The Crisis at Fukushima Dai-ichi Nuclear Power Plant

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Prologue The crisis at Fukushima Daiichi NPP is still very much in progress. Given the extraordinary circumstances and unprecedented scale of this emergency, there are many important facts that are unknown to me and many things that have been reported that are probably incorrect. Please keep this in mind as you read this presentation. Past experience has shown that our first impressions of event progression are often wrong and have to be completely revised once a thorough investigation has been carried out. The present account will be no exception.

The purpose of this presentation was to provide background on these particular reactors, gather in one place the reported information on the sequence of events, and provide an interpretation based on my understanding of severe accidents in NPPs. My goal was to help others understand what is being reported and how to interpret information in scientific and engineering terms as well as to put this in the context of the past 40 years of nuclear reactor safety research. In doing so, I have over-simplified some explanations, drawn cartoons with impossible locations of pipes and equipment, and rounded off numbers. Detailed and precise information can be found in the references I have provided on most slides.

I am grateful to the Japanese community at Caltech for a chance to help them and express my sympathy to everyone affected by the Tohoku earthquake both in Japan and around the world.

Joe Shepherd
Pasadena, CA
9 April 2011

http://www.galcit.caltech.edu/~jeshep/fukushima/

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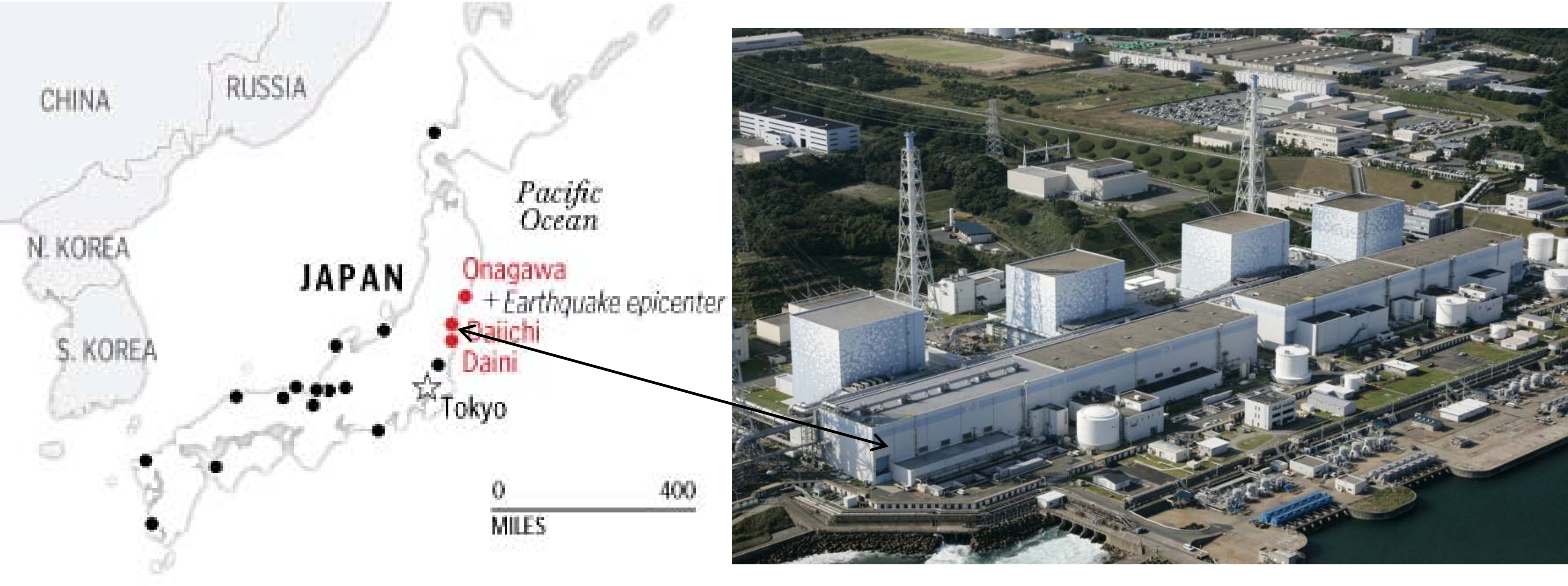
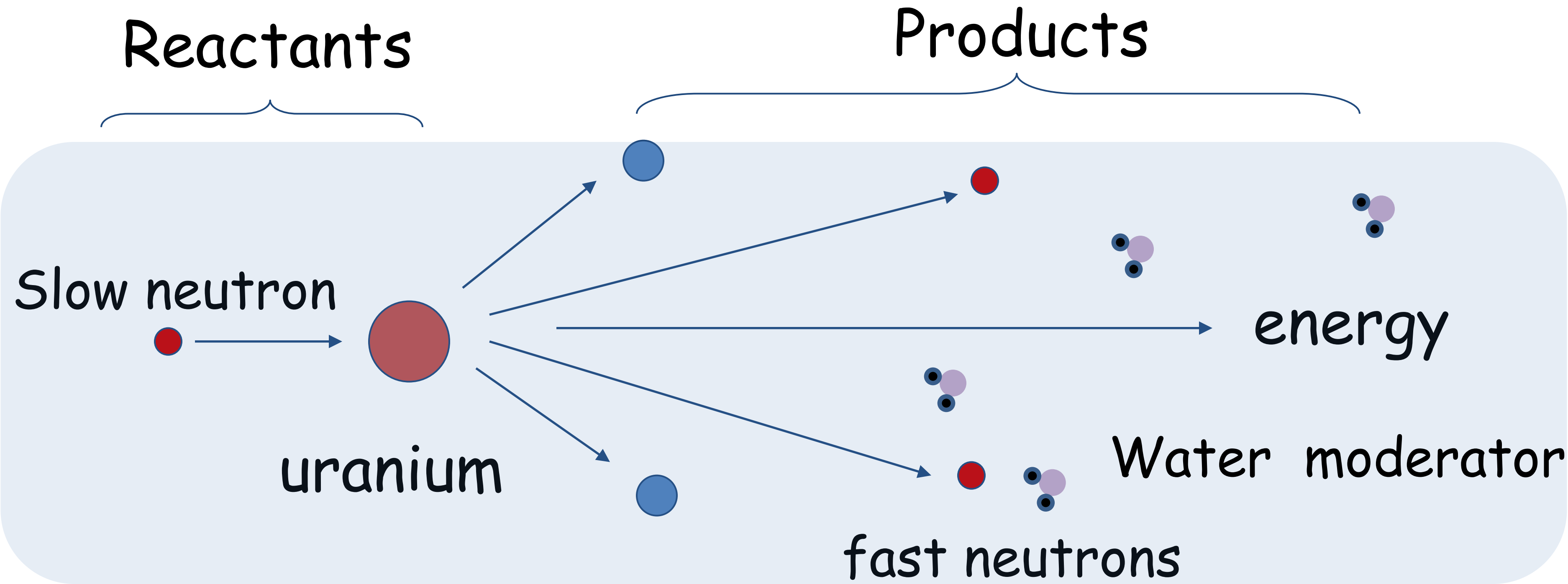
Fukushima Nuclear Power Plants



- Fukushima-Daiichi 1, 2, 6 made by GE, rated at 439, 760, 1067 MWe, started up in Nov. 1970, Dec. 1973, May 1979
- Fukushima-Daiichi 3 and 5 made by Toshiba, rated at 760 MWe, started up in Oct. 1974 and September 1977
- Fukushima-Daiichi 4 made by Hitachi, rated at 760 MWe, started up in Feb 1978.
- Fukushima-Daini 1 and 3 made by Toshiba, rated at 1067 MWe, started up in July 1981 and Dec. 1984.
- Fukushima-Daini 2 and 4 made by Hitachi, rated at 1067 MWe, started up in June 1983 and Dec. 1986.

Nuclear Fission in Power Reactors



$$n + {}^{235}U \longrightarrow 2.5n + \text{products} + 200\ \text{MeV}$$

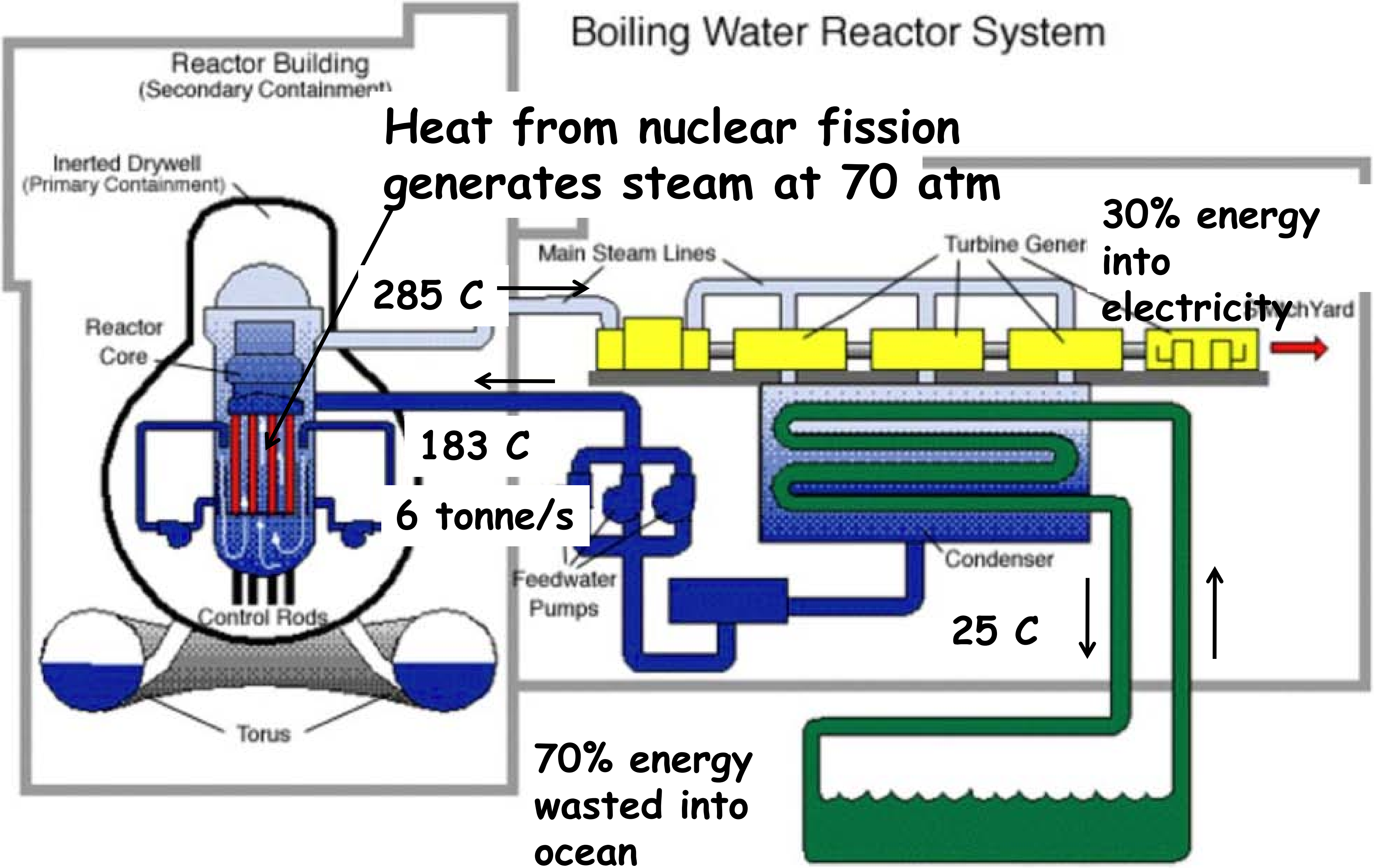
1 tonne ^{235}U produces 1 GW(e) for 1 year at 32% thermal efficiency. Fuel is a mixture of ^{235}U (3%) and ^{238}U (97%) - 33 tonne fuel per GW-yr of electricity.

Simplification Caution

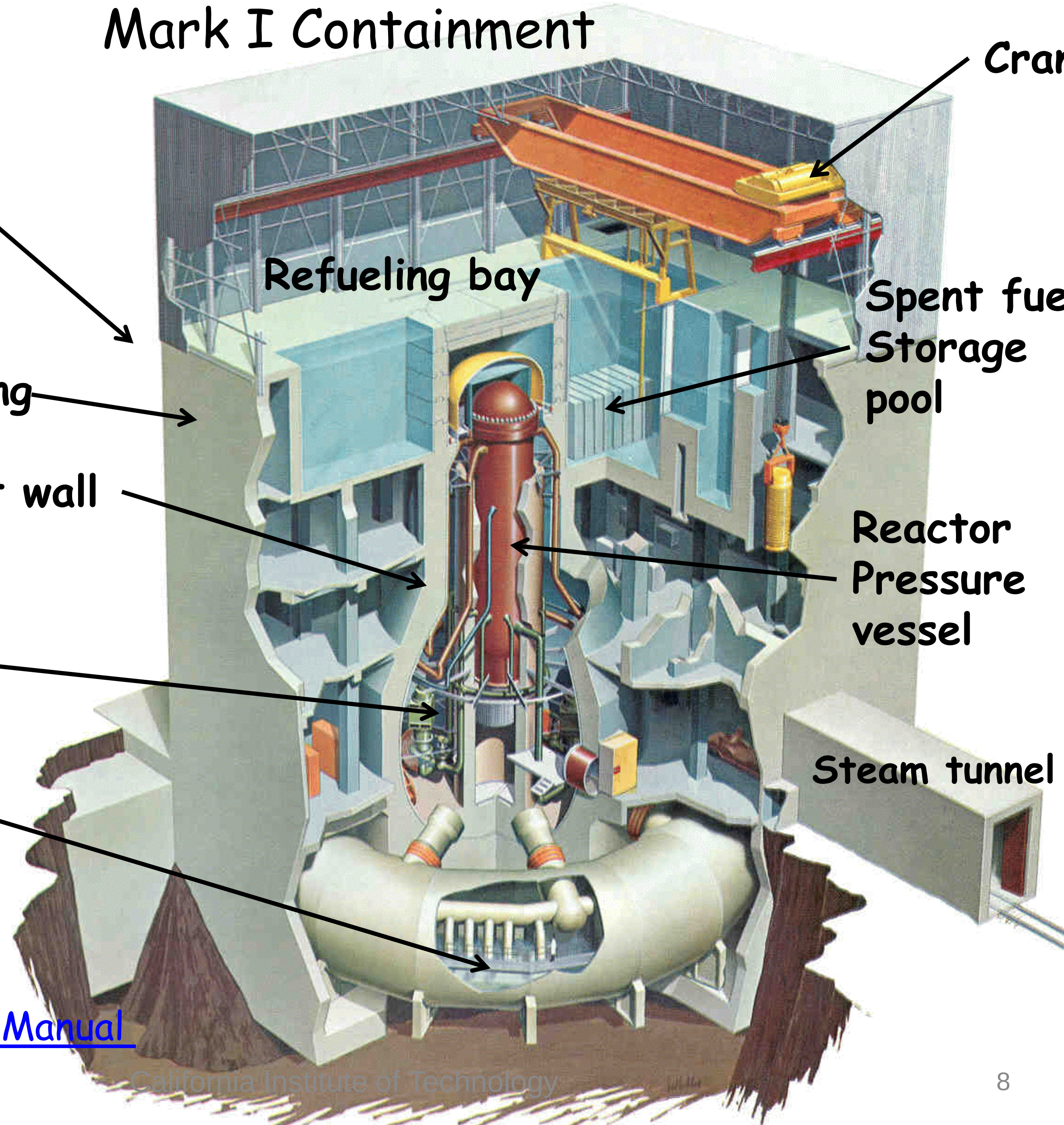
- Many of the examples in this presentation use an enrichment of 3% but this is only a nominal value
- Modern practice is to use as high an enrichment as possible – up to 5% possible in US
  - Increases time between fuel reloading outages and utilization of fissile material
  - Precise enrichment used in Fukushima is not known
- Situation is complicated by the use of fuel (Mixed OXide) containing 3-7% plutonium (Pu-239, Pu-241 are fissile) as well as uranium.
  - Exact composition will depend on source of Pu which can be from reprocessed fuel or nuclear weapons stockpiles.
- Worldwide usage of MOX fuel increasing – currently 2% of fuel is MOX
- Unit 3 contained a small number (6%) of MOX fuel assemblies that were loaded in Nov 2010.
- Units 1 and 2 only used standard U-235 enriched fuel.
- Enrichment and fuel reloading schedule have a significant influence on estimations of decay heat and fission product inventory so the estimates of these quantities will also be nominal.

ANS Technical Brief - March 25, 2011 and World Nuclear Assoc

Schematic of a Single BWR Unit

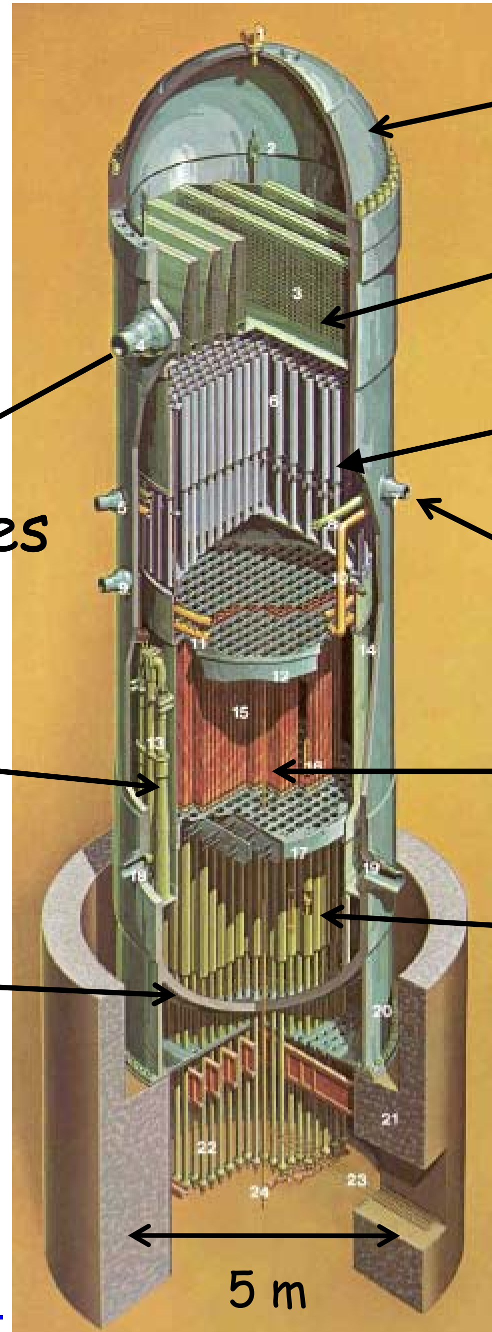


Mark I Containment



NRC Reactor Concepts Manual

Reactor Pressure Vessel and fuel "core"



500 tonne steel
6-in thick

NRC Reactor Concepts Manual

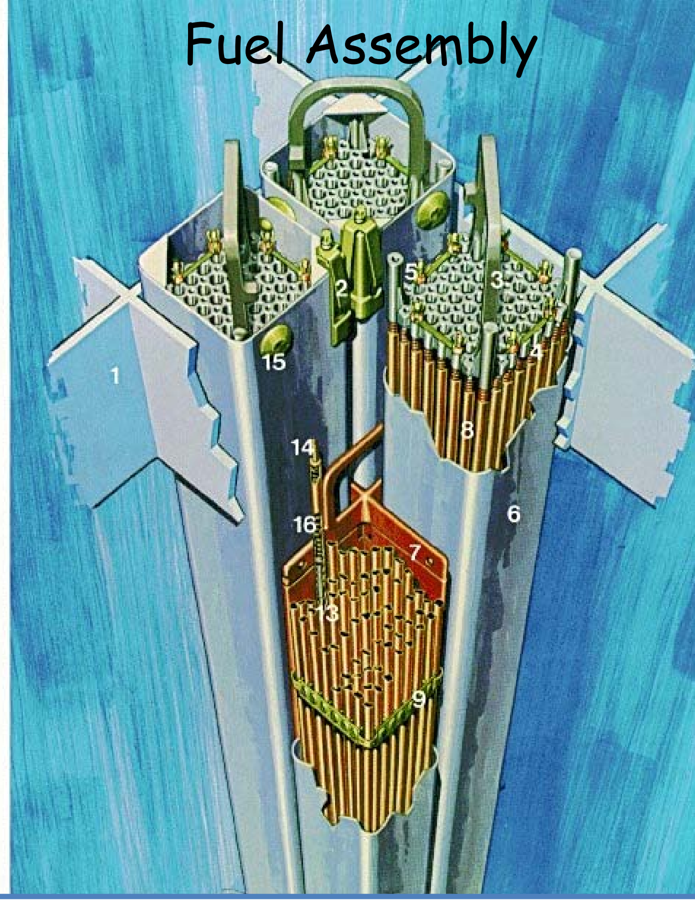
Typical set of 4 fuel assemblies.

Each 8x8 set of pins are surrounded by Zircaloy channel boxes.

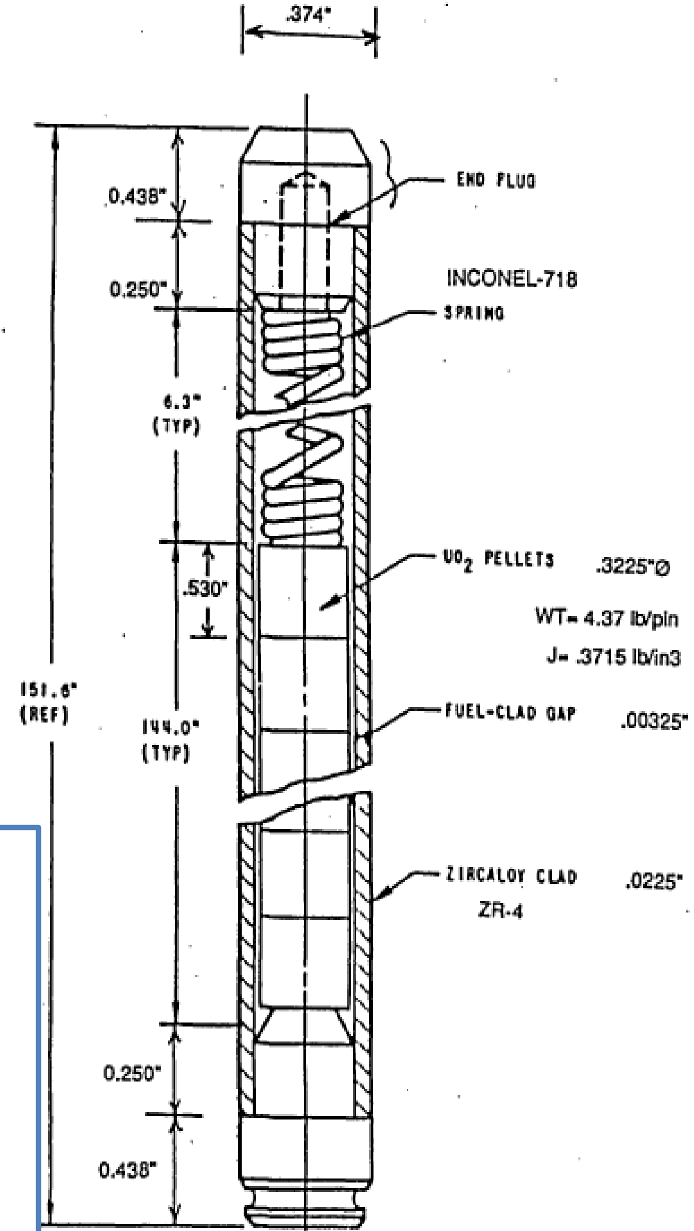
There is one common cruciform control blade for the set.

Cores in units 2 and 3 are larger than 1.

Tepco



- 94 (68) tonne of uranium metal in core
  - 548 (400) fuel assemblies
  - 63 fuel pins in each (8 x 8 array)
  - 137 (97) control blades (Boron Carbide)



Typical fuel pin

Primary Containment

Pressure limits:
Design 4 atm
Limit 8 atm
Fail 10 atm?

Brown's Ferry

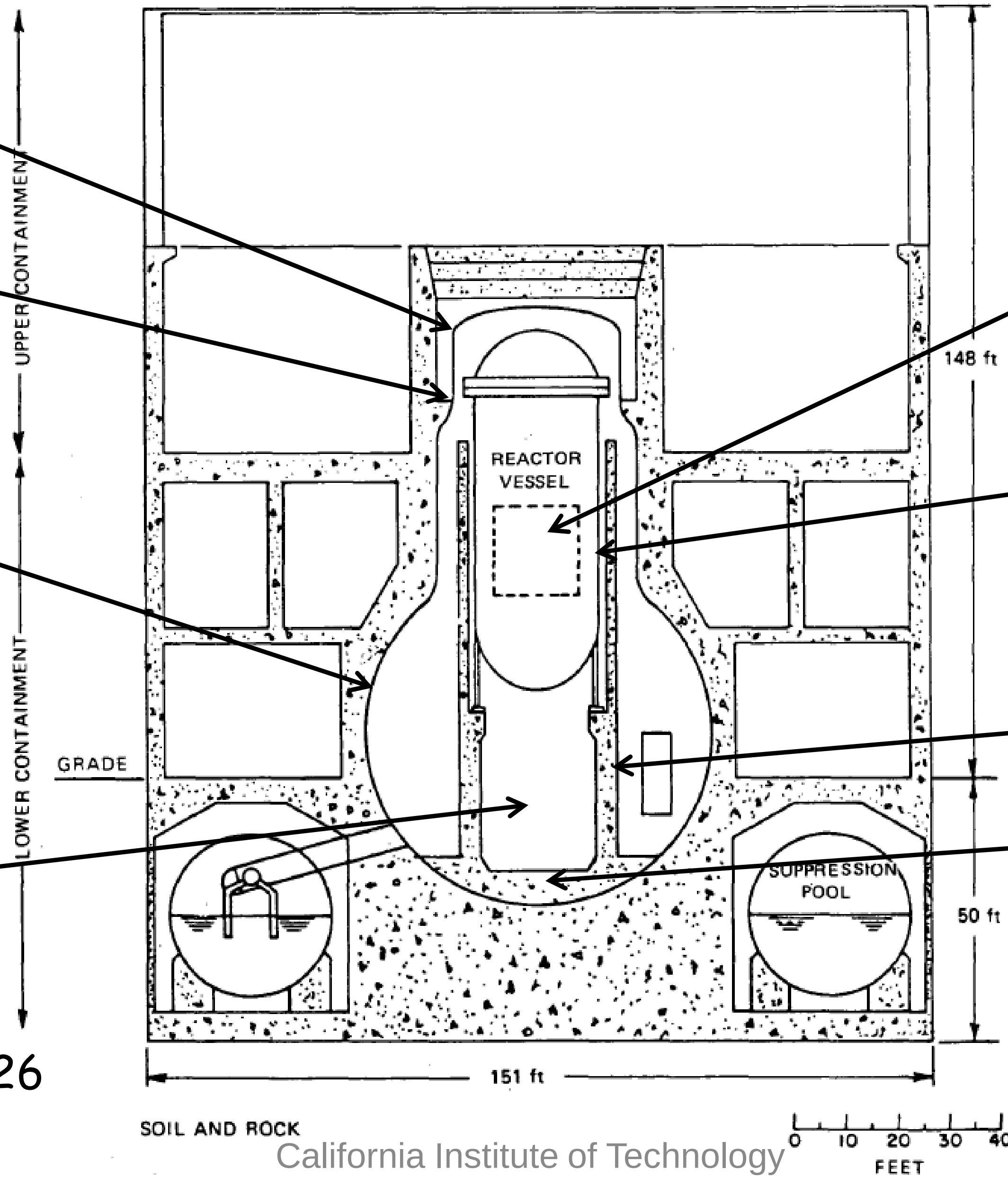
Containment Structure – Mark I

Dry well head

seal

Primary containment vessel

Reactor cavity



Core

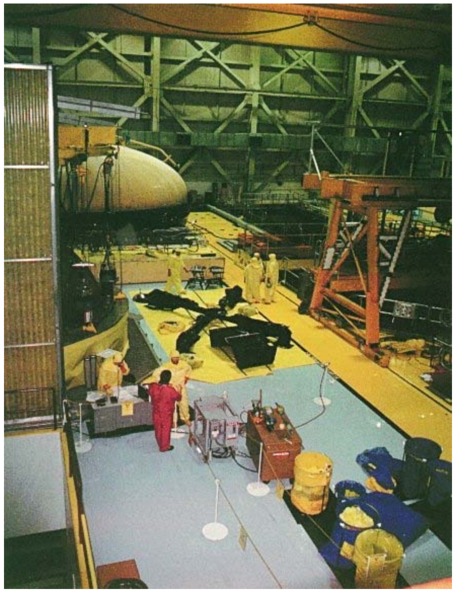
Reactor Pressure Vessel

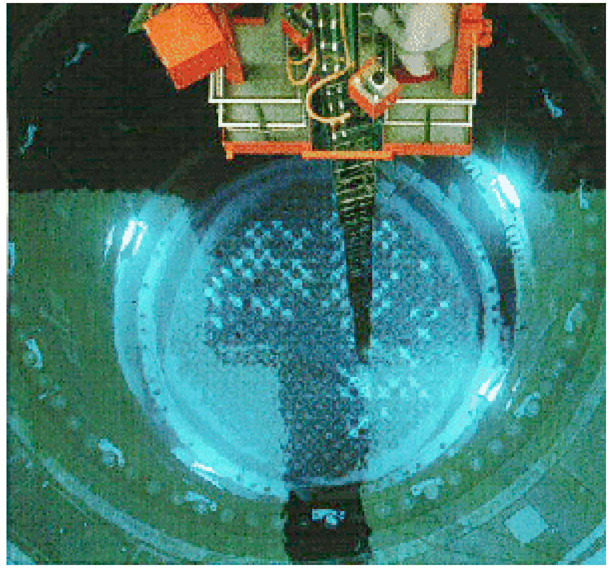
Pedestal

Basemat

NUREG/CR-2726

Refueling – For a typical BWR, 1/3 of core changed out every 12 to 24 mos





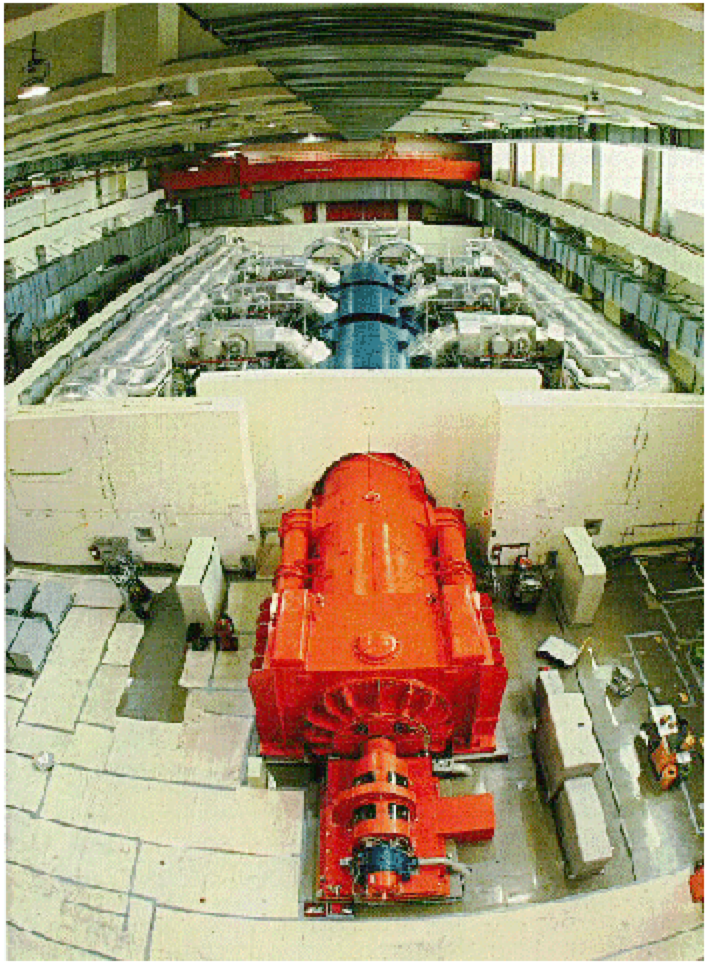
Primary containment and reactor pressure vessel heads are removed

Blue glow is Cerenkov radiation – water serves as “biological shield”

Fuel assembly is being handled with operators standing on the platform

Nuclear Tourist

Turbine and generator



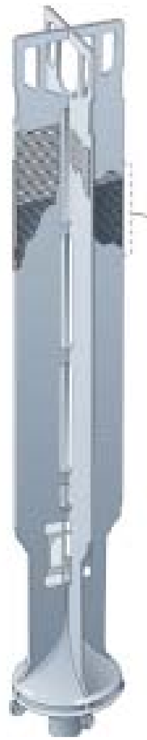
Turbine surrounding by shielding to protect operators.

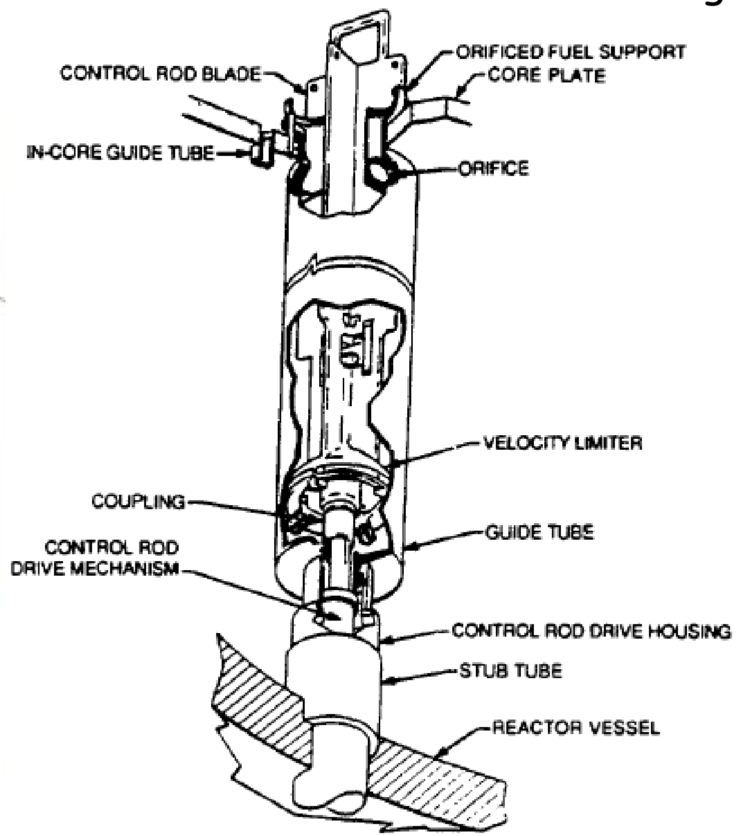
Water passing through reactor picks up radionuclides that are released from fuel pins through defects or diffusion. Impurities in water are activated. Radiolysis generates H2 and O2 in water

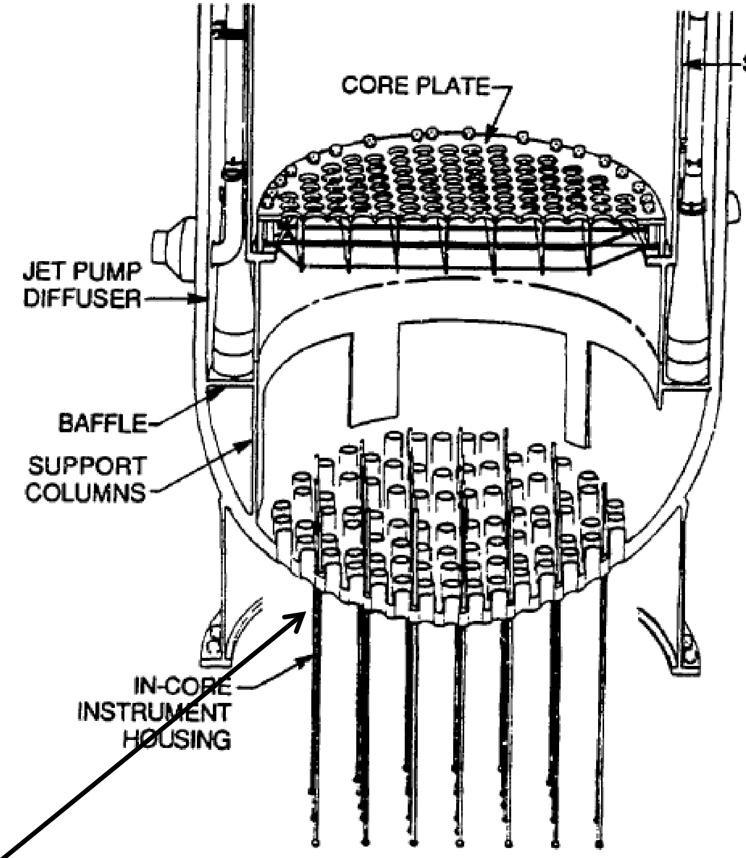
[Nuclear Tourist]

Control Rod System

Hodge and Ott 1989, Hodge 1989



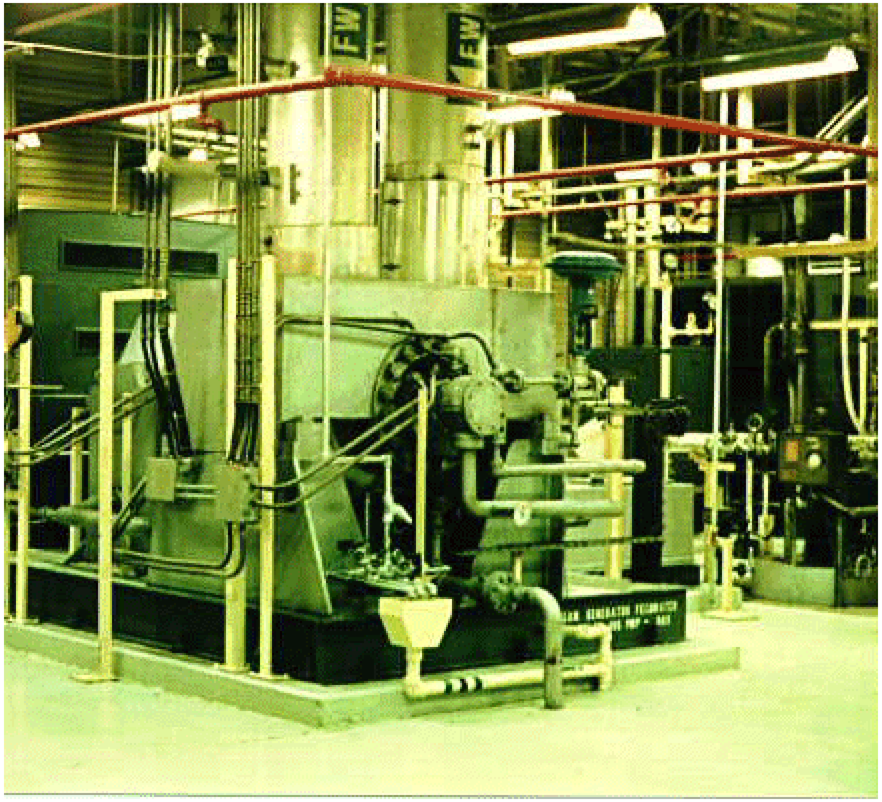




Control rods enter through lower head in BWR due to interference with steam dryer in upper portion of reactor vessel.

More that 200 penetrations for control rods and instruments in lower head. These are the likely locations for failure in degraded core event.

Steam Driven Feedwater Pump

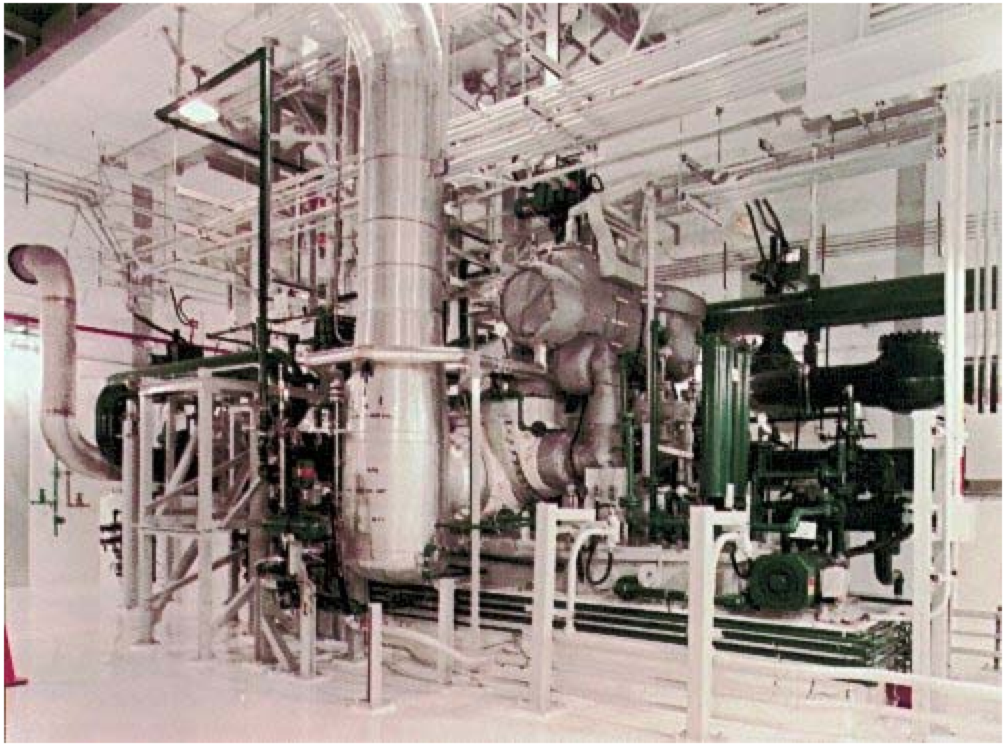


600 gpm, 150-1000 psi

138 t/h 1- 6.8 MPa

Nuclear Tourist

High Pressure Coolant Injection Pump

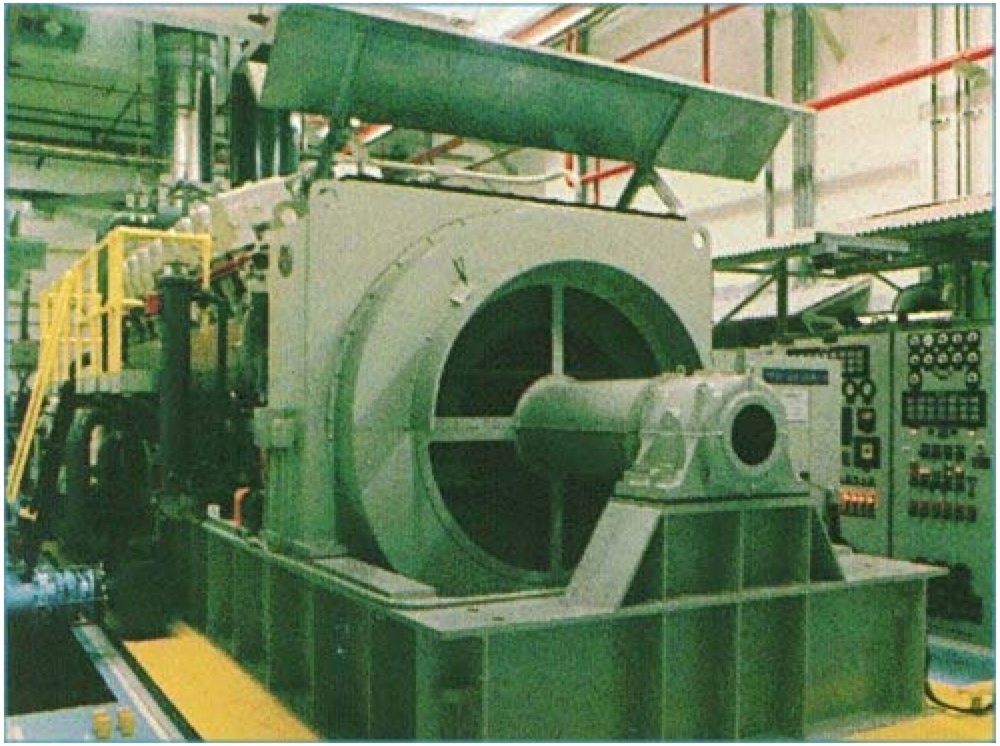


5000 gpm @ 150 to 1000 psig

1134 t/h   1 to 6.8 MPa

Nuclear Tourist

Emergency Diesel Generator



Typical installation is 2 - 6 MWe per generator set.

Usually at least 2 per reactor unit.

Nuclear Tourist

Backup Battery Power

Connected to inverters to generate AC power.

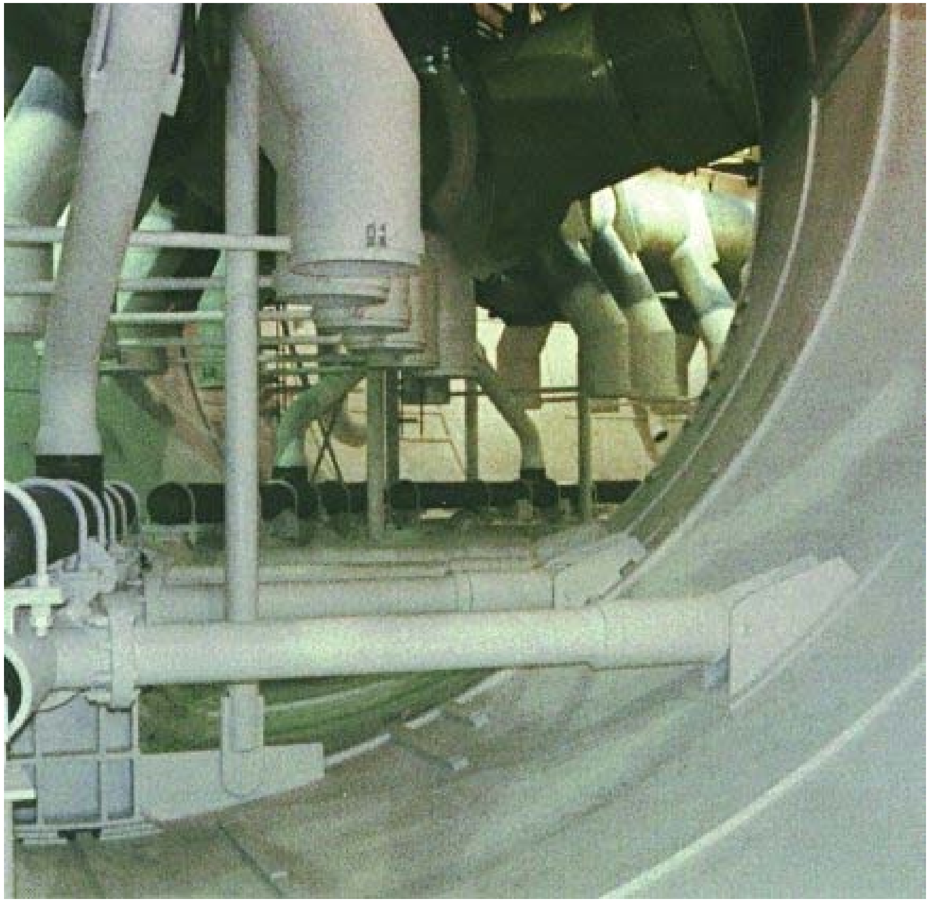
Used only to power key instruments and controls.

Enough capacity for 8 hrs operation.

Nuclear Tourist

Suppression Pool Torus

Units 2,3,4 contain 2980 tonne water (1750 for unit 1)
Connected to sphere with vent lines, vacuum breakers for reverse flow



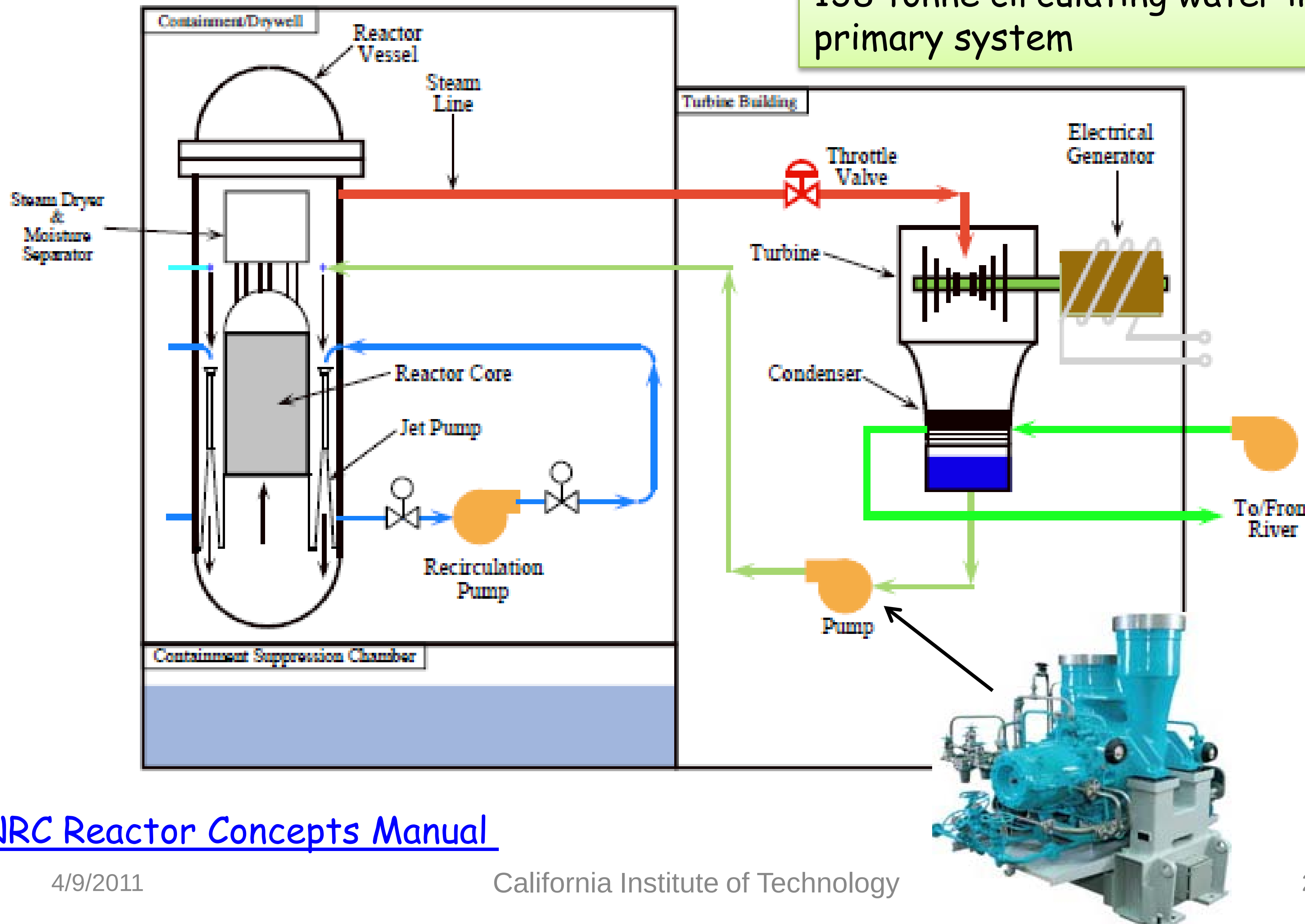
Nuclear Tourist

Control Room

[Nuclear Tourist]

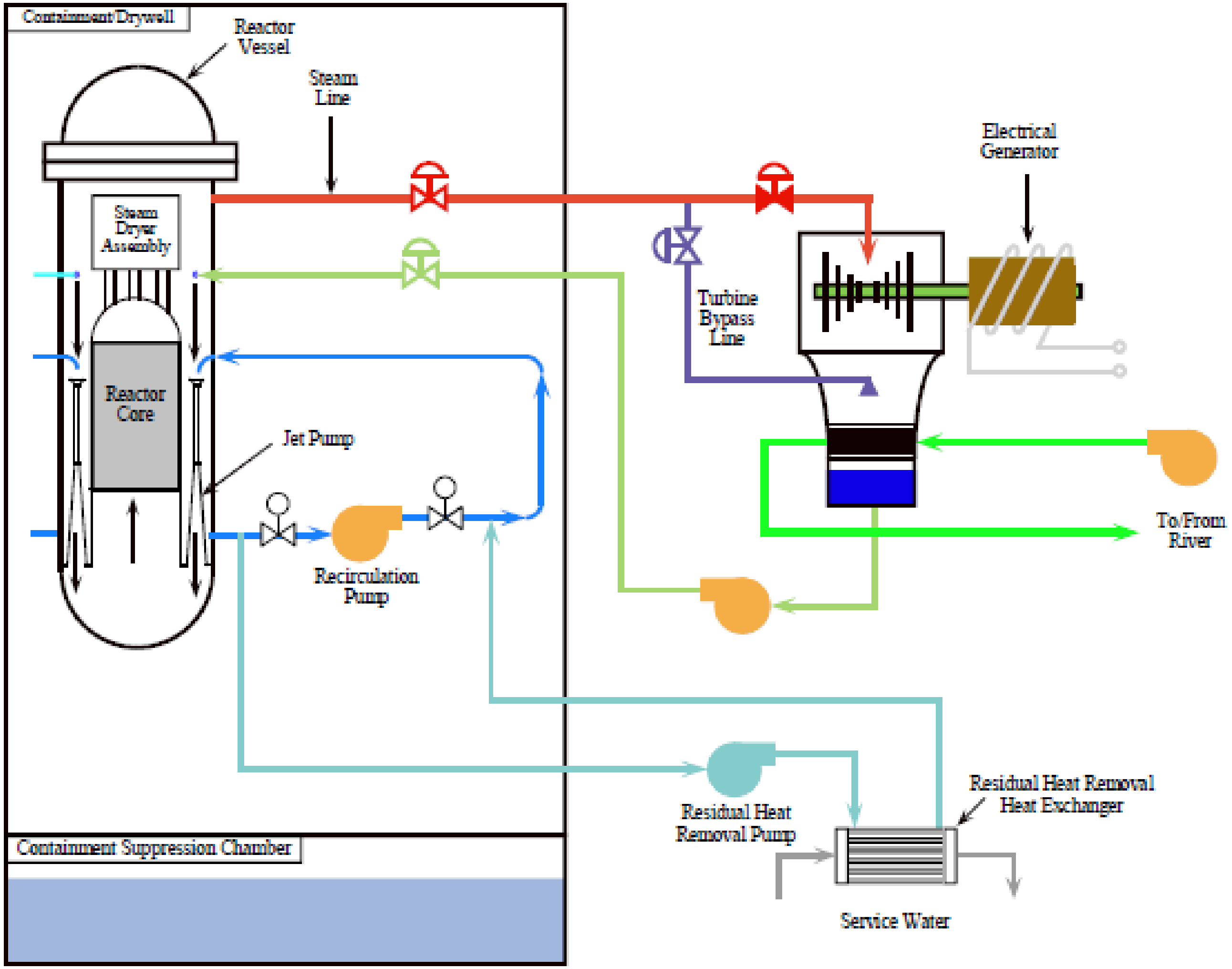
Normal Operation

138 tonne circulating water in primary system



[NRC Reactor Concepts Manual](#)

Normal Shut down - Residual Heat Removal



Control blades inserted

Turbine bypassed

Electrically-driven feedwater pumps circulate water through core

Condenser cooling water removes energy from decay heat

Reactor slowly cooled off and depressurized.

[NRC Reactor Concepts Manual](#)

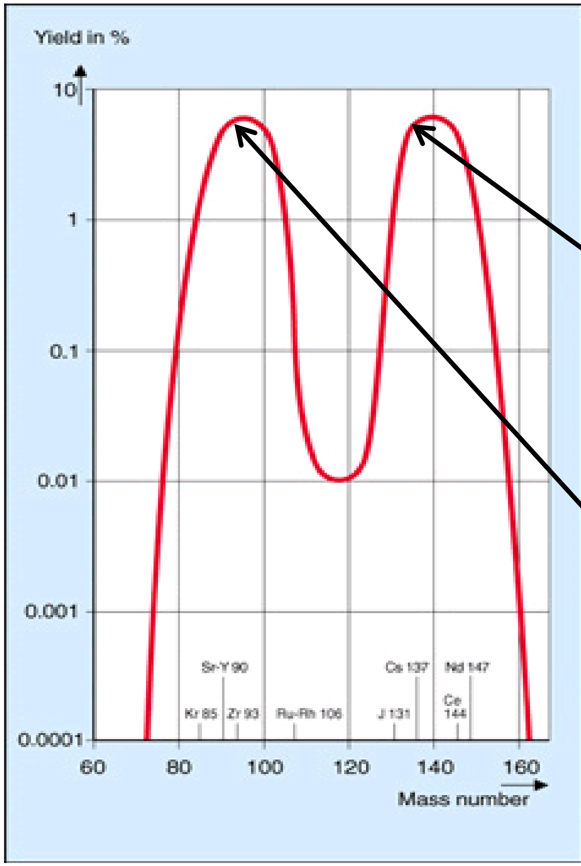
Radioactive Isotopes and NPP

- 1000 kg of fuel metal
  - 30 kg of U-235
  - 970 kg of U-238
- After 3 years in reactor
  - 7 kg U-235
  - 940 kg U-238
  - 9 kg Pu
  - 6 kg actinides
  - 38 kg Fission Products, ~100 radioisotopes including Ce-137, I-131, Sr-90.
- Multiple Barriers to release
  - Cladding on fuel rods
  - Reactor Pressure Vessel, piping, turbine, condenser
  - Primary containment vessel
  - Suppression pool
  - Reactor, turbine building at negative pressure
  - Filter ventilation and exit through stack

Bodansky 2nd Ed

Fission Product Decay

- The radioactive isotopes that result from fission are unstable (too many neutrons) and when they decay, they release energy – heat that goes into the fuel.
- This process is spontaneous and cannot be stopped.



Process occurs through a chain of beta decay $n \rightarrow p + e^- + \bar{\nu}$ and gamma decay $A^* \rightarrow A + \gamma$ releasing an additional ~1 Mev energy per decay.

$^{137}Te \rightarrow {}^{137}I \rightarrow {}^{137}Xe \rightarrow {}^{137}Cs \rightarrow {}^{137}Ba^* \rightarrow {}^{137}Ba$

Chain terminates when a stable isotope is formed

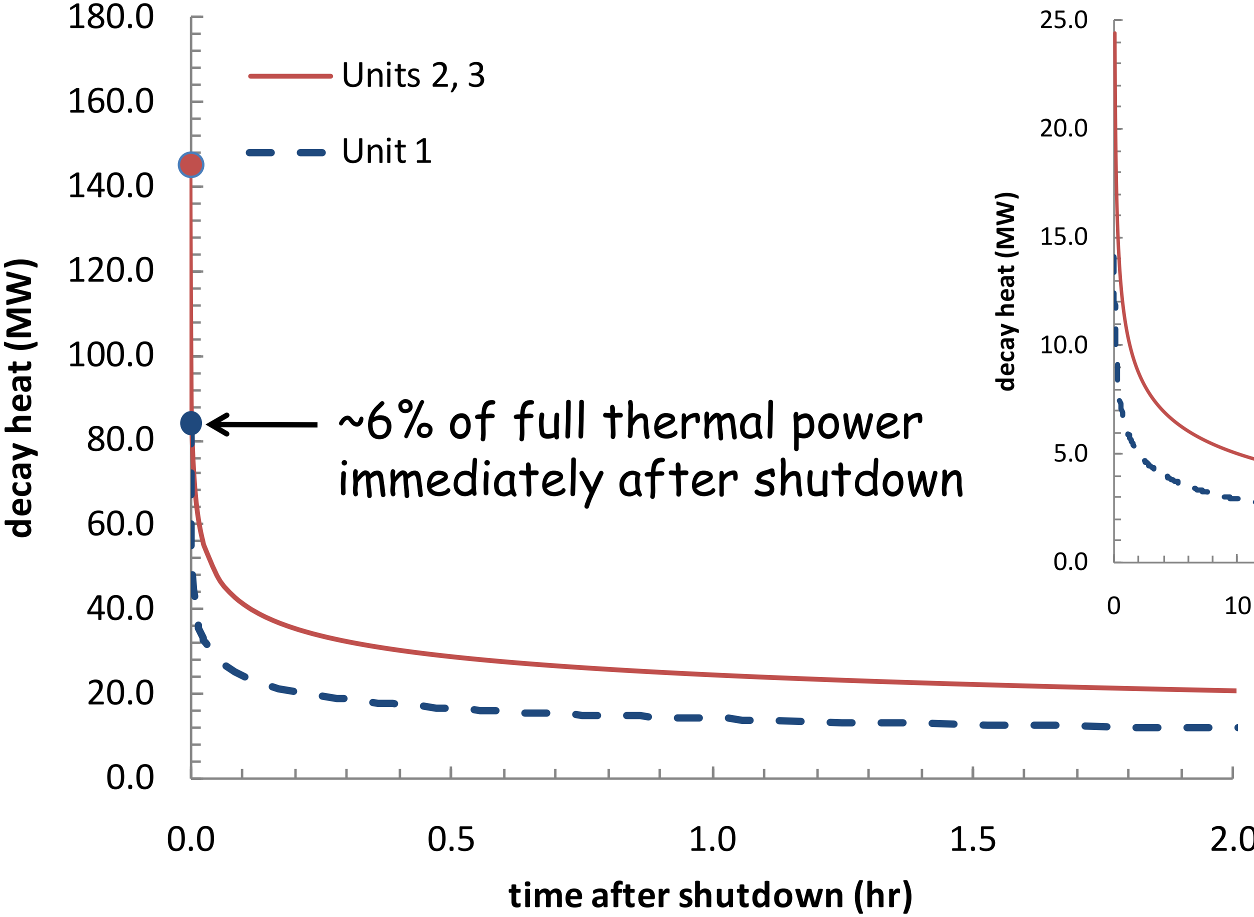
$^{90}Kr \rightarrow {}^{90}Rb^* \rightarrow {}^{90}Rb \rightarrow {}^{90}Sr \rightarrow {}^{90}Y^* \rightarrow {}^{90}Y \rightarrow {}^{90}Zr^* \rightarrow {}^{90}Zr$

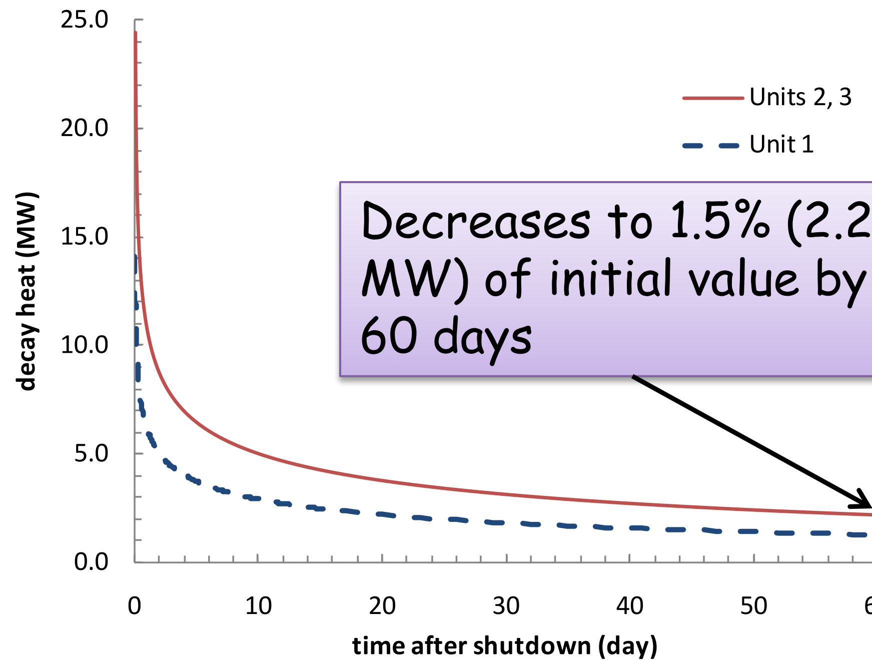
http://www.euronuclear.org/info/encyclopedia/f/fissionyield.htm

Fission Products Create Decay Heating

Decay heat is due to beta and gamma decay of fission products. Decreases rapidly with time because many FP have a short ½-life.

Estimates based on Wigner-Way model, see p. 16 of EE Lewis, Fundamentals of Nuclear Reactor Physics.

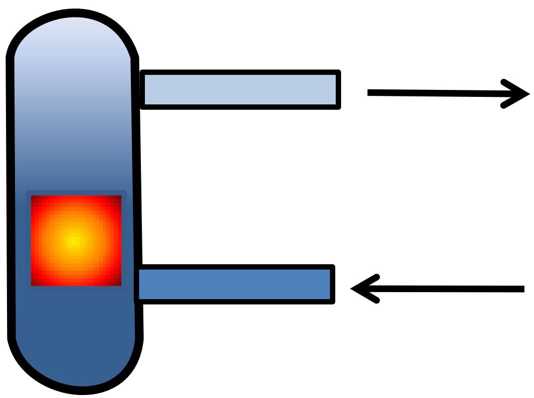




Decreases to 1.5% (2.2 MW) of initial value by 60 days

Thermal power during normal operation
Unit 1 1380 MWt
Unit 2 & 3 2381 MWt

Cooling Water requirements



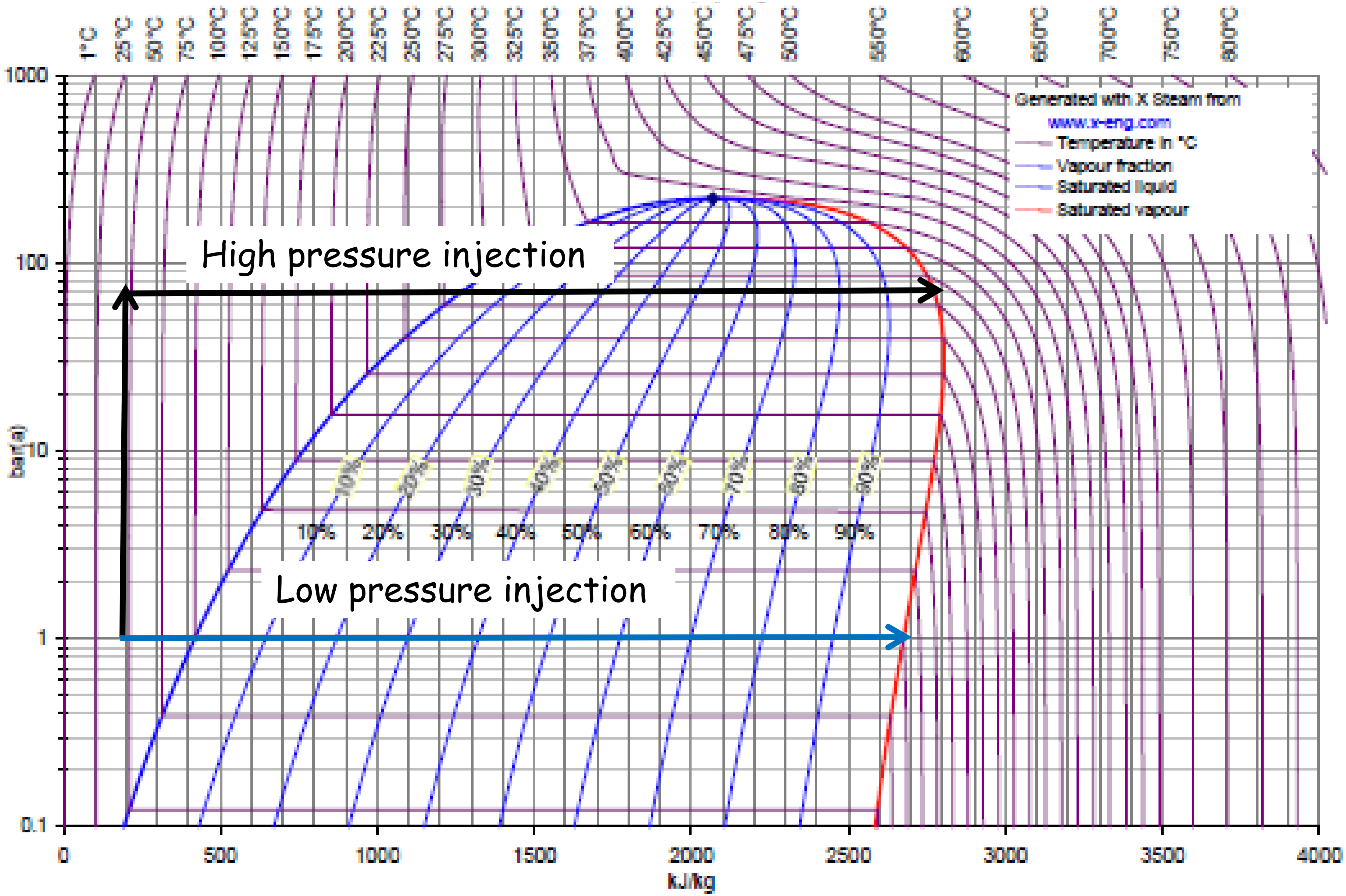
Energy balance

$$(H_{out} - H_{in})\dot{M} = \dot{Q}$$

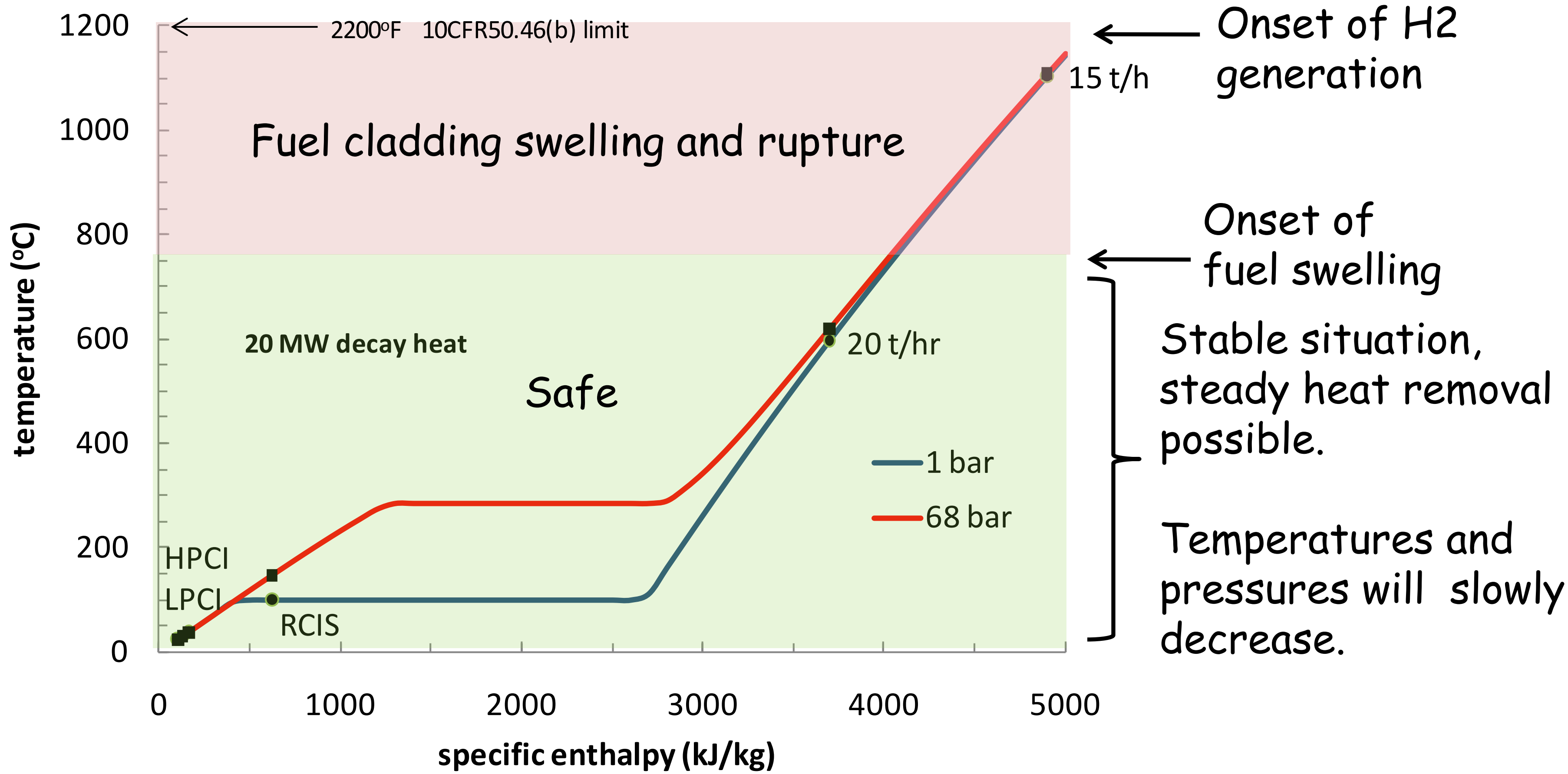
$$\dot{Q} = 20 \text{ MW}$$

Capability	$\dot{M}$ (t/h)	H_{out} (kJ/kg)	T_{out} (°C)
Portable pumps	15	4900	1103
RCIC	138	622	100
HPCI	1134	163	39
LPCI	2478	129	31
Main feedwater	21600	103	25

Pressure-Enthalpy Diagram

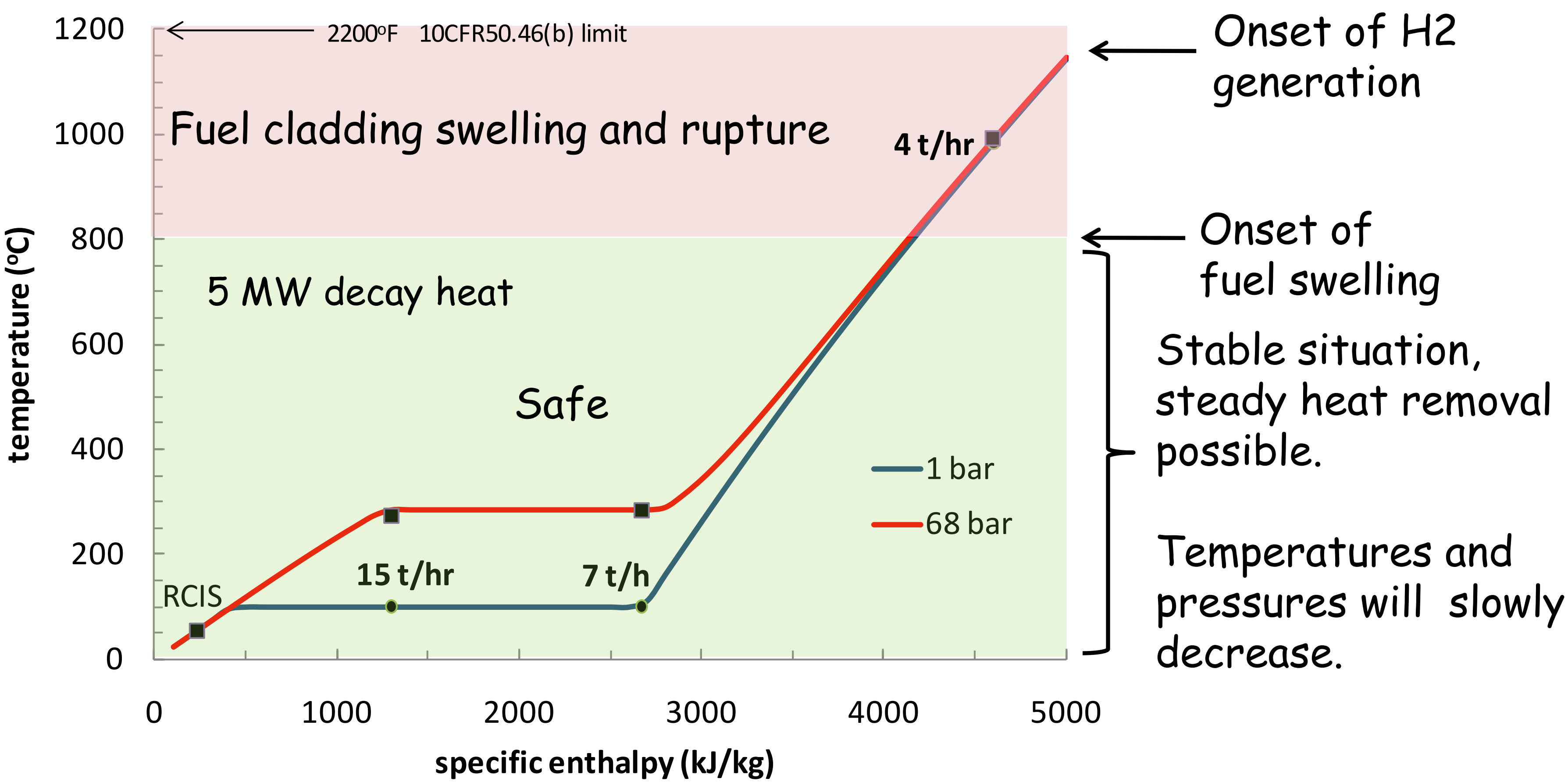


Heat removal estimates (20 MW)



Caution: Extremely simplistic "back of the envelope" estimate! Power drops below 20 MWt after 2 hr in units 2 and 3, 12 min in unit 1.

Heat removal estimates (5 MW)



Caution: Extremely simplistic "back of the envelope" estimate! Power drops below 5 MWt in 10 days for units 2 and 3, 2 days in unit 1.

Caution

- The values are nominal since the details of the fuel loading and burnup have not been accounted for.
- All of these estimates depend on the core geometry being intact.
- If the core has suffered extensive damage then it is possible for there to be localized "recriticality" which means the induced fission will resume, creating more heat and neutrons.
  - Some unexpected "beams" of neutrons were reported during the early days and there were some radioisotopes detected that indicated recriticality might have occurred. But there is no evidence of ongoing criticality events at this time.

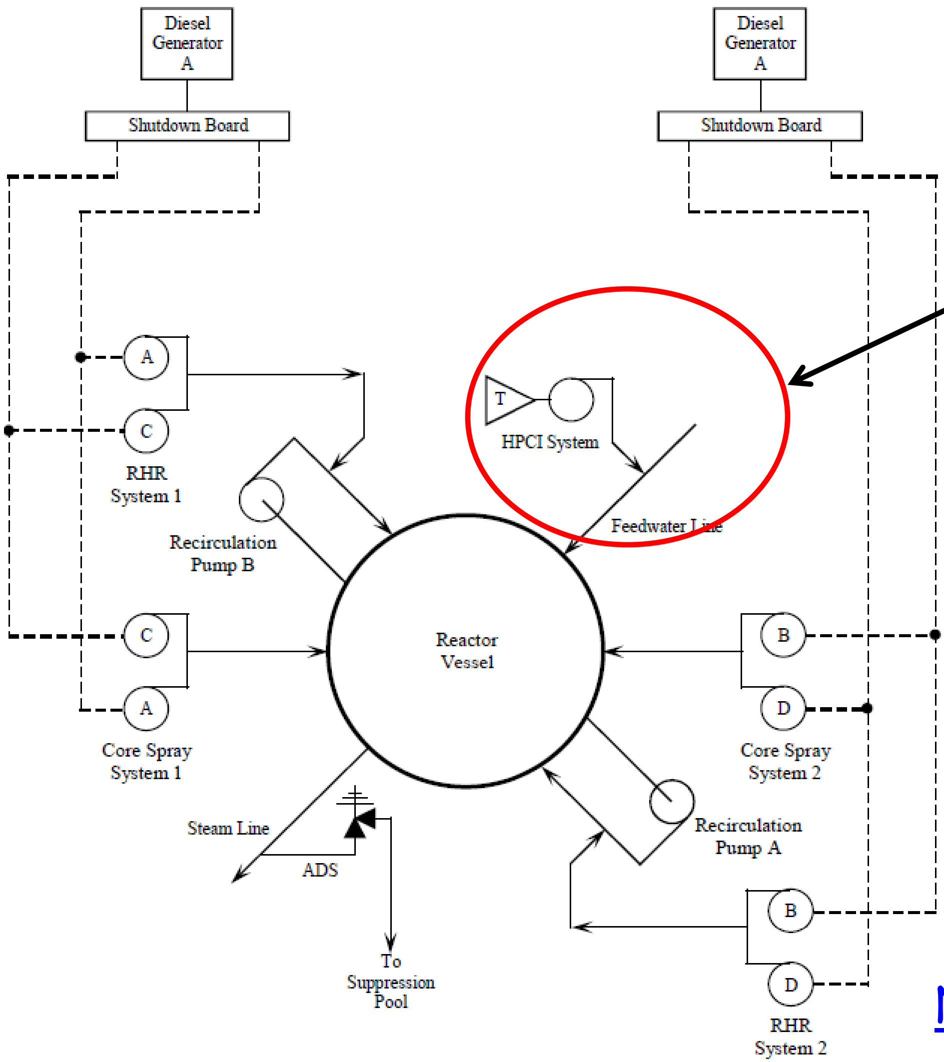
Accident Management "normal"

- Control reactivity – control rods/poison
- Maintain water inventory in reactor pressure vessel
  - Keep core covered with cooling water
  - Maintain cladding integrity, don't generate H2
- Keep pressure in reactor vessel below failure pressure
- Keep pressure in containment vessel below failure pressure
- Cool suppression pool below boiling point
- Vent gases through suppression pool and stack

Cooling Systems Designed for Post-Accident Heat Removal and Control

- Standby Liquid Control System – Boron poison
- Emergency Core Cooling Systems
  - High Pressure Coolant Injection
  - Reactor Core Isolation Cooling
  - Automatic Containment Depressurization
  - Low Pressure Coolant Injection
  - Core Spray

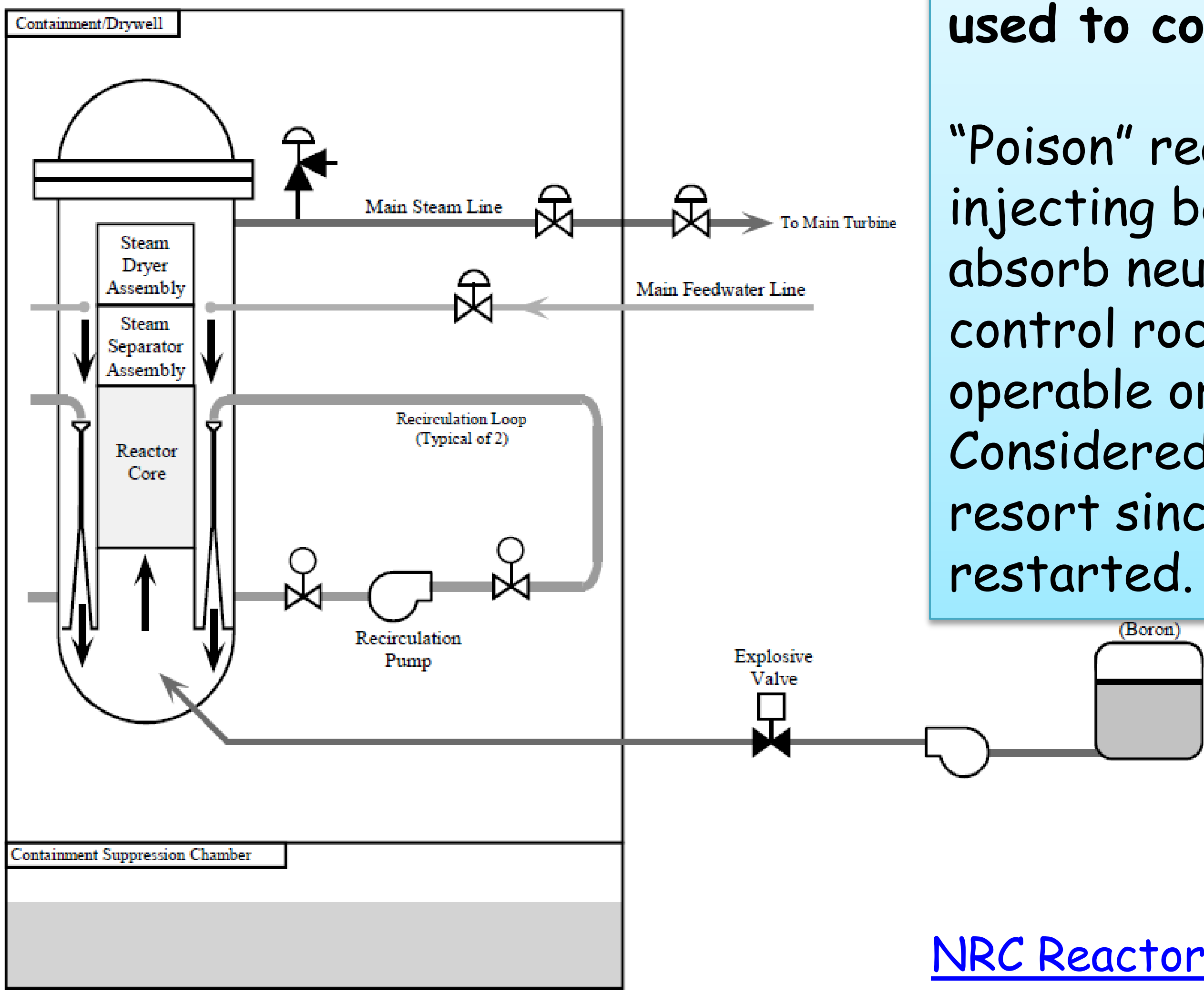
Off-Site or Diesel Electrical Power Required for Most ECCS Systems



RCIC pump is steam Driven, only needs valve operation

NRC Reactor Concepts Manual

Standby Liquid Control System



Not heat removal system but used to control reactivity.

"Poison" reactor core by injecting borated water to absorb neutrons. Used when control rod function is not operable or core is damaged. Considered system of last resort since reactor cannot be restarted.

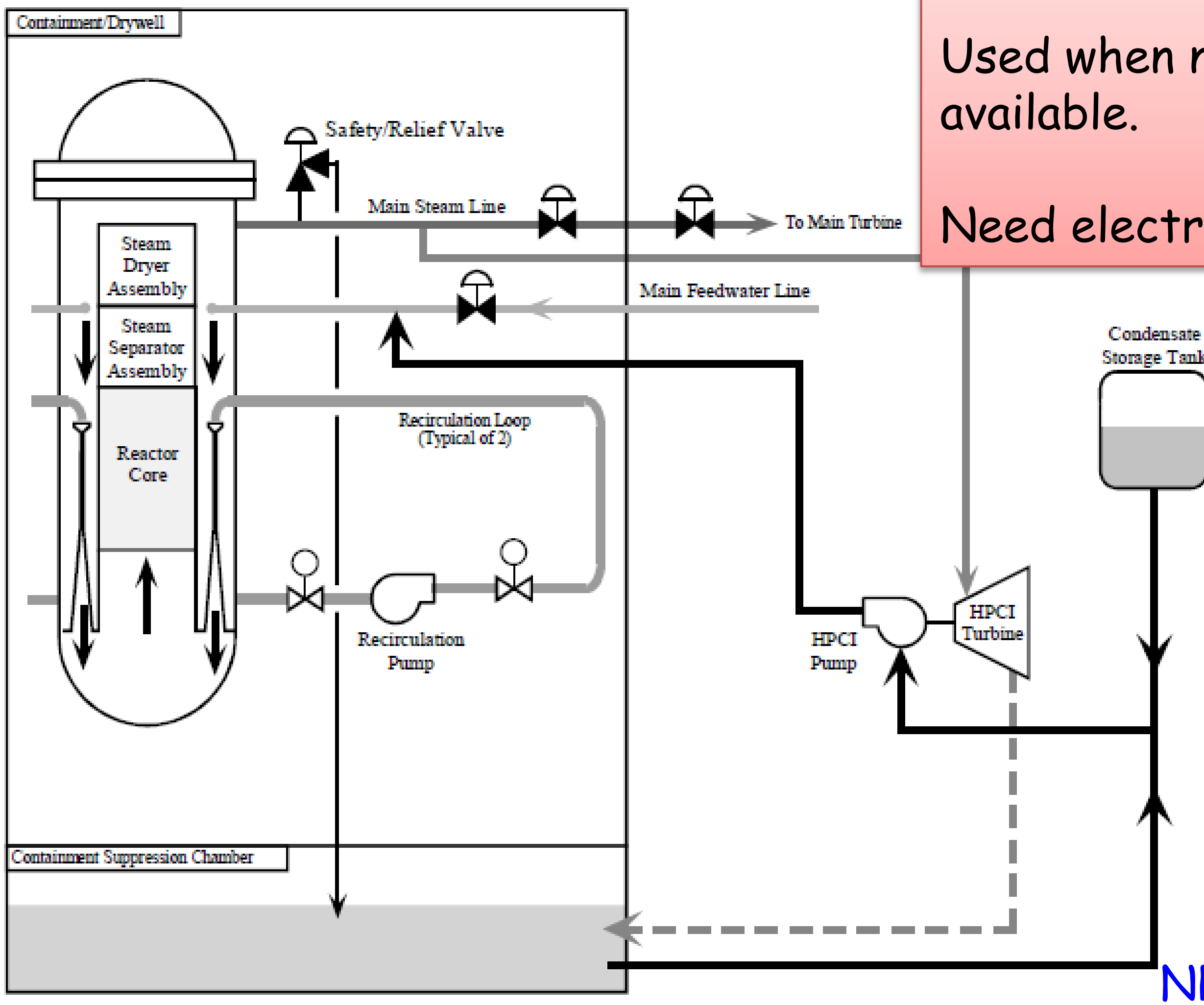
NRC Reactor Concepts Manual

High Pressure ECCS - RCIC

Pump is driven by steam

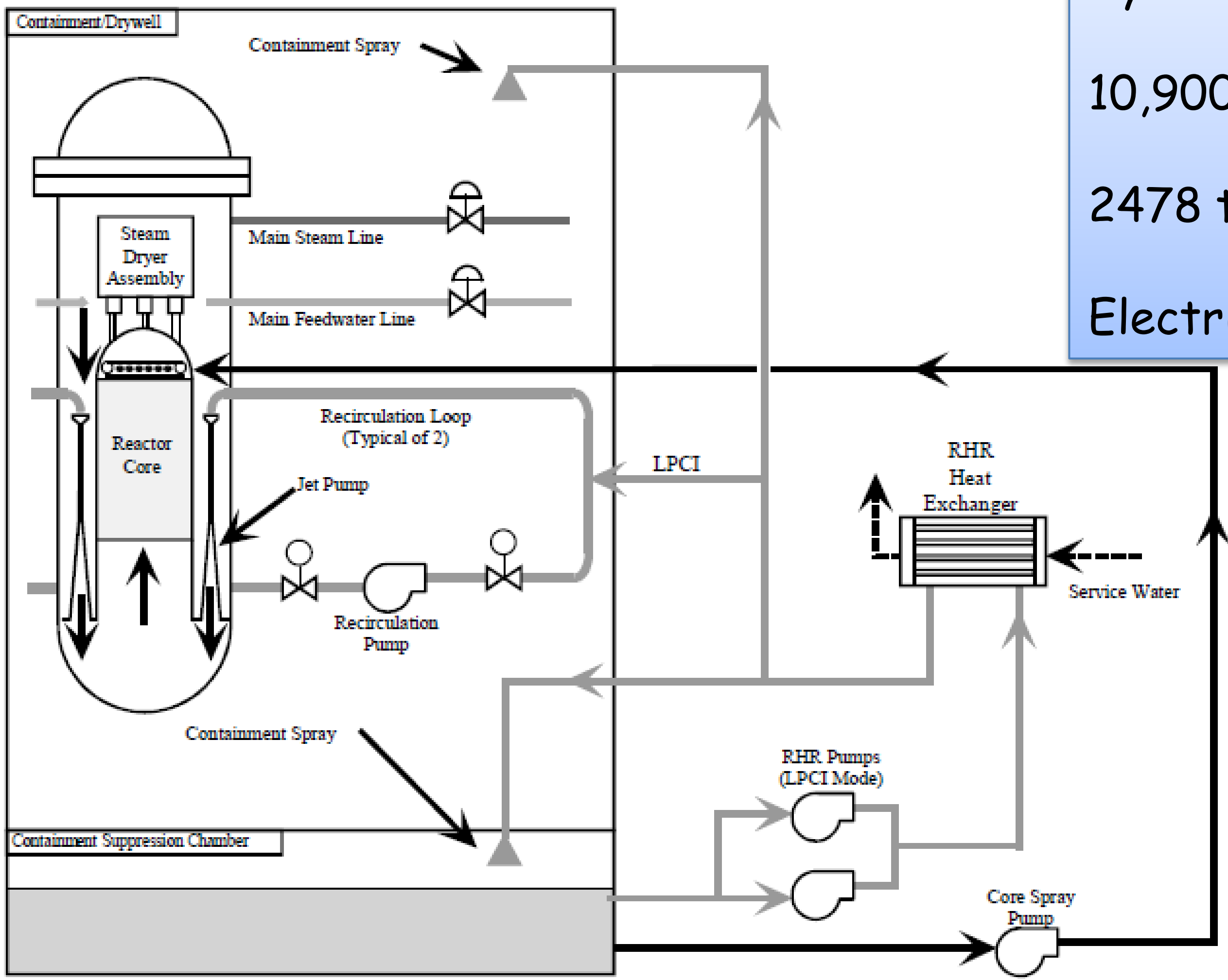
Used when normal feedwater is not available.

Need electrical power to operate valves



[NRC Reactor Concepts Manual]

Low Pressure ECCS - LPCI



System at low pressure

10,900 gpm @ 20 psig

2478 tonne/h   136 kPa

Electrical power required

[NRC Reactor Concepts Manual]

DEFENSE-IN-DEPTH

Multiple reactivity control systems

Multiple coolant injection and heat removal systems

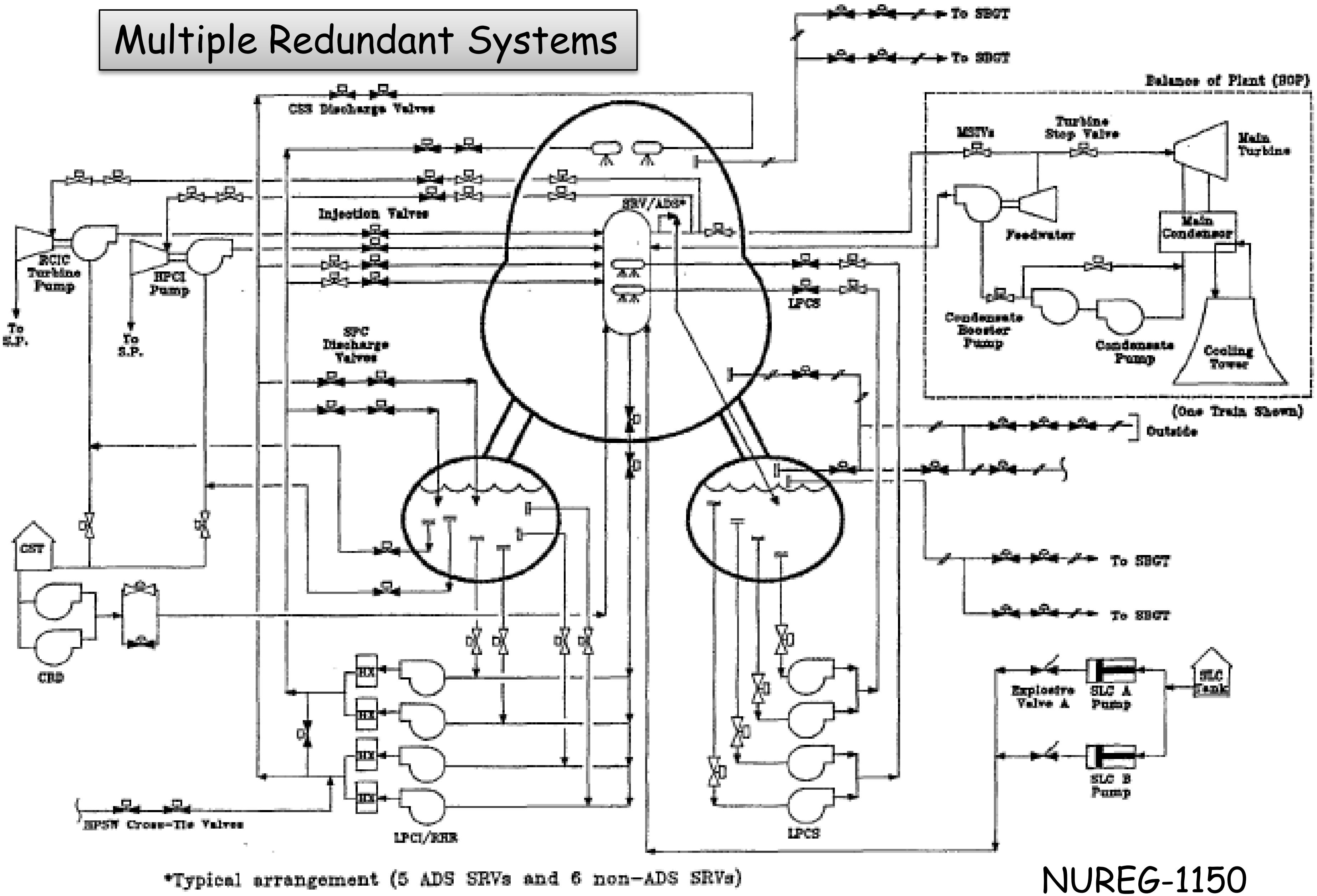
Multiple barriers to fission product release

Table 4.1 Summary of design features: Peach Bottom Unit 2.

1.	Coolant Injection Systems	a.	High-pressure coolant injection system provides coolant to the reactor vessel during accidents in which system pressure remains high, with 1 train and 1 turbine-driven pump.
		b.	Reactor core isolation cooling system provides coolant to the reactor vessel during accidents in which system pressure remains high, with 1 train and 1 turbine-driven pump.
		c.	Low-pressure core spray system provides coolant to the reactor vessel during accidents in which vessel pressure is low, with 2 trains and 4 motor-driven pumps.
		d.	Low-pressure coolant injection system provides coolant to the reactor vessel during accidents in which vessel pressure is low, with 2 trains and 4 pumps.
		e.	High-pressure service water crosstie system provides coolant makeup source to the reactor vessel during accidents in which normal sources of emergency injection have failed (low RPV pressure), with 1 train and 4 pumps for crosstie.
		f.	Control rod drive system provides backup source of high-pressure injection, with 2 pumps/210 gpm (total)/1,100 psia.
		g.	Automatic depressurization system for depressurizing the reactor vessel to a pressure at which the low-pressure injection systems can inject coolant to the reactor vessel: 5 ADS relief valves/capacity 820,000 lb/hr. In addition, there are 6 non-ADS relief valves.
2.	Key Support Systems	a.	dc power with up to approximately 10–12-hour station batteries.
		b.	Emergency ac power from 4 diesel generators shared between 2 units.
		c.	Emergency service water provides cooling water to safety systems and components shared by 2 units.
3.	Heat Removal Systems	a.	Residual heat removal/suppression pool cooling system to remove heat from the suppression pool during accidents, with 2 trains and 4 pumps.
		b.	Residual heat removal/shutdown cooling system to remove decay heat during accidents in which reactor vessel integrity is maintained and reactor at low pressure, with 2 trains and 4 pumps.
		c.	Residual heat removal/containment spray system to suppress pressure and remove decay heat in the containment during accidents, with 2 trains and 4 pumps.
4.	Reactivity Control Systems	a.	Control rods.
		b.	Standby liquid control system, with 2 parallel positive displacement pumps rated at 43 gpm per pump, but each with 86 gpm equivalent because of the use of enriched boron.
5.	Containment Structure	a.	BWR Mark I.
		b.	0.32 million cubic feet.
		c.	56 psig design pressure.
6.	Containment Systems	a.	Containment venting—drywell and wetwell vents used when suppression pool cooling and containment sprays have failed to reduce primary containment pressure.

NUREG 1150

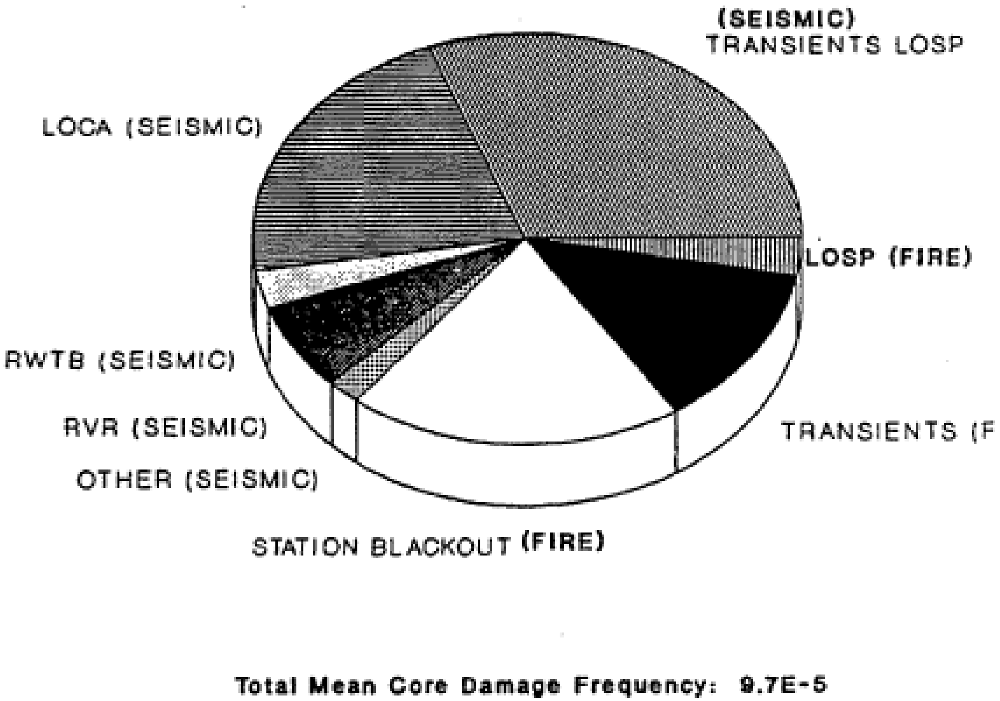
Multiple Redundant Systems

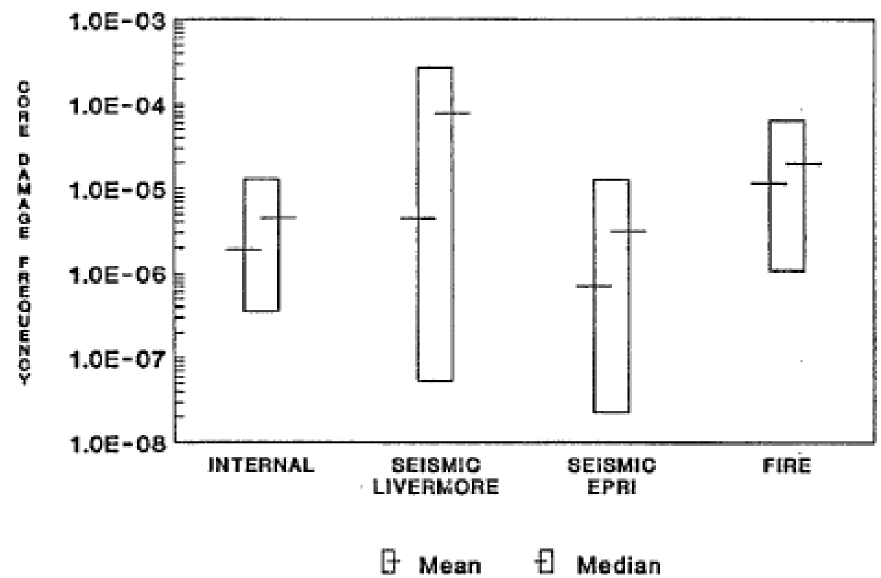


NUREG-1150

What is the risk of core damage?

1/10,000 Reactor-years





NUREG-1150 Peach Bottom results –frequency is per reactor-year of operation

Factors Contributing to Risk

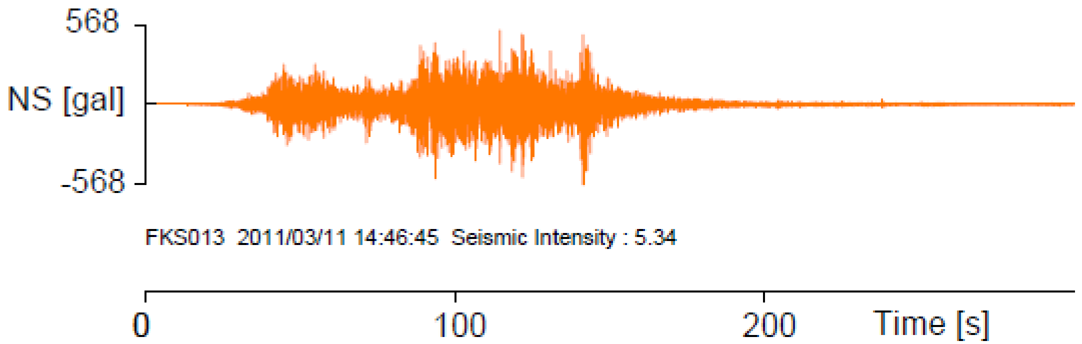
The risk from the internal events are driven by long-term station blackout (SBO) and anticipated transients without scram (ATWS). The dominance of these two plant damage states can be attributed to both general BWR characteristics and plant-specific design. BWRs in general have more redundant systems that can inject into the reactor vessel than PWRs and can readily go to low pressure and use their low-pressure injection systems. This means that the dominant plant damage states will be driven by events that fail a multitude of systems (i.e., reduce the redundancy through some common-mode or support system failure) or events that only require a small number of systems to fail in order to reach core damage. The station blackout plant damage state satisfies the first of these requirements in that all systems ultimately depend upon ac power, and a loss of offsite power is a relatively high probability event. The total probability of losing ac power long enough to induce core damage is relatively high, although still low for a plant with Peach Bottom's design. The ATWS scenario is driven by the small number of systems that are needed to fail and the high stress upon the operators in these sequences. NUREG 1150 4.6.2

Four Reactors in Crisis

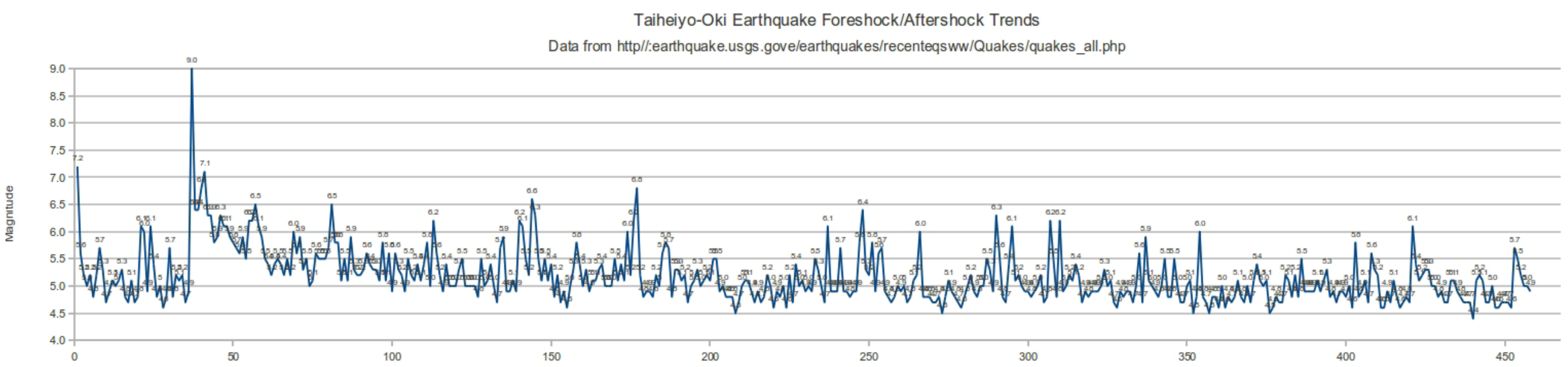
Pre-March 10, 2011

Digital Globe

Huge Earthquake, 500 gal > 250 gal

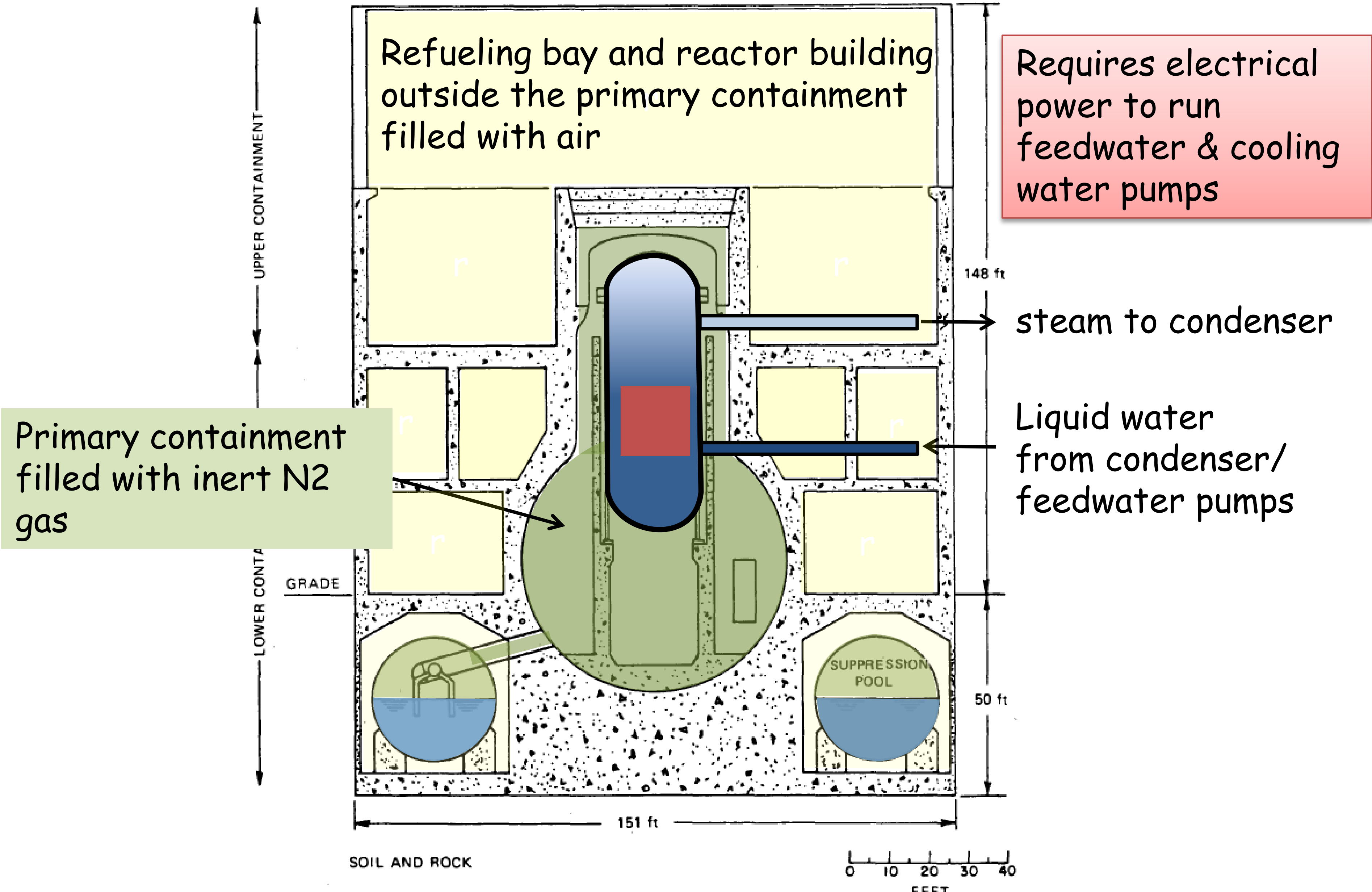


Electrical grid failed, Loss of Offsite Power (LOOP) and shaking initiated reactor shutdown



NIED and USGS

Normal Cooling Through Main Condenser



Huge tsunami(s) 10-15 m > 6 m

Plant Inundated

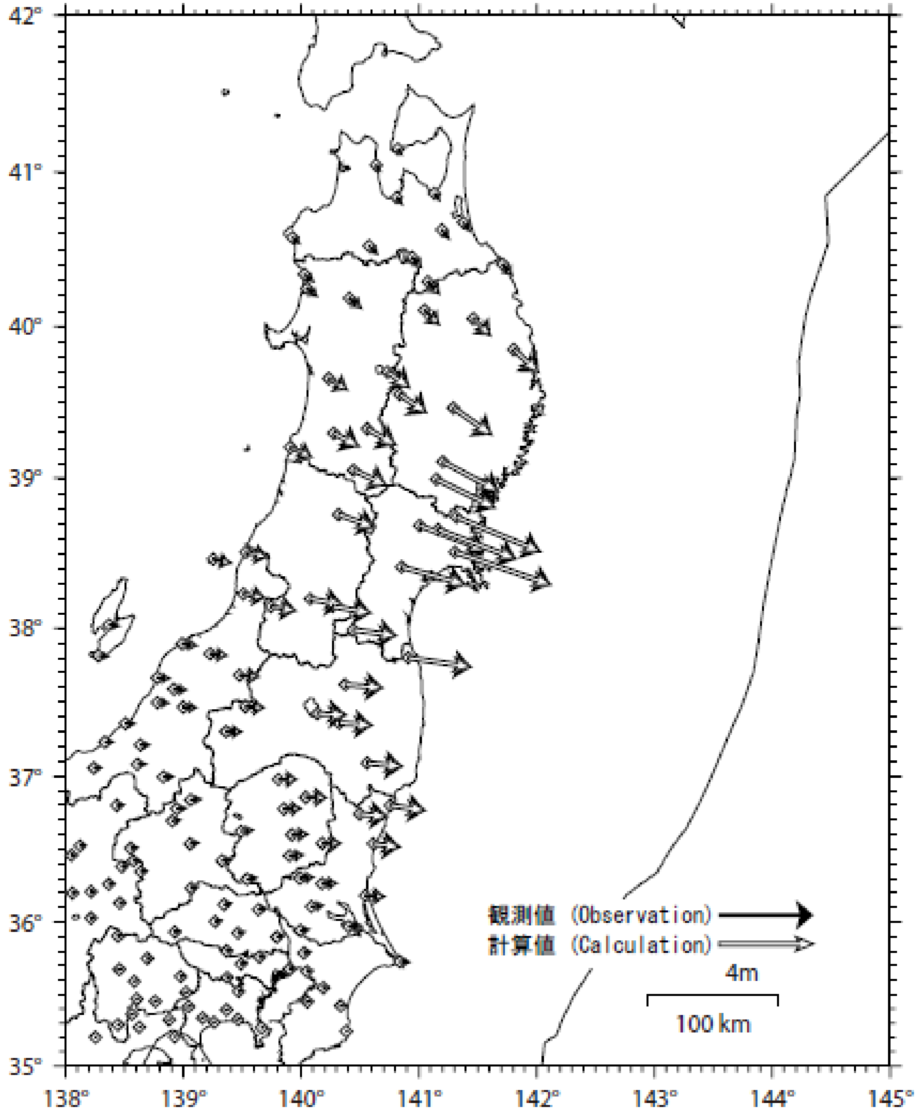


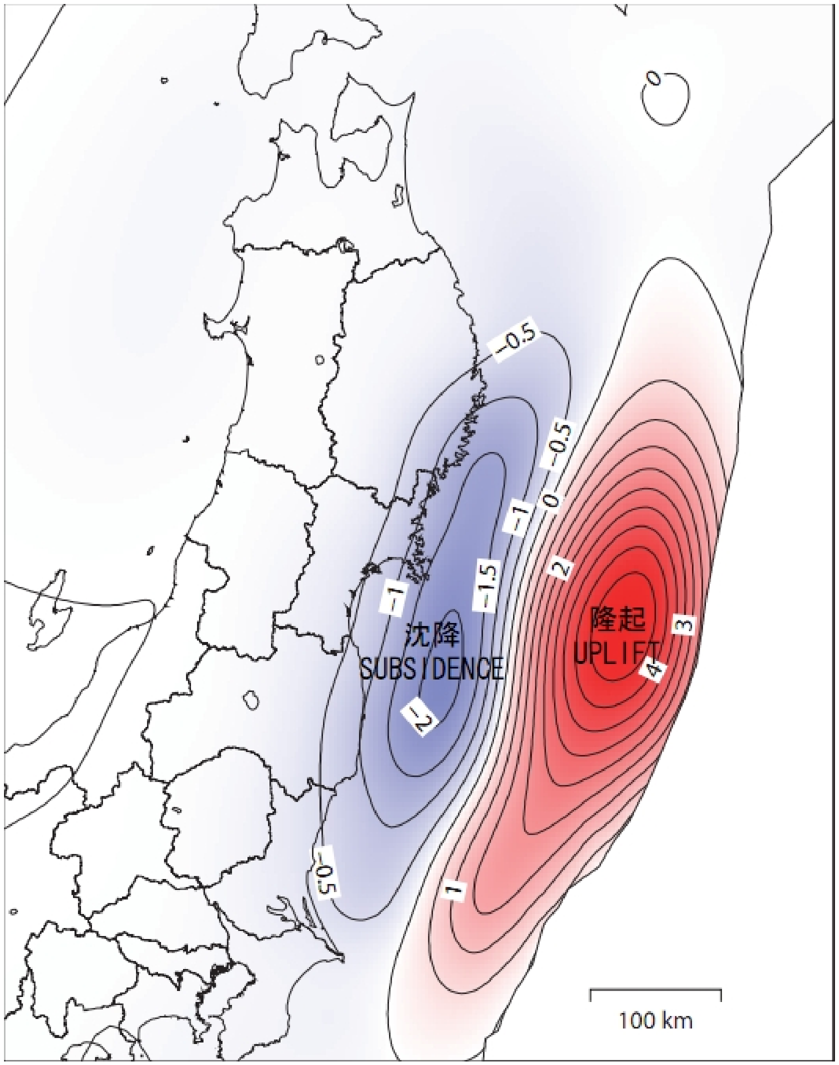


Tepco/Reuters released May 19

Land subsidence in Coastal Region

http://www.gsi.go.jp/cais/topic110315-index-e.html





12 Back-up generators out of 13 fail!

Tepco/Japan Times

Equipment Rooms Flooded

STATION BLACKOUT! →

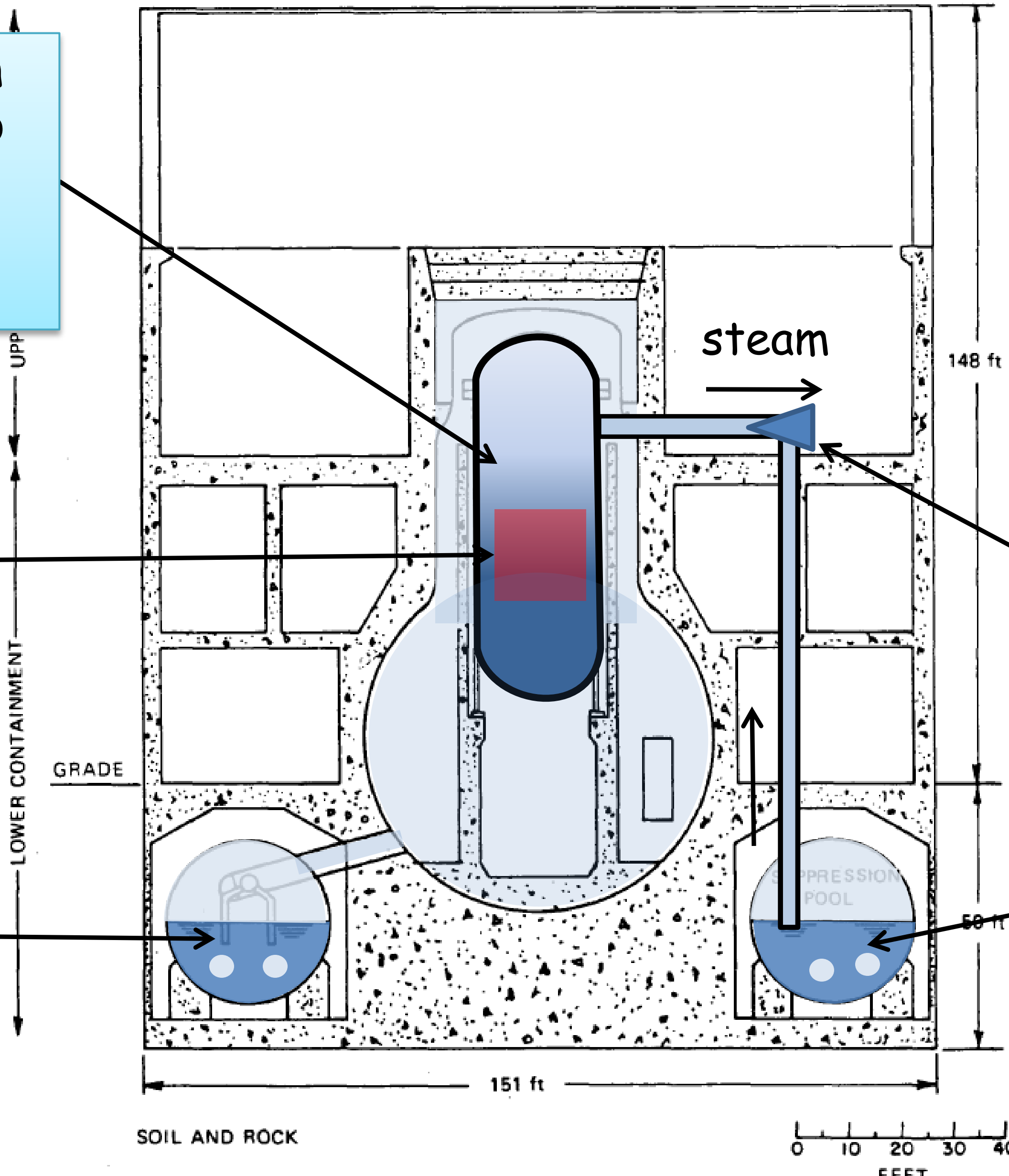
Friday, March 11, 2011				
	14:46:00	11.62	0.00	Tohoku-Pacific megathrust earthquake magnitude 9.0, shaking at Fukushima 1 was about 500 cm/S^2
	14:48:00Fir	11.62	0.00	Reactors and turbines shut down. Control blades inserted into units 1, 2, and 3 and main steam isolation valve closed. Residual heat removal started. Loss of -site power, diesel engines started to provide electrical power.
	15:41:00	11.65	0.88	Tsunami reaches Fukushima. Wave initially estimated at 10 m and revised to be up to 23 m overtops 6.5 m barrier. Diesel generators stop, power switched to battery backup.
	15:42:00	11.65	0.90	Article 10 emergency reported by Tepco for units 1, 2, and 3.
	16:36:00	11.69	1.80	Batteries fail in Unit 1
	16:45:00	11.70	1.95	Article 15 nuclear emergency declared for units 1 and 2 because ECCS function could not be confirmed.
	17:07:00	11.71	2.32	Article 15 Emergency cleared when water level was determined then reinstated for Unit 1.
	17:07:00	11.71	2.32	Unit 1 cooled by isolation condenser. Units 2 and 3 cooled by Reactor Core Isolation Cooling System.
	18:08:00	11.76	3.33	Unit 1 of Fukushima 2 declared to be in Article 10 emergency.
	18:33:00	11.77	3.75	Units 2, 3, and 4 of Fukushima 2 declared to be in Article 10 emergency.
	19:03:00	11.79	4.25	Government declared state of nuclear emergency.
	20:50:00	11.87	6.03	1864 people within 2 km of plant evacuated.

Safety Relief Valve (SRV) Releases Steam to Lower Reactor Pressure

Water level in core begins to drop as steam is vented through SRV.

Decay heat in core generates steam and increases pressure.

suppression pool heats up as steam is added.



Pressure inside reactor rises if not enough heat is being removed after MSIV is closed.

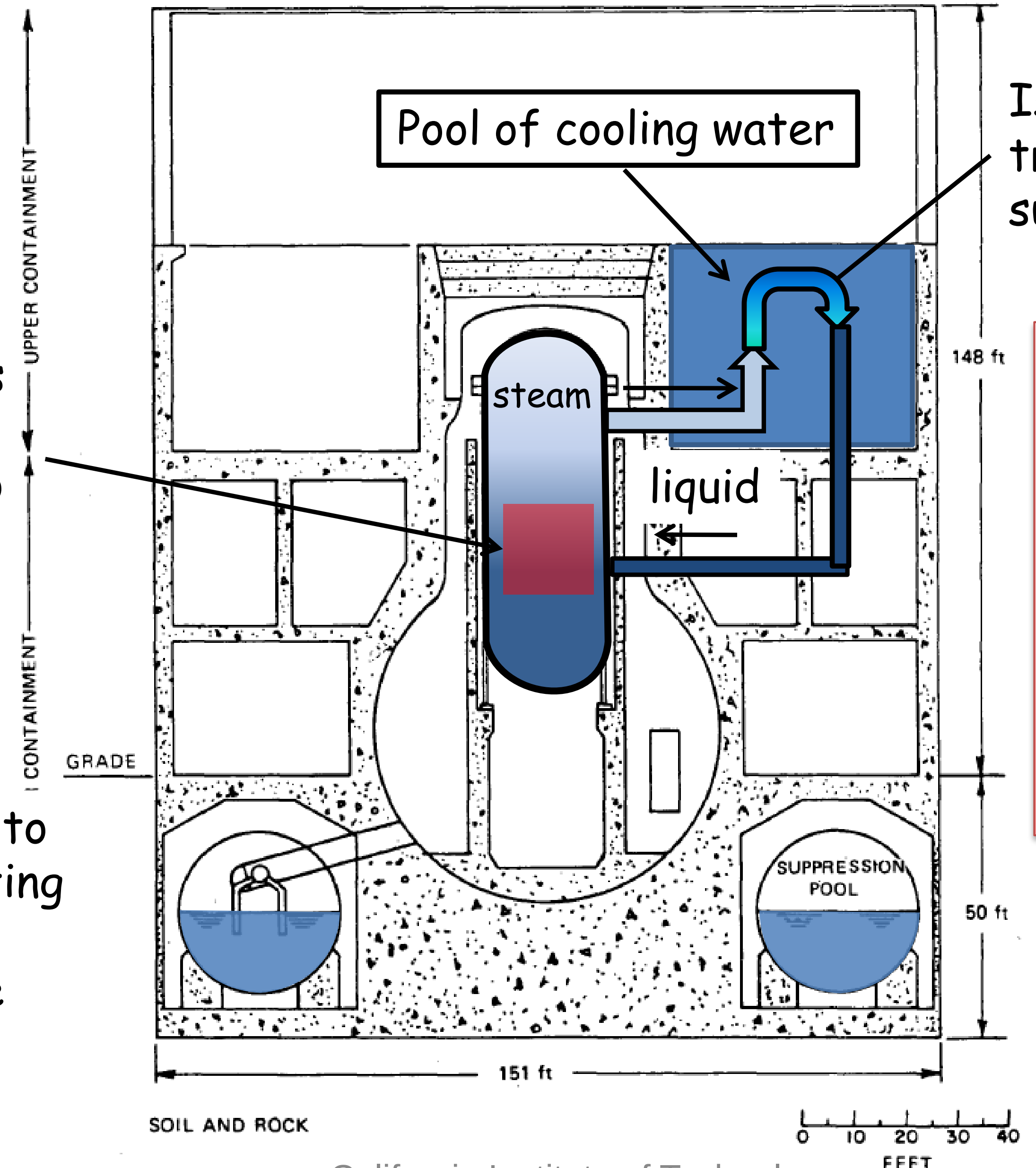
SRV valve opens when pressure >76 Mpa, closes when pressure < 69 MPa

Suppression pool condenses steam

Emergency Cooling Isolation Condenser in Unit 1

Decay heat in core generates steam to drive circulation into isolation condenser

SRV continues to operate, resulting in water level dropping inside reactor.



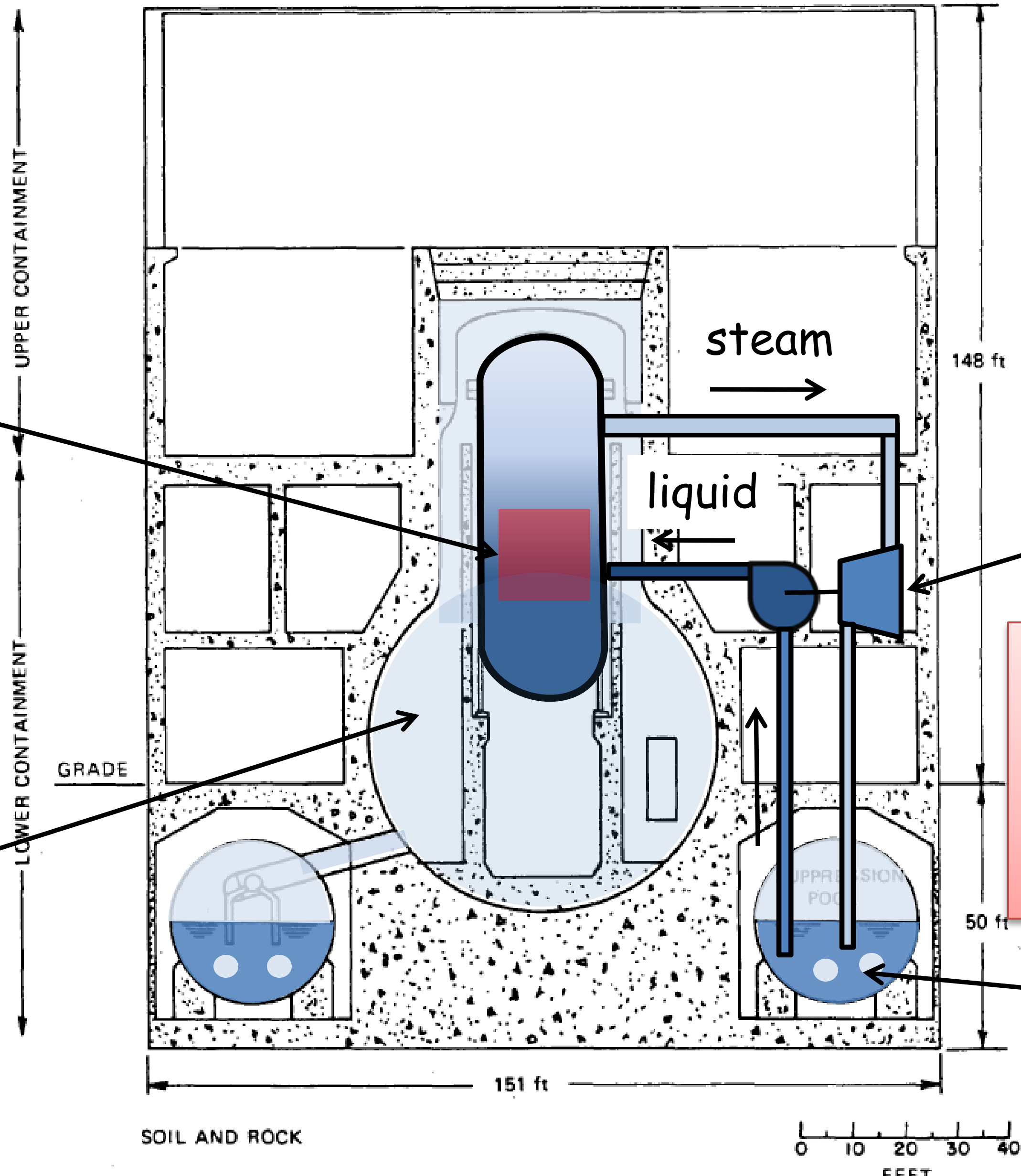
Isolation condenser transfers heat to surrounding pool

Cooling can only occur for a limited time since residual heat removal systems are not working for pool. Pool will eventually boil away.

Emergency Cooling with RCIC in units 2 and 3

Decay heat in core generates steam to drive pump.

Primary containment fills with steam as suppression pool heats up



Cooling can only occur for a limited time since residual heat removal systems are not working for pool.

RCIC Steam turbine driven pump

SRV continues to operate, resulting in water level dropping inside reactor.

Suppression pool condenses steam

Nuclear Emergency Notification

Outcome of 1999 JCO accident
At Tokai-mura, Japan

<Special Act for Nuclear Emergency>

(1) To ensure swift initial activation (Article 10)

A) Clarification of the notification criteria → **Notification by the licensee**

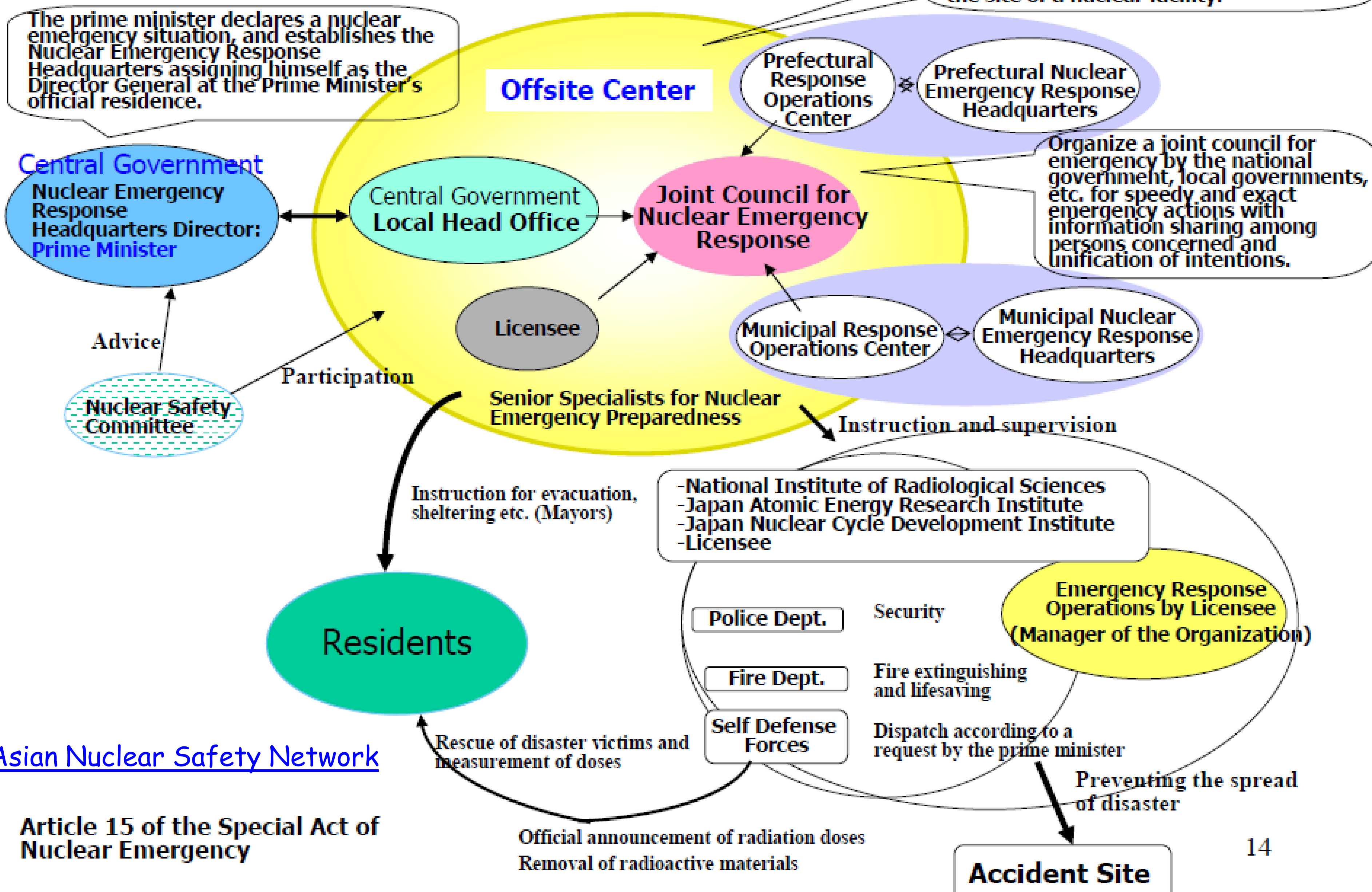
B) Clarification of the decision criteria for nuclear emergency → **Establishment of the "Nuclear Emergency Response Headquarters " and the "Local Nuclear Emergency Response Headquarters "**

Notification criteria	Decision criteria for nuclear emergency
● When radiation doses of 5micro-Sv/h or more for ten minutes or more are detected with radiation measuring equipment installed near the site boundary. ● When radioactive materials equivalent to 5micro-Sv/h for ten minutes or more are detected at the site boundary with considering diffusion etc. from the normal release point such as a ventilation stack. ● When radiation doses of 50micro-Sv/h for continuous ten minutes or more or radioactive materials equivalent to 5micro-Sv/h are detected in the vicinity of the controlled area. ● When radiation doses of 100micro-Sv/h or more are detected at a point one meter away from a shipping cask ● When the possibility of criticality at a facility other than the nuclear reactor core. ● When an incident occurred according to the characteristic of each plant that may result in a nuclear emergency such as a situation incapable of reactor shutdown by control rods.	● Detection of radiation doses of 500micro-Sv/h or more with radiation measuring equipment installed by the licensee near the site boundary or installed by the prefecture concerned. ● Detection of one-hundred times of numeric values of the notification event at a normal release point such as a ventilation stack, in the vicinity of a controlled area, or at a point one meter away from a shipping cask. ● A criticality state at a facility other than in the nuclear reactor core. ● An incident according to the characteristic of each plant that indicates the occurrence of a nuclear emergency situation such as a situation incapable of shutting down the liquid neutron absorber(boric acid solution) in addition to control rod insertion. Asian Nuclear Safety Network 12

Nuclear Emergency Response

<Special Act for Nuclear Emergency>

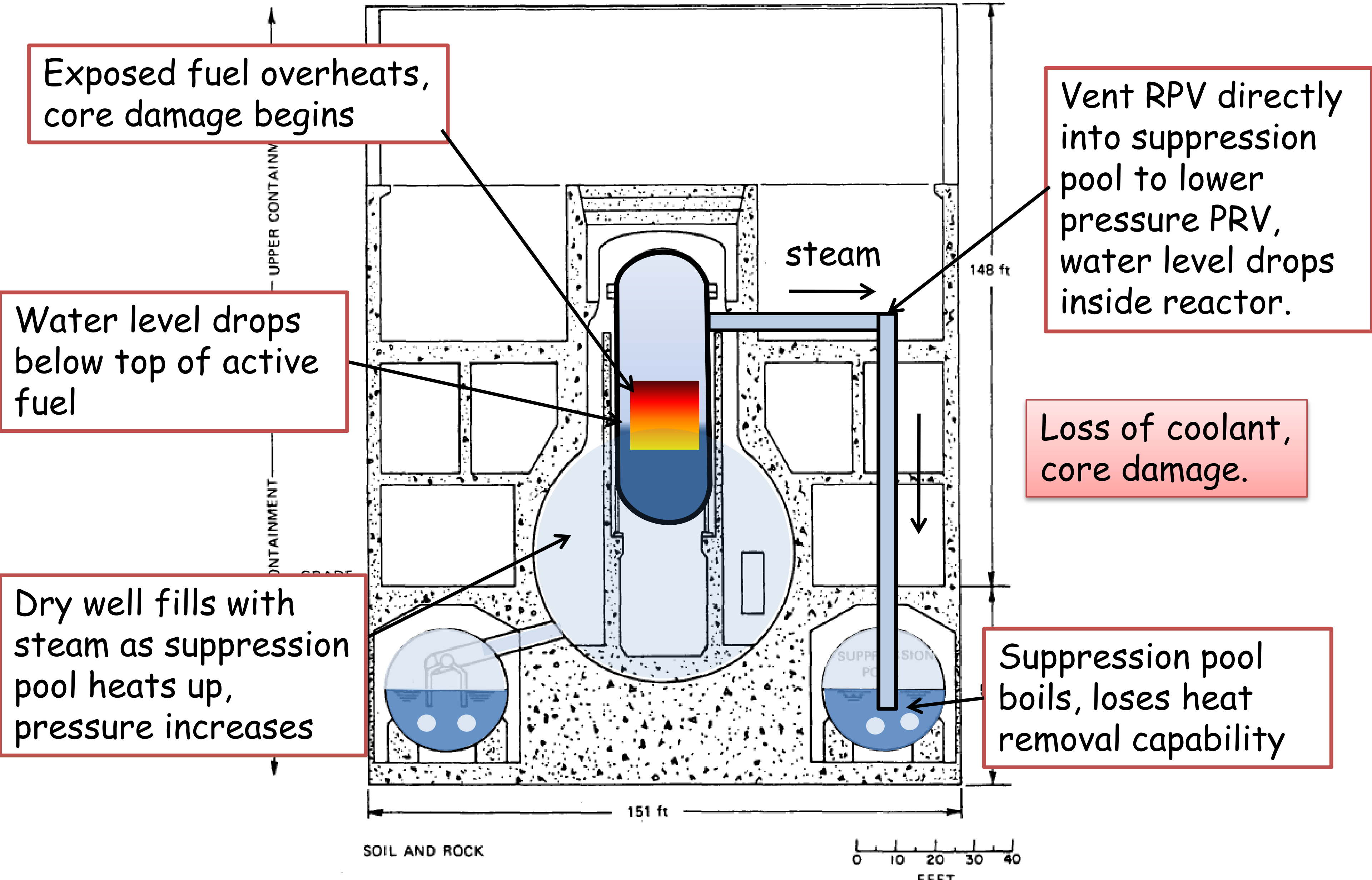
(3) Enhancement of emergency response by the central government



Asian Nuclear Safety Network

Article 15 of the Special Act of Nuclear Emergency

Emergency Cooling Fails After Pools Overheat, Pumps Stop

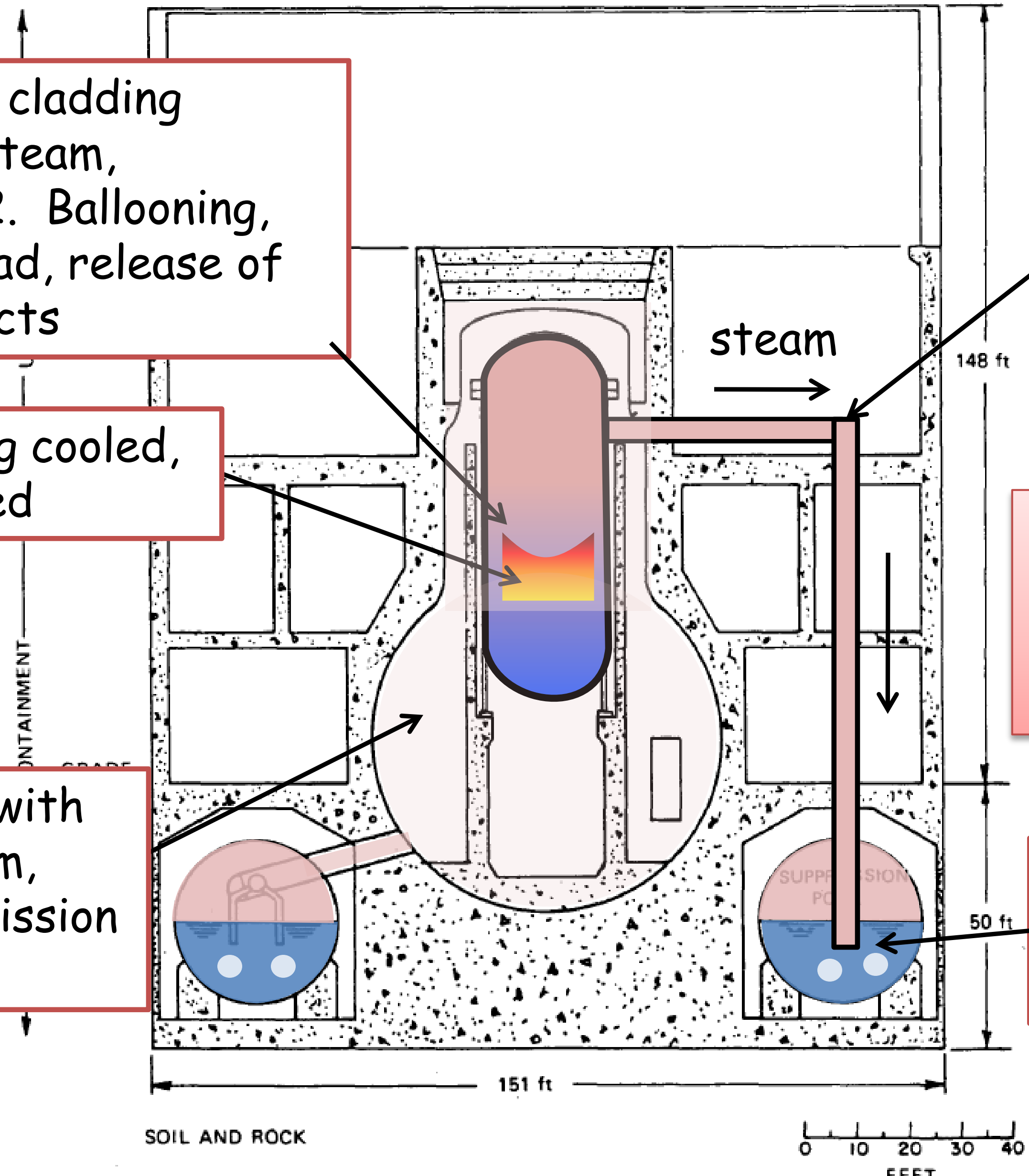


Damaged core releases fission products, generates hydrogen

Exposed fuel cladding oxidized by steam, generates H2. Ballooning, rupture of clad, release of fission products

Core not being cooled, highly damaged

Dry well filled with nitrogen, steam, hydrogen and fission products



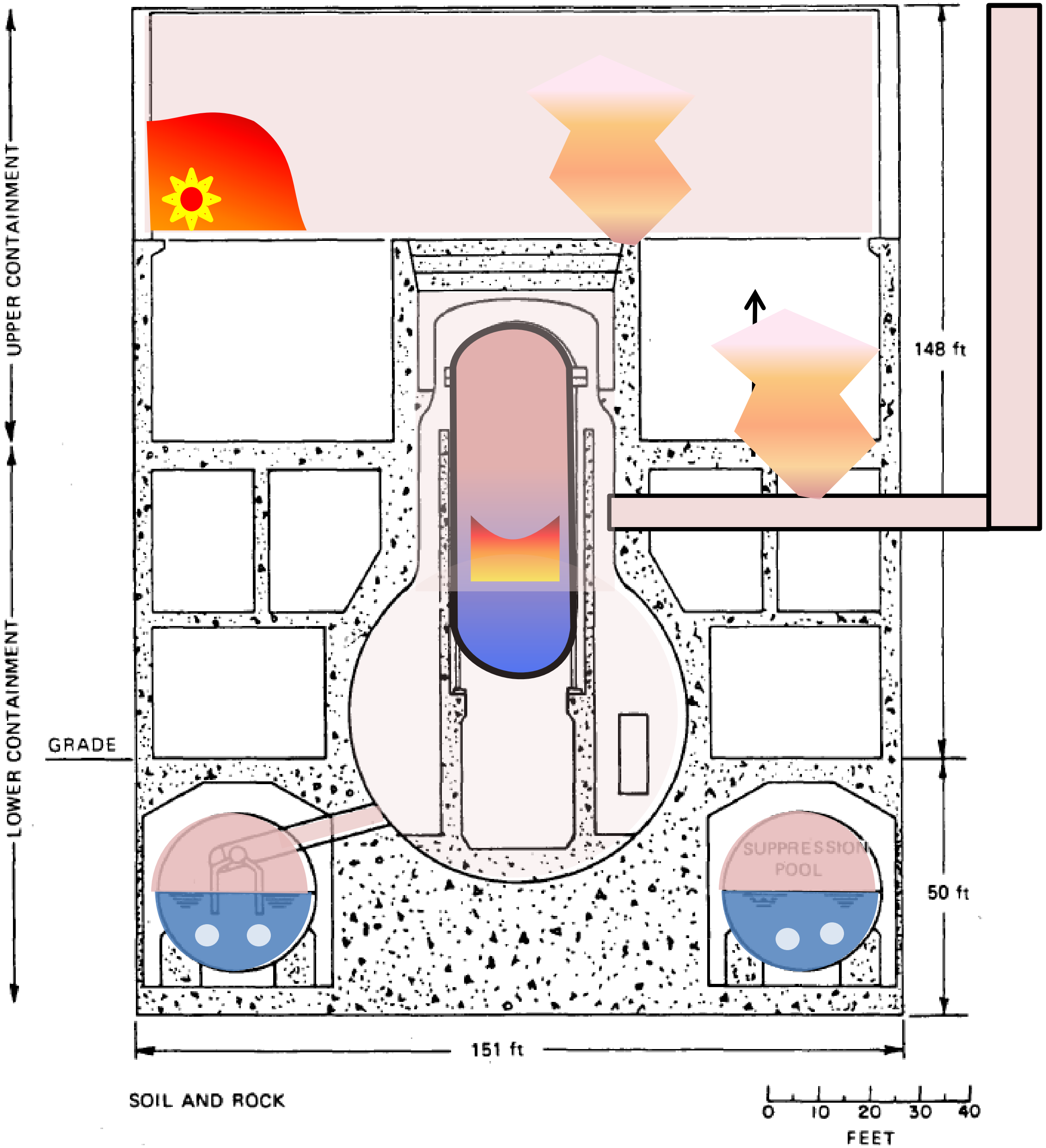
Mixture of steam H2 and fission products (FP) flow out of reactor

Pressure approaching failure level in primary containment

Suppression pool scrubs some FP from steam/H2

Saturday, March 12, 2011				
	1:20:00	12.06	10.53	Unusual pressure rise in PCV Unit 1 - Article 15 notification.
	2:00:00	12.08	11.20	Unit 1 primary containment at 600 kPa
	5:30:00	12.23	14.70	Unit 1 primary containment at 820 kPa
	5:40:00	12.24	14.87	Evacuation zone extended to 10 km
	6:50:00	12.28	16.03	Government give order to vent.
	9:00:00	12.38	18.20	Planning to vent
	10:17:00	12.43	19.48	Unit 1 primary containment venting to atmosphere.
		12.44	19.76	0.38 mSv/hr spike at front gate MP
	11:20:00	12.47	20.53	90 cm of fuel rods exposed in Unit 1. Final assessment (March 16) is 70 % damage to fuel.
		12.51	21.44	0.05mSv/hr spike at front gate MP
	13:30:00	12.56	22.70	Water level dropping in unit 1
	13:30:00	12.56	22.70	Ce-137 and I--131 detected near unit 1
	14:40:00	12.61	23.87	Steam release from primary of Unit 1
	15:29:00	12.65	24.68	Radiation dose at site boundary exceeds limit value at MP4 and Article 15 emergency declared at 16:17.
UNIT 1 H2 EXPLOSION →	15:36:00	12.65	24.80	Large quake followed by explosive sound and large white cloud from unit 1. Later determined to be explosion inside refueling bay, all panels blown off reactor building above the refueling floor level. Presumed to be H2 released into building by primary containment venting. 4 workers injured.
	18:25:00	12.77	27.62	Prime minister orders evacuation to 20 km
		12.81	28.64	0.025mSv/hr spike at front gate MP
	19:55:00	12.83	29.12	Prime minister order sea water injection into unit 1
	20:00:00	12.83	29.20	RCICS shut down in Unit 2. RCICS still running in Unit 3.
	20:20:00	12.85	29.53	Seawater injection into core of Unit 1 started, followed by borated water injection. Using fire lines to inject. 2 m3/hr
	20:41:00	12.86	29.88	Starting to vent Unit 3.
	22:15:00	12.93	31.45	Injection in unit 1 stopped due to quake.
	23:00:00	12.96	32.20	No ECCS in Unit 2, low water level, getting ready to vent.

Vent Primary Containment to Reduce Pressure



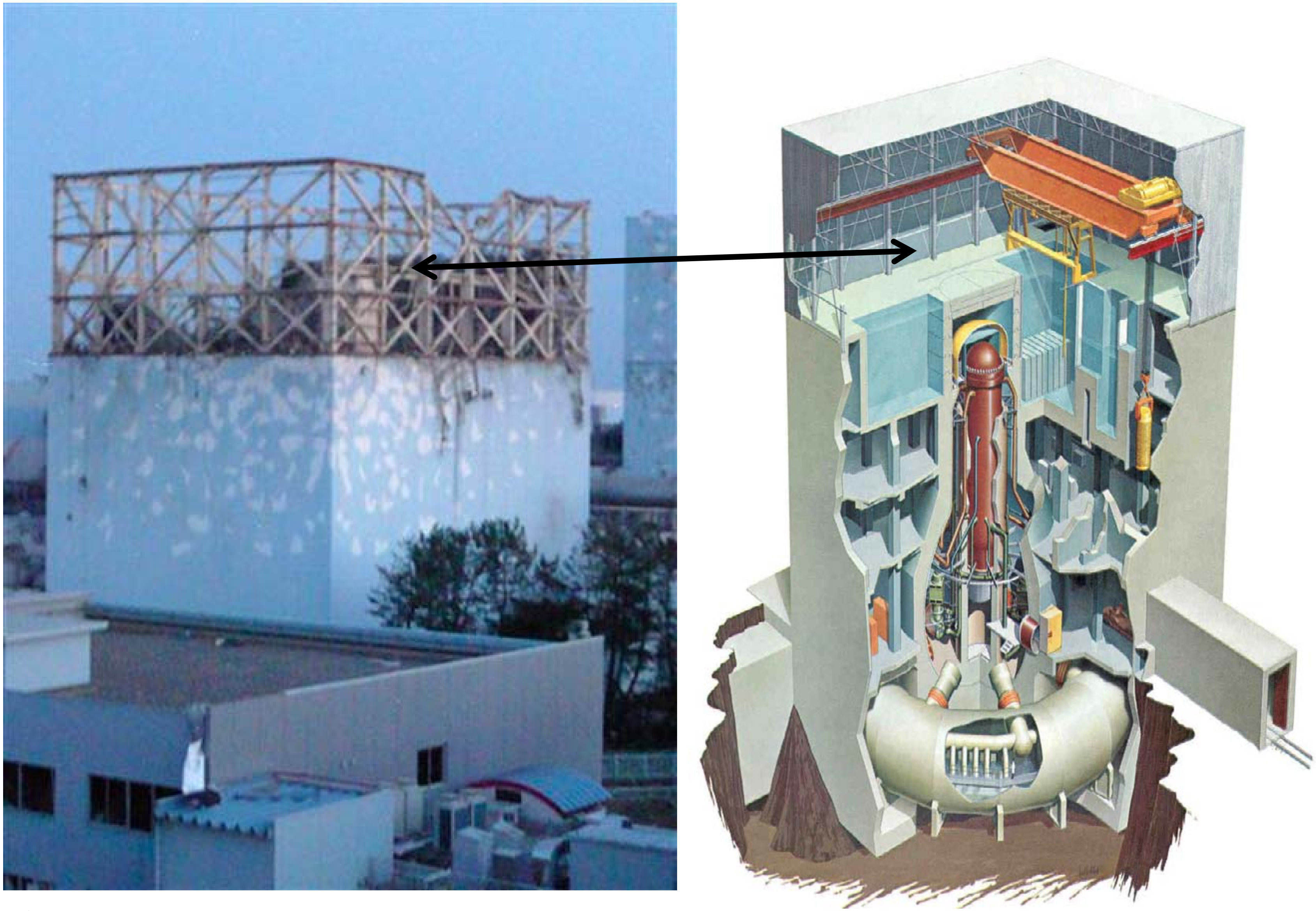
Vent primary containment. Some gas enters reactor building. Exact path unclear but H2 fills refueling bay region, mixes with air and explodes.

Unit 1 Explosion

Reuters

[Video of Explosion (YouTube)]

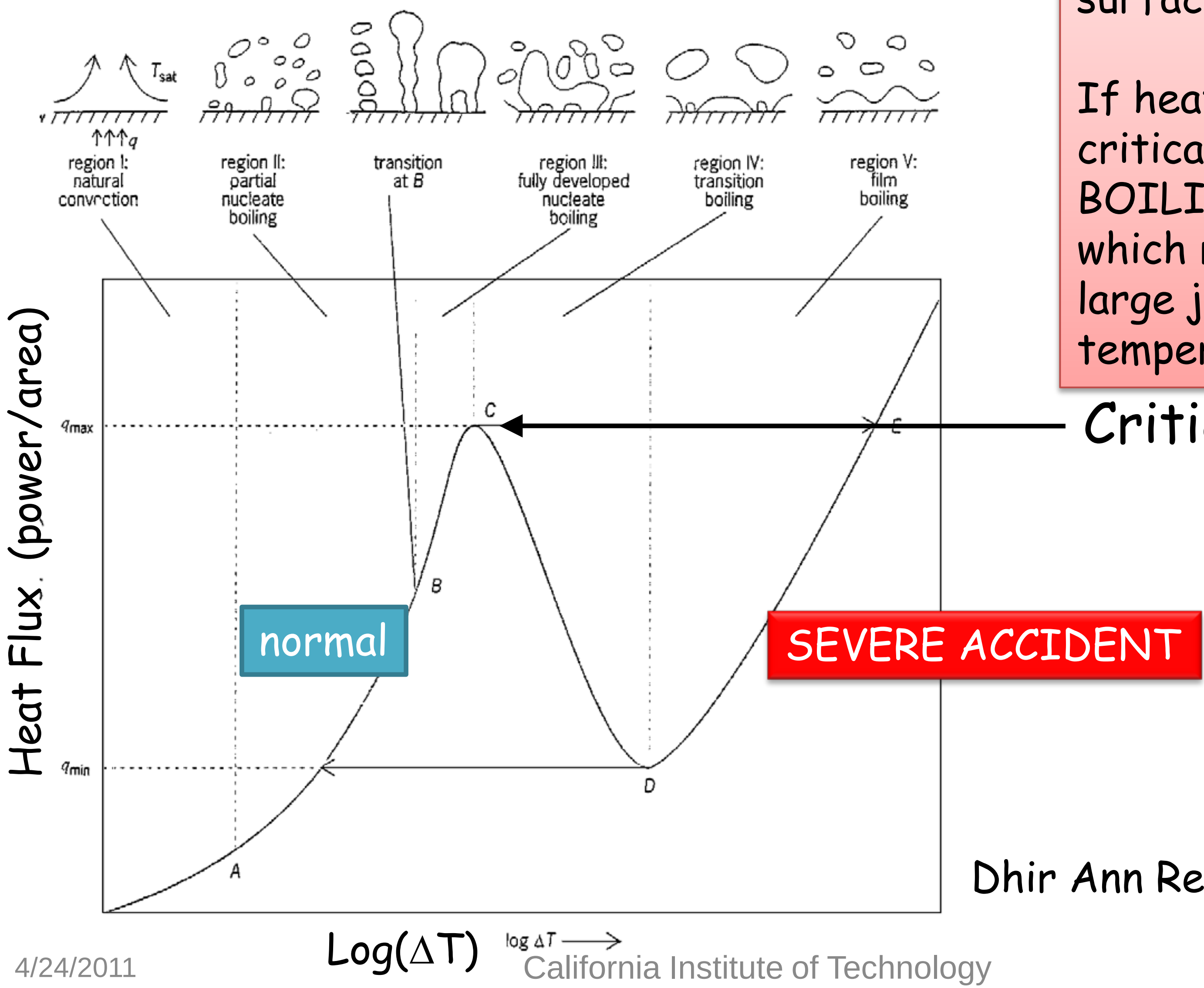
Unit 1 Reactor Building Damage



Reuters

Hydrogen Generation and Combustion

Loss of coolant drives up fuel pin temperature



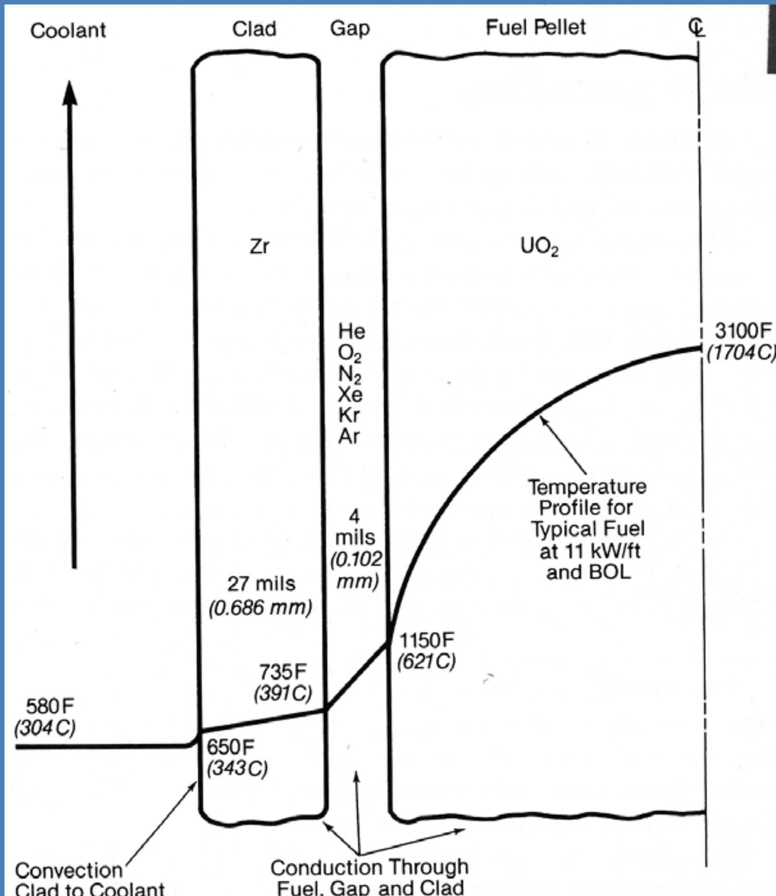
Steam insulates fuel pins, drives up surface temperature.

If heat flux exceeds critical value FILM BOILING occurs, which results in a large jump in surface temperature.

Critical Heat Flux

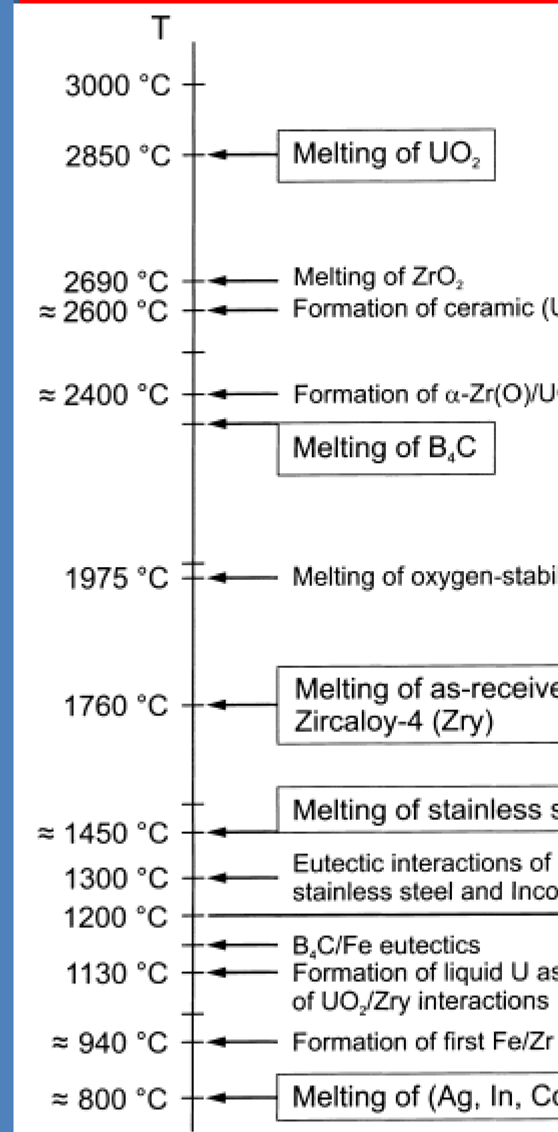
Dhir Ann Rev Fluid Mech 1998

NORMAL CONDITIONS



Steam – Its generation and uses, 41rst Ed Babcock - Wilcox

SEVERE ACCIDENT CONDITIONS



Hofman, J. Nuclear Matl., 1999

Cracking and Rupture of Zr Clad

Peak cladding temperature of 900 C.

Internal pressure of FP gases creates hoop stress on clad.

Creep strength drops rapidly after 700 C.

Strains up to 50% result in:

Ballooning and relocation of fuel.

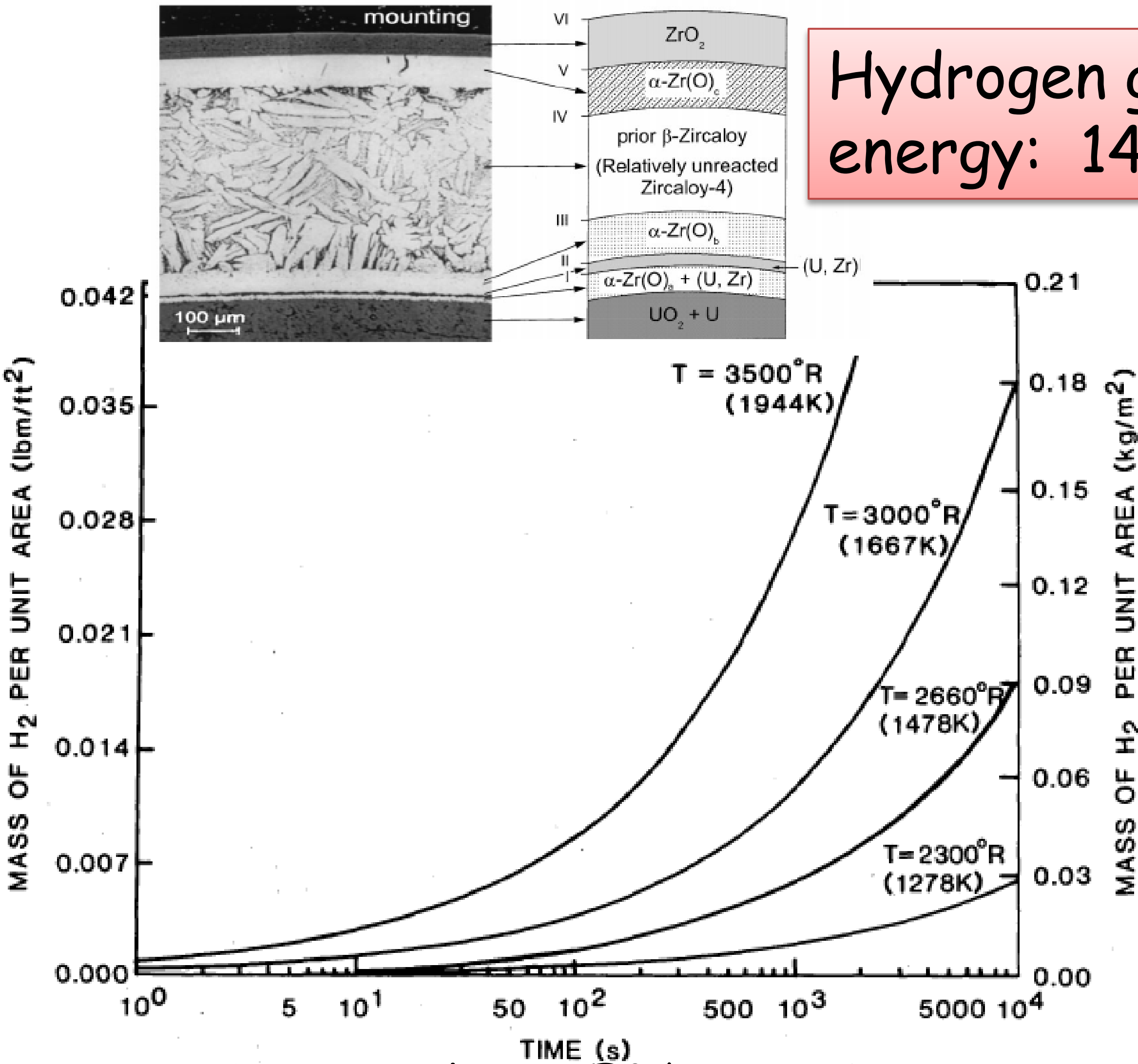
Through wall cracks.

Rupture of cladding → releasing FP gases and fuel

NEA 6846 2009

$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$

Hydrogen generation also releases energy: 14.6 MJ/kg of Zr

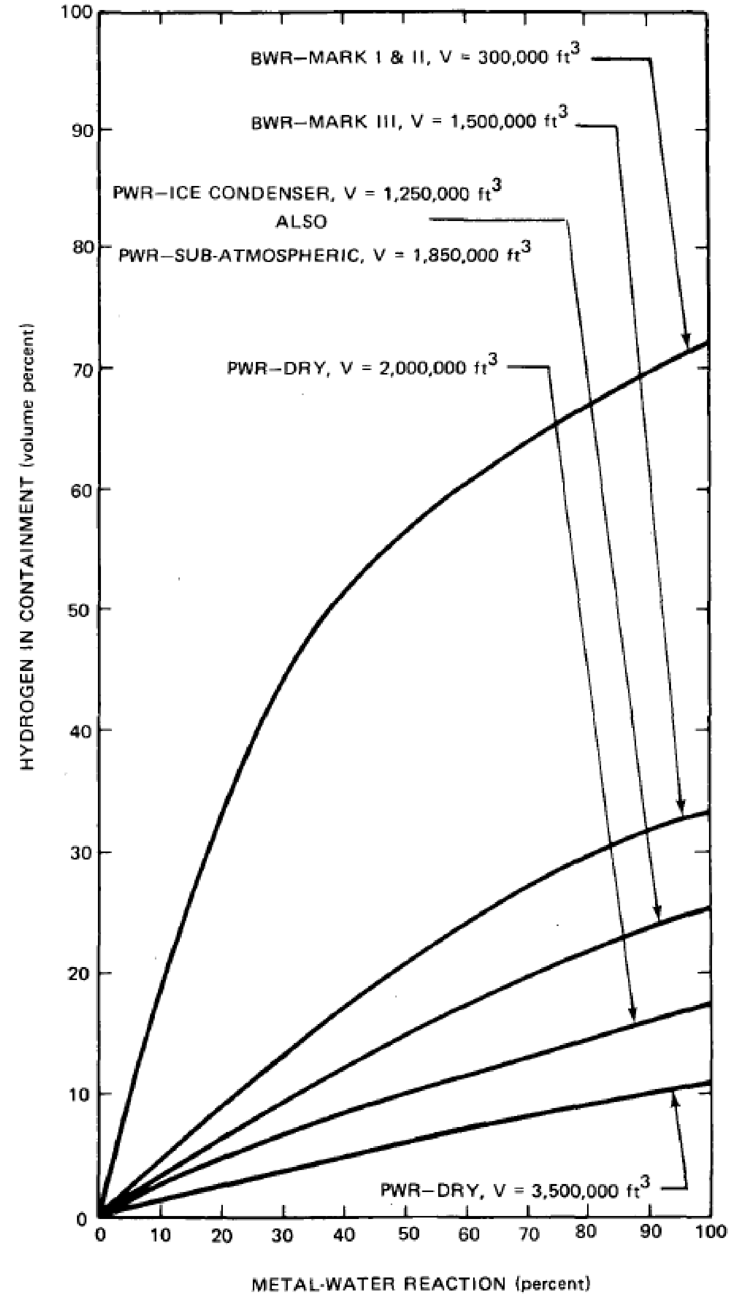


LWR H2 Manual NUREG/CR-2726

900°C	Rupture cladding
1200°C	H2 generation
1800°C	Melt clad, melt steel
2500°C	Break fuel rods, debris bed
2700°C	Zr-U eutectics

Containment Size

- Mark I primary is 300,000 ft^3
- Smallest of all designs
- Quickly reaches high H2 concentration if core overheats
- All Mark I reactors operate with inert – N2 filled – primary systems



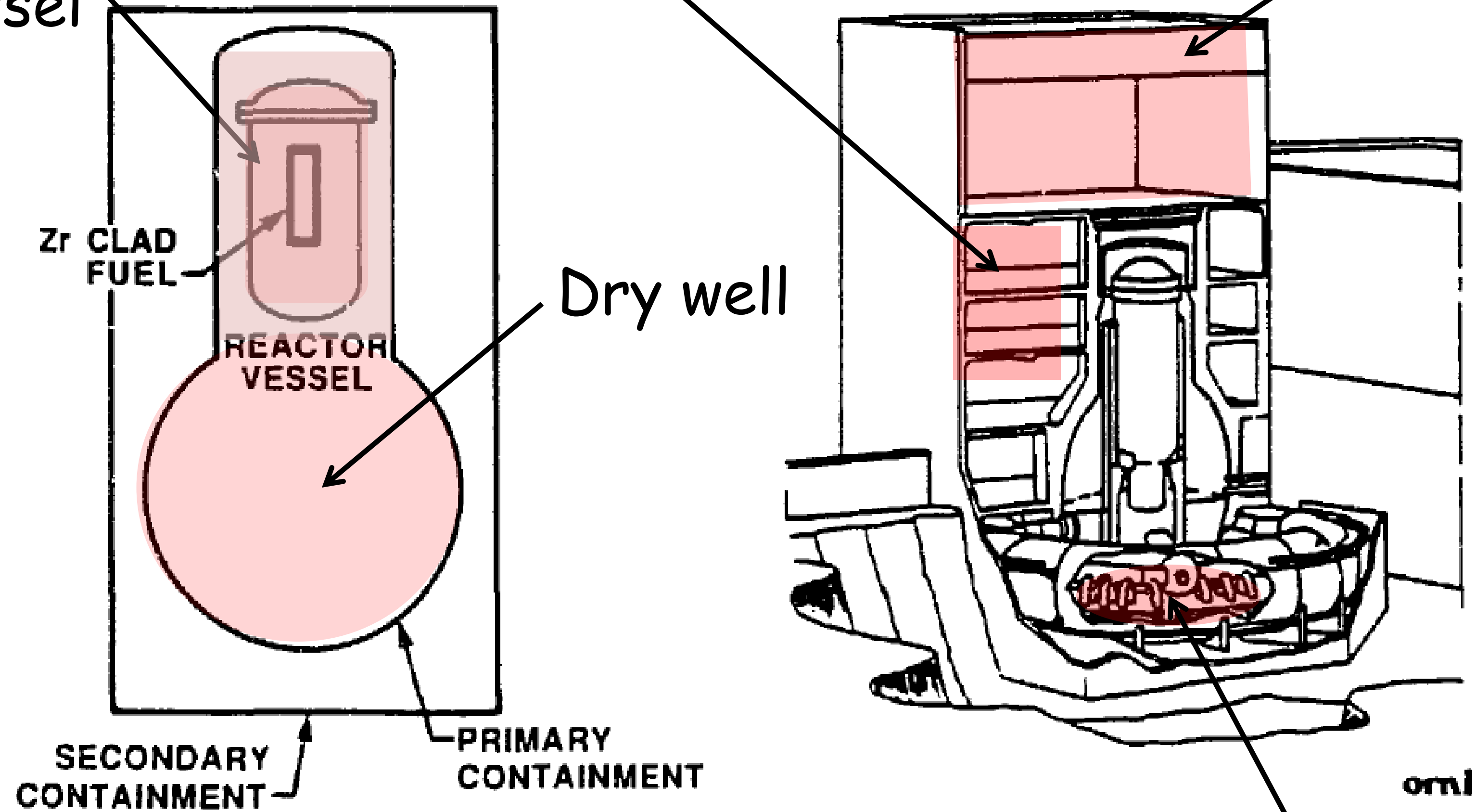
LWR H2 Manual NUREG/CR-2726

Observations

- Fuel pin overheating and H2 production occurs very rapidly (~1 hr) once pins are no longer covered by water
  - Deflagration and FP release with 24 hr of SBO predicted (SAND2007-7697)
- Volume of refueling bay (~10^6 ft^3 or 2.8 $x10^4$ m^3) is 3 X larger than primary containment but pressure is nearly atmospheric.
- Inventory of Zr initially in each reactor, H2 assuming 100% reaction and expansion to NTP.

Unit	ZR (tonne)	H2 (tonne)	H2 (m^3)
1	44	2	23804
2 or 3	60	3	32612

Where Can the H2 go?

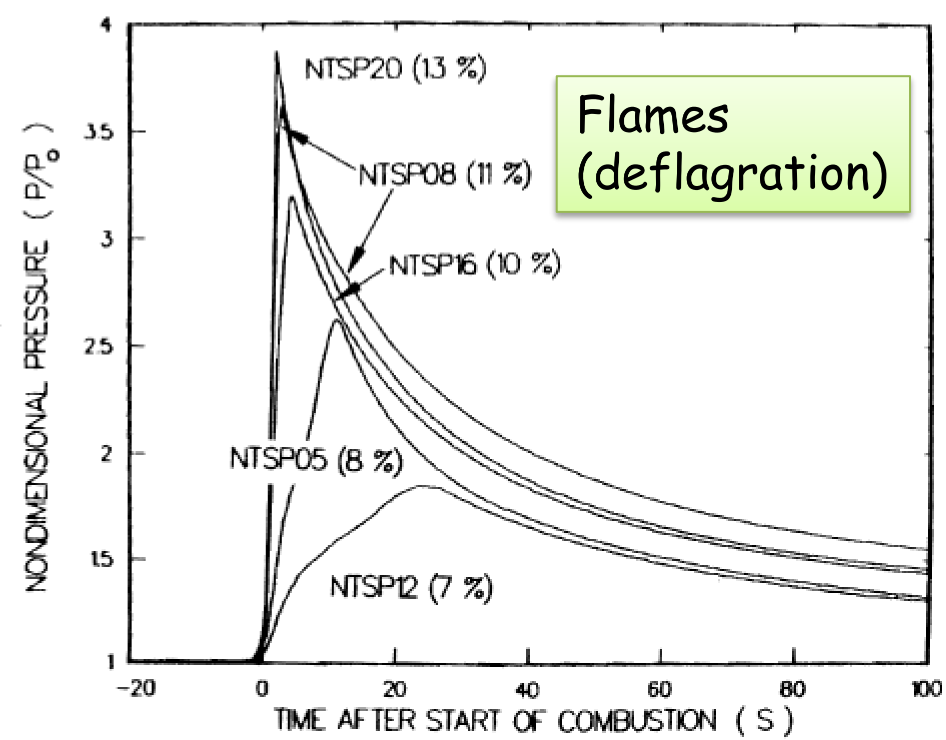


S. Greene CONF-8806153-1 ORNL

Hydrogen Combustion

- $H_2 + 1/2\ O_2$ (+N_2 & H_2O) → H_2O (+N_2 & H_2O)
  - 240 kJ/mol H2 energy release
  - 120 MJ/kg H2
- Steam and nitrogen absorb much of energy of combustion
- Wide range of flammable mixtures
  - 4-70% H2 in dry air
- Easy to ignite
  - Low energy requirements for sparks or arcs
  - Hot surfaces above 1000 C
- Combustion Modes
  - Flames (slow 0.5 to 50 m/s)
  - High speed flames (50-500 m/s)
  - Detonations (1500-3000 m/s)

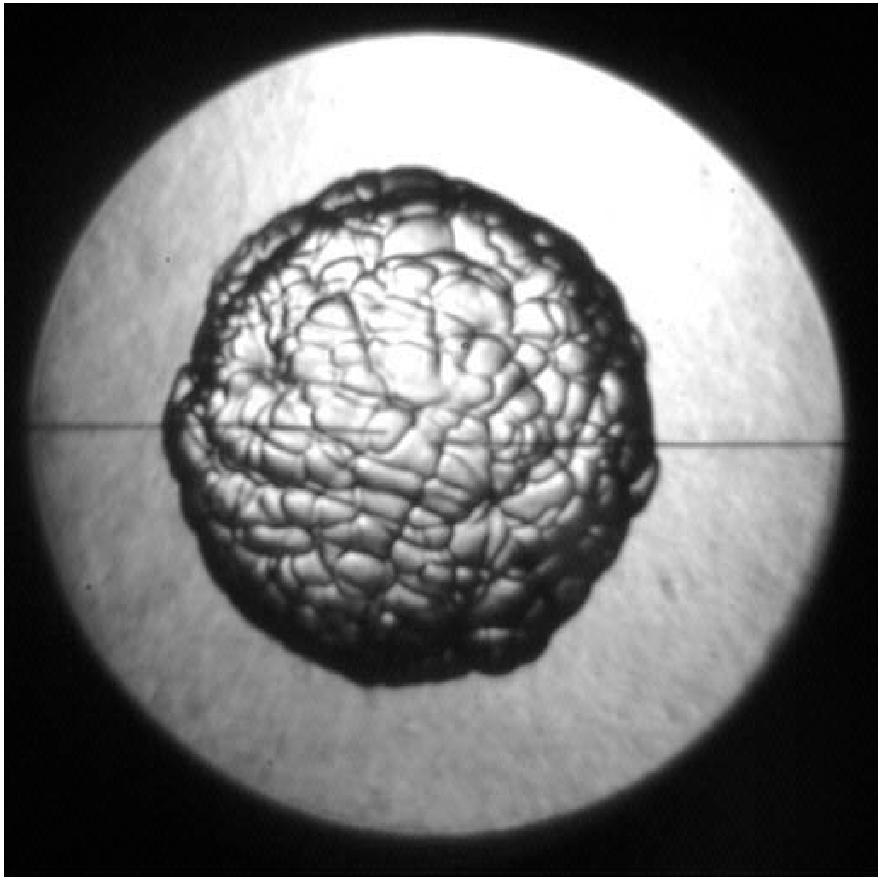
NUREG/CR-4138 Ratzel 1986



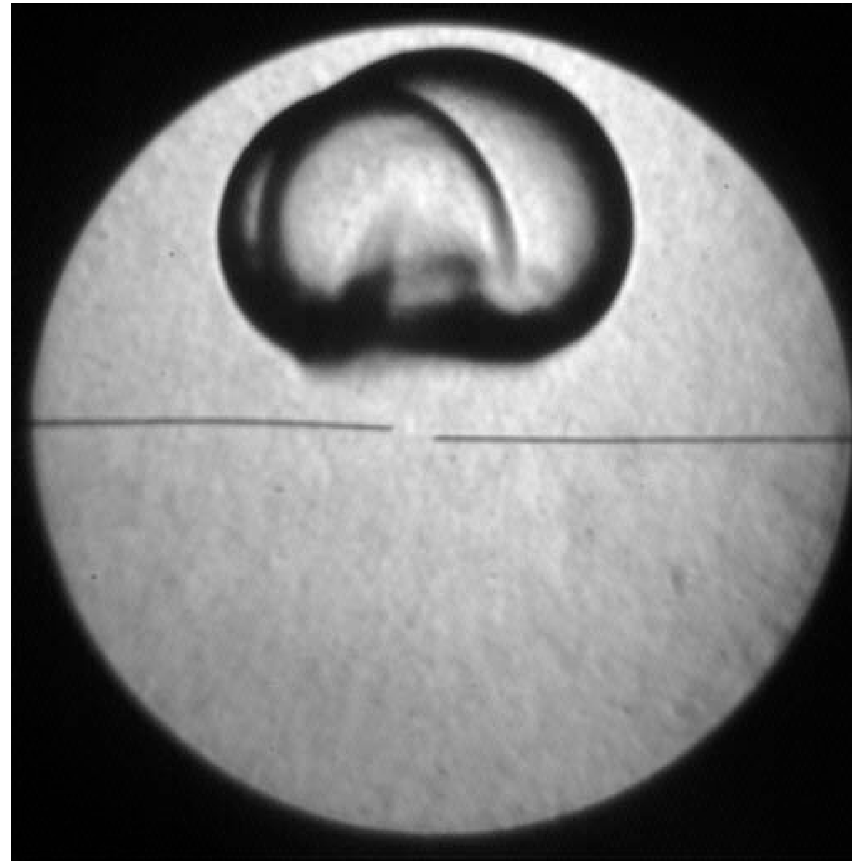
50 m^3 test facility in Nevada, 30% steam

RPV	8500 m^3
Refueling bay	32,000 m^3

Hydrogen Flames



10% H2 in O_2/Ar

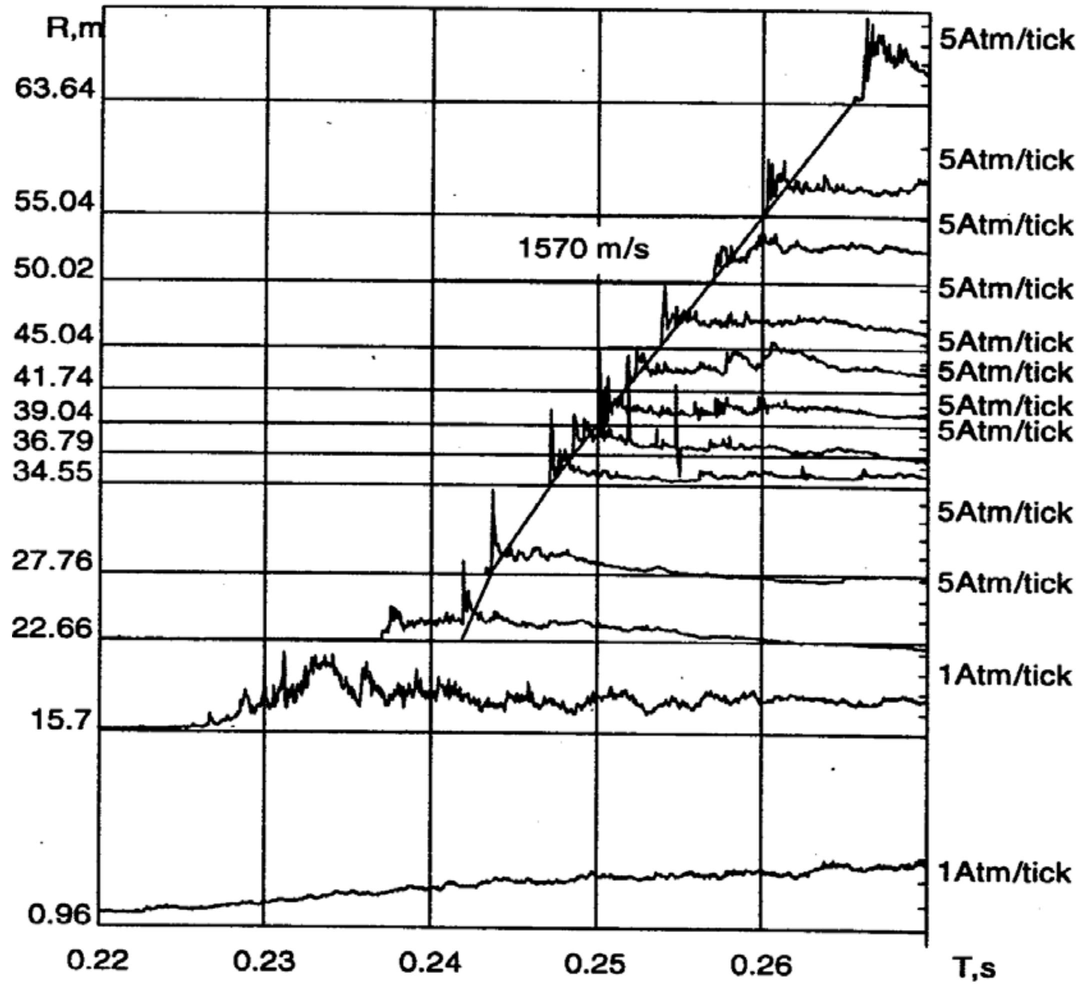


5% H2 in O_2/Ar

SPM Bane – Caltech Explosion Dynamics Lab 2010

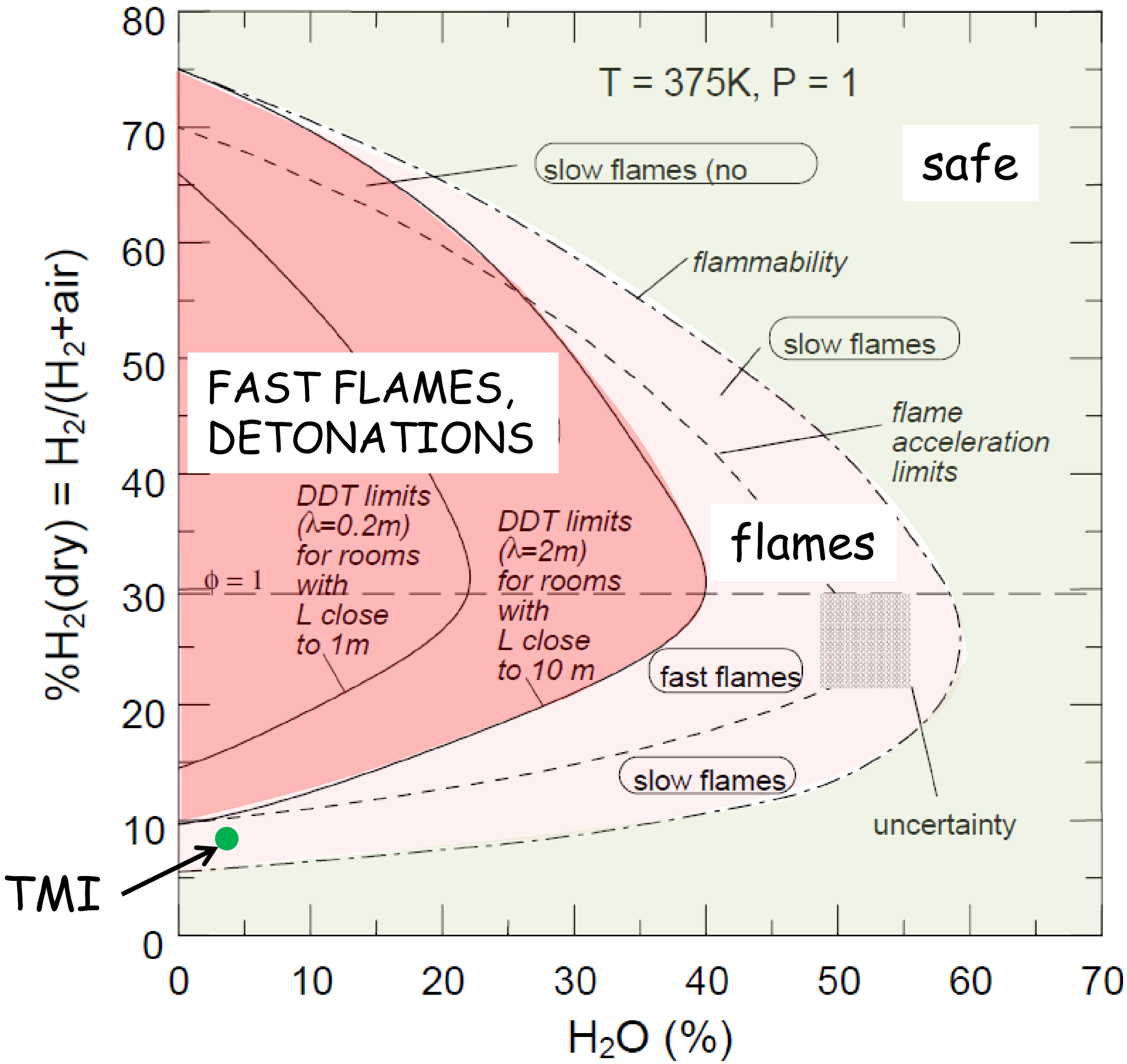
Deflagration or Detonation?

- Multiple combustion modes
  - Low speed (5-100 m/s) flames or deflagration
  - High speed (1500-2500 m/s) detonation waves
  - Transition from flames to detonations possible
    - Deflagration to Detonation Transition or DDT
    - Requires turbulent-inducing obstacles or compartments
- Pressure rise depends on
  - Composition of atmosphere, eg, amount of H2 and steam
  - Temperature and pressure
  - Mode of combustion
  - Venting or failure of structures



18% H2 (dry) 15% steam RUT (60 x 2.5 x 2.5 m) Dorofeev 1995

Combustion Regimes in H2-Air-Steam Mixtures

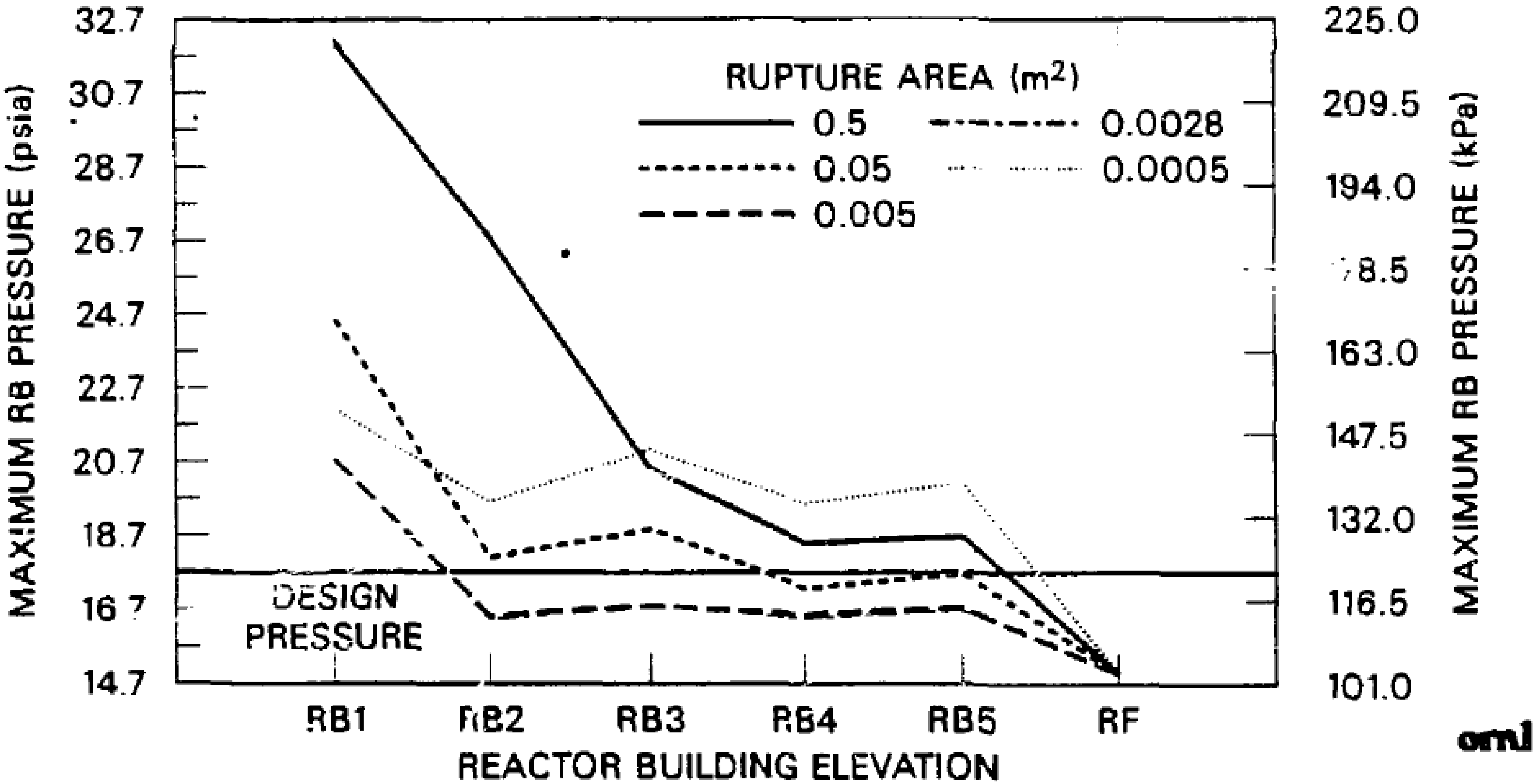


OECD NEA/CSNI/R(2000)7

Extensive research programs in USA, Europe, Japan, FSU from 1980-2000 on H2-air-steam. Motivation was TMI accident and follow-on studies.

Programs in Japan, Germany on H2-O2-steam after 2001 pipe ruptures in Hamaoka Unit 1 and Brunsbüttel.

Deflagrations Easily Fail Secondary Containment



S. Greene CONF-8806153-1 ORNL

Observations on Unit 1

- 24 hr from SBO to explosion, about 5-1/2 hr after first starting to vent.
- Initial blast primarily lateral, some visible debris lofted to ~100 m initially.
- Panels surrounding refueling bay blown off as expected from design
- Supporting structure remains mostly intact
- Damage to reactor building internals unknown
- Large cloud apparently mostly dust from concrete
  - FP release appears to be similar in dose or smaller to earlier venting (see release data below)
- RPV and PCV both appear to hold pressure as of 3 April indicator readings.
- Explosion appears to be a deflagration
  - Relatively low concentration <10-15%) of H2 at time of explosion so DDT did not occur.

Station Blackout Unit 3 →

Sunday, March 13, 2011				
	2:00:00	13.08	35.20	Seawater injection into unit 1 in progress.
	2:44:00	13.11	35.93	Batteries fail in Unit 3
	5:30:00	13.23	38.70	Containment integrity in Unit 1 verified
	6:23:00	13.27	39.58	RCICS fails in Unit 3.
	8:41:00	13.36	41.88	Controlled venting in Unit 3. Fuel exposed up to 3 m.
	8:56:00	13.37	42.13	Radiation dose at site boundary MP4 exceeds limit value.
		13.39	42.56	0.28 mSv/hr spike at front gate MP
	11:00:00	13.46	44.20	Starting to vent Unit 2
	11:55:00	13.50	45.12	Fresh water injection into Unit 3 through fire line in progress.
	13:12:00	13.55	46.40	Sea water injection into Unit 3 through fire lines in progress.
	14:00:00	13.58	47.20	RCICS working for Unit 2.
	14:15:00	13.59	47.45	Radiation dose at site boundary MP4 exceeds limit value.
		13.60	47.60	0.06 mSv/hr spike at front gate MP
	15:38:00	13.65	48.83	Warning of H2 explosion in unit 3

Monday, March 14, 2011				
	1:10:00	14.05	58.37	Injection to Units 1 and 3 halted - ran out of water in pit. Unit 1 injection "temporarily interrupted" - not clear when this was restarted.
		14.10	59.60	0.75 mSv/hr spike at front gate MP
	3:20:00	14.14	60.53	Injection to Unit 3 restarted.
	3:50:00	14.16	61.03	Radiation dose at site boundary MP6 exceeds limit value.
	4:08:00	14.17	61.33	Temperature up to 84 C in Unit 4 spent fuel pool
	4:15:00	14.18	61.45	Radiation dose at site boundary MP2 exceeds limit value.
	5:20:00	14.22	62.53	Starting to vent Unit 3.
	7:44:00	14.32	64.93	Pressure rise in PCV of Unit 3.
	7:52:00	14.33	65.07	Article 15 emergency notification.
	9:27:00	14.39	66.65	Radiation dose at site boundary around MP3 exceeds limit value.
	9:37:00	14.40	66.82	Radiation dose at site boundary around main entrance exceeds limit value.
Unit 3 H2 Explosion	11:01:00	14.46	68.22	Explosion destroys Unit 3 refueling bay superstructure, panels, extensive damage. Visible flash at beginning of explosion. Large dark cloud at least 500 m high, fragments possibly impact unit 2 and 4 reactor buildings. 11 workers injured.
	11:01:00	14.46	68.22	Blowout panel in unit 2 reactor building opened up following unit 3 explosion.
		14.48	68.72	0.05 mSv/hr spike at front gate MP
	13:18:00	14.55	70.50	Water level in unit 2 RPV falling.
RCICS Unit 2 fails	13:25:00	14.56	70.62	RCICS fails for Unit 2. Potentially caused by secondary effects of explosion in Unit 3.
	13:49:00	14.58	71.02	Article 15 emergency notification for Unit 2.
	19:20:00	14.81	76.53	Seawater injection by fire line prepared for Unit 2 RPV. Difficulty in injection apparently due to not being able to open pressure relief valves.
	20:33:00	14.86	77.75	Seawater injection by fire line for Unit 2 RPV. NISA has this happening at 16:34
		14.90	78.80	3.13 mSv/hr spike at front gate MP
	22:50:00	14.95	80.03	Water level in unit 2 RPV falling. Rise of pressure in PCV.

Unit 3 H2 Explosion

Video of explosion (YouTube)

Unit 3 reactor building damage

March 17 – Tepco

March 14, 2011

NY Times – DigitalGlobe

Observations on Unit 3

- Explosion 32 hours after battery failure, 6 hours after venting.
- Visible flash at beginning of video sequence
  - Occurs as panels blow out, probably luminosity from entrained debris
- Explosion lofted material (roof panels?) > 300-500 m height
- Sound reported 40-50 km away
- Vertical panels and supporting structures blown outward and roof collapsed downward.
  - Debris in pool – not clear where crane structure is now located
  - Damage to turbine building roof may be associated with building fragments or equipment hurled out of refueling bay
- Concrete beams and panels below refueling deck damaged
- RPV and PCV now depressurized

Tuesday, March 15, 2011				
	0:02:00	15.00	81.23	Starting to vent Unit 2
	6:00:00	15.25	87.20	Explosive sound and fire near 5th floor of Unit 4 .
	6:10:00	15.26	87.37	Pressure drop in suppression torus in Unit 2
	6:14:00	15.26	87.43	Damage to reactor wall in operation area confirmed for Unit 4
	6:20:00	15.26	87.53	Explosive sound near torus in Unit 2.
		15.00	81.20	All personnel evacuated and only 50 remain to operate plant.
	6:51:00	15.29	88.05	Radiation dose at site boundary around main entrance exceeds limit value.
	8:11:00	15.34	89.38	Radiation dose at site boundary around main entrance exceeds limit value.
		15.38	90.32	11.9 mSv/hr spike at front gate MP
	9:38:00	15.40	90.83	Explosion followed by fire in Unit 4
	10:00:00	15.42	91.20	Radiation dose on 400 mSv/h on inland side of Unit 3 and 100 mSv/h on inland side of Unit 4.
	11:00:00	15.46	92.20	Fire in Unit 4 reported to spontaneously extinguish.
	12:00:00	15.50	93.20	Large release starts and continues into Wednesday.
	16:17:00	15.68	97.48	Radiation dose at site boundary around main entrance exceeds limit value.
	23:05:00	15.96	104.28	Radiation dose at site boundary around main entrance exceeds limit value.
		15.98	104.72	8.08 mSv/hr spike at front gate MP

Observations on Unit 2

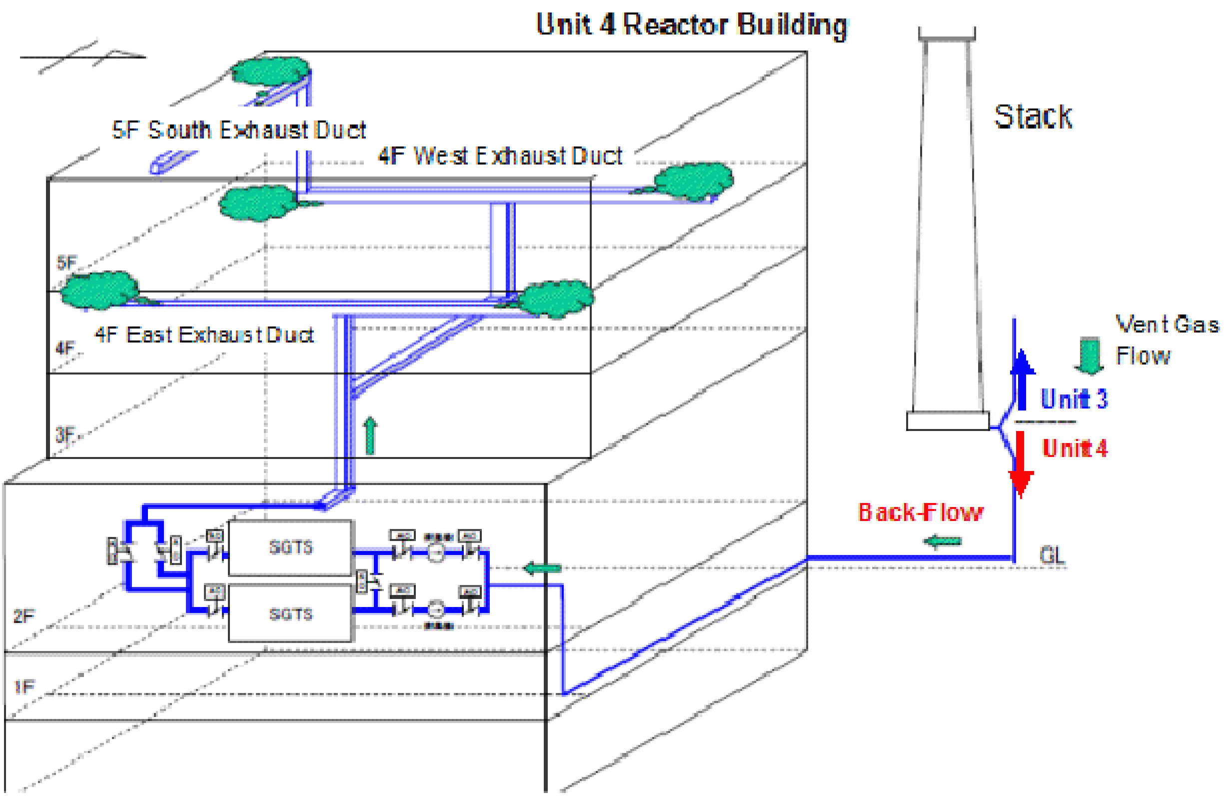
- Explosion 17 hr after RCIC fails, unclear when venting was done
- Explosion/fire events in 2 and 4 very close in time
  - Coupled through shared vents & buildings?
  - Coincidence?
- Event in #2 very different than #3 & #1
  - Explosive "sound" in torus area, no apparent damage to building exterior at refueling level.
  - Preceded by rapid drop in pressure in containment
  - Suggests failure of containment – most likely torus itself or connections to sphere.
- Possible events (pure speculation)
  - Small H2 explosion in torus room only (seems unlikely) and/or
  - Core melt relocation within RPV resulting in
    - Steam "spike" and/or
    - Core penetrates failed lower head and drops into water in reactor cavity
- Reactor and containment have been depressurized since these events.

Observations on Unit 4

- Sequence of events still unclear
  - Fire → explosion *or* explosion → fire
  - One explosion or multiple explosions?
  - What was burning?
    - Zircaloy itself?
    - Hydrogen generated by ongoing reaction with steam
    - Other materials in refueling bay?
    - Hydrogen leak from generator cooling system?
    - Hydrogen from Unit 3 via vent lines (Tepco May 16)
- Very substantial damage from explosion
  - Blow out of a larger number of panels suggests significant buildup of hydrogen within refueling bay.

Possible H2 source for Unit 4

Backflow through venting lines from unit 3 release – not confirmed.

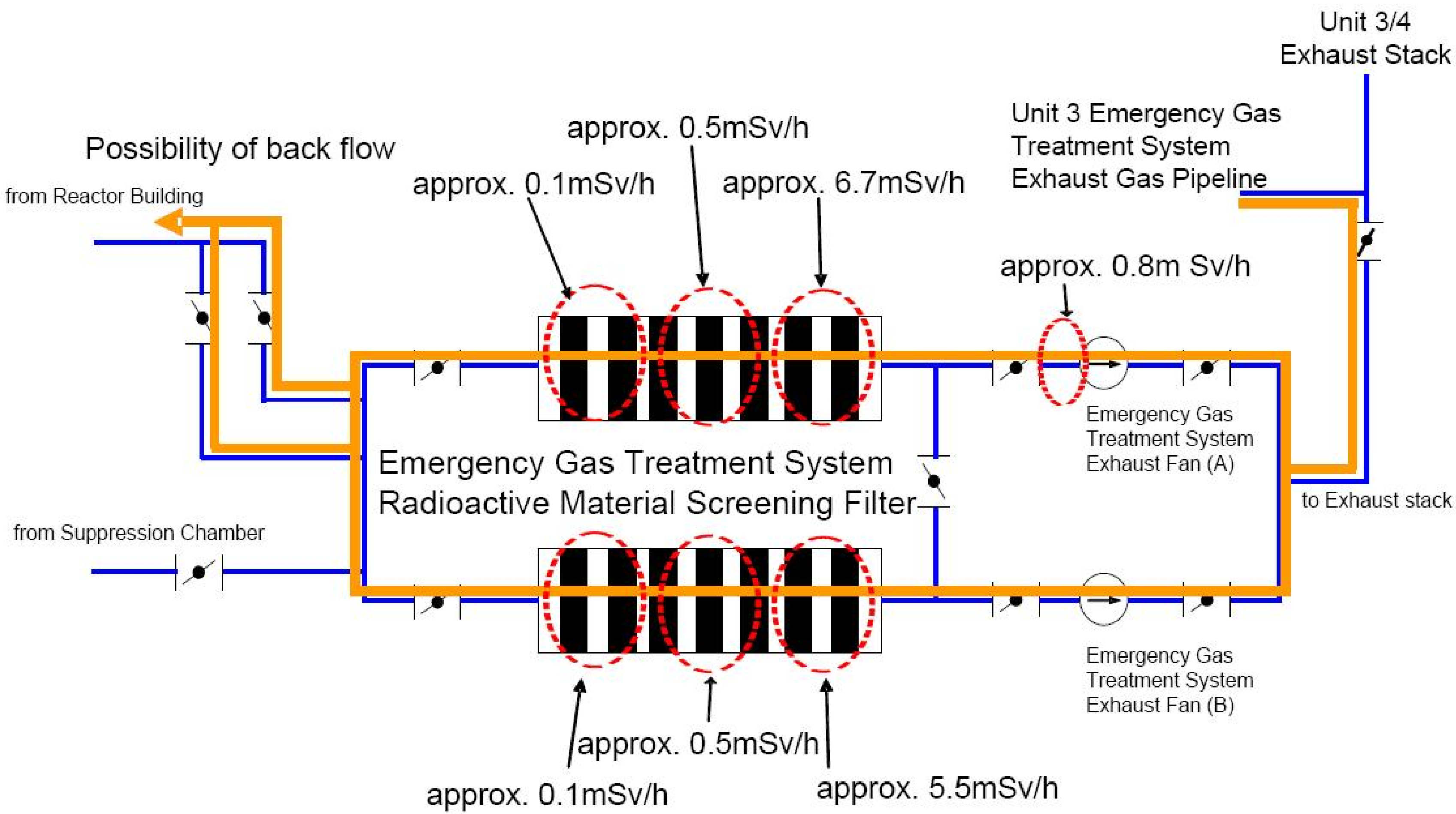


Tepco May 16

Evidence of Backflow

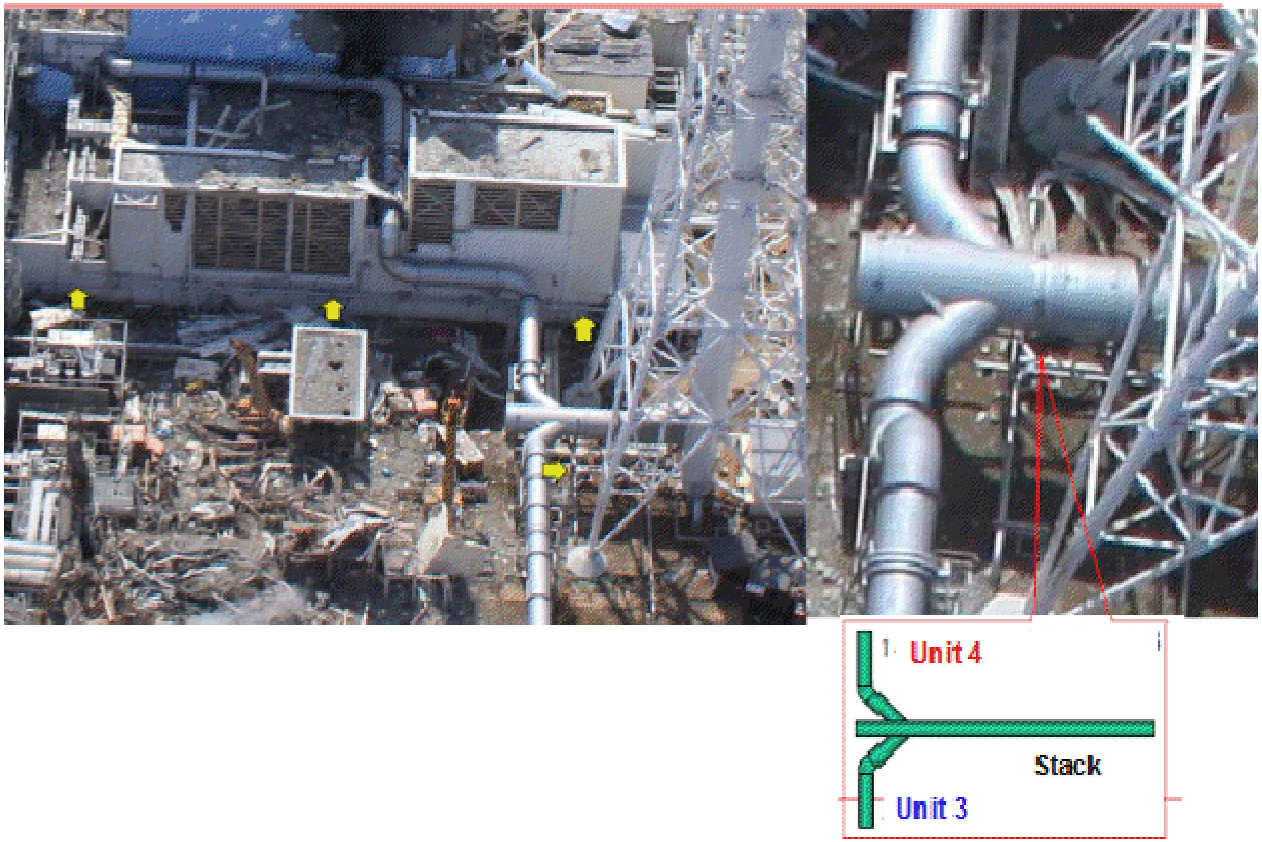
August 27, 2011
Tokyo Electric Power Company

Result of Radioactive Dose Measurement at Unit 4 Emergency Gas Treatment System in Fukushima Daiichi Nuclear Power Station

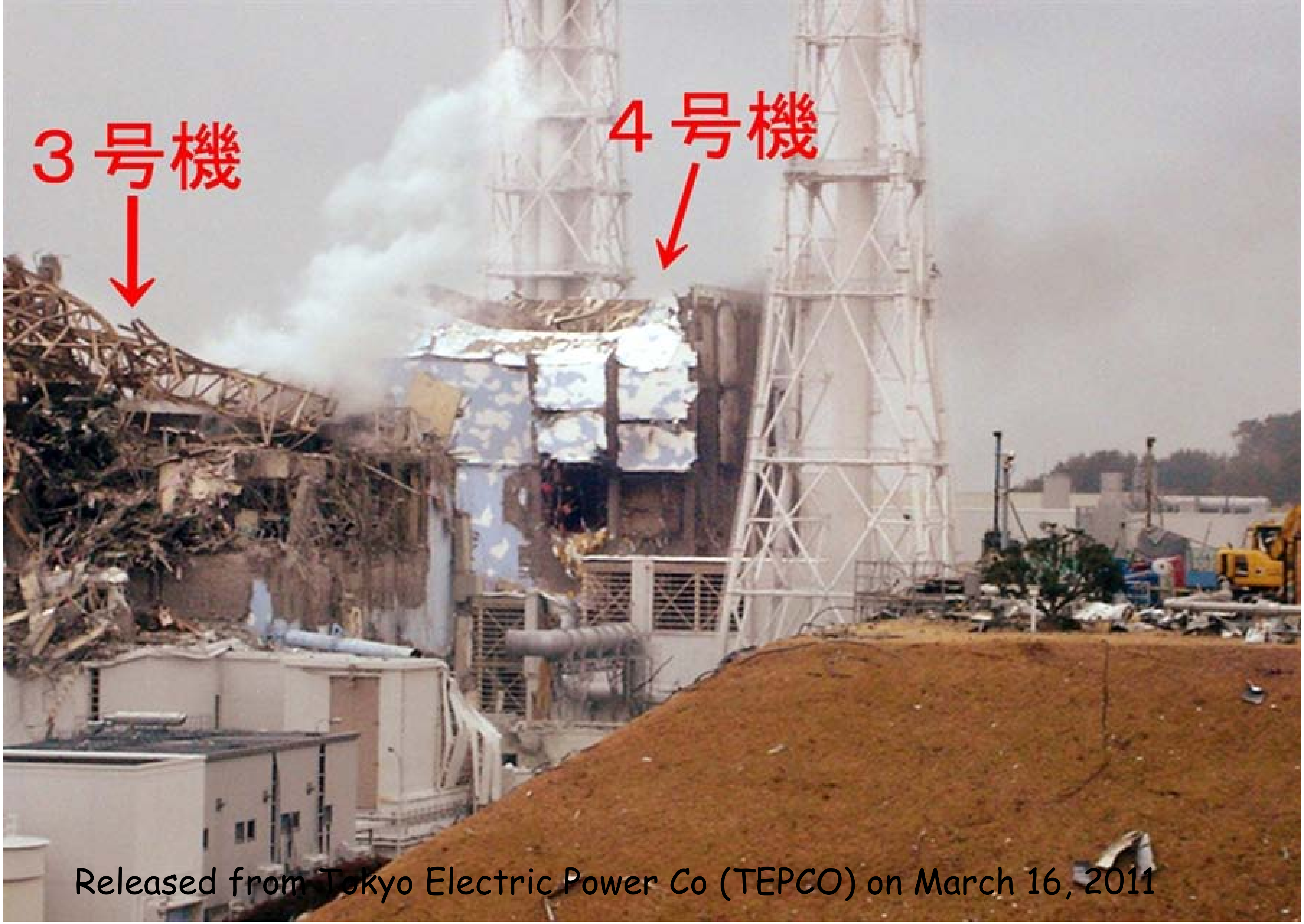


Tepco

Unit 3 – Unit 4 Stack Connection



Tepco May 16



MS-NBC Photoblog

March 17, 2011 Tepco image of damage to Unit 4.

Frame from video taken on March 16 by SDF helicopter overflight. Unit 3

Frame from video taken from SDF helicopter overflight. Unit 4

Spent Fuel

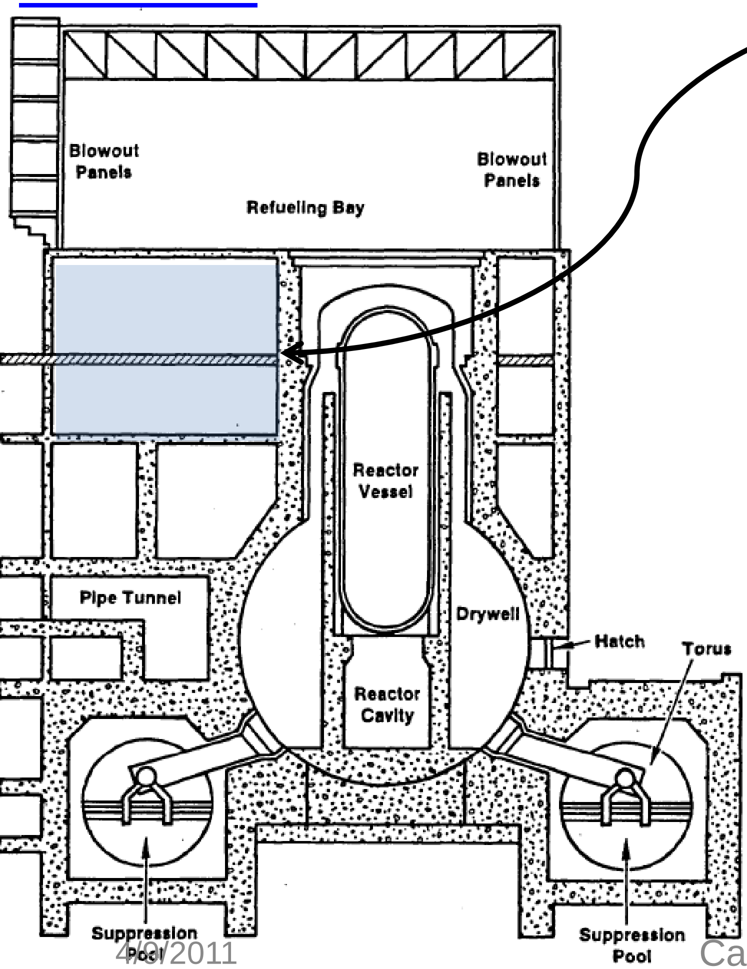
Number of Fuel Assemblies in Cooling Pools at Fukushima Daiichi
(Reported 17 March by Japan's Ministry of Economy, Trade and Industry)

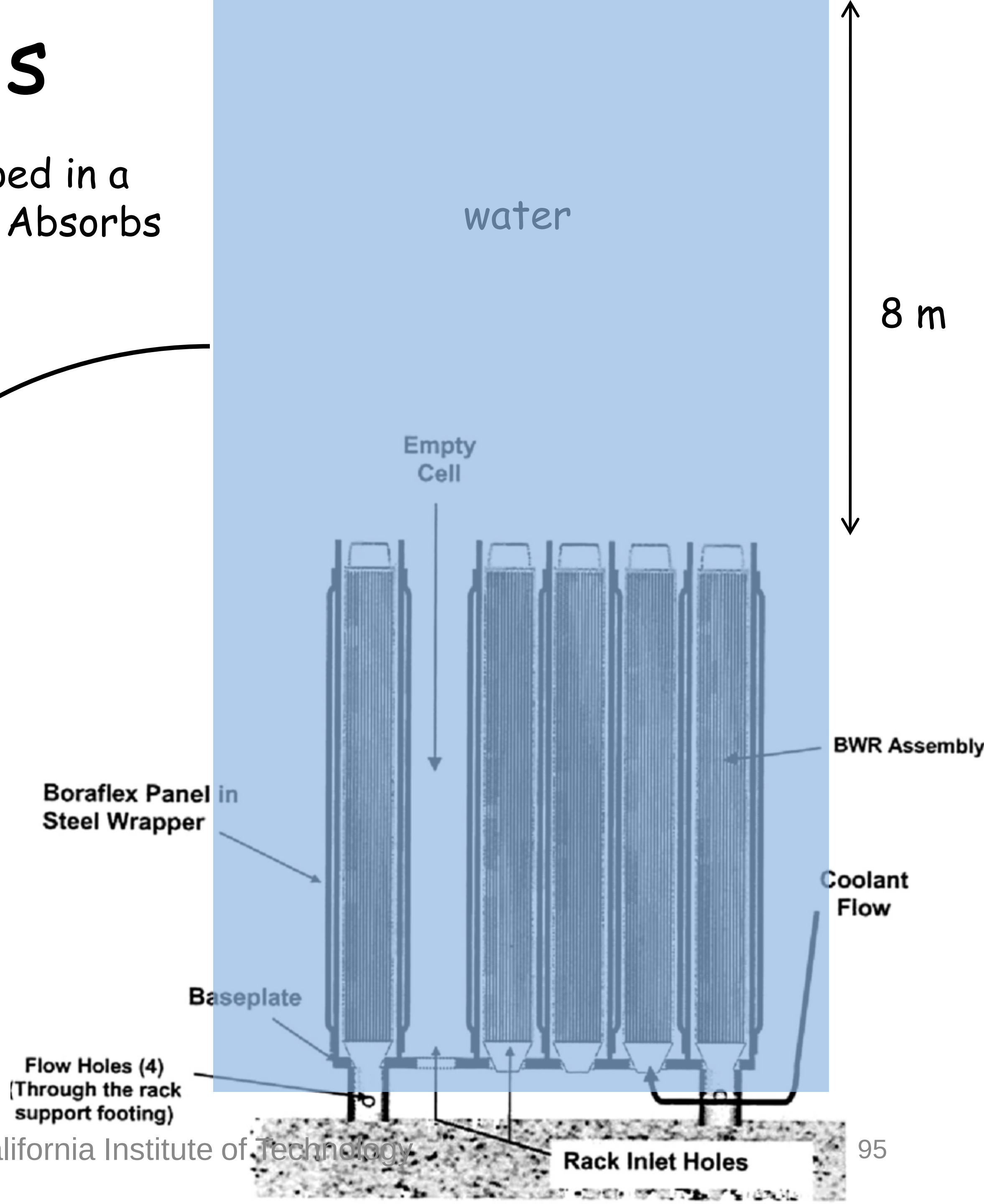
	Capacity	Irradiated Fuel Assemblies	Unirradiated Fuel Assemblies	Most Recent Additions of Irradiated Fuel
Unit 1	900	292	100	Mar-10
Unit 2	1,240	587	28	Sep-10
Unit 3	1,220	514	52	Jun-10
Unit 4	1,590	1,331	204	Nov-10
Unit 5	1,590	946	48	Jan-11
Unit 6	1,770	876	64	Aug-10

Cooling Pools

Boraflex™ - boron carbide trapped in a matrix of polydimethylsiloxane. Absorbs neutrons, prevents criticality.

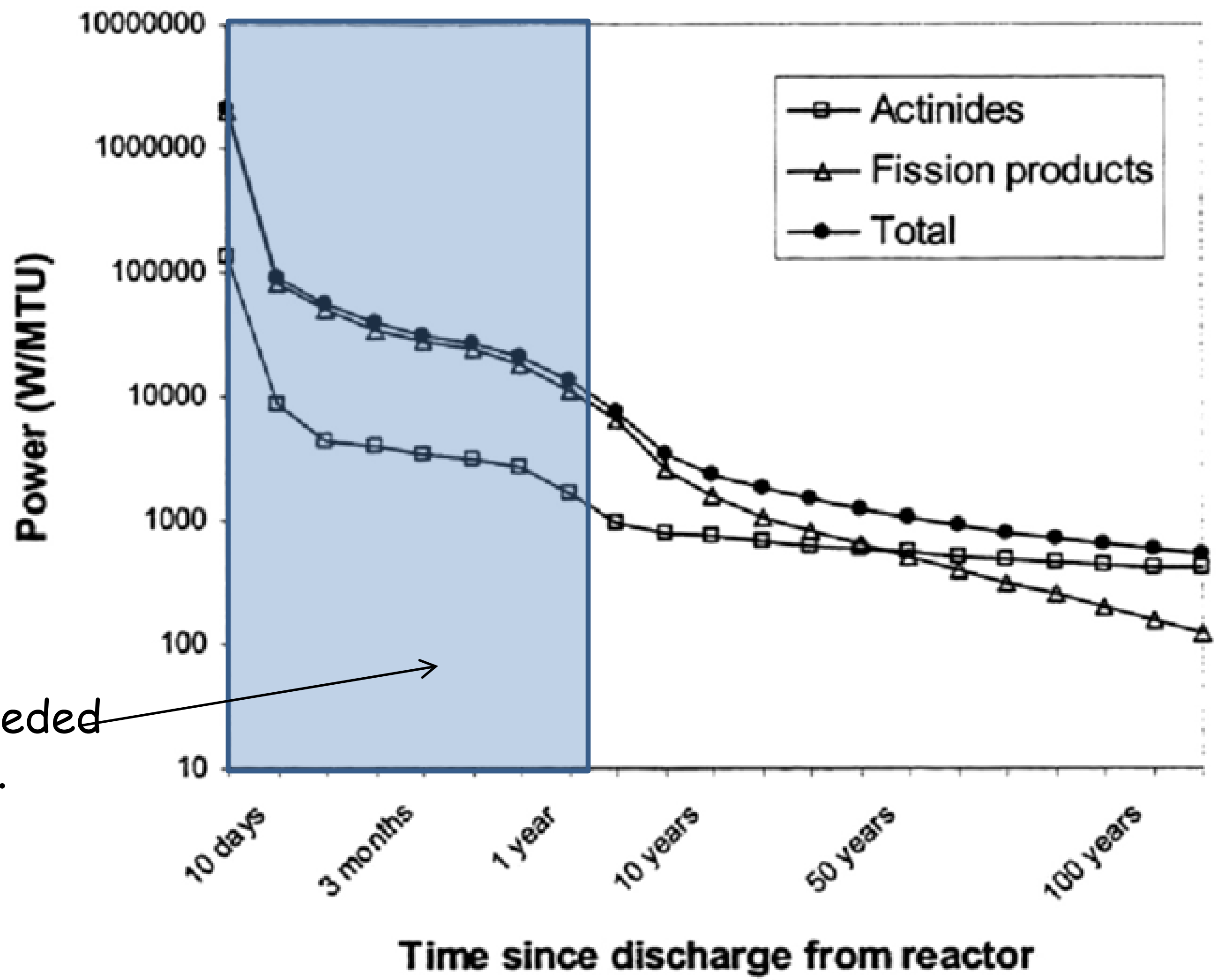
[NAS 2006]





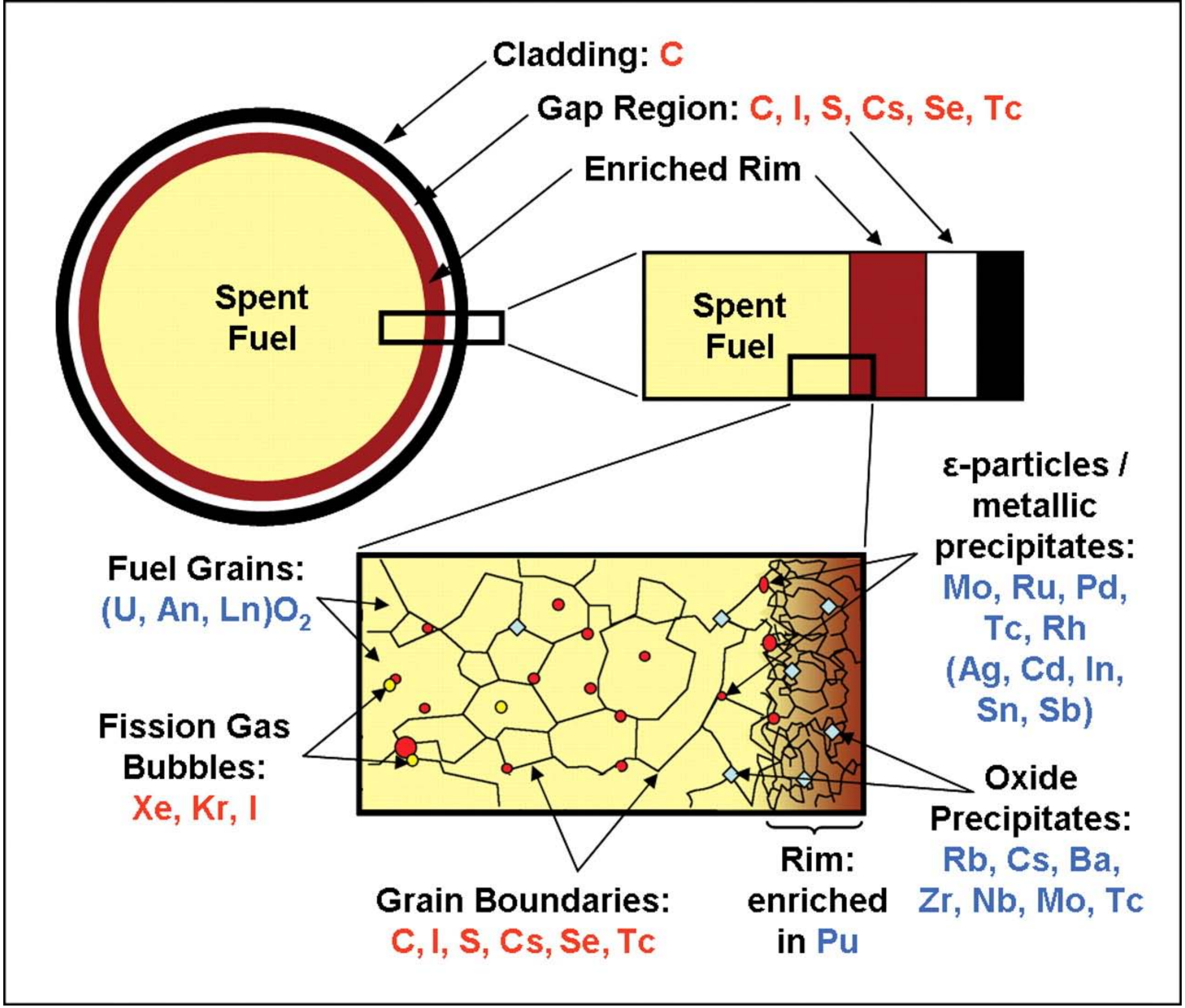
Decay heat

Actinides are U, Pu, Np, Am



Active cooling needed for first 3 years.

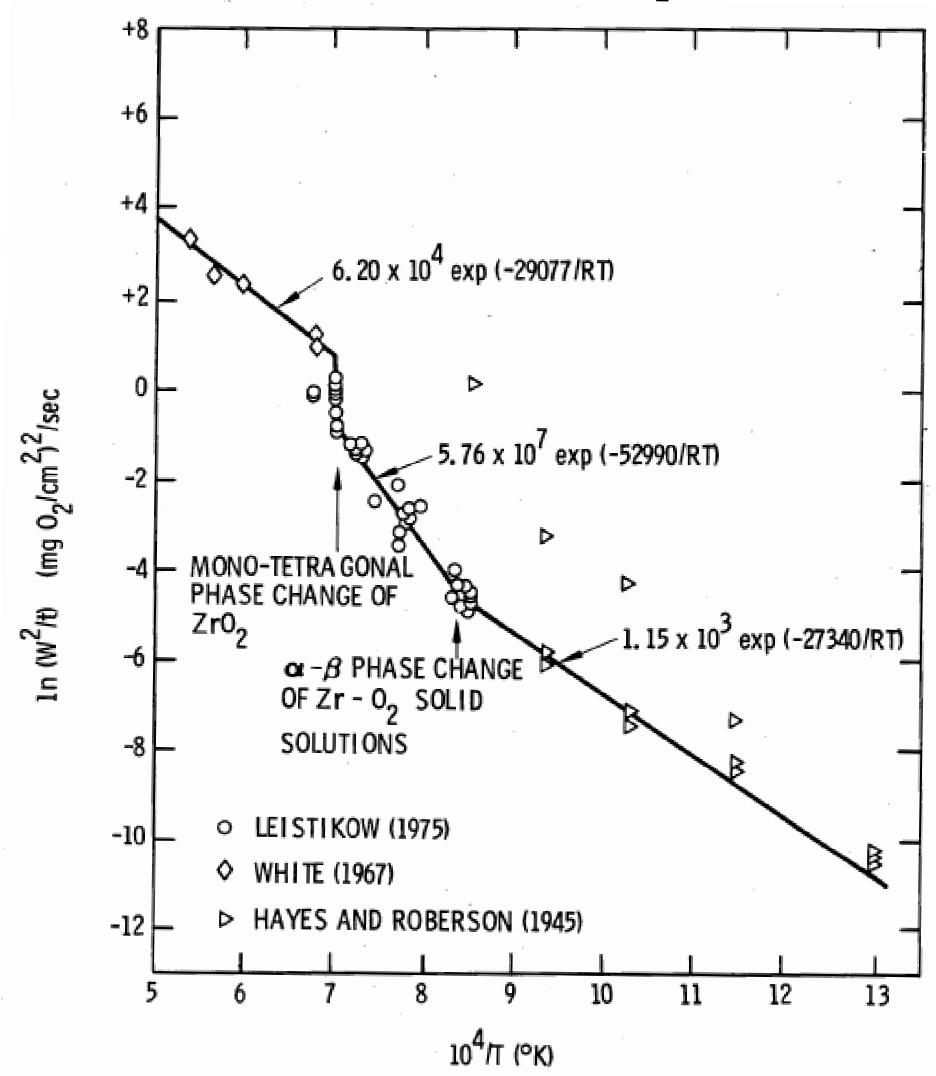
[Safety and Security of Commercial Spent Nuclear Fuel Storage]



Bruno and Ewing 2006

Air Oxidation of Zircaloy

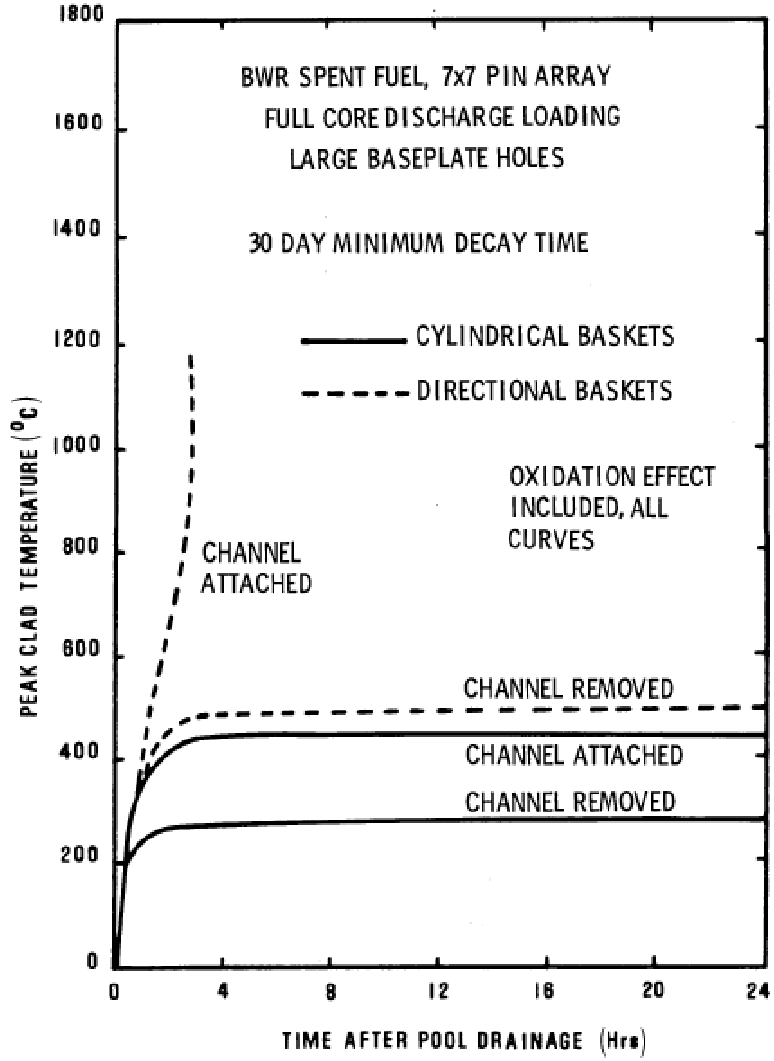
- $Zr + O_2 \rightarrow ZrO_2$
- +1260 kJ/mole Zr
- Parabolic rate law
  $$\frac{d}{dt}m^2 = K_o \exp(-E_a/RT)$$
- m = mass of O2/area
- Diffusion-controlled if starved for O2
- Decay heat and oxidation heating cause cladding failure (rupture) at 850 – 950 C.
- Combustion (fire) of Zr in air may be possible under some conditions.



NUREG/CR-0649 Spent Fuel Heatup Following Loss of Water During Storage

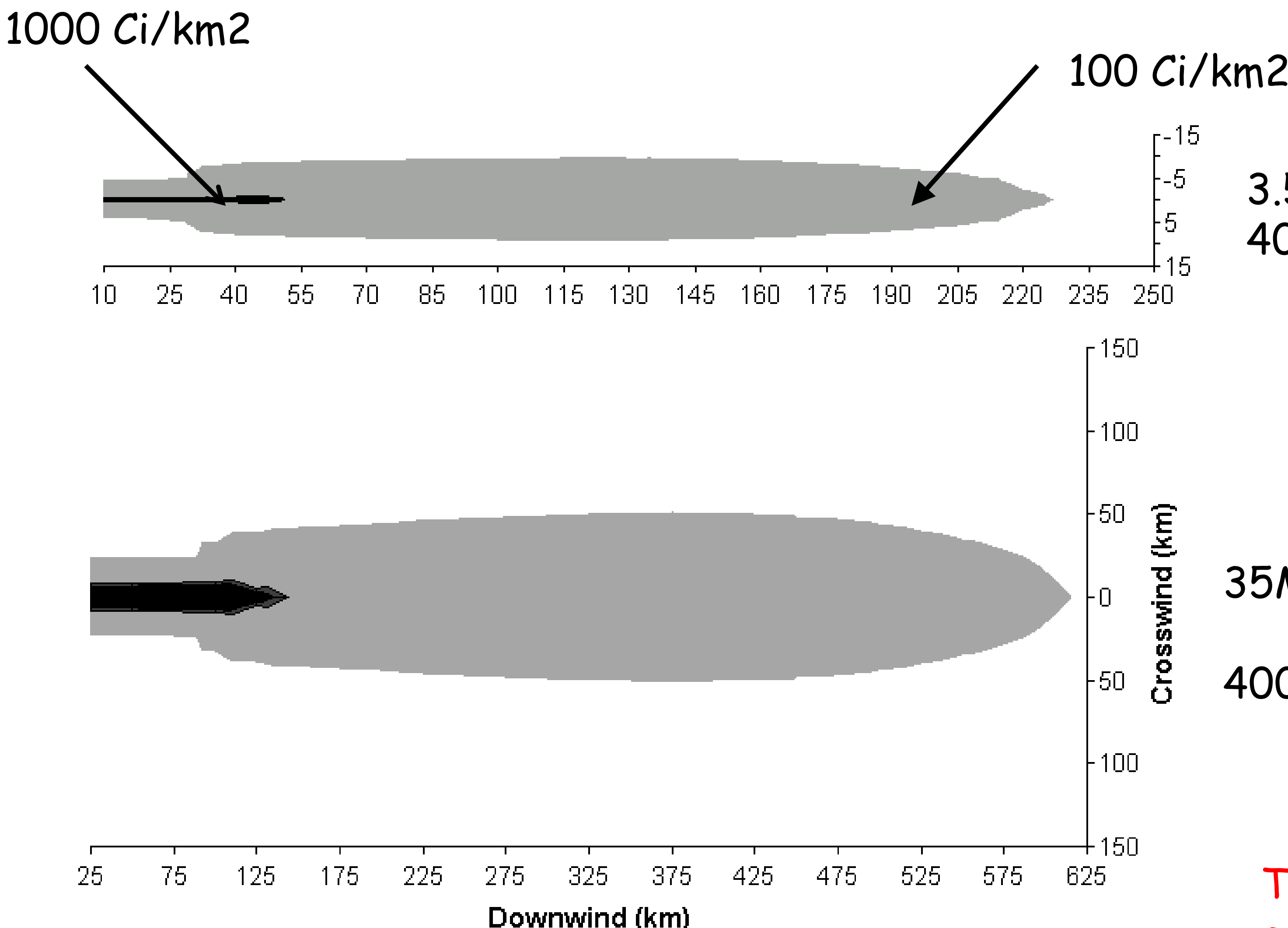
Loss of Pool Water Accident

- Factors
  - Density of fuel assemblies
  - Decay time
  - Ventilation
  - Design of assembly racks
- Incomplete draining
  - Inhibits natural convection
  - Temperatures may be higher
- Water spray
  - Effective even in modest amounts (100 gal/min)



NUREG/CR-0649 Spent Fuel Heatup Following Loss of Water During Storage

Cesium-137 Dispersal from SNF fire



3.5MCi total
40 tonne spent fuel

35MCi total

400 tonne spent fuel

These results are controversial!

Alvarez et al Science and Global Security 11,1-51, 2003

Considerations for SNF pools

- Cooling for pools as important as for reactors.
- 2724 fuel assemblies, representing a total of 470 MTHM.
- Special concerns about Unit 4 pool which has almost ½ of SNF inventory.
- Water could have been lost initially by sloshing, damage to removable barriers used for refueling, damage to structure.

Important questions for Pools

- Are pools and fuel assemblies intact?
  - Earthquake
  - H_2 explosion
  - Crane and structural fragments hurled into pool? Possible for Unit 3.
  - No filtering or containment of FP in all four units.
- What are the conditions
  - Water level, temperature?
- Are heat release removal systems functional?
  - If not, they will continue to have to dump liquid into pools – where is it going? Vaporization vs leaking out into building.

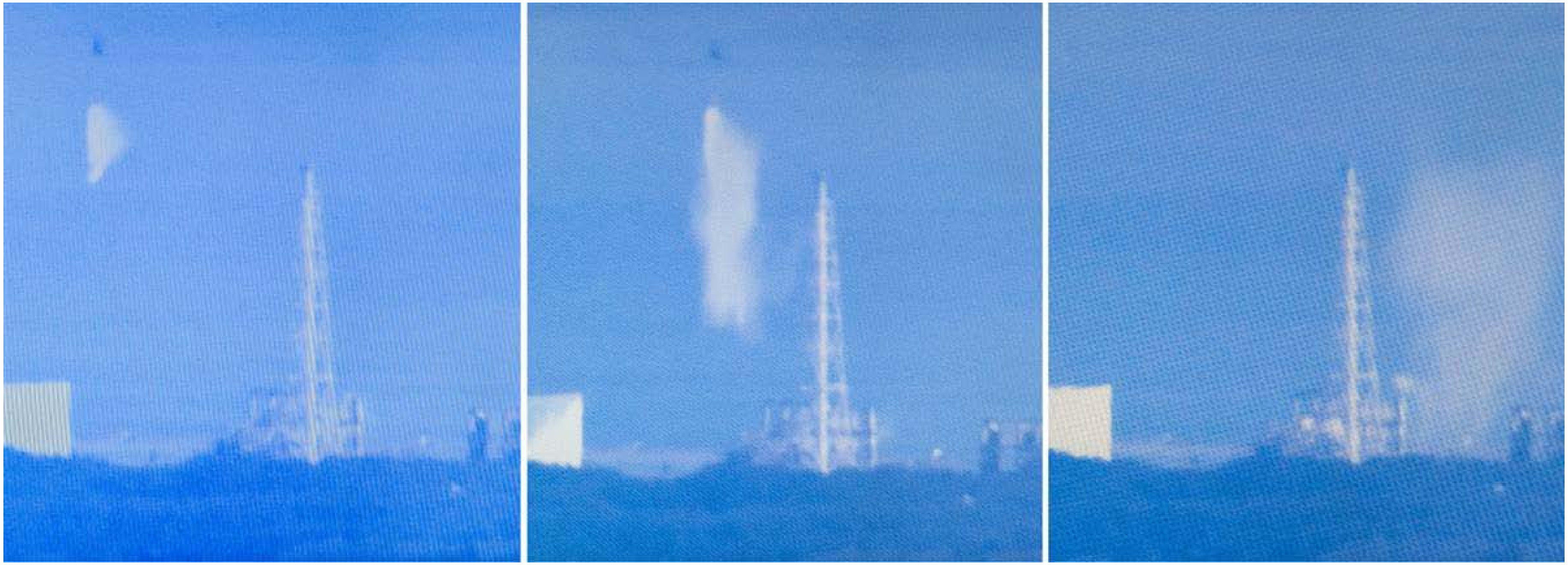
Thursday, March 17, 2011				
	6:15:00	17.26	135.45	Unit 3 - Pressure of suppression pool increased, considered venting.
	9:48:00	17.41	139.00	Helicopters drop water on Unit 3 roof until 10:01.
	11:30:00	17.48	140.70	Workers return, restart water injection in Unit 3.
	19:05:00	17.80	148.28	Water spray on Unit 3 from high pressure trucks from ground until 20:09
Friday, March 18, 2011				
	14:00:00	18.58	167.20	Water spray onto unit 3 by 6 fire engines of SDF until 14:38
	14:45:00	18.61	167.95	Water spray onto unit 3 by US Military fire engine
Saturday, March 19, 2011				
	0:30:00	19.02	177.70	Water spray onto unit 3 by Tokyo Fire Dept until 1:10
	14:10:00	19.59	191.37	Water spray onto unit 3 by Tokyo Fire Dept until 3:40 on 20 March.
Sunday, March 20, 2011				
	11:00:00	20.46	212.20	Unit 3 PCV pressure rose to 320 kPa then fell.
	15:05:00	20.63	216.28	Seawater injection into Unit 2 SFP via cooling line. Continues until 17:20 40 tonne water injected.
	15:46:00	20.66	216.97	Power center electricity restored on Unit 2.
	18:30:00	20.77	219.70	Unit 4 SFP water spray until 19:46 by SDF.
	21:36:00	20.90	222.80	Water spray onto unit 3 by Tokyo Fire Dept until 3:58 on 21 March.

Monday, March 21, 2011				
	6:37:00	21.28	231.82	Unit 4 SPF water spray by SDF until 8:41
	8:58:00	21.37	234.17	Radiation dose at site boundary around main entrance exceeds limit value. Only large fluctuations beyond 0.5 mSv/hr will be reported as new events from now on.
	10:37:00	21.44	235.82	Water spraying on common spent fuel pool started, ended at 3:30 pm
	15:37:00	21.65	240.82	Electricity connected to common spent fuel pool
	15:55:00	21.66	241.12	Grayish smoke from Unit 3 refueling area continuing until 17:55
		21.75	243.20	1.75 mSv/hr spike at front gate MP
	18:22:00	21.77	243.57	Light gray smoke from Unit 2 refueling floor area. Continued to 07:11 22 March, decreasing amount, white color.
Tuesday, March 22, 2011				
	10:35:00	22.44	259.78	Unit 4 power center electricity on.
	15:10:00	22.63	264.37	water spray on Unit 3 from Tokyo and Osaka Fire Dept until 16:00
	16:07:00	22.67	265.32	Injection of 18 tonne seawater to Unit 2 SFP
	17:17:00	22.72	266.48	Water injection by concrete pumping truck into Unit 4 fuel pool, 50 t/hr until 20:30
	22:46:00	22.95	271.97	Lights turned on in Unit 3 control room
Wednesday, March 23, 2011				
	2:33:00	23.11	275.75	Seawater injection into Unit 1 RPV through feed water system in addition to fire lines. Flow rate increased to 18 m3/h
	9:00:00	23.38	282.20	Unit 1 Switched to feed water system only. Flow rate is 11 m3/h
	10:00:00	23.42	283.20	Core temperature 400C in Unit 1
	10:00:00	23.42	283.20	Pumping water into Unit 4 fuel pool until 13:02
	11:03:00	23.46	284.25	Pumping 35 tonne of seawater into Unit 3 fuel pool until 13:20
	16:20:00	23.68	289.53	Black smoke belching from Unit 3 building. Not observed at 11:30 pm or 04:50 next day.
Thursday, March 24, 2011				
	5:35:00	24.23	302.78	Injecting 120 tonne seawater into Unit 3 SFP until 16:05
	10:50:00	24.45	308.03	White fog-like steam from roof of Unit 1 reactor bldg.
	11:30:00	24.48	308.70	Lights on in main control room, Unit 1.
	13:28:00	24.56	310.67	Unit 3 water spray on SFP until 16:00
	18:02:00	24.75	315.23	Unit 3 fresh water injection to core started

March 18 Aerial View

NY Times – DigitalGlobe

Helicopter water drops



17 March NHK/Getty/AFP

Unit 4 pool cooling March 18

Japan SDF

Unit 3 Plume -March 22

Tepco

Cooling Spent Fuel Unit 4

Tokyo Electric Power Co. . Picture taken
March 22, 2011

Friday, March 25, 2011				
	6:05:00	25.25	327.28	Sea water injection into Unit 4 SFP through fuel cooling lines until 10:20
	10:30:00	25.44	331.70	Seawater injection into Unit 2 SFP until 12:19
	13:28:00	25.56	334.67	Water spray onto unit 3 until 16:00
	15:37:00	25.65	336.82	Begin fresh water injection into Unit 1 RPV started.
	18:02:00	25.75	339.23	Begin fresh water injection into Unit 3 RPV started.
	19:05:00	25.80	340.28	Water pumping into Unit 4 SFP by concrete pumping truck until 22:07
Saturday, March 26, 2011				
	10:10:00	26.42	355.37	Begin injecting fresh water with boric acid into Unit 2.
	16:46:00	26.70	361.97	Lights on in main control room Unit 2
Sunday, March 27, 2011				
	12:34:00	27.52	381.77	Water spray on unit 3 by concrete pumping truck
	15:30:00	27.65	384.70	Water in trenches outside units 1 and 2 inspected. 0.4 mSv/h unit 1 and >1000 mSv/hr in unit 2.
	16:55:00	27.70	386.12	Water spray on unit 4 by concrete pumping truck
Monday, March 28, 2011				
	12:00:00	28.50	405.20	High levels of radiation found in water of turbine hall basements for units 1, 2, and 3
	17:40:00	28.74	410.87	Transferring water from Unit 3 condensate storage tank to suppression pool surge tank until 8:40 on March 31.
	20:30:00	28.85	413.70	Unit 3 water injection to core using motor-driven pump.
Tuesday, March 29, 2011				
	8:32:00	29.36	425.73	Unit 1 switched to the water injection to the core using the temporary motor-driven pump.
	11:50:00	29.49	429.03	Lights on in Unit 4 central control room.
	14:17:00	29.60	431.48	Water spray on unit 3 SFP by concrete pumping truck until 18:18
	16:45:00	29.70	433.95	Transferring water from Unit 2 condensate storage tank to suppression pool surge tank until 1:50 on April 1.

Videos & Photos of Damaged Plant

[Tepco helicopter video of plant from Mar 17 - 3:07]

[Water spraying Unit 3 from ground by fire trucks March 19 – 4:58]

[View from the ground of adding water to Unit 4, Mar 22 0:56]

[SDF helicopter footage from 23 Mar – 5:00]

[Commentary on SDF helicopter footage on NHK, March 27]

[High resolution aerial photography]

Powering Instruments – March 22

Tepco June 20

Control Room – March 23

Tepco March 23

Working in the Dark

Tepco March 23

Reading Instruments

Tepco March 23

Control Room Unit 2 March 26

Tepco March 26

Fire engines injecting cooling water – March 16

Tepco June 20

Continuing Updates

- http://www.nisa.meti.go.jp/english/
- http://www.tepco.co.jp/en/index-e.html
- http://www.iaea.org/

Status at Beginning of April

The situation at the Fukushima Daiichi plant remains very serious. - IAEA April 6

"This will not lead to a sustainable condition. We want to restore power and rebuild the cooling system, but such efforts are hampered by the stagnant water," Kyodo News quoted Japanese Nuclear and Industrial Safety Agency spokesman Hidehiko Nishiyama as saying. "We have to find a way out of the contradictory missions." March 30

Status as of April 6

This is IAEA version of information from http://www.jaif.or.jp/english/
For more quantitative data see http://www.nisa.meti.go.jp/english/

Unit	1	2	3	4
Core and fuel integrity	Damaged	Severe damage	Damaged	No fuel in the Reactor
RPV & RCS integrity	RPV temperature high but stable	RPV temperature stable	RPV temperature stable	Not applicable due to outage plant status
Containment integrity	No information	Damage suspected	Damage suspected	
AC Power	AC power available - power to instrumentation – Lighting to Central Control Room	AC power available – power to instrumentation – Lighting to Central Control Room	AC power available – power to instrumentation – Lighting to Central Control Room	AC power available – power to instrumentation – Lighting to Central Control Room
Building	Severe damage	Slight damage	Severe damage	Severe damage
Water level of RPV	Around half of Fuel is shown uncovered (Stable)	Around half of Fuel is uncovered (Stable)	Around half of Fuel is uncovered (Stable)	Not applicable due to outage plant status
Pressure of RPV	Increasing	Stable	Stable	
CV Pressure Drywell	Decreasing trend	Stable	Stable	
Water injection to RPV	Injection of freshwater – via mobile electric pump with off-site power	Injection of freshwater – via mobile electric pump with off-site power	Injection of freshwater – via mobile electric pump with off-site power	
Water injection to CV	No information	No information	No information	
Spent Fuel Pool Status	Fresh water spraying completed by concrete pump truck	Freshwater injection to the Fuel Pool Cooling Line	Freshwater injection via Fuel Pool Cooling Line and Periodic spraying	Fresh water spraying completed by concrete pump truck

Cooling Water Issues - 4 April 2011

- Cooling is by "total loss"
  - Residual heat removal systems not working
  - Cold water pumped in, heats up, boils off as steam
  - Steam leaves as vapor plume into the environment or condenses inside structure, runs off into basement/sumps/condensate tanks
- Cooling water flow rates currently quite limited
  - 2 to 15 t/hr
  - Higher flow rate needed for effective heat removal .
- Damage to plumbing/containment/buildings resulting in some highly contaminated water leaking out into environment, going directly into ocean.
  - Running out of storage volume (1000 tonne/day needed)
  - Dumping less contaminated water to make room
- If you stop water inflow, the cores will melt, followed by RPV and containment failure, potentially a large FP release into atmosphere.

"contradictory missions"

The Salt Problem

- Seawater is nominally 38 kg dissolved NaCl per tonne of seawater.
- Seawater used for up to 200 hr as emergency cooling water source in all three reactors and spent fuel pools.
- Low flow rates and high heat loads in reactors and pools will result in H2O evaporating leaving NaCl-rich solution behind in pools and reactor vessels.
- If solution becomes supersaturated (>260 kg/tonne @ 25C), salt will precipitate out of solution.
- Estimated seawater amounts and upper bound on salt in each reactor vessel
  - Unit 1: 1174 t seawater, 44 t NaCl (138 t water usually in primary circuit)
  - Unit 2: 555 t seawater, 20 t NaCl
  - Unit 3: 538 t seawater, 21 t NaCl
- Conclusion: there could be as much as 80 t of NaCl inside the reactor vessels.
- Consequences:
  - Accelerated corrosion of reactor vessel, internal structure, and piping.
  - Some salt may have come out of solution and have deposited onto reactor internal surfaces, core, etc.

Estimates based on Tepco/NISA reported durations and flow rates of seawater. Salt amounts assume H2O evaporates leaving all salt behind in RPV. Solubility of salt increases slightly with increasing temperature.

Overall Outlook – April 6

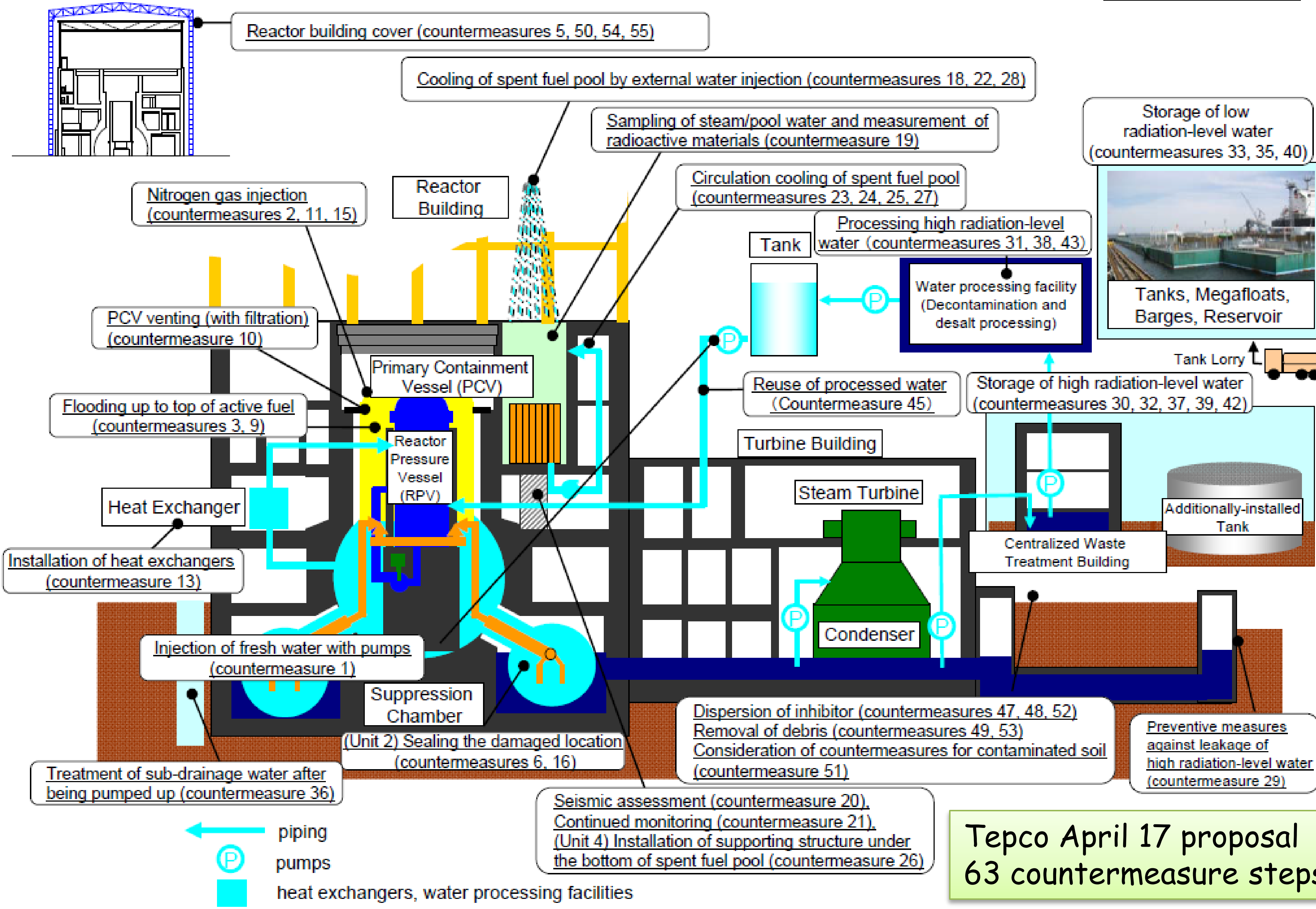
- Units 1-4 written off by Tepco
- Inside and around reactor buildings/turbine halls highly contaminated
- Extremely hazardous environment (high radiation, debris), difficult to even assess damage much less make repairs
- Although off-site power is restored to some systems, unclear how much of plant equipment can be brought back on line.
- Precarious operation condition – no safety systems, lack of containment, ad hoc cooling measures, extremely vulnerable.
- Very substantial efforts needed to
  - Maintain cooling
  - Contain FP release
  - Decontaminate area
- Long (10s years based on TMI/Chernobyl) decommissioning effort ahead.

Update April 27

- Tepco has proposed a series of 63 "countermeasures" (see next slide) to address many of the issues identified on the previous slide.
- Some of the more significant steps are:
  - Using remotely controlled heavy machinery to remove and store contaminated material.
  - Filling containment vessels with water to help cool the reactor pressure vessels to cold shutdown condition
  - Fabricating and installing external heat exchangers and plumbing to cool the reactor and pools with closed loop instead of current total loss method. This indicates that the existing systems within the reactor probably cannot be repaired.
  - Building storage tanks and a processing plant to clean up contaminated water
  - Installing new backup generators on higher ground.
  - Constructing buildings to surround the existing structures and using filtered exhaust to contain further releases.
  - Seismic reinforcement to reactor building 4 to support spent fuel pool.
- The goal appears to be achieving cold shutdown and sufficient decontamination to remove fuel from both pools and reactors.
- The schedule will probably be paced by the speed of the clean-up. Doing major construction will require a large crew to be onsite for an extended time. This is not possible without a substantial reduction in radiation level which requires removing the large amount of debris and fallout from the explosions.

Overview of Major Countermeasures in the Power Station

Reference 2



Tepco April 17 proposal
63 countermeasure steps

Big robots!

Tepco 28 April

Little Robots!
Packbots inside the Unit 3 Bldg

Tepco April 17

Robot Drivers

Entering Unit 1

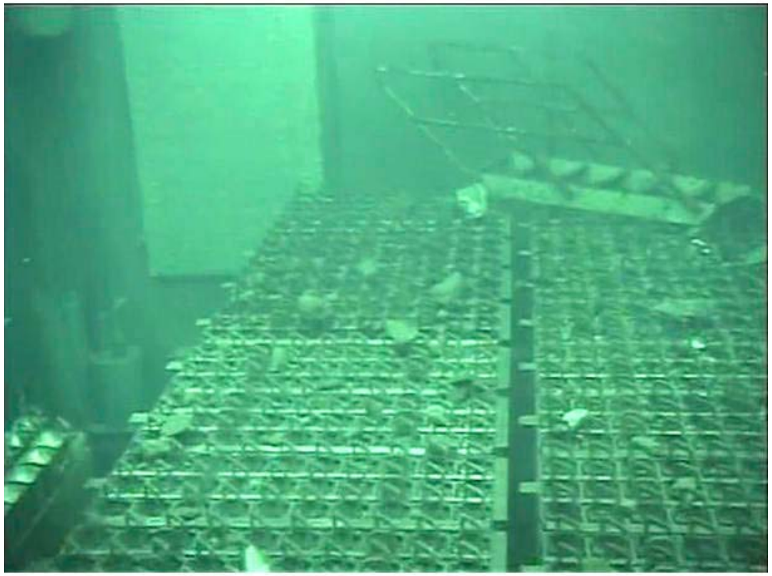
Repairing the Water Level Sensor – May 10 Tepco

Measuring radiation levels – May 5

Update on Unit 4 Fuel Pool

Unit 4 - Video footage shows that fuel assemblies appear intact
hydrogen source for fire/explosions may have been from other reactor buildings

May 11



[Inside Fuel Pool]

April 15

[Interior of Refueling area]

Update on Unit 3 Fuel Pool

Fuel rods not visible – extensive
Debris in pool – fuel rods damaged?

May 10 video inside pool

Japan News Today

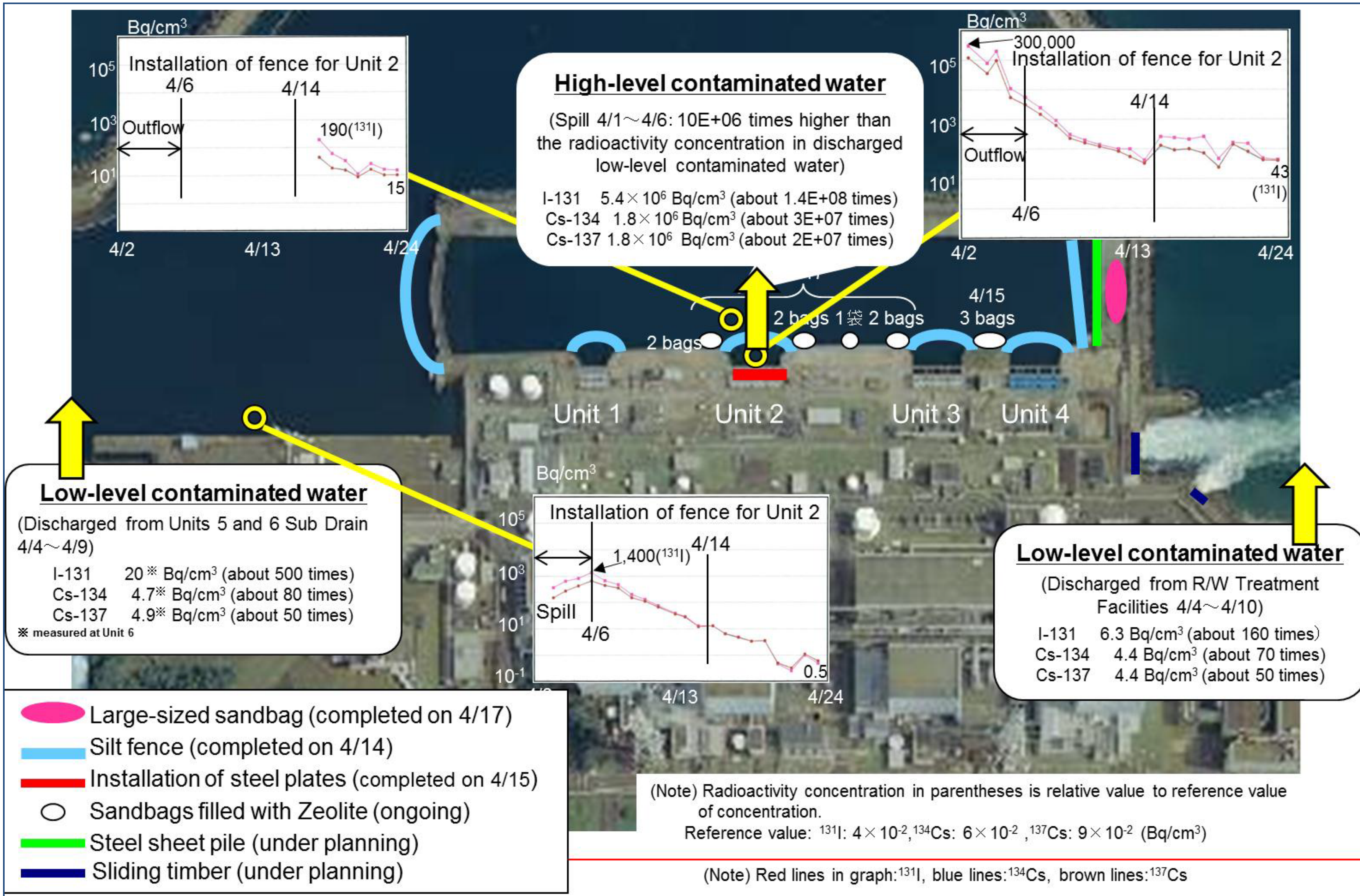
Activity in Pool and Sea Water

Data source: Tepco reports.

Nuclide	Unit 3 SF pool (May 9)	Unit 4 SF Pool (May 7)	Unit 2 Bar Screen (April 1-6)	Unit 2 Turbine basement (March 27)	Notification level
	Activity (Bq/L)	Activity (Bq/L)	Activity (Bq/L)	Activity (Bq/L)	Activity (Bq/L)
Cs-134 (2 y)	1.4×10^8	5.6×10^4	1.8×10^9	3.1×10^9	90
Cs-136 (13 d)	1.6×10^6	-	-	3.2×10^8	-
Cs-137 (30 y)	1.5×10^8	6.7×10^4	1.8×10^9	3.0×10^9	60
I-131 (8 d)	1.1×10^7	1.6×10^4	5.4×10^9	1.3×10^{10}	40

At the beginning of June, there was about 100 tonne of contaminated water created by cooling activities. At the March 27 specific activity levels this implies about 6×10^{14} Bq of CS activity in the water, a factor of ~10^2 lower than the estimated airborne release total.

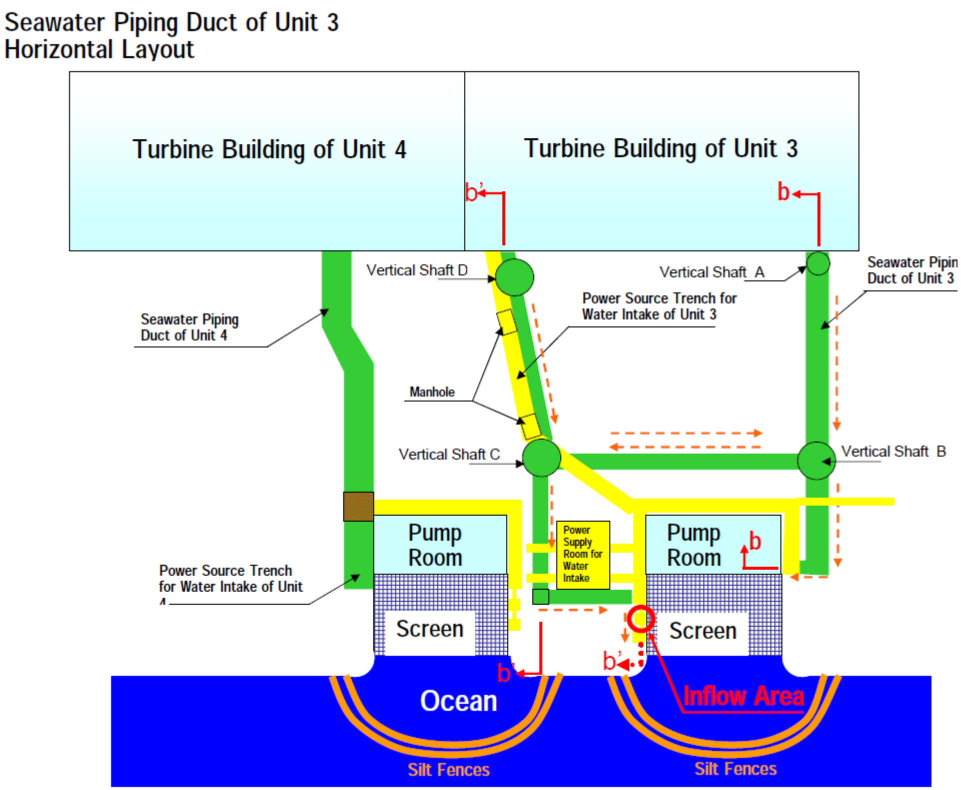
Releases into Ocean

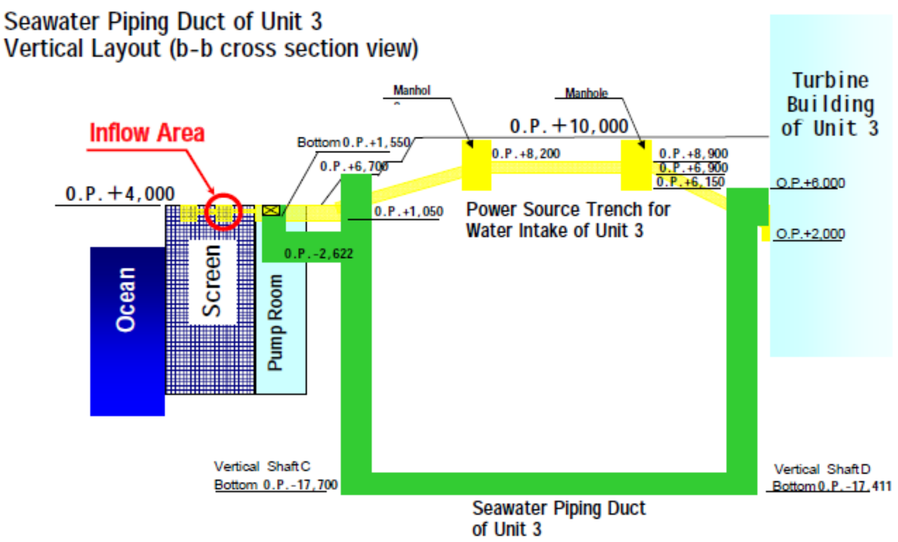


IAEA May 5

Where is the water coming from?

May 10-11, total of 250 m3, from Unit 3 Turbine Building through power trench.
Cut wires, packed with fabric, blocked pit with concrete, silt fence, zeolite.

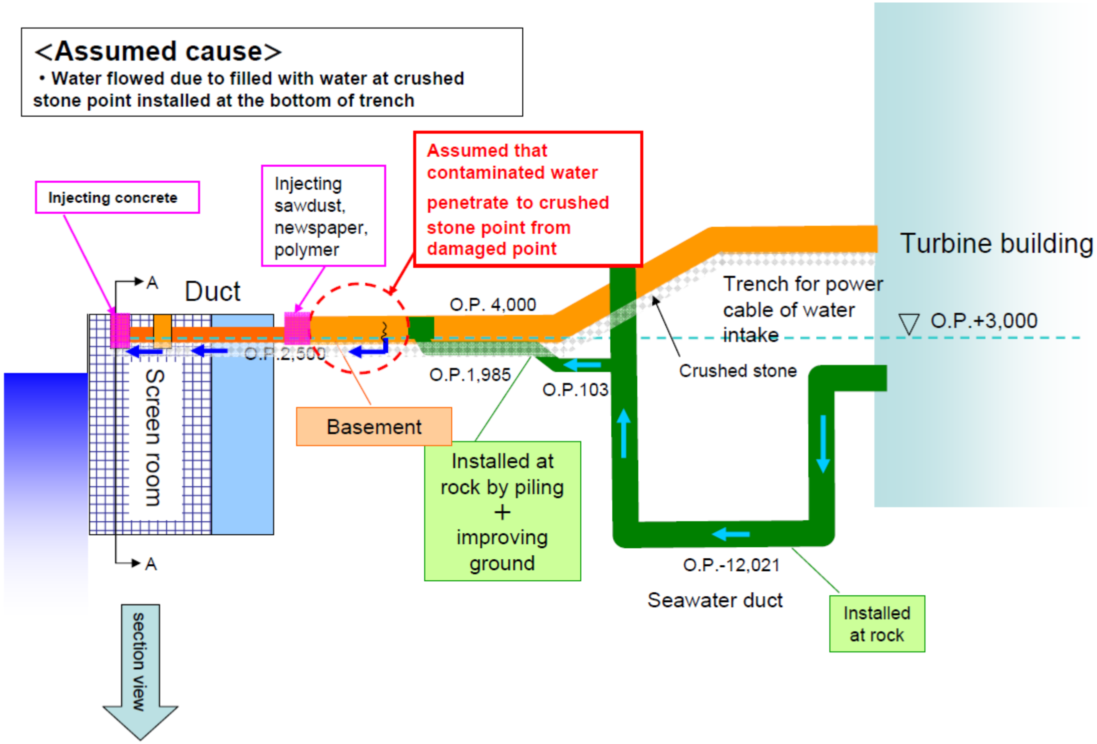




Tepco

Unit 2 Outflow

Unit 2 turbine building basement filled with contaminated water. ~500 m3 outflow through crack from April 2-6. Filled pit with concrete, steel plates in 'screen rooms', silt fence, zeolite in ocean by quay.

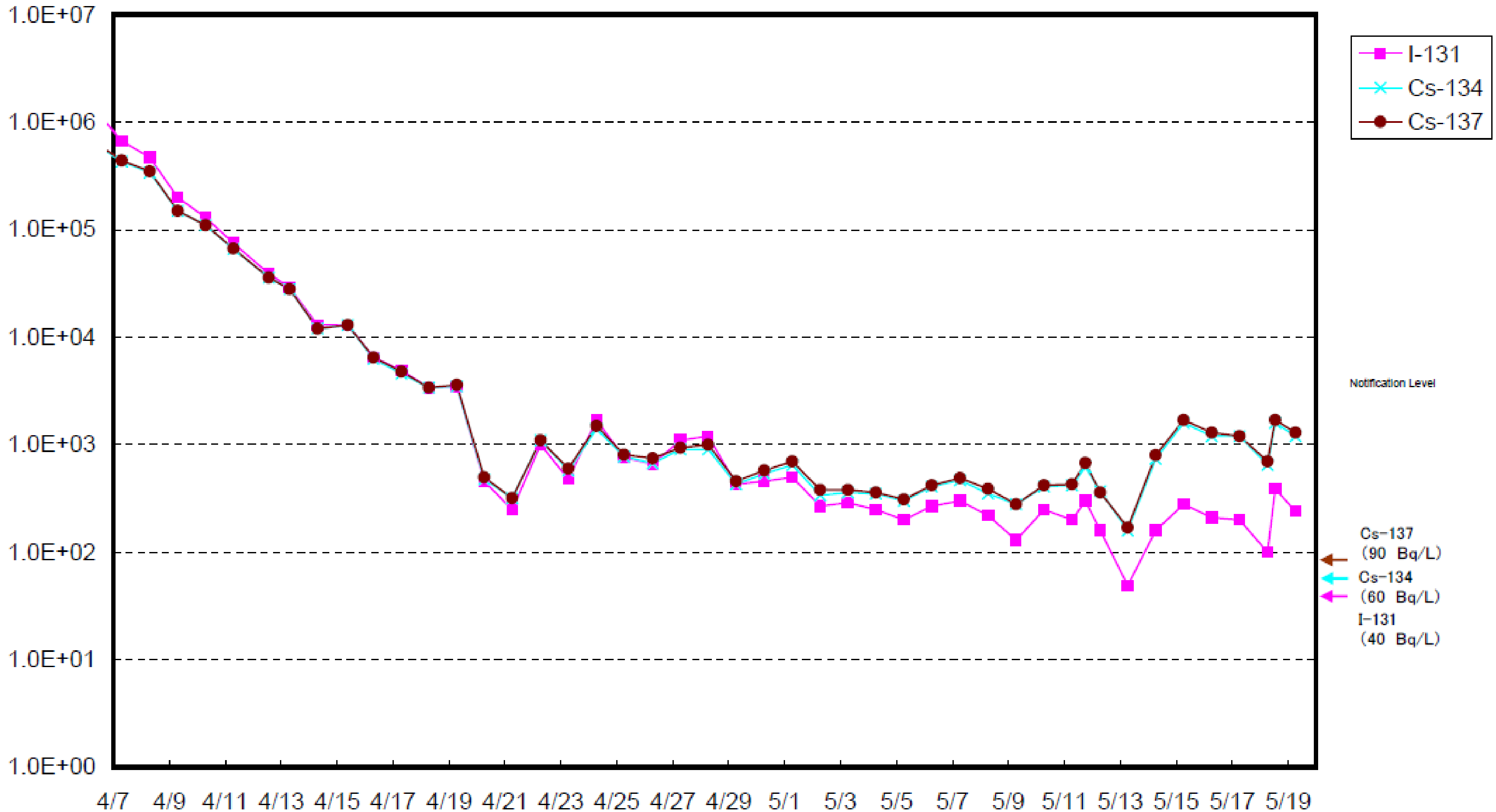


Tepco

Silt Fence – Unit Two Intake

Tepco/Japan News Today

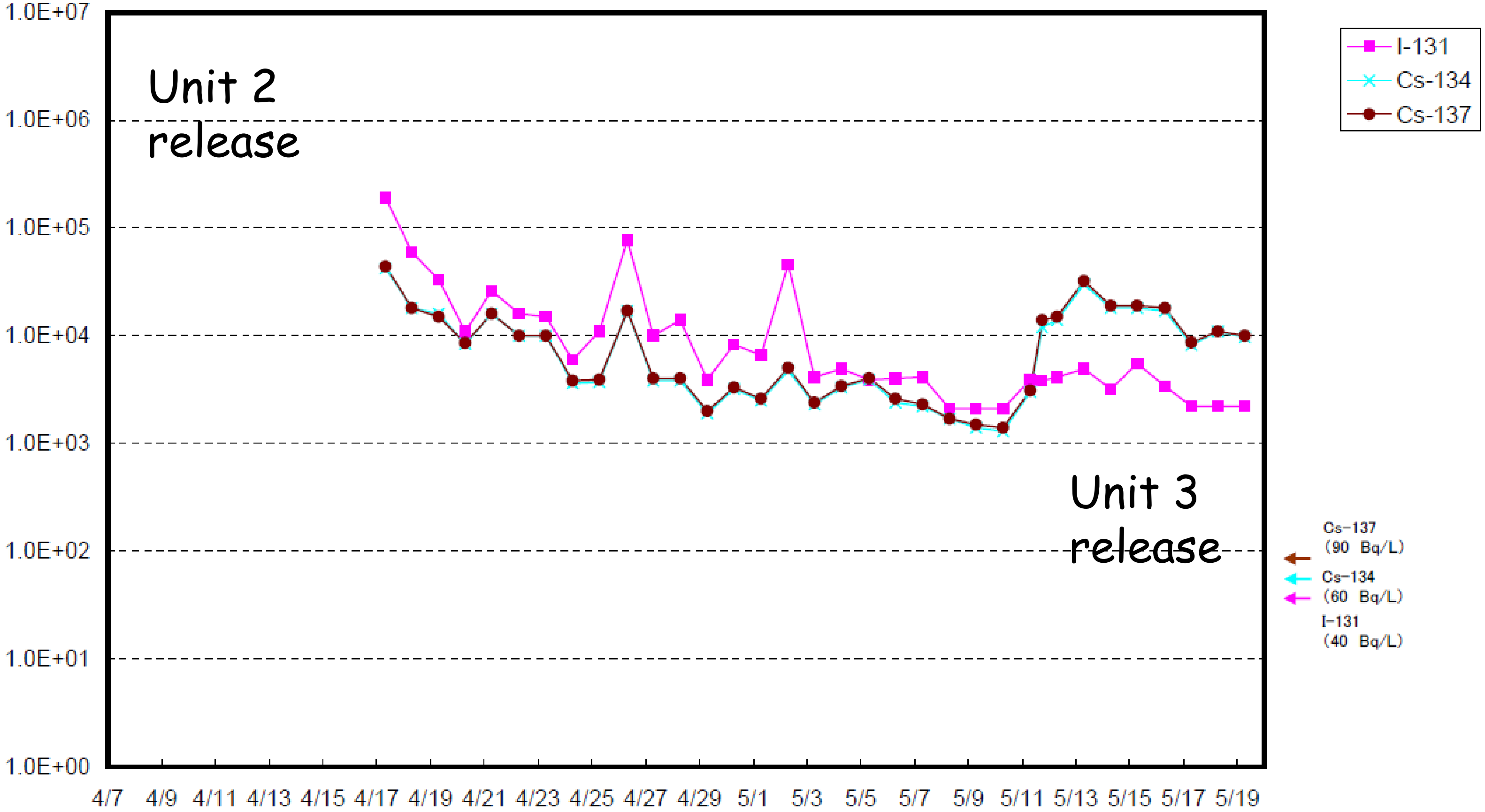
Sea Water Activity (Bq/L) Near Shallow Draft Quay



Tepco May 20

Bar Screen of Unit 2 Intake

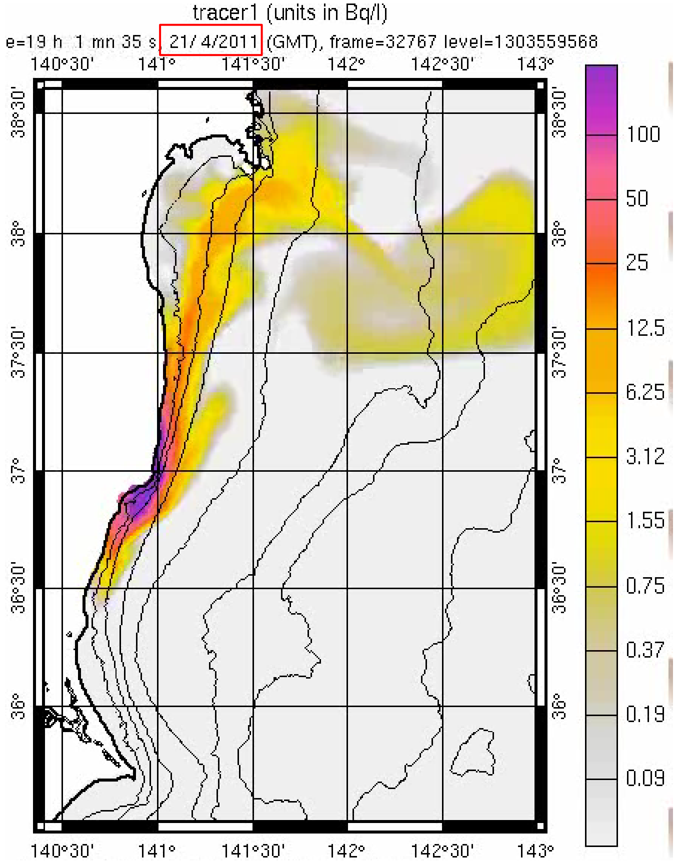
(outside silt fence)

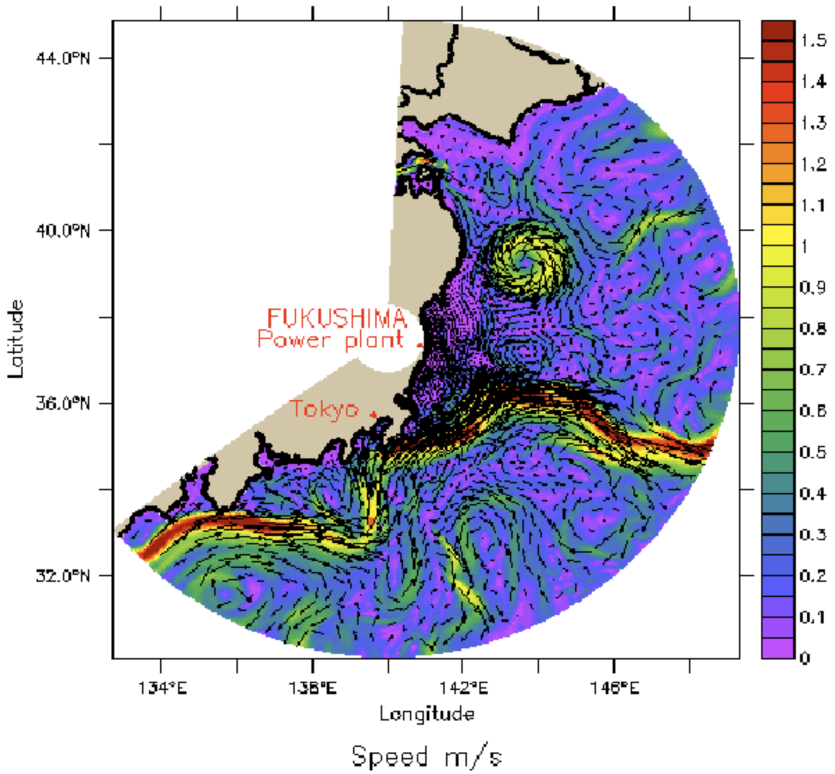


Tepco May 20

Where is the water going?

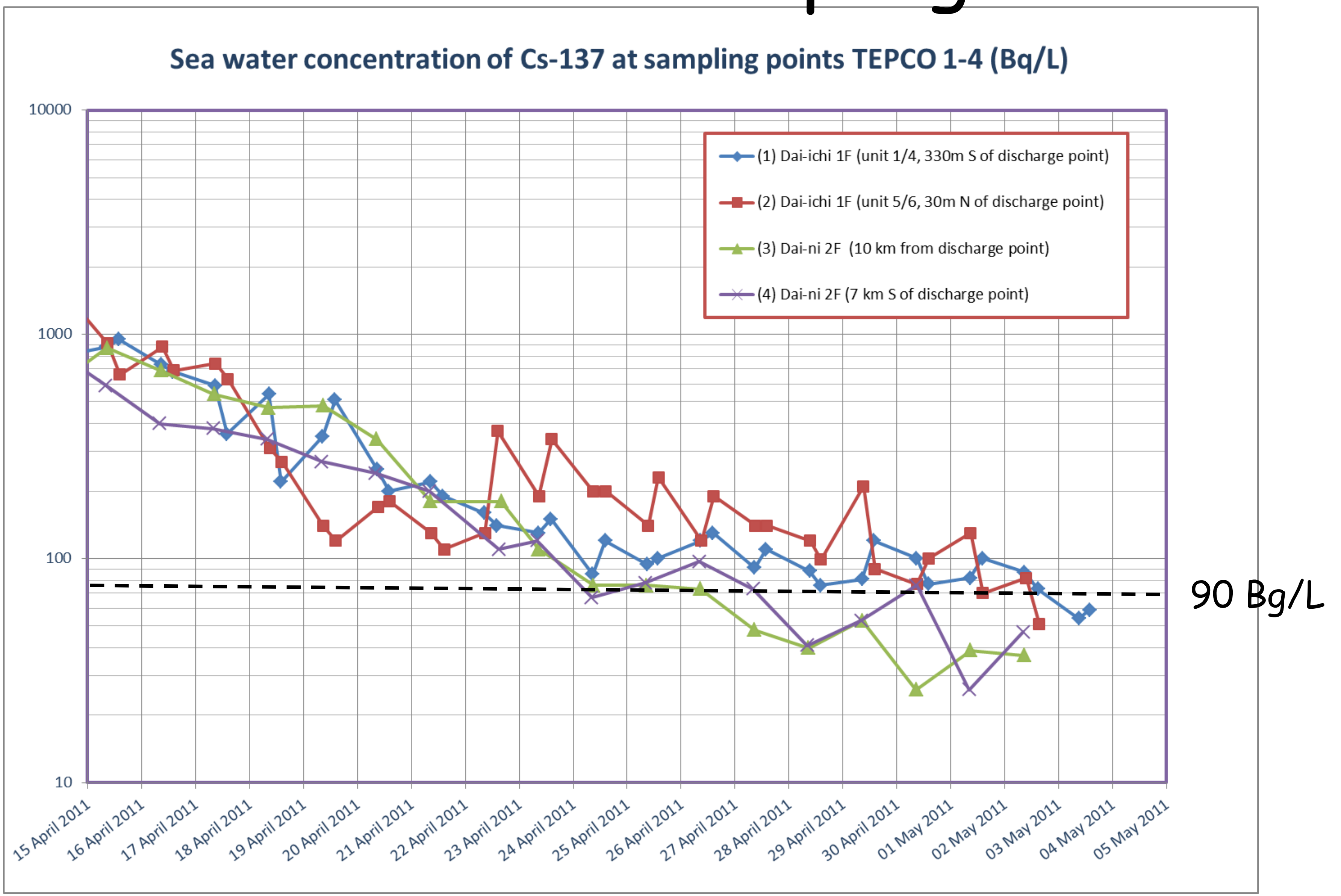
Liquid release simulation by [Toulouse-CNRS]





[Scirroco Animation of Activity Concentration]

Offshore Sampling



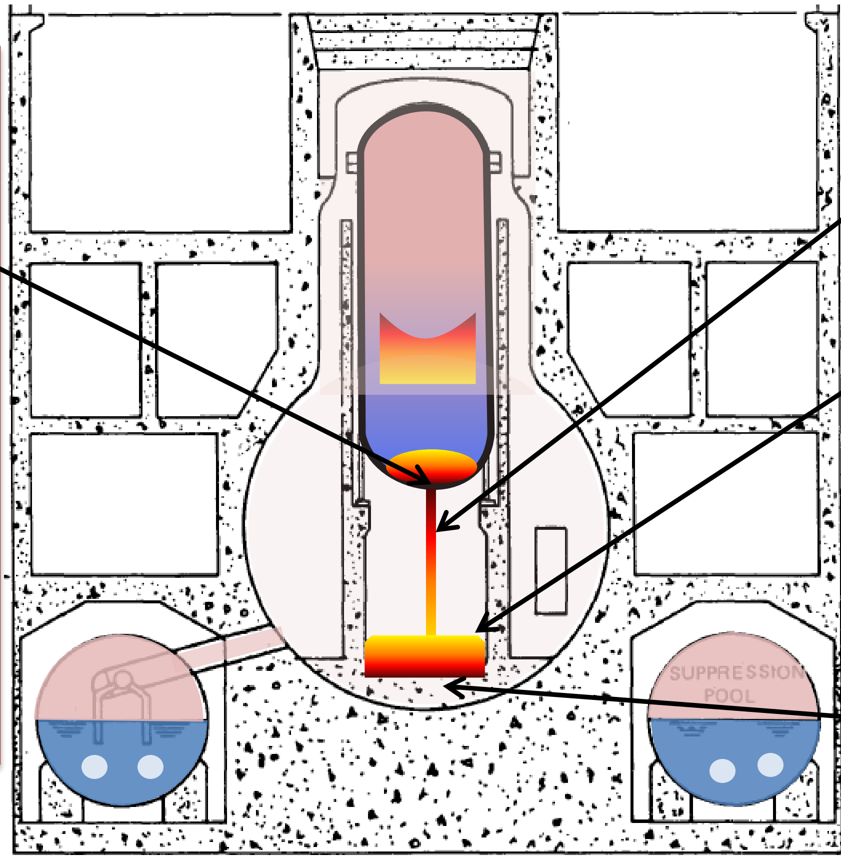
IAEA May 5

Where are the cores? Are they "molten"?

Damaged core material may slump to lower head.

Now becomes much more difficult to cool.

If temperature is sufficiently high, melting may take place.



If core is molten, it can dissolve RPV steel and penetrate lower head.

A portion of the molten core could then fall to bottom of the reactor cavity.

If that happens, core will wind up eating into concrete "basemat" and possibly through primary containment

Can the cores melt through the pressure vessel?

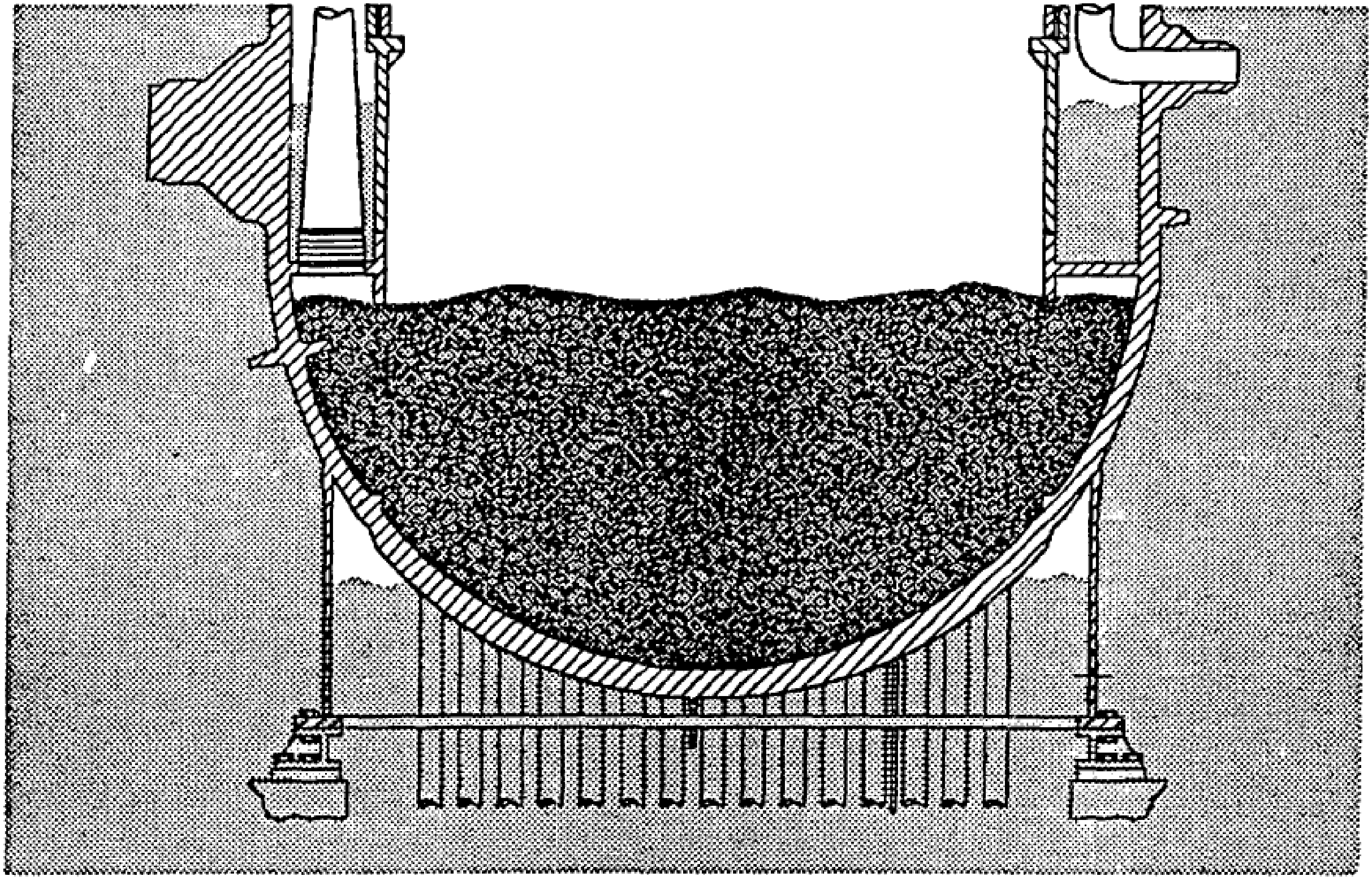
It depends on temperature and location of core. TMI came close.

Current situation

- Cores are severely damaged
- Some core material may have moved to lower head
- Difficulty getting sufficient water into reactor to keep reactor vessel and core cool
- Emergency Procedure Guidelines
  1. Keep vessel depressurized
  2. Vent to keep containment depressurized
  3. Restore injection in a controlled manner
  4. Inject boron
  5. Flood containment to delay/prevent lower head failure

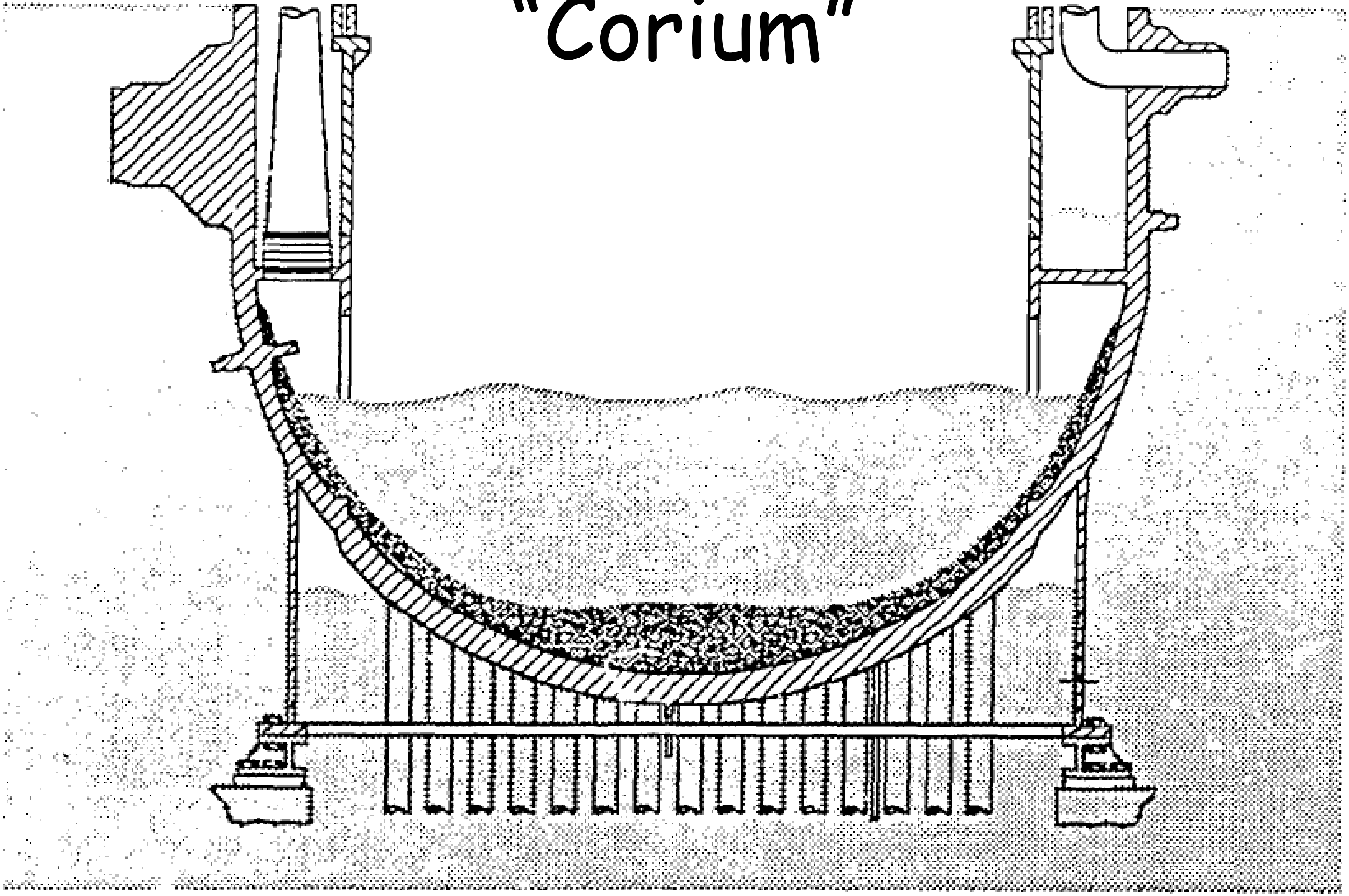
NUREG/CR-5869 Hodge et al CONF-921007—31 ORNL

Core Debris in Lower Head



Hodge et al CONF-921007—31 ORNL

Formation of Molten Pool of "Corium"



Hodge et al CONF-921007—31 ORNL

Failure Mechanisms

Drywell Flooded?	Skirt Vented ?	Failure Mechansim	Time to Failure (hr)
N	N	Penetrations	4.
N	N	Bottom head creep rupture	10
Y	N	Bottom head creep rupture	13
Y	Y	Melting upper vessel wall	>20

Drywell can only be flooded up to vents. "The mass of the BWR internal structures is large…nevertheless, decay heating of the debris pool and the associated upward radiation would be relentless and, after exhaustion of the stainless steel, the only remaining internal heat sink above the pool surface would be the carbon steel of the vessel wall."

Hodge et al. CONF-921007—31 ORNL

Reactor Pressure Vessel & Internals

Upper vessel wall

Core

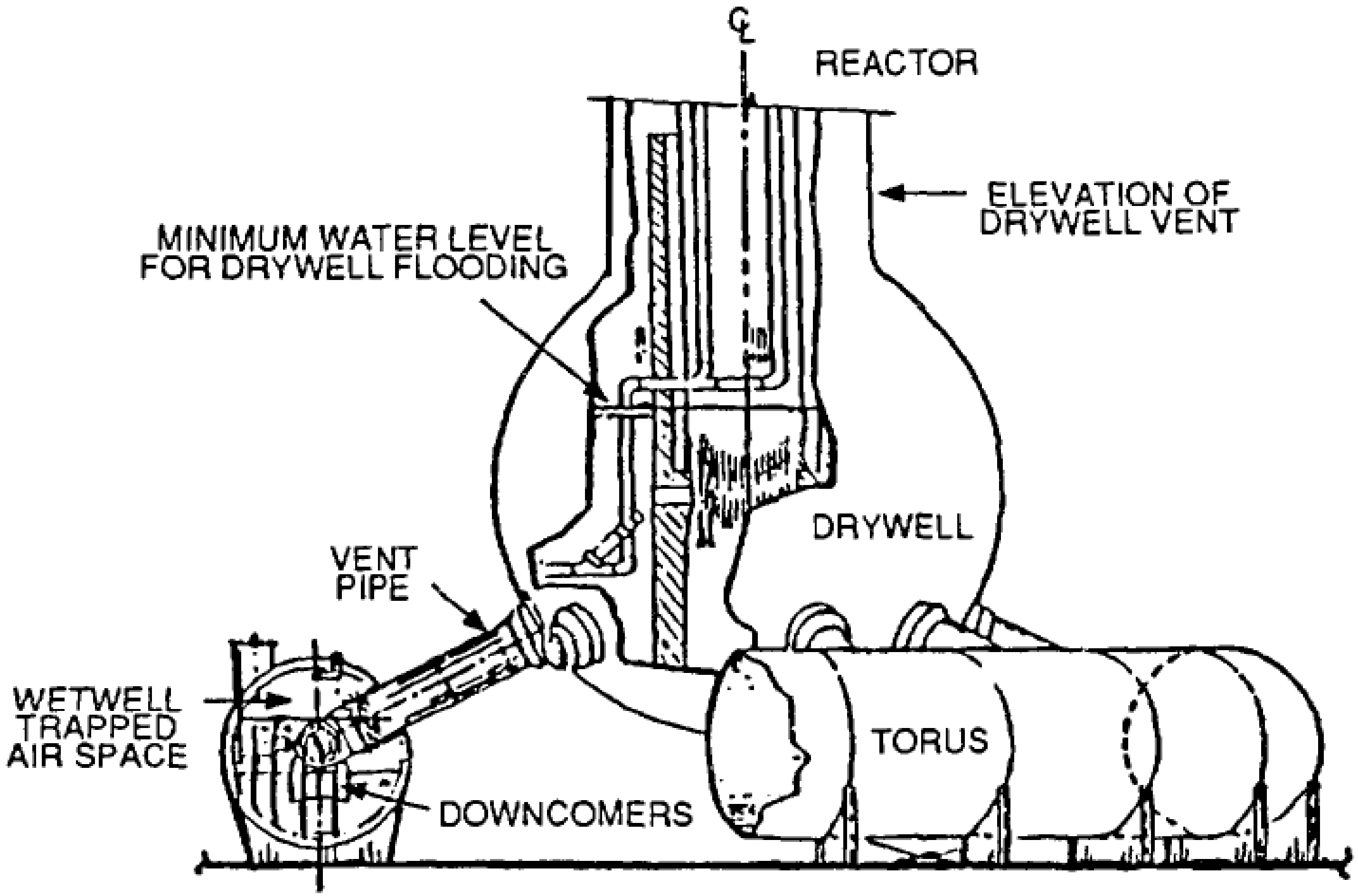
Lower head

Penetrations in lower head

Tepco/Japan News Today

Delaying or Preventing Head Failure

Containment Flooding to cover vessel lower head



Hodge et al CONF-921007—31 ORNL

Venting

- Used to reduce primary containment pressure to avoid failure and associate release
- Design pressure 400 kPa
- Failure pressure (estimated) 1000 kPa
- Vent through filters to stack
- Careful! High pressures will failure duct work and contaminate reactor building.
- Primary initially inert, environment will be steam/N2/H2 after severe accident

- Venting paths
  - 18-inch torus vent path,
  - 18-inch torus supply path,
  - 2-inch drywell vent to SBGT,
  - Two 3-inch drywell sump drain lines,
  - 6-inch ILRT line from drywell (does not fail ducts)
  - 18-inch drywell vent path, and (fails ducts)
  - 18-inch drywell supply path. (fails ducts)

NUREG 1150

Ventilation System

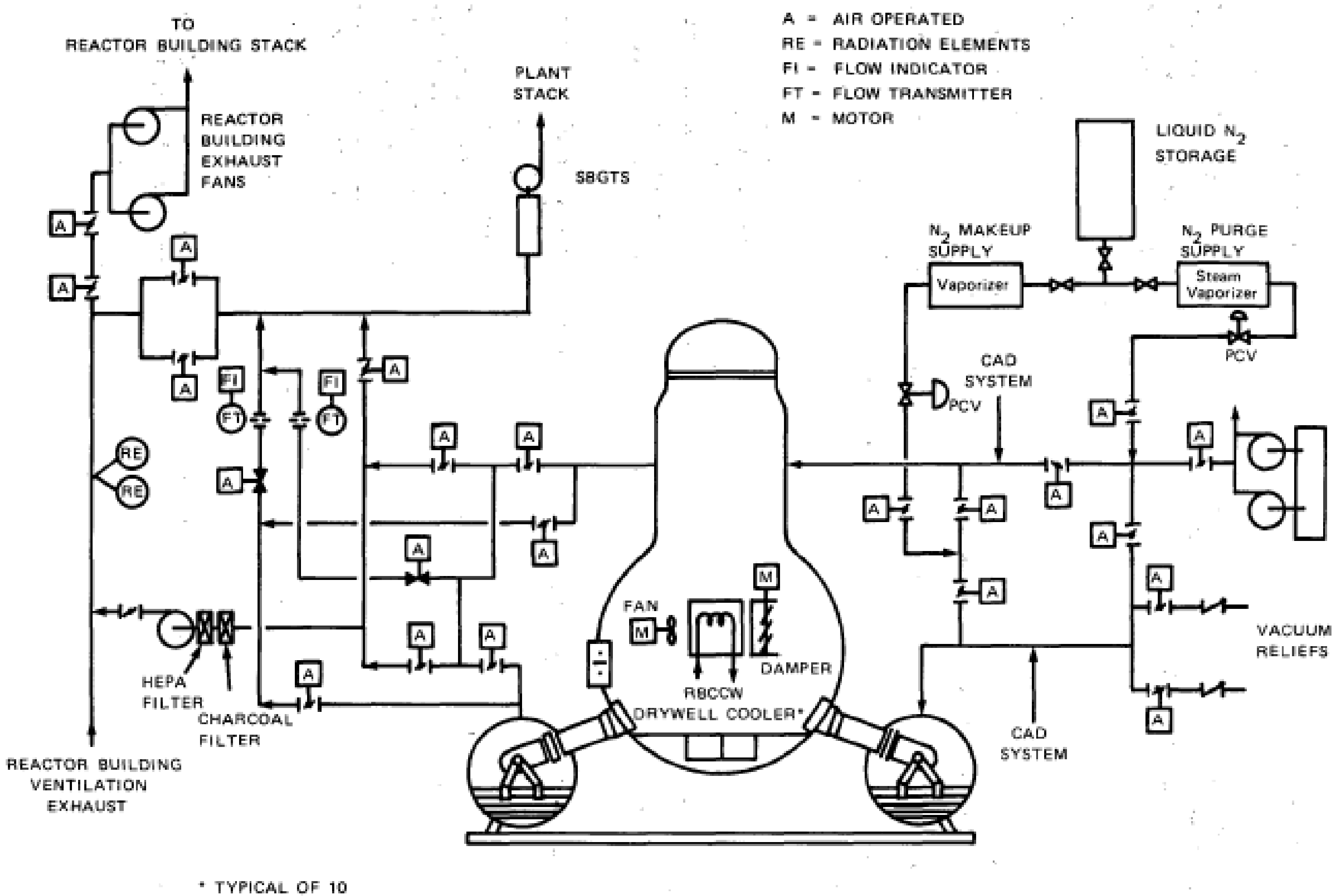


Fig 4-31 NUREG/CR-2726 LWR H2 Manual 1983

Venting EPGs

- Why vent?
  - Minimize H2 accumulation
  - Maintain primary containment integrity by reducing overpressure
- Only BWRs approved to vent during severe accidents
  - Suppression pool expected to “scrub out” some fission products – but bypasses standard air filtration
  - Success depends on accident progression, venting timing
  - Need to chose vent path carefully, make sure valves close (!) after completion
  - Need to protect operators from release
- May reduce risk for loss of long-term decay heat removal.

Dallman et al Nuclear Engineering and Design 121, 421-429, 1990.

Consequences of High Pressure Venting

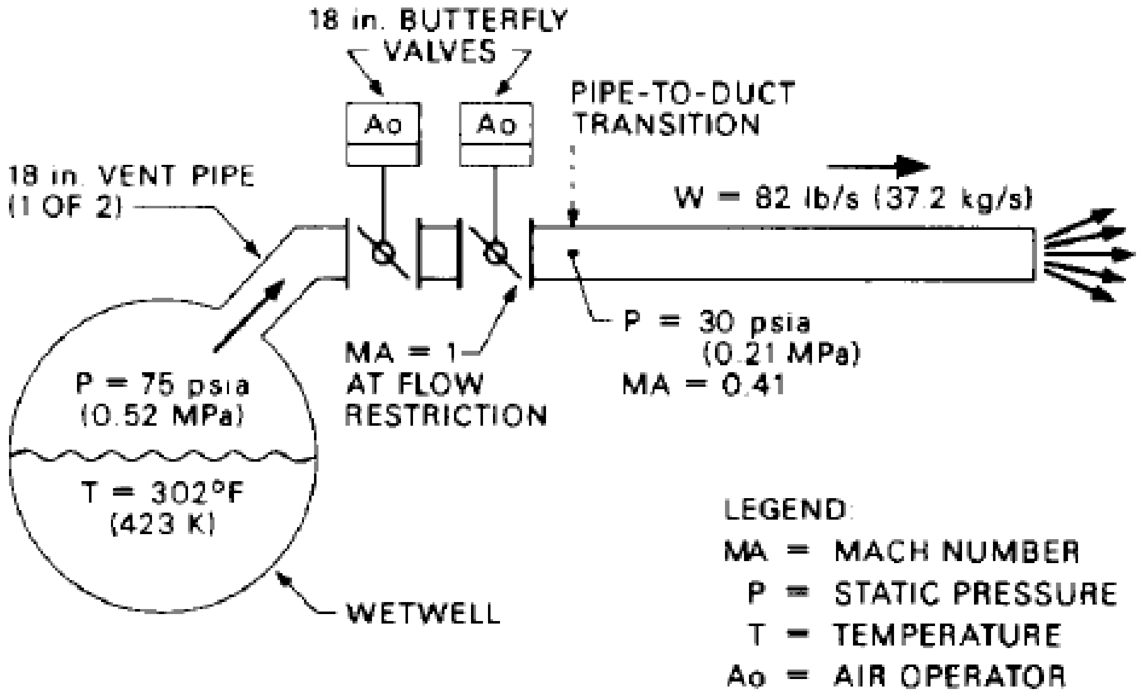


Fig. 3. Venting at elevated pressure would fail ventilation system ductwork in the torus room.

Harrington et al 1988, Kelly 1991,
US NRC Generic Letter 89-16, Sept 1989.

Flashing of suppression pool water leading to Loss of "net positive suction head" and failure of RCIC pump

Filling reactor building with hot steam, H2 and possibly, fission products.

US NRC recommended all US Mark I BWRs install a hard vent line to avoid venting directly into the reactor buildings

Containment Failure Potential

NUREG 1150 4.3.1 The estimated mean failure pressure for Peach Bottom's containment system is 148 psig, which is very similar to that for large PWR containment designs. However, its small free volume relative to other containment types significantly limits its capacity to accommodate noncondensible gases generated in severe accident scenarios in addition to increasing its potential to come into contact with molten core material. The complexity of the events occurring in severe accidents has made predictions of when and where Peach Bottom's containment would fail heavily reliant on the use of **expert judgment** to interpret and supplement the limited data available.

4.4.2 An important consideration in determining the magnitude of building decontamination is whether hydrogen combustion occurs in the building and whether combustion is sufficiently energetic to fail the building.

Possible Outcomes

1. Maintain cooling capability – core damaged but can be cooled. Plant contaminated, has to be cleaned up enough to repair key systems, allow human entry and dispose by dismantling (TMI). If too damaged or contaminated, may require entombment in place (Chernobyl).
2. Core cannot be cooled – molten material melts through RPV and drops to bottom of primary containment vessel, failure of containment, possible steam explosion, generation of gases due to core-concrete interactions. Requires entombment and long term custody of unconfined core.

A View from Japan

"Everyone has different view on the extent of the melting of the core.The government says the core is molten at 20–70%, depending on the units. I suspect the reactor core is almost all molten by this stage.

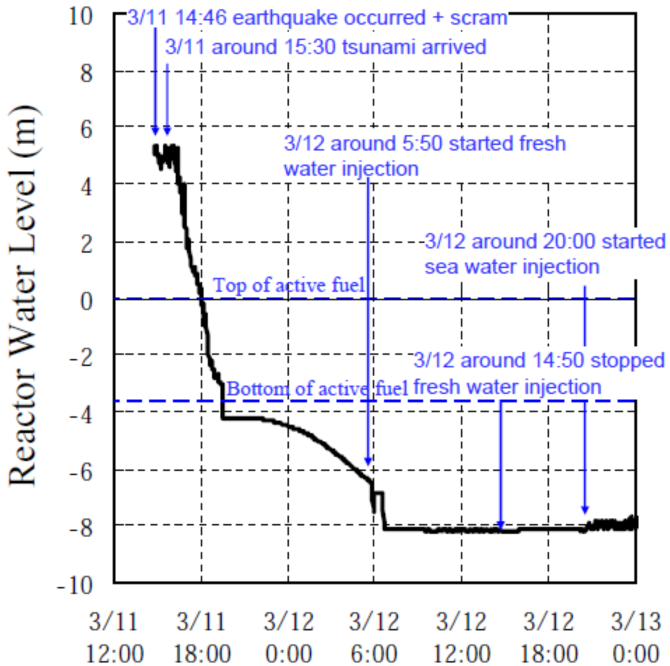
In this case, if the molten core is still contained in the pressure vessel, it should be clam-shaped mass measuring 4 meters in diameter and 2 meters in height, its center boiling at the temperature of over two thousand degrees Celsius. The surface should form 20–30 centimeter-thick crust that resembles cast iron. Gaseous molten core (radioactive materials) should be constantly released through cracks of this crust. It is, indeed, a chilling image, but should be close to reality."

Dr. Michio Ishikawa
Chief Adviser(Former President & CEO)
Japan Nuclear Technology Institute(JANTI)
Published on April 26 '2011 : The Denki shinbun (The Electric Daily News)

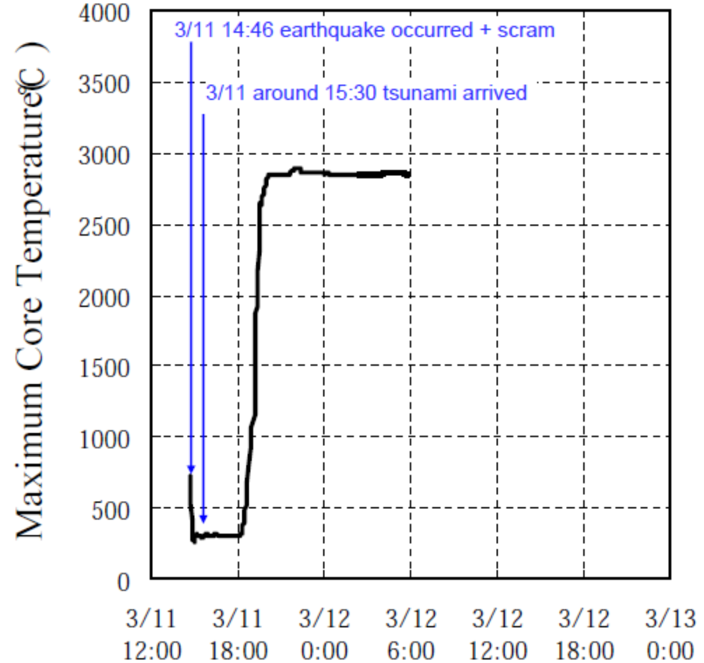
Tepco Unit 1 Analysis

Unit 1:Reactor Water Level, Maximum Core Temperature (Analysis Result)

Key assumption: IC lost its function after the tsunami arrived at around 15:30



- reached top of active fuel in 3 hours (around 18:00) after the scram
- reached bottom of active fuel in 4 and a half hours (around 19:30) after the scram



The core temperature started increasing when the reactor water level became lower than top of active fuel, then reached the core melting temperature.

[Tepco May 15]

Estimate Based on γ-dose rate

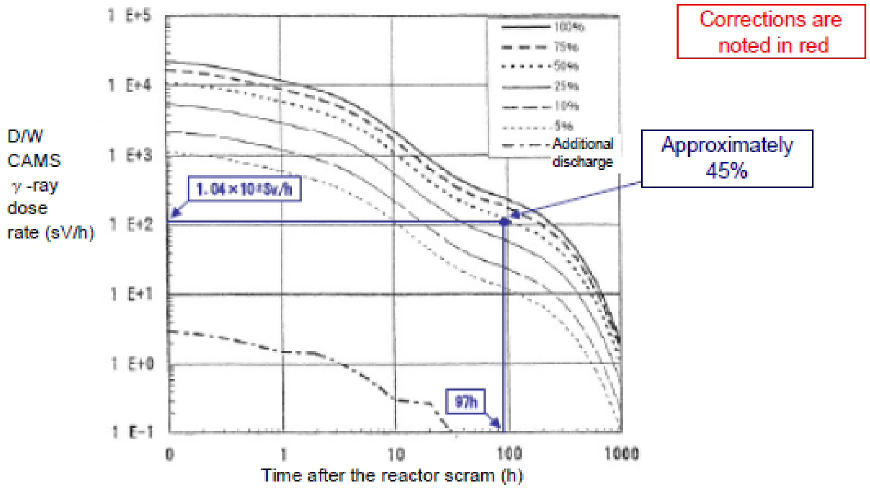


Figure 1-1 Behavior of the γ-ray dose rate in dry well area of Unit 1

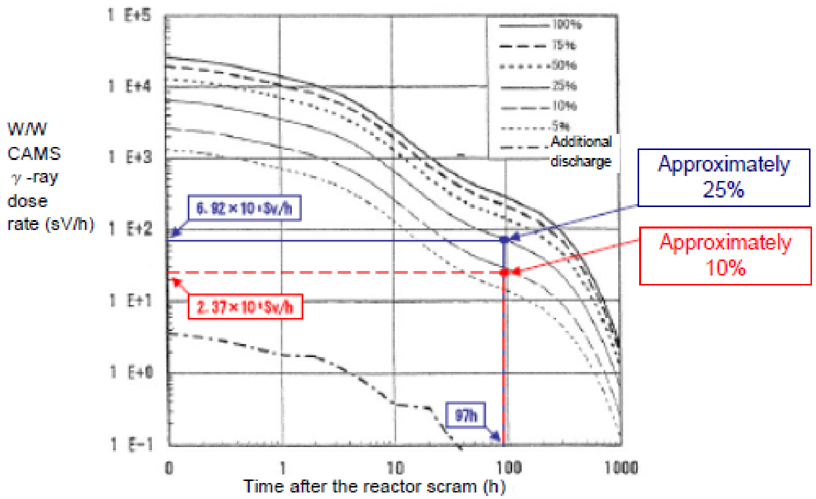


Figure 1-2 Behavior of the γ-ray dose rate in wet well area of Unit 1

Before Correction: Approx. 45% + Approx. 25% = Approx. 70%
After Correction : Approx. 45% + Approx. 10% = Approx. 55%

Cracks and rupture of fuel pin cladding release volatile fission products: Kr, I, Xe, Cs.

Decay of fission products can be used as a "clock" to determine how many products have been released at a given time after the shutdown or reaction SCRAM.

Calculation is based on estimated FP inventory and known decay chains and rates for each of the isotopes.

CAMS = Containment Atmosphere Monitoring System measures dose rate in dry well and wet well.

Molten Fuel in all Units?

"regarding the Unit 1, nuclear fuel pellets have melted, falling to the bottom of the reactor pressure vessel at a relatively early stage after the tsunami reached the station." - Tepco May 15

"…Tokyo Electric estimated that the pressure vessels of the Nos. 2 and 3 reactors containing the fuel rods may have been damaged if it turns out that the levels of the water inside the vessels are lower than data now shown by measuring gauges.

If the water levels are lower, then it can be assumed a large part of the fuel in the No. 2 reactor dropped to the bottom of the vessel about 101 hours after the reactor automatically shut down following the quake, while the same must have happened at the No. 3 reactor in about 60 hours, TEPCO said." - Kyodo News May 24

Evolution of core damage percentages

	March 15	April 27	May 12	May 26
Unit 1	70	55	100	-
Unit 2	30	35	-	54-88
Unit 3	25	30	-	42-84

May 22 Situation

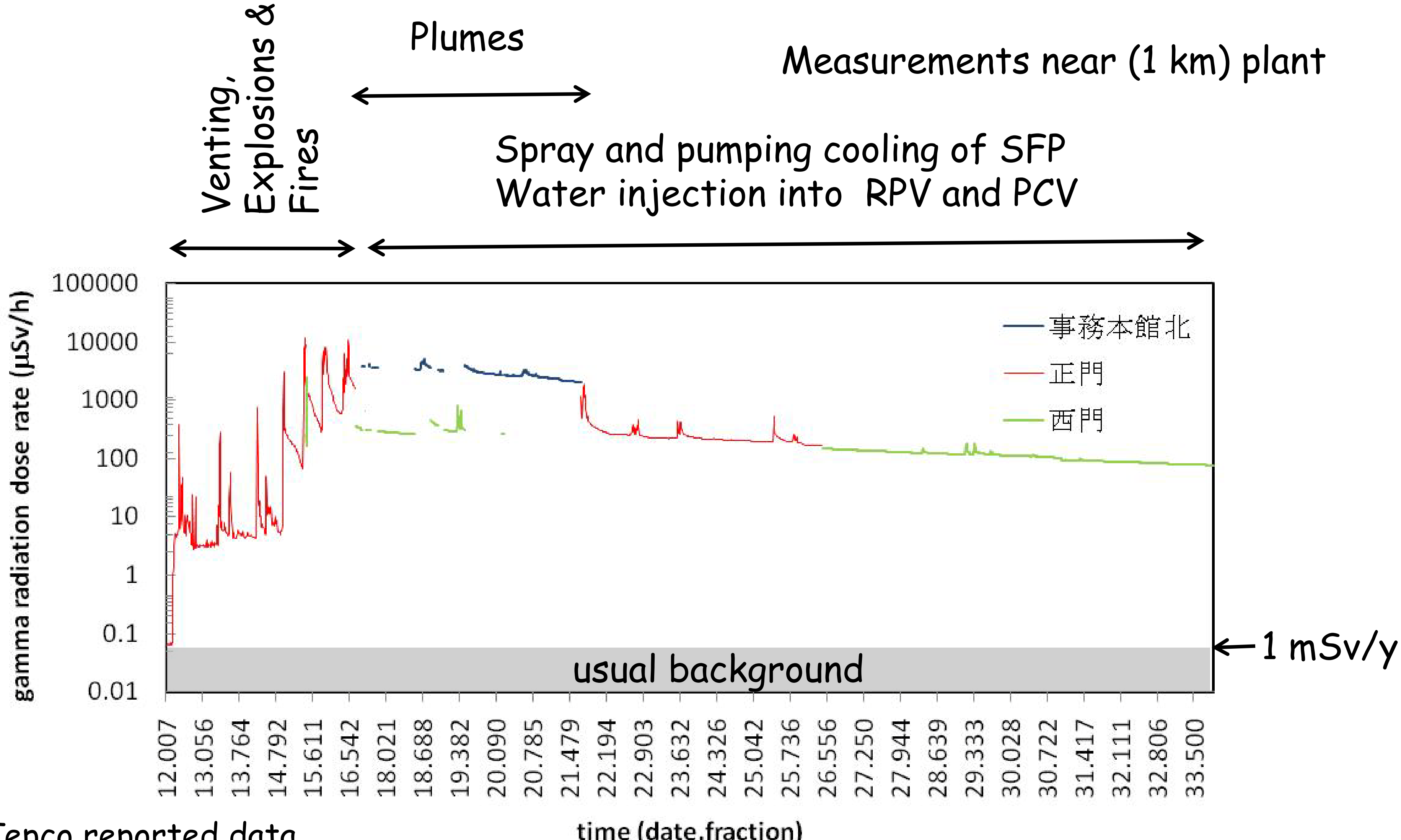
- Water level in Unit 1 much lower than originally thought –below bottom of fuel
  - RPV assumed to have hole in bottom
- Efforts to flood Unit 1 primary containment unsuccessful
  - 4 m of water (6000 m^3) in basement
  - Containment vessel leaking, building flooded instead
  - Flooding stopped, alternative steps explored
- Heat exchanger plans changed
  - Treat, cool, and recirculate water through building basement, reactor pressure vessel, and containment.
  - Attempt to seal PCV using grout
- Planning to store and treat more contaminated water
- Barriers planned to prevent water from leaking from buildings into ocean, ground
- Now assuming core situation in Unit 2 and 3 similar to Unit 1
- Working on cover for Unit 1 building
- Working on reinforcing structure under Unit 4 SFP

Tepco May 17 Press Release

Radiological Consequences

Extent of contamination and possible exposure of public to radiation

Releases of Fission Products into Air



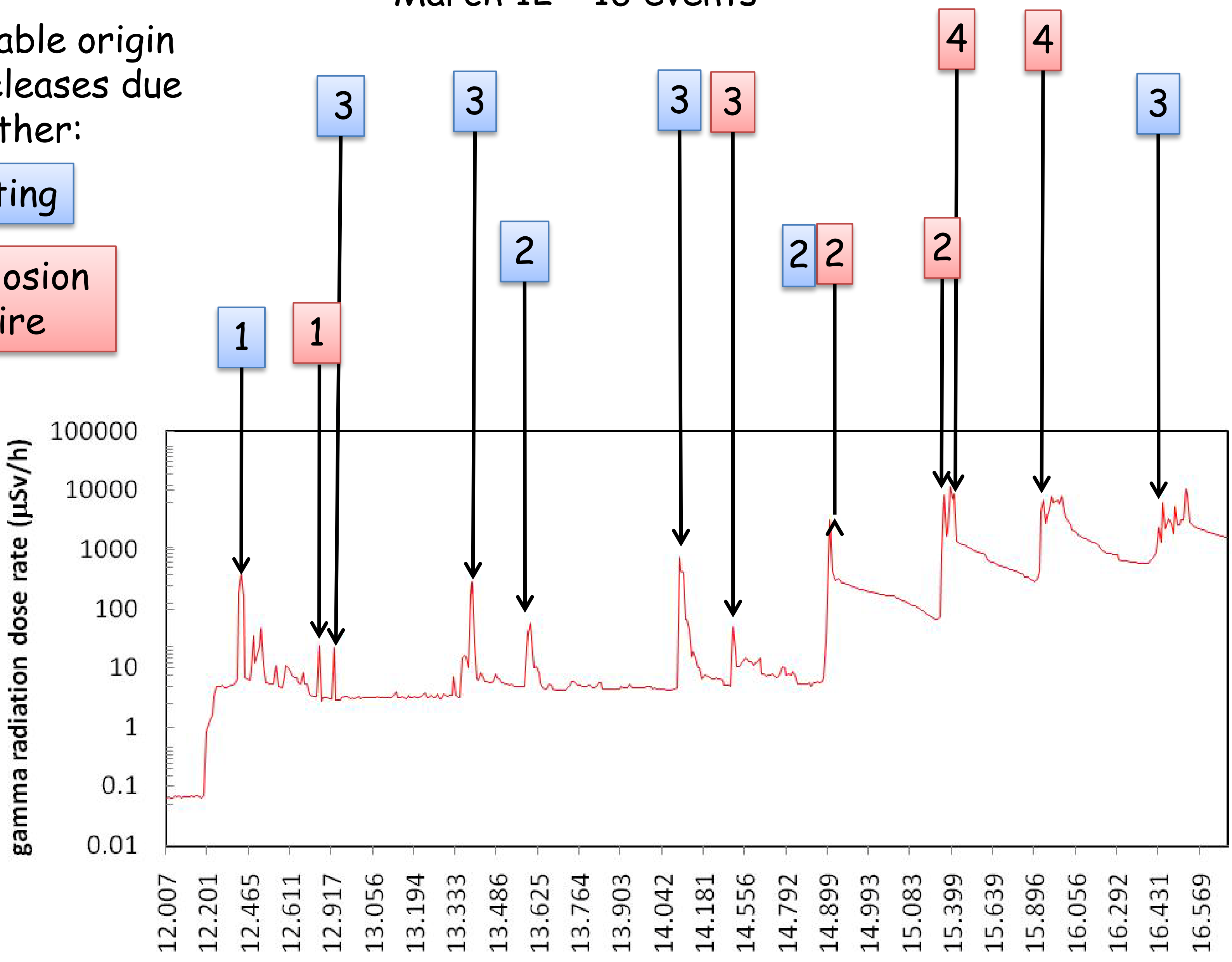
Tepco reported data

March 12 – 16 events

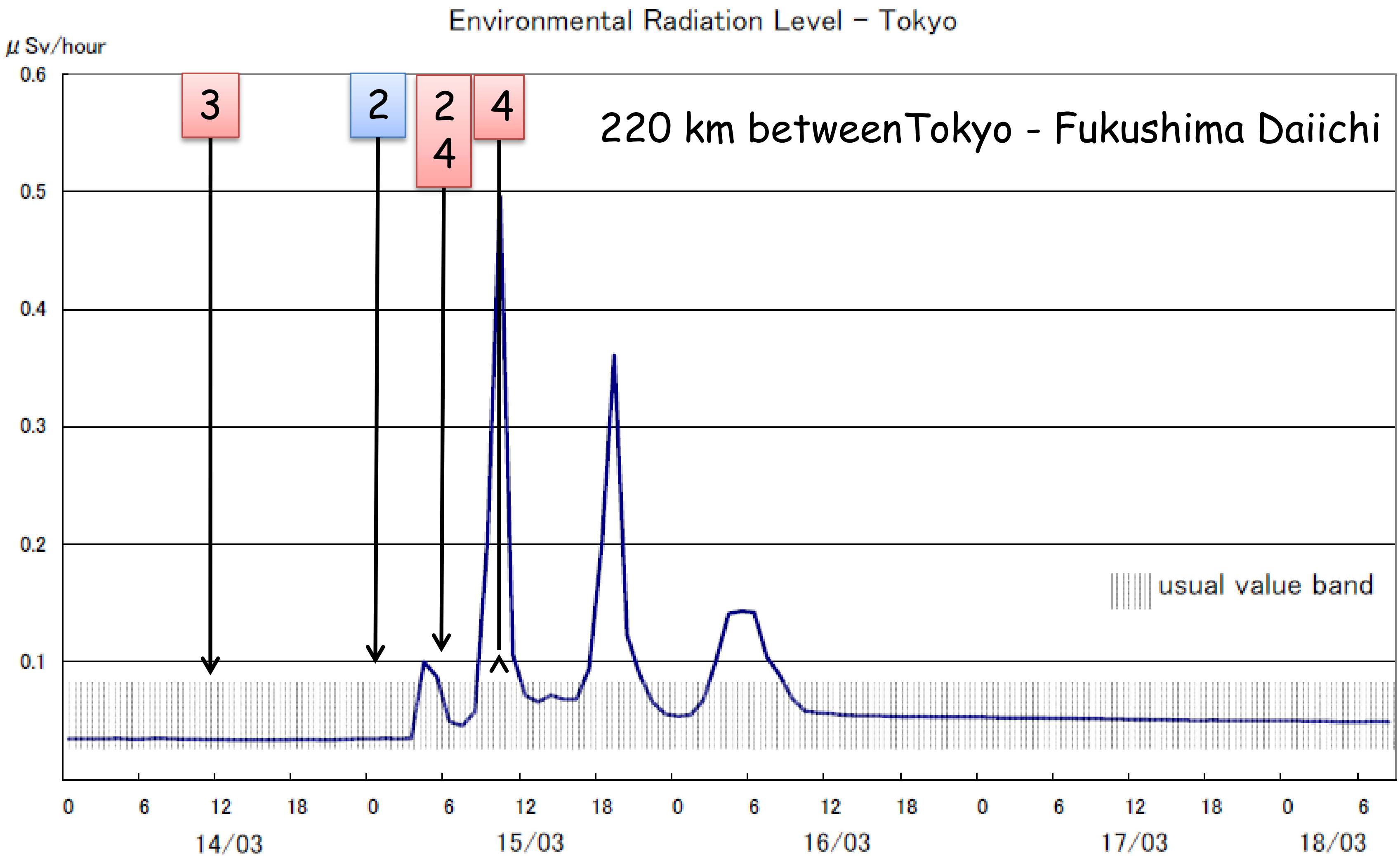
Probable origin of releases due to either:

venting

explosion or fire



Tepco reported data

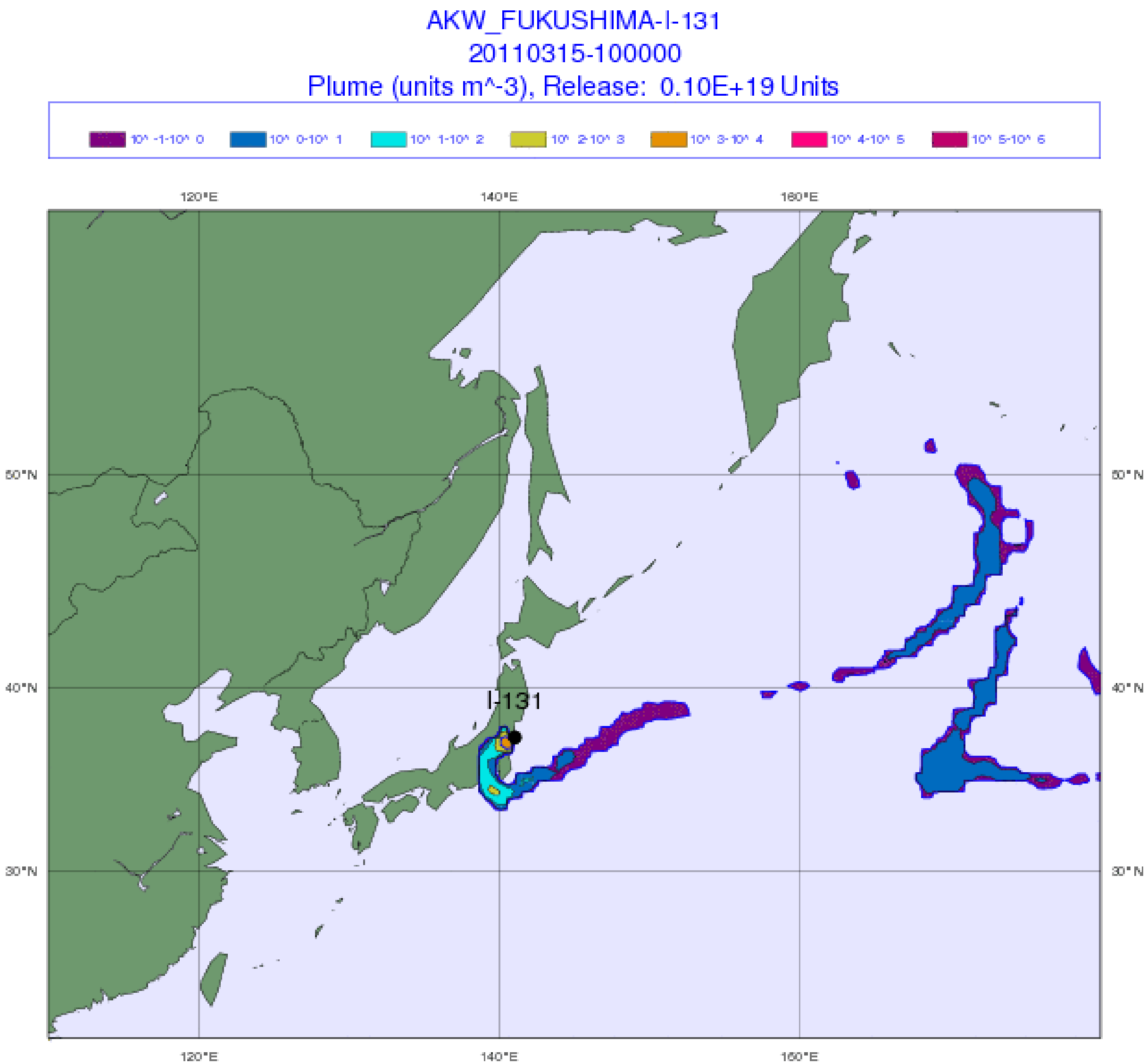


Data from MEXT on 19 March

Fission Products of Most Concern

- Gases
  - Krypton (Kr-85)
  - Xenon (Xe-133)
- Low melting point solids
  - Iodine (I-131, -132) mp = 113°C
  - Caesium (Cs-134, -136, -137) mp = 28.5°C
  - Tellurium (Te-127, -129, -132) mp = 450°C
- Radiation hazard: γ–decay and β–decay
  - $^{137}Cs \rightarrow {}^{137}Ba + \gamma + e^-$ (0.97 MeV) $t_{1/2}$ = 30 y
    long term concern – contamination spread by air, fallout on ground, vegetation, etc.
  - $^{131}I^- \rightarrow {}^{131}Xe + \gamma + e^-$ (1.17 MeV) $t_{1/2}$ = 8 d
    short term concern, uptake by thyroid gland

Predictions of I-131 Dispersion



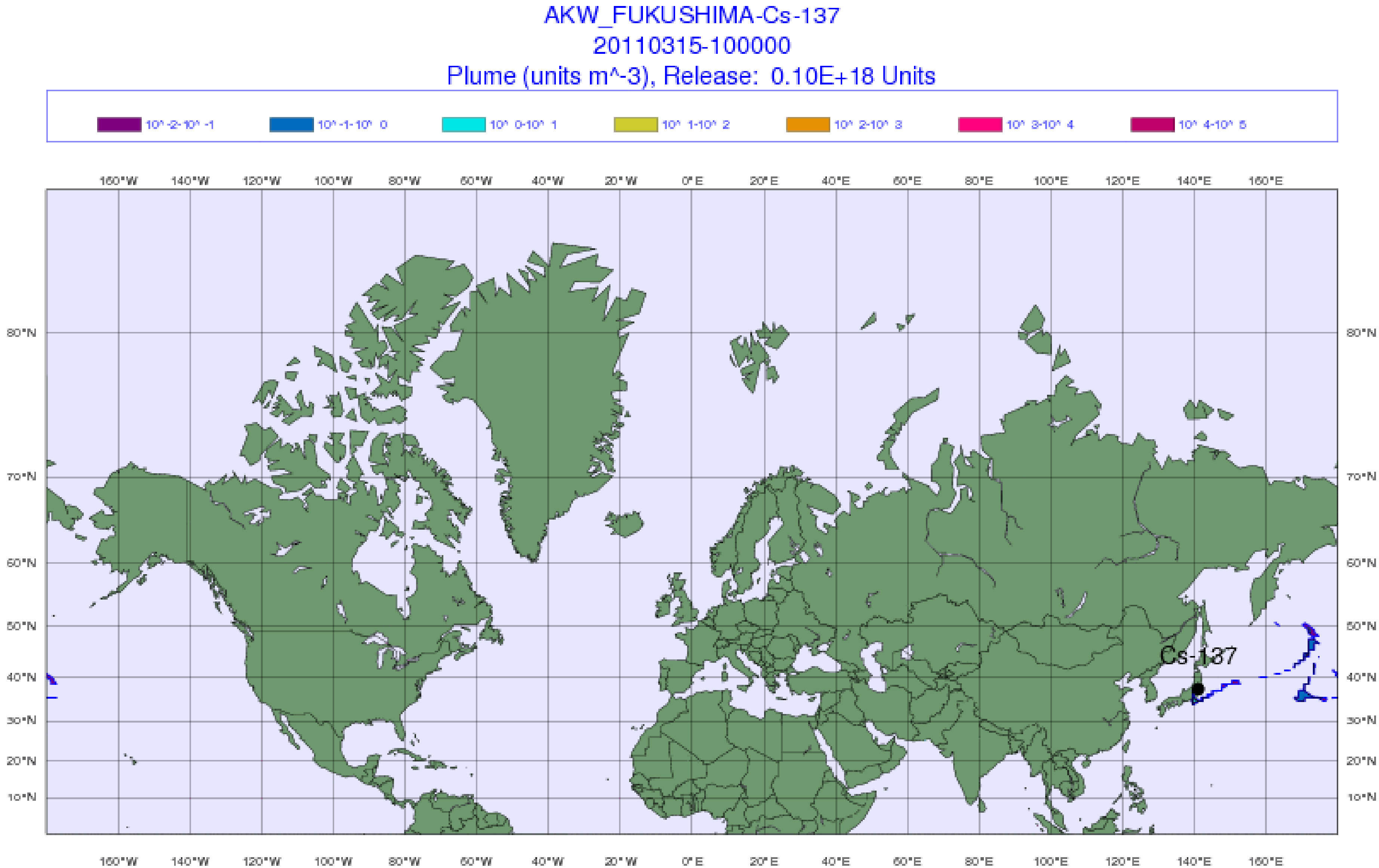
Predictions by [ZAMG]

Continuous source term.

Global circulation model

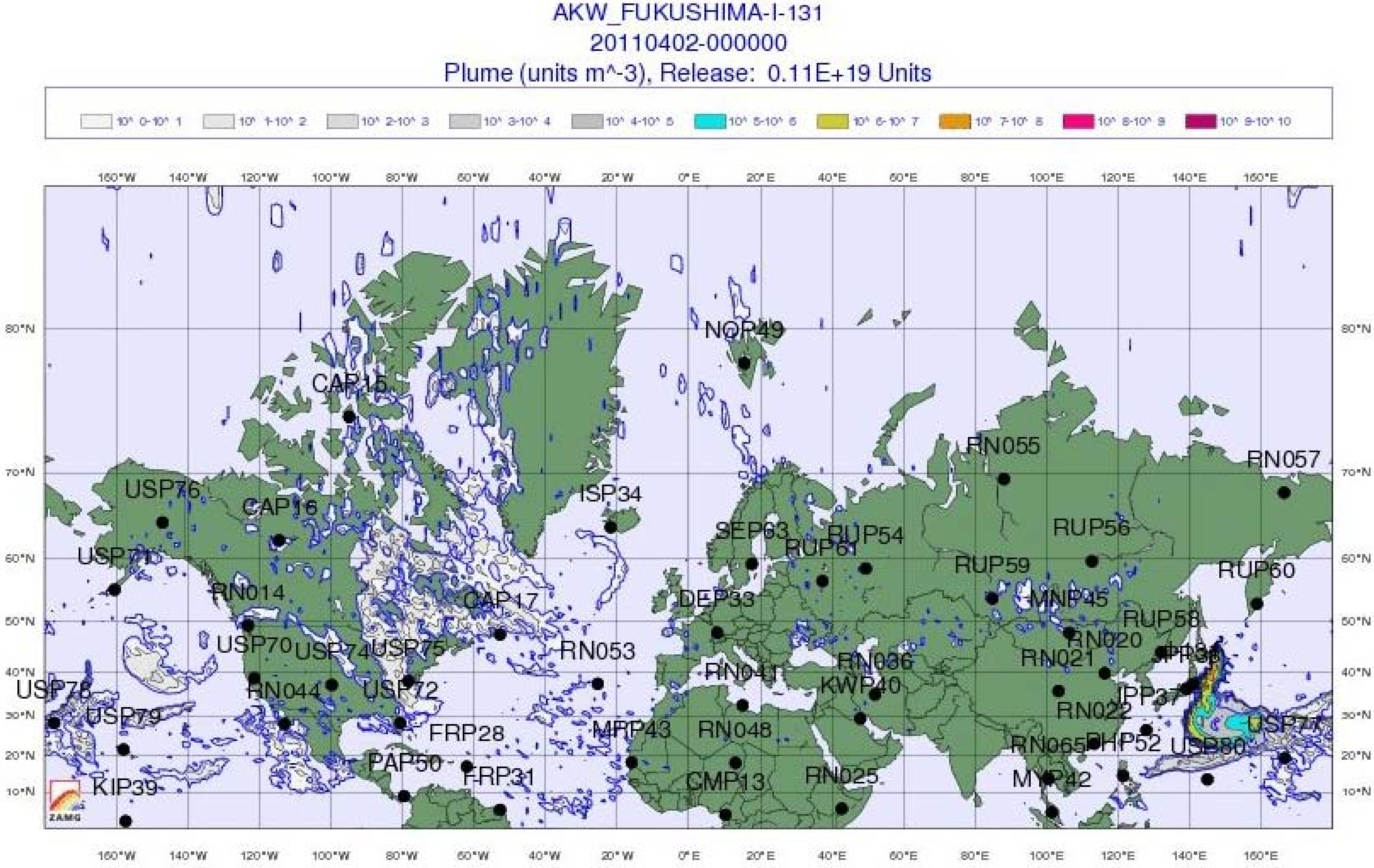
Bounding assumptions about chemistry

Predictions of Cs-137 Dispersion



ZAMG

CTBT Detection Stations

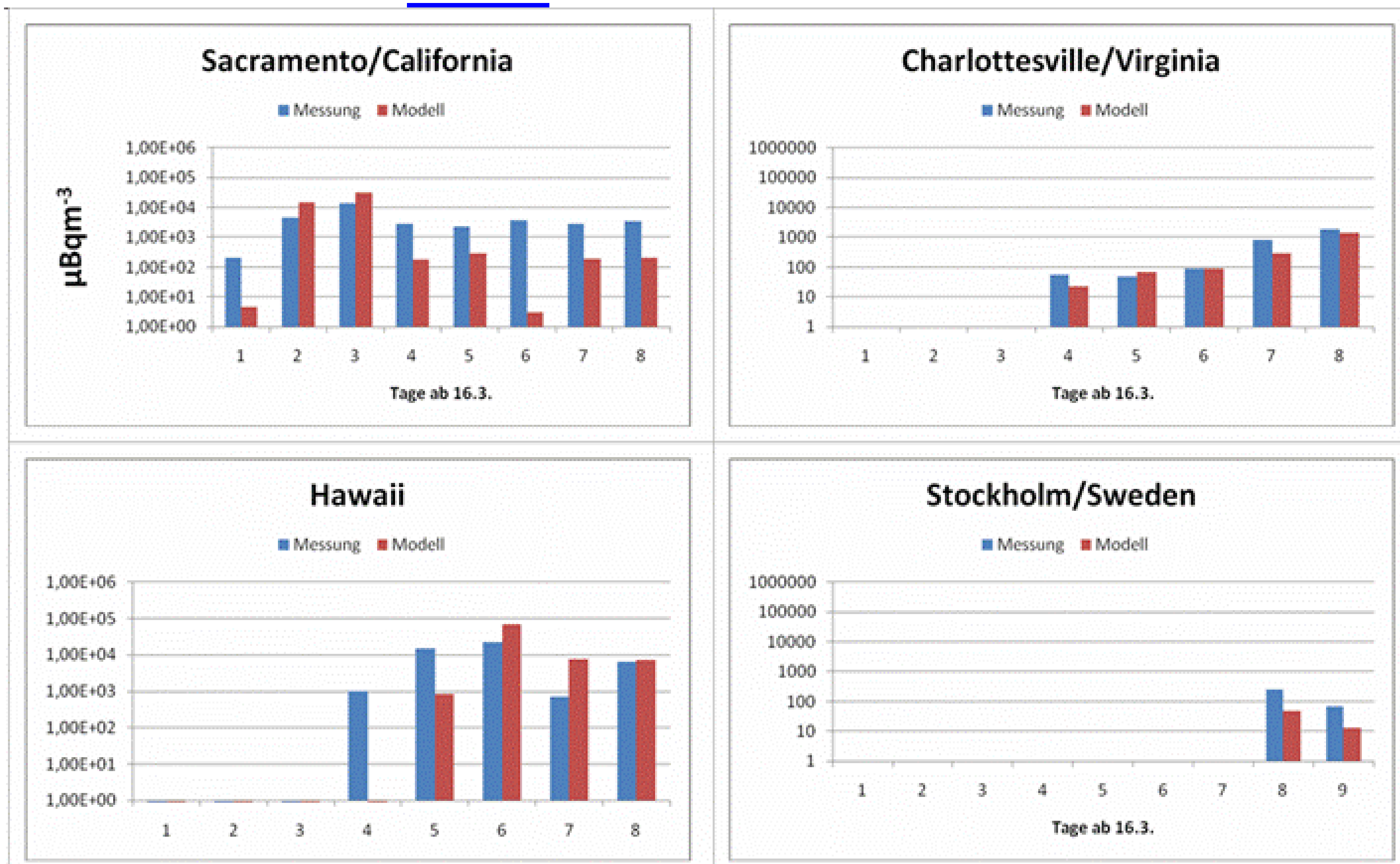


ZAMG

I-131 Detection by CTBT Stations

Model results based on a release of 10^{17} Bq per day at Fukushima since 12. March 2011 08:30 UTC. In the model, dry deposition (contact with the ground) and wet deposition (to wash out the particles) are fully considered. The input comes from the European center for medium-term weather forecast. The dispersion model is FLEXPART version 8. ZAMG

EPA 22 March analysis of SF air samples	
	μBq/m³
Cs-137	48
Te-132	277
I-132	244
I-131	2516



Estimating Source Term

- ZAMG (Austria) numerical simulations
  - Weather forecast from the ECMWF global circulation model
    - 25 km horizontal, 91 vertical levels, 12 min time step
  - Lagrangian particle dispersion model FLEXPART V. 8
  - Adjusted source term to match selected CTBT station data
- NSC (Japan) used JANTI estimates of core releases
- IRSN (France) used FP estimates of core content and
  - Report accident progression
  - Previous work on degraded core accident and fuel behavior
  - Inventory of FP in reactor

Total release ~10% of Chernobyl and limited to volatile FP

Species	Fukushima Dai-ichi			Chernobyl Unit 4	Aboveground nuclear testing
I-131	9×10^{16}	1.5×10^{17}	10^{16} - 7×10^{17}	1.8×10^{18}	9×10^{20}
Cs-134	1×10^{16}	-	-	5.0×10^{16}	-
Cs-137	1×10^{16}	1.2×10^{16}	10^{15} - 7×10^{16}	8.5×10^{16}	1.3×10^{18}
Total	$>1 \times 10^{18}$		$> 7.7 \times 10^{17}$	9.4×10^{18}	
	IRSN 22 Mar	NSC 12 Apr	ZAMG 30 March	UNSCEAR 2000	UNSCEAR 1982

Airborne Release Fraction

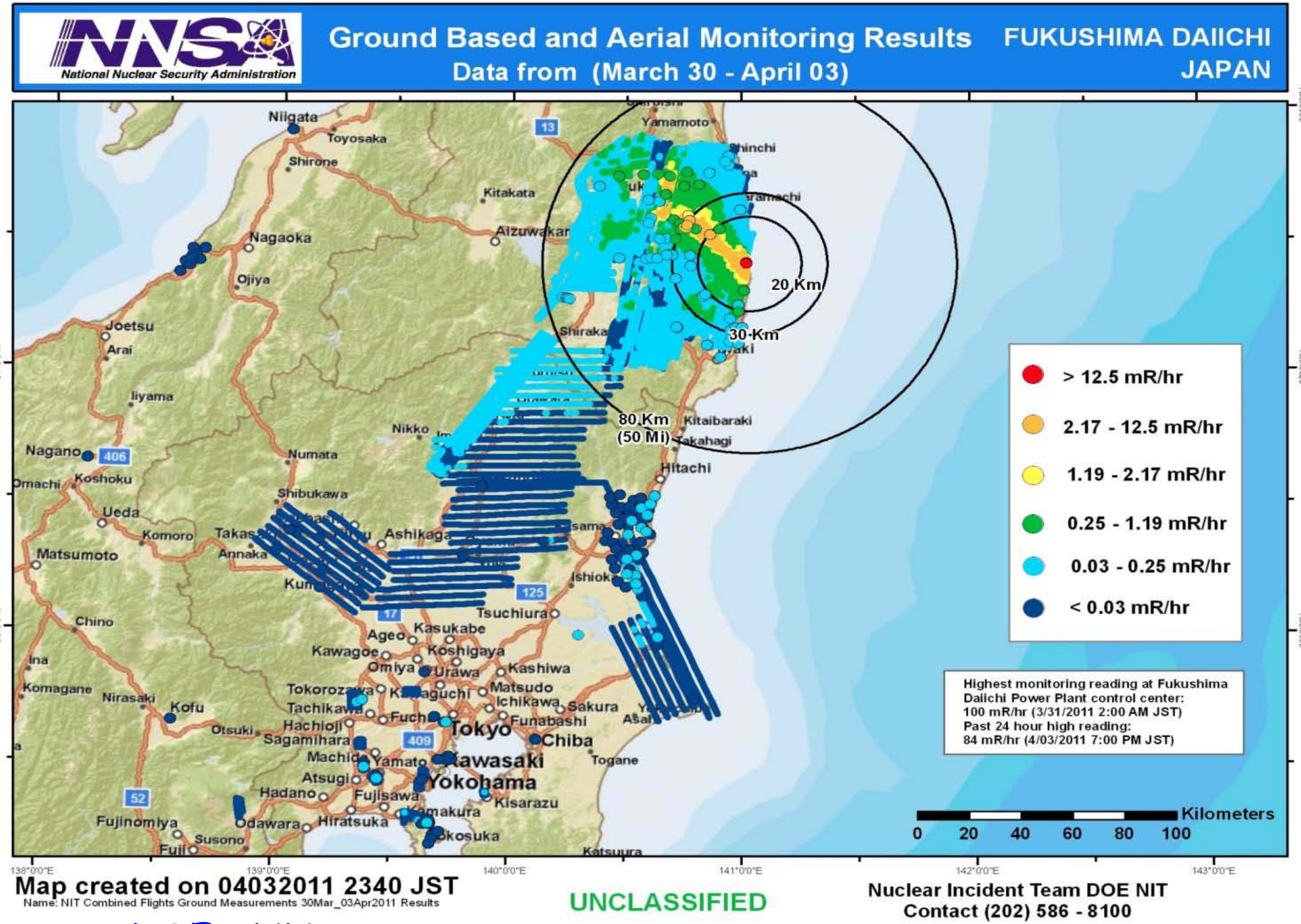
- Based on total of 256 tonne of heavy metal (U) in cores
- Nominal FP inventory for generic LWR fuel cycle
- Small fraction (< 1%) of FP released to environment in comparison to Chernobyl (30-50% of volatiles I, Cs according to UNSCEAR 2000)

	Total inventory (Bq)	Release estimate	Fraction
I-131	9.6×10^{18}	1.0×10^{17}	1.0 %
Cs-134	2.5×10^{18}	1.0×10^{16}	0.4 %
Cs-137	1.0×10^{18}	1.0×10^{16}	1.0 %
Xe-133	1.9×10^{19}	-*	-#
Kr-85	1.0×10^{17}	-*	-#

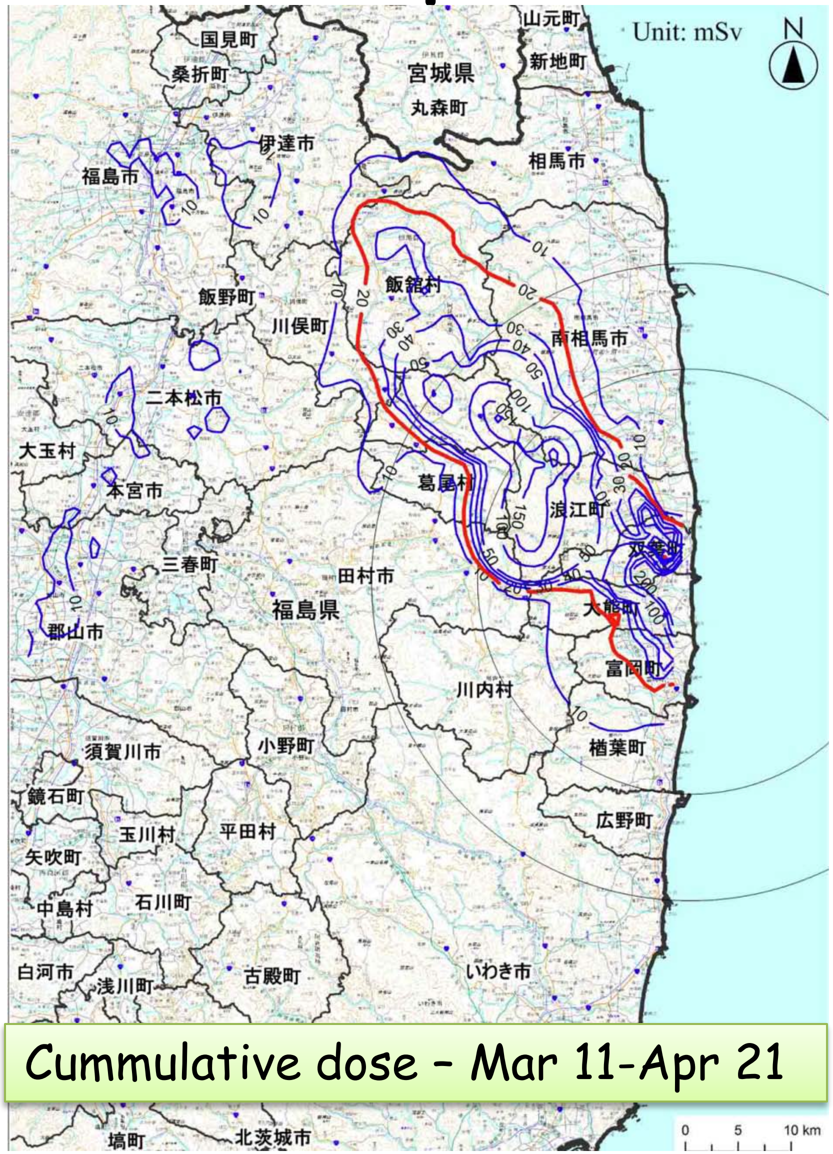
* Not available

\# Probably at least 3% and may be as high as 100%

NNSA Aerial & Ground Survey

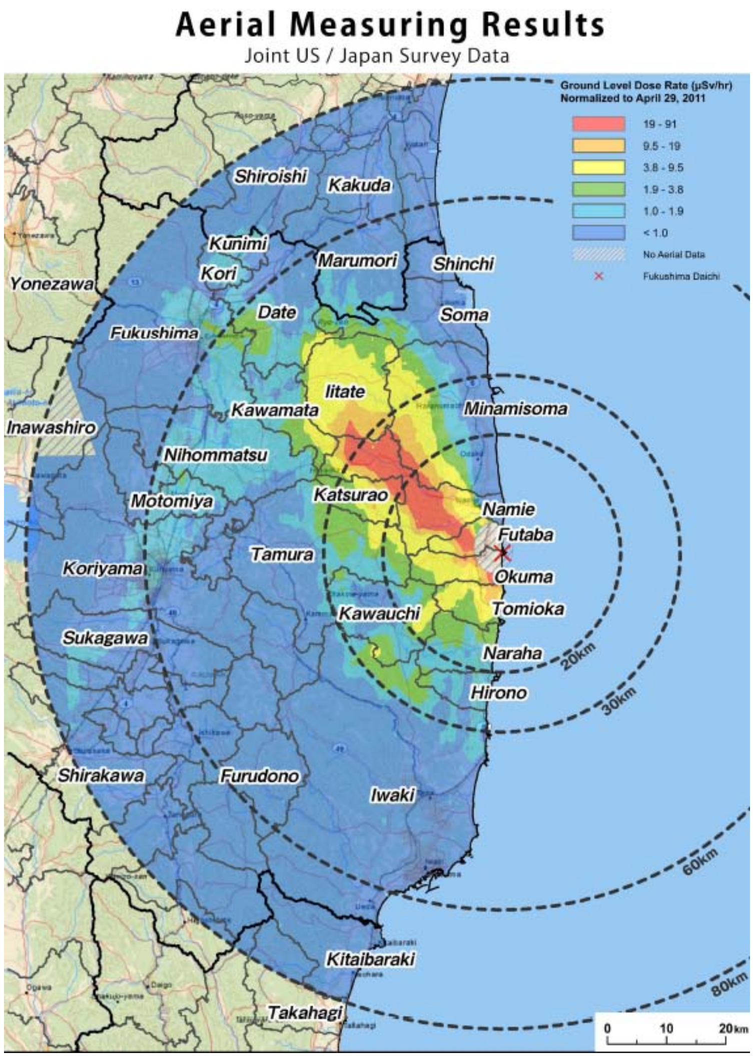


26 April MEXT Map



Data (in Japanese) from MEXT

Ground Level Dose Rate (Apr 29)



1 μSv/hr → 8.76 mSv /yr

Normal background range:

4-6 mSv /yr

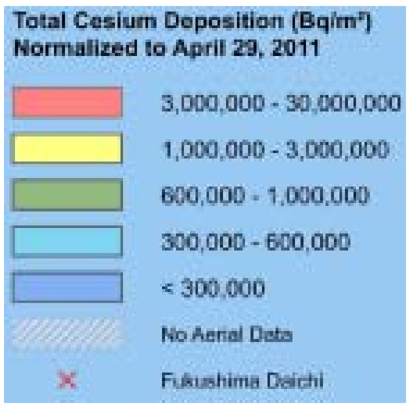
ANS

- These results are from a joint MEXT, DOE/NNSA and USFJ survey
- Data based on 42 fixed wing and helicopter survey flights at altitudes ranging from 150 to 700 meters between April 6 and April 29
- Exposure rates are averaged over areas 300 m to 1500 m in diameter

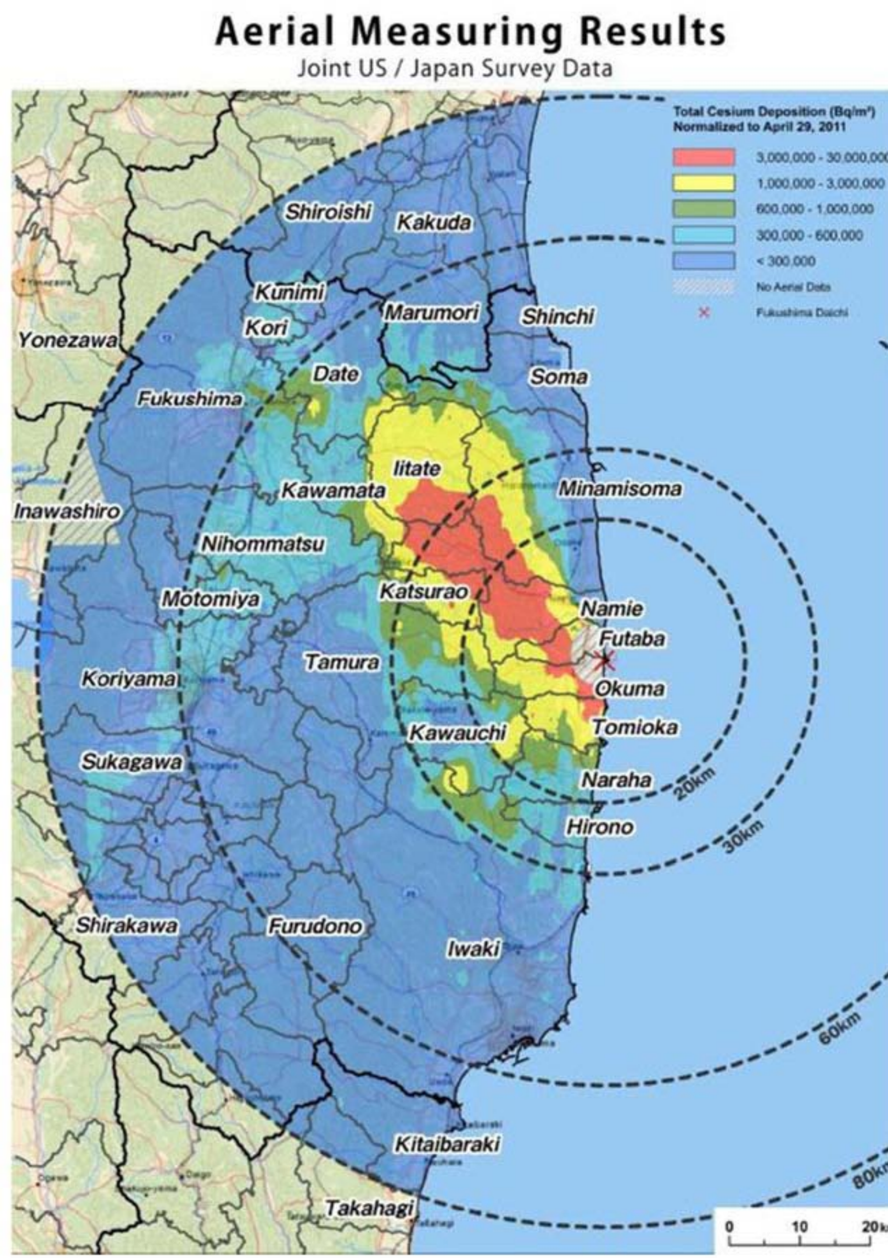
May 6 NNSA Briefing Material

Total Cesium Deposition up to Apr 29

Sum of Cs-137 and Cs-134



May 6 NNSA Briefing Material



US-DOE NNSA Conclusions

April 3

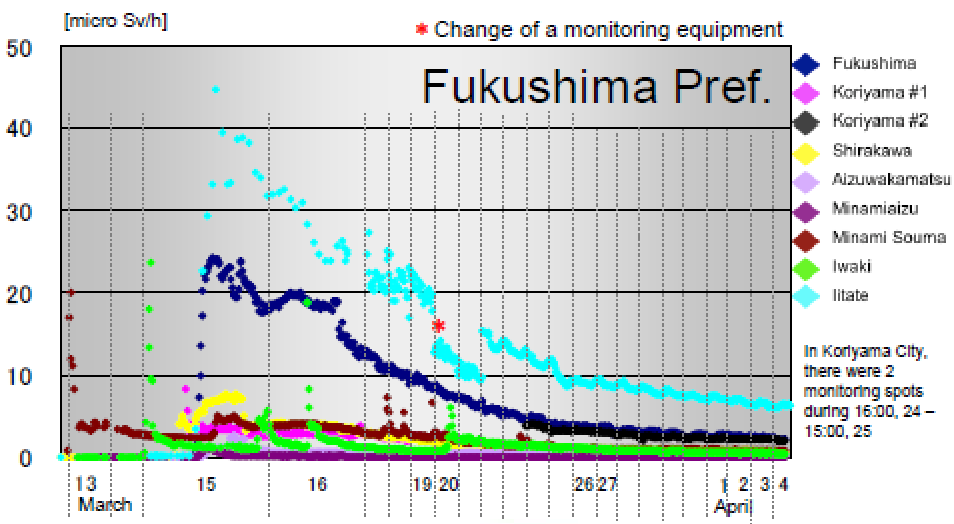
- Dose is at 1 m height above ground (1 mR/h = 10 mSv/h)
- All measurements in this plot are below 30 mR/h (300 mSv/h) – a low but not insignificant level.
  - background is 0.1 to 1 mSv/h (0.7 mSv/h = 6.2 mSv/yr average dose)
- Radiation levels consistently below actionable levels for evacuation or relocation outside of 25 miles (40 km)
- Radiological material has not deposited in significant quantities since March 19

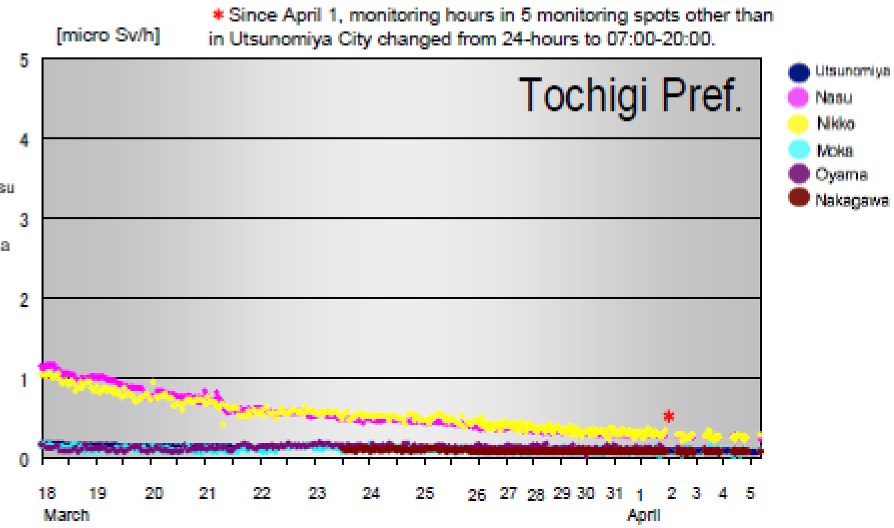
May 6

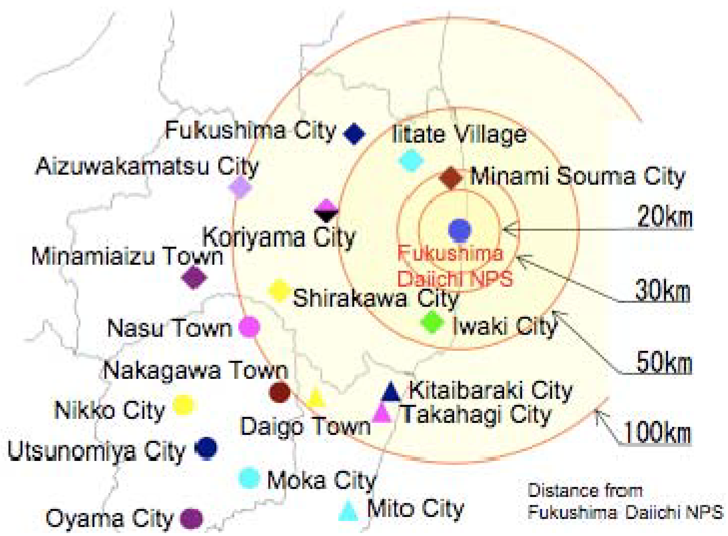
- Radiation levels continue to decrease
- No measurable deposit of radiological material since March 19
- Agricultural monitoring and possible intervention will be required for several hundred square kilometers surrounding the site:
  - Soil and water samples are the only definitive method to determine agricultural countermeasures
  - Ground monitoring can give better fidelity to identify areas that require agricultural sampling

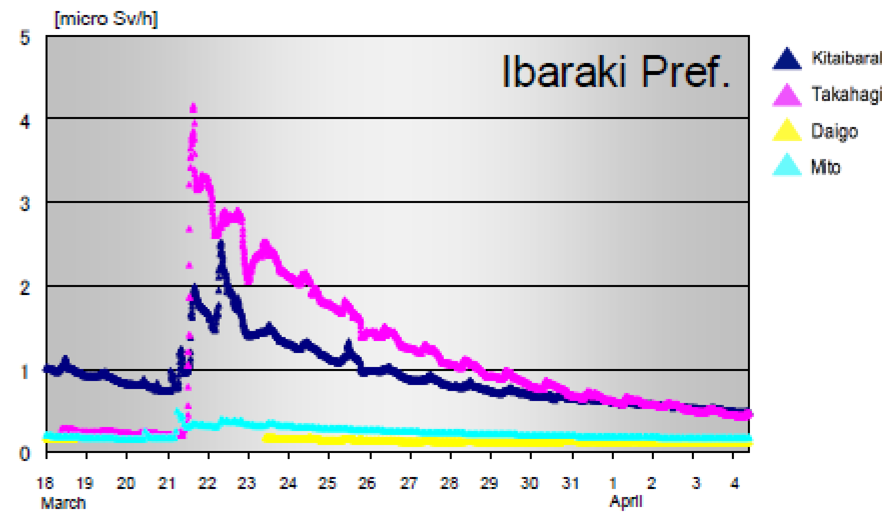
DOE - NNSA

Decay in Fukushima and Surrounding Prefectures



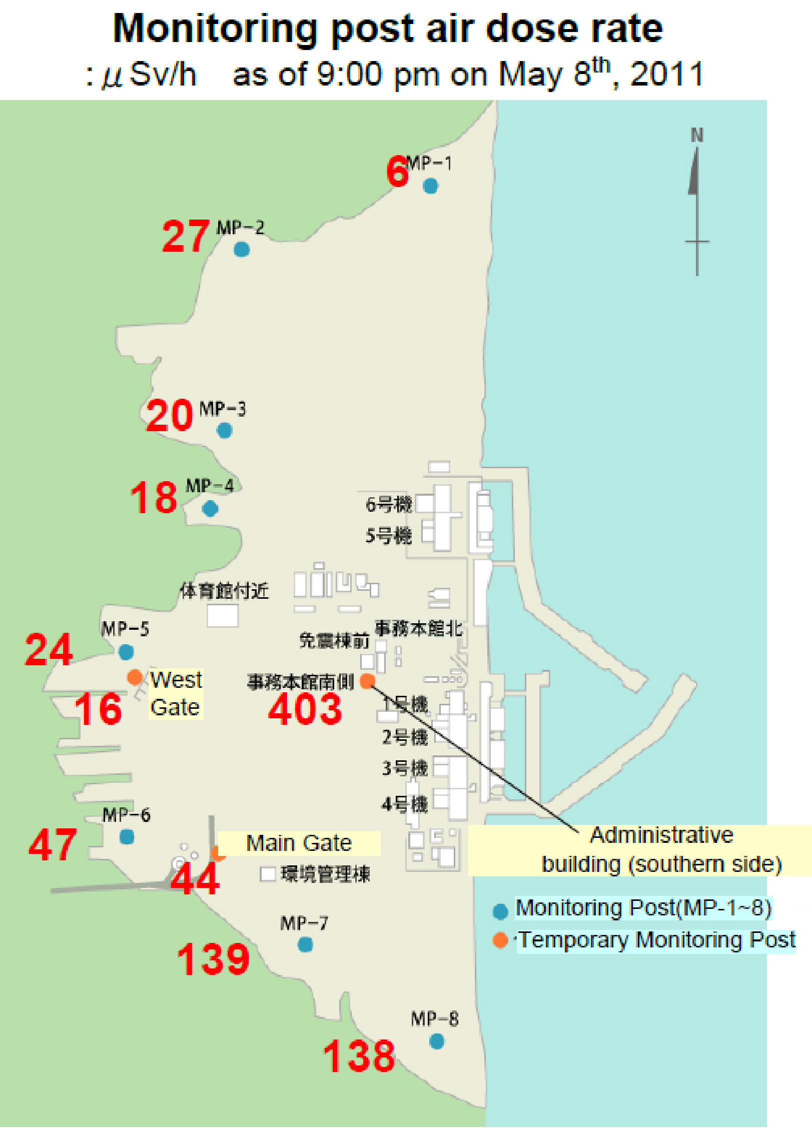






[Data from JAIF Reports]

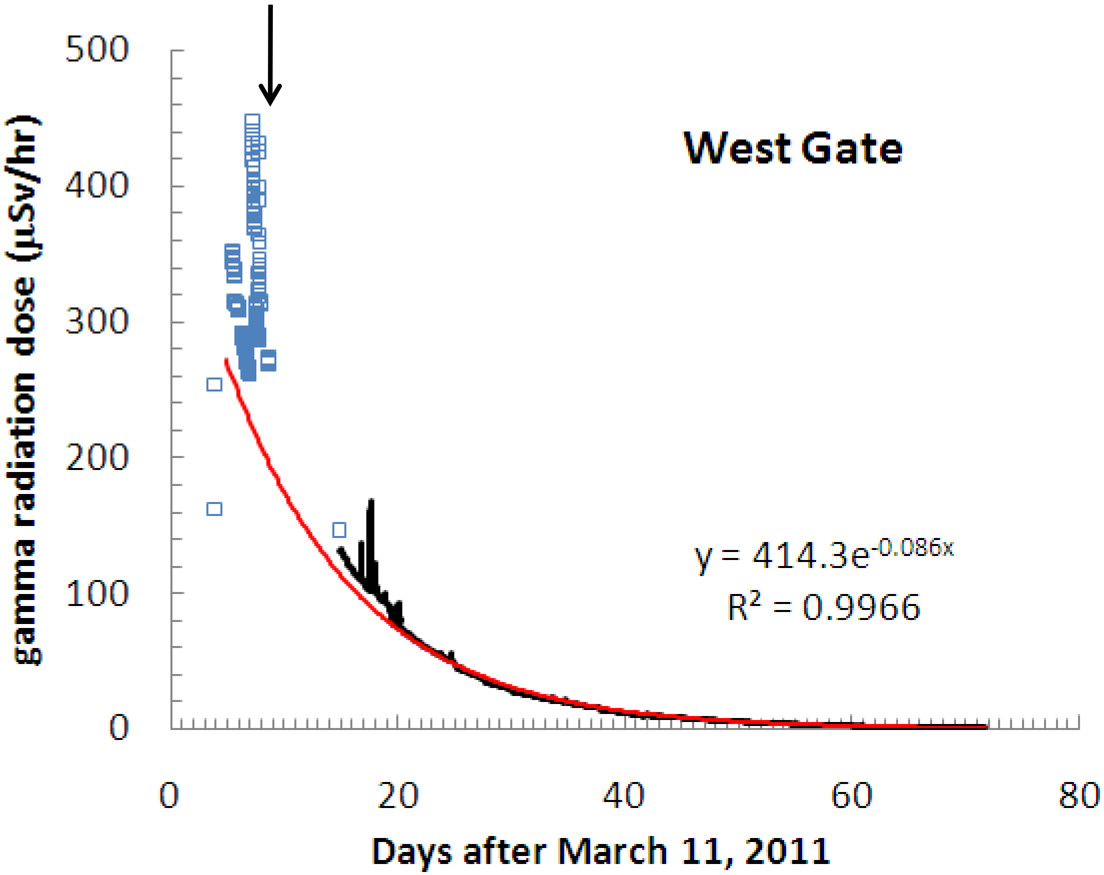
Monitoring Near Plant



Tepco Handout May 9

Decay of Radiation at West Gate

19 March



Data of West Gate monitoring Point (MEXT website).

Red line is exponential decay fit from 26 March to 22 May.

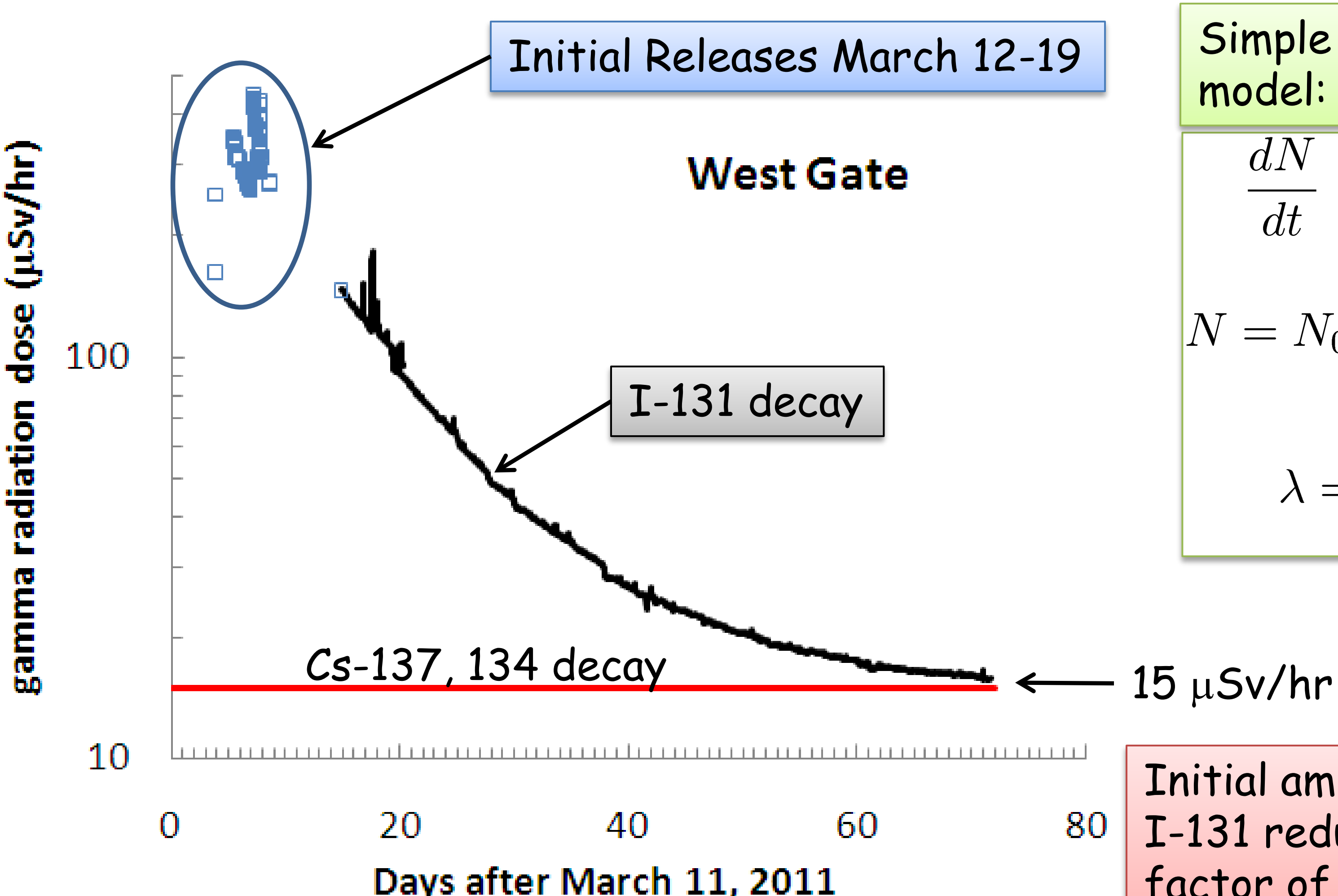
Activity of 0.0086/day corresponds to effective half-life of 8.06 day, consistent with decay being associated with I-131, $T_{1/2}$ = 8 day.

Analysis of residuals indicates long time activity (presumed to be mostly Cs-137) is about 15 μSv/hr.

Plotted activity has a constant value of 15 μSv/hr subtracted from all points.

Data from MEXT

Residual Dose



Simple decay model:

$$\frac{dN}{dt} = -\lambda N$$

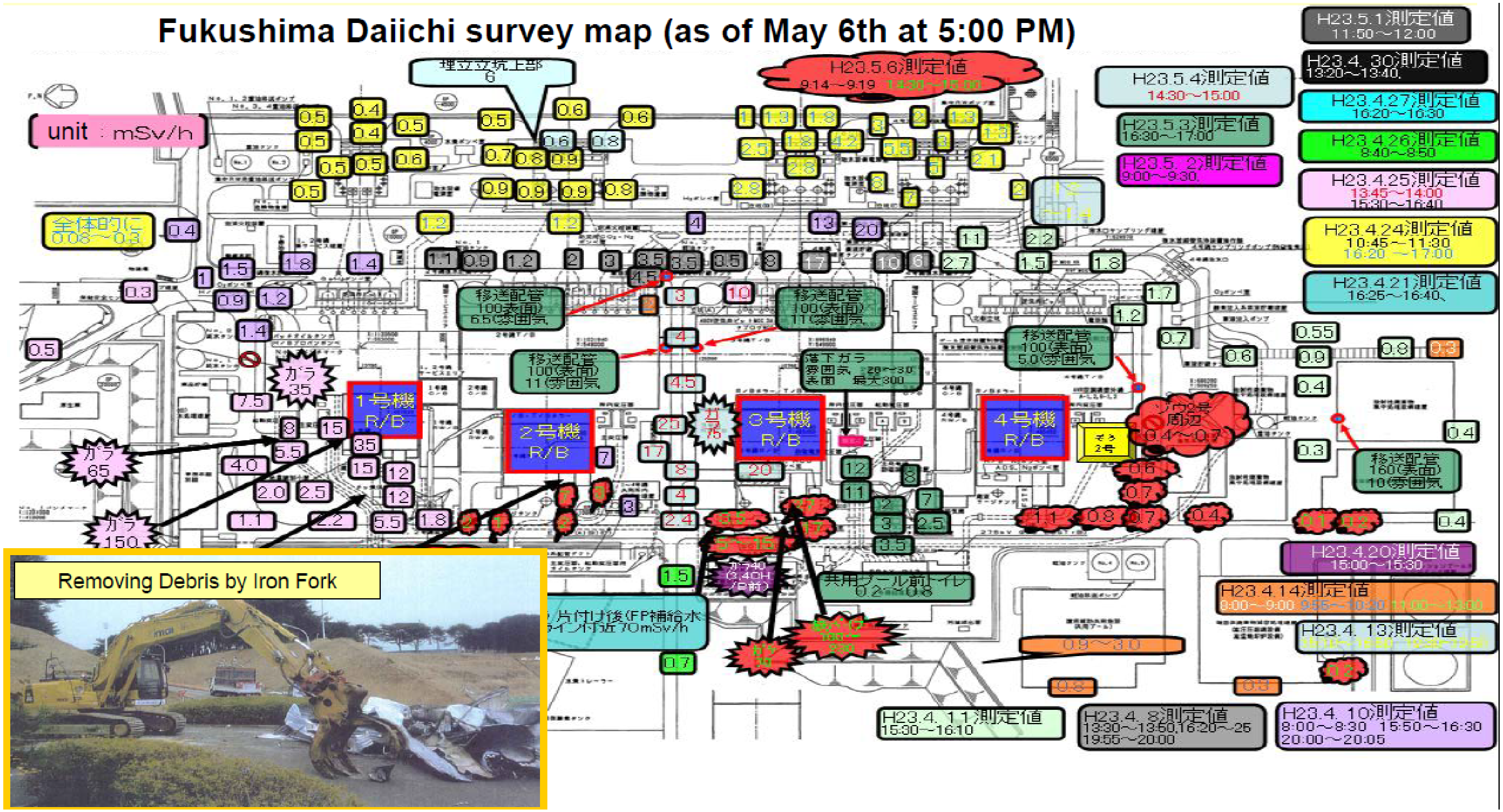
$$N = N_0 \exp(-\lambda t)$$

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

Initial amount of I-131 reduced by a factor of 660 after 75 days

Raw data from MEXT

Plant Area Contaminated with Radioactive Debris



Removing Debris by Iron Fork

Tepco Handout May 9

Other Fission Products

- There are 100s of other fission products, all heavier, but some fraction could be dispersed by the explosive events or contaminate cooling water.
- Total inventory postulated for unit 2

Radionuclide Group	(kg)
Noble Gases (Xe, Kr)	361.8
Halogens (I, Br)	14
Alkali Metals (Cs, Rb)	207.8
Tellurium (Te, Se)	33.2
Alkaline (Ba, Sr)	154.1
Platinoids (ru, Pd, Rh)	234.3
Early Transition (Mo, Tc, Nb)	263.7
Lanthanides (La, Nd, Pr, Sm, Y, Pm, Eu, Am, Gd)	485.7
Cerium (Ce, Pu, Zr, Np)	1213.1

This is for a slightly larger reactor operating at lower enrichment

SAND2007-7697

Plutonium

- Detected in soil near reactors
- Possible sources
  - Fallout from nuclear testing
  - Dispersed out of fuel by venting/explosions
    - By-product of U-238 absorbing neutrons
    - MOX fuel (6% of fuel assemblies in unit 2 contained plutonium)
  - Environmental contaminant from waste
- Not a health hazard – levels comparable with worldwide distribution of Pu from nuclear testing although significantly higher than previous samples at site.
- Preliminary analysis of 238/(239, 240) ratio indicates origin is fission by-product from normal reactor operation – another indication of breach of containment.
- Isotope ratio inconsistent with MOX fuel composition, solid waste, ordinary soil, or nuclear weapons testing
- Exceeding small amounts and further testing/confirmatory independent analysis is needed.

IRSN Evaluation

Release ~1/10 Chernobyl

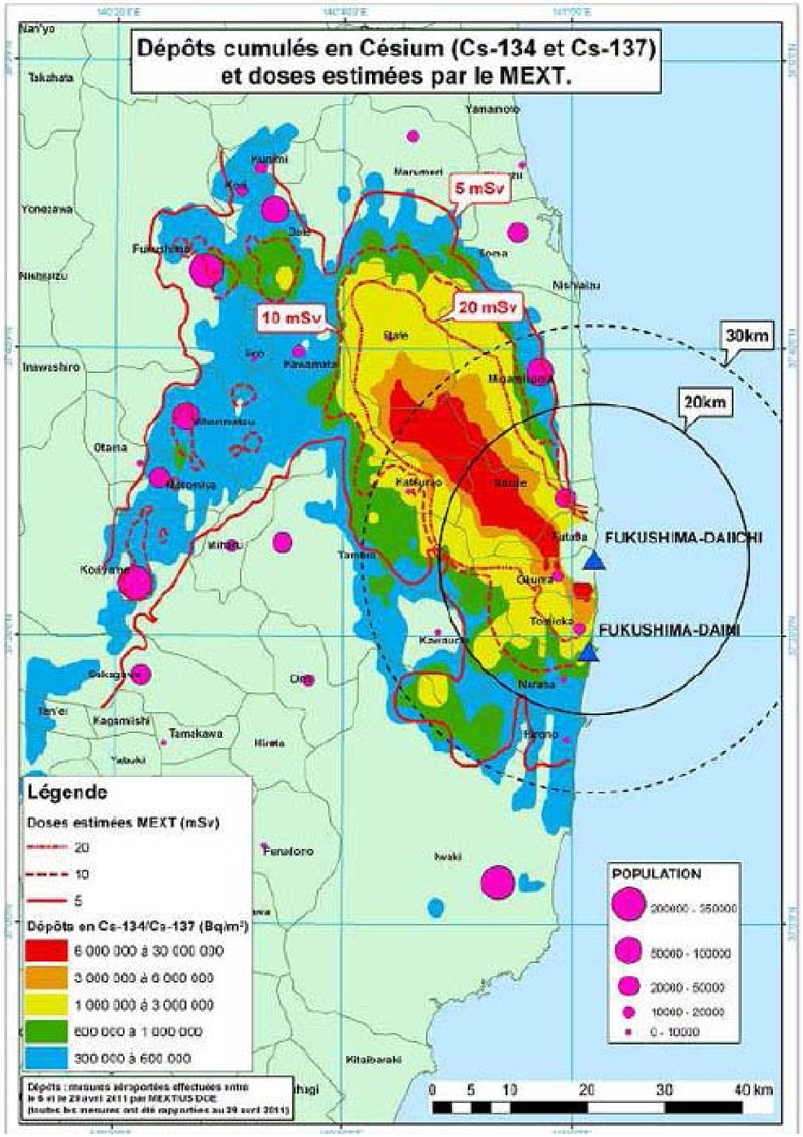
Contamination as high as 30 x 10^6 Bq/m^2, comparable to Chernobyl.

Rain and winds on March 15 and 16 created strip 60-70 lm long and 20-30 km wide contaminated more than 550,000 Bq/m^2

Evacuation needed in region of NW outside 20 km zone where dose rate exceeds 10 mSv/year or Cs-137, -134 contamination exceeds 600,000 Bq/m2.

[IRSN Report DRPH/2011-10]

Carte des dépôts des césiums 137 et 134 en Bq/m²
et des doses estimées par MEXT pour les 3 valeurs : 5, 10 et 20 mSv



Chernobyl vs Fukushima

TCHERNOBYL								
	Régions plus faiblement contaminées			Régions fortement contaminées				
ORGANISATION ADMINISTRATIVE des ZONES CONTAMINEES	ZONE Contrôle Radiologique	ZONE « Relogement Volontaire » Création d'entreprises agricoles et industrielles interdite Développement des entreprises existantes interdit		« STRICT CONTROL ZONES (SCZs) » « Zone de Relogement Obligatoire » Productions agricoles et industrielles interdites Entrées et sorties soumises à autorisation spéciale				ZONE EVACUATION INITIALE 30 km
				EVACUATION (sans caractère obligatoire)	EVACUATION OBLIGATOIRE			
Dépôts de césium-137	37 000 Bq/m^2 (1 Ci/km^2)	185 000 Bq/m^2 (5 Ci/km^2)	370 000 Bq/m^2 (10 Ci/km^2)	555 000 Bq/m^2 (15 Ci/km^2)	1,5 million Bq/m^2 (40 Ci/km^2)	3,7 millions Bq/m^2 (80 Ci/km^2)	7,4 millions Bq/m^2 (200 Ci/km^2)	Jusqu'à 37 millions Bq/m^2 (1 000 Ci/km^2)
Dose externe 1ère année (13 mSv par MBq de Cs-137 /m^2)	> 0,5 mSv	> 2,4 mSv	> 5 mSv	> 7 mSv	> 20 mSv	> 50 mSv	> 100 mSv	
Surface	116 000 km^2	19 000 km^2		7 200 km^2	3 100 km^2			2 830 km^2
Population	5 281 000 (1995)	1 300 000 (1995)		270 000 (1986)				135 000

FUKUSHIMA Dai-ichi								
Dépôts de césium-137 (MEXT)			> 150 000 Bq/m^2	> 300 000 Bq/m^2	> 500 000 Bq/m^2	> 1,5 million Bq/m^2	3 -15 million Bq/m^2	ZONE EVACUATION INITIALE 20 km
Dose externe 1ère année (33 mSv par MBq de Cs-137 /m^2)			> 5 mSv	> 10 mSv	> 16 mSv	> 50 mSv	100 - 500 mSv	
Surface hors zone d'exclusion	?	?	1 241 km^2	320 km^2	384 km^2	91 km^2	79 km^2	628 km^2
Population hors zone d'évacuation initiale	?	?	292 000	69 400				85 000
				43 000	26400			
					21 100	3 100	2 200	

IRSN Report DRPH/2011-10

Contamination of Soil

- 700 km^2 area has > 600,000 Bq/m^2 of Cs-137,134 in soil
- Comparable to Chernobyl levels in some areas
- Cesium strongly binds to soil, requiring removal of top soil layer to prevent excess long-term γ-radiation exposure and uptake of cesium by plants.
- >70,000 people affected (IRSN)
- "A massive soil decontamination project will be indispensable before residents in those areas can return…" - Tomio Kawata, researcher for NWMO.

Manichi Daily News, May 28

“Contamination of Seafood Limited”

- May statement:

  “Radioactive contamination of the Pacific Ocean following the nuclear incident has raised public concerns about seafood safety. Based on currently available information, only one fish species (sand lance) in the direct vicinity of the nuclear power plant has been found to be contaminated at levels above the regulatory limits set by the Japanese Government, and control measures are in place to prevent its distribution. Radionuclide contamination, if any, in seafood outside these areas, is expected to be significantly below any public health concern, even in Pacific islands with high seafood consumption. Any additional radiation levels will contribute only a small amount to natural background radiation exposure.”

  World Health Organization (WHO)

"Health Consequences Small"

John D. Boice, Jr., Sc.D. Distinguished Emeritus Member NCRP Testimony to Congress, May 12, 2011

- Fukushima is not Chernobyl
  - Much smaller (10%) total release and mostly volatile FP (Kr, Xe, I, Cs, Te)
  - Many FP not released to environment
  - Rapid evacuation/shelter in place response actions
  - Stopped milk consumption/distributed stable Iodine (KI) for children immediately
  - Exposure to workers and public minimal by comparison
- The health consequences for Japanese workers and public appear to be minor.
- The health consequences for United States citizens are negligible to nonexistent.
- We live in a radioactive world.
- There is a pressing need to learn more about the health consequences of radiation in humans when exposures are spread over time at low levels and not received briefly at high doses such as in atomic bomb survivors

"Thus, while Fukushima is clearly a major reactor accident, the potential health consequences associated with radiation exposures in terms of loss of life and future cancer risk are small, particularly in contrast with those resulting from the Chernobyl accident some 25 years ago."

Collective Effective Dose and Cancer

- Estimates by NRDC based on MEXT data and BIER VII methodology for 9 prefectures from March 14 to May 23.

	Population Exposed	Collective Dose (person-rem)	Excess Cancers	Excess Mortality
Fukushima	48×10^6	6.2×10^5	700	350
TMI	2×10^6	2×10^3	2	1
Chernobyl	-	3.8×10^7	4×10^4 (*)	2×10^4 (*)

* 2008 UNSCEAR study did not give projections for LNT model, the values for Chernobyl are controversial, these are from NRDC report.

NRDC Conclusion: Collective Effective Dose ~100 x larger than TMI and ~100 times smaller than Chernobyl.

McKenzie and Cochran 10 April 2011

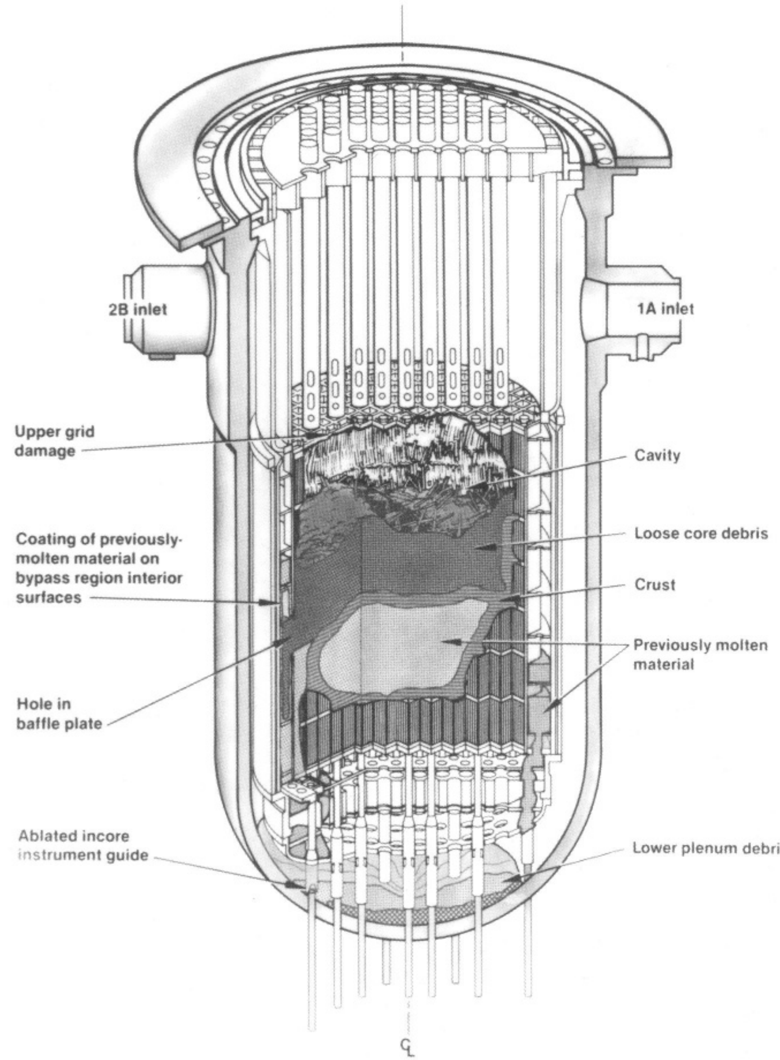
Cochran May 26 2011

Major Commercial Reactor Incidents

- Three Mile Island Unit 3 (1979)
- Chernobyl Unit 4 (1986)
- Fukushima Daiichi Units 1, 2, 3, 4 (2011)

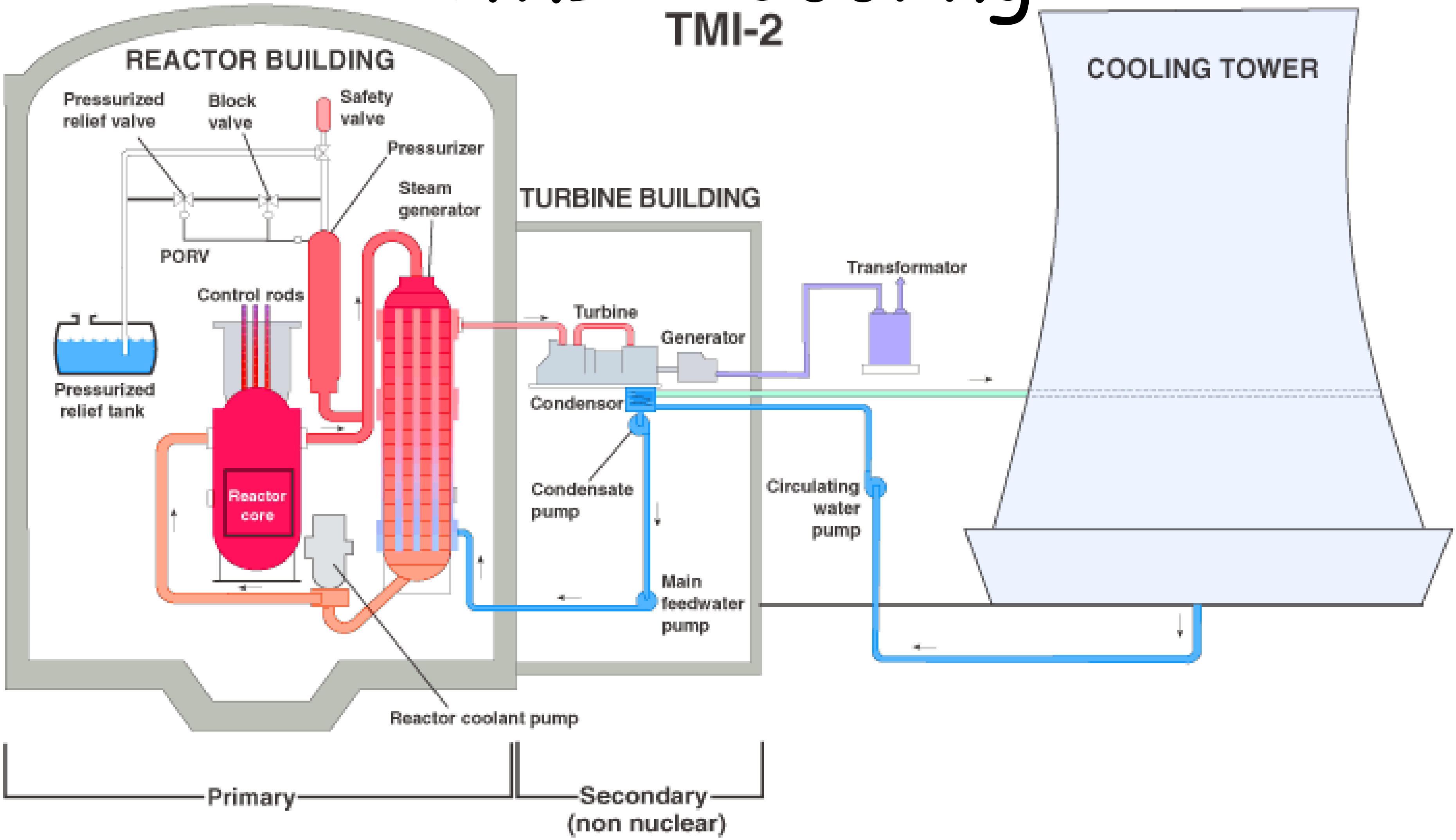
Three-Mile Island (TMI) Unit 2

- March 28, 1979
- 900 Mwe PWR
- Concrete containment
- Initiating event was interruption of feedwater
- Loss of coolant from stuck open relief valve
- Core badly damaged, nearly melted through lower head
- Hydrogen generation, explosion inside containment
- Minimal release of radioactivity
  - 20 person-Sv committed dose
  - 3.7×10^{17} Bq (10 Mci) total
  - 3×10^{17} Bq (8 Mci) of Xe-133
  - 1.8×10^{15} (57 kCi) Krypton-85
  - 5.5×10^{11} Bq (15 Ci) of Iodine-131
  - 3.8×10^{6} Bq (40 microCi) Cs-137



Wright, Advances in Nuclear Science and Technology, Volume 24, 283-314, 1996

TMI-2 Cooling



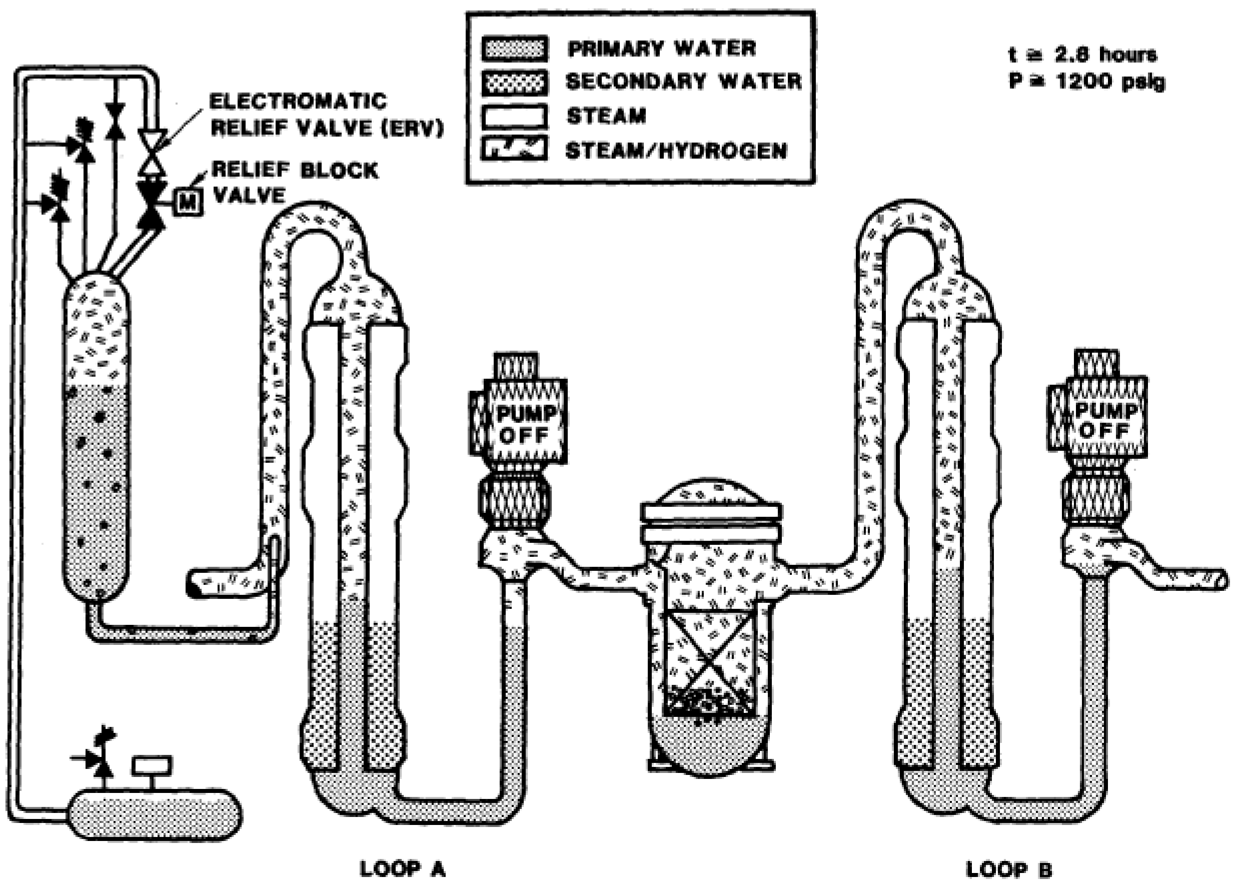
[US NRC 3-mile Fact Sheet]

What happened?

- Feed water interrupted
- Reactor scrammed
- ECCS pumps started/stopped
  - block valve closed, had to be opened by hand
- Heat exchangers boiled dry (2 min!)
- Pressure increased, relief valve opened automatically
  - Stayed stuck open for 2 hours
- ECCS pumped restarted then manually shut down
  - system appeared to be "solid"
- Core uncovered for at least 1 hr
  - 50% degraded, 20% in rubble bed at bottom of RPV
  - Hydrogen generation of 300-400 kg corresponding to oxidizing 45% of Zircaloy
- Water and H2 dumped into containment from PORV
- H2 (8%) burn in containment - 200 kPa pressure rise < 450 kPa design pressure (Henrie and Postma 1981 and 1987)
- Gaseous and volatile FP released accidentally and deliberately into atmosphere
- 14 year clean-up process, core removed & stored at INEL by 1990, 2.8 Mgal of contaminated water processed by 1993, required 1000 workers on site & $973 million

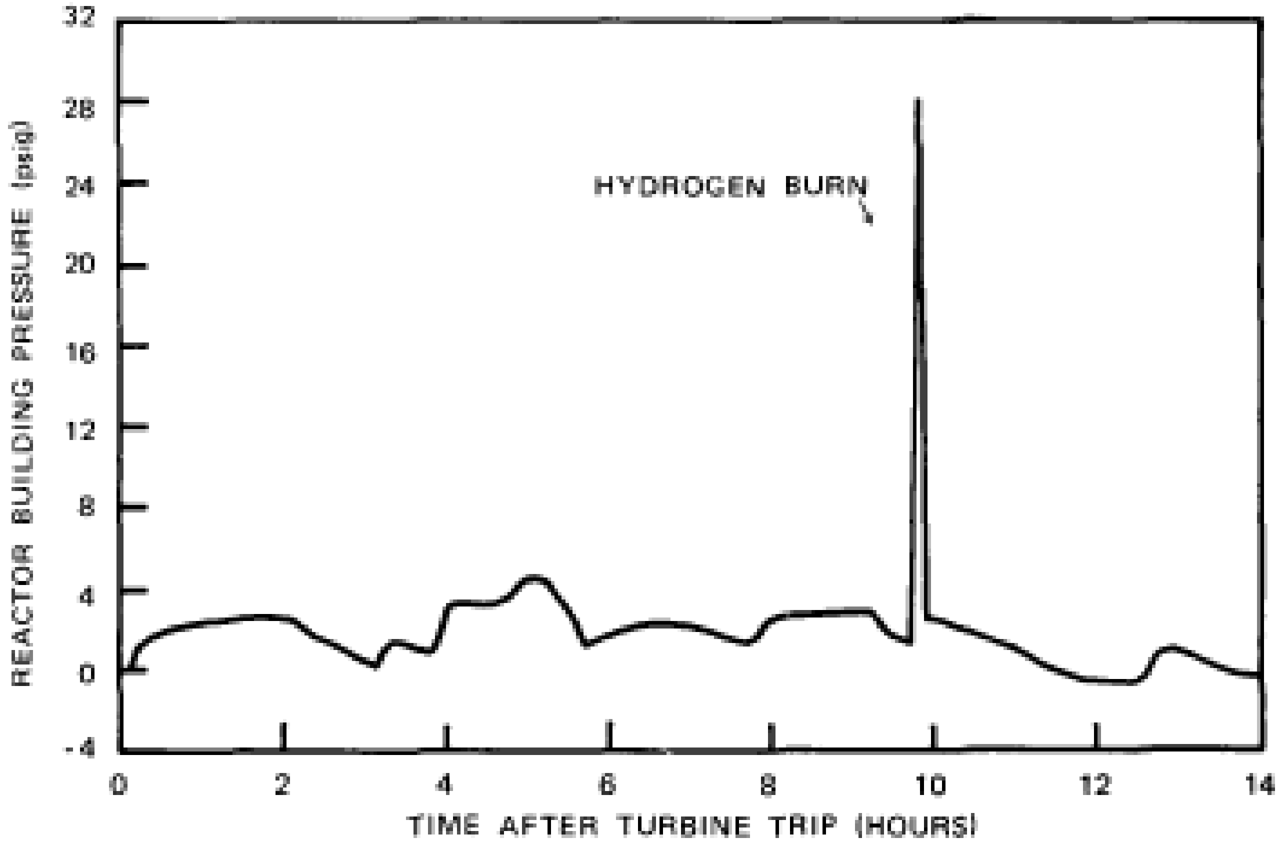
Sources:
US NRC
Dickinson College

Core Uncovered for Extended period



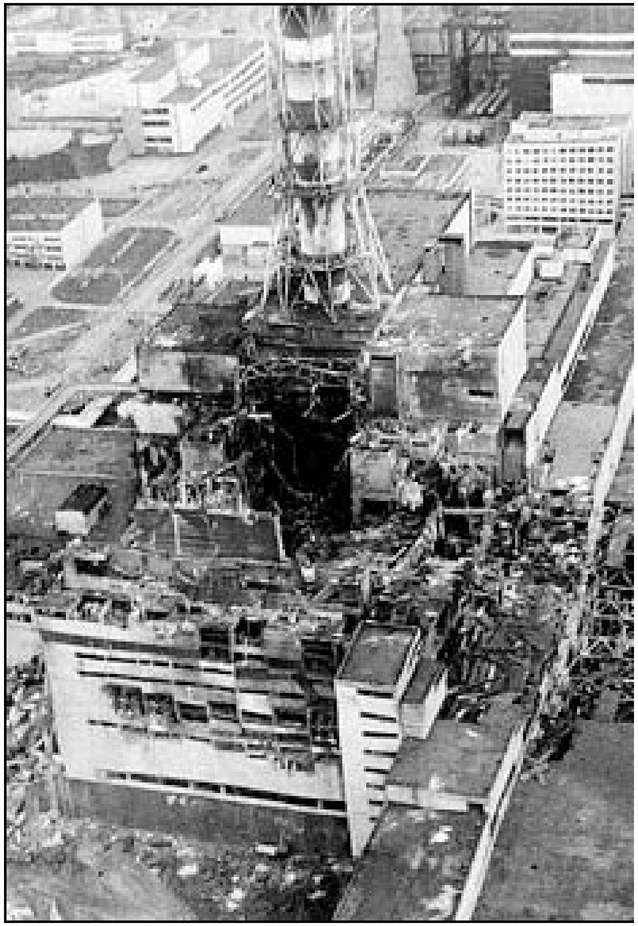
LWR H2 Manual NUREG/CR-2726

Hydrogen Combustion inside Containment Building



LWR H2 Manual NUREG/CR-2726

Chernobyl Unit 4



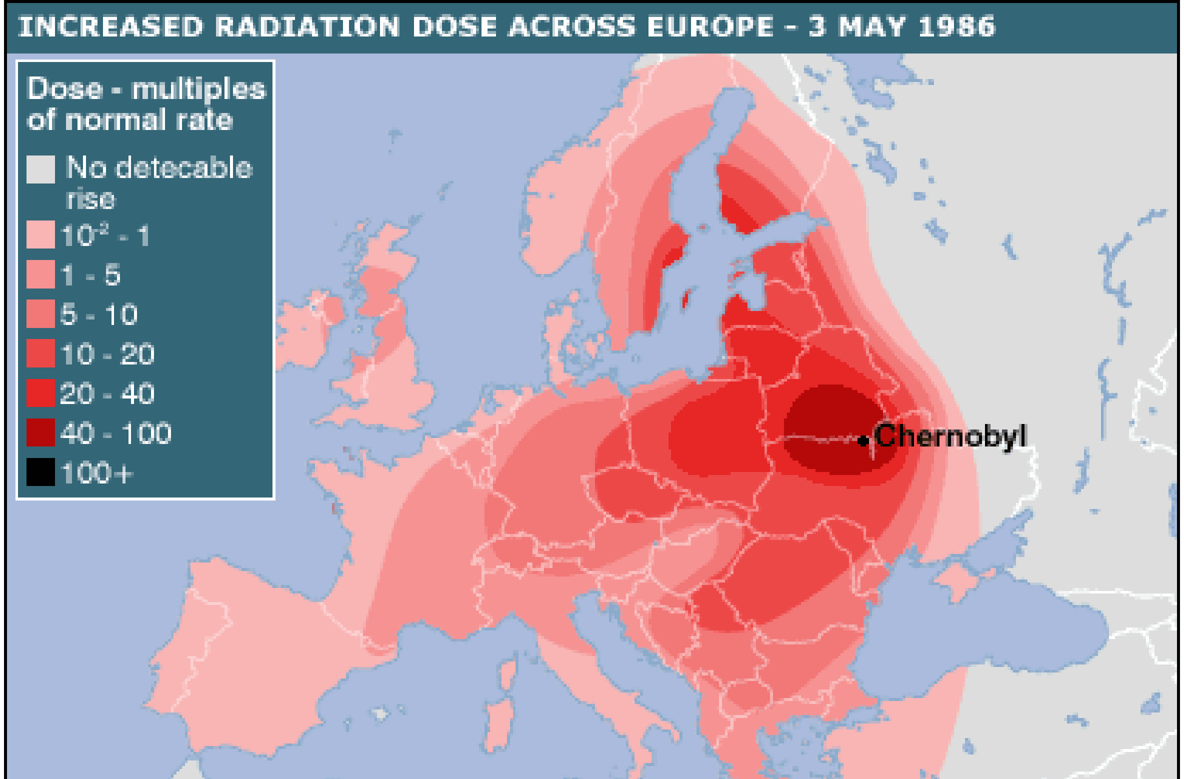
- 1000 Mwe RBMK-type reactor: Graphite-moderated, water-cooled, no containment structure or pressure vessel
- 26 April 1986
- Criticality accident caused by multiple factors including poor design, willful disregard of regulations, ignorance of reactor physics by operators
- Explosion and fire completely destroyed reactor, created large plume of contamination
- Required resettlement of 350,000 people
- 600,000 "liquidators" involved in cleaning up site and building containment structure.

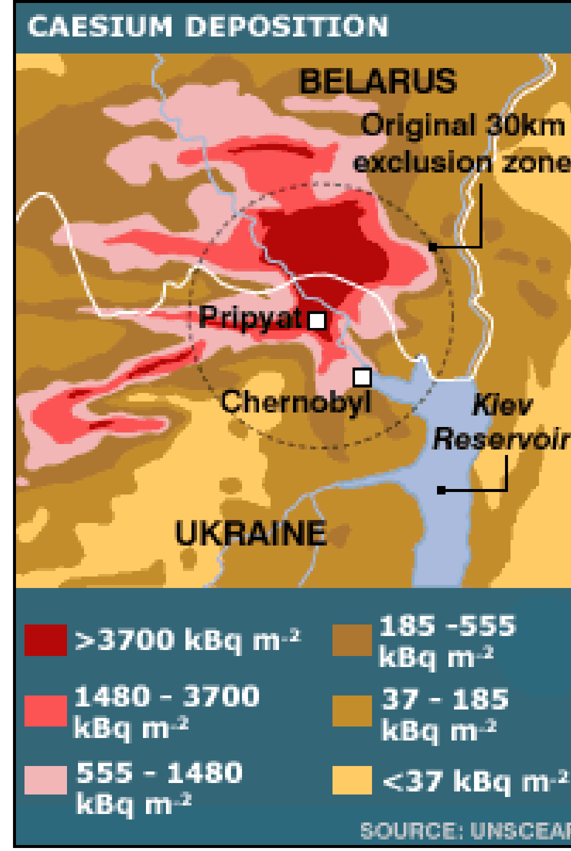
UNSCEAR 2000

Entombment – again and again.

- Remaining molten core materials (~200 tonne) enclosed in concrete "sarcophagus"
- 400,000 m^3 of concrete and 7,300 tonnes steel
- Deteriorating and cannot be repaired.
- 100-yr cover building to be installed in 2013
- €990M in EU funds so far, need another €710M .

[Chernobyl 25 Project]





Species	Half-life	Released Amount	
		MCi	Bq
85Kr	10.8 yr	0.89	3.3×10^{16}
133Xe	5.2 dy	176	6.5×10^{18}
131I	8 dy	49	1.8×10^{18}
134Cs	2 yr	1.4	5×10^{16}
137Cs	30 yr	2.3	8.5×10^{16}
90Sr	29 yr	0.27	8×10^{15}

Cs-137 fallout
- 37 kBq/m^2 contaminated
- 555 kBq/m^2 restricted

UNSCEAR 2000

Contamination and Effects

- 10 mSv - 30 km exclusion zone, 116,000, all relocated
- 50mSv - Strict control zone, 270,000, some relocated
- 100 mSv – "Liquidators", 200,000
- 5 mSv – general population, 6,500,000

UNSCEAR 2000, 2008

- Main contaminants are Cs-137 and Sr-90
  - 30 year half-life
- Collective dose commitment (2056) is 600,000 person-Sv
- Illness
  - 28 immediate deaths
  - 237 acute radiation syndrome
  - >4000 thyroid cancers from Iodine-131

Three Incidents – Three Different Situations

- TMI – Unit 2
  - 1 PWR, reactor pressure vessel, containment building
  - Feedwater upset caused loss of coolant leading to core degradation
  - 50% core damage, hydrogen explosion in containment
  - Pressure vessel, containment intact
  - Small release of volatile FP, no contaminated exclusion zone
  - No health implications for workers or public
  - Complete cleanup
- Chernobyl – Unit 4
  - 1 RBMK reactor, no pressure vessel and weak containment
  - Unauthorized and unsafe reactor operation
  - Core and reactor building destroyed by critical disassembly
  - Release of substantial fraction of FPs including refractories during explosion/fire
  - ~250 cases of acute radiation sickness, 28 deaths, >4000 thyroid cancers
  - Large contaminated zone (up to 10,000 km^2), 350,000 displaced
  - reactor entombed, long term care, new enclosure needed after 25 yrs
- Fukushima Dai-ichi – Unit 1, 2, 3, and 4
  - 3 Mark I BWR reactors and 4 spent fuel pools
  - Severe damage to plant systems by earthquake & tsunami leading to long term station blackout
  - Loss of coolant in reactors ond spent fuel pools causing severe damage of fuel
  - 30-100% core damage to 3 reactors, suspect RPV and PCV damage
  - At least 4 hydrogen explosions/fires, severe damage to reactor buildings, spent fuel pools
  - No acute radiation sickness or worker/public sickness or deaths reported due to radiation
  - Plant highly contaminated, substantial release of volatile FP in air, sea
  - Extent of contaminated (>20 mSv/yr) zone, 700-1000 km^2 , 70,000-150,000 people displaced

Information on the www

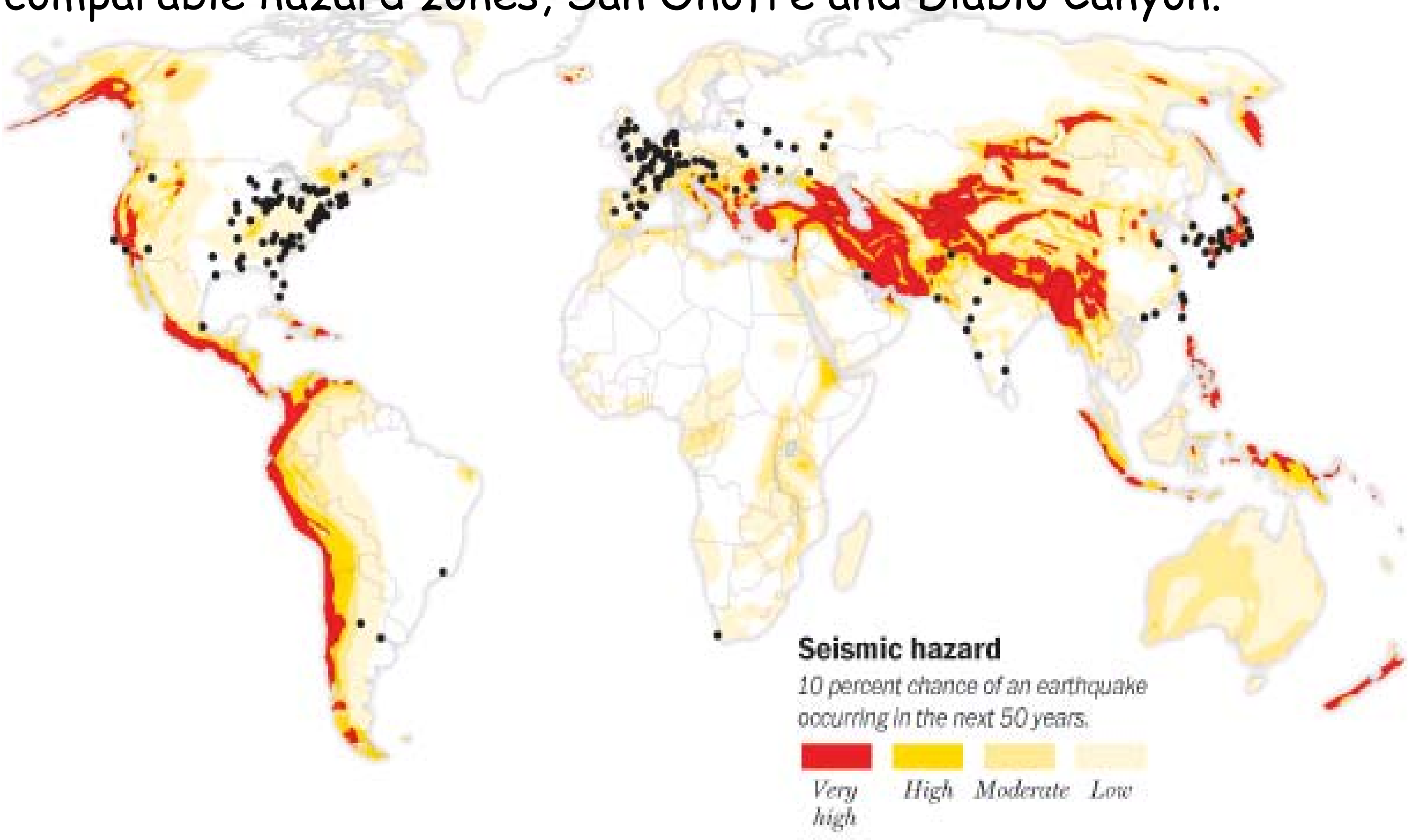
- NHK World News
- Nuclear and Industrial Safety Agency (NISA/METI)
- Tepco English press releases   Tepco Press Photographs
- Japan Nuclear Energy Safety Organization (JNES)   Nuclear Safety Commission (NSC) of Japan
- Japan Atomic Industrial Forum (JAIF)
- Japan Nuclear Technology Institute (JANTI)
- Ministry of Education, Culture, Sports, Science and Technology Japan (MEXT)
- World Health Organization
- International Atomic Energy Association (IAEA)
- UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)
- Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
- Zentralanstalt für Meteorologie und Geodynamik (ZAMG)
- Sirocco (CNRS & Toulouse University)
- Comprehensive Test Ban Treaty Organization Preparatory Commission (CTBTO)
- Nuclear Engineering International
- World Nuclear News
- Nuclear Energy Institute (NEI)
- American Nuclear Society (ANS)
- Nuclear Tourist
- US Nuclear Regulatory Commission (US NRC)
- US DOE - NNSA
- US EPA (Radiation)
- National Council on Radiation Protection and Measurement (NCRP)
- Union of Concerned Scientists
- Natural Resources Defense Council
- Wikipedia - Fukushima I accident timeline
- Wikipedia - Fukushima I accident

Outlook for Nuclear Power

- World-wide impact of Fukushima Incident
  - Will result in extensive re-examination of safety basis and risk assessment – much more so than Chernobyl or TMI.
  - Setback to "nuclear renaissance"
- Significant to all ~440 plants world wide
- Economic ramifications: Nuclear is 14% of electrical generating capacity worldwide. Top three producers:
  - 20% of electricity capacity in USA (101 GWe)
  - 75% in France (63 GWe)
  - 27% in Japan (47.5 GWe), planned to → 50% by 2030
- Intense political pressure to shut down operation in some regions: Germany
- Intense economic pressure to maintain in operation in some regions
- Plants aging, 40 year licenses ending, requests to extensions to 60 years in USA
- Engineering challenge:
  - Can older plants be backfitted economically?
  - Are new designs sufficiently robust?
- Societal challenge:
  - What level of risk are we willing to accept to have baseload electrical power?
  - Continuing operation or just cleanup requires waste disposal repositories. How do we move forward with this process?

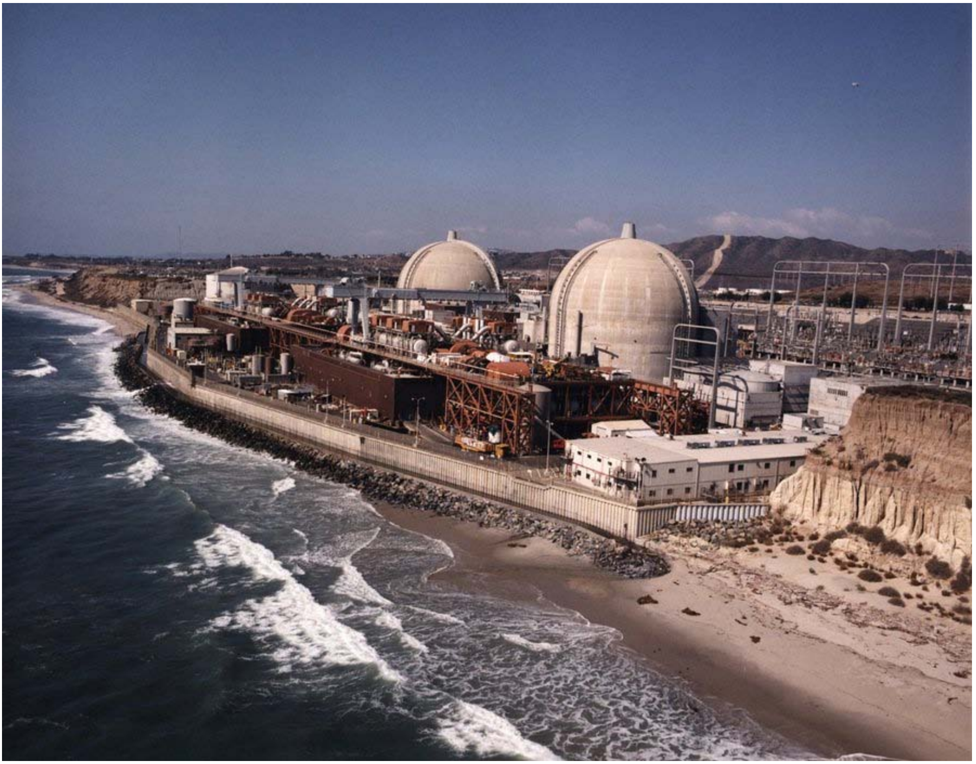
Reactors and Seismic Hazards

Japan reactors are "test bed" for earthquake and tsunami design standards. All reactors in Japan are in seismically active areas and near ocean. Only two US reactors are in comparable hazard zones, San Onofre and Diablo Canyon.



NY Times

US Plants in High Hazard Zones

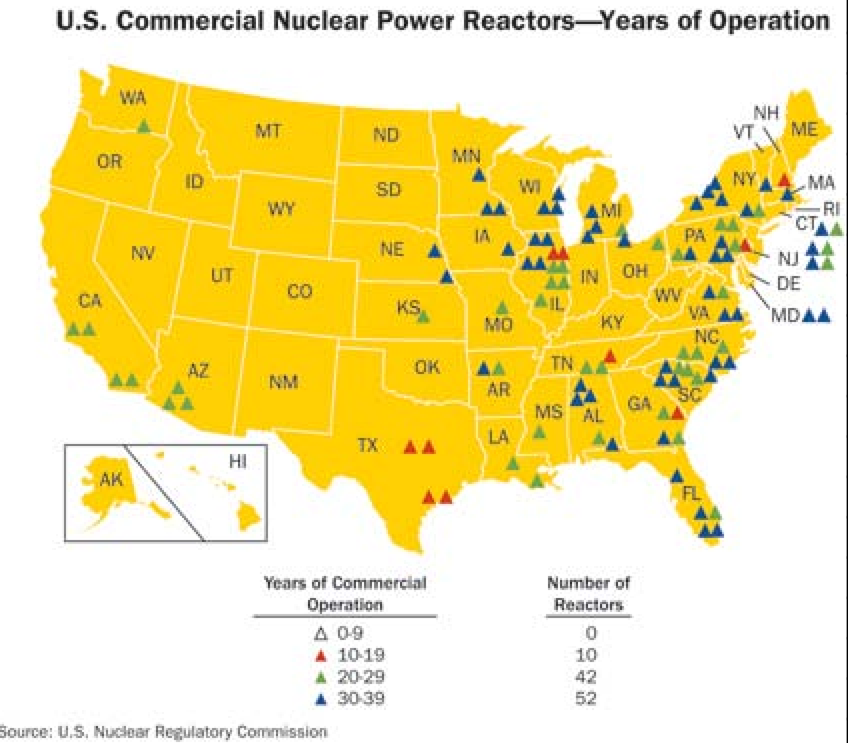


San Onofre

Diablo Canyon

104 Operating Reactors in US

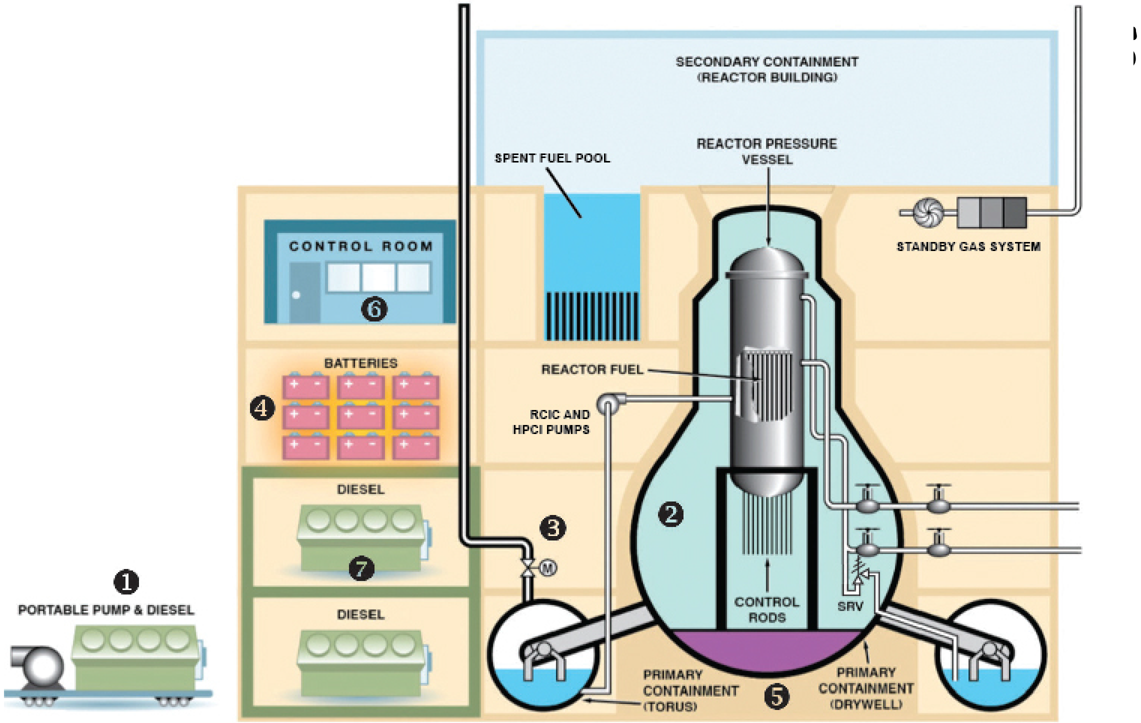
- 23 are BWR Mark 1 containment type



(US NRC)

Reactor	State	Operation	Renewal	Expiration
Browns Ferry Nuclear Plant, Unit 1	AL	12/20/1973	5/4/2006	12/20/2033
Browns Ferry Nuclear Plant, Unit 2	AL	8/2/1974	5/4/2006	6/28/2034
Browns Ferry Nuclear Plant, Unit 3	AL	8/18/1976	5/4/2006	7/2/2036
Brunswick Steam Electric Plant, Unit 1	NC	9/8/1976	6/26/2006	9/8/2036
Brunswick Steam Electric Plant, Unit 2	NC	12/27/1974	6/26/2006	12/27/2034
Cooper Nuclear Station	NE	1/18/1974		1/18/2014
Dresden Nuclear Power Station, Unit 2	IL	2/20/1991	10/28/2004	12/22/2029
Dresden Nuclear Power Station, Unit 3	IL	1/12/1971	10/28/2004	1/12/2031
Duane Arnold Energy Center	IA	2/22/1974		2/21/2014
Edwin I. Hatch Nuclear Plant, Unit 1	GA	10/13/1974	1/15/2002	8/6/2034
Edwin I. Hatch Nuclear Plant, Unit 2	GA	6/13/1978	1/15/2002	6/13/2038
Fermi, Unit 2	MI	7/15/1985		3/20/2025
Hope Creek Generating Station, Unit 1	NJ	7/25/1986		4/11/2026
James A. FitzPatrick Nuclear Power Plant	NY	10/17/1974	9/8/2008	10/17/2034
Monticello Nuclear Generating Plant, Unit 1	MN	1/9/1981	11/8/2006	9/8/2030
Nine Mile Point Nuclear Station, Unit 1	MI	12/26/1974	10/31/2006	8/22/2029
Oyster Creek Nuclear Generating Station, Unit 1	NJ	7/2/1991	4/8/2009	4/9/2029
Peach Bottom Atomic Power Station, Unit 2	MI	10/25/1973	5/7/2003	8/8/2033
Peach Bottom Atomic Power Station, Unit 3	MI	7/2/1974	5/7/2003	7/2/2034
Pilgrim Nuclear Power Station	MI	6/8/1972		6/8/2012
Quad Cities Nuclear Power Station, Unit 1	IL	12/14/1972	10/28/2004	12/14/2032
Quad Cities Nuclear Power Station, Unit 2	IL	12/14/1972	10/28/2004	12/14/2032
Vermont Yankee Nuclear Power Plant, Unit 1	VT	3/21/1973	03/21/2011	03/21/2032

Major Modifications and Upgrades to U.S. Boiling Water Reactors with Mark I Containment Systems



1. Added spare diesel generator and portable water pump – 2006
2. Added inerting of primary containment – 1980
3. Added containment vent – 1992
4. All plants increased station black out coping duration, some with additional batteries – 1988
5. Structural strengthening of torus – 1980
6. Control room reconfiguration – 1980
7. Back-up safety systems separated – 1979

[Nuclear Energy Institute]

Influence on Nuclear Policy

- Countries with pro-nuclear policy - Reactors operational/ under construction or planned
  - France 58/2
  - India 18/11
  - Russia 32/12
  - China 14/54
  - South Korea 22/14
  - Japan 56/14 (13 operating reactors currently not in service)
  - USA 105/1
    - 20 life extension applications, 15 more on the way
  - Canada 19
  - Taiwan 7/2
- Countries that previously planned expansion that are reconsidering
  - UK 20/4
    - EDF Scheduled to build 4 reactors at Hinkley point
  - Poland 0
  - Czech Republic 4/2
  - Finland 4/1
  - Spain 9
- Countries with moratoriums (EU "stress testing" NPP)
  - Italy 0 (New construction depends on voter referendum, now postponed)
  - Switzerland 6 (Planned to renew 3 of 5 plants on hold)
  - Germany 18 (7 plants shut down, delayed life extension plans to 2022, NPP phase out likely)
- Countries with anti-nuclear policy
  - Austria, Denmark, Greece, Ireland and Portugal

270 PWR
93 BWR
45 PHWR
18 GCR
15 LWGR
3 FBR
______
443

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Consequences of NPP Closure

- Loss of 14% of generating capacity in world would be made up with fossil fuel plants
  - Closure unthinkable in some countries (France, Japan)
  - Substantial new non-nuclear power plant construction required in other countries (USA?)
  - Many countries will not be affected
- Primary replacement energy source probably NG but coal is also an option
  - NPP provides baseload power – renewables can't replace this.
  - Increase in CO_2 emissions
    - 11 billion tonnes additional without any NPP
  - Rethink energy/climate change policy?
    - Renege on previous commitments to reach CO_2 reduction targets?
  - Increased reliance of EU on Russian NG
    - "full withdrawal from nuclear by OECD countries would increase demand for gas by more than 400 billion cubic metres a year by 2045." – Economist Mar 24, 2011
  - Canada and USA would simply continue shale gas exploitation that is in progress

The Economist

Japan NPP Situation

- Special situation
  - Energy security overriding concern
    - Energy-intensive society with few natural energy resources (80% imported primary energy)
    - Nuclear generation of 30% of electricity (45 GWe)
    - Large investment in
      - Heavy industry for NPP design/construction (JSW, Toshiba, Hitachi, MHI)
      - Fuel cycle industry (mining investment, enrichment, U and MOX fuel fabrication, reprocessing, disposal)
  - Commitment to CO2 reduction based on growth of NPP
  - Highly-educated, technology-friendly society
    - Many believe NPP technology can be safe
  - Public lacks confidence in Utilities and Regulators
    - Numerous recent scandals in regulation, data falsification
    - Revolving door between regulators and utility executives
    - 1999 JCO criticality accident badly handled
  - External events (seismic, tsunami) drive design/safety
  - Significant seismic upgrades have been carried out on damaged plants
    - Nonnuclear structures of Kashiwazaki-Kariwa NPP (7 units) were damaged by Niigataken Chuetsu oki earthquake in 2007
    - Signficant repair work and strengthening carried out
    - New JNES research center established at Niigata, cooperative research with IAEA
    - JNES Symposium in 2010
- Cultural Issues
  - Relationship between government, regulation, vendors, and utilities has to be addressed.
- Plant closures severely affecting electricity supply
  - 37 of 54 units closed as of May 16. 13 due to seismic damage, 2 at request of Government, 22 shut down for inspection.

World Nuclear Assoc

Clean-up Updates (May-July)

- Spraying down area with dust control polymer
- Mapping hotspots
- Remote control rubble removal
- Filtering air in reactor buildings
- Strengthening unit 4 building under pool
- Designing and erecting air-tight covers and ventilation systems for reactor buildings
- Designing, installing, and making operational a water treatment system.
- Storing and recycling contaminated water for cooling reactors
- Installing permanent barriers at seawater intakes to prevent further contamination
- Nitrogen injection to units 1, 2, preparation for unit 3.
- Cooling spent fuel pools

Air Filtration System

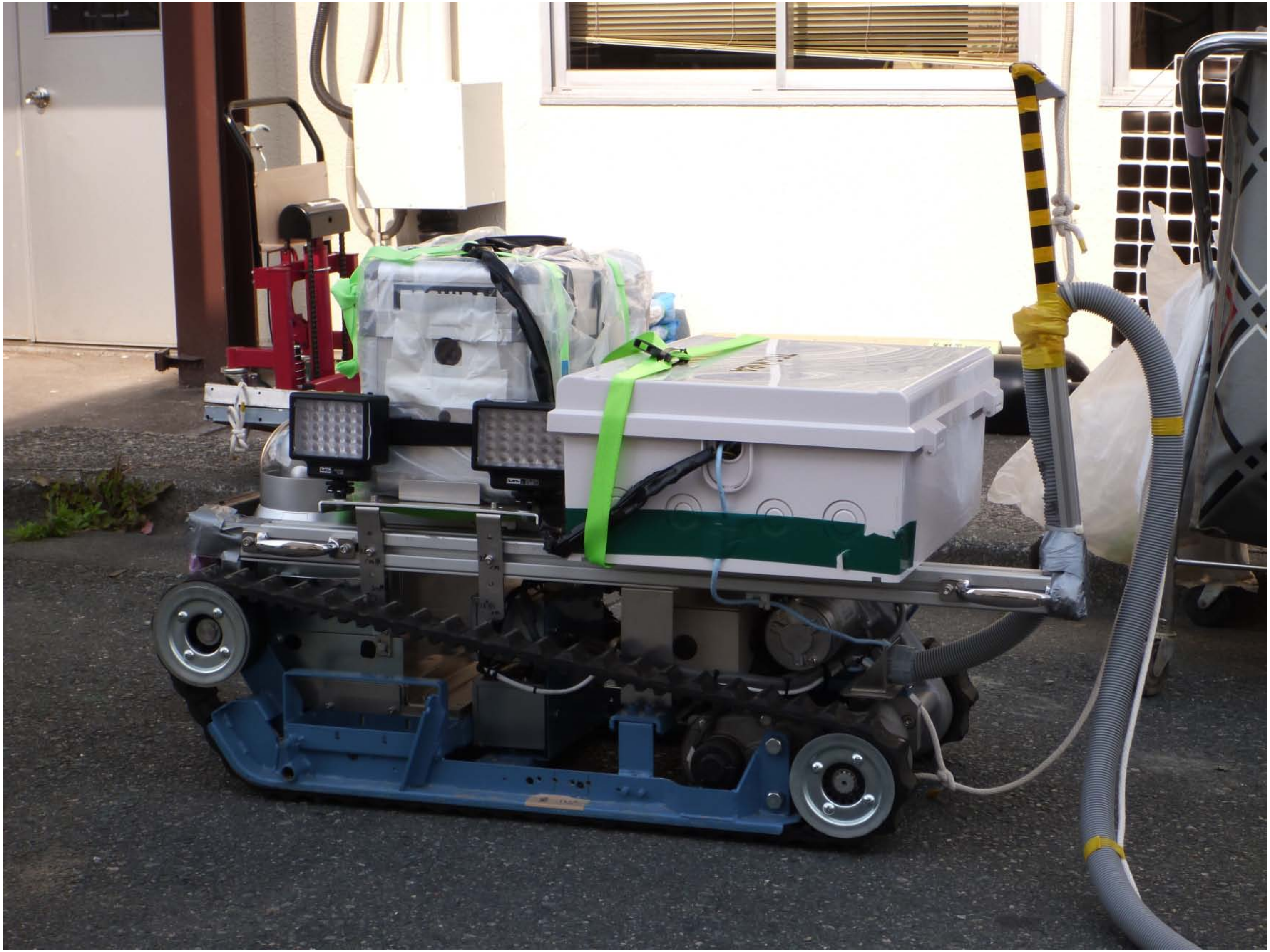
Unit 1 reactor building temporary duct work

Tepco May 5

Remote Rubble Removal

Tepco May 17

Robotic Gamma Camera



Tepco May 19

Rubble Hotspot – Unit 1

Tepco May 21

Spraying Dust Inhibitor

Tepco May 27

Decontamination Plant

Tepco May 31

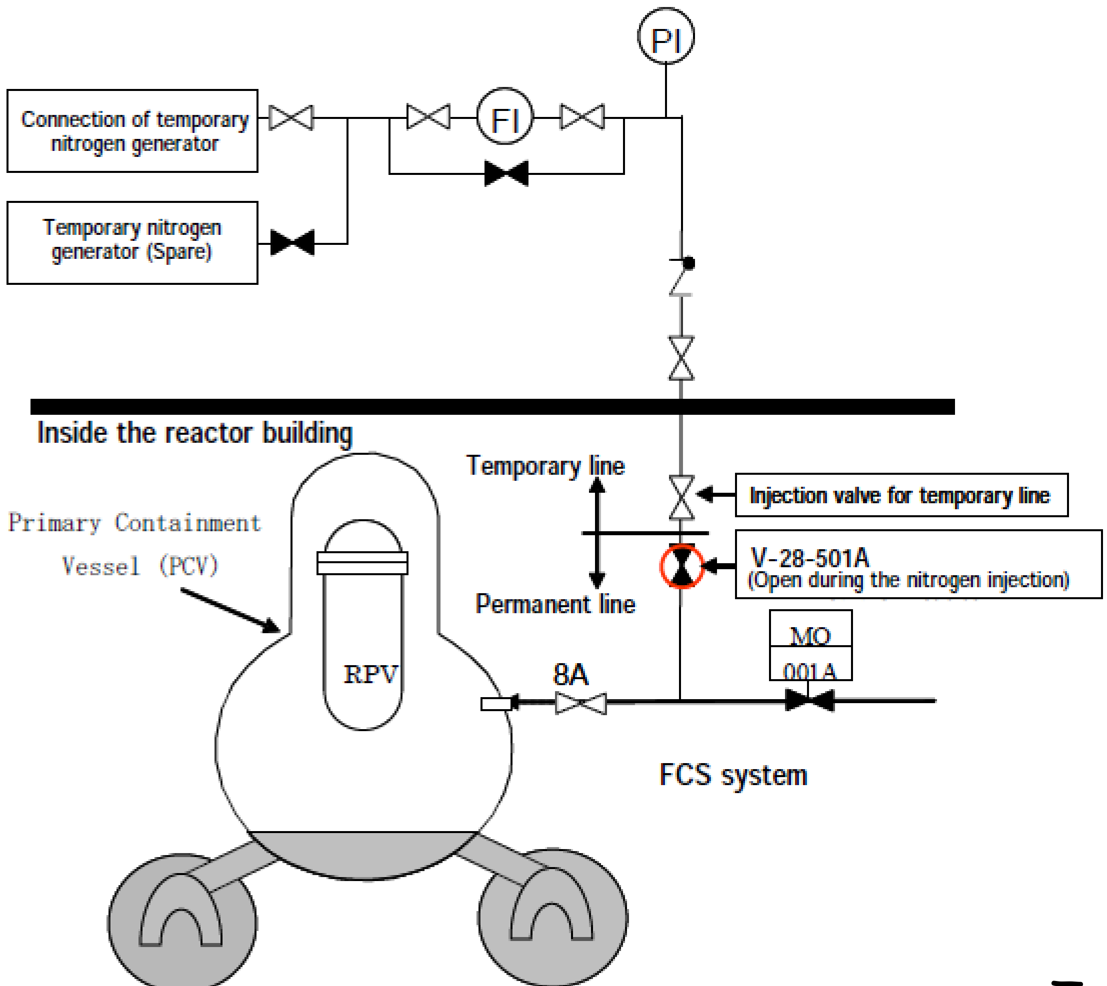
Water Treatment Facility – Cesium Absorption Tower

Tepco June 1

Treated Water Storage

Tepco June 5

Nitrogen Injection in Unit 2



Tepco June 25

Water Storage Tanks

Tepco June 29

Reinforcing Unit 4 Pool Floor

Tepco June 7

Barriers at Seawater Intake

Tepco June 30

Inside Unit 4 – 4th Floor S.

Tepco June 29

Unit 4 Spent Fuel Pool

Tepco June 29

Cleaning Up Unit 3

Tepco June 30

Model of Unit 1 Cover

Tepco June 14

Trial of Erecting Cover

Tepco June 24

Reporting Updates

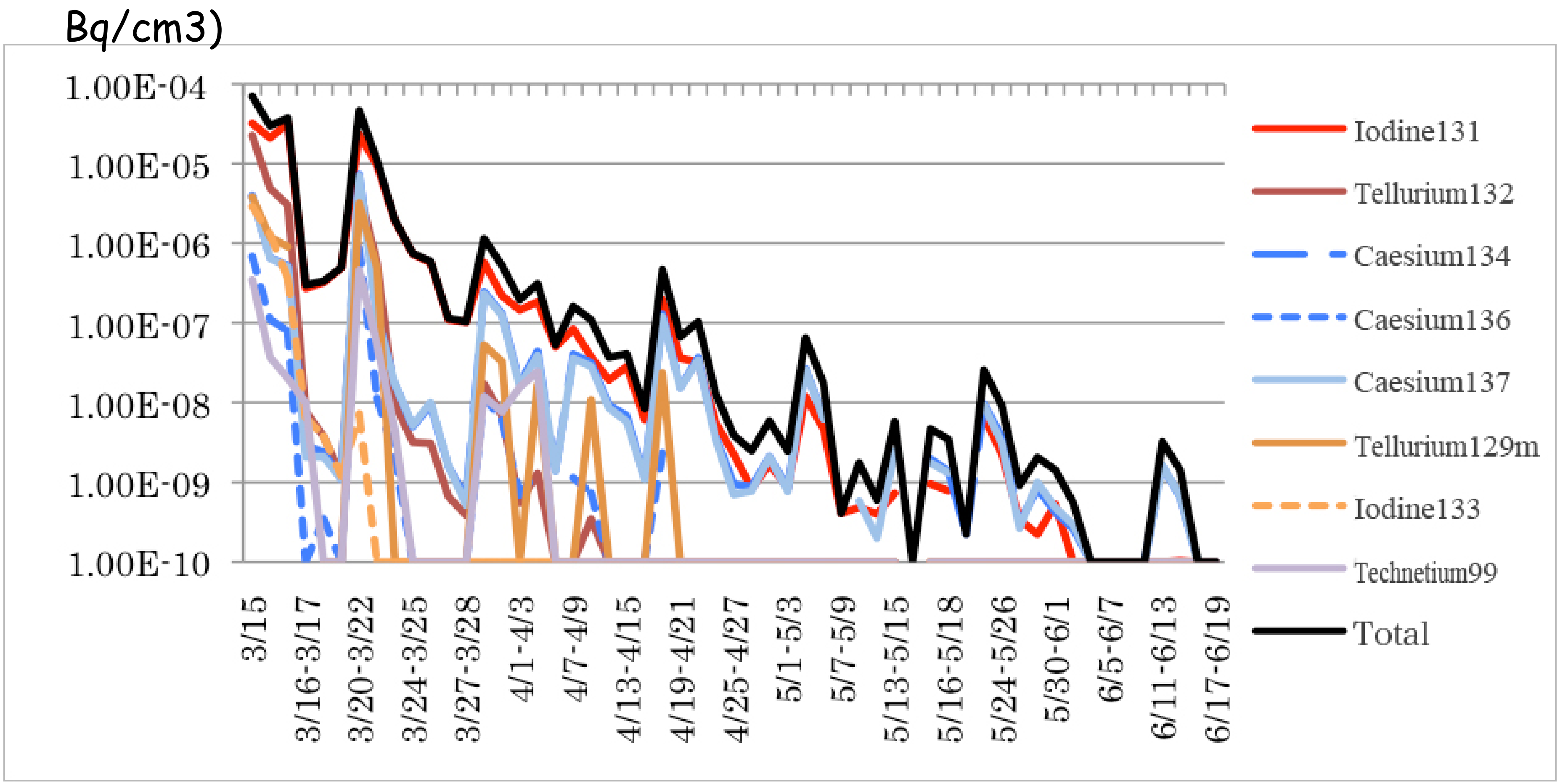
- Report (June 7) of the Japanese government to the IAEA
  English Translation
- Timeline of events March 11-15
  - Tepco report (June 18)
- Report of the IAEA Expert Mission to Japan (June 16)
- Report of US NRC Japan Task Force (13 July 2011)
- Interim report of HSE (18 May)

Current view of timeline

- Prime Minister Naoto Kan, July 9 2011 press conference:

  "It is expected to take three, five, or 10 years for controlling it, and even several decades until the accident settles finally."

Air sampling at KEK Tsukuba - high resolution Ge detector



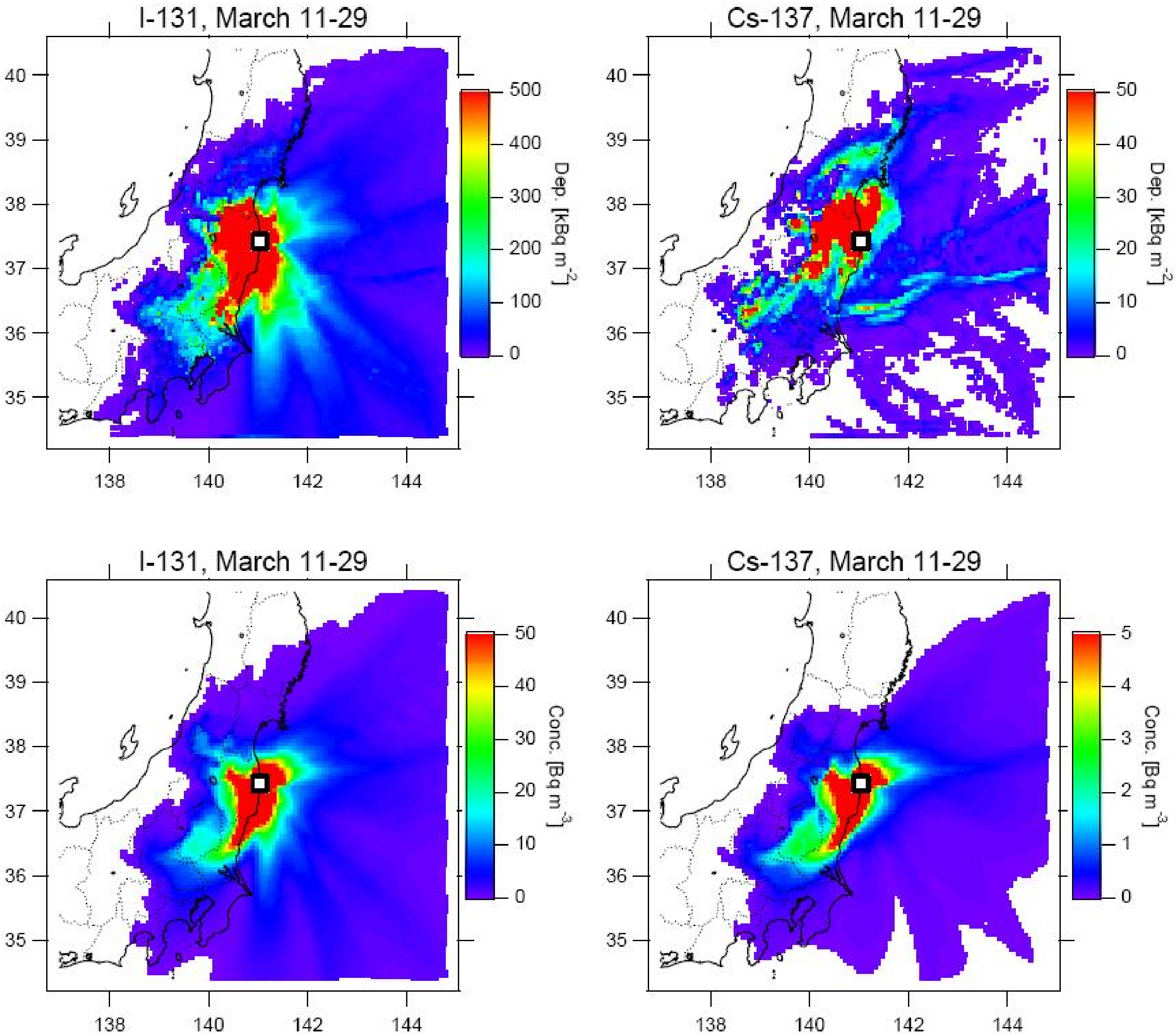
http://www.kek.jp/quake/radmonitor/GeMonitor10-e.html

Testimony of Professor Tatsuhiko Kodama (Tokyo U) to diet

- Videos of testimony with english subtitles
  - http://www.youtube.com/watch?v=Dlf4gOvzxYc
  - http://www.youtube.com/watch?v=mDlEOmcALwQ
- 27 July 2011
  - First, I request that the Japanese government, as a national policy, innovate the way to measure radiation of food, soil, and water, through using the Japan's state-of-the-art technology such as semiconductor imaging detectors. This is absolutely within Japan's current technological capability.
  - Second, I request that the government enact a new law as soon as possible in order to reduce children's radiation exposure. Right now, what I'm doing is all illegal. The current Radiation Damage Prevention Laws pecifies the amount of radiation and the types of radionuclides that each institution can handle.
  - Third, I request that the government as a national policy mobilize technological power of the private sector in order to decontaminate the soil.

"What on earth is the Diet doing, when 70,000 people are forced out of their homes and wandering?"

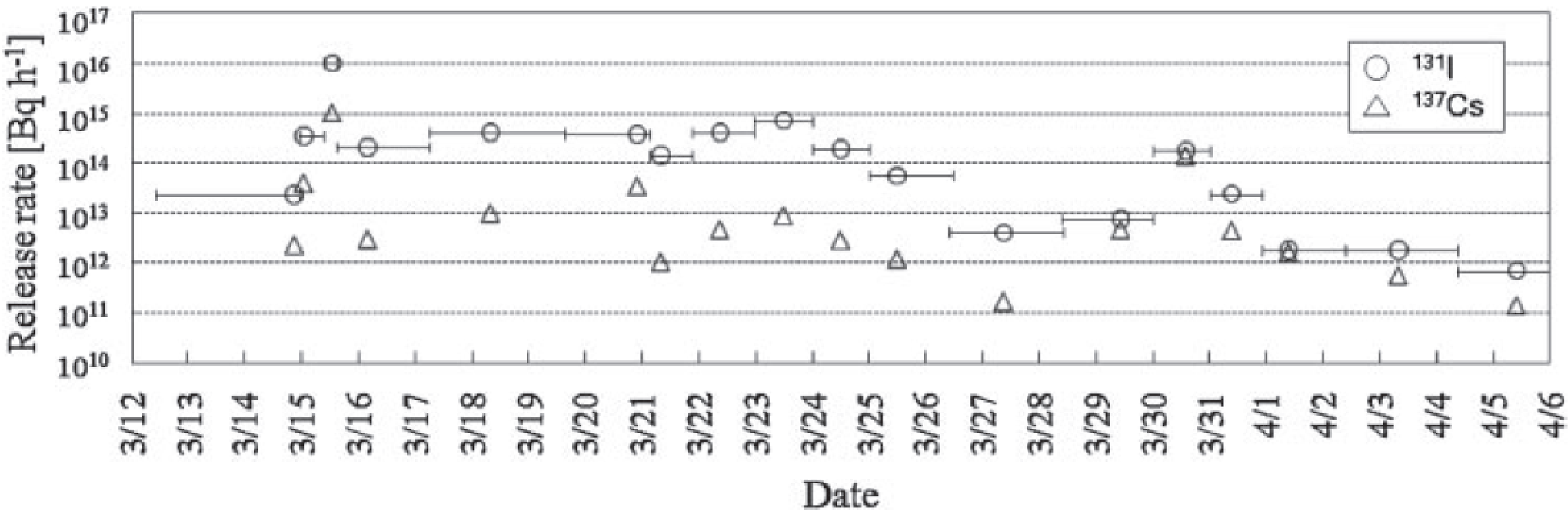
Analysis of Fallout



13% of iodine-131 and 22% of cesium-137 were deposited over land in Japan, and the rest was deposited over the ocean or transported out of the model domain

Morino, Ohara, Nishizawa, GRL, accepted 11 Aug 2011, in press.

Estimates of Release Rate (JAEA)



Based on SPEEDI and WSPEEDI2 atmospheric dispersion codes and data from MEXT sampling

Total release between 12 Mar and 6 Apr
I-131: 1.5×10^{17} Bq ; Cs-137: 1.2×10^{16} Bq

Chino et al J. Nuclear Science and Technology 48 (7), 1129-1134, 2011.

Erecting Cover on Unit 1

Tepco

Attaching walls

Tepco

Dust Collection System

Tepco

Treated Water Storage

August-Sept Updates

- 26 August 2011 Prime Minister Kan resigns
- Extent of contamination from fallout further quantified
  - JAEA release estimates
  - Fallout analysis by NIES
- Tepco Press releases
  - handouts
  - Photos and movies
- Desalination of Unit 4 SFP started
- Recirculation of spent fuel pools, T< 40°C
- Erecting cover around unit 1 commenced, steel framework installed, wall panels in progress.
- Rubble removal continues
- Dust removal from roads and paved surfaces
- Isolating intakes from ocean by installing steel pilings
- Cleanup and recirculation of water in turbine buildings to cool reactors
  - 2nd cesium tower operational for water treatment
  - More storage tanks installed
  - Evaporation concentration pools in operation
- Core spray used in units 2/3 for additional cooling
  - Reactor lower heads less than 100°C
- Restoration of port facilities and increasing breakwater height
- Sept 9 2011 Second report of METI to IAEA
- World Nuclear News Report (updated Dec 22, 2011)

Overview of the status of countermeasures at Fukushima Daiich Unit 1 - 4 (Sep. 22nd-28th Refer to the attached table for details of ①-⑤)

⑤Radioactive materials in the atmosphere / soil

【Goal】 Mitigation of dispersion of radioactive materials

【Status】The release rate of radioactive materials from the facilities is declining (the release rate at the end of July was estimated to be one fifth of the one of the end of June)

【The latest challenge & action】 Installing a cover over the highly damaged reactor building to prevent further release of radioactive materials. (Under construction at Unit 1, Being designed at Unit 3 and 4.

Planning to install a facility to maintain the PCV pressure at around atmospheric one so as to reduce the leak of radioactive materials from the vessel after RPV bottom temperatures going down below 100℃.

②Spent Fuel Pool cooling (Unit 1 - 4)

【Goal】 More stable cooling (achieved)

【Status】 Circulation cooling with heat exchanger in progress

【The latest challenge & action】 Desalination of the pool water in progress unit by unit

③Accumulated water

【Goal】 Reduction of total amount of contaminated water

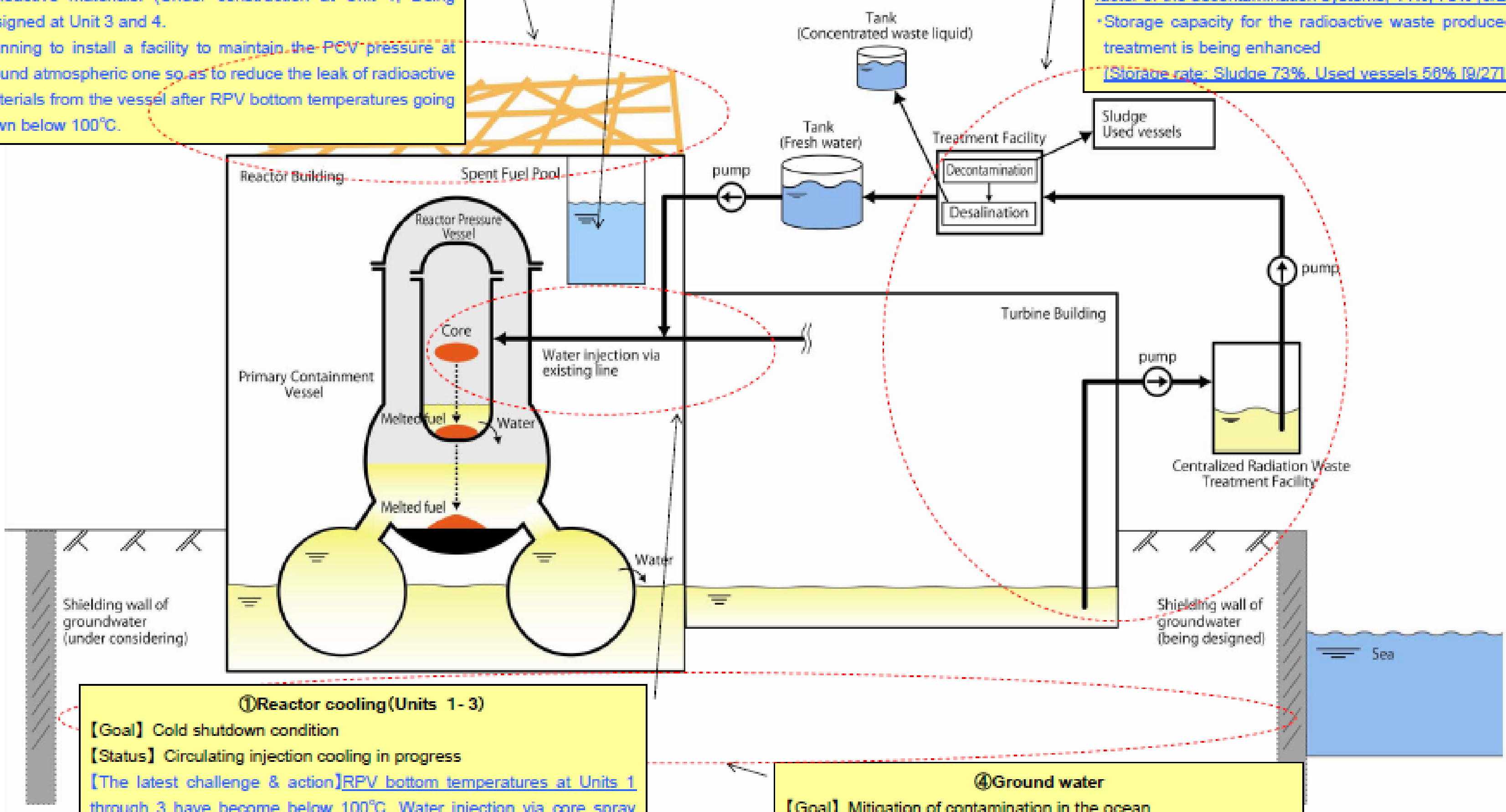
【Status】Treatment of high level radioactive wastewater (Approx. 82,000m3 [9/27]) in progress

【The latest challenge & action】

・Water treatment facility is being enhanced. The challenge is to operate the treatment facility stably and effectively. (Capacity factor of the decontamination systems; 44%, 70% [9/21-27])

・Storage capacity for the radioactive waste produced by water treatment is being enhanced

[Storage rate: Sludge 73%, Used vessels 58% [9/27])



①Reactor cooling (Units 1 - 3)

【Goal】 Cold shutdown condition

【Status】 Circulating injection cooling in progress

【The latest challenge & action】RPV bottom temperatures at Units 1 through 3 have become below 100℃. Water injection via core spray line, in addition to the feed water line currently used, started at Unit 3 [9/1-] and Unit 2 [9/14-].

④Ground water

【Goal】 Mitigation of contamination in the ocean

【Status】 Monitoring the radioactive materials in the groundwater

【The latest challenge & action】 Shielding wall of groundwater is being designed

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Status 29 Sept

			Unit 1	Unit 2	Unit 3	Unit 4	Notes
Basic information		Type of plant	BWR-3	BWR-4	BWR-4	BWR-4	
		Electric / Thermal power output	460/1380	784/2381	784/2381	784/2381	
Plant status when hit by the earthquake		Operation status	In service -> Shutdown	In service -> Shutdown	In service -> Shutdown	Outage	
		No. of nuclear fuels loaded in the reactor	400	548	548	0	
		No. of spent fuels stored in the SFP	292	587	514	1331	
		External power supply	Stopped due to the earthquake				
		Emergency power supply	Emergency Diesel Generator once had started in response to loss of external power stopped when the tsunami hit these plants.				
Current status of the plant and the progress of countermeasures taken: ①Reactor cooling	Status	Core and fuel integrity	Damaged (core melt*1)	Damaged (core melt*1)	Damaged (core melt*1)	No fuels loaded	
	Status	RPV structural integrity	Partially damaged and leaking	Unknown	Unknown	No damage	
	Status	PCV structural integrity	Damage and leakage suspected	Damage and leakage suspected	Damage and leakage suspected	No damage	
	Status	Core cooling	Cooling with the alternative system created after the tsunami			Not required	
	Goal of STEP 2 (Jul. through Jan., 2012)		To achieve Cold shutdown condition: 1) Temperature of RPV bottom is, in general, below 100℃, 2) Release of radioactive materials from PCV is under control and public radiation exposure by additional release is being significantly held down			—	"Cold shutdown status" is redefined in the status progress report issued on July 19.
	measu	Circulating injection cooling	System in operation [partial operation: 6/27–, full operation: 7/2–]			—	
	measu	Nitrogen gas injection into PCV	Injection continued [4/6–]	Injection continued [6/28–]	Injection started [7/14–]	—	
	Challenge	Continuation and enforcement of the circulating injection cooling	**RPV bottom temperatures at Units 1 through 3 have become below 100℃.** Water injection via core spray line, in addition to the feed water line, started at Unit 3 [9/1–] and Unit 2 [9/14–]. The effect of the diversified water injection on the RPV temperature is being comfirmed while adjusting its flow rate.			—	
②SFP cooling	Status	Fuel integrity in SFP	Unknown	Most spent fuels not damaged*2	Unknown	Most spent fuels not damaged*2	
	Status	SFP cooling	Function recovered	Function recovered	Function recovered	Function recovered	
	Goal of STEP 2 (Jul. through Jan., 2012)		More stable cooling: Establishment of circulation cooling with Hx (already achieved at Unit 2 and 3)				
	measures	Circulation cooling with Hx	Hx newly installed in operation [8/10–]	Hx newly installed in operation [5/31–]	Hx newly installed in operation [6/30–]	Hx newly installed in operation [7/31–]	
	measures	desalting of water in the pool	— (No seawater injected)	Operation of the desalting facility will start after the operation of unit 4.		operation of the desalting facility started[8/20–]	
③Accumulated water	Status	Increase and accumulation of radioactively contaminated water	High level radioactive wastewater is accumulating in the R/B, T/B and RW/B of each unit. (Approx. 81,930m3 [9/27])				
	Goal of STEP 2 (Jul. through Jan., 2012)		Reduction of total amount of contaminated water				
	measures	Installation of water process facility	-Highly radioactive wastewater treatment system installed on June 17 is now working on a full-scale basis. (Capacity 1200m3/day) -Water processed with this system has been reused for core injection for cooling since June 27.				
	measures	Elimination, continuous processing and system enhancement of accumulated water in the building	-Highly radioactive wastewater in Unit 2 and unit 3 has been transferred to the Centralized Radiation Waste Treatment Facility since April 19. -The cesium adsorption unit No. 2 started operation on August 18. Currently these No.1 and No.2 unit is working in parallel operation mode. -Works for installing additional desalination unit that consists of 8 components is in progress. 5 of them started operation [8/7–, 8/31–]				
	measures	Storage / management of sludge waste etc.	-Sludge waste generated from the high-level radioactive water processing facility has been properly managed. -Facility for storing sludge waste is to be built.				
	measures	Securing storage place	-Storage capacity of 14800m3 (10,000m3 + 4,800m3)for highly radioactive wastewater are secured by using the Centralized Radiation Waste Treatment Facility as water storage place. -Work for installing underground tank for high level radioactive wastewater in progress (2,800m3 installed [9/7]) -Storage tanks to receive processed, low to middle level radioactive wastewater with the capacity of approx. 76,000m3 installed (–9/16). Additional capacity to be installed at about 20,000m3/month				
	measures	Preventing contamination of the sea, etc.	-Silt fences installed. -Seawater circulatory purification system goes into full-scale operation. [6/13] -Blocking the concrete tunnels outside the T/Bs completed [6/10], etc.				
	Challenge	Preventing overflow of high level radioactive waste water	Highly radioactive wastewater treatment system should be operated in stable and effective manner to prevent wastewater overflowing to the environment. **The accumulated water level reached the target level (OP. +3,000). Namely, the level of accumulated water has dropped as low as the leakage or overflow of the water will not happen in the case of heavy rains and long-term processing facility outage [9/11]. TEPCO plans to maintain the current level in the meanwhile.**				
	Goal of STEP 2 (Jul. through Jan., 2012)		Reduction of total amount of contaminated water				
	meas.	Increasing storage capacity Decontaminating radioactive water	-18,400 tons(2,200 + 6,200 + 10,000) of tanks installed. 10,000 tons of Mega-Float prepared. 2,000 tons of receiving capacity to be secured. -Decontamination with zeolite continued				
④Ground water	Status	Radioactive materials in the ground water	Radioactive iodine, I-131, cesium, Cs-134, 137, and Sr-89, 90 were detected from the subdrain, underground water collected and controlled in the facility, and the well water in the Fukushima Daiichi site. [4/7–]				
	Goal of STEP 2 (Jul. through Jan., 2012)		Mitigation of contamination in the ocean (continuing from Step 1)				
	measure	Mitigation of groundwater contamination	Pumps for correcting underground water called "subdrain" have been restored. Subdrain is being treated in accordance with the contaminated water management plan. Shielding wall of groundwater is being designed.				

[Significance judged by JAIF]
🟩 :Low
🟨 :High
🟥 :Severe (Need immediate action)

[Progress of countermeasures]
▨ :Completed
▨ :Under construction
□ :To be done (including studying and manufacturing)

JAIF

Status 29 Sept

			Unit 1	Unit 2	Unit 3	Unit 4	Notes
⑤Radioactive materials in the atmosphere / soil	Status	Scattering of radioactive materials to the outside of the facilities	-Radioactive materials and radioactively contaminated debris scattered due to the hydrogen explosion occurred at Unit 1 and 3 R/Bs and other events. -The release rate of radioactive materials from Unit 1 through 3 as of the early September was estimated to be about 200 million Bq/h (Cs-134 and 137) at maximum. [TEPCO announced on 9/20] -Exposure doses at the site boundary caused by radioactive substance currently being released was estimated to be 0.4 mSv/y at maximum on the assumption of the above release rate. (※Approx. one 4-millionth of the maximum emission rate on 3/15, approx. one 12,500th of the rate for 3/25-26, approx. one 1450th of the rate for 4/4-6, approx. one 5th of the rate for June.)				Survey map on the site: http://www.tepco.co.jp/en/nu/fukushima-np/f1/index3-e.html
		R/B integrity	Severely damaged	Partly opened	Severely damaged	Severely damaged	
	Goal of STEP 2 (Jul. through Jan., 2012)		Mitigation of dispersion				
	measures	Dispersion of inhibitor	Splaying dispersion inhibitor outside and inside the R/Bs and T/Bs completed				
		Removal of debris	Removal of debris using remote-controlled heavy machine in progress [4/10-]				
		Installing R/B cover	Preparation work in progress [5/13-] Installation work of the cover started [6/28-]	—	Designing Preparation work in progress [6/20-]	Designing Preparation work in progress [6/24-]	Covers for Unit 3 and 4 to be installed after Step 2
		Installation of PCV gas control system	Preparation work in progress	Detailed design in progress	Detailed design in progress	—	To be installed after RPV bottom temperatures going down below 100℃
Tsunami, reinforcement, etc.	Goal of STEP 2 (Jul. through Jan., 2012)		Mitigation of further disasters				
	measures	Countermeasures against tsunami	-Relocating emergency power sources to the upland [4/15] -multiplexing injection lines [-4/15] -Deploying fire trucks etc. at the upland [-4/18] -Building temporary tide barriers [-6/30]				
		Planning and implementation of reinforcement work of each unit	Enough seismic capacity confirmed by structural assessment [5/28]	Enough seismic capacity confirmed by structural assessment [8/26]	Enough seismic capacity confirmed by structural assessment [7/13]	-Enough seismic capacity confirmed by structural assessment [5/28] -Installation of supporting structure under the bottom of the pool completed [7/30]	
Plant parameters	Reactor	Reactor injection flow rate(m3/h) [9/29 11:00]	3.8	3.9 via feed wate line 6.0 via core spray line	2.6 via feed wate line 8.0 via core spray line	—	■"A", "B" shows the group of the redundant instruments ■Reactor water level monitors to be calibrated. Unit 1 Ch.A done.[5/11] Unit 2 Ch.A conducted.[6/22-24] ■Primary parameters' trend is available at JANTI's HP; http://www.gengikyo.jp/english/shokai/special_4.html **Continuously monitoring the status
		Reactor water level (mm) [9/29 11:00]	A: Below the lower end of gauge, B: -1750**, Mostly steady	A: -1850, B: -2200 Mostly steady**	A: -2400, B: -2300 **	—	
		Reactor pressure (MPa) [9/29 11:00]	A: 0.013, B: -, Mostly steady Measured with temporary pressure indicator [8/4-]	A: 0.006, B: - Mostly steady	A: -0.174, B: -0.115 Mostly steady**	—	
		RPV temperature at feedwater nozzle (℃) [9/29 11:00]	75.5 Slightly going down	90.7 Going down	75.3 Going down	—	
		RPV temperature at the bottom of the vessel (℃) [9/29 11:00]	77.5 Slightly going down	99.7 Going down	78.7 Going down	—	
	PCV	Pressure of drywell (MPa) [9/29 11:00]	0.1235 Mostly steady	0.109 Mostly steady	0.1015 Mostly steady	—	
		Pressure of suppression pool (MPa) [9/29 11:00]	0.100 Mostly steady	Below the lower end of gauge Instrument failure	0.1885 Mostly steady	—	
	Pool	Water temperature of SFP [9/29 11:00]	24.5℃	28.0℃	26.7℃	36℃	
	High level accumulated water	Storage volume[9/27]	17,030m3	20,300m3	25,900m3	18,700m3	
		Water level in T/B[9/27]	OP.+5,026mm	OP.+2,840mm	OP.+3,055mm	OP.+3,098mm	OP.: Onahama Bay mean sea level Near-term target: OP. +3,000mm*3
		Total stored volume[9/27]	Approx. 81,930m3 (Approx. 101,510m3 including the wastewater transferred to the Centralized Radiation Waste Treatment Facility)				
		Total volume of processed water [-9/27]	Approx. 105,190 m3 decontaminated (Approx. 42,476m3 desalinated*)				*Just for reference as the reading of level monitor of the desalinated water tank was not stable.
		Waste produced [-9/27]	Sludge: 581m3 (Storage capacity 800m3), Used vessels: 220 (Storage capacity 393), Concentrated waste liquid: 2,473m3* (Storage capacity 10,000m3)				
Environmental effect in the vicinity of the station			-Air dose rate: 5-101 μSv/h at the NPS border (Monitoring Post), 304 μSv/h at the south side of the office building, 30 μSv/h at the main gate, 12 μSv/h at the wet gate [9/29 09:00] -Some radioactive materials (I, Cs, Pu, Am Cm and Sr) has been detected in the soil sampled at the site. Radioactive materials have been detected in samples collected from underground water and seawater at or near the site.				
Radiation exposure of the workers			TEPCO has been examining radiation exposure of some 10,700 workers who worked at the plants. Intermediate result of this examination as of 8/10 is as follows. 103 workers received more than 100mSv. (100-150mSv: 81 workers, 150-200mSv: 14 workers, 200-250mSv: 2 workers, 250mSv-: 6 workers) Definite exposure doses of 6 workers who received more than 250mSv are distributed from 309 to 678mSv. *The allowable emergency limit for radiation doses: 250mSv				

[Significance judged by JAIF]
- (green) :Low
- (yellow) :High
- (red) :Severe (Need immediate action)

[Progress of countermeasures]
- (cyan) :Completed
- (light cyan) :Under construction
- (white) :To be done (including studying and manufacturing)

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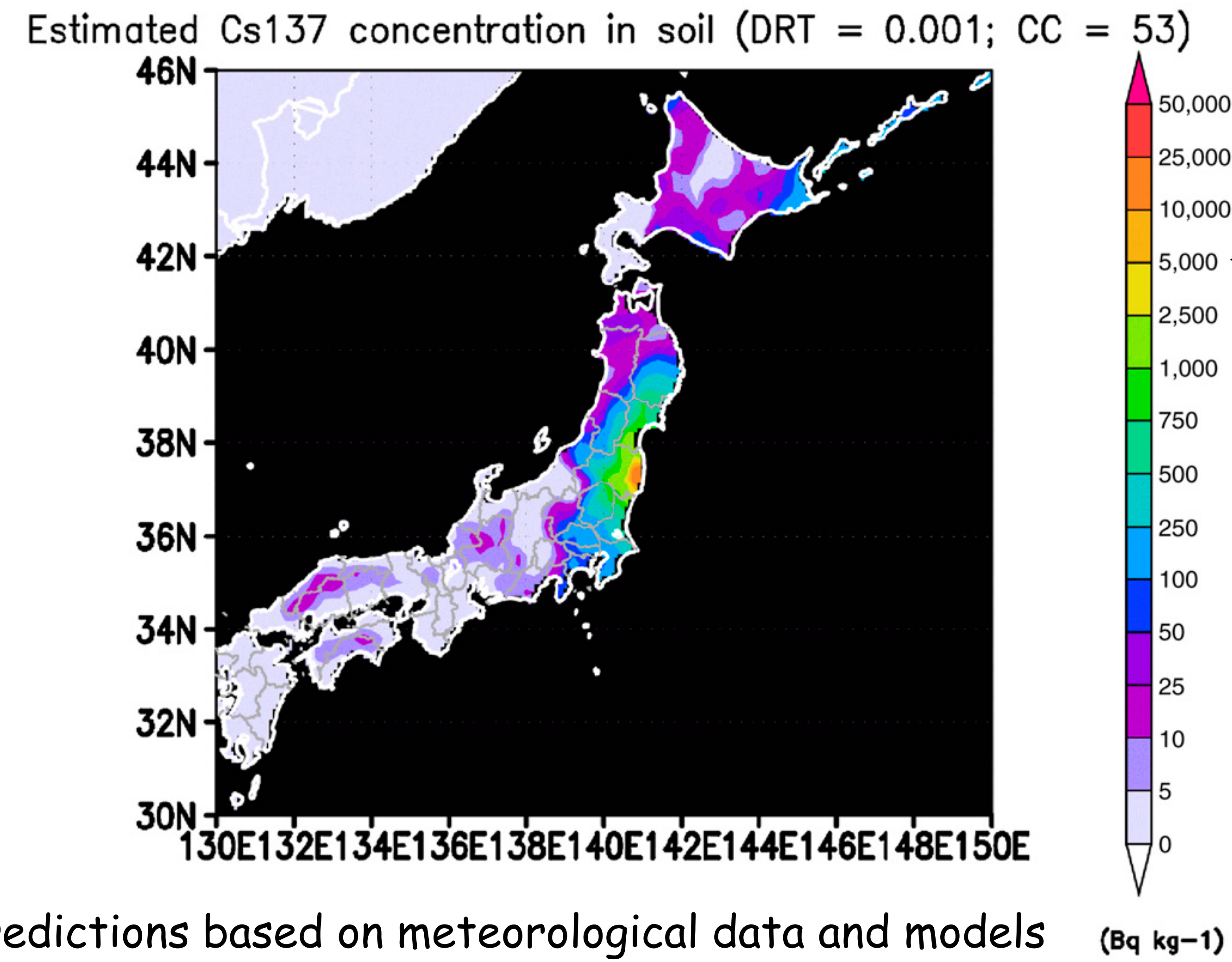
Soil Contamination Estimate



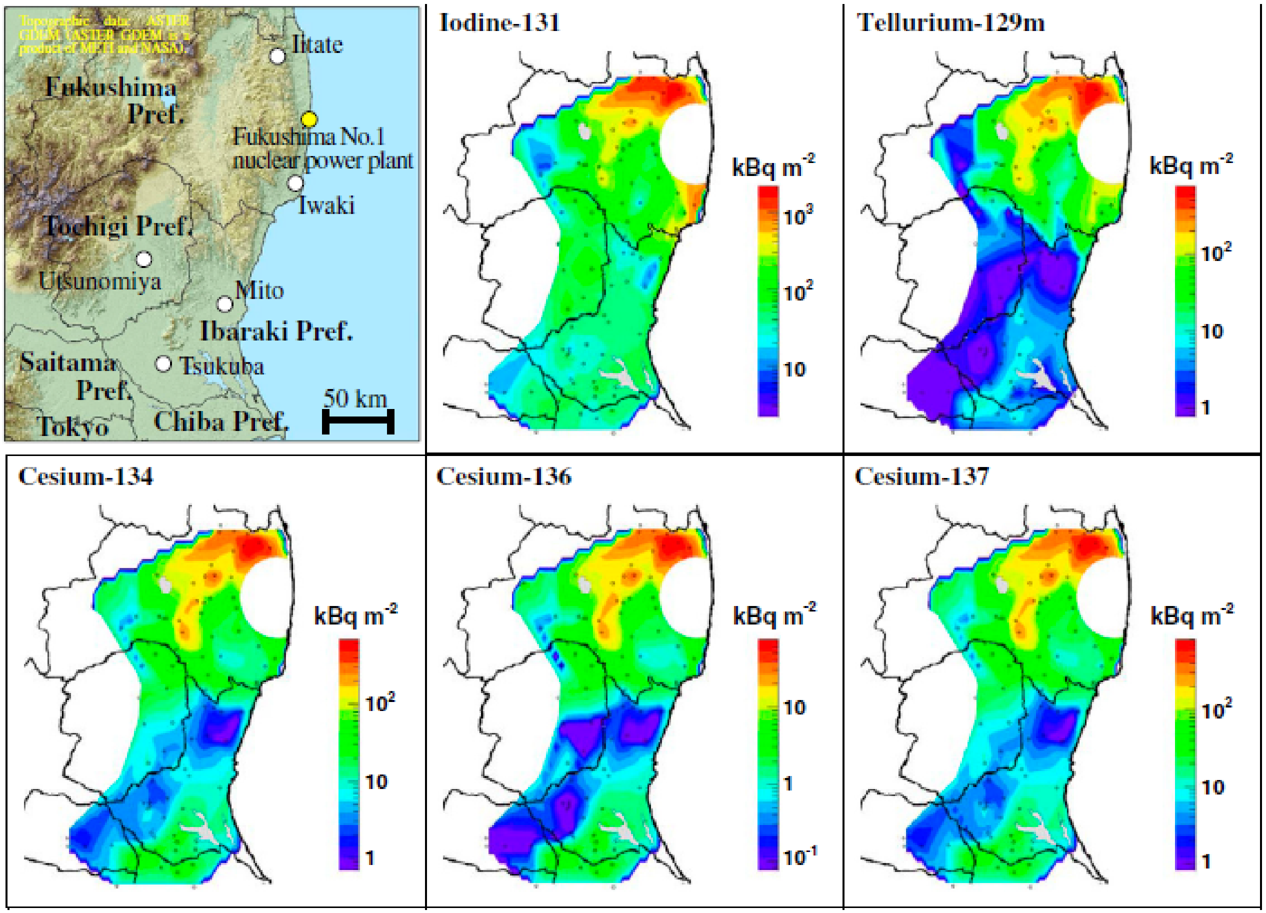
Legal limit on total Cesium (137 and 134) for agriculture is 5000 Bq/kg

Release was roughly 50% 134 and 50% 137

Predictions based on meteorological data and models

PNAS Nov 14, 2010 Yasunari Et Al

Deposition Close to Plant



Majority of deposition due to to rainfall events:

March 15 - Fukushima Prefecture

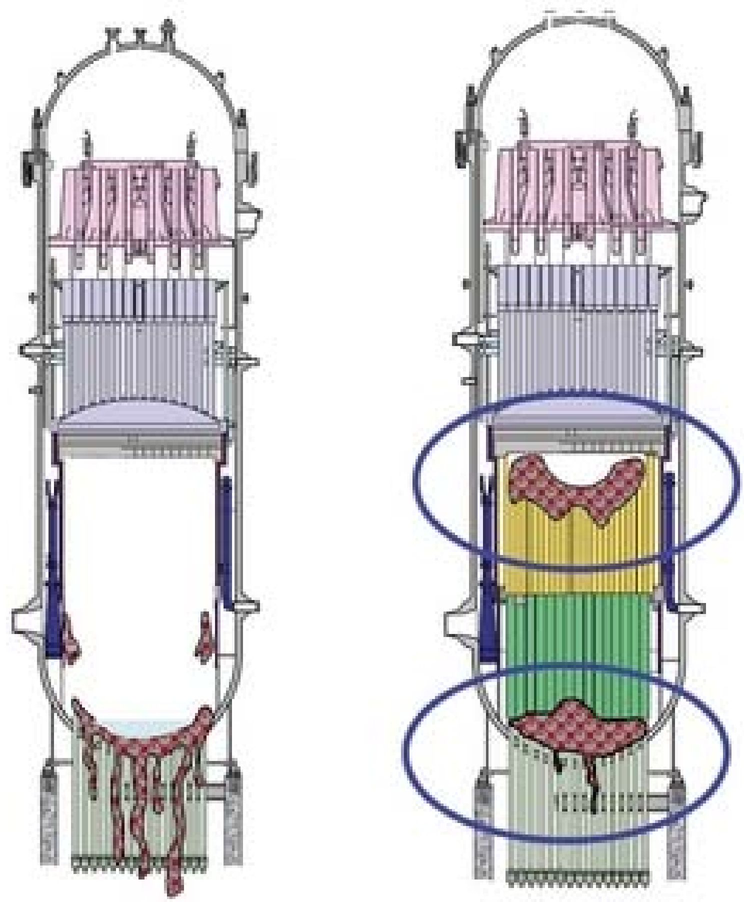
March 21 – Ibaraki, Tochigi, Saitama, Chiba prefecturs, and inTokyo.

Measurements of soil samples

[PNAS Nov 14, 2011 Kinoshita et al]

Status of Molten Fuel

Based on computer simulations of accident progress.



Best case

Worst case

Unit 1

Units 2 & 3

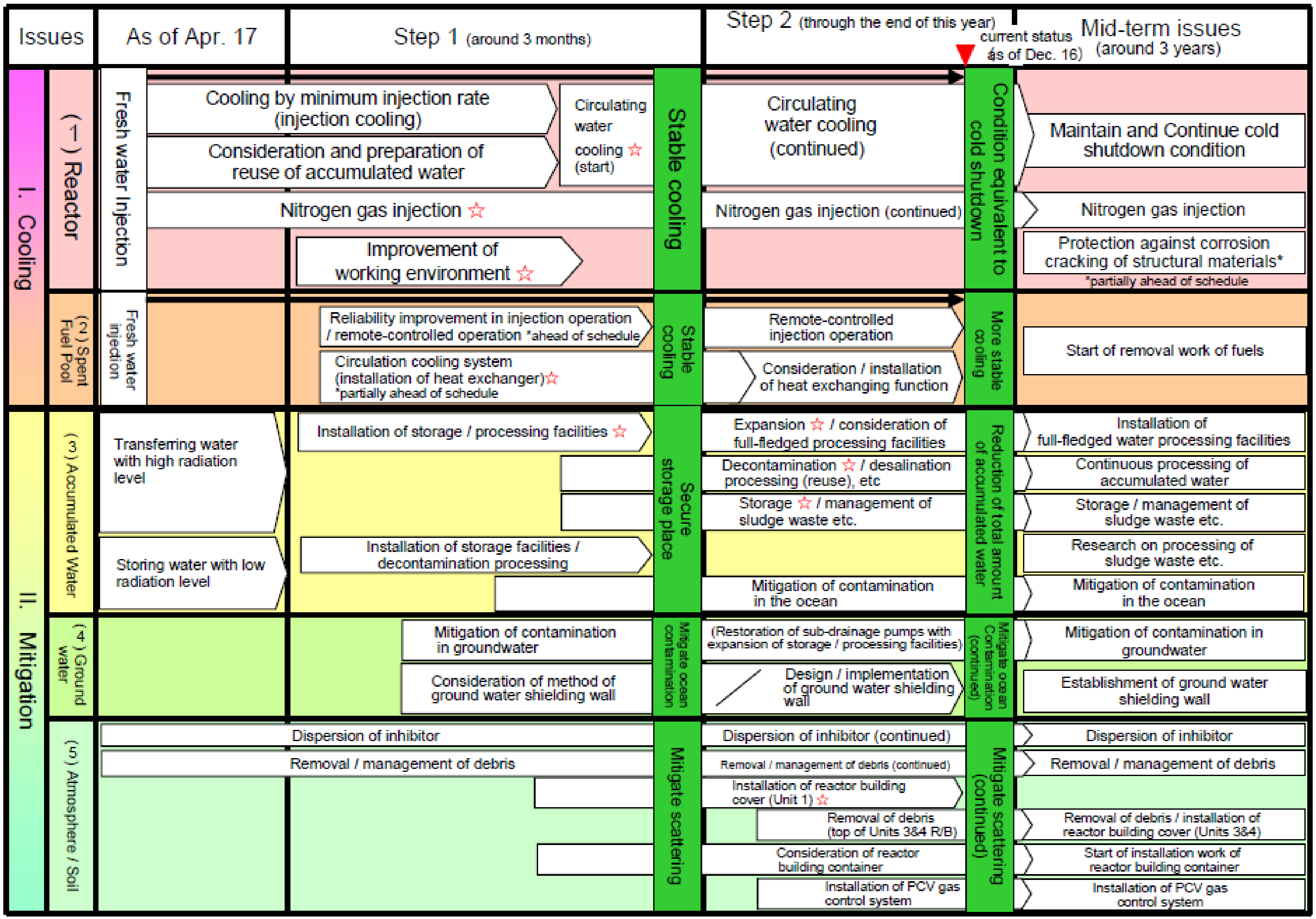
[Tepco analysis reported by Nuclear Engineering Institute 06 December 2011](#)

Current Status of "Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station, TEPCO" (Step2 completion)

Appendix 1-3

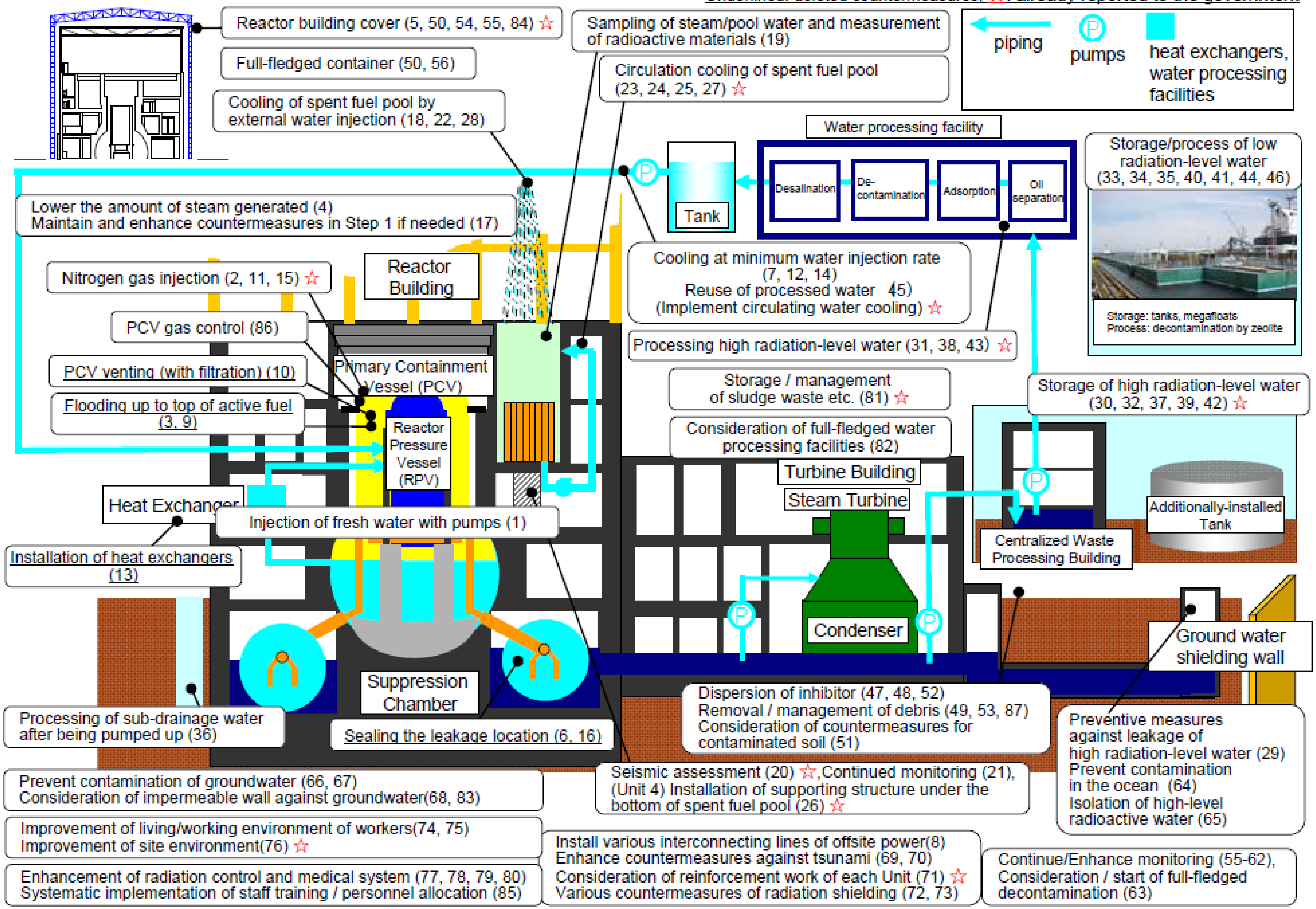
December 16, 2011
Nuclear Emergency Response Headquarters
Government-TEPCO Integrated Response Office

☆: already reported to the government, Green colored shading: achieved target



Overview of Major Countermeasures in the Power Station, Final Edition

Underlined: deleted countermeasures. ☆: already reported to the government



Long Term Decommissioning Roadmap

Present	(Completion of Step 2)	*Within 2 Years*	*Within 10 Years*	*After 30-40 Years*
	Step 1, 2	**Phase 1**	**Phase 2**	**Phase 3**
		Period to the start of fuel removal from the spent fuel pool (Within 2 years)	**Period to the start of fuel debris removal (Within 10 years)**	**Period to the end of decommissioning (After 30-40 years)**
	<Achieved Stable Conditions> -Condition equivalent to cold shutdown -Significant Suppression of Emissions	-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

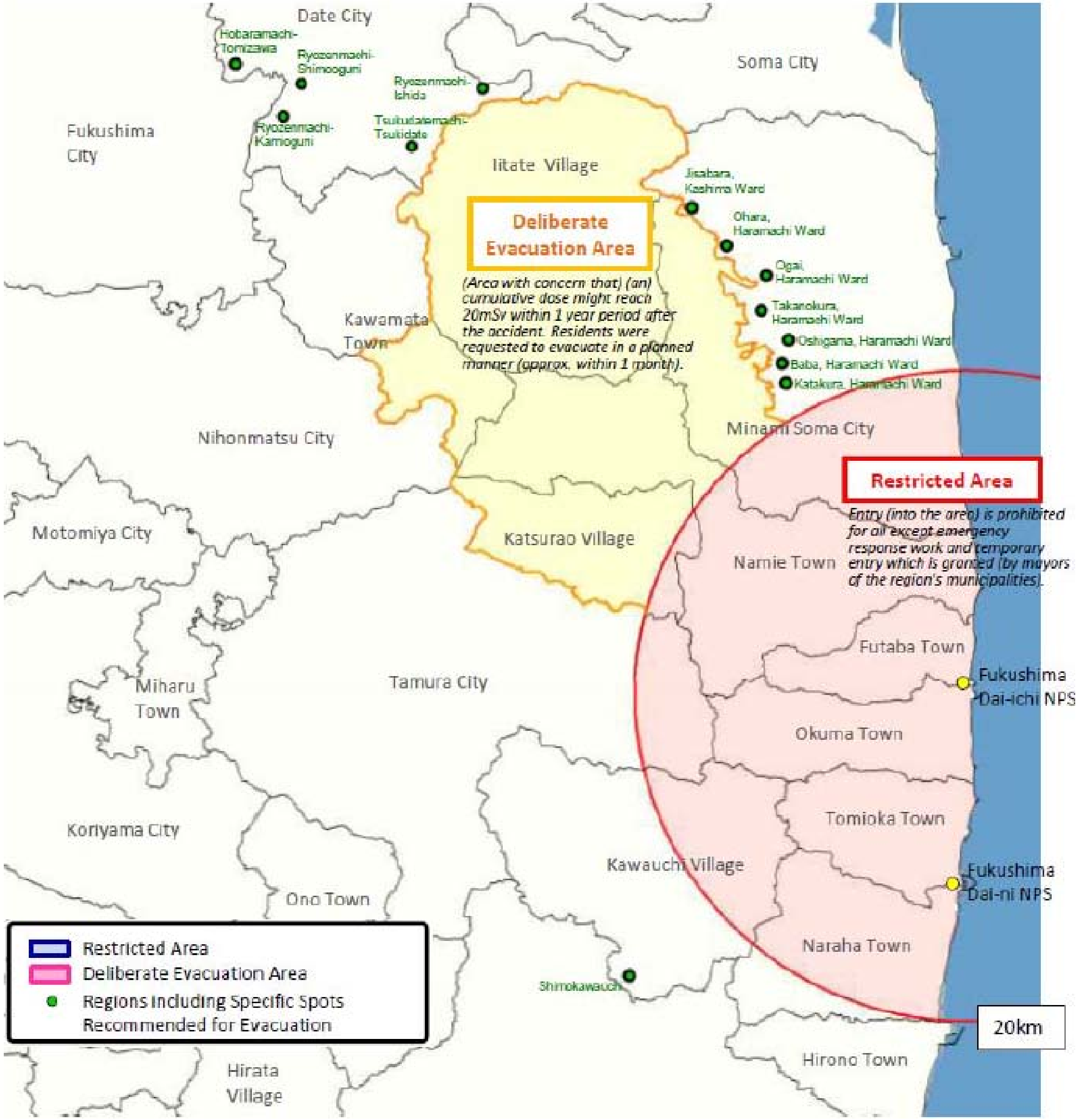
Actions towards systematic staff training and allocation, improving motivation, and securing worker safety will be continuously implemented.

[Tepco]

F1 Status - December 2011

- Dec 16, 2012 - Cold shutdown declared by [Tepco] for units 1, 2, & 3
  - Based on measurements at bottom of RPV
  - State of fuel presumed to be molten, substantial amounts external to RPV
- Dec 21, 2012 – Long term plans announced by [Tepco]
  - Spent fuel removal started within 2 yrs
  - Molten fuel removal started within 10 yrs
  - Decommissioning completed within 30-40 yrs

Evacuation and Remediation Status



- Ministry of Environment Released plan on Jan 26. 2012
- Evacuation

< 20 mSv/yr – allow return

20-50 mSv/yr – restriction – no overnighting

>50 mSv/yr – difficult to return

Remediation schedule:

Dec 2012 – Areas with 10 to 20 mSv/yr and schools with more than 5 mSv/yr

March 2013 - areas with 5 to10 mSv/yr

March 2014 - areas with 1to 5 mSv/yr and 20 to 50 mSv/yr

See [IRSN map]for contours of estimated dose

[IAEA]

Status - April 22, 2012

- Activities planned for 2012
  - Cover Unit 3 and 4 buildings
  - Preparation to remove fuel from Unit 4 SFP
  - Improving containment of air and water releases
  - Debris removal & storage, water cleanup continues
- Reactor building and plant site contamination are still significant issues
  - Prevents work teams from entering, only robotic surveillance possible in many areas
- 53 of 54 Japan reactors shutdown, loss of 30% of national electric generating capacity
  - Restart requires “stress tests”, regulatory approval, local and national civic approval
- Evacuation restrictions lifted in some limited areas
  - ~160,000 people reportedly still displaced due to fallout
- Remediation of soil and buildings contaminated by fallout in progress
  - Exposure limit target set at 20 mSv/yr except for schools, 1 mSv/yr.

A perspective from Japan

You can't adequately prepare for a disaster that you don't admit can ever happen

- attributed to Koichi Kitazawa   NPR

Koichi Kitazawa is Chairman of Rebuild Japan Initiative Foundation, they sponsored an investigative commission that included journalists, lawyers and scholars. RJIF will release an independent report on the accident in the summer of 2012.