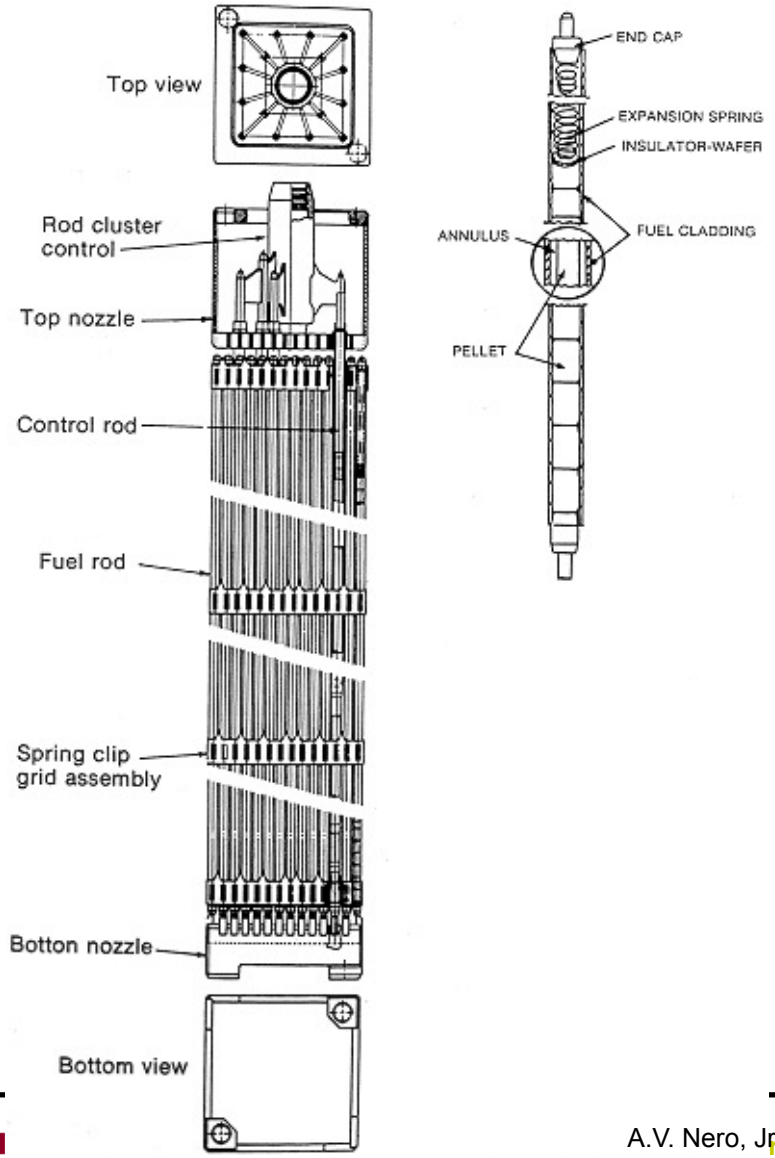
POWER REACTOR AND SITE DAMAGE

- Broken Piping and Other Equipment, Containment Shell, Fuel Pool, Reinforced Concrete Structures Due to Earthquake
- Flooding of Low Elevation Spaces Due to Tsunami

STATION BLACKOUT EFFECTS

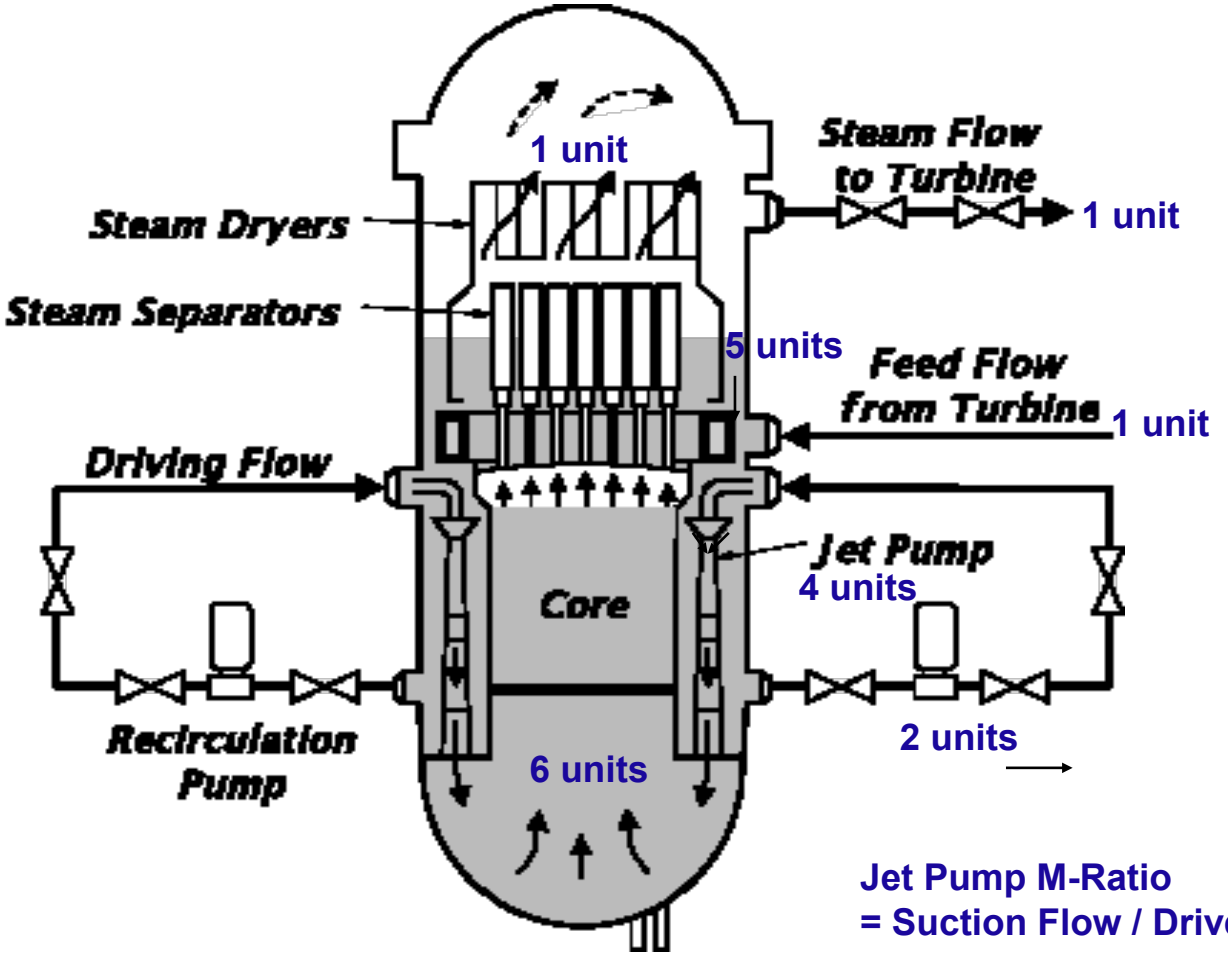
- All AC Power Lost, Later All DC Power Lost
- All Electricity Supported Functions (e.g., pumping, instrumentation, HVAC, lighting, electric motor, remote activation, telecommunications) Lost

PWR FUEL ASSEMBLY AND CUTAWAY OF OXIDE FUEL FOR COMMERCIAL LWR POWER PLANTS



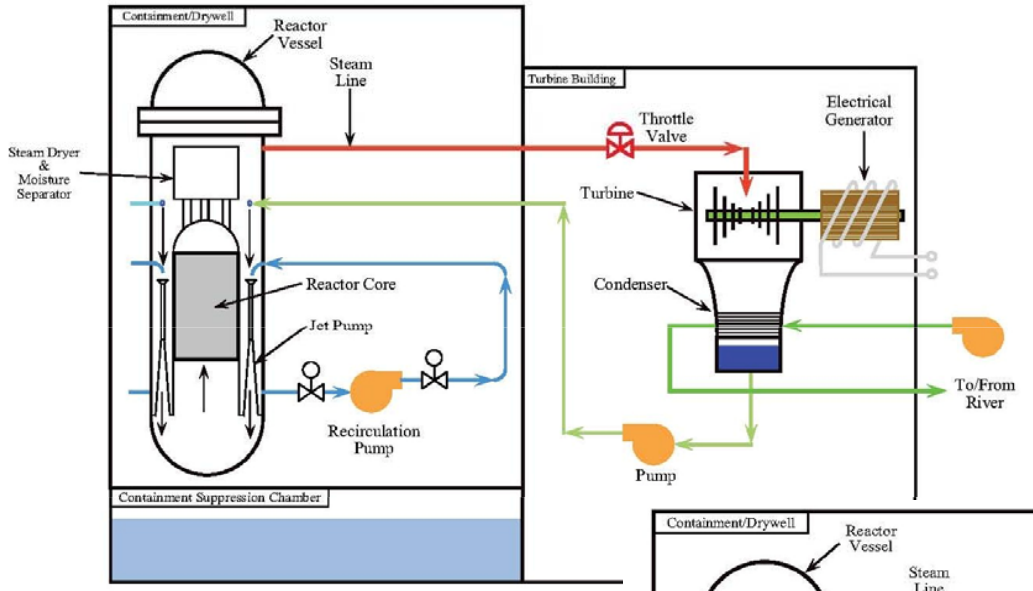
A.V. Nero, Jr., *A Guidebook to Nuclear Reactors*, 1979.

BWR STEAM AND RECIRCULATION FLOW

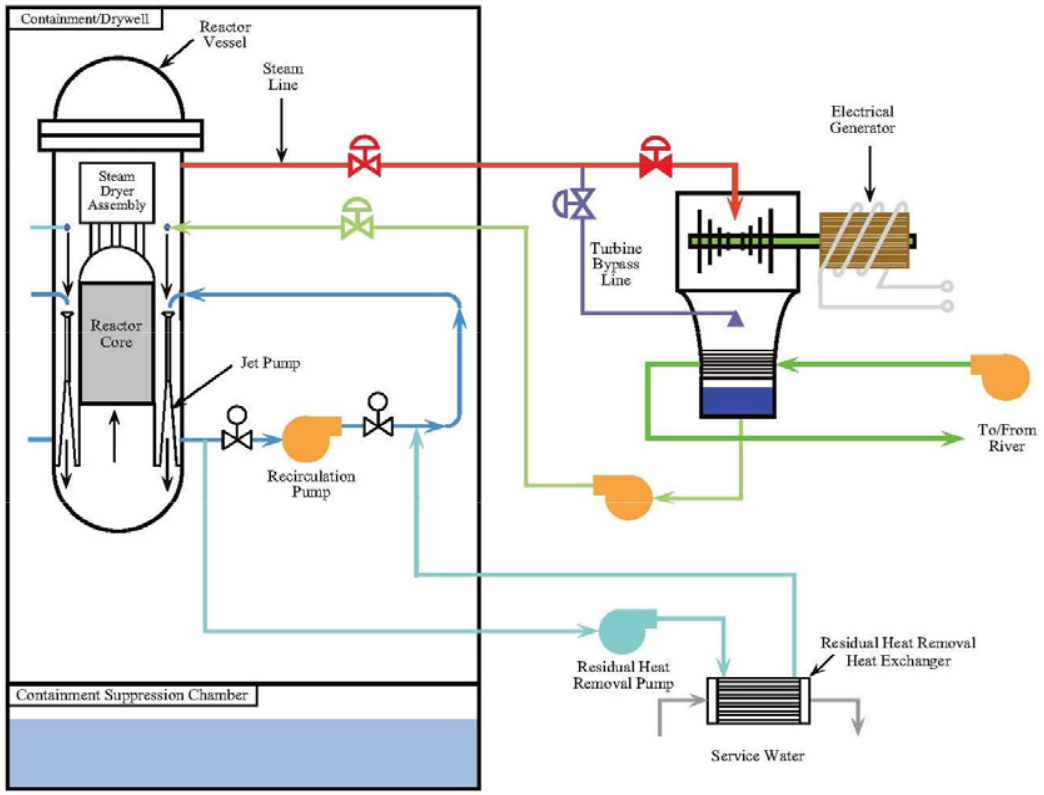


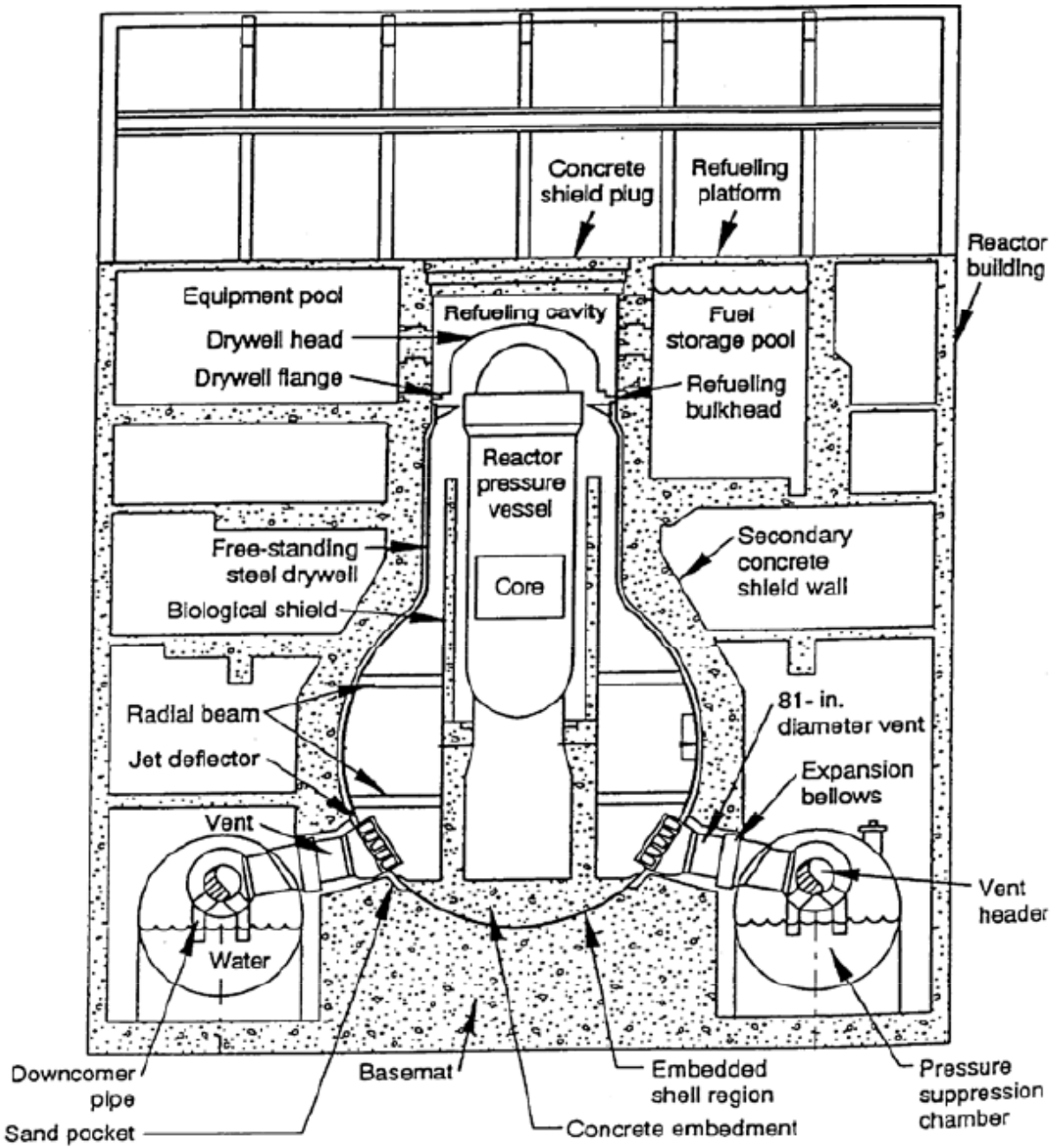
Jet Pump M-Ratio
= Suction Flow / Drive Flow = 2

Normal Operation



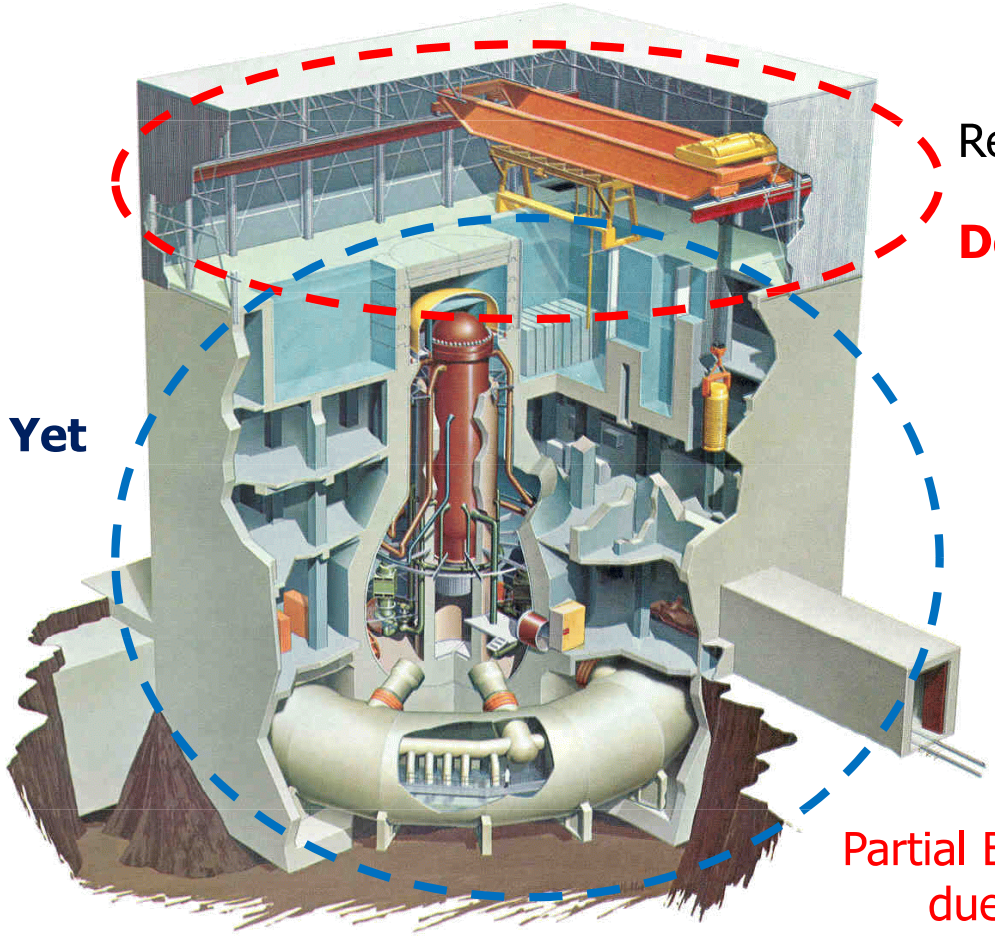
Decay Heat Cooling





Mark 1 General Electric,
GE BWR Containment

MARK 1 TYPE (LIGHT BULB TORUS) CONTAINMENT STRUCTURE



Refueling and Service Zone

Destroyed by Hydrogen Explosion

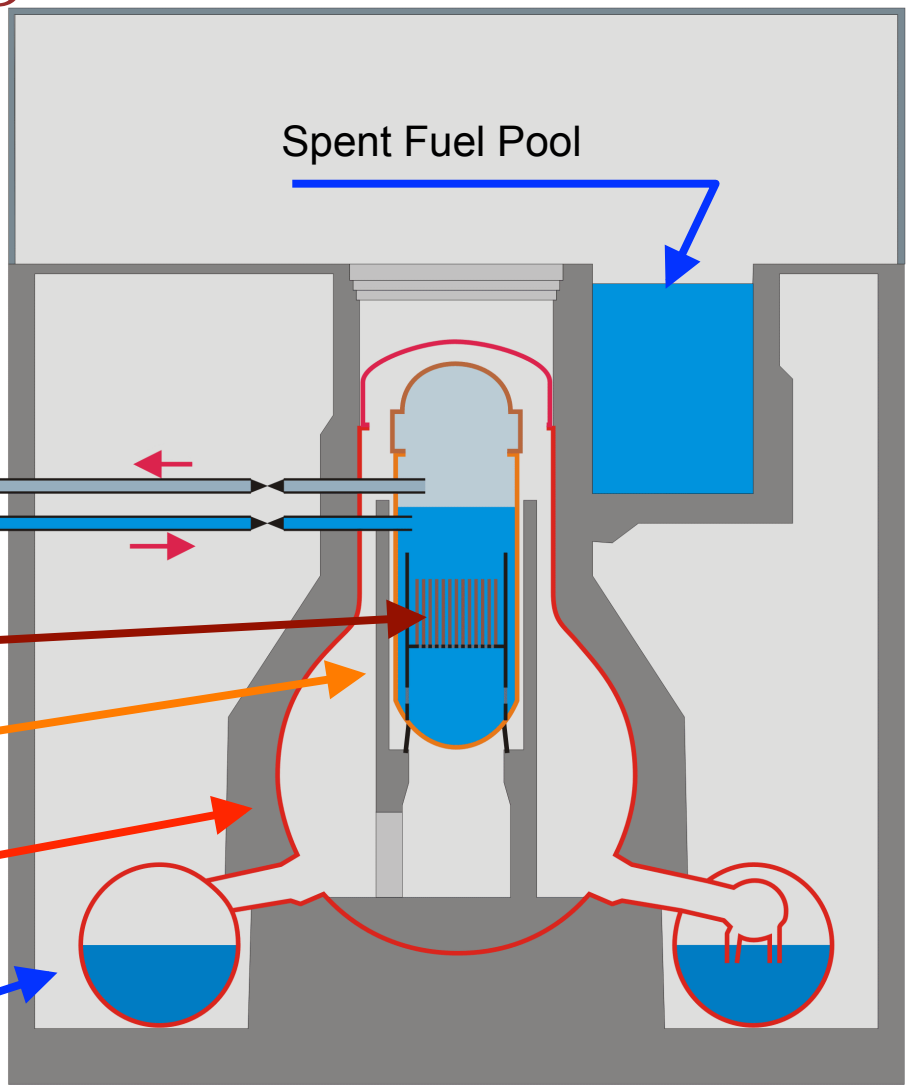
Intact Yet

Partial Core-Melt leaked Hydrogen

Partial Break of Coolant Circuit due to Earthquake

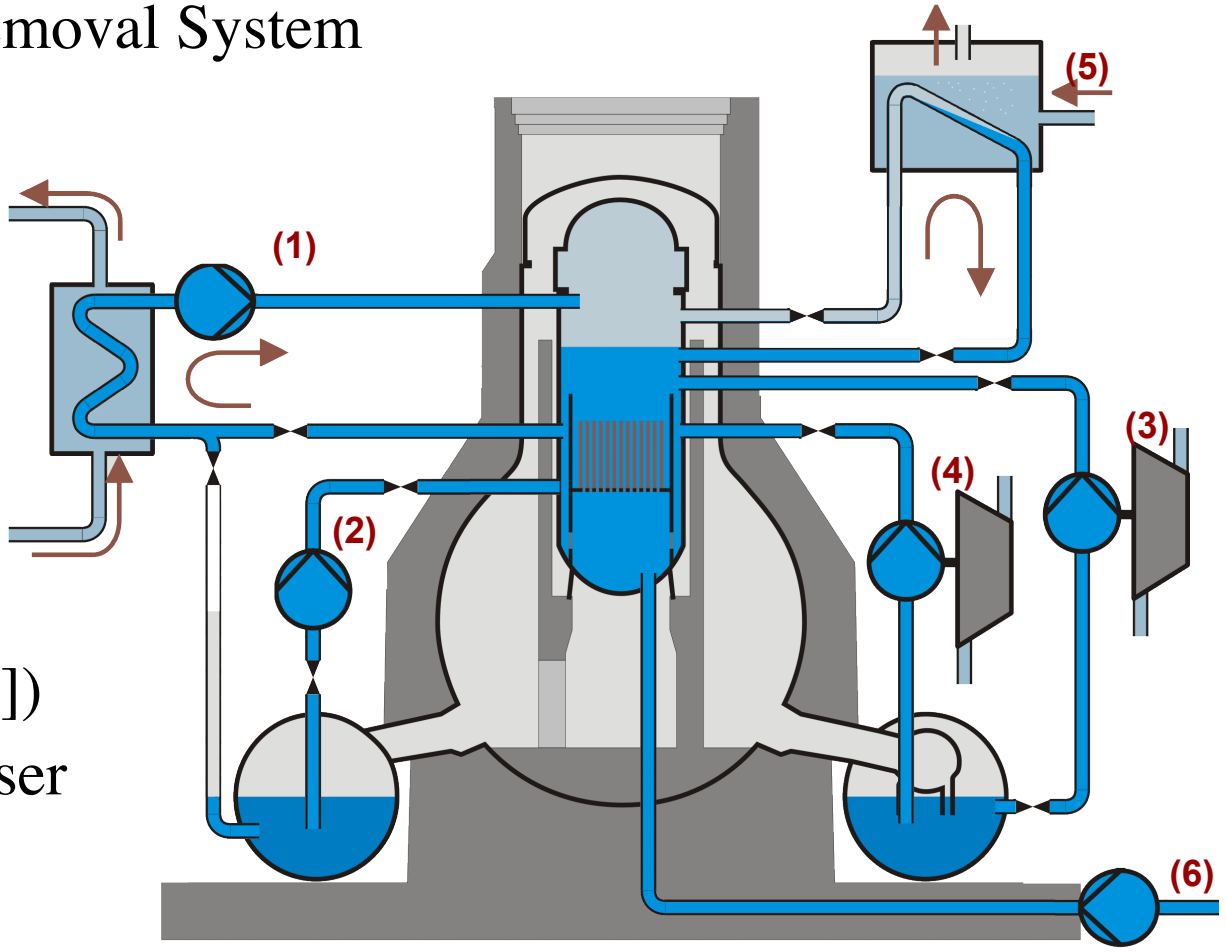
THE FUKUSHIMA DAIICHI INCIDENT
1. Plant Design of Unit 1-4

- Reactor Service Floor (Steel Construction)
- Concrete Reactor Building (Secondary Containment)
- Reactor Core
- Reactor Pressure Vessel
- Containment (Dry well)
- Containment (Wet Well) / Condensation Chamber



THE FUKUSHIMA DAIICHI INCIDENT
1. Plant Design of Unit 1-4

1) Emergency Core Cooling Systems
2) Residual Heat Removal System
3) Low-Pressure Core Spray (for LOCA)
4) High-Pressure Core Injection (for LOCA)
5) Reactor Core isolation cooling (Unit 2,3 [BWR4])
6) Isolation Condenser (Unit 1 [BWR3])
7) Borating System



EFFECTS WITHIN REACTOR BUILDING
(Containing Reactor, Containment Building, Surrounding Reactor Building Spaces and Uncontained Spent Fuel Pool)

- Fuel Under Cooled While Continually Heated via Fission Product Decays
- Fuel Partially Uncovered by Water in Reactor Pressure Vessels and Pools
- Fuel Overheated and Cladding Oxidation Occurred
- [Zr (ductile) + H_2O ➔ ZrO (brittle) + H_2 (explosive) + Heat]
- Improvised Cooling Using Seawater Pumped via Fire Trucks into Pressure Vessels, Fuel Pools and Containment Pools (power unit becomes economic loss)
- When Reactor Coolant System was Overpressurized Relief Valves Directed Flow to Containment Vapor Suppression Pool, Where Steam was Condensed and Entrained Materials Partially Scrubbed

EFFECTS WITHIN REACTOR BUILDING
(Continued)

- Later, as Suppression Pools Heated Toward Saturation Temperature, Condensation and Scrubbing Ceased and Containment Overpressurized
- Containment Venting Occurred Manually via Standby Gas Treatment System, Not via Duct Leading to Reactor Building Vent
- Vented H_2 Collected at Reactor Building High Point Above Refueling Deck and Spent Fuel Pool
- H_2 Explosion Removed Metal Panels Above Refueling Deck, and Exposed Fuel Pool to Open Sky, but Reactor Building Undamaged by Explosion (except for explosion within reactor building)
- Spent Fuel Pools Lost Water (via leaks and evaporation), Exposing Fuel Rods to Air and Steam ➔ Fuel Damage and Uncontained Fission Product Releases

TRANSPORT OF RADIOACTIVE MATERIALS – GASEOUS PATHWAYS

- Fission Products Partially Released from Damaged Fuel
  - Nobel gases (Xe, Kr)
  - Volatile fission products (I, Sr, Cs, Ru, …)
  - Non-volatile fission products retained, but may have been leached by water
- Flow From Damaged Fuel via Reactor Coolant System to Break or to Containment Building
- Flow into Containment Building via Vapor Suppression Pool to Wetwell, and Sometimes to Drywell
- Flow from Reactor Building into Biosphere
- Flows According to Current Wind and Precipitation
  - Out to sea (dominant pattern)
  - Over local terrain, with resulting surface and aquatic contamination (most radiation levels are consistent with chronic high levels tolerated by human populations elsewhere (e.g., Kerala))

STORAGE STATUS OF SPENT FUEL AT FUKUSHIMA-DAIICHI NPS

- Approximately 700 Spent Fuel Assemblies are Generate Every Year
  - Stored in spent fuel pools/dry casks

Storage Status of Spent Fuel* (assemblies)

Storage Method	Storage Amount	Capacity (existing facilities)
Spent fuel pool at each reactor unit	3,450	8,310
Dry cask	408	408
Common pool	6,291	6,840
TOTAL	10,149	15,558

* as of March 2010

Approximately 450% of the total core capacity of six plants

TRANSPORT OF RADIOACTIVE MATERIALS – AQUATIC PATHWAYS

- Soluble Fission Products Released from Damaged Fuel into Cooling Water
- Flow of Cooling Water into Sea or (later) into Closed Cooling System
- Flow via Seaborne Currents to NE, Away from Japanese Islands, but with Likely Local Contamination

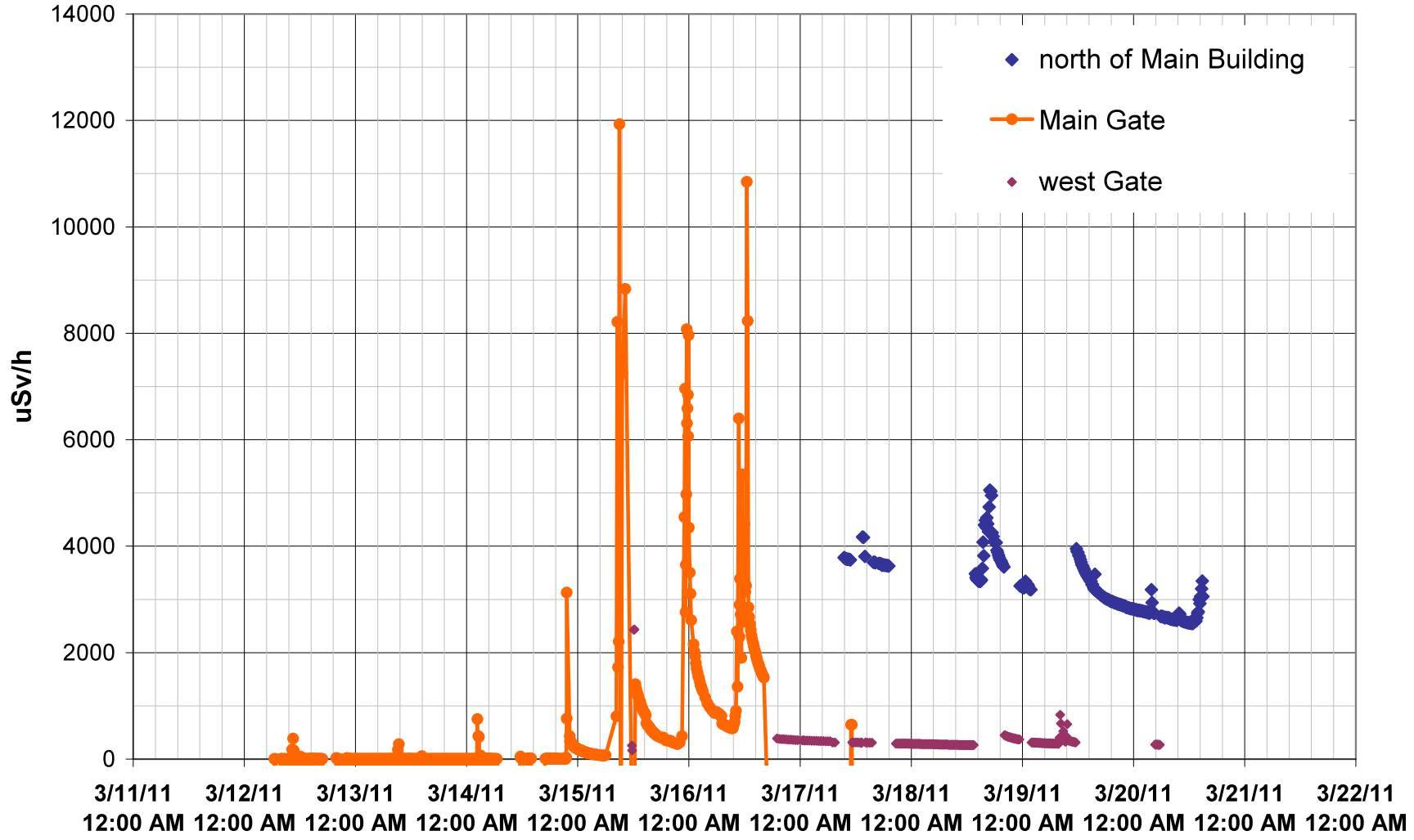
EMERGENCY RESPONSE

- Populations Within 20 km Evacuated, with Short Duration Return Visits Permitted (USNRC Chairman recommended that US nationals within 50 km evacuate)
- Others Ordered to Shelter In-Situ
- Agricultural Products from Fukushima Region Embargoed/Shunned (people, too?)
- Contaminated Materials Can Be Collected and Removed at Some Cost

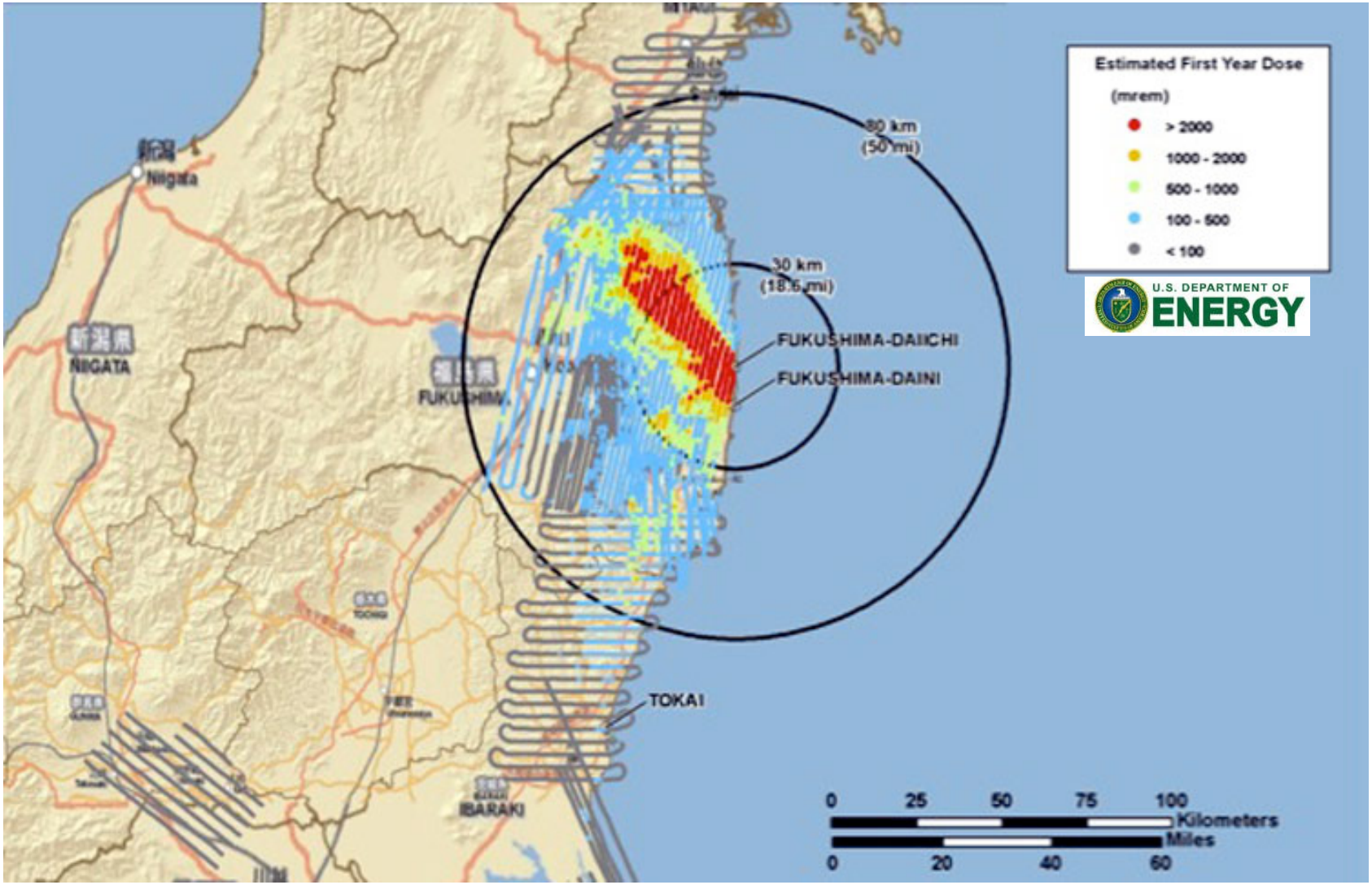
POWER PLANT CLEANUP AND RECOVERY

- Diagnosis, Using Scouts and Robots
  - Locations, Conditions of Radioactive Materials
  - Degree of Access to Contaminated Plant Sections
  - Locations and Degree of Mechanical Damage and Flooding
- Processes for Restoring Essential Services
- Exploration and Planning for Decommissioning
- Removal of Radioactive Materials (mostly damaged fuel rods)
- Remote, Permanent Storage of Removed Materials
- Decontamination, Sealing and Monitoring of Remaining Plant Structures

THE FUKUSHIMA DAIICHI INCIDENT
3. Radiological Releases



RADIATION RISKS



THE FUKUSHIMA DAIICHI INCIDENT
3. Radiological Releases

- Outside the Plant site
  - Reactor building mostly intact => reduced release of Aerosols
  - Fission product release in steam => fast Aerosol growth
  - Large fraction of Aerosols deposited in close proximity of plant
  - Main contribution to dose outside plant are the radioactive noble gases => No "Fall-out" of the noble gases, so no local high contamination of soil
- ~20km around the plant
  - Evacuations were adequate
  - Measured dose up to 0.3mSv/h for short times
  - Maybe destruction of crops / dairy products this year
  - Probably no permanent evacuation of land necessary
- ~50km around the plant
  - Control of Crop / Dairy products
  - Distribution of Iodine pills, no usage recommended yet (Pills can interfere with heart medicine)

STATUS OF NUCLEAR POWER PLANTS IN FUKUSHIMA AS OF 19:00 MARCH 16 (estimated by JAIF)

Type of Reactor	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Operation Status at the earthquake occurred	Service	Service	Service	Outage	Outage	Outage
Core and Fuel Integrity	Damaged	Damaged	Damaged	No fuel rods	Not Damaged	Not Damaged
Containment Integrity	Not Damaged	Damage Suspected	Damage Suspected	Not Damaged	Not Damaged	Not Damaged
Core cooling requiring AC power	Not Functional	Not Functional	Not Functional	Not necessary	Not necessary	Not necessary
Core cooling not requiring AC power	Not Functional	Not Functional	Not Functional	Not necessary	Not necessary	Not necessary
Building Integrity	Severely Damaged	Slightly Damaged	Severely Damaged	Severely Damaged	Not Damaged	Not Damaged
water level of the pressure vessel	Around half of the Fuel	Recovering after Dried-up	Around half of the Fuel	Safe	Safe	Safe
pressure of the pressure vessel	Stable	Fluctuating	Stable	Safe	Safe	Safe
Containment pressure	Stable	D/W: Unknown, S/P: Atmosphere	Stable	Safe	Safe	Safe
Water injection to core (Accident Management)	Continuing (Seawater)	Continuing(Seawater)	Continuing(Seawater)	Not necessary	Not necessary	Not necessary
Water injection to Containment Vessel (AM)	Continuing(Seawater)	to be decided(Seawater)	to be decided(Seawater)	Not necessary	Not necessary	Not necessary
Containment venting (AM)	Continuing(Seawater)	Preparing(Seawater)	Continuing(Seawater)	Not necessary	Not necessary	Not necessary
Fuel Integrity in the spent fuel pool	(No info)	(No info)	Level Low, Preparing Water Injection	Level Low, Preparing Water Injection Damage to Fuel Rods Suspected	Pool Temp. Increasing	Pool Temp. Increasing
Environmental effect	NPS border: 1937 μSv/h at 14:30, Mar. 16					
Evacuation Area	20km from NPS * People who live between 20km to 30km from the Fukushima #1NPS are to stay indoors.					
Remarks	A fire broke on the 4th floor of the Unit-4 Reactor Building around 6AM, Mar. 15, and the radiation monitor readings increased outside of the building: 30mSv between Unit-2 and Unit-3, 400mSv beside Unit-3, 100mSv beside Unit-4 at 10:22, Mar. 15. It is estimated that spent fuels stored in the spent fuel pit heated and hydrogen was generated from these fuels, resulting in explosion. TEPCO later announced the fire was been burned out. Another fire was observed at 5:45, Mar. 16, and then disappeared later. Other staff and workers than fifty TEPCO employees who are engaged in water injection operation have been evacuated. White smoke was seen rising from the vicinity of Unit-3 at around 8:30, Mar. 16. TEPCO estimates that failing to cool the SFP has resulted in evaporation of pool water, generating steam.					

Power Station	Fukushima #2 Nuclear Power Station			
Unit	1	2	3	4
Electric / Thermal Power output (MW)	1100 / 3293			
Type of Reactor	BWR-5	BWR-5	BWR-5	BWR-5
Operation Status at the earthquake occurred	Service	Service	Service	Service
Core and Fuel Integrity	Not Damaged	Not Damaged	Not Damaged	Not Damaged
Containment Integrity	Not Damaged	Not Damaged	Not Damaged	Not Damaged
Core cooling requiring AC power	Functioning	Functioning	Functioning	Functioning
Core cooling not requiring AC power	Not necessary	Not necessary	Not necessary	Not necessary
Building Integrity	Not Damaged	Not Damaged	Not Damaged	Not Damaged
water level of the pressure vessel	(No info)	(No info)	(No info)	(No info)
pressure of the pressure vessel	(No info)	(No info)	(No info)	(No info)
Containment pressure	(No info)	(No info)	(No info)	(No info)
Water injection to core (Accident Management)	Not necessary	Not necessary	Not necessary	Not necessary
Water injection to Containment Vessel (AM)	Not necessary	Not necessary	Not necessary	Not necessary
Containment venting (AM)	Not necessary	Not necessary	Not necessary	Not necessary
Fuel Integrity in the spent fuel pool	(No Info)	(No Info)	(No Info)	(No Info)
Environmental effect	NPS border: 29.4 μSv/h at 12:00, Mar. 16			
Evacuation Area	10km from NPS			
Remarks	All the units are in cold shutdown.			

[Source]
Governmental Emergency Headquarters: News Release (3/16 7:00), Press conference (3/14 11:45, 16:15, 3/15 8:00, 11:00, 16:25, 3/16 11:15)
NISA: News Release (3/14 7:30), Press conference (3/16 12:00)
TEPCO: Press Release (3/14 16:00, 17:35, 3/15 6:00, 12:00, 16:30, 23:35, 3/16 0:00),
Press Conference (3/14 12:10, 20:00, 3/15 8:00, 8:30, 3/16 early morning)

[Abbreviations]
INES: International Nuclear Event Scale
NISA: Nuclear and Industrial Safety Agency
SFP: spent fuel pool
TEPCO: Tokyo Electric Power Company, Inc.

[Significance judged by JAIF]
: low
: high
: severe

POLITICAL REACTIONS

- Politicians Must Do Something
  - Reconsideration of whether to use nuclear power
  - Reconsideration of the conditions for using it are typical
- Japan
  - Ex-Prime Minister Kan
    - History of tantrums in public, prior to current office
    - TEPCO bashing
    - Declaration of nuclear emergency level 7 status for Fukushima daiichi (same as Chernobyl)
    - Scrapping of nuclear energy expansion policy
    - Temporary shutdown of Hamaoka nuclear Power Plant

POLITICAL REACTIONS (continued)

- Japan (continued)
  - TEPCO
    - Responding well at plant, as far as can be judged
    - Plant stabilized & becoming recovered
    - Poor coordination/communication, political interference
    - Severely criticized (deflection by others of criticism?)
    - Potential bankruptcy
    - Executive career disruptions

POLITICAL REACTIONS (continued)

- Future use of nuclear power in Japan?
  - More fossil fuel use
  - Complex relationship of society, regulator, nuclear power operators
  - Appearances are very important, kabuki
  - Citizenry accepts and resents policies of government and establishment

POLITICAL REACTIONS (continued)

- Europe
  - Germany and Italy flee from nuclear power, Switzerland?
  - Others are staying with it, but requiring political theatre of "stress tests"
  - Climate change concerns are strong
- North America
  - Nuclear power "renaissance" was stalled by 2008 recession
  - Licenses for 35 reactors are in pipeline, four moving forward to construction
  - Policies remain to expand use of nuclear power
  - Climate change concerns support nuclear expansion
- Asia and Developing Countries
  - Most countries retain policies to expand nuclear power use
  - Four AP-1000 units are under construction in China

SAFETY IMPLICATIONS

- Seismic/Tsunami Hazards Will Be Reexamined
- Siting Questions
  - How many reactor per site?
  - Where to site them?
- Toleration of Vulnerabilities?
- How to Set Acceptable Risk Limits?
- Require Use of Passive Safety Features, Perhaps Blended with Active Ones?

GETTING SERIOUS ABOUT SPENT FUEL HAZARDS?

- Spent Fuel Has Been Good for the Anti-Nuclear Lobbies
- Has Been Viewed as a Manageable Problem
- Limit On-Site Spent Fuel Storage
- Development of Interim Storage Facilities
- Recognition that Terrestrial Waste Repositories are Only Implemented in Long Term
- Global Reconsideration of Fuel Cycle Could Lead to Global Waste, Proliferation Solutions

SOCIETAL REACTIONS

- Less Severe Than with Three Mile Island, Chernobyl
- View within Society?
  - Nuclear Power is Not So Scary?
  - Nuclear Power Has Become More Ordinary
  - Nuclear Power is Necessary

NUCLEAR POWER IS HERE TO STAY

- Where?
- How Much?
- Private or Public?
- Many Possibilities Exist, Only a Few Have Been Explored So Far