The Crisis at Fukushima Dai-ichi Nuclear Power Plant

Prof. Joseph E Shepherd
Aerospace and Mechanical Engineering
California Institute of Technology
Pasadena, CA

Caltech

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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 accident 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.

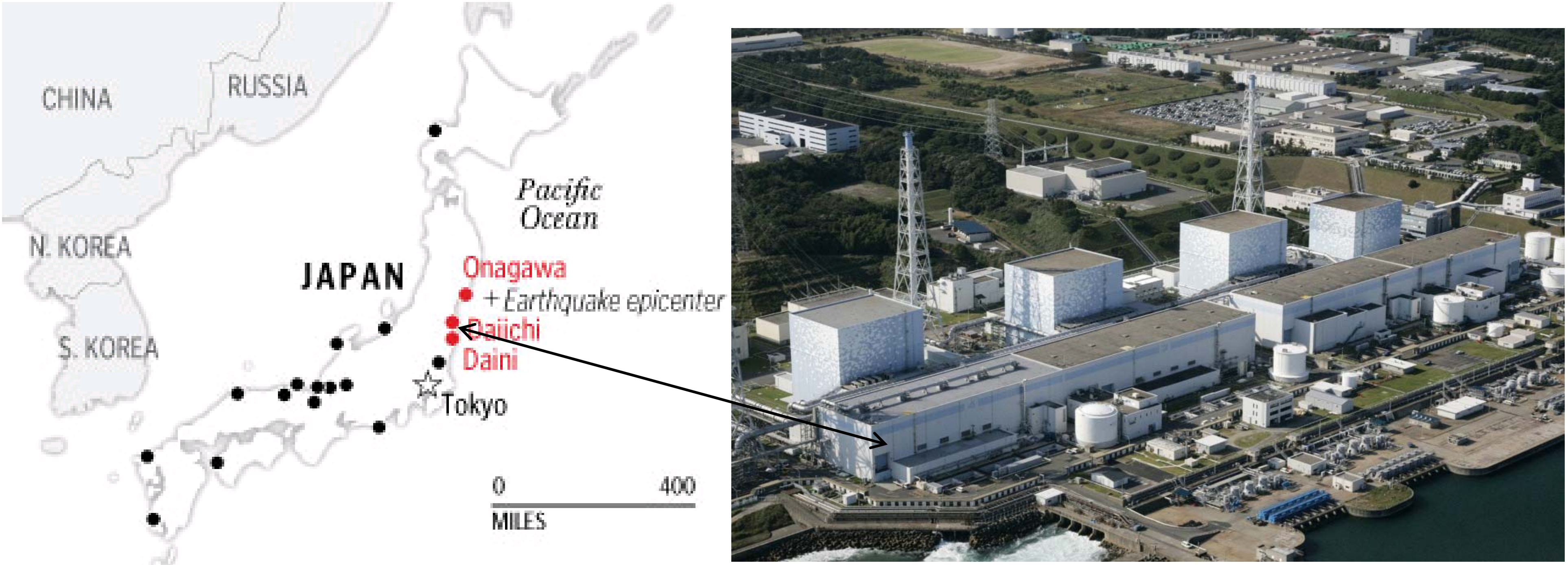
The purpose of this presentation was to provide background on these particular reactors, gather in one place the reported information on the sequence of events, and provide an interpretation based on my understanding of severe accidents in NPPs. My goal was to help others understand what is being reported 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

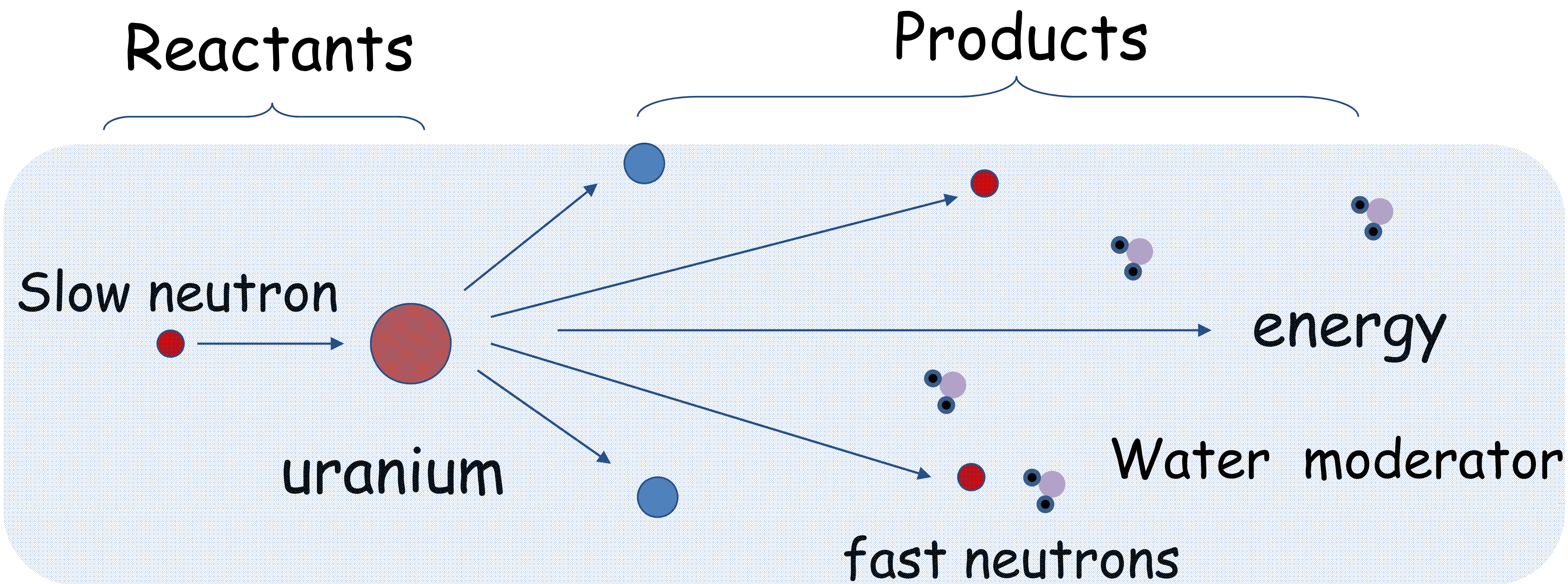
http://www.galcit.caltech.edu/~jeshep/fukushima/

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.

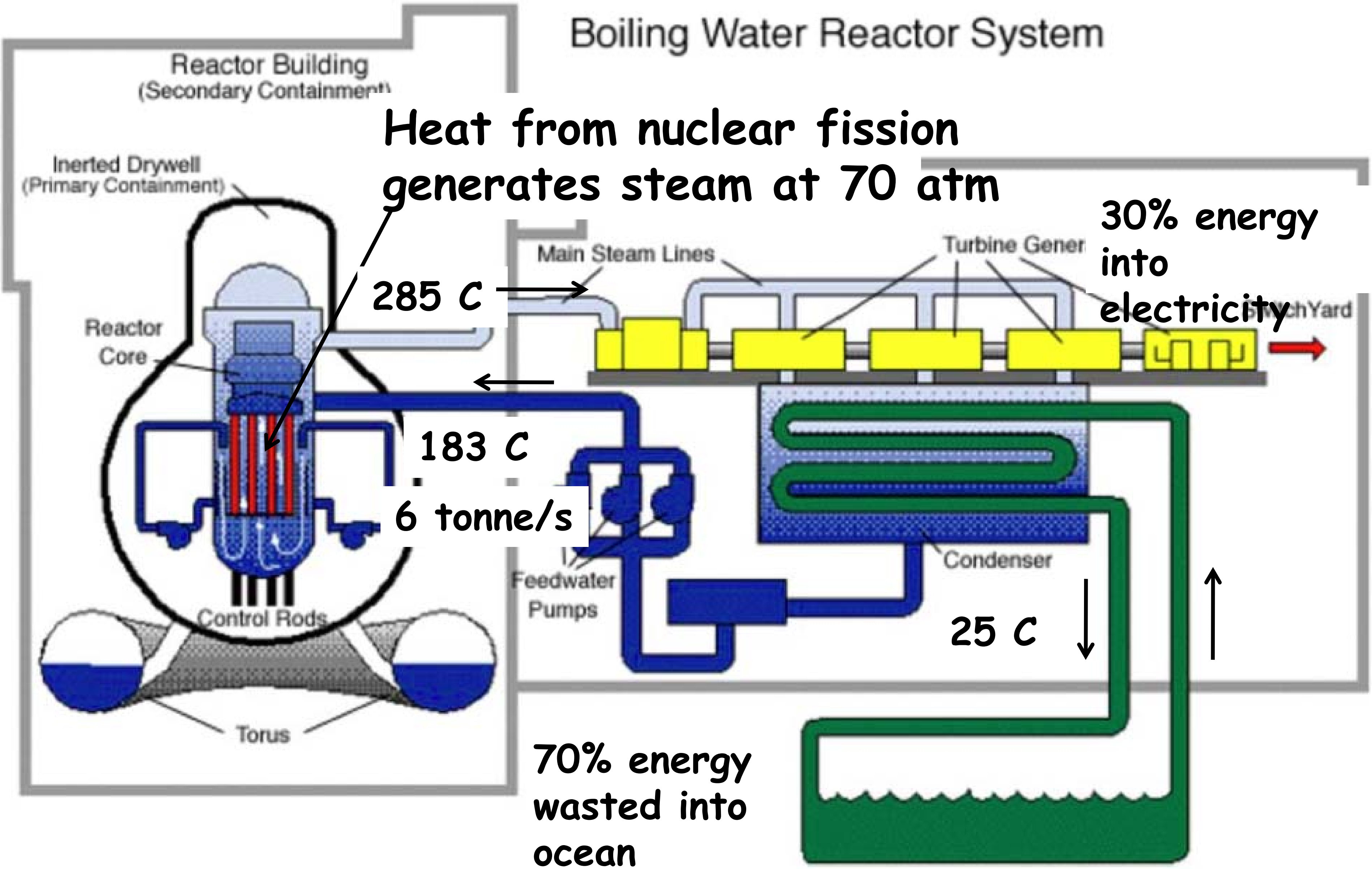
Nuclear Fission in Power Reactors



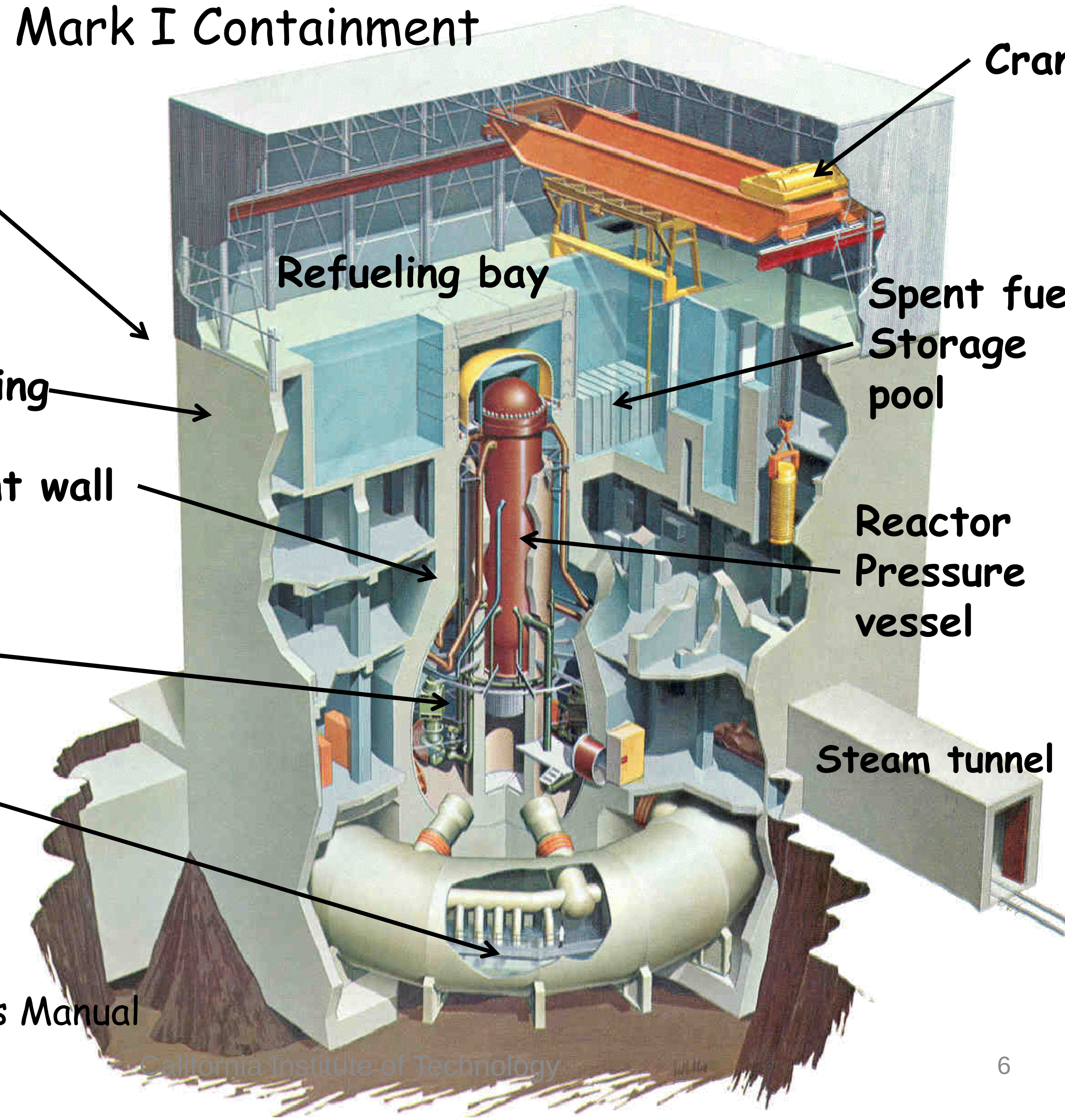
$n + {}^{235}U \longrightarrow 2.5n + \text{products} + 200\ \text{MeV}$

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.

Schematic of a Single BWR Unit

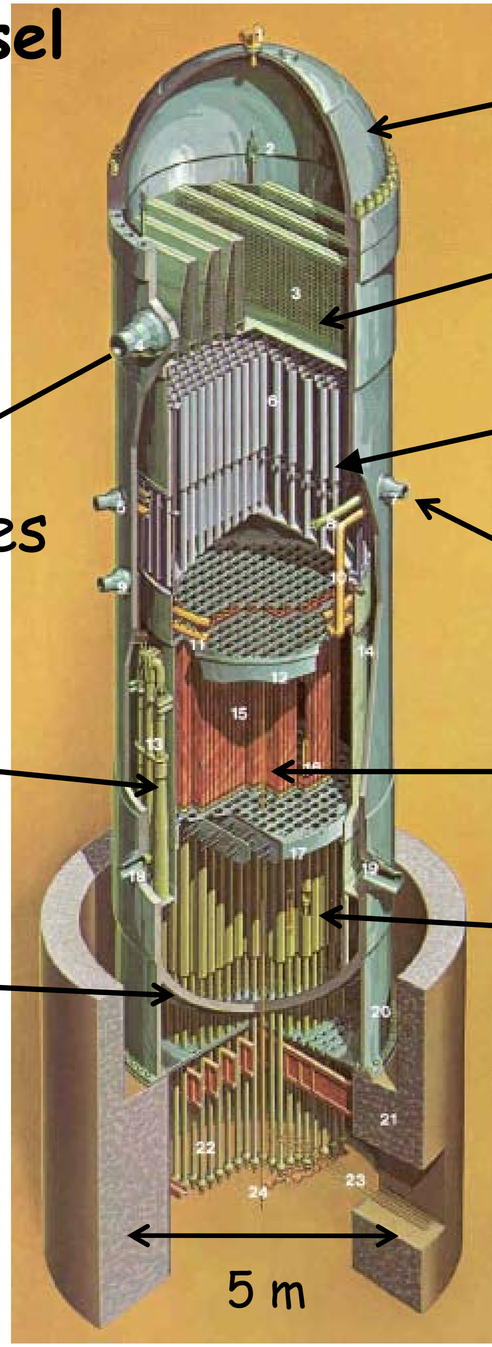


Mark I Containment



NRC Reactor Concepts Manual

Reactor Pressure Vessel and fuel "core"



500 tonne steel
6-in thick

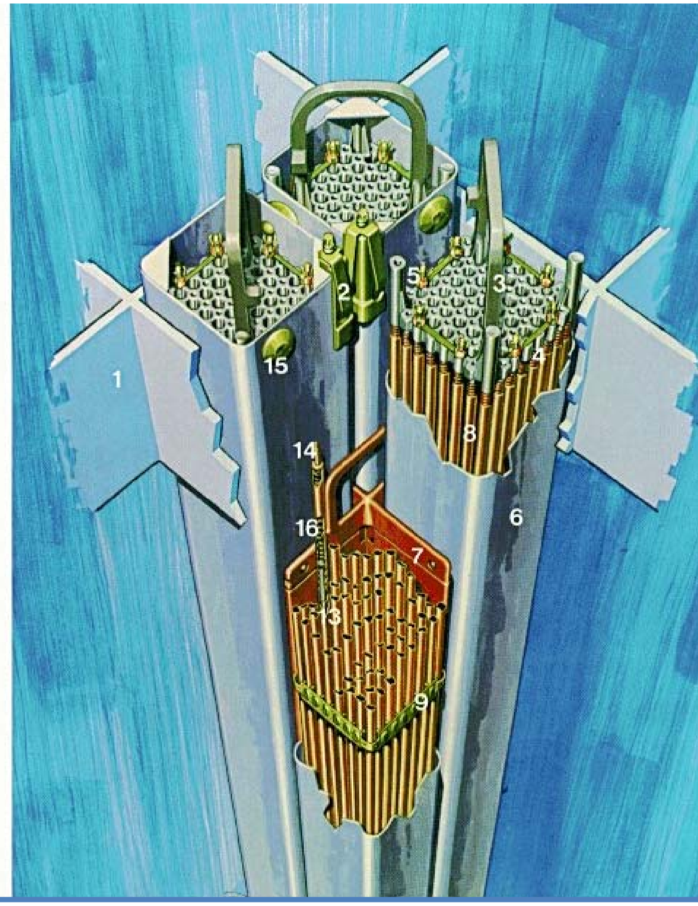
NRC Reactor Concepts Manual

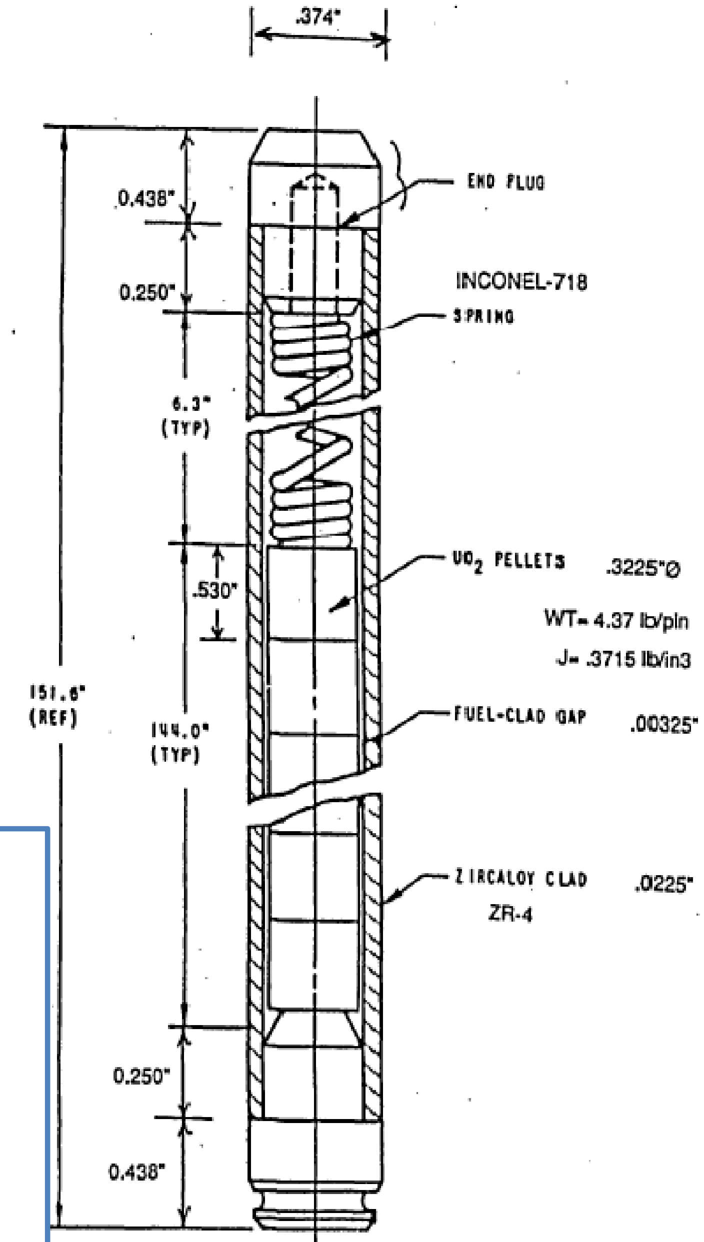
Typical set of 4 fuel assemblies.

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.





- 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)

Primary Containment

Dry well

Wet well

Inverted light bulb, contains reactor pressure vessel,
Body: 33 m high
11 m diameter
Sphere: 20 m diam.

Vent pipes

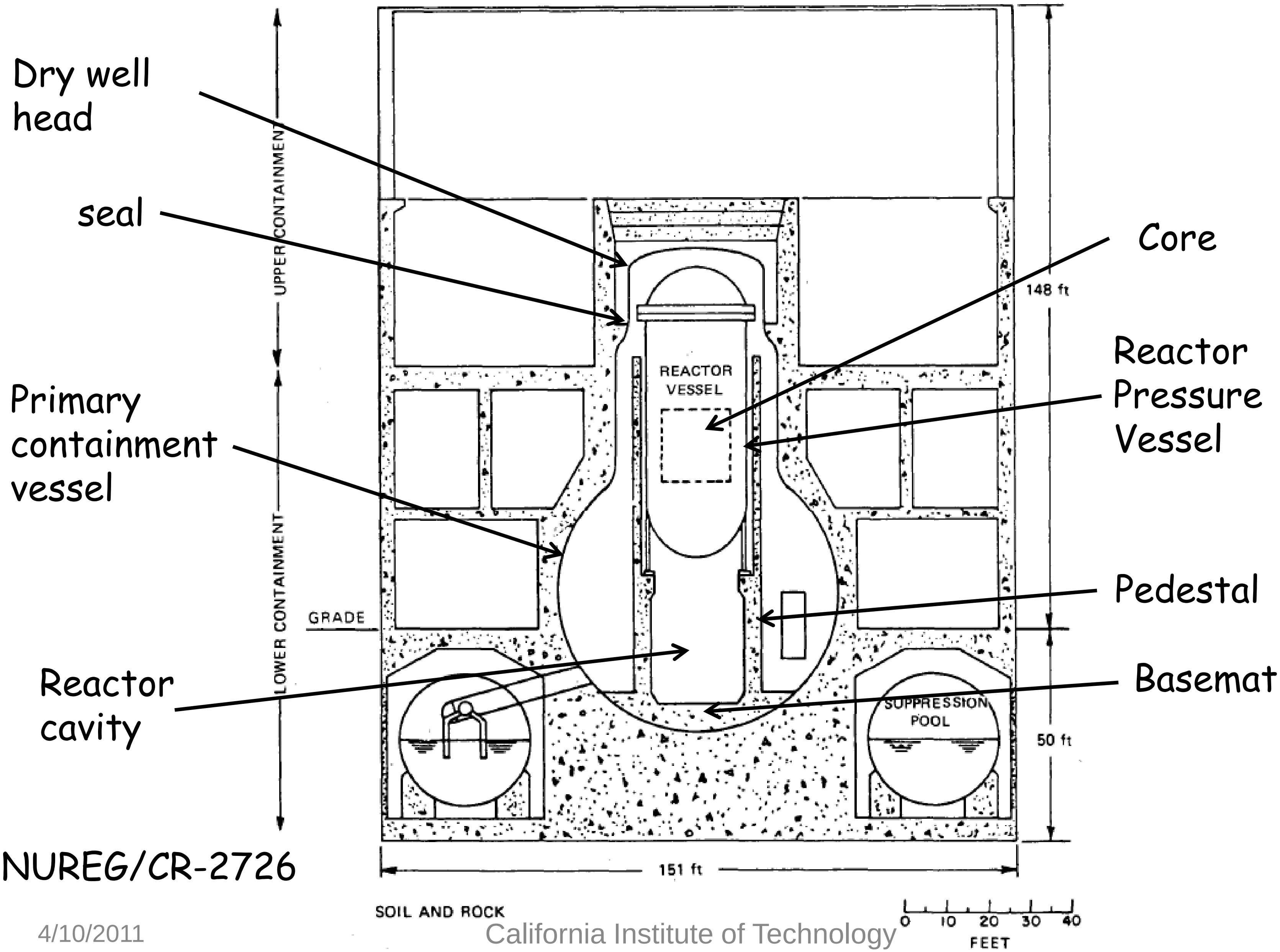
Torus containing suppression pool

Primary containment or "Dry well" head

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

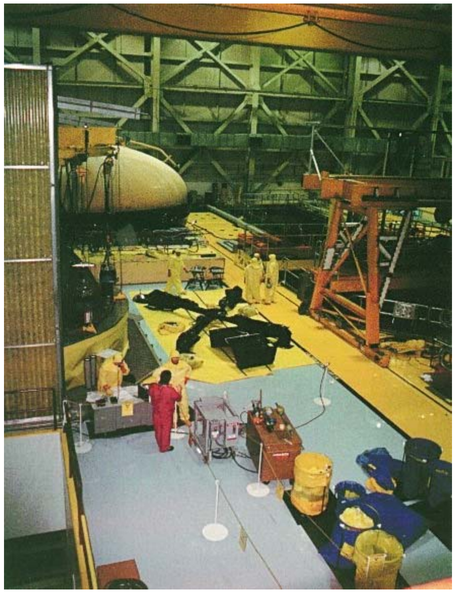
Brown's Ferry

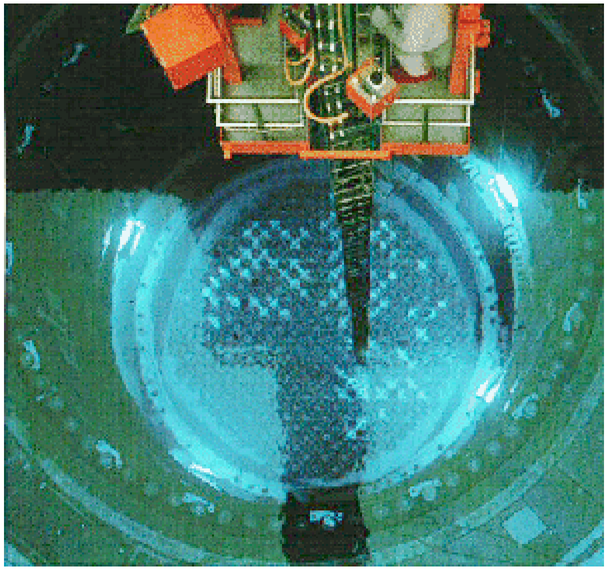
Containment Structure – Mark I



NUREG/CR-2726

Refueling – 1/3 core changed out every 12 – 15 mos





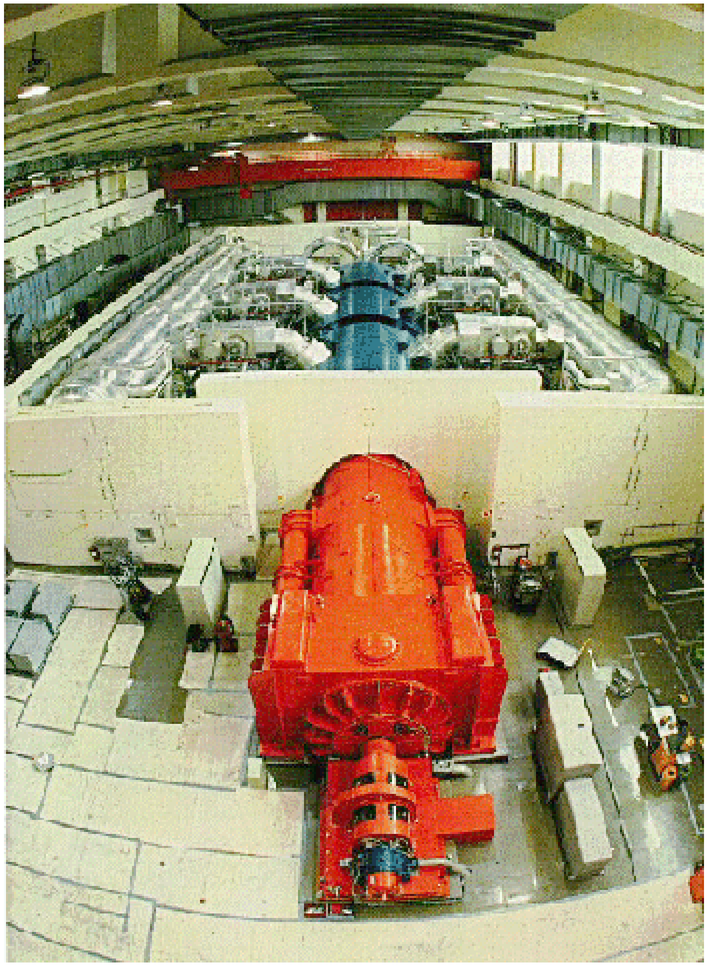
Primary containment and reactor pressure vessel heads are removed

Blue glow is Cerenkov radiation – water serves as "biological shield"

Fuel assembly is being handled with operators standing on the platform

http://www.nucleartourist.com/

Turbine and generator



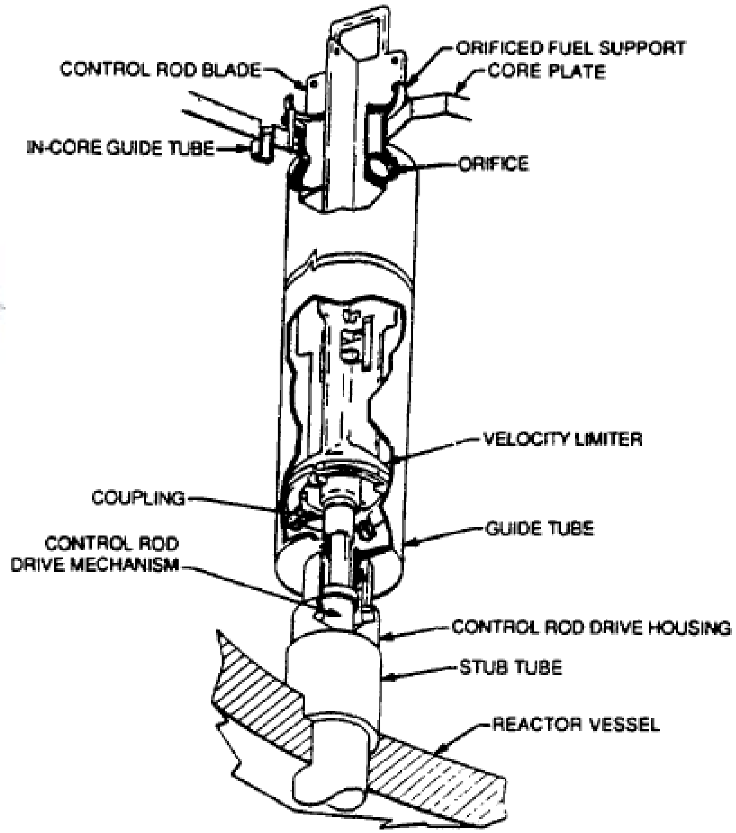
Turbine surrounding by shielding to protect operators.

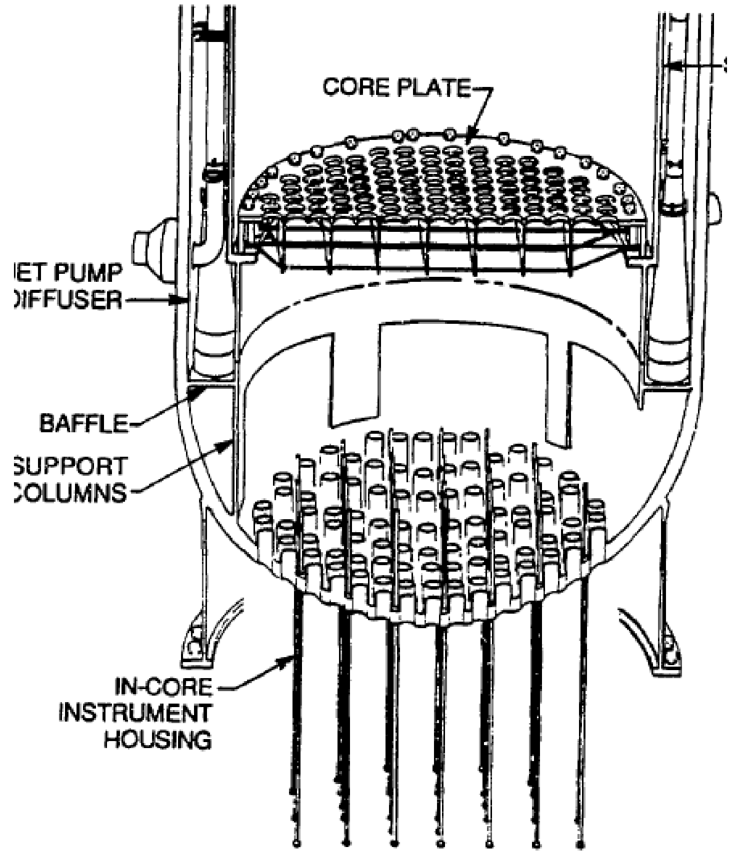
Water passing through reactor picks up radionuclides that are released from fuel pins through defects or diffusion. Impurities in water are activated. Radiolysis generates H_2 and O_2 in water

http://www.nucleartourist.com/

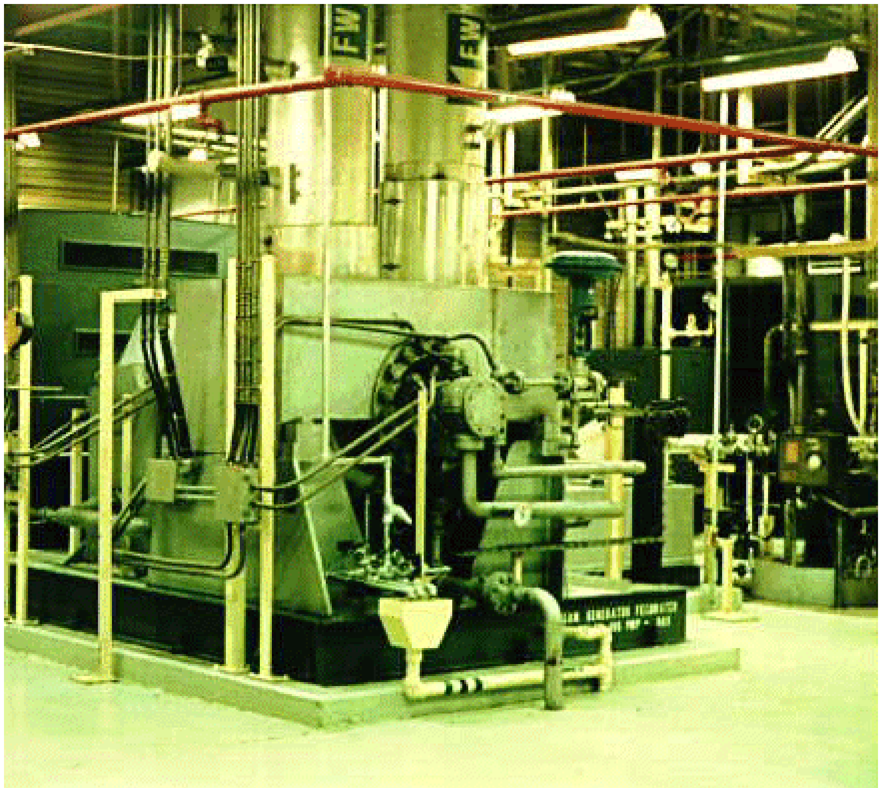
Control Rod System

Westinghouse BWR control rod CR 82M-1





Steam Driven Feedwater Pump

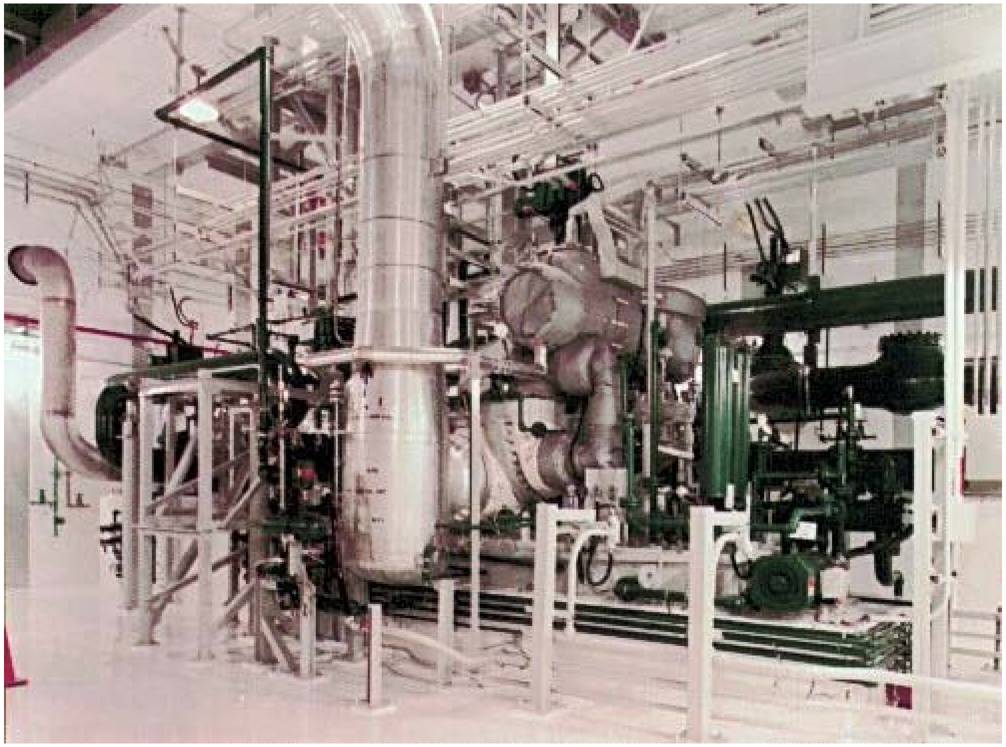


600 gpm, 150-1000 psi

138 t/h 1- 6.8 MPa

http://www.nucleartourist.com/

High Pressure Coolant Injection Pump

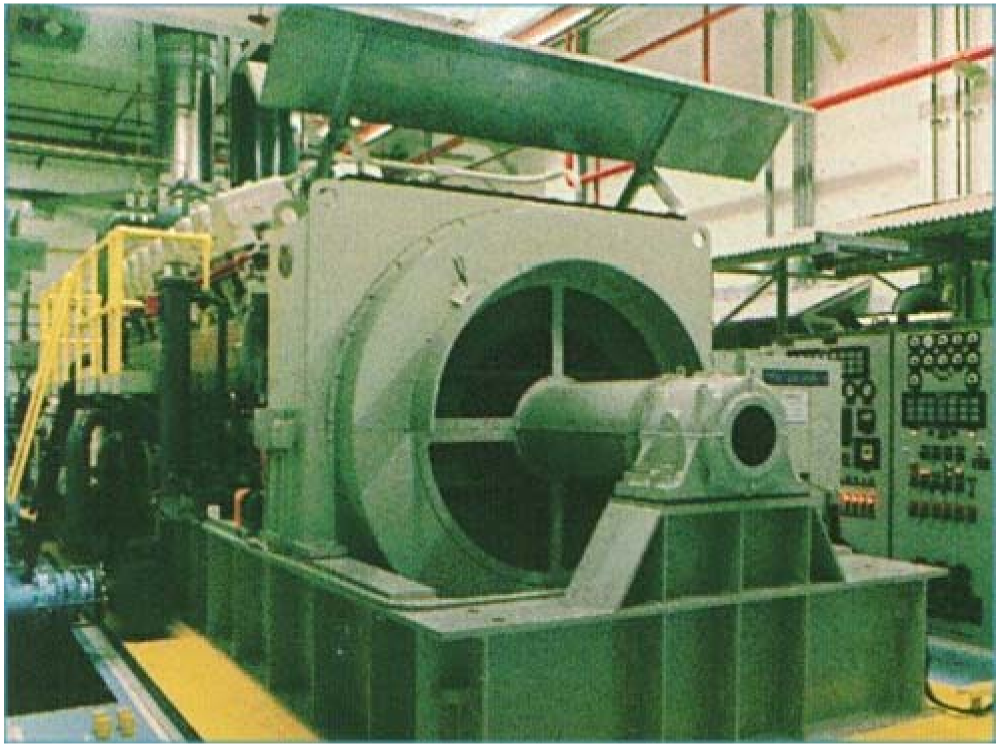


5000 gpm @ 150 to 1000 psig

1134 t/h   1 to 6.8 MPa

http://www.nucleartourist.com/

Emergency Diesel Generator



Typical installation is 2 - 6 MWe per generator set.

Usually at least 2 per reactor unit.

http://www.nucleartourist.com/

Backup Battery Power

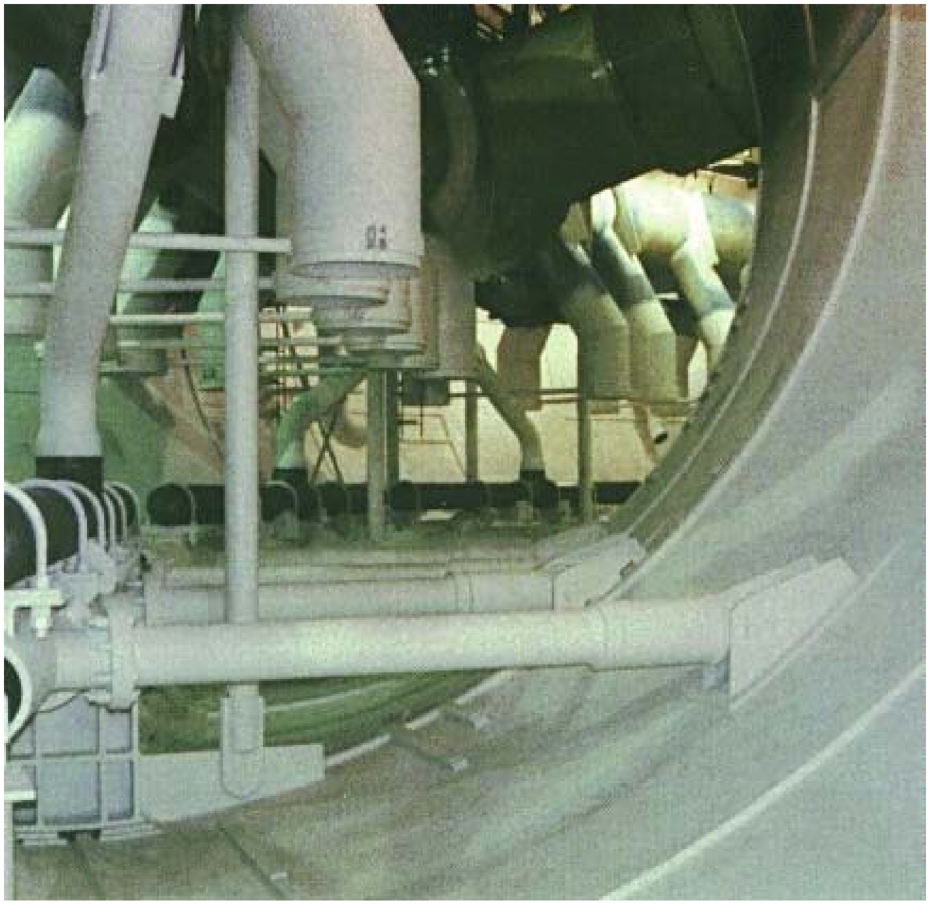
Connected to inverters to generate AC power.

Used only to power key instruments and controls.

Enough capacity for 8 hrs operation.

Suppression Pool Torus

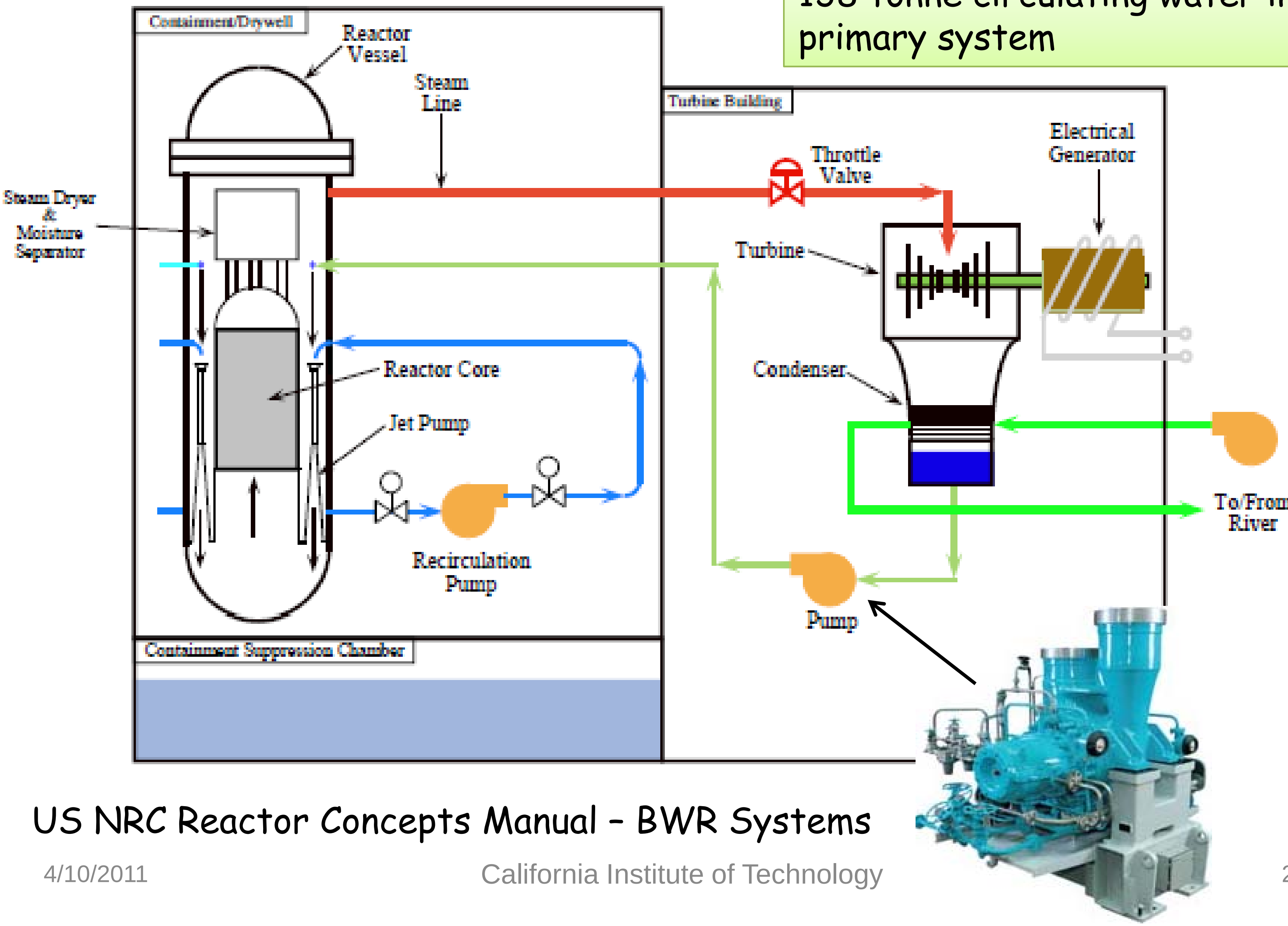
Units 2,3,4 contain 2980 tonne water (1750 for unit 1)
Connected to sphere with vent lines, vacuum breakers for reverse flow



Control Room

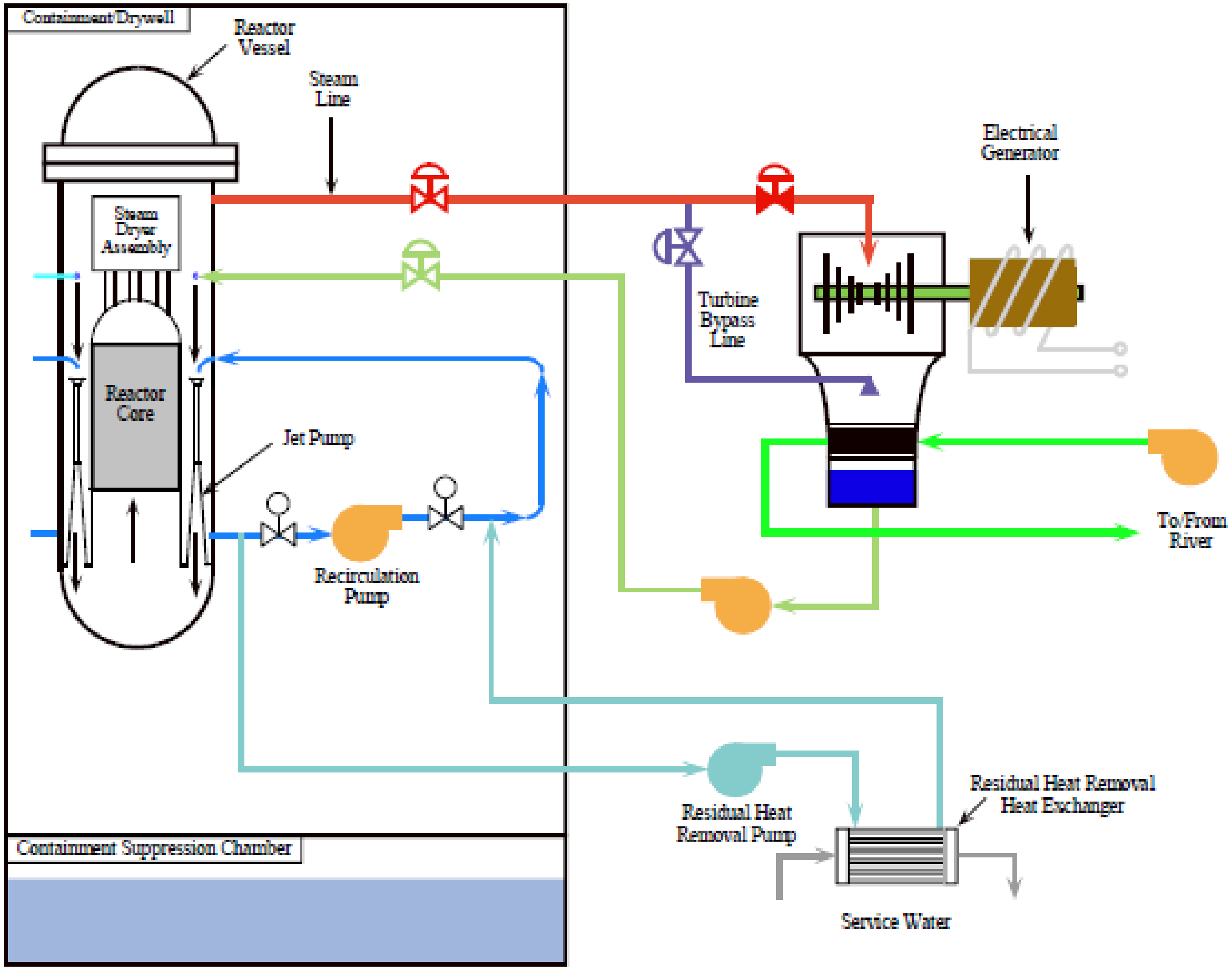
Normal Operation

138 tonne circulating water in primary system



US NRC Reactor Concepts Manual – BWR Systems

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.

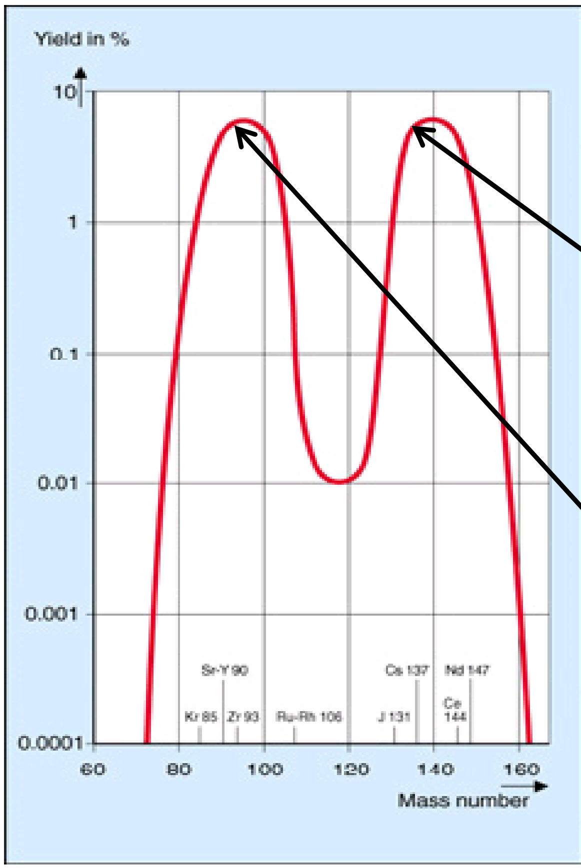
US NRC Reactor Concepts Manual – BWR Systems

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

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.

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

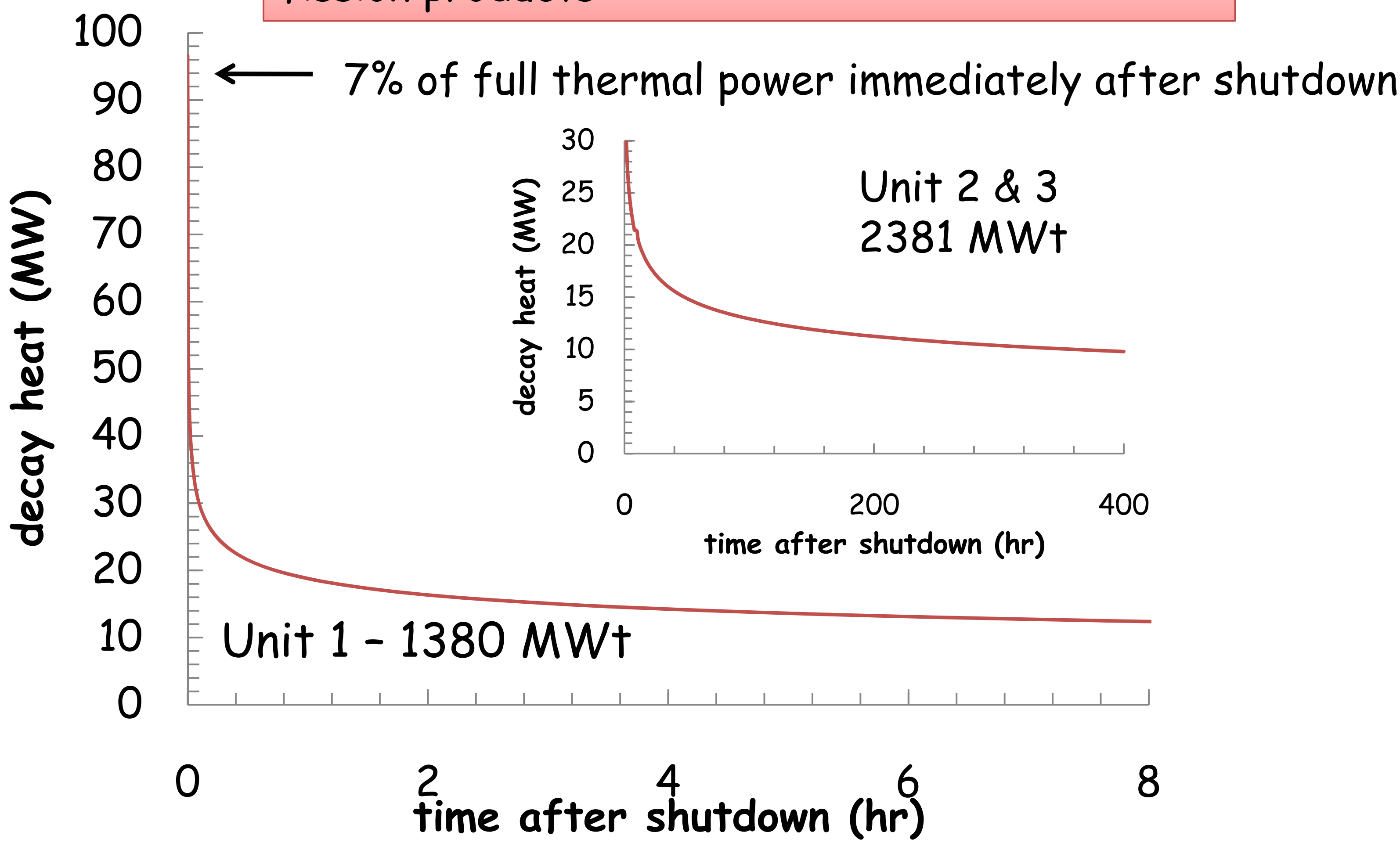
Chain terminates when a stable isotope is formed

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

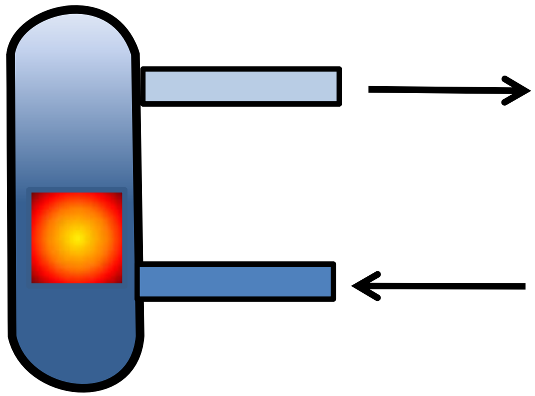
http://www.euronuclear.org/info/encyclopedia/f/fissionyield.htm

Fission Products Create Decay Heating

Decay heat is due to beta and gamma decay of fission products



Cooling Water requirements

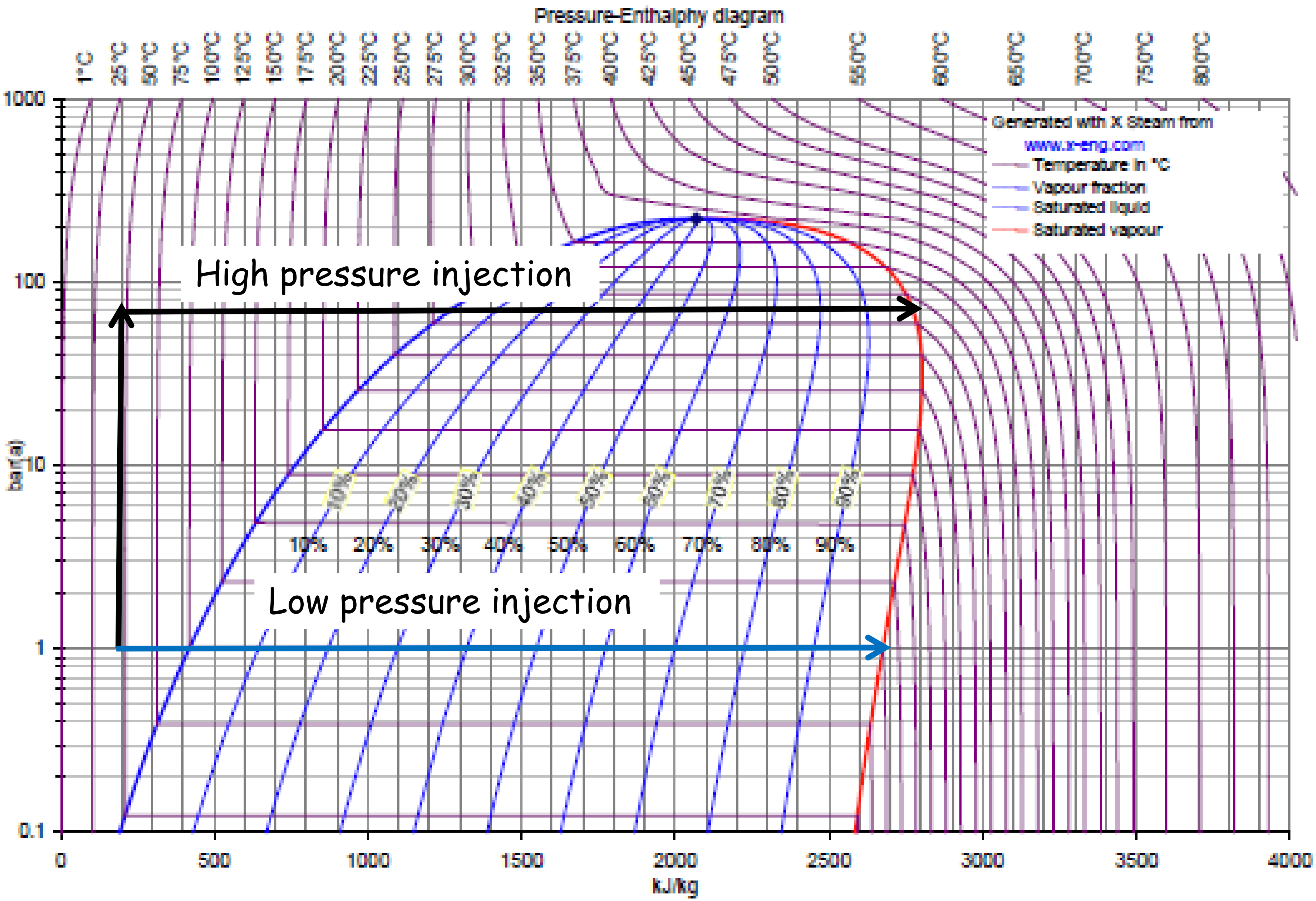


Energy balance

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

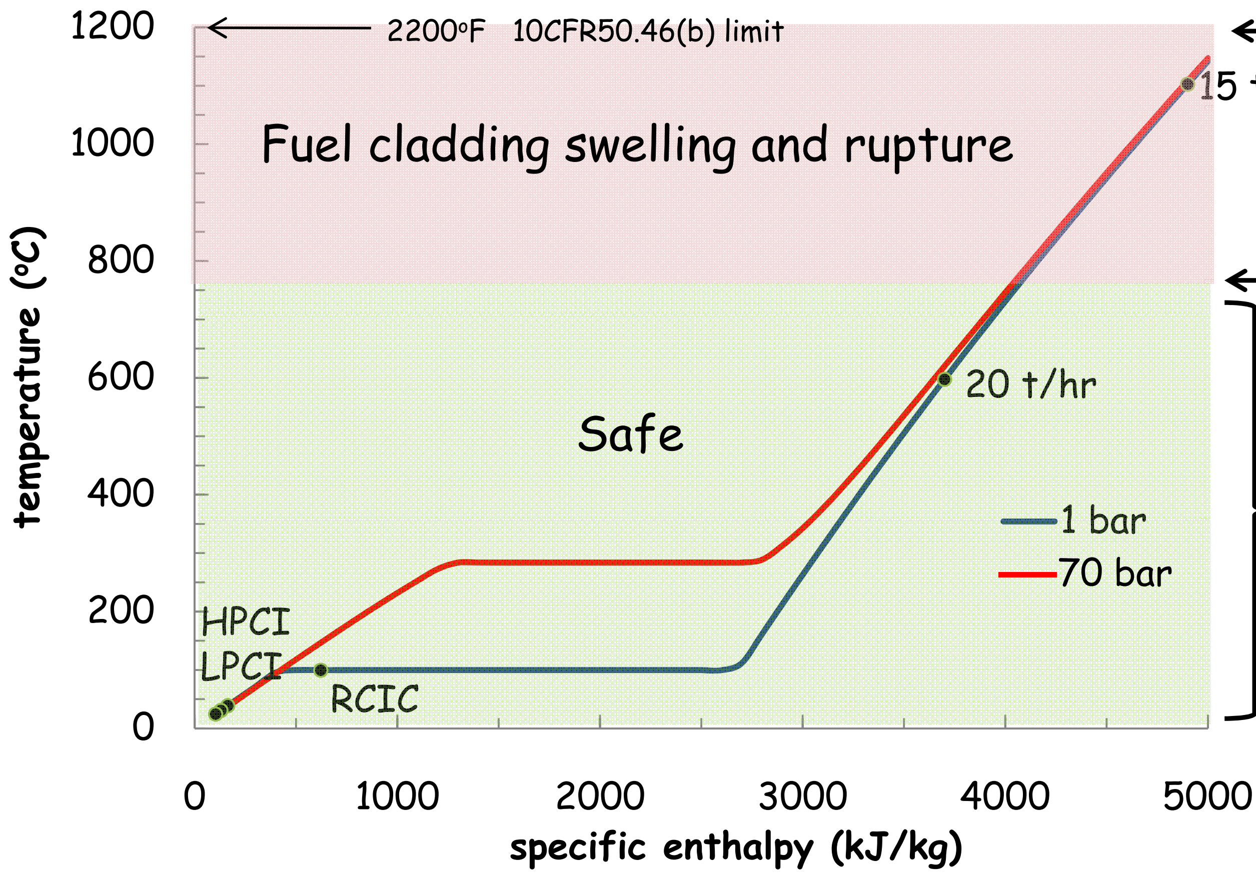
$$\dot{Q} = 20 \text{ MW}$$

Capability	$\dot{M}$ (t/h)	H (kJ/kg)	T °C
Portable pumps	15	4800	1103
RCIC	138	522	100
HPCI	1134	63	39
LPCI	2478	29	31
Main feedwater	21600	3	25



Pressure-Enthalphy diagram
1°C
25°C
50°C
75°C
100°C
125°C
150°C
175°C
200°C
225°C
250°C
275°C
300°C
325°C
350°C
375°C
400°C
425°C
450°C
475°C
500°C
550°C
600°C
650°C
700°C
750°C
800°C
Generated with X Steam from
www.x-eng.com
Temperature in °C
Vapour fraction
Saturated liquid
Saturated vapour
High pressure injection
Low pressure injection
bar(a)
1000
100
10
1
0.1
10%
20%
30%
40%
50%
60%
70%
80%
90%
0
500
1000
1500
2000
2500
3000
3500
4000
kJ/kg

Heat removal estimates



Onset of H2 generation

Onset of fuel swelling

Stable situation, steady heat removal possible.

Temperatures and pressures will slowly decrease.

Caution: Extremely simplistic "back of the envelope" estimate!

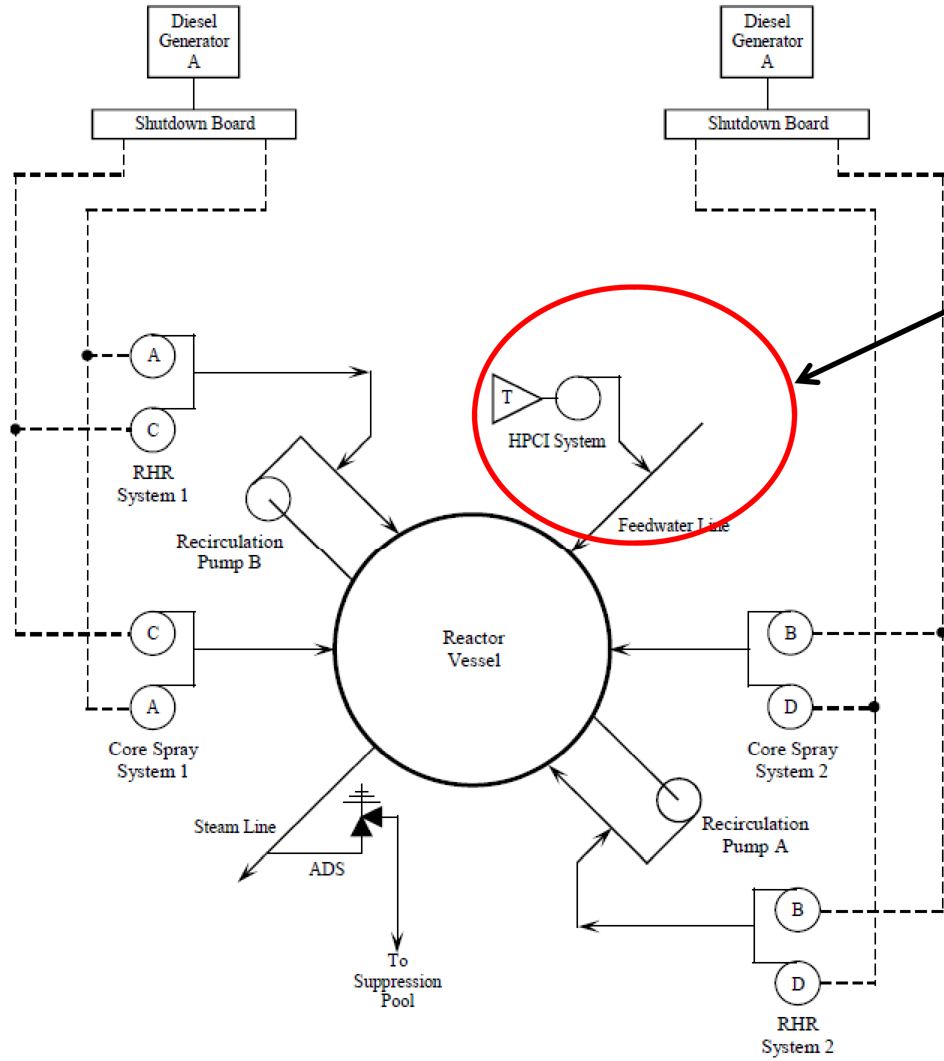
Accident Management "normal"

- 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

- **S**tandby **L**iquid **C**ontrol **S**ystem – Boron poison
- **E**mergency **C**ore **C**ooling **S**ystems
  - High Pressure Coolant Injection
  - **R**eactor **C**ore **I**solation **C**ooling
  - **A**utomatic **C**ontainment **D**epressurization
  - **L**ow **P**ressure **C**oolant **I**njection
  - **C**ore **S**pray

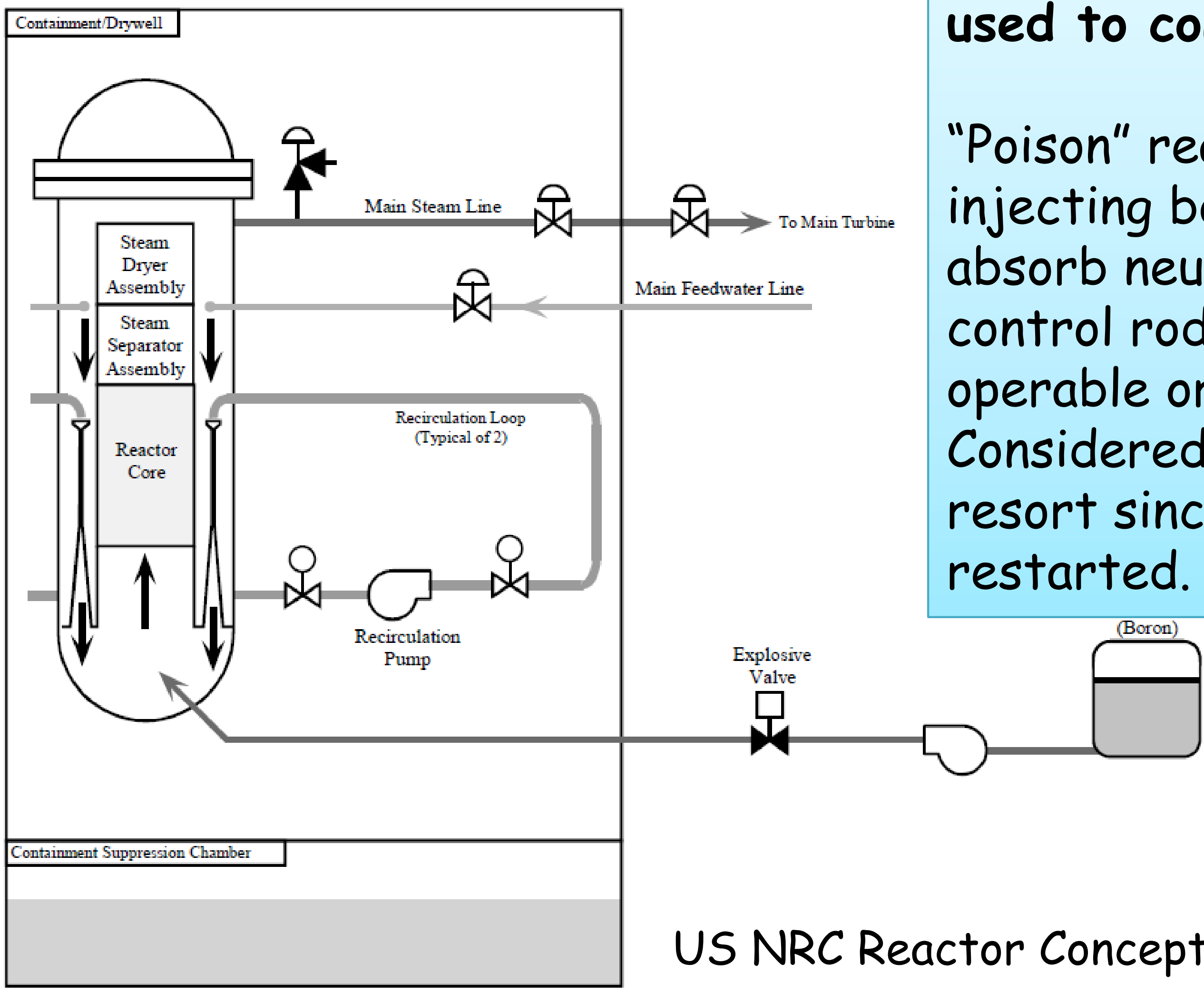
Off-Site or Diesel Electrical Power Required for Most ECCS Systems



RCIC pump is steam Driven, only needs valve operation

US NRC Reactor Concepts Manual – BWR Systems

Standby Liquid Control System

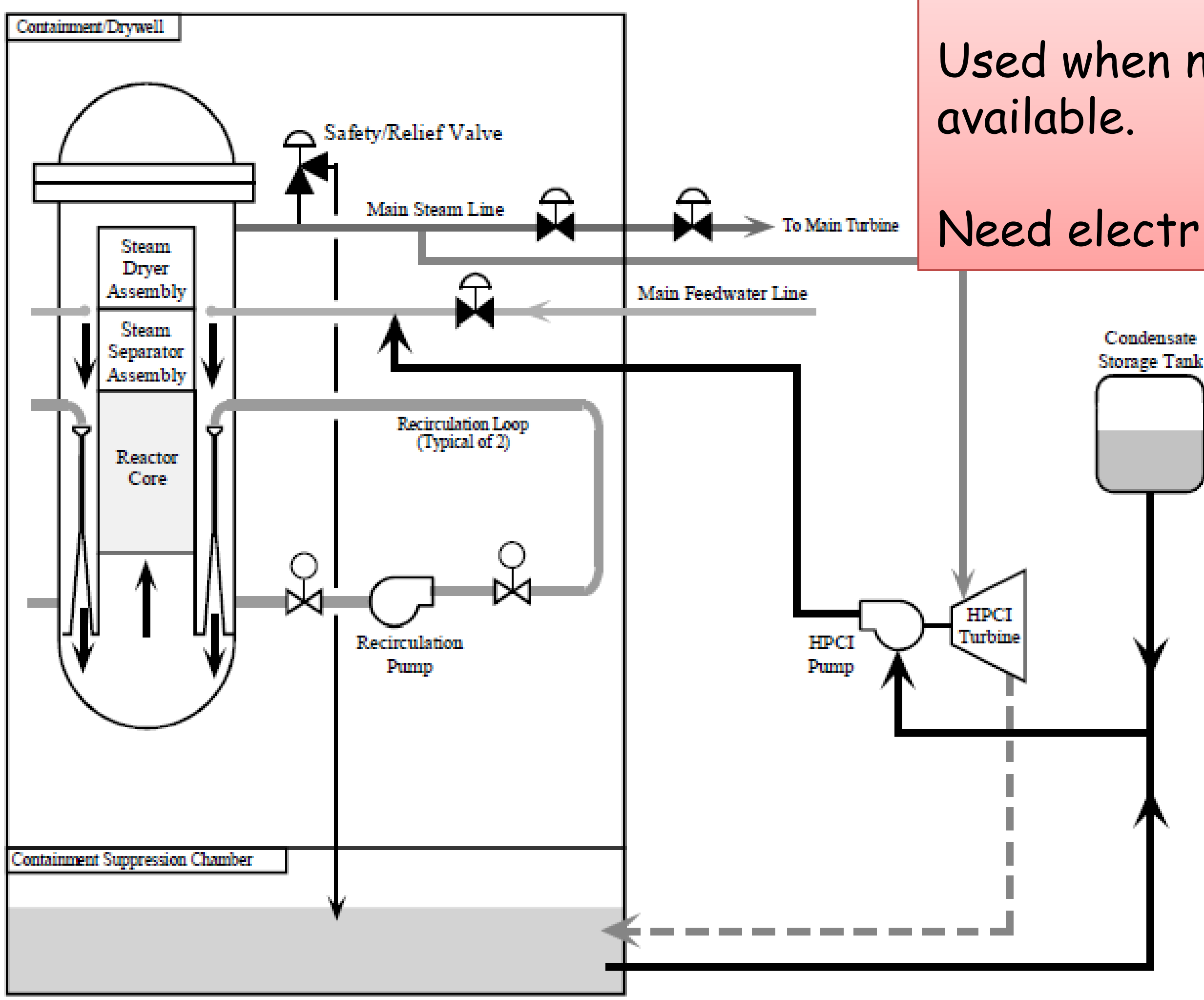


Not heat removal system but used to control reactivity.

"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.

US NRC Reactor Concepts Manual – BWR Systems

High Pressure ECCS - RCIC



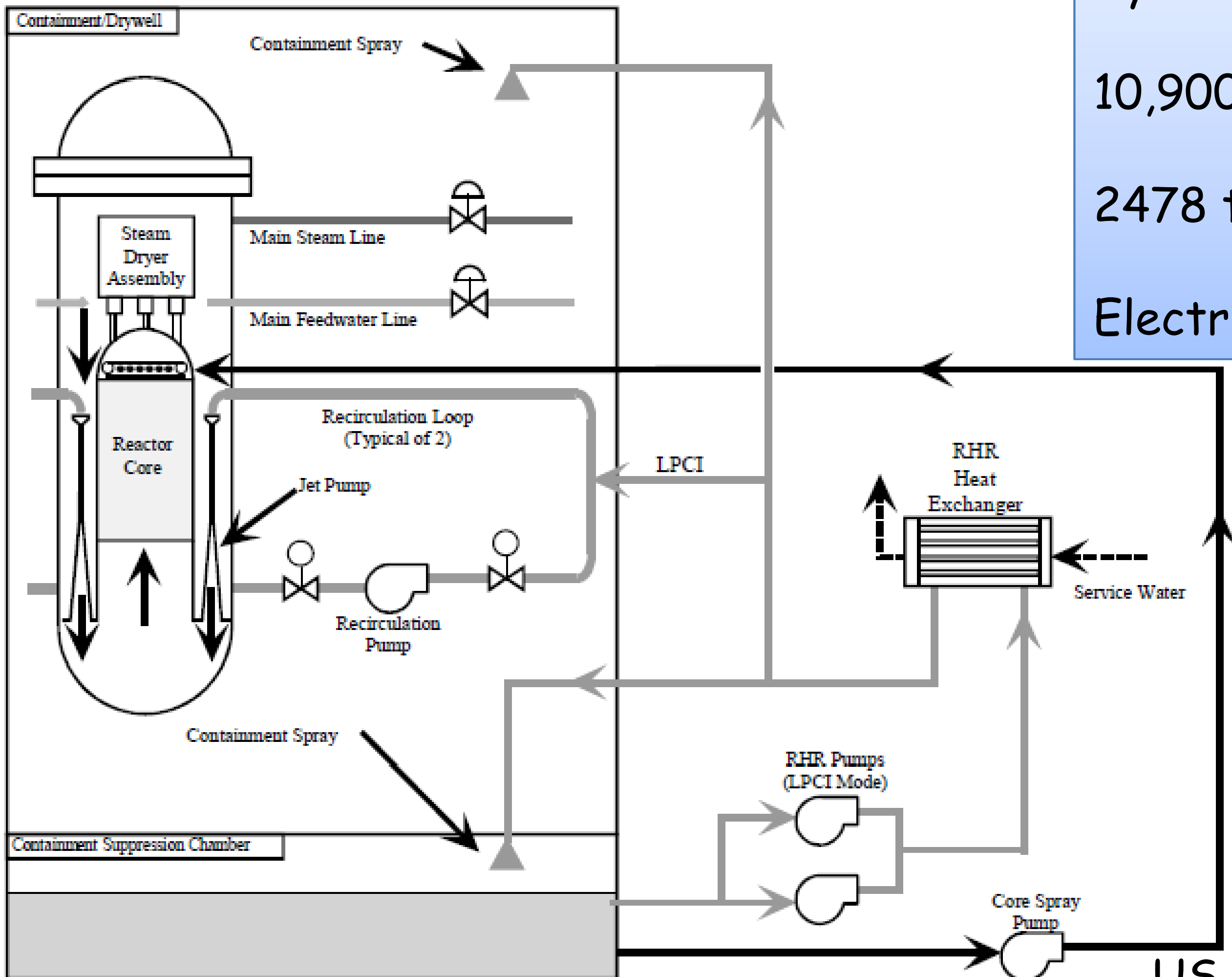
Pump is driven by steam

Used when normal feedwater is not available.

Need electrical power to operate valves

US NRC Reactor Concepts Manual – BWR Systems

Low Pressure ECCS - LPCI



System at low pressure

10,900 gpm @ 20 psig

2478 tonne/h   136 kPa

Electrical power required

US NRC Reactor Concepts Manual – BWR Systems

DEFENSE-IN-DEPTH

Multiple reactivity control systems

Multiple coolant injection and heat removal systems

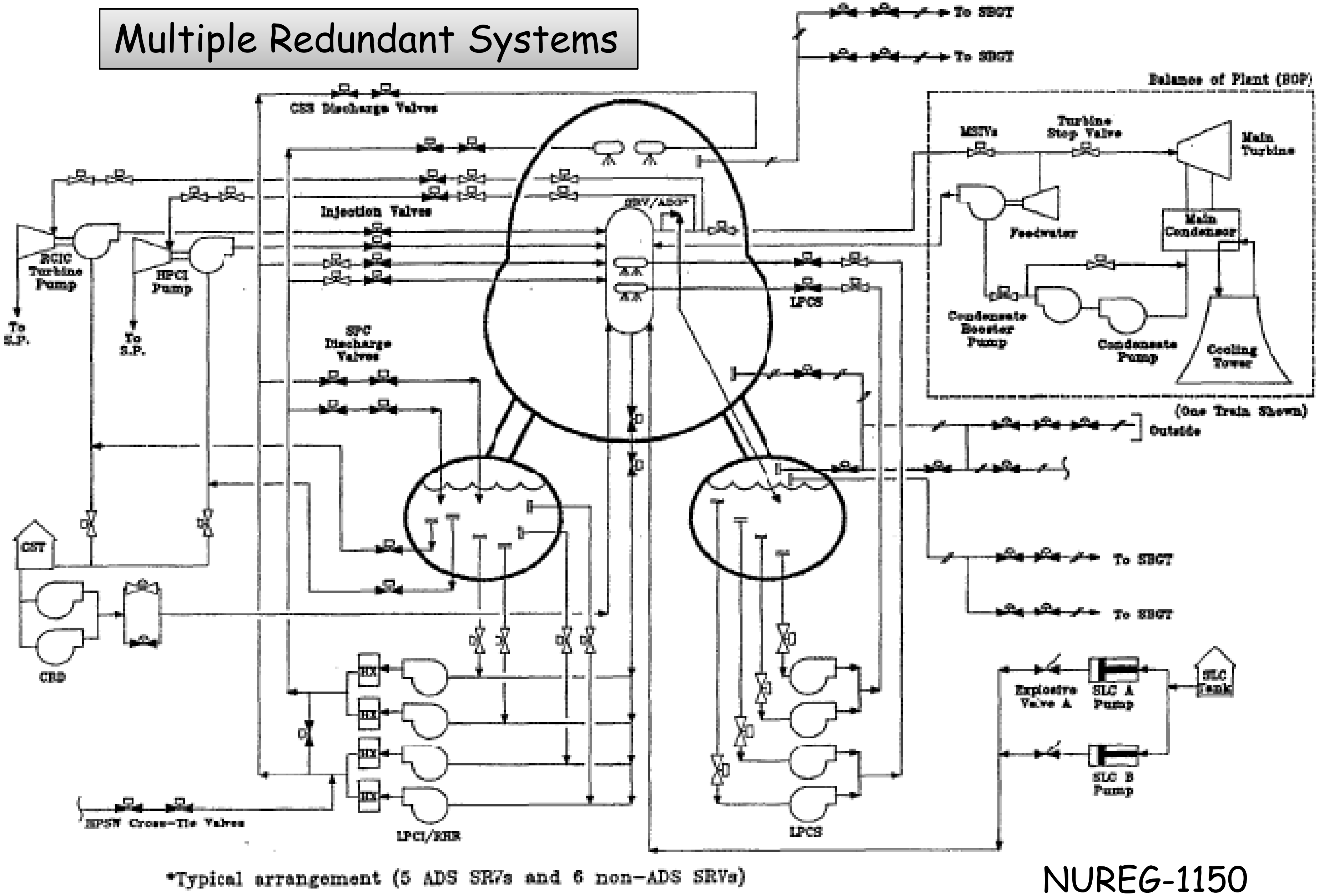
Multiple barriers to fission product release

NUREG 1150

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.

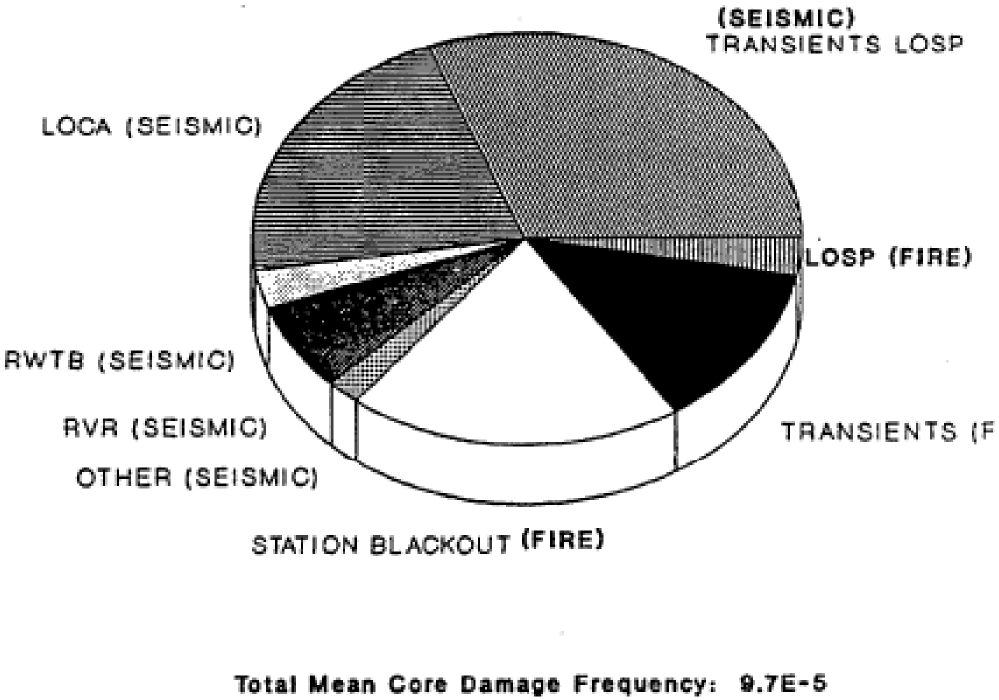
Multiple Redundant Systems

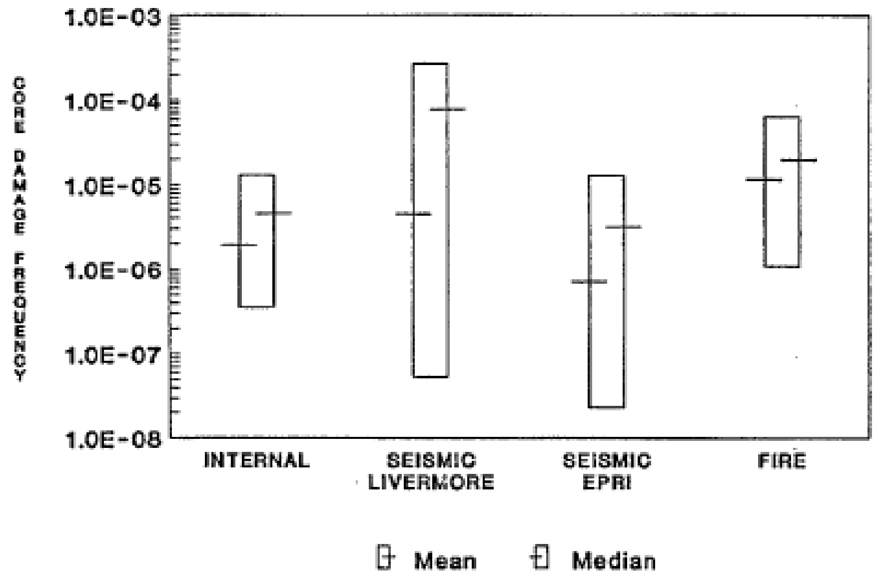


NUREG-1150

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

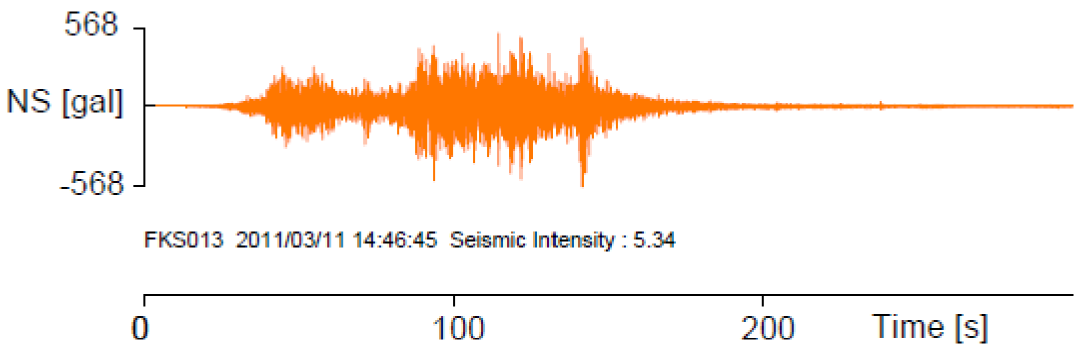
The risk from the internal events are driven by long-term station blackout (SBO) and anticipated transients without scram (ATWS). The dominance of these two plant damage states can be attributed to both general BWR characteristics and
plant-specific design. BWRs in general have more redundant systems 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

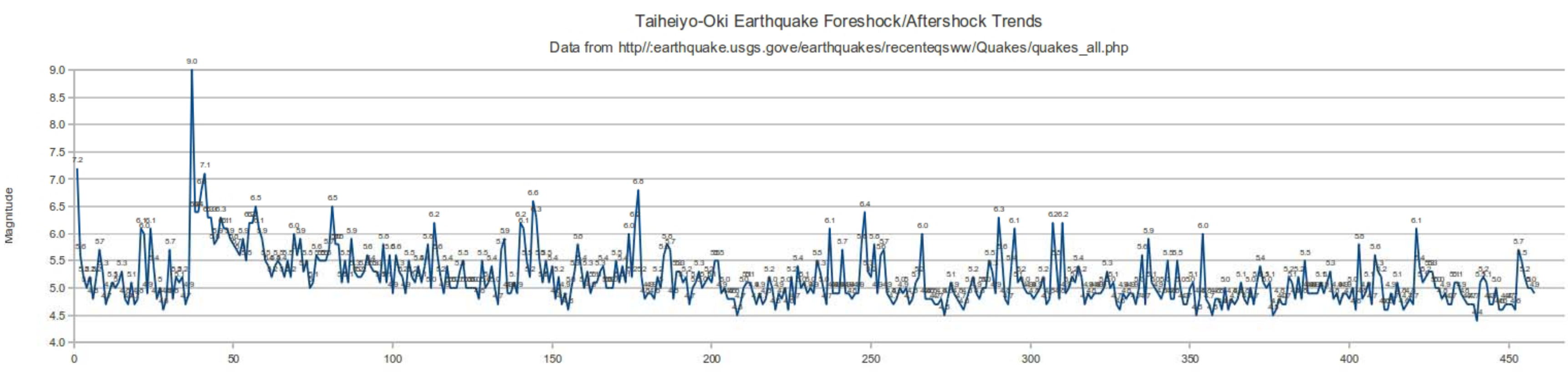
Pre-March 10, 2011

Digital Globe

Huge Earthquake, 500 gal > 250 gal

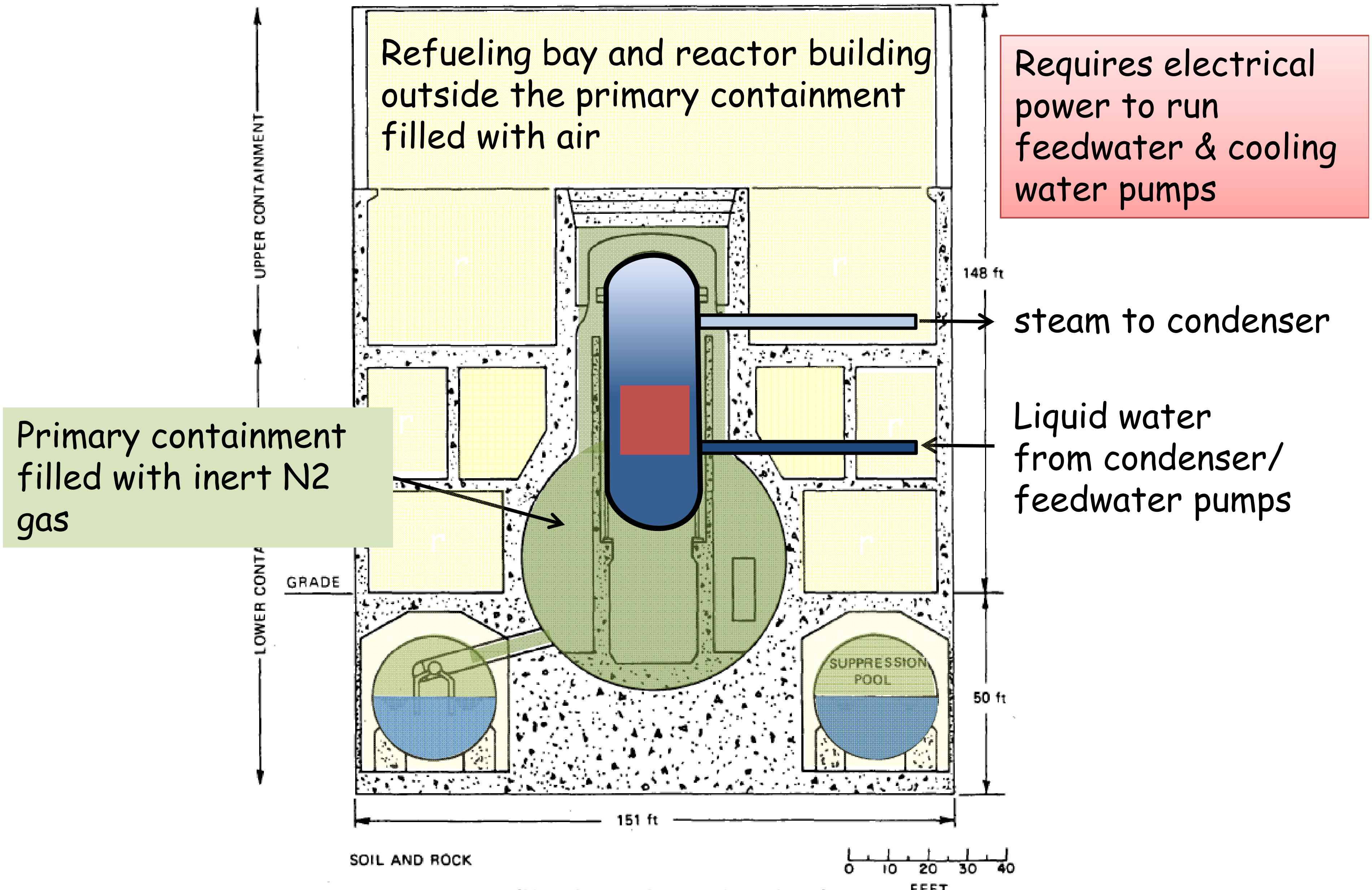


Electrical grid failed, Loss of Offsite Power (LOOP) and shaking initiated reactor shutdown



NIED and USGS

Normal Cooling Through Main Condenser

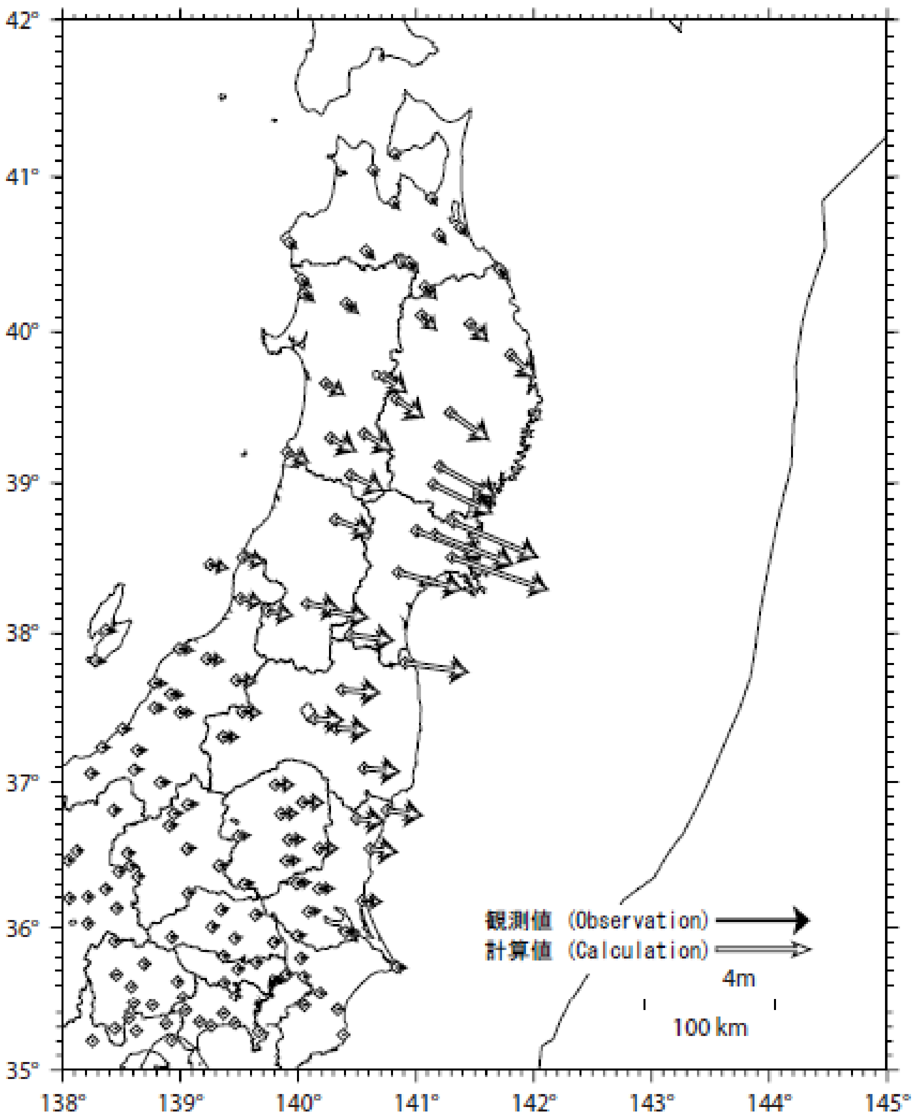


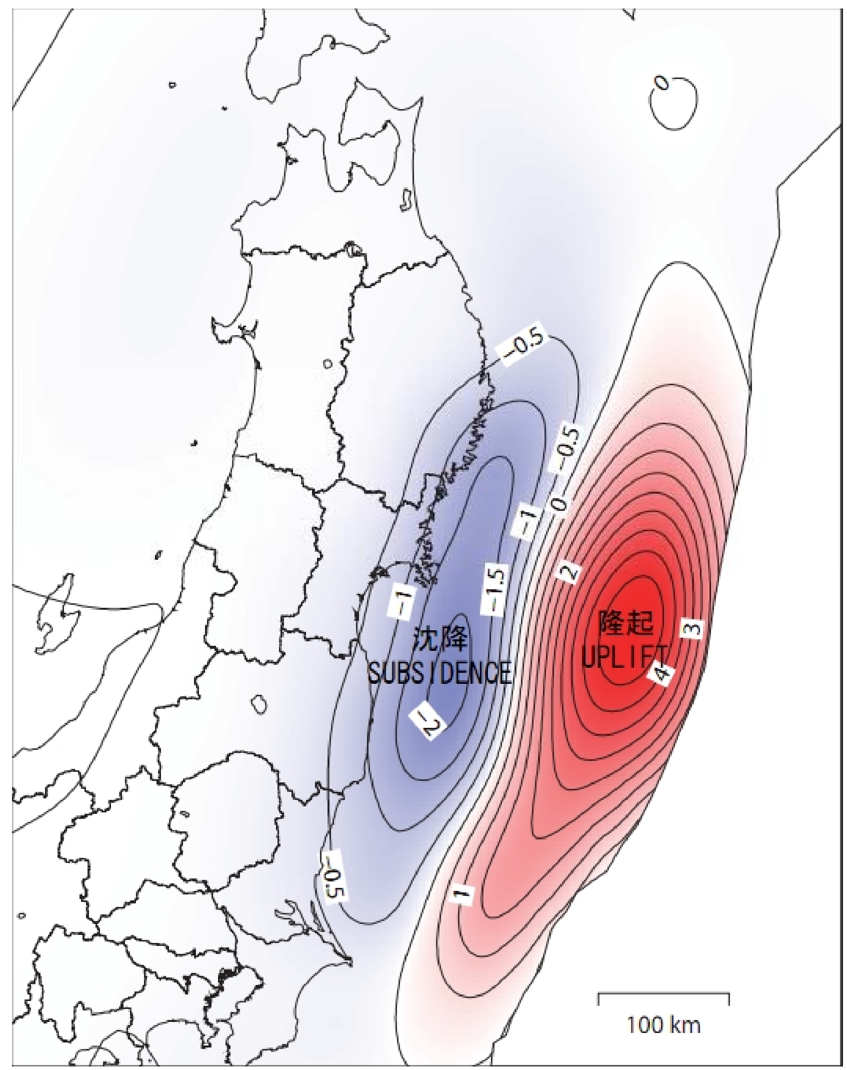
Huge tsunami(s) 10-15 m > 6 m


http://photoblog.msnbc.msn.com/_

Land subsidence in Coastal Region

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





Back-up generators (13) all fail!

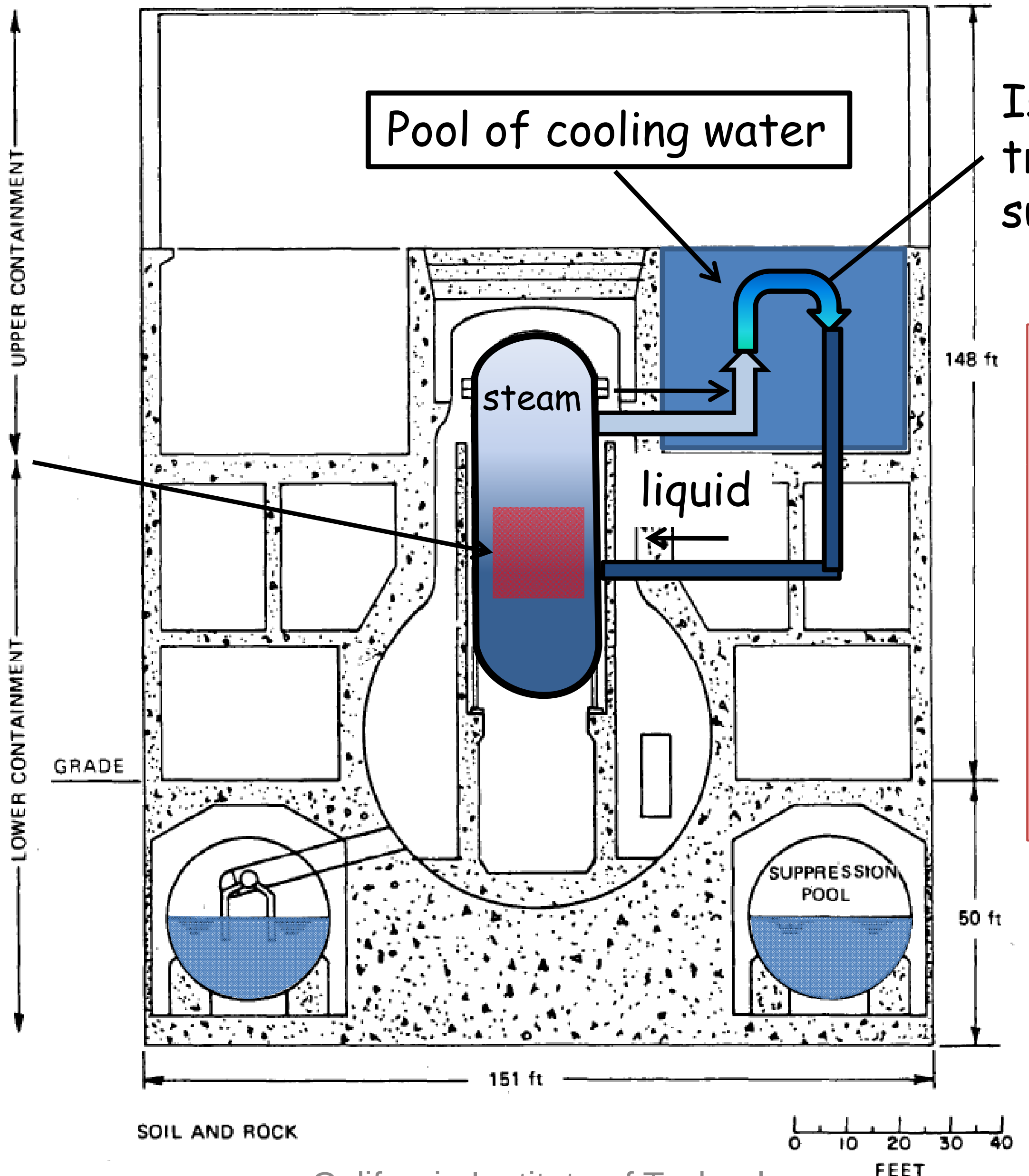
http://photoblog.msnbc.msn.com/

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
	14:48:00	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.

Emergency Cooling Isolation Condenser in Unit 1

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



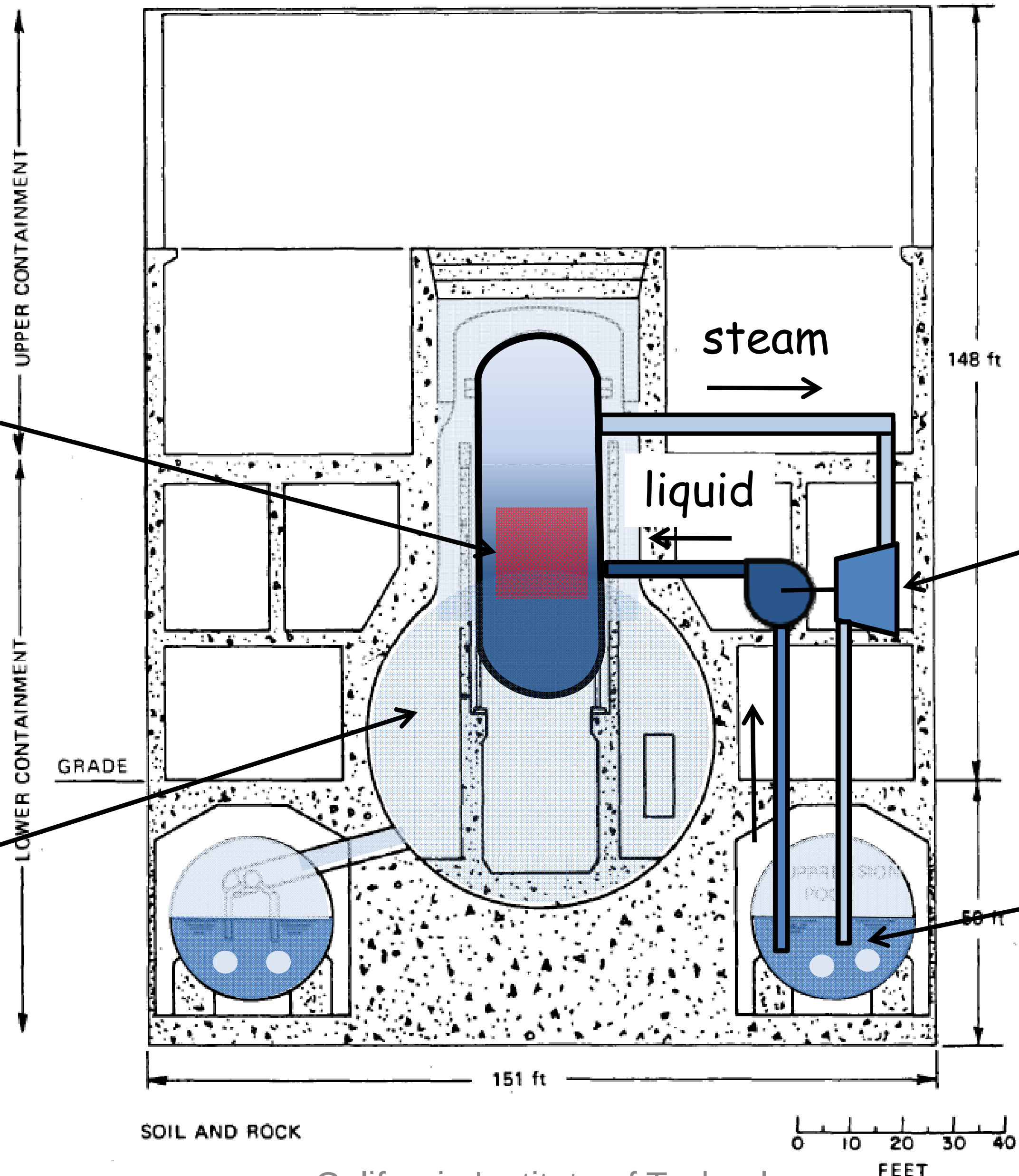
Isolation condenser transfers heat to surrounding pool

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

Suppression pool condenses steam

Efforts to Restructure the Nuclear Safety System (5)

<Special Act for Nuclear Emergency>

Outcome of 1999 JCO accident
At Tokai-mura, Japan

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

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

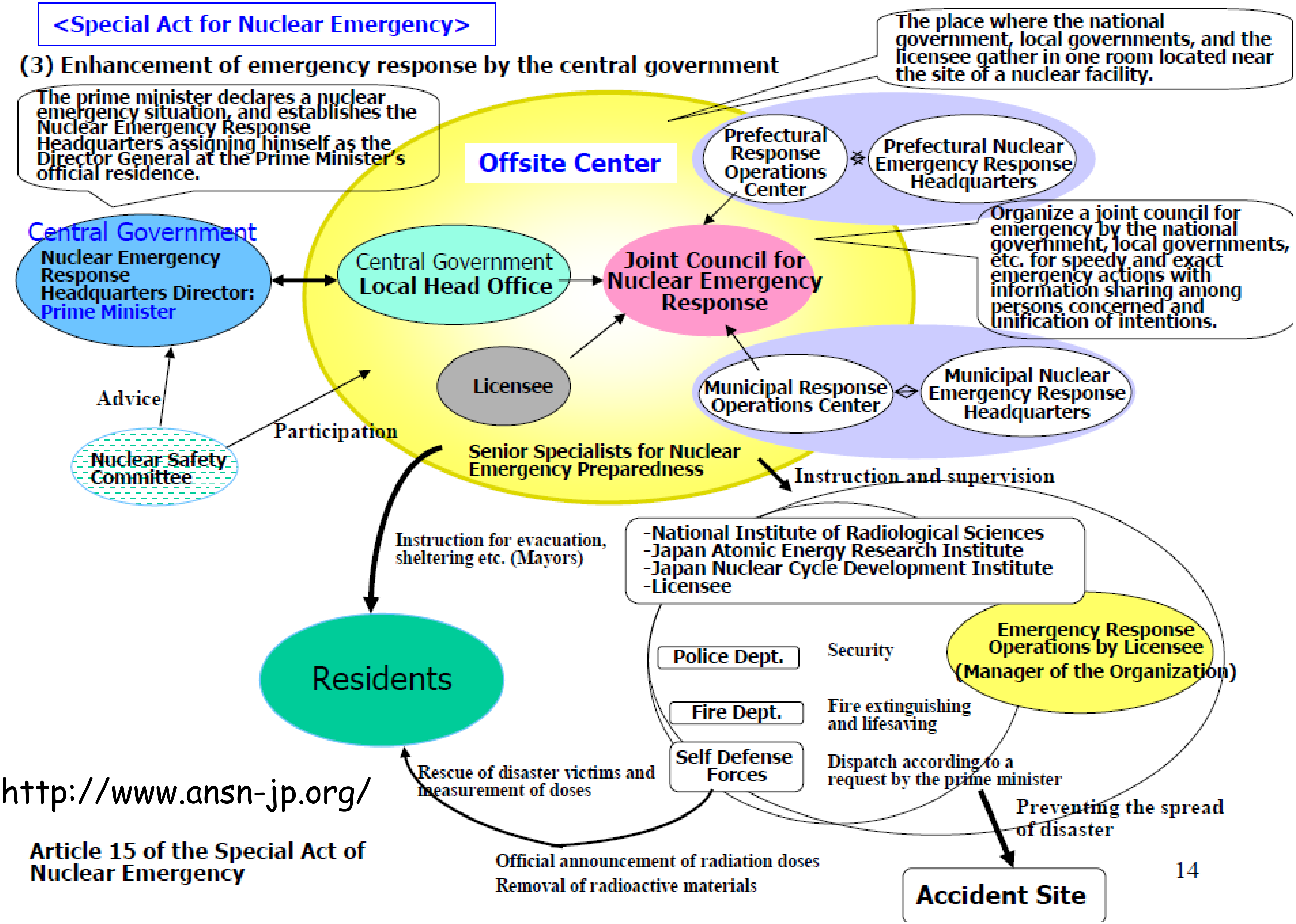
B) Clarification of the decision criteria for nuclear emergency → **Establishment of the "Nuclear Emergency Response Headquarters " and the "Local Nuclear Emergency Response Headquarters "**

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. http://www.ansn-jp.org/ 12

Efforts to Restructure the Nuclear Safety System (7)

<Special Act for Nuclear Emergency>

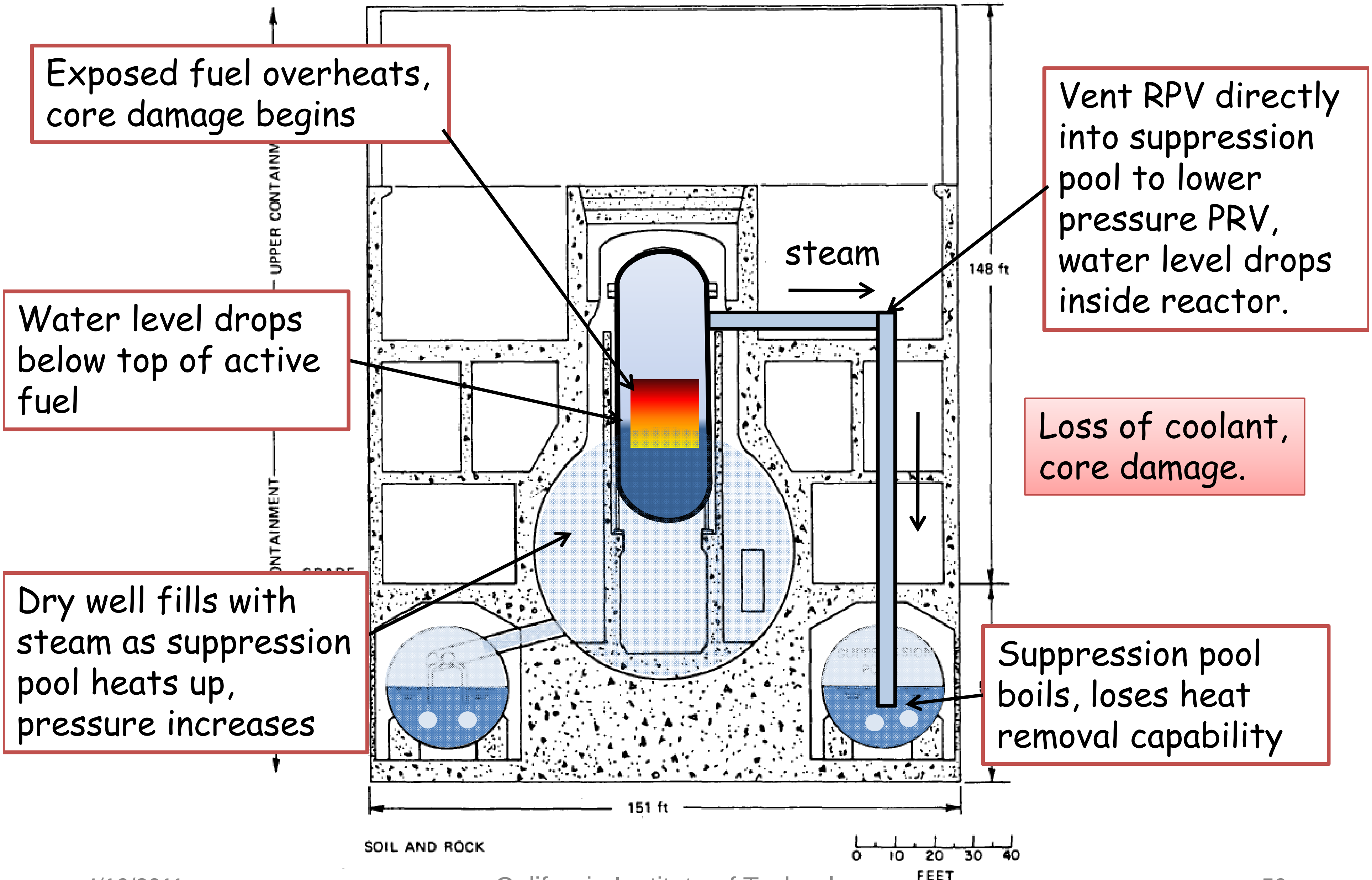
(3) Enhancement of emergency response by the central government



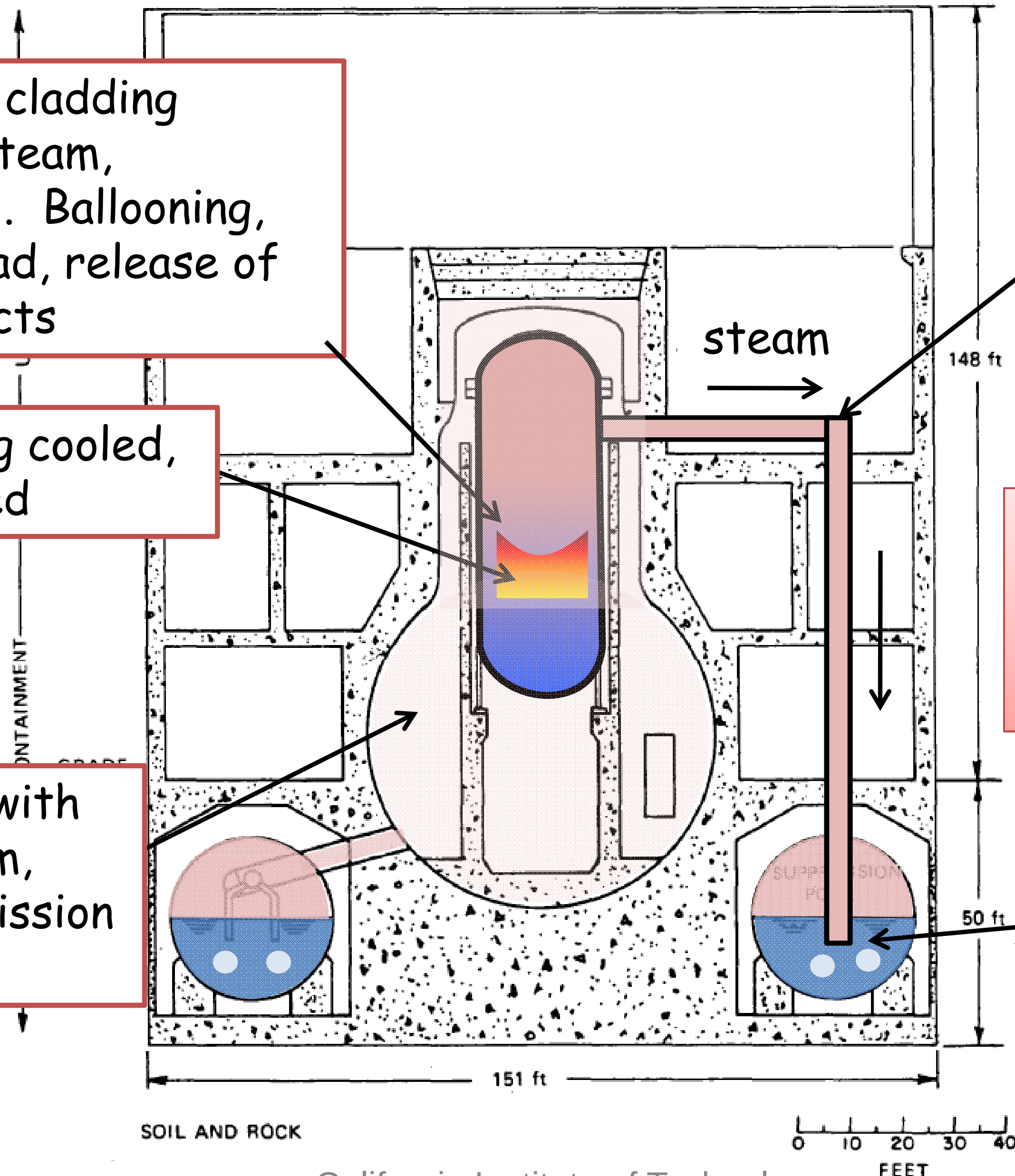
http://www.ansn-jp.org/

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

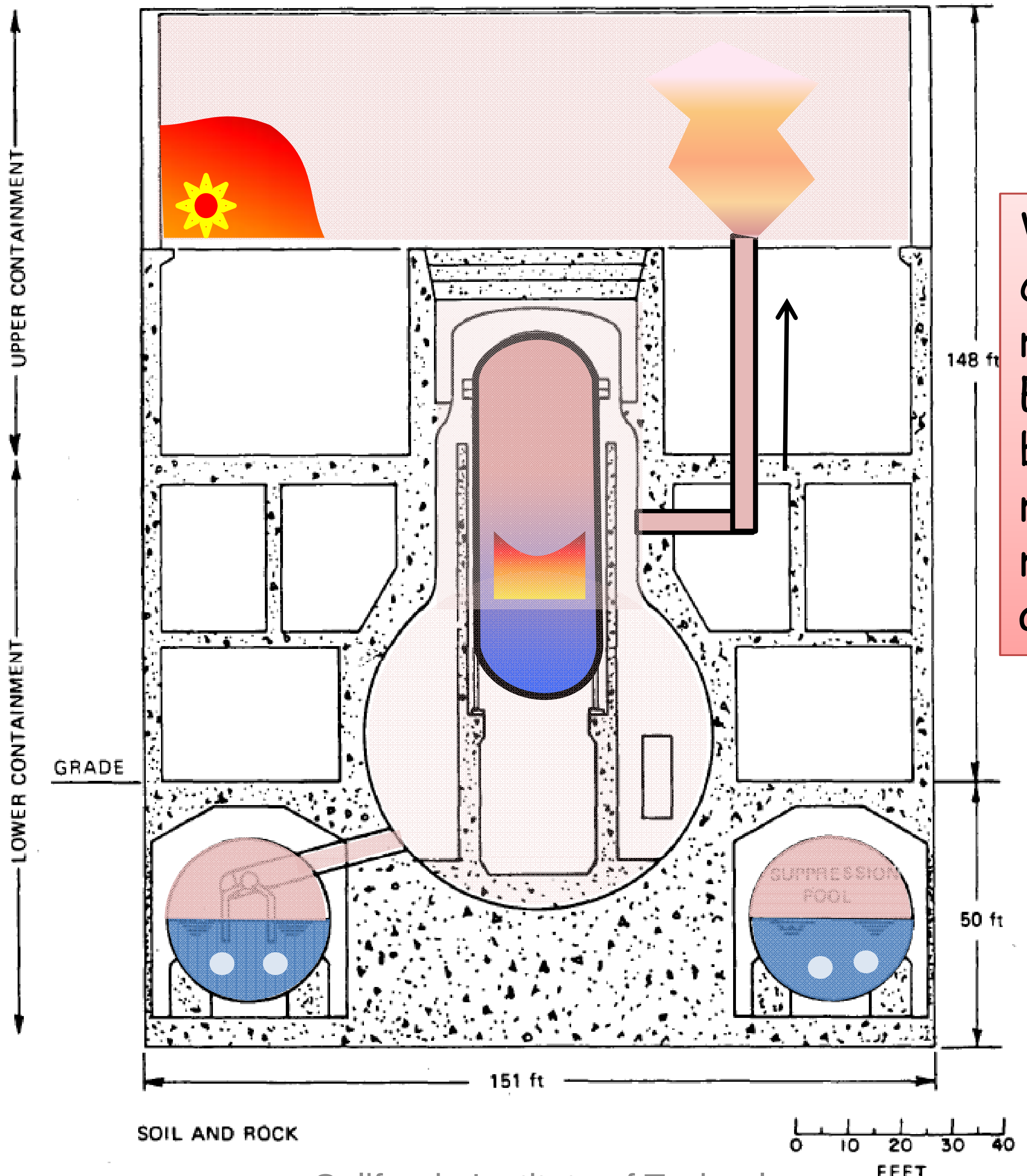
Pressure approaching failure level in primary containment

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.
	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.

UNIT 1
H2 EXPLOSION

Vent Primary Containment to Reduce Pressure

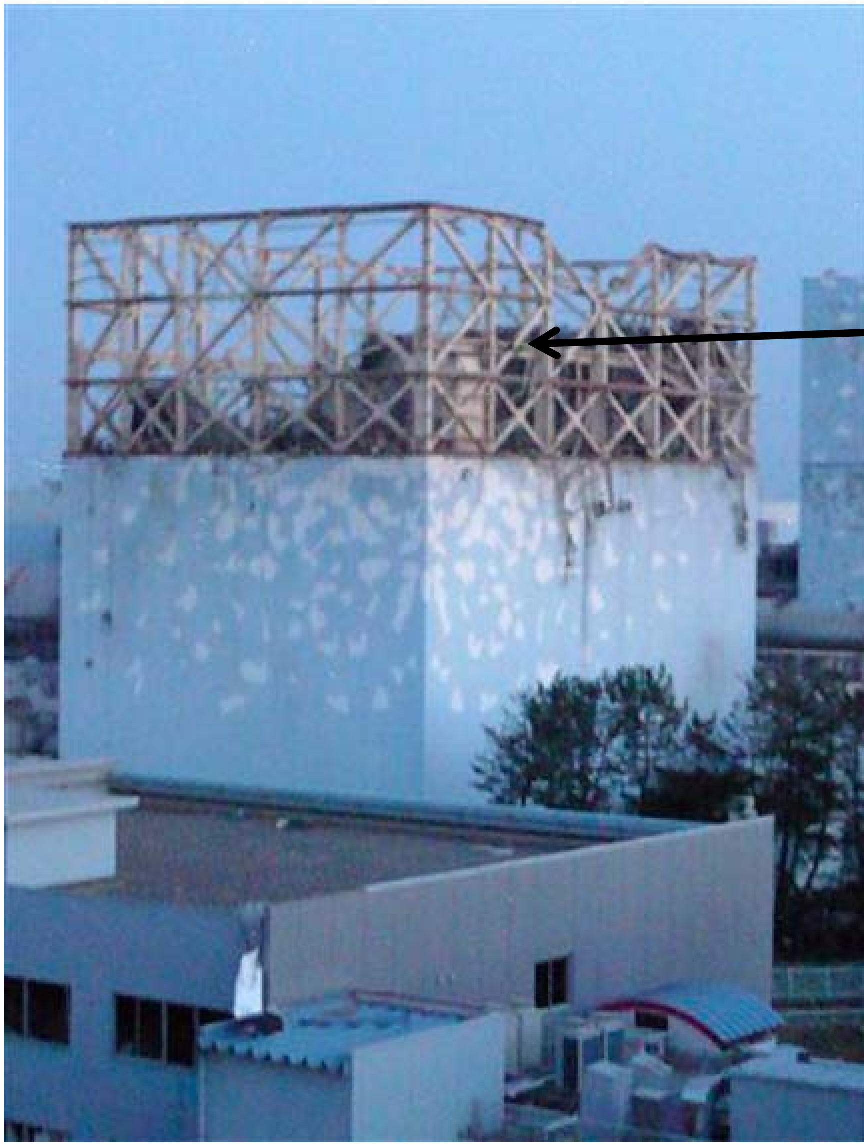


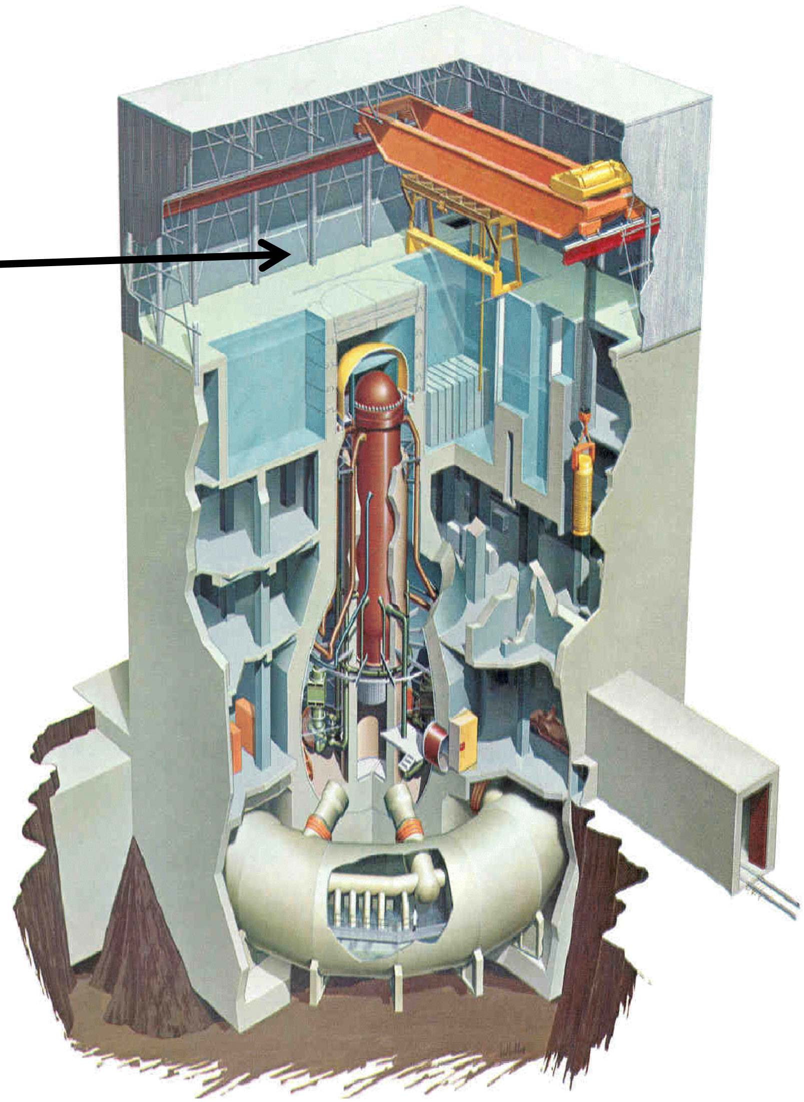
Vent primary containment into reactor building. Exact path unclear but H2 fills refueling bay region, mixes with air and explodes.

Unit 1 Explosion

Reuters

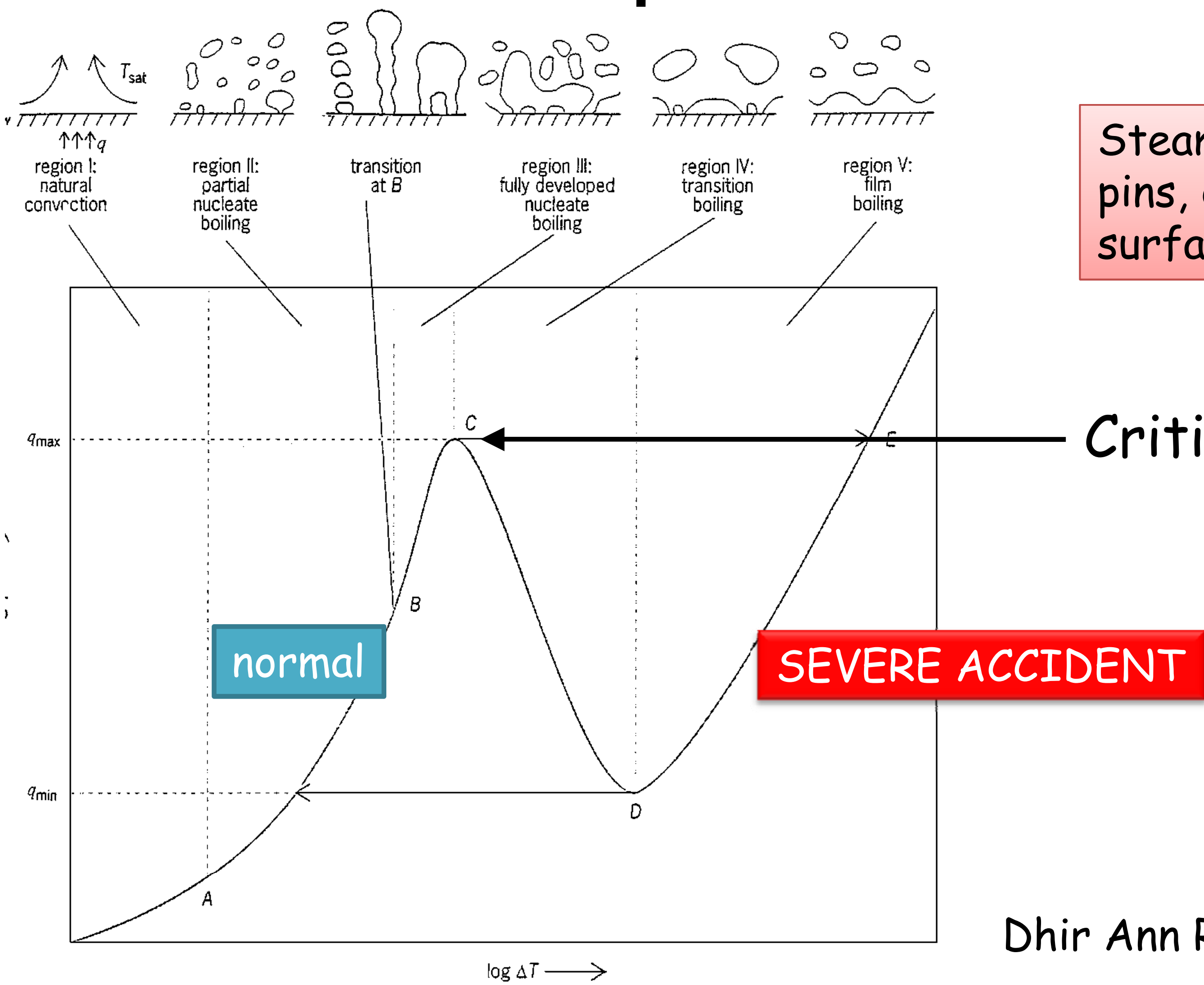
http://www.youtube.com/watch?v=KknHVL43YJ0&feature=player_detailpage





Reuters

Loss of coolant drives up fuel pin temperature

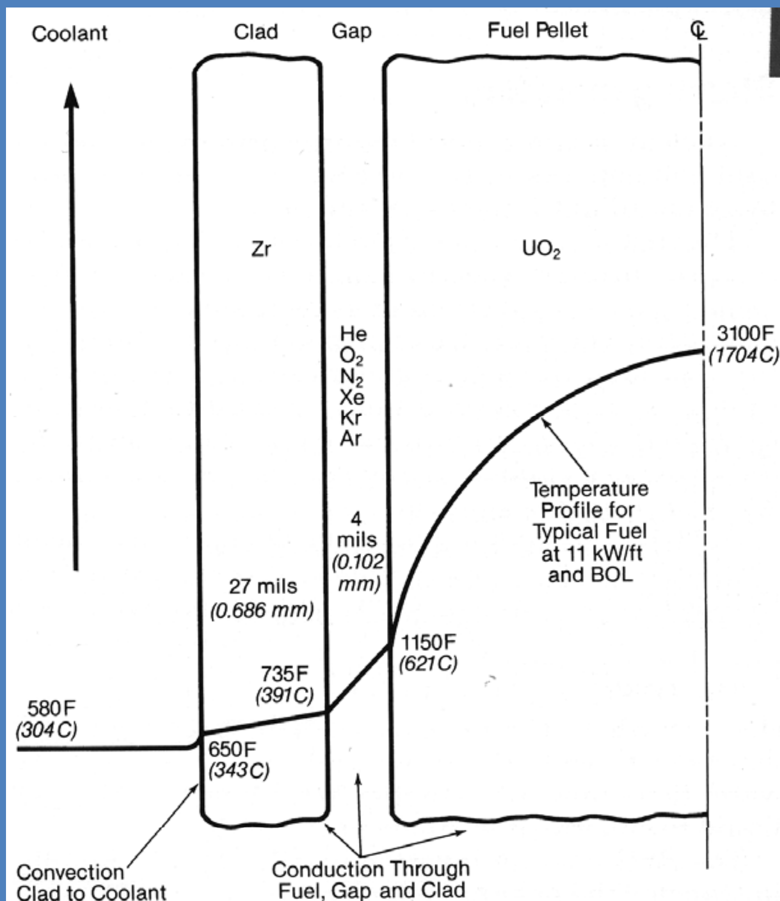


Steam insulates fuel pins, drives up surface temperature

Critical Heat Flux

Dhir Ann Rev Fluid Mech 1998

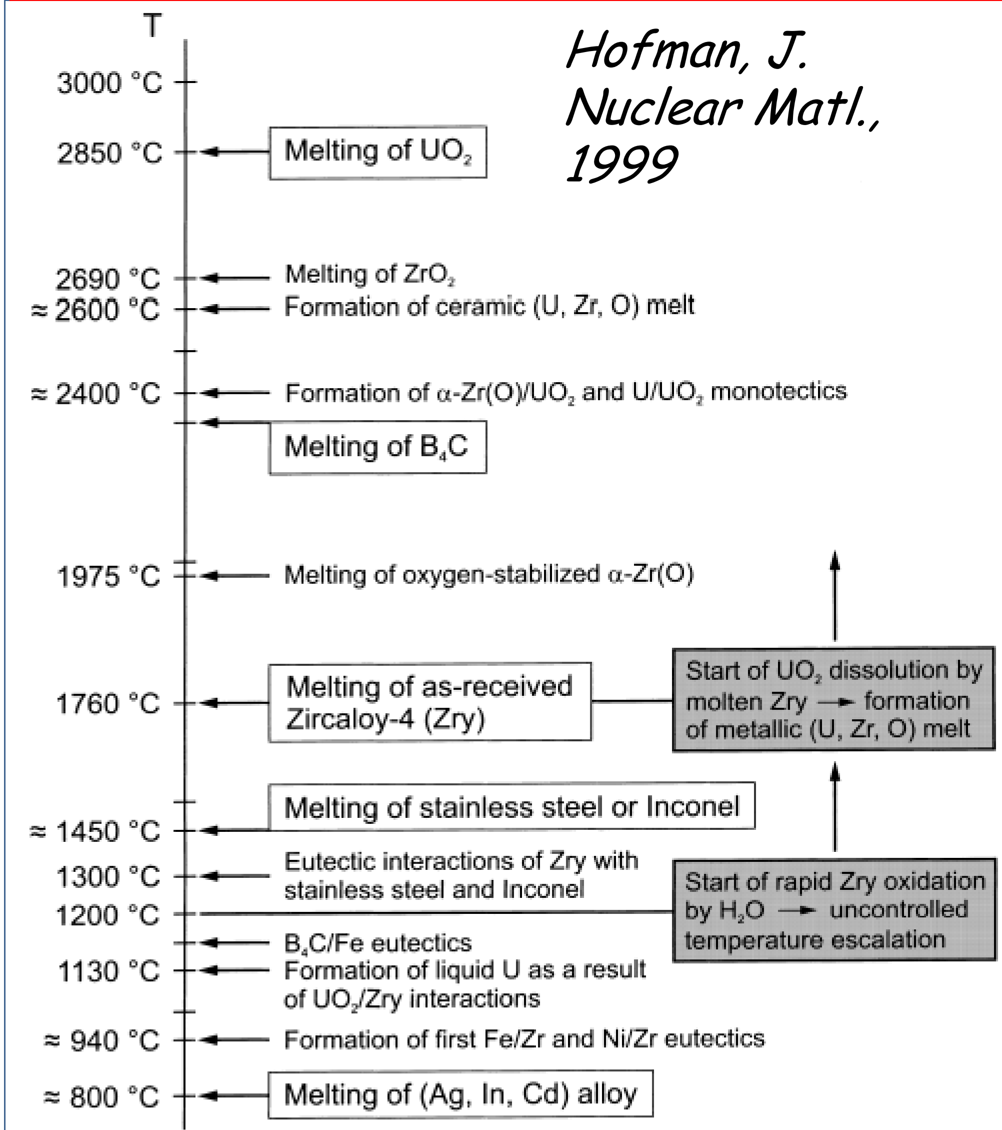
NORMAL CONDITIONS



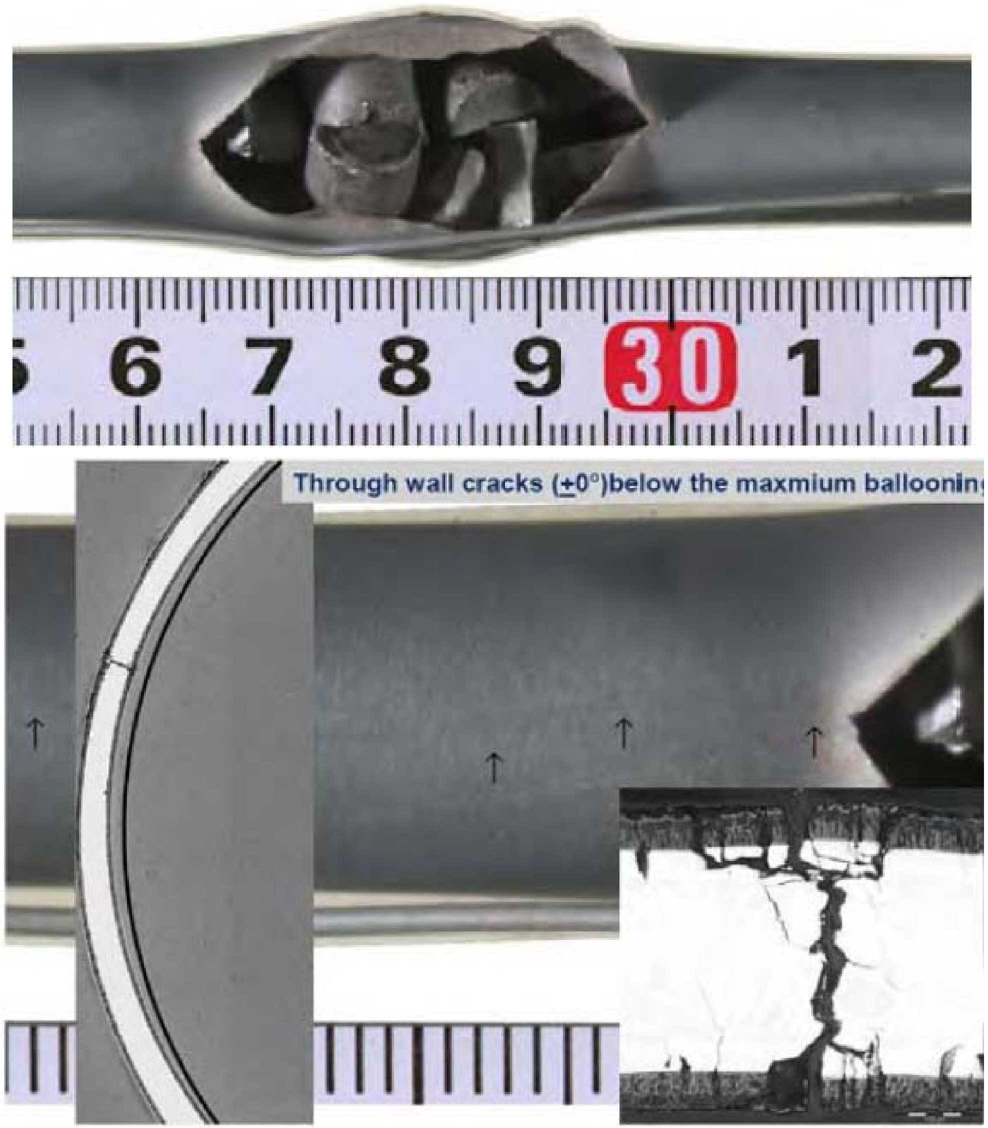
Steam – Its generation and uses, 41rst Ed Babcock - Wilcox

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:

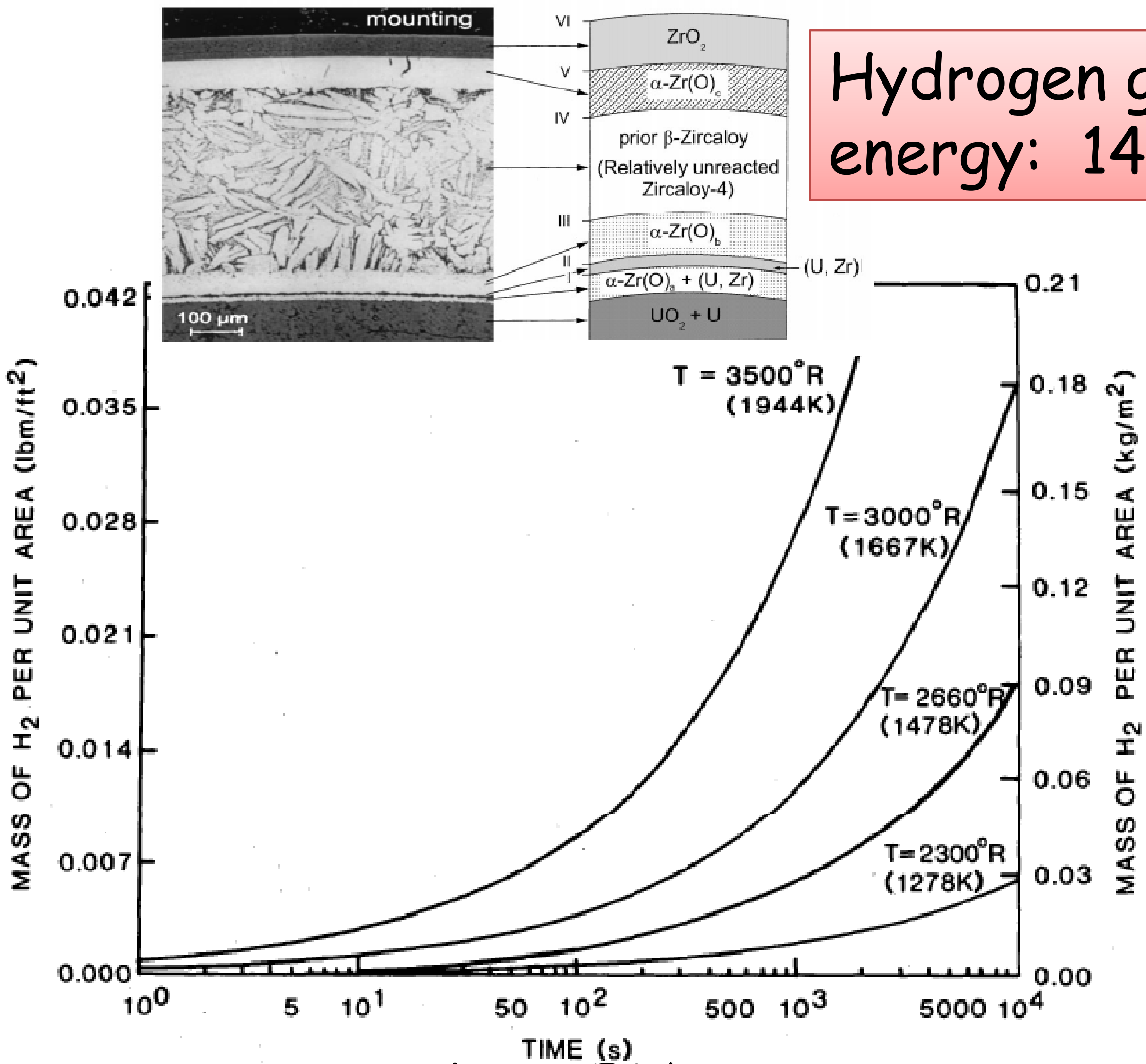
Ballooning and relocation of fuel.

Through wall cracks.

Rupture of cladding → releasing FP gases and fuel

NEA 6846 2009

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



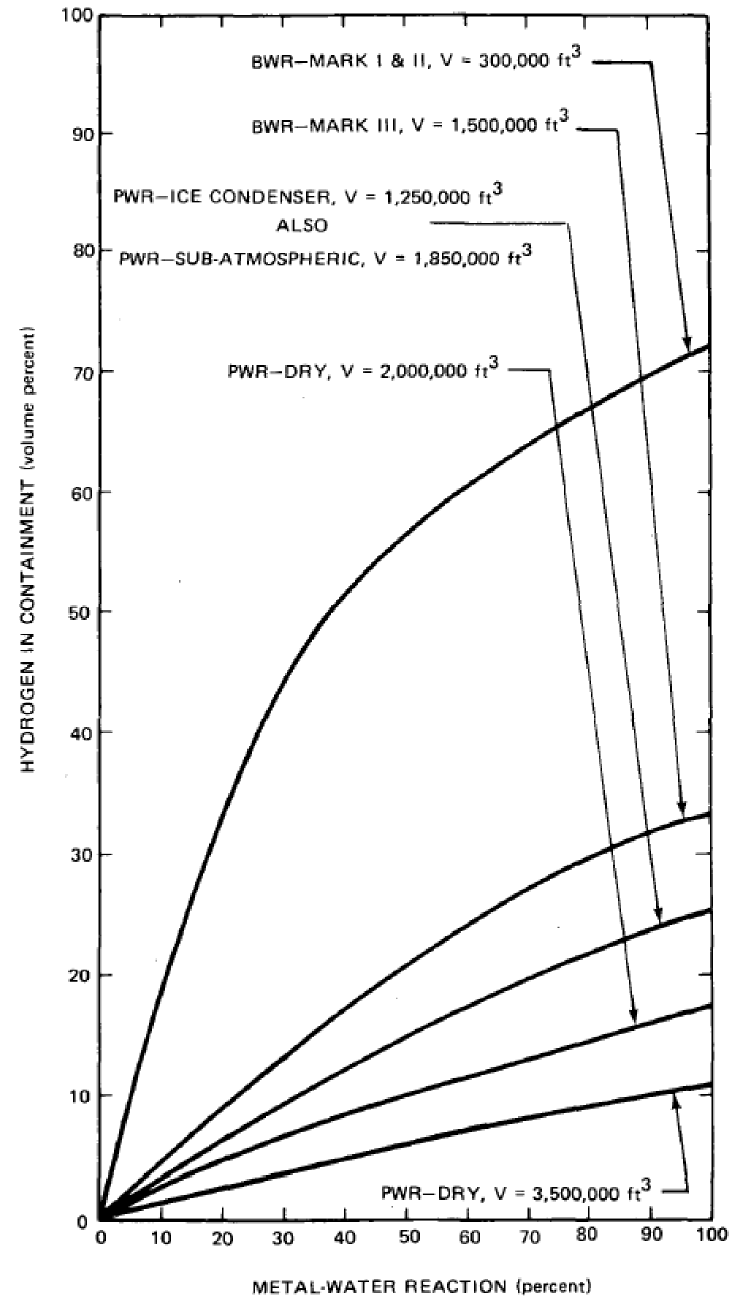
LWR H2 Manual NUREG/CR-2726

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

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



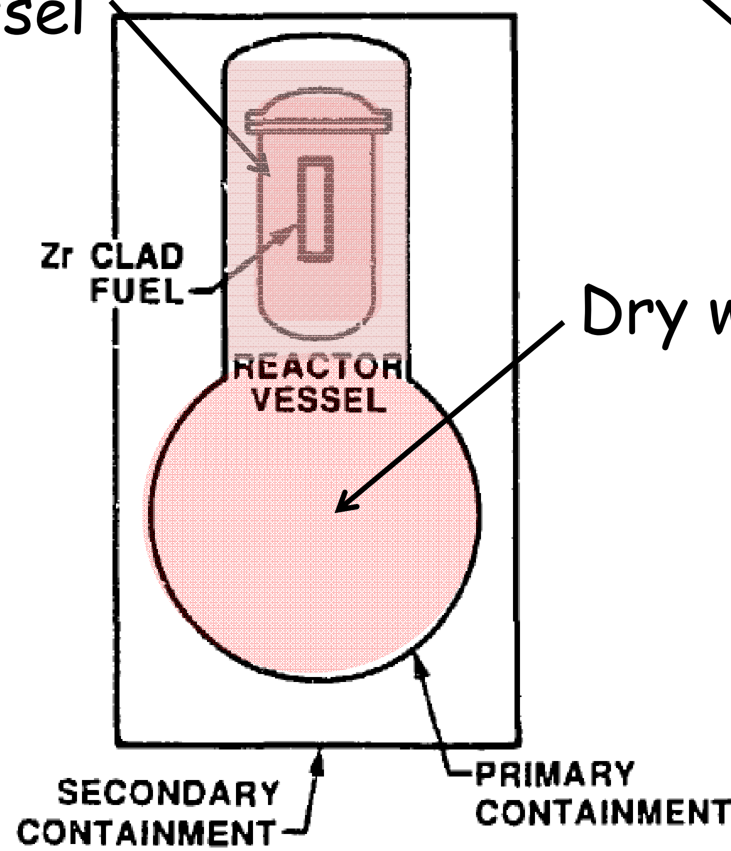
LWR H2 Manual NUREG/CR-2726

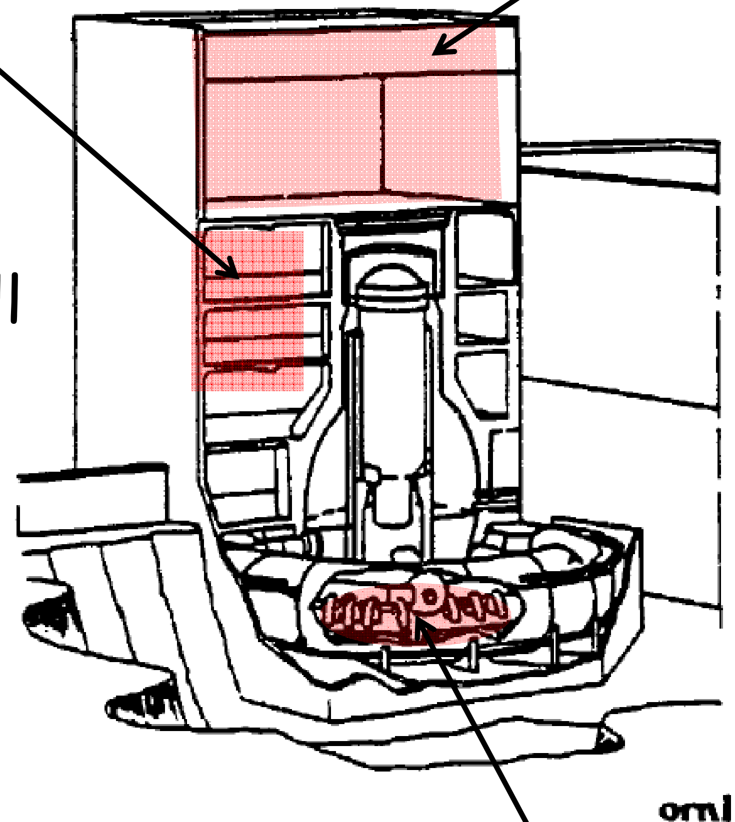
Observations

- 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

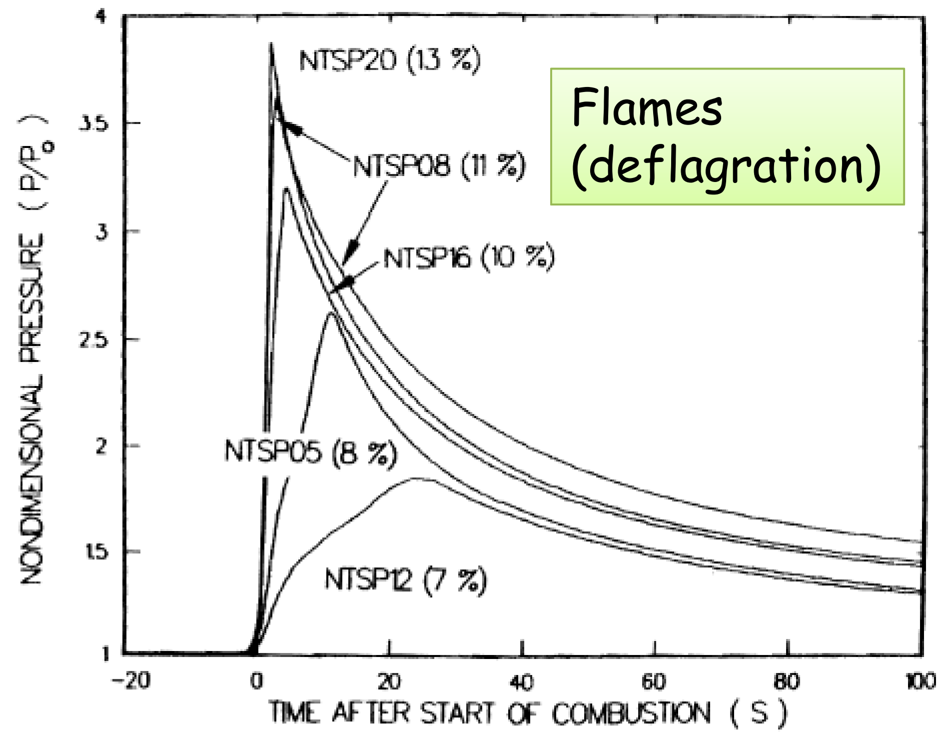
Hydrogen Combustion

- $H_2 + 1/2\ O_2$ (+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)

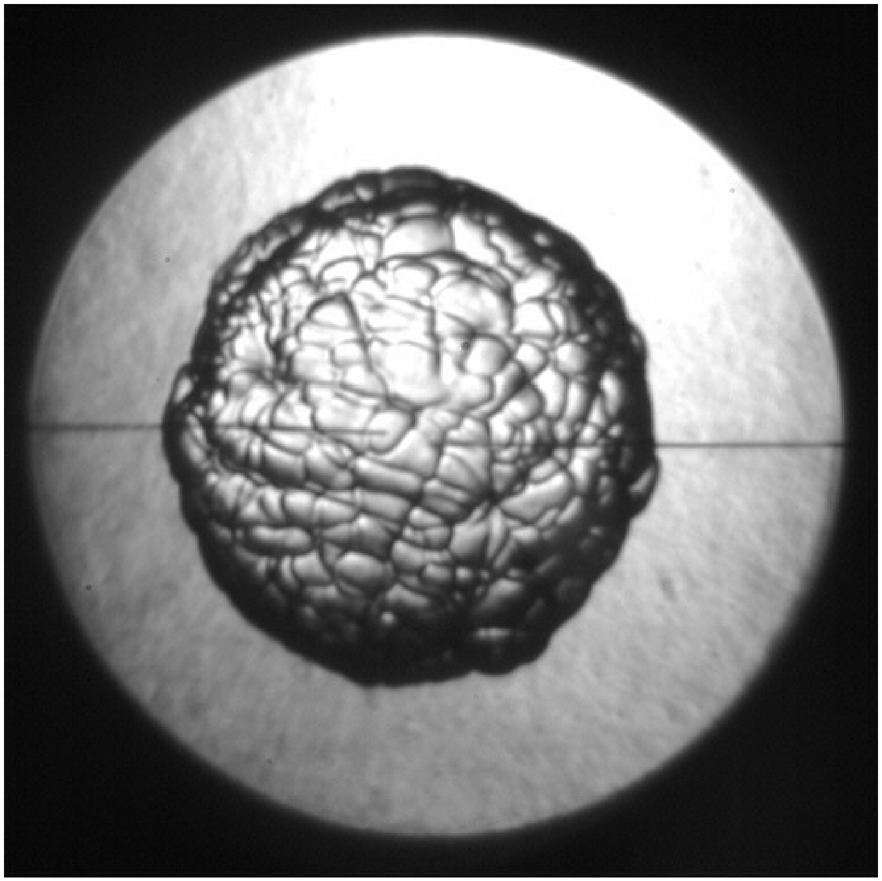
NUREG/CR-4138 Ratzel 1986

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

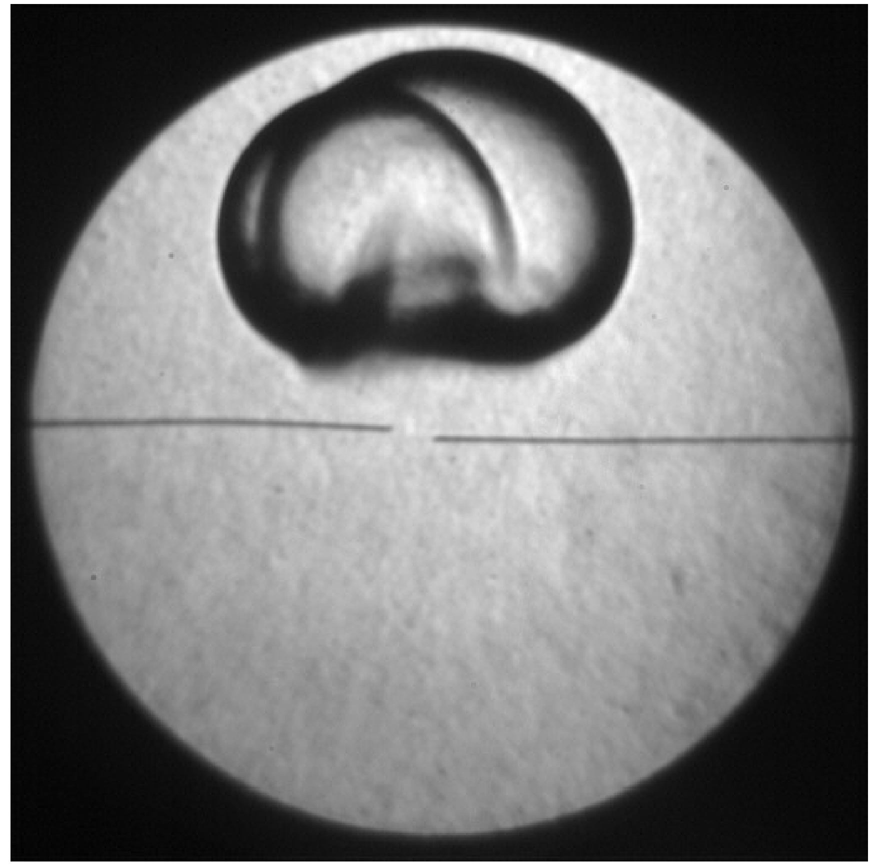
RPV 8500 m^3
Refueling bay 32,000 m^3



Hydrogen Flames



10% H2 in O_2/Ar

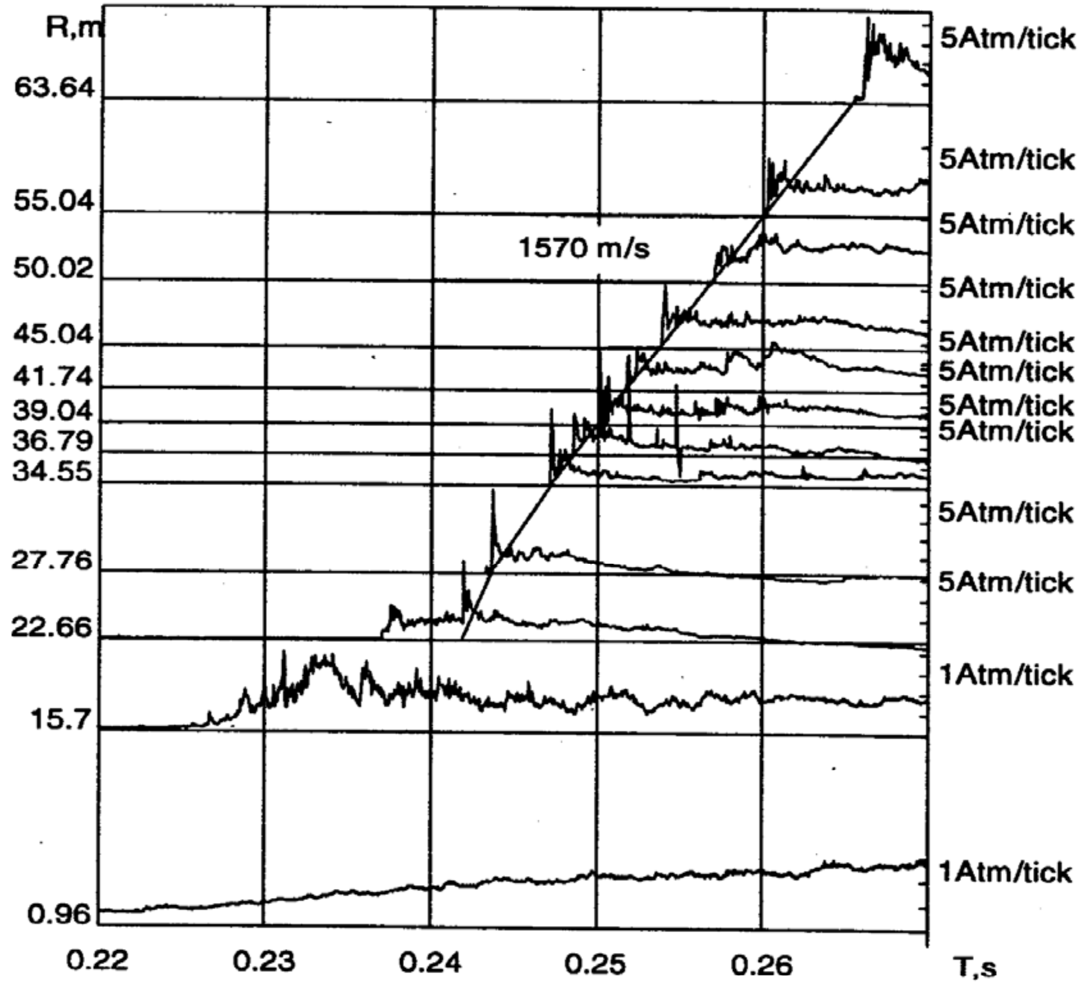


5% H2 in O_2/Ar

SPM Bane – Caltech Explosion Dynamics Lab 2010

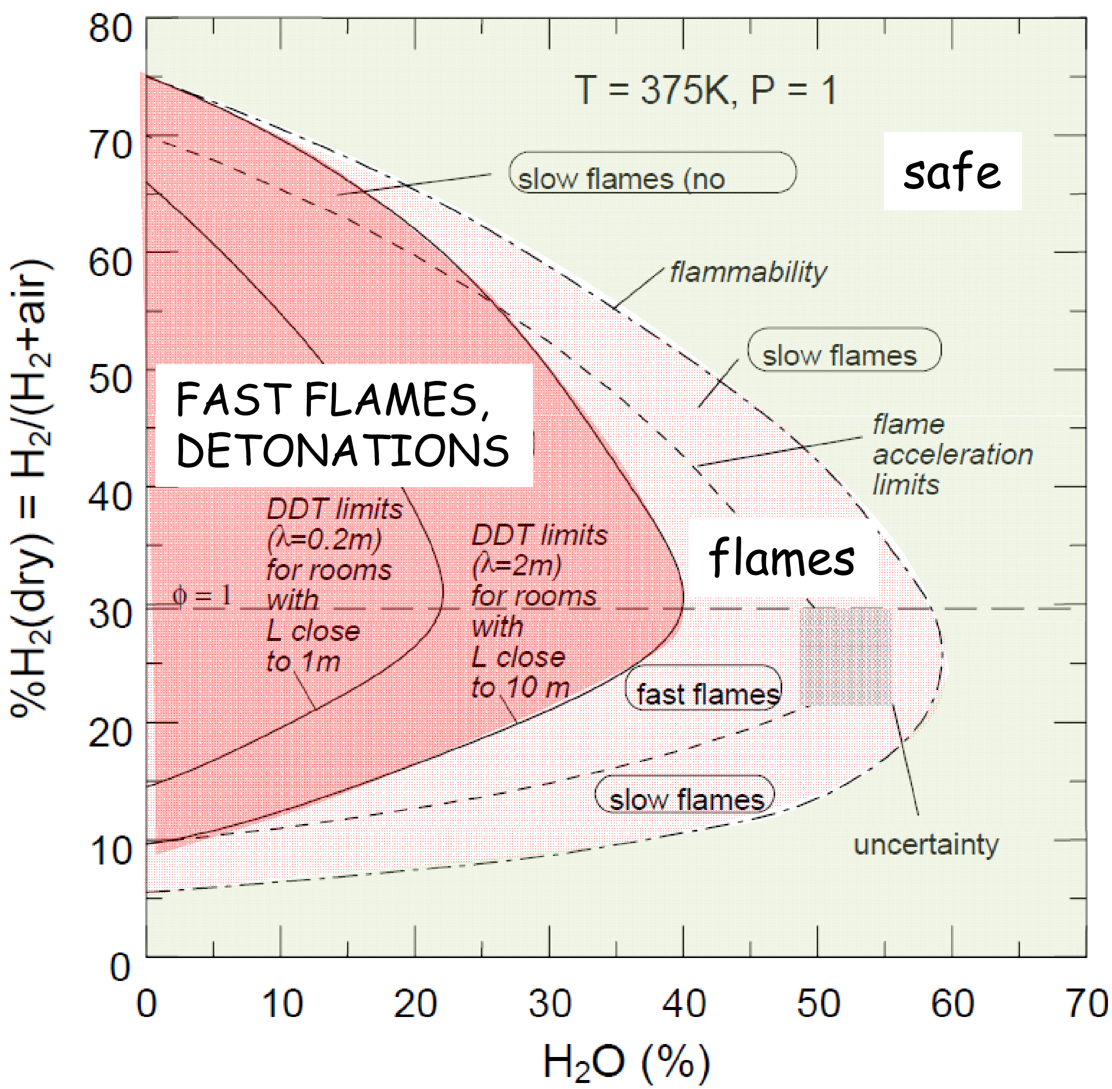
Deflagration or Detonation?

- 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

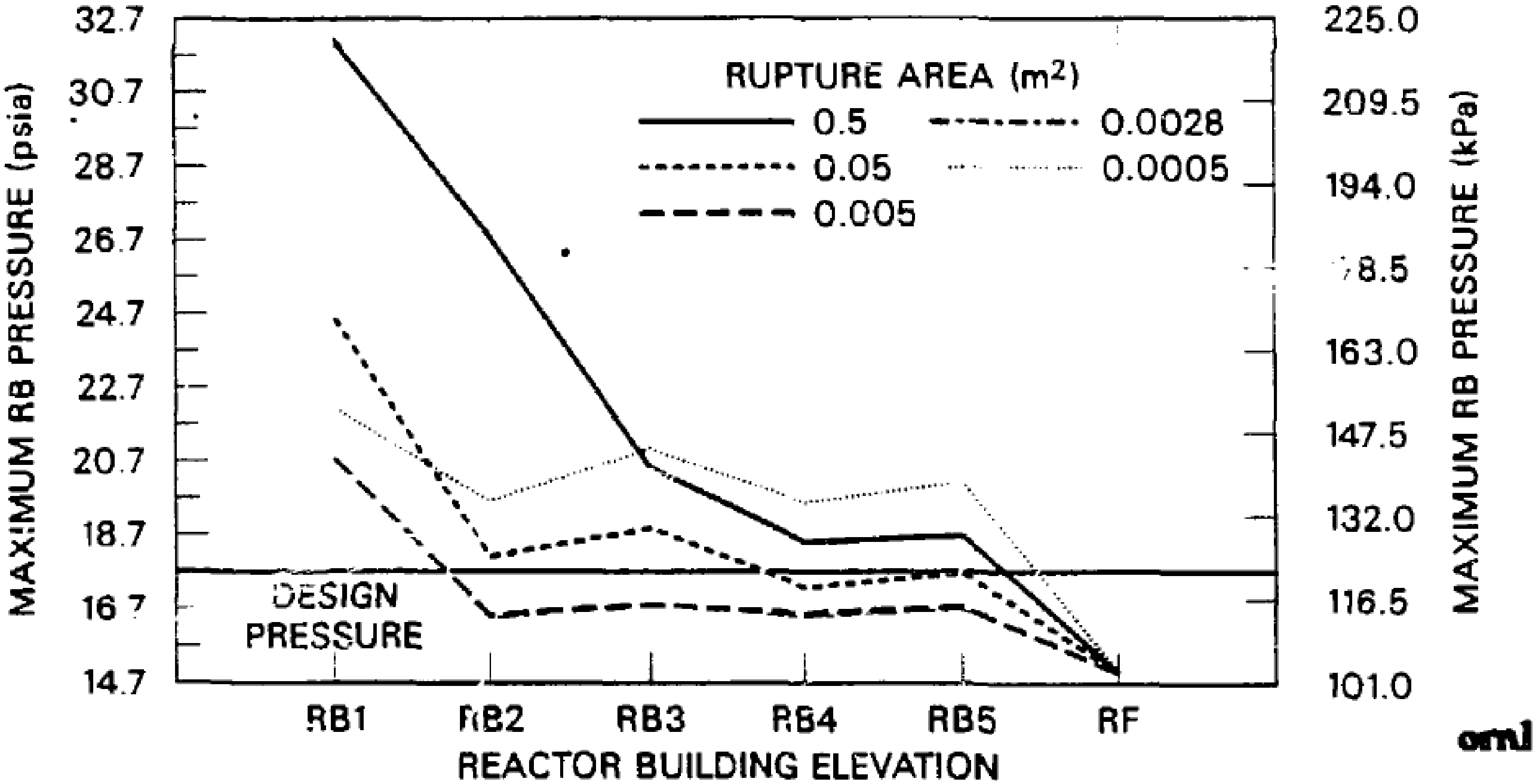


OECD NEA/CSNI/R(2000)7

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

http://www.guardian.co.uk/world/video/2011/mar/14/fukushima-nuclear-plant-reactor-explosion-video

Unit 3

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 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?
- Very substantial damage from explosion
  - Blow out of a larger number of panels suggests significant buildup of hydrogen within refueling bay.

Released from Tokyo Electric Power Co (TEPCO) on March 16, 2011
http://photoblog.msnbc.msn.com/_news/2011/03/16/6277564-tokyo-electric-power-company-released-new-images-of-damaged-nuclear-reactors

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

Accident Progression so Far

- Seismic event, strong shaking, land subsidence and displacement
- Loss of off-site power (grid connection fails)
- Tsunami event
- Loss of all back-up diesel generators
- Battery back-up only powers instruments/some valves
- Batteries fail
- Decay heat removal (Isolation condenser in unit 1, RCICS in unit 2, 3) fails
- Cores uncovered, Zr cladding overheats and oxidized by steam
- Cores severely damaged, generate hydrogen
- Vent RPV in order to lower pressure and fill with water
- Fill RPV with sea water with fire lines, vent steam into suppression pool
- Primary containment inert – filled with steam/N2/Hydrogen
- Vent primary to avoid failing containments
- Reactor building is filled with hydrogen-air-steam mixture that ignites
- Hydrogen explosion causes building panels to blow out - creates release path for fission products to atmosphere – ejects particulates into atmosphere

Spent Fuel Pools

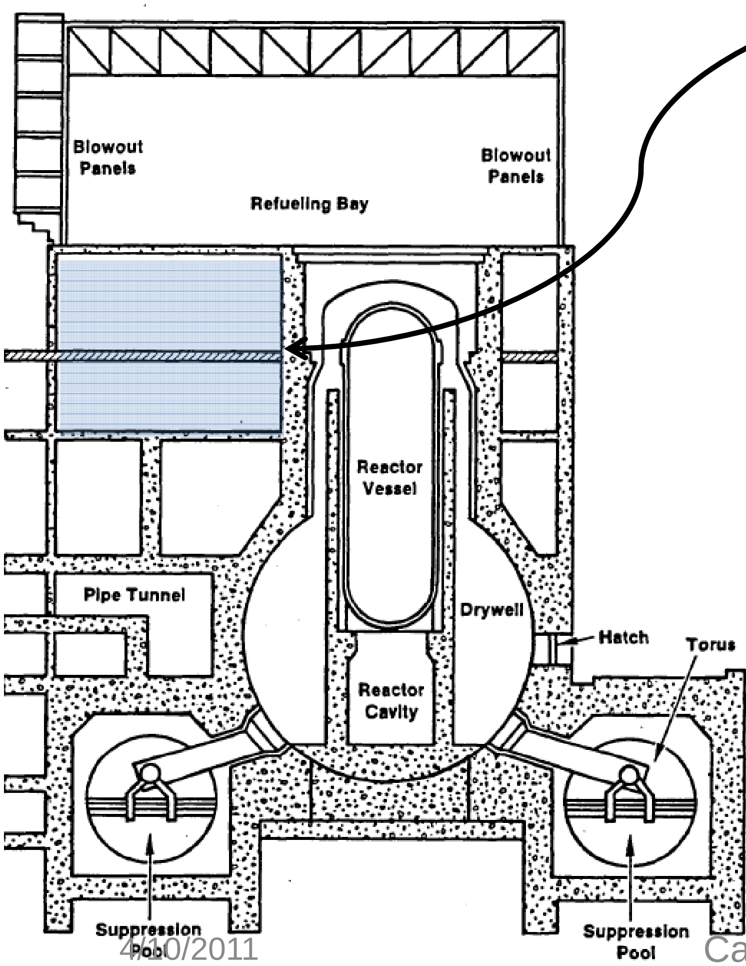
Number of Fuel Assemblies in Cooling Pools at Fukushima Daiichi
(Reported 17 March by Japan's Ministry of Economy, Trade and Industry)

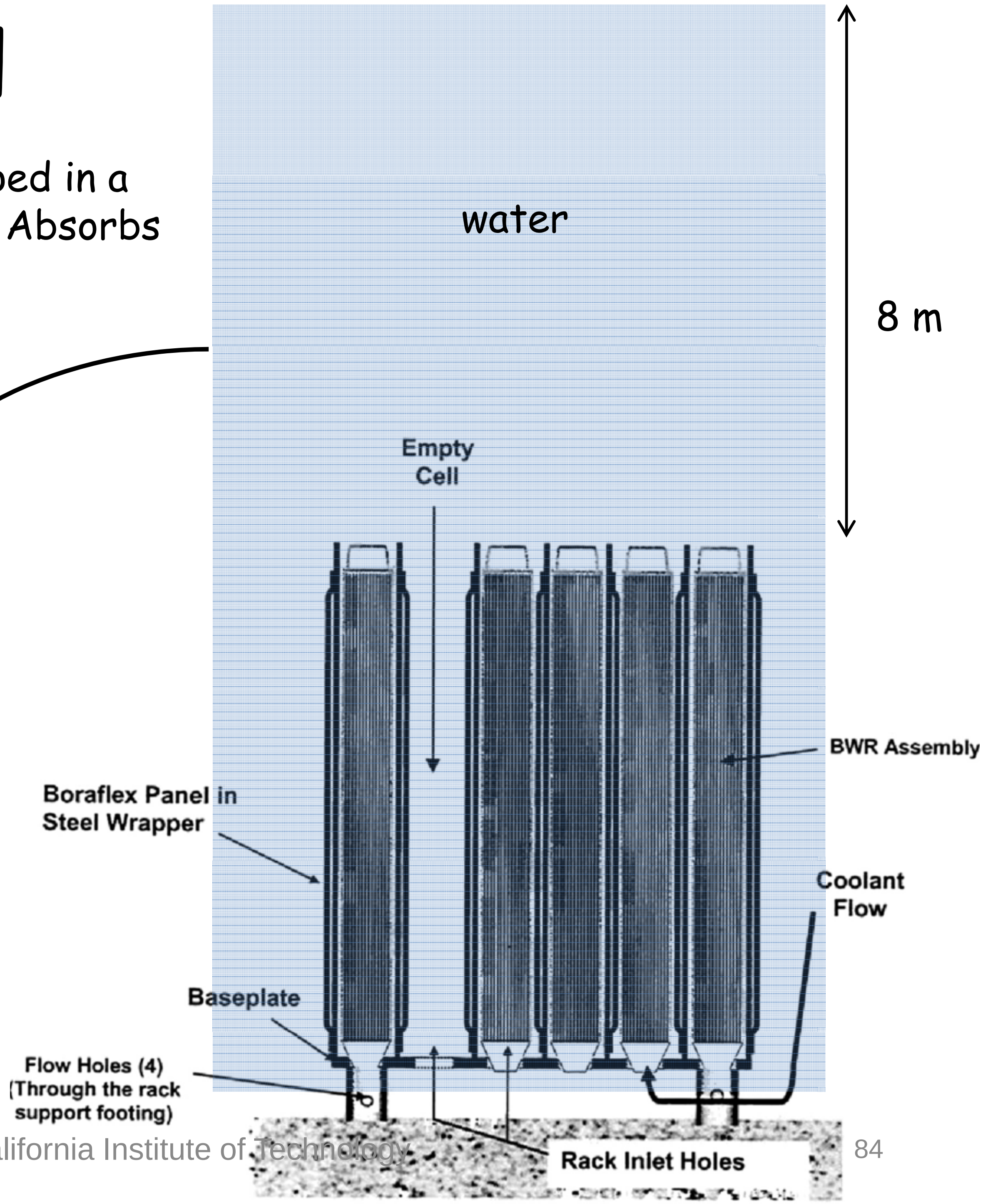
	Capacity	Irradiated Fuel Assemblies	Unirradiated Fuel Assemblies	Most Recent Additions of Irradiated Fuel
Unit 1	900	292	100	Mar-10
Unit 2	1,240	587	28	Sep-10
Unit 3	1,220	514	52	Jun-10
Unit 4	1,590	1,331	204	Nov-10
Unit 5	1,590	946	48	Jan-11
Unit 6	1,770	876	64	Aug-10

Spent Fuel

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

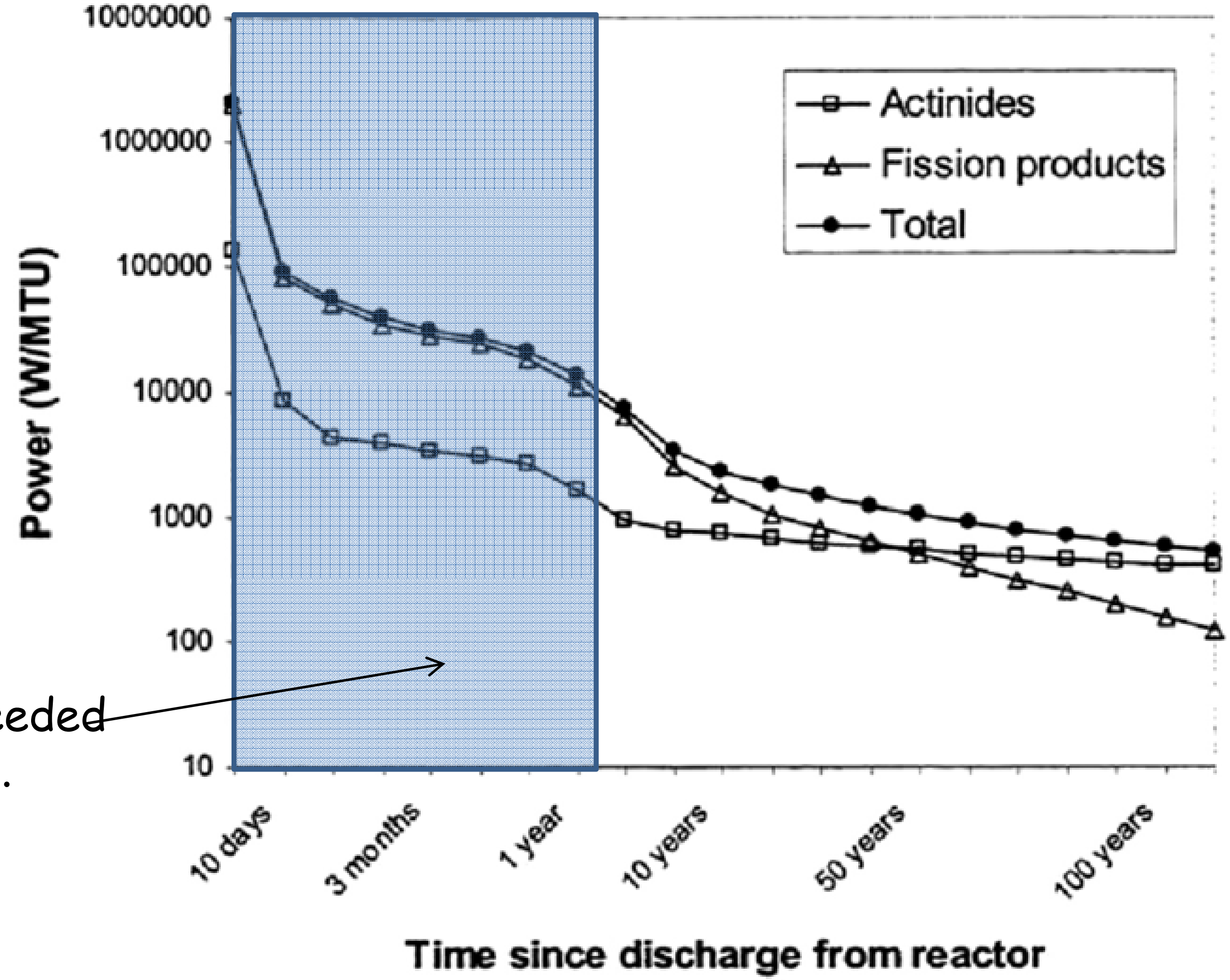
NAS 2006





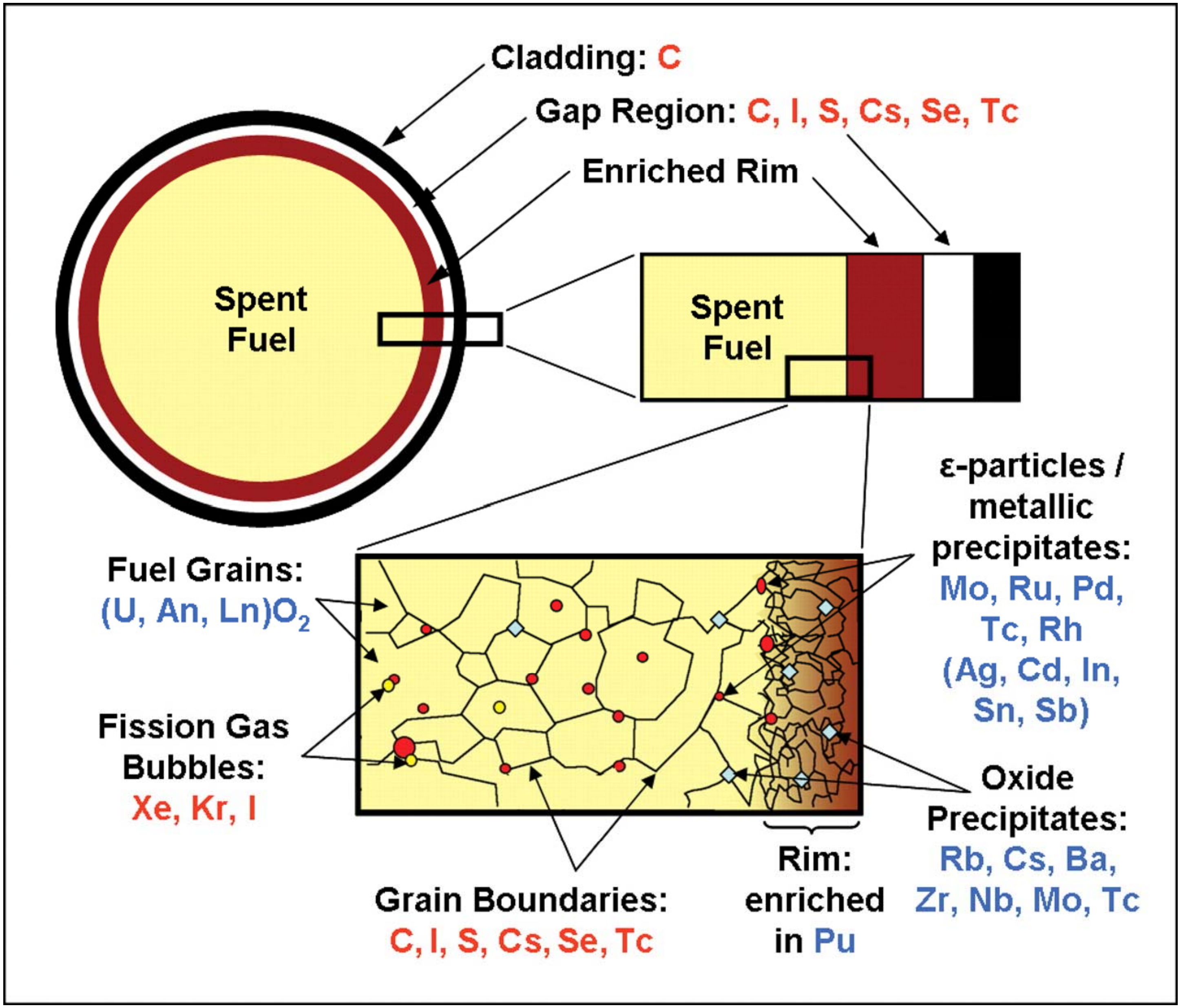
Decay heat

Actinides are U, Pu, Np, Am



Active cooling needed for first 3 years.

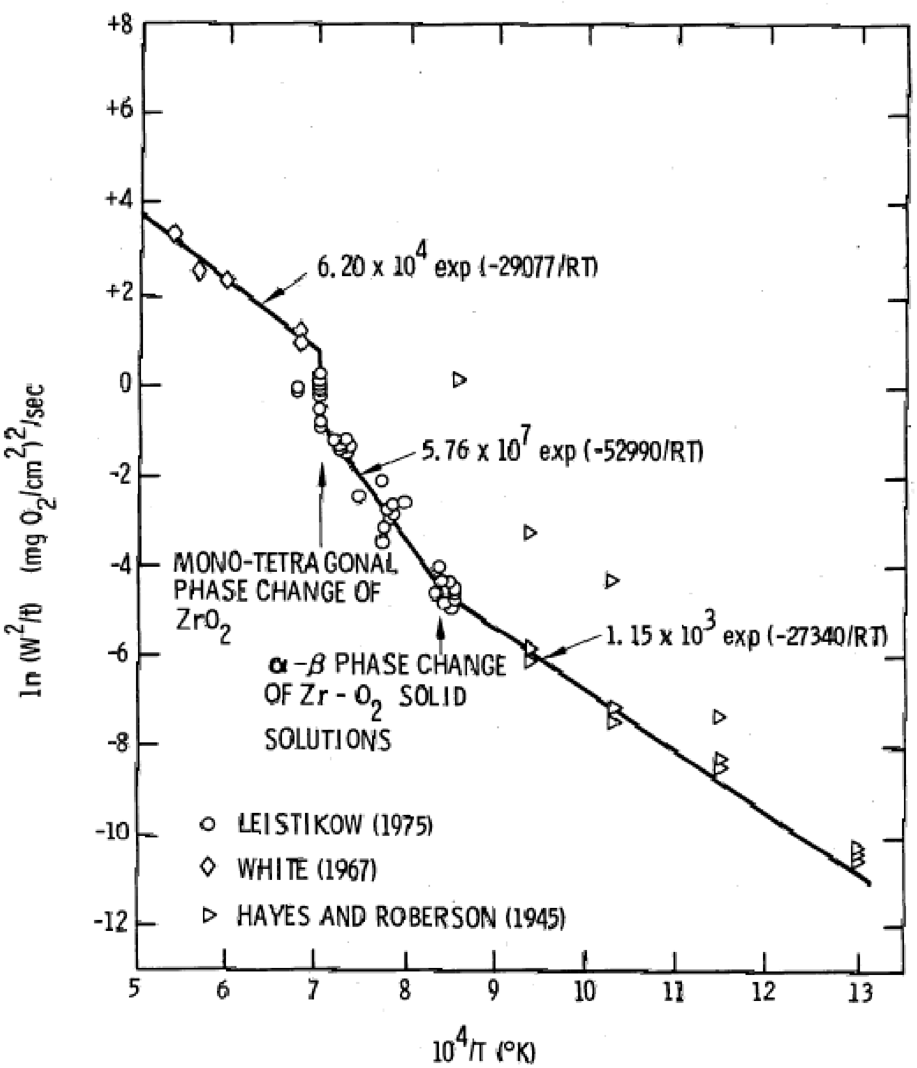
Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report http://www.nap.edu/catalog/11263.html



Elements; December 2006; v. 2; no. 6; p. 343-349; DOI: 10.2113/gselements.2.6.343

Air Oxidation of Zircaloy

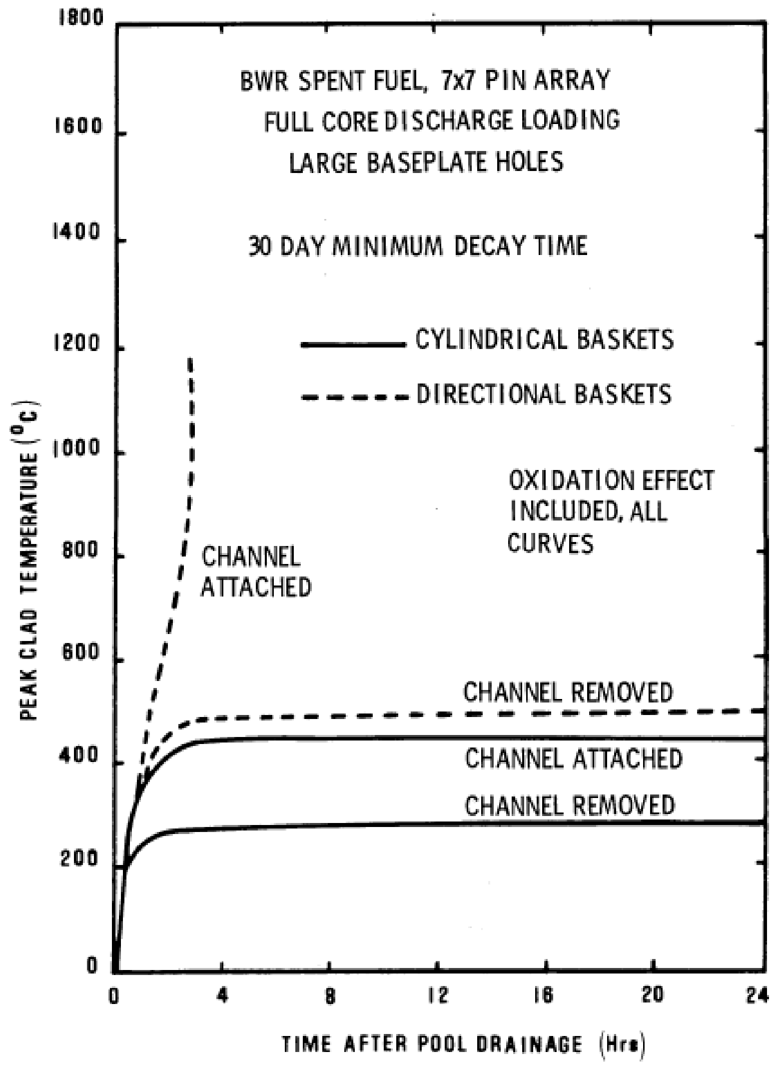
- $Zr + O_2 \rightarrow ZrO_2$
- +1260 kJ/mole Zr
- Parabolic rate law
  $$\frac{d}{dt}m^2 = K_o \exp(-E_a/RT)$$
- *m* = mass of O_2/area
- Diffusion-controlled if starved for O2
- Decay heat and oxidation heating cause cladding failure (rupture) at 850 - 950 C.



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

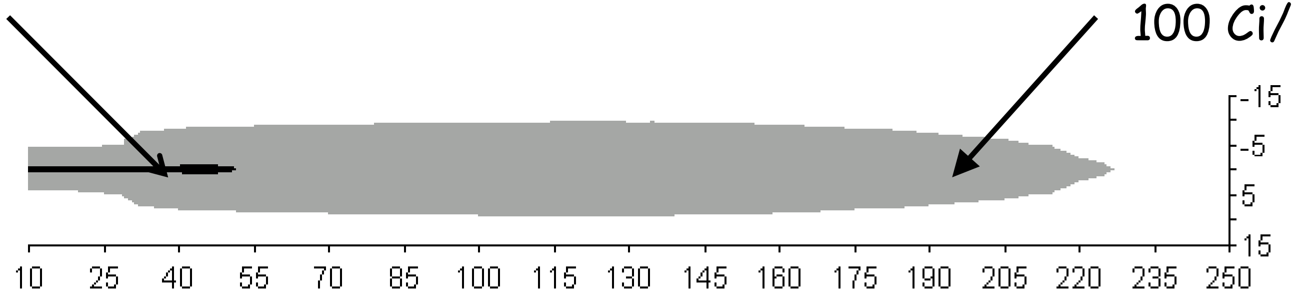
Loss of Pool Water Accident

- 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)

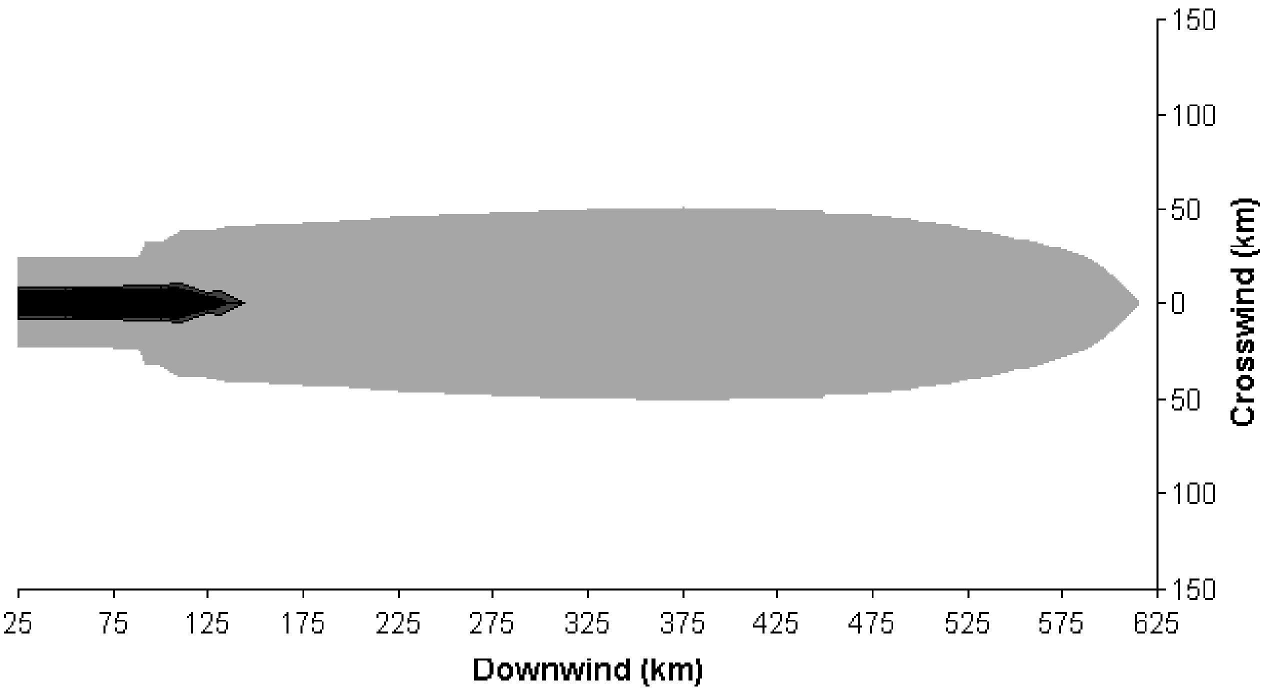


NUREG/CR-0649 Spent Fuel Heatup Following Loss of Water During Storage

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
  - H2 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

NY Times – DigitalGlobe

Helicopter water drops

17 March NHK/Getty/AFP

Unit 4 March 18

Japan SDF

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
http://www.youtube.com/watch?v=oQ4TqMZq-rs&feature=player_detailpage

Water spraying Unit 3 from ground by fire trucks March 19 – 4:58
http://www.youtube.com/watch?v=v8Tds5d-ApU&feature=player_detailpage

View from the ground of adding water to Unit 4, Mar 22 0:56
http://www.youtube.com/watch?v=Hs2AUmmUcKQ&feature=player_detailpage

SDF helicopter footage from 23 Mar – 5:00
http://www.youtube.com/watch?v=mI2vYcxc16A&feature=player_detailpage

Commentary on SDF helicopter footage on NHK, March 27
http://www.youtube.com/watch?v=wAEixbcPhG4&feature=player_detailpage

High resolution aerial photography
http://cryptome.org/eyeball/daiichi-npp/daiichi-photos.htm

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

Continuing Updates

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

Current (April 6) Situation

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"

Overall Outlook – April 6

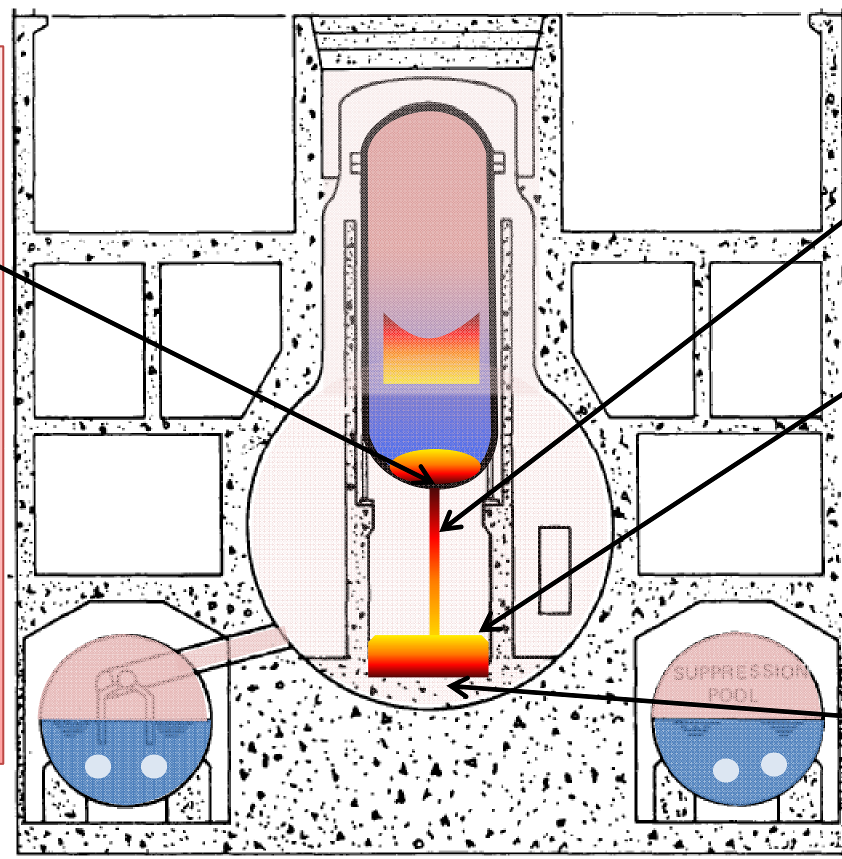
- Units 1-4 written off by Tepco
- Inside and around reactor buildings/turbine halls highly contaminated
- Extremely hazardous environment (high radiation, debris), difficult to even assess damage much less make repairs
- Although off-site power is restored to some systems, unclear how much of plant 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.

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

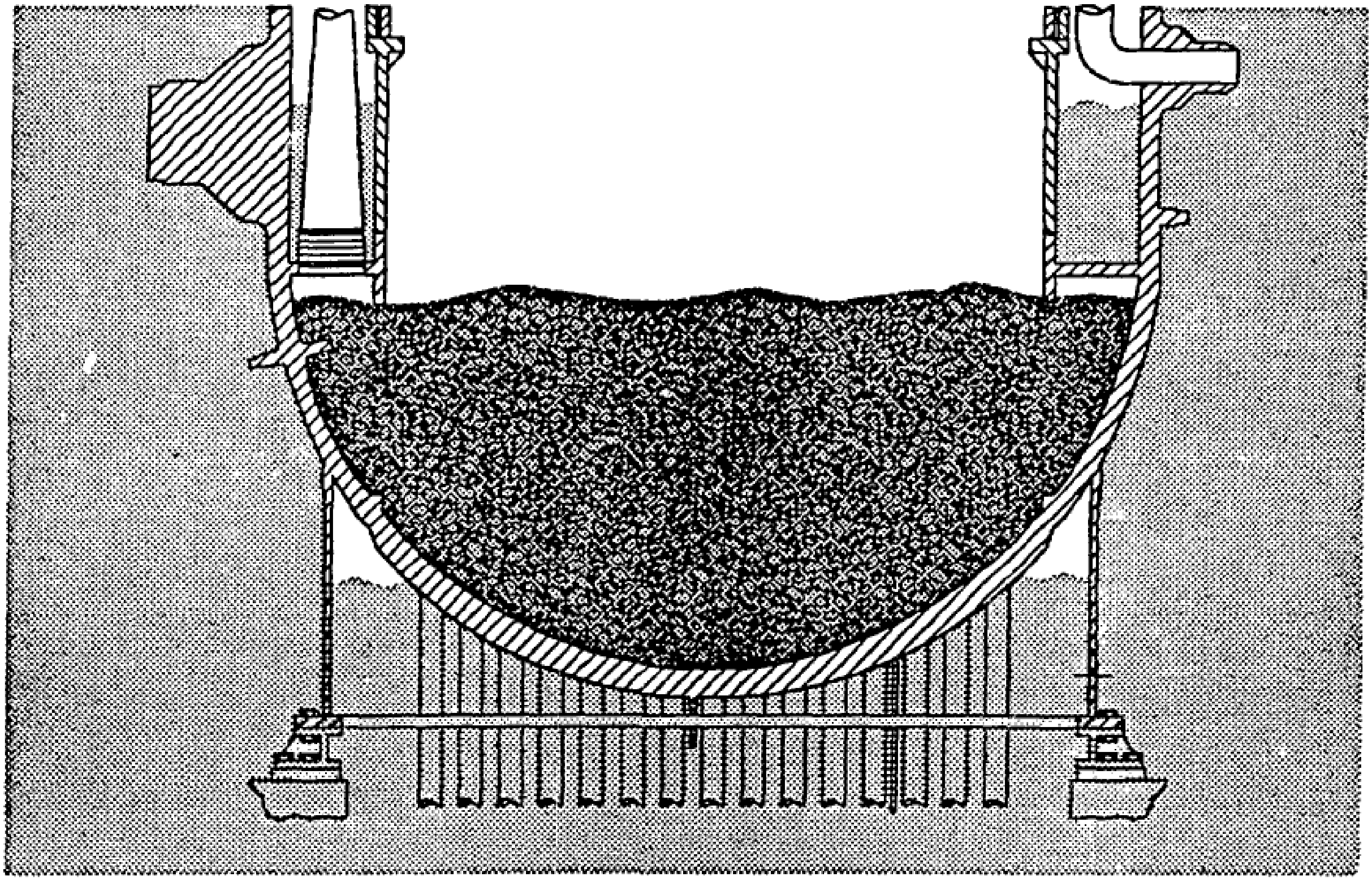
Can the cores melt through the pressure vessel?

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

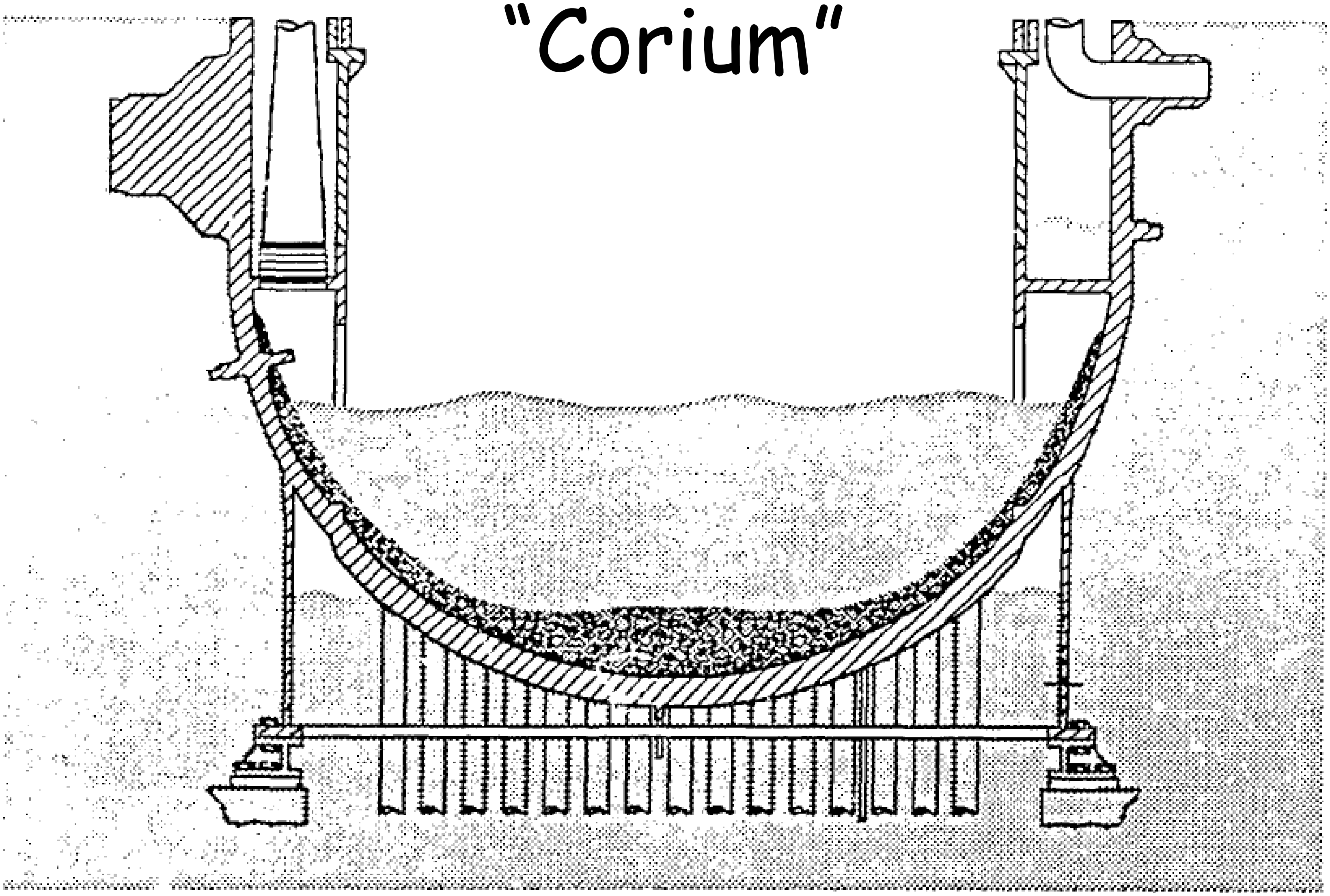
NUREG/CR-5869   Hodge et al CONF-921007—31 ORNL

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

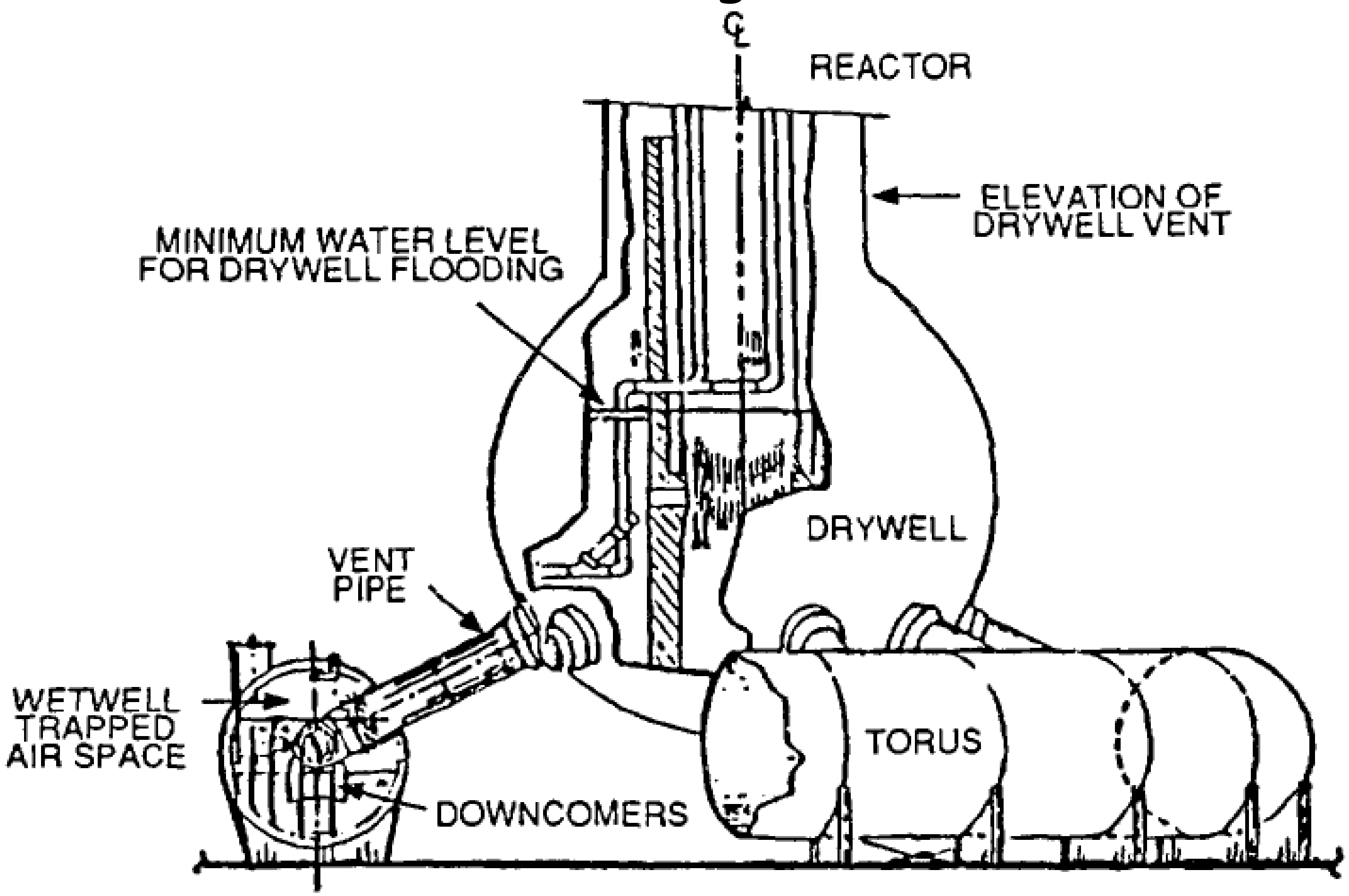
Failure Mechanisms

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

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

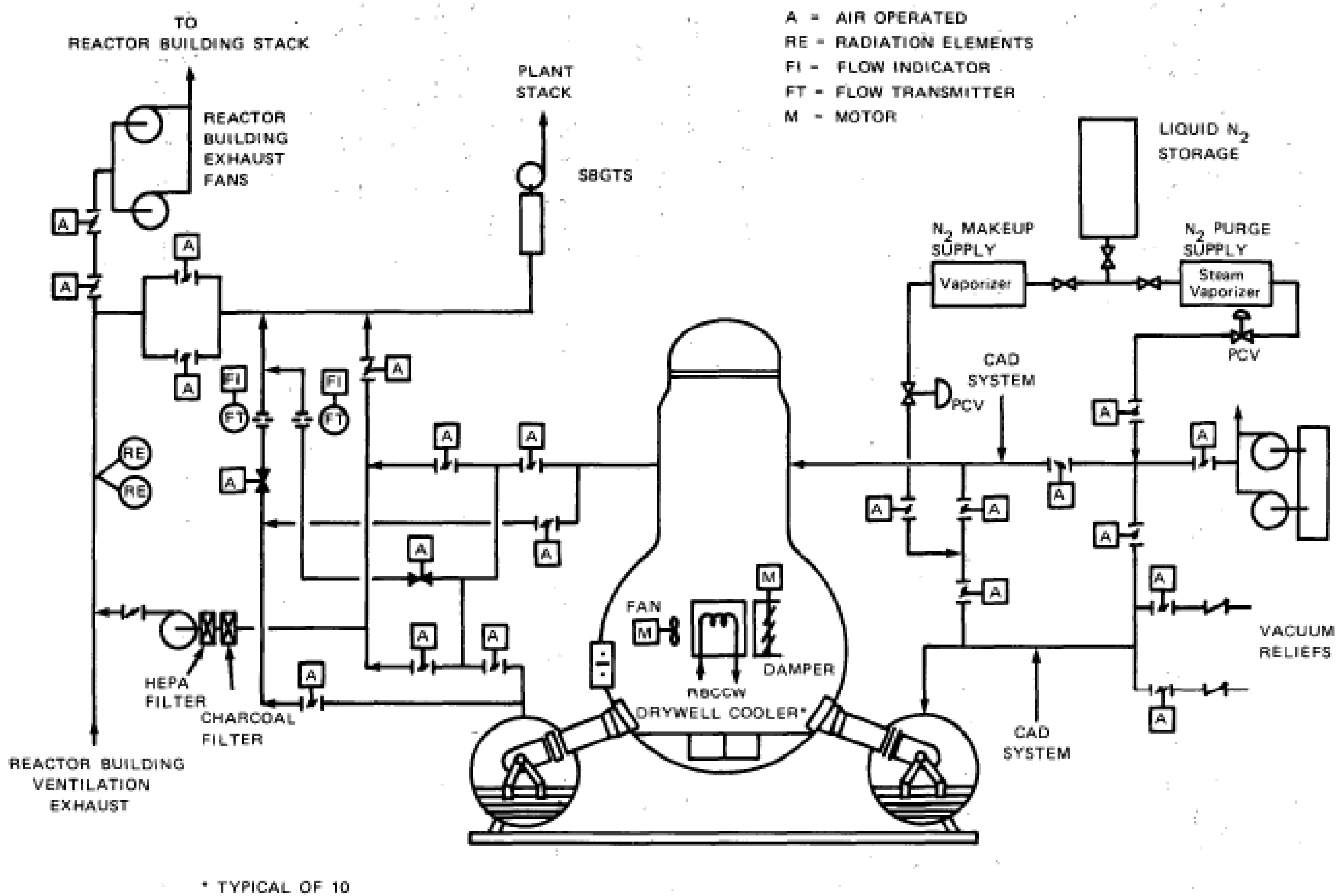


Fig 4-31 NUREG/CR-2726 LWR H2 Manual 1983

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

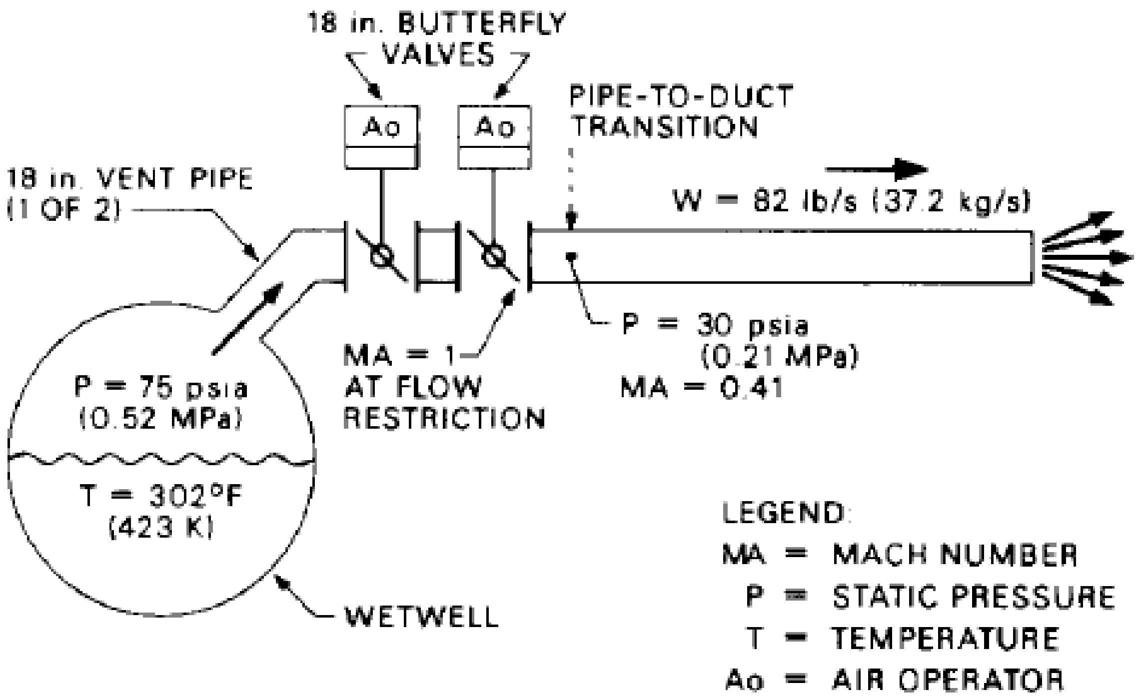


Fig. 3. Venting at elevated pressure would fail ventilation system ductwork in the torus room.

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.

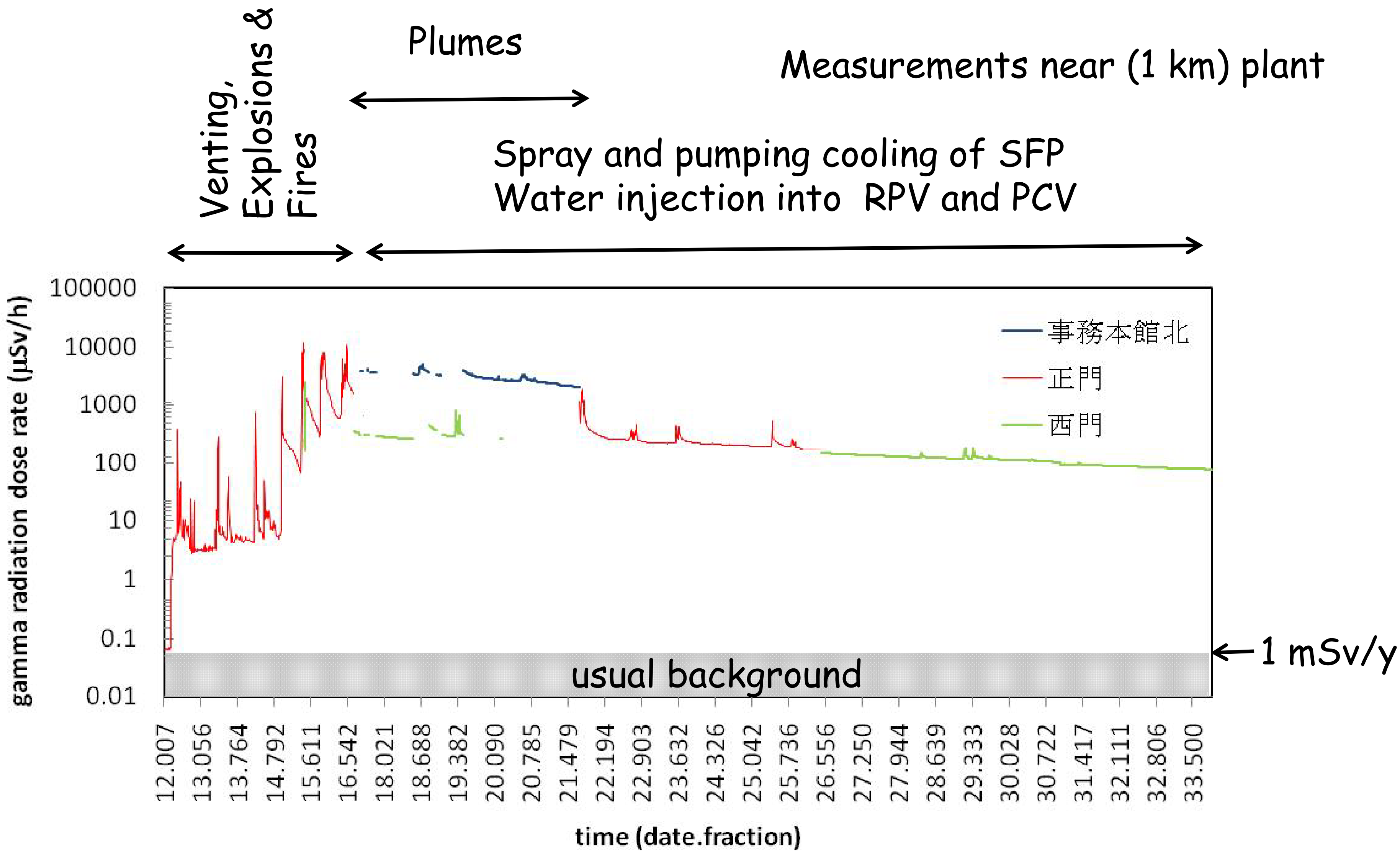
Possible Outcomes

1. Maintain cooling capability – core damaged but does not fail RPV.   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, requires 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.

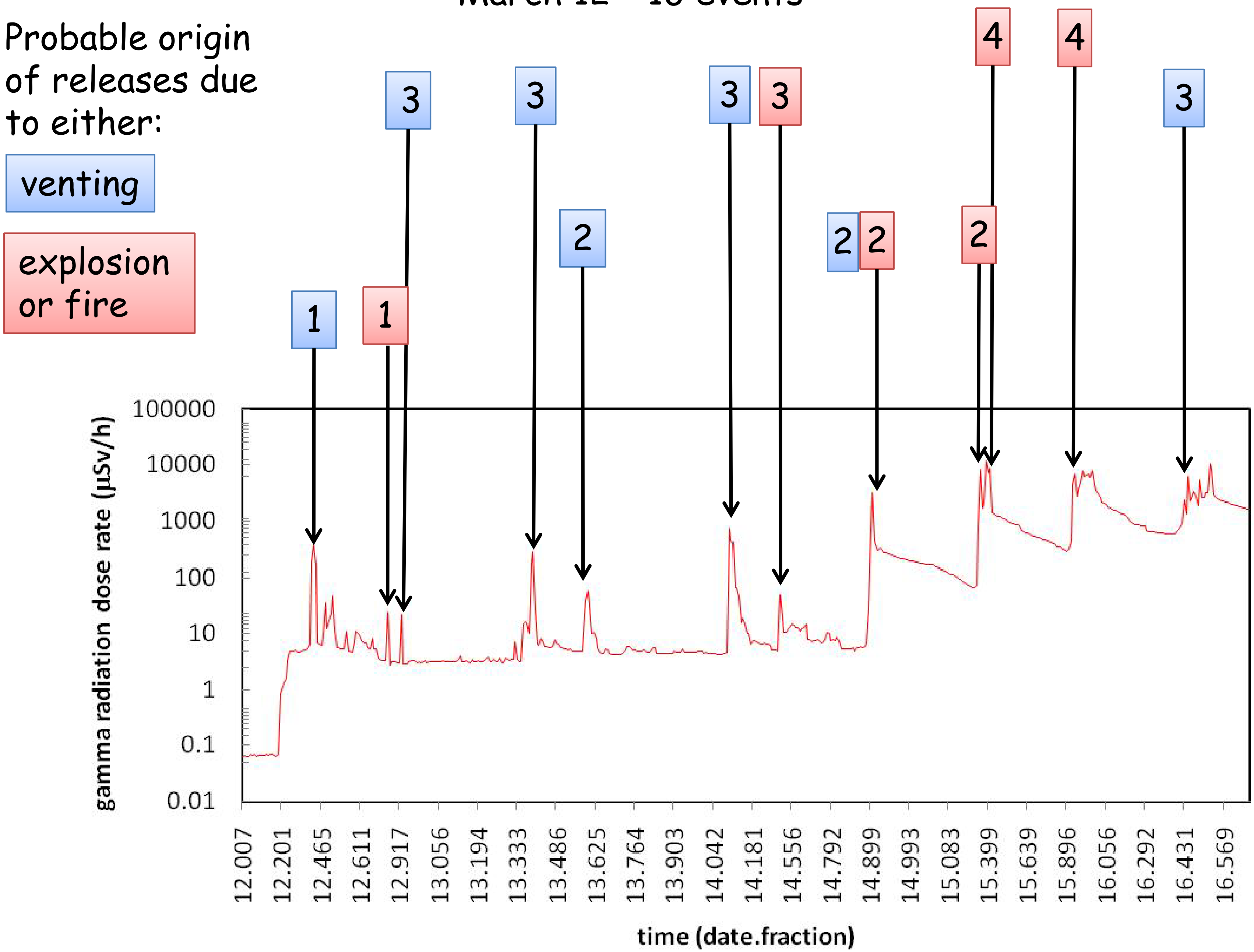
Radiological Consequences

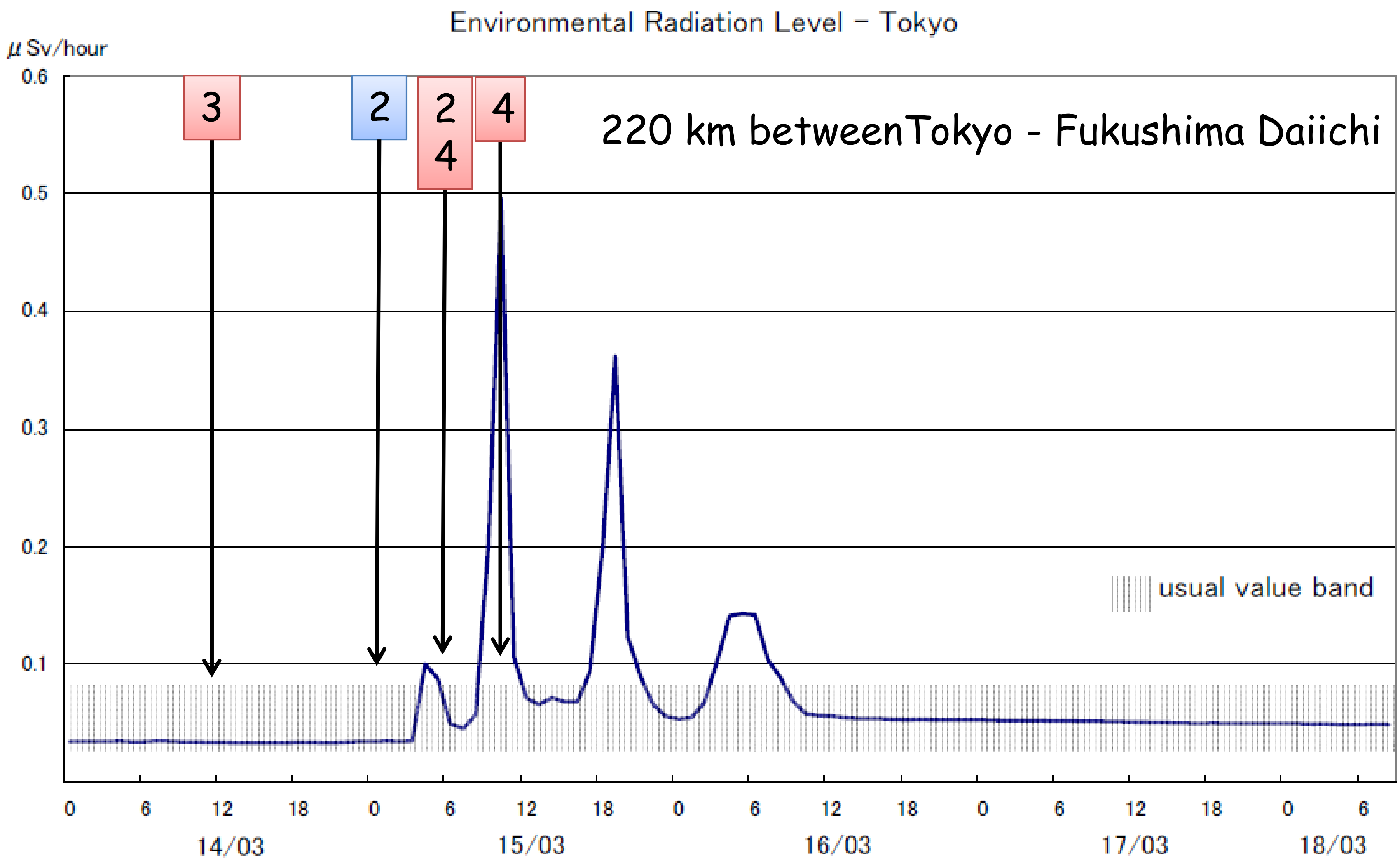
Extent of contamination and possible exposure of public to radiation

Releases of Fission Products into Air



March 12 – 16 events



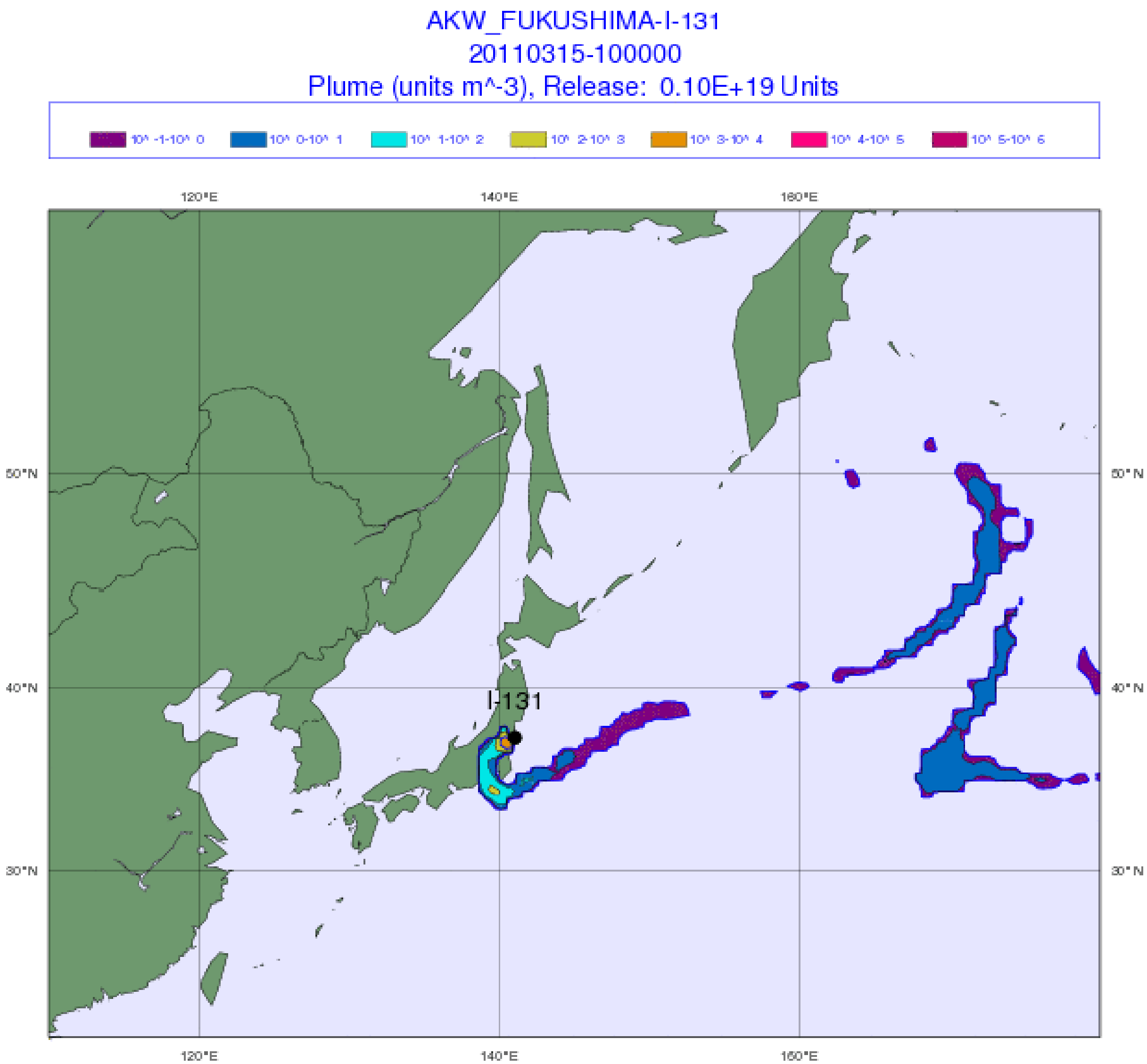


http://www.mext.go.jp/component/a_menu/other/detail/__icsFiles/afieldfile/2011/03/19/1303902_1818_5_2.pdf

Fission Products of Most Concern

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

Predictions of I-131 Dispersion



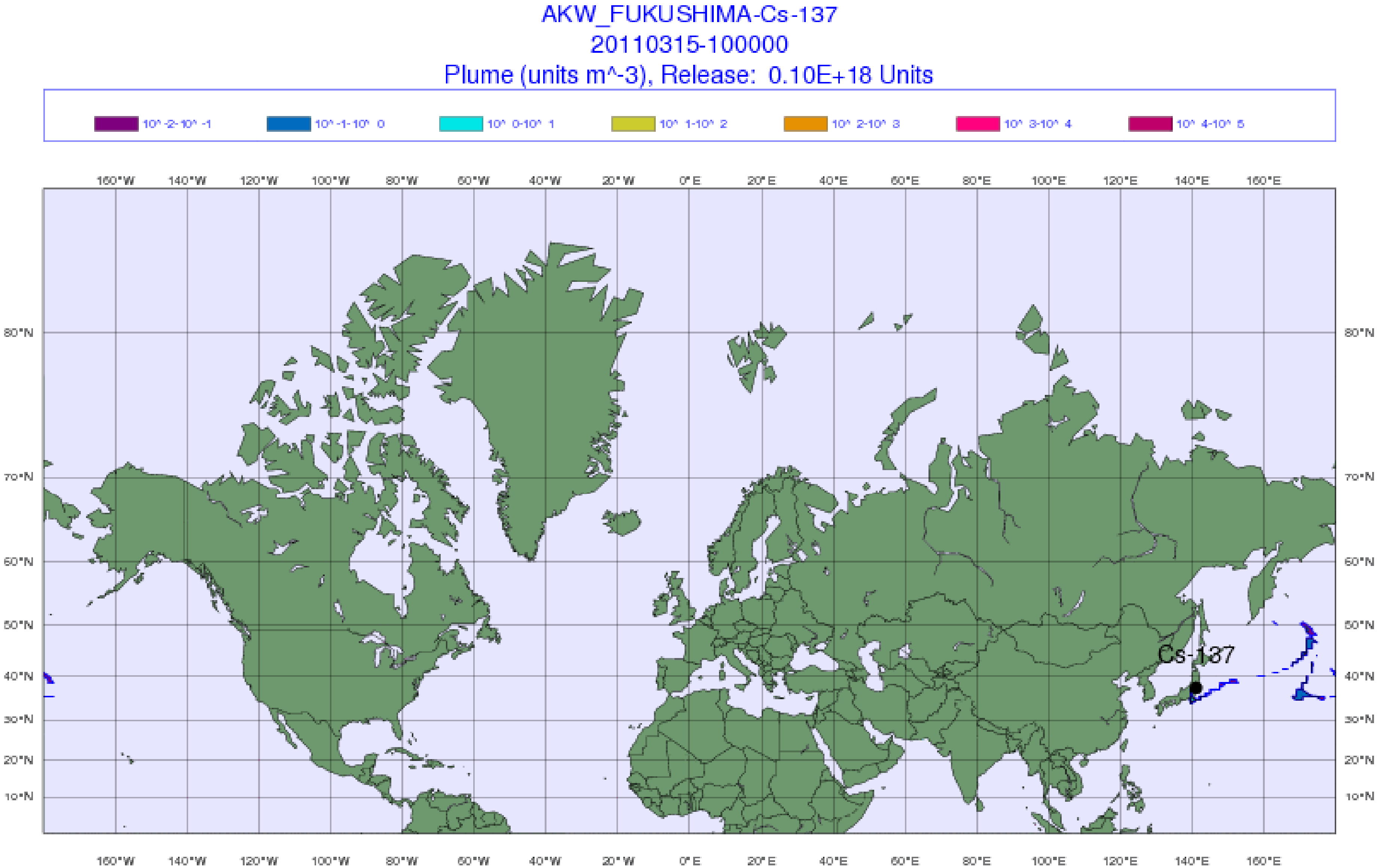
http://www.zamg.ac.at/

Continuous source term.

Global circulation model

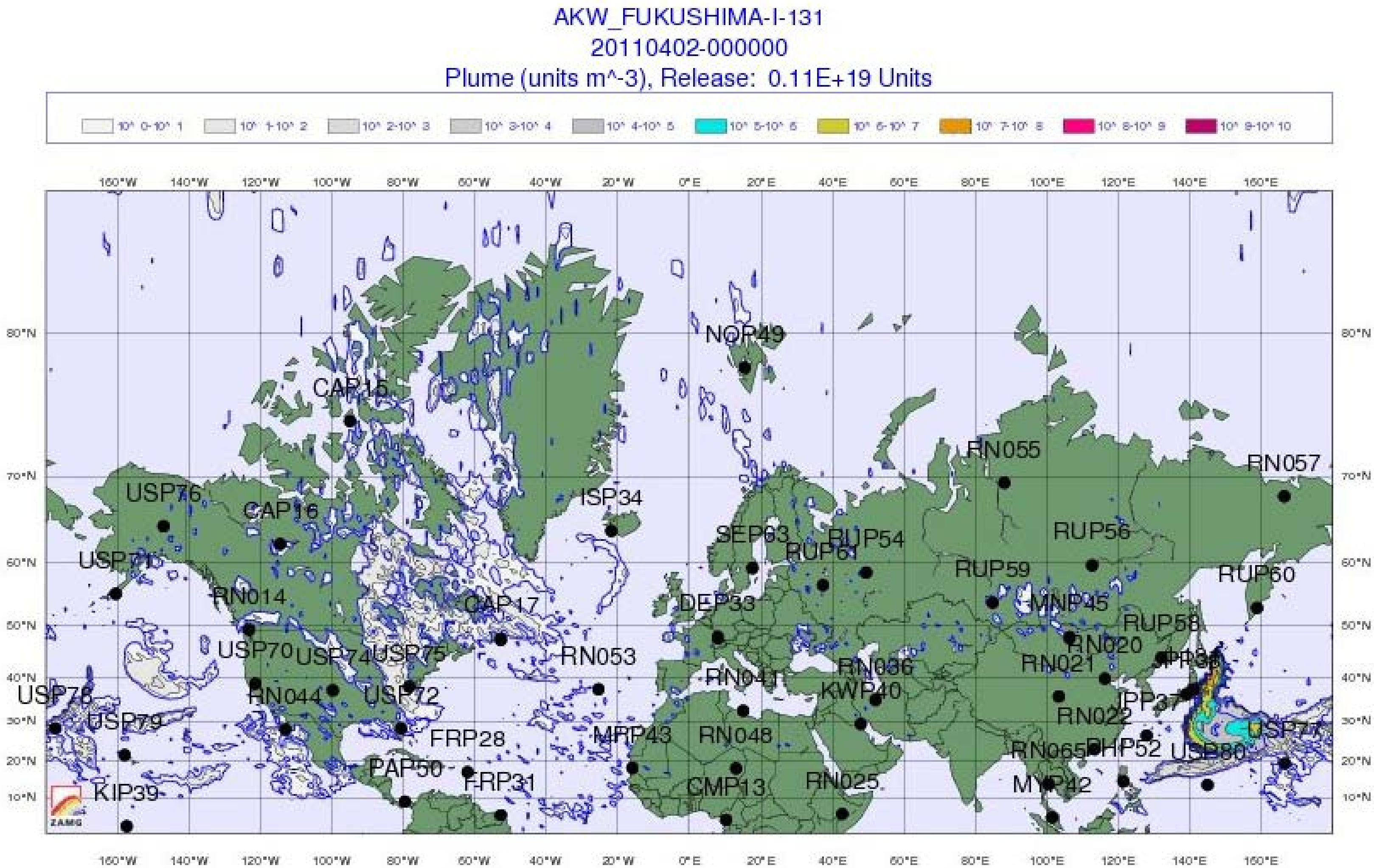
Bounding assumptions about chemistry

Predictions of Cs-137 Dispersion



http://www.zamg.ac.at/

CTBT Detection Stations

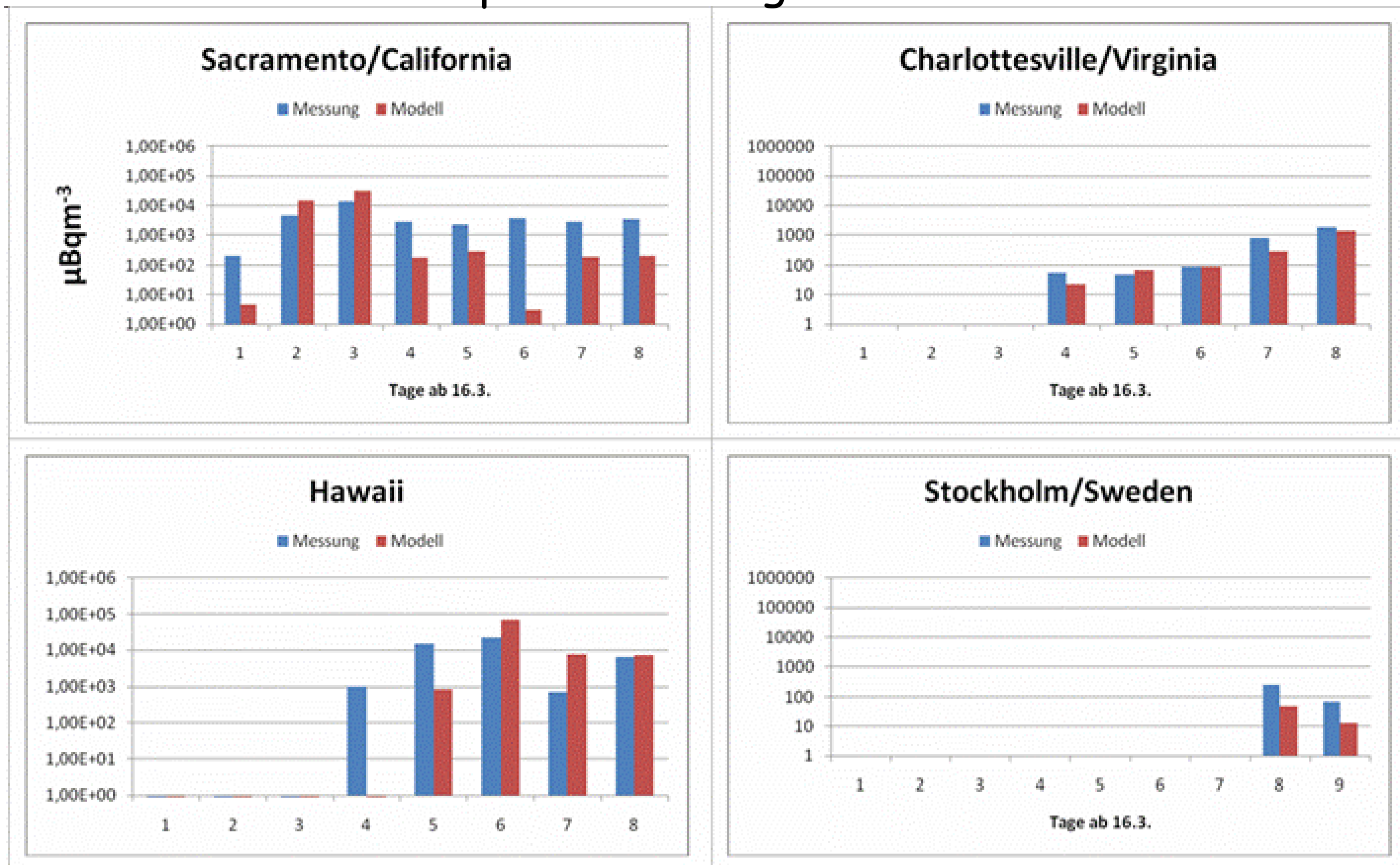


http://www.zamg.ac.at/

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. http://www.zamg.ac.at/

EPA 22 March analysis of SF air samples	
	$\mu Bq/m^3$
Cs-137	48
Te-132	277
I-132	244
I-131	2516

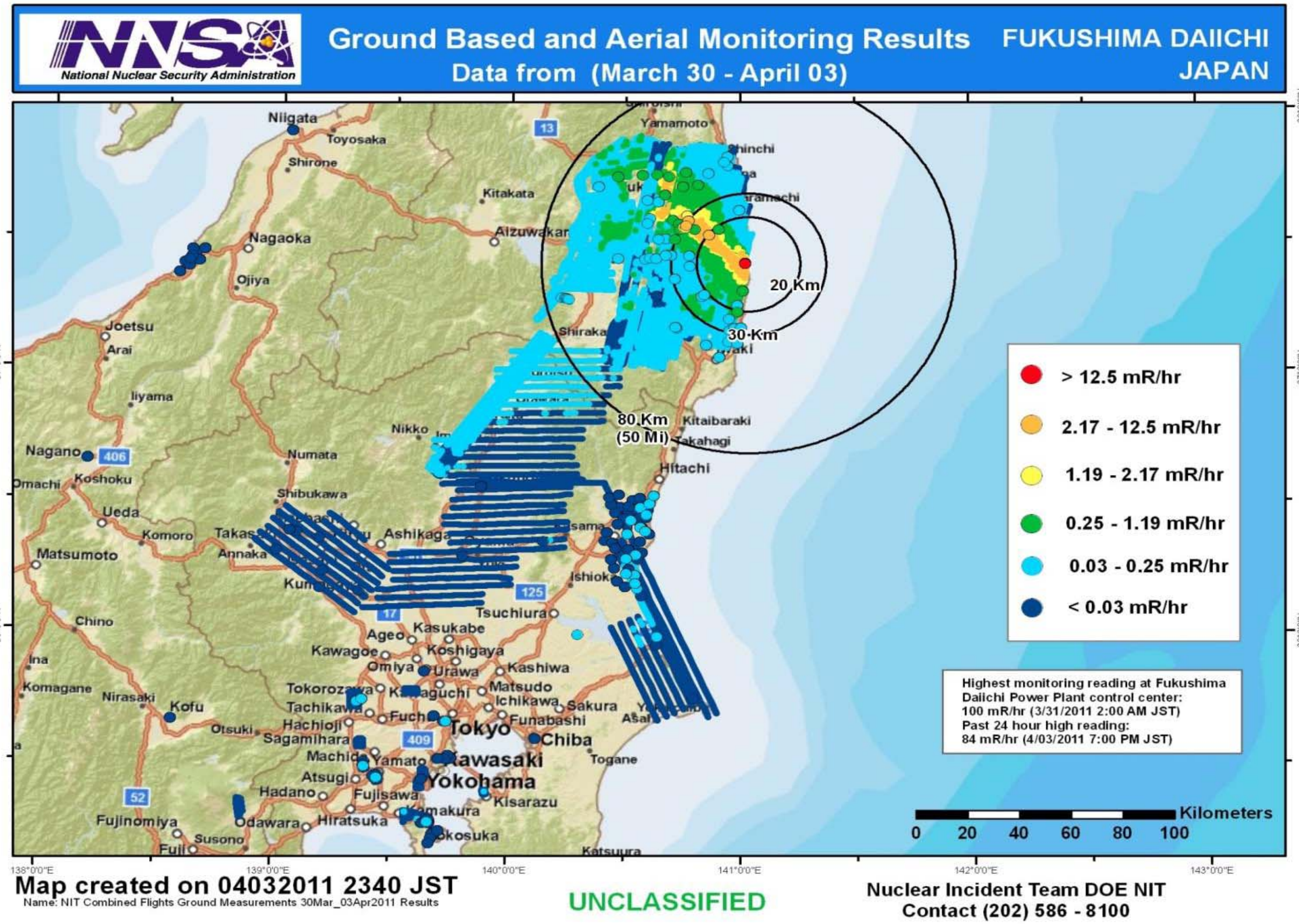


Estimating Source Term

- 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
- Results as of 1 April 2011. Release in Bq

Species	Fukushima Dai-ichi	Chernobyl Unit 4	Aboveground nuclear testing
I-131	10^{16} to 7×10^{17}	1.8×10^{18}	9×10^{20}
Cs-134	?	5.0×10^{16}	-
Cs-137	10^{15} to 7×10^{16}	8.5×10^{16}	1.3×10^{18}
Total	$> 7.7 \times 10^{17}$	9.4×10^{18}	
	ZAMG 30 March 2011	UNSCEAR 2000	UNSCEAR 1982

NNSA Aerial & Ground Survey

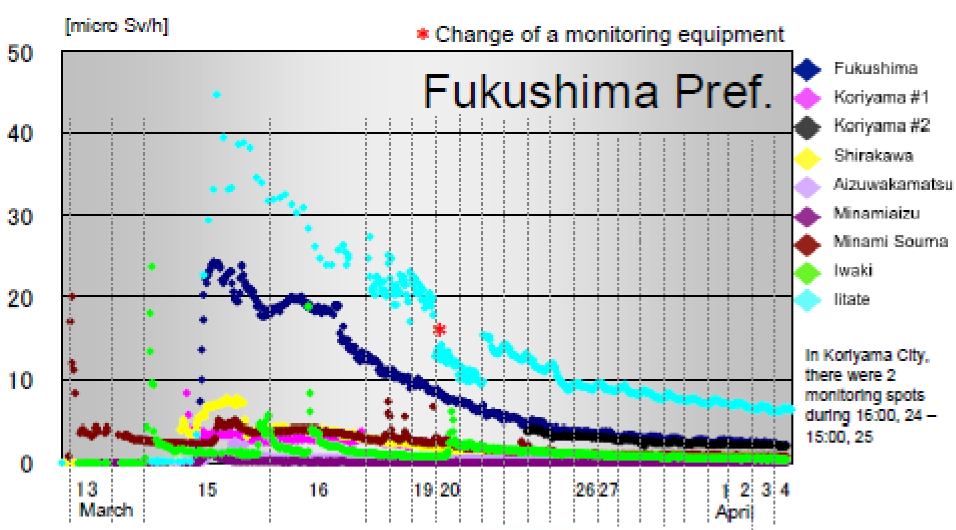


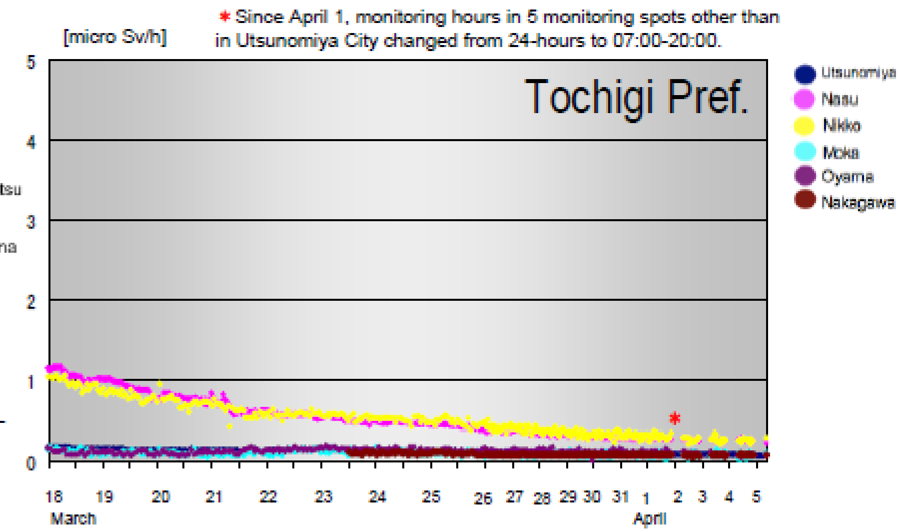
NNSA Conclusions (April 3)

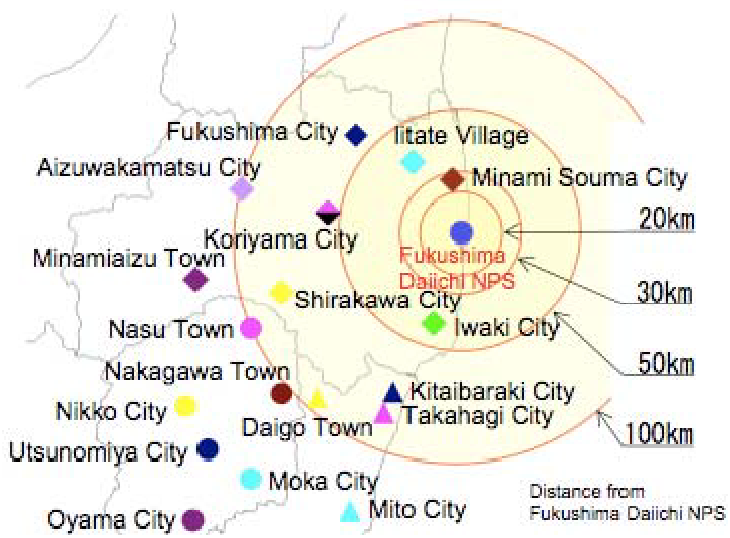
- Dose is at 1 m height above ground (1 mR/h = 10 μSv/h)
- All measurements in this plot are below 30 mR/h (300 μSv/h) – a low but not insignificant level.
  - background is 0.1 to 1 μSv/h (0.7 μSv/h = 6.2 mSv/yr average dose)
- Radiation levels consistently below actionable levels for evacuation or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

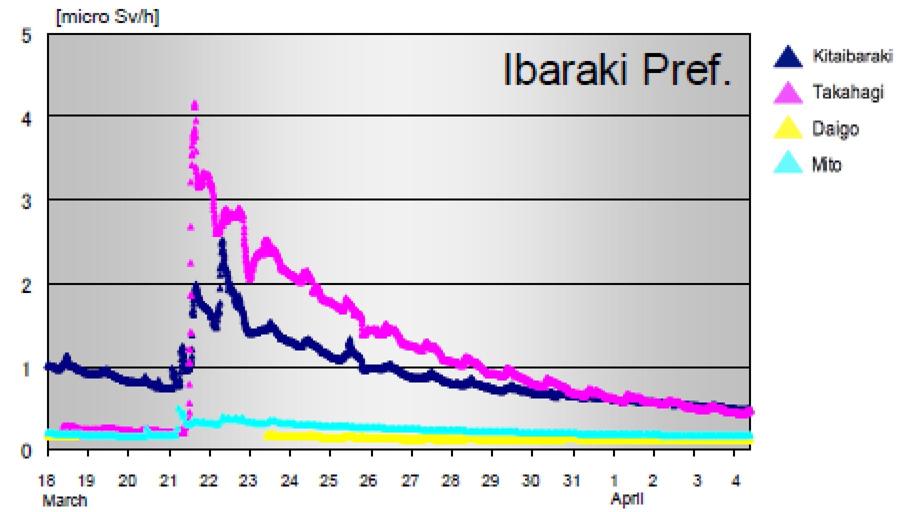
http://blog.energy.gov/content/situation-japan/

Data from MEXT/NISA









http://www.jaif.or.jp/english/

IAEA Assessment – 28 March

On 28 March, deposition of iodine-131 was detected in 12 prefectures, and deposition of cesium-137 in 9 prefectures.

Prefecture of Fukushima

23000 Bq/m^2 for iodine-131
90 Bq/m^2 for caesium-137.

Other prefectures

1.8 to 280 Bq/m^2 for iodine-131
5.5 to 52 Bq/m^2 for caesium-137

In the Shinjyuku district of Tokyo

$<$ 50 Bq/m^2 iodine-131 and cesium-137 was

No significant changes were reported in the 45 prefectures in gamma dose rates compared to yesterday.

IAEA Assessment April 5

- On 5 April, low levels of deposition of both iodine-131 and cesium-137 were detected in 5 and 7 prefectures respectively. The values for iodine-131 ranged from 12 to 70, for cesium-137 from 3.6 to 41 becquerel per square metre.
- Gamma dose rates reported for 6 April showed no significant changes compared to yesterday. Since 23 March, values have tended to decrease. Gamma dose rates were reported for 45 prefectures to be between 0.02 to 0.1 microsievert per hour. In one prefecture the gamma dose rate was 0.16 microsievert per hour. These values are within or slightly above the natural background of 0.1 microsievert per hour.
- As of 4 April, iodine-131 and cesium-134/137 was detectable in drinking water in a few prefectures. All values were far below levels that would initiate recommendations for restrictions of drinking water. As of 6 April, one restriction for infants related to I-131 (100 Bq/l) remains in place as a precautionary measure in only one village of the Fukushima prefecture.
- On 6 April the IAEA monitoring team made measurements at 7 locations at distances of 23 to 39 km South and Southwest of the Fukushima nuclear power plant. The dose rates ranged from 0.04 to 2.2 microsievert per hour. At the same locations, results of beta-gamma contamination measurements ranged from 0.03 to 0.36 megabecquerel per square metre.

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

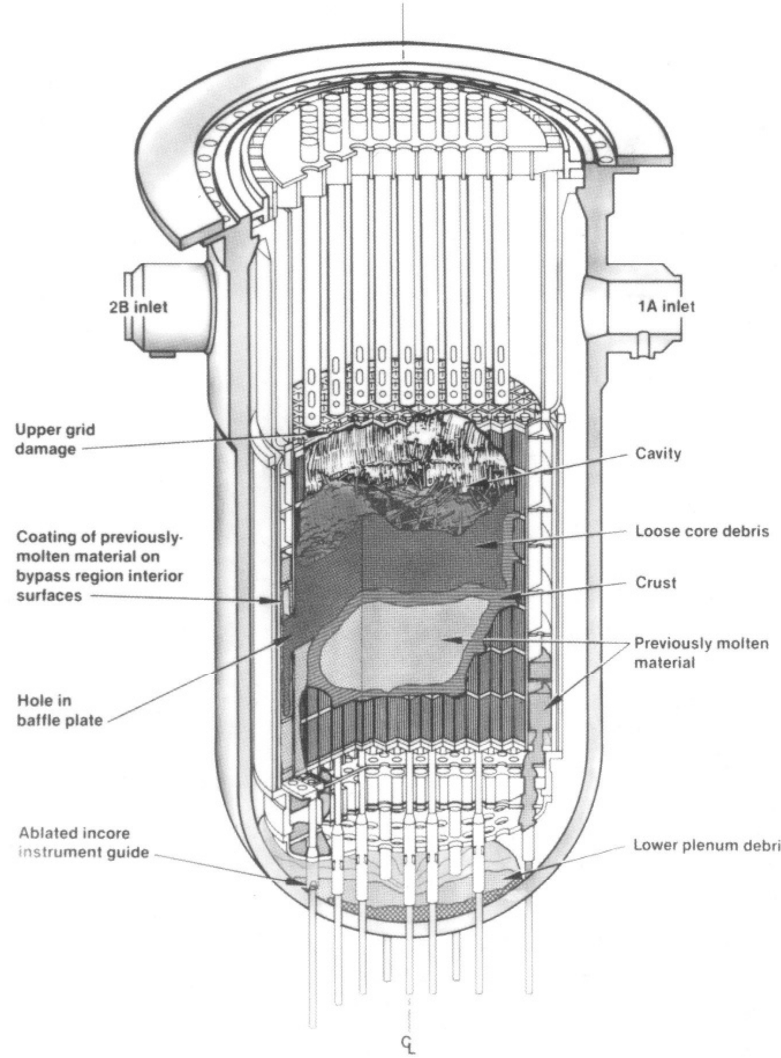
- Detected in soil near reactors
- Possible sources
  - Fallout from nuclear testing
  - Dispersed out of fuel by venting/explosions
    - By-product of U-238 absorbing neutrons
    - MOX fuel (6% of fuel assemblies in unit 2 contained plutonium)
  - Environmental contaminant from waste
- Not a health 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.

Major Commercial Reactor Incidents

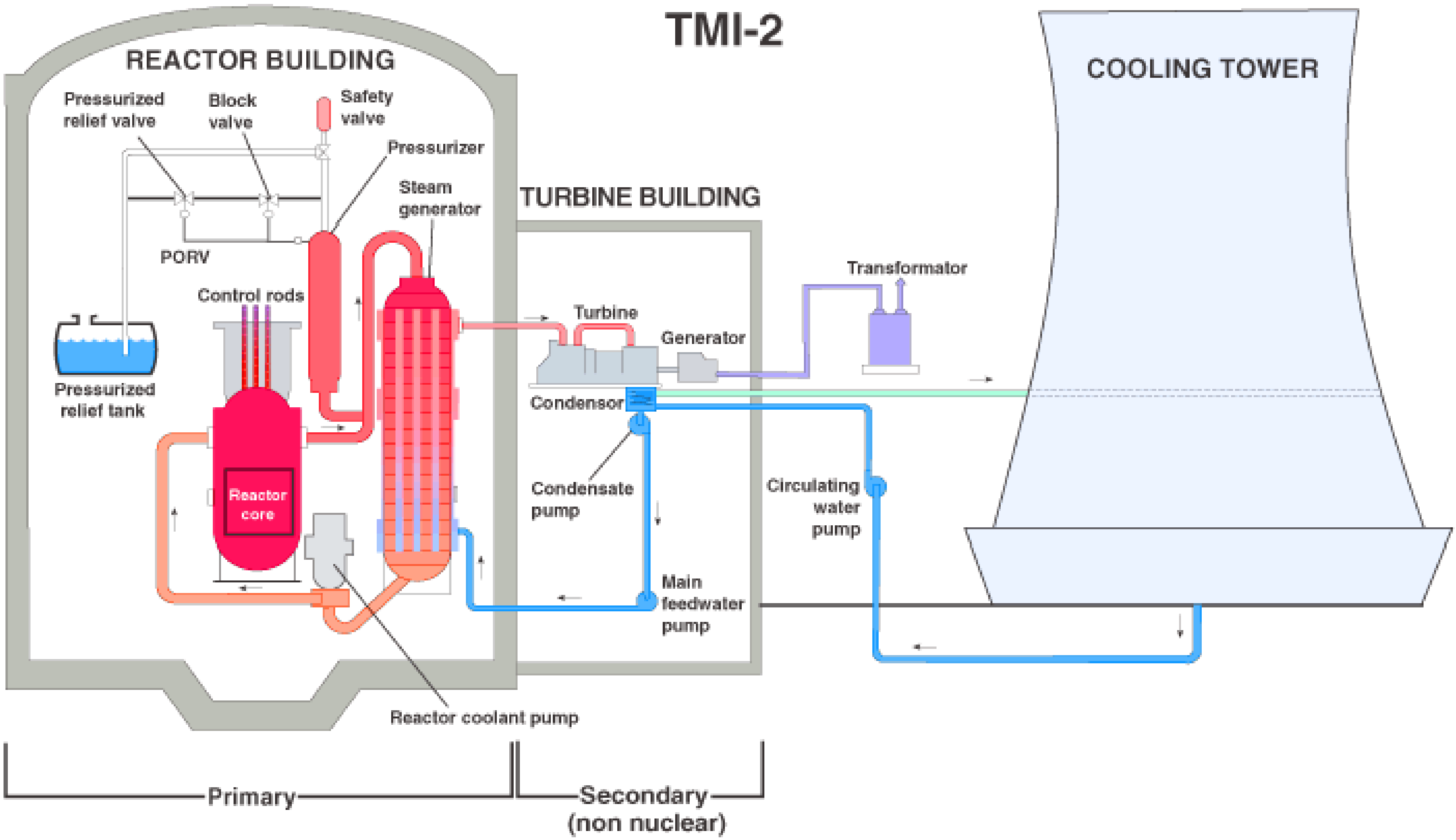
- Three Mile Island Unit 3 (1979)
- Chernobyl Unit 4 (1986)
- Fukushima Daiichi Units 1, 2, 3, 4 (2011)

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 x 10^{17} Bq (10 Mci) total
  - 3 x 10^{17} Bq (8 Mci) of Xe-133
  - 1.8 x 10^{15} (57 kCi) Krypton-85
  - 5.5 x 10^{11} Bq (15 Ci) of Iodine-131
  - 3.8 x 10^{6} Bq (40 microCi) Cs-137



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

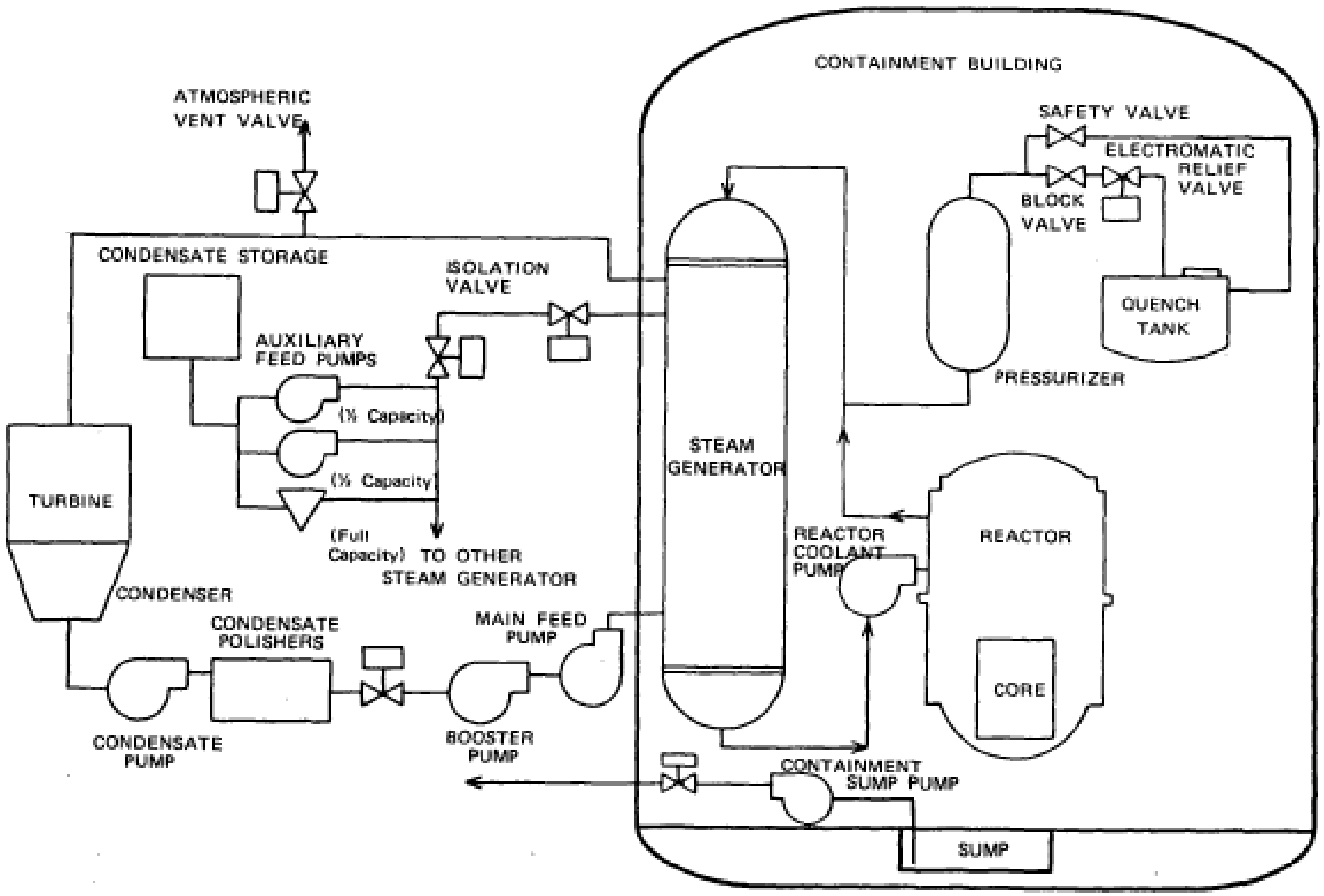


http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

What happened?

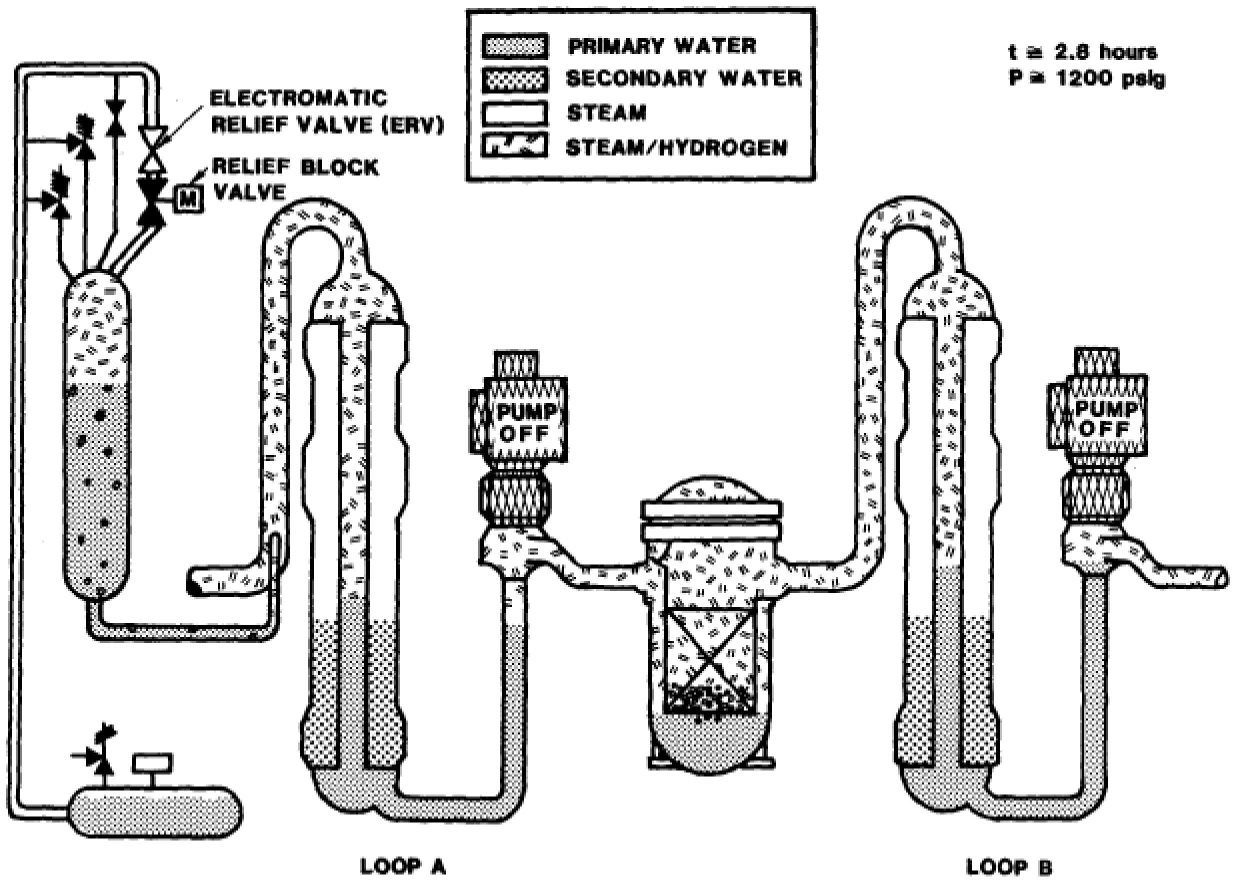
- Feed water interrupted
- Reactor scrammed
- ECCS pumps started/stopped
  - block valve closed, had to be opened by hand
- Heat exchangers boiled dry (2 min!)
- Pressure increased, relief valve opened automatically
  - Stayed stuck open for 2 hours
- ECCS pumped restarted then manually shut down
  - 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

PWR reactor at TMI



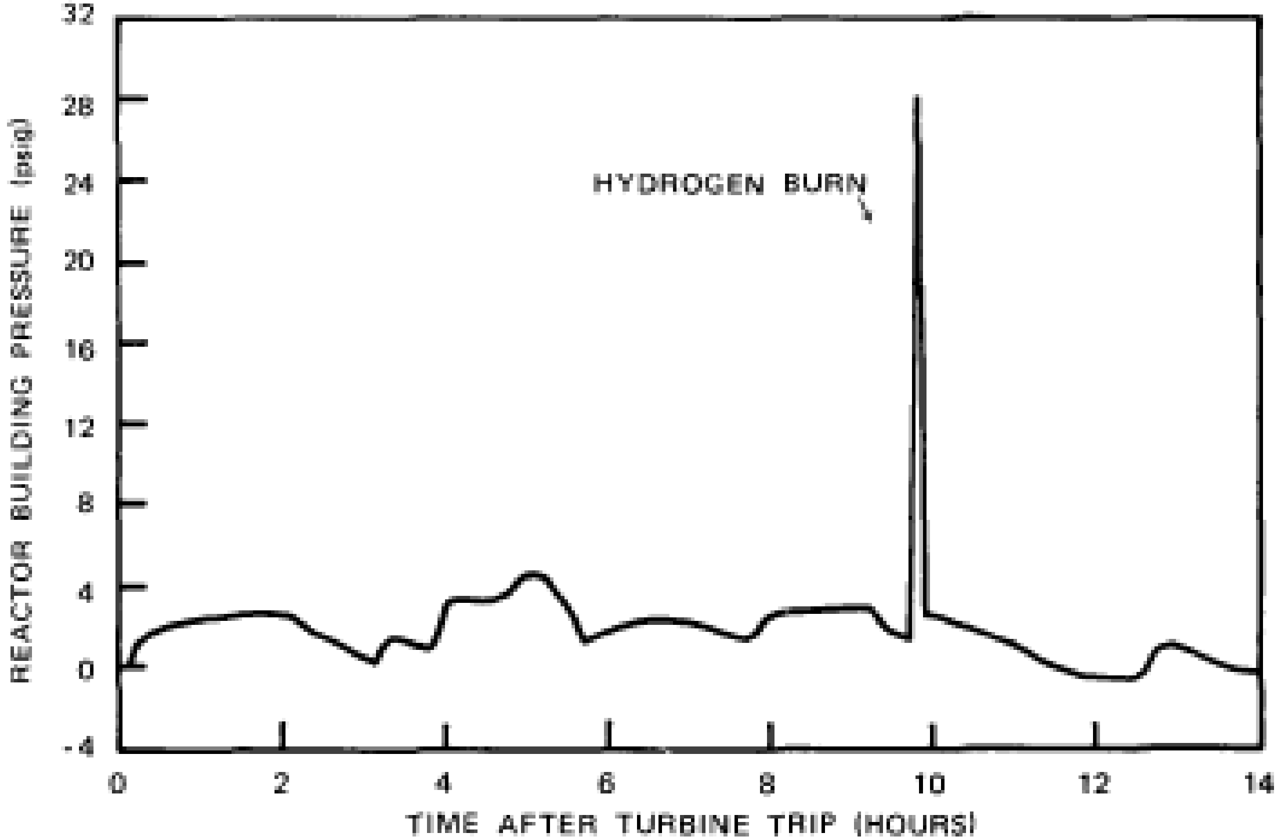
LWR H2 Manual NUREG/CR-2726

Core Uncovered for Extended period



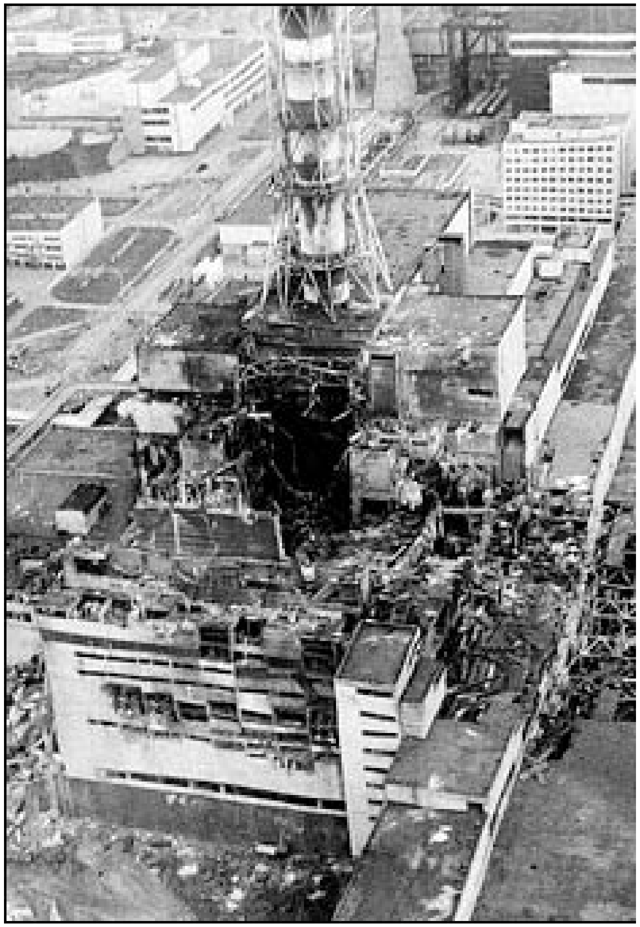
LWR H2 Manual NUREG/CR-2726

Hydrogen Combustion inside Containment Building



LWR H2 Manual NUREG/CR-2726

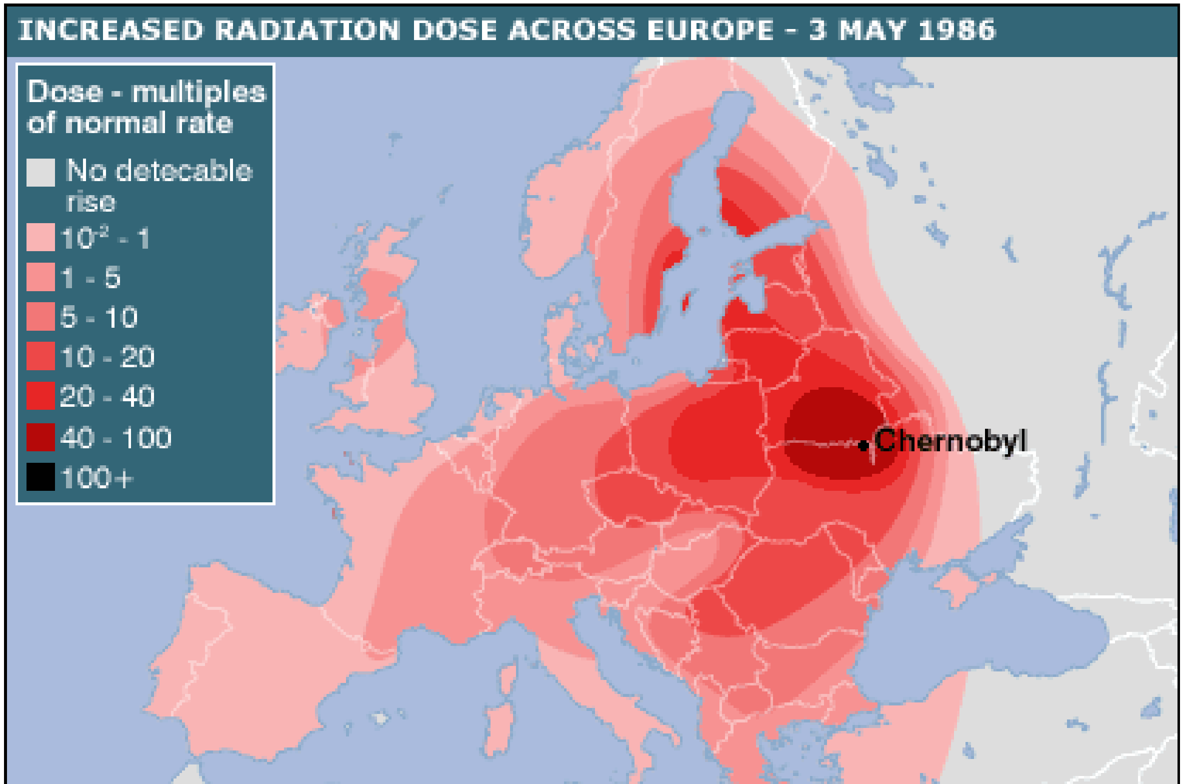
Chernobyl Accident

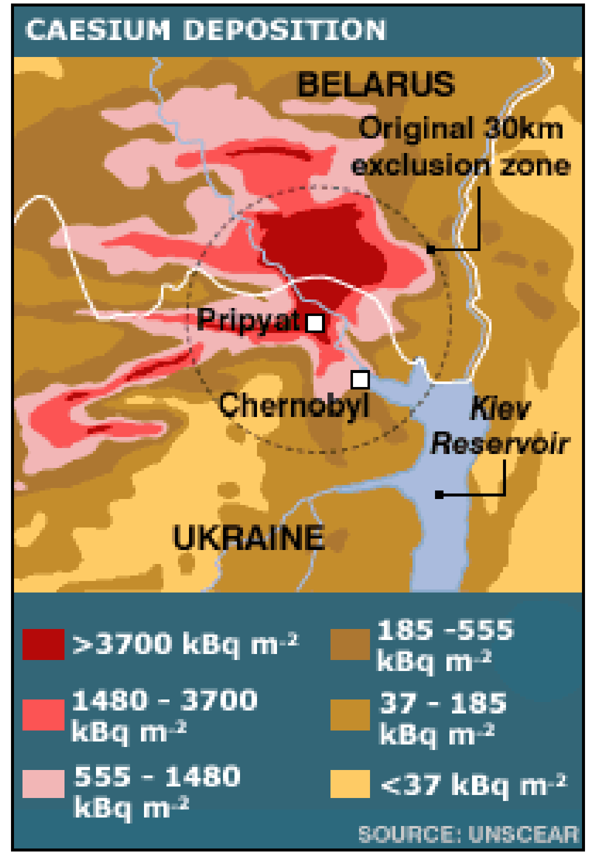


- 1000 Mwe RBMK-type reactor: Graphite-moderated, water-cooled, no containment structure or pressure vessel
- 26 April 1986
- Criticality accident caused by multiple factors including poor design, willful disregard of regulations, ignorance of reactor physics by operators
- Explosion and fire completely 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.

Entombment

- 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





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

- 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 Accidents – Three Different Situations

- TMI – Unit 2
  - 1 PWR, reactor pressure vessel, containment building
  - Loss of coolant accident, 50% core damage, hydrogen explosion in containment
  - Pressure vessel, containment intact
  - Small release, no contaminated exclusion zone
  - Complete cleanup
- Chernobyl – Unit 4
  - 1 RBMK reactor, no pressure vessel and weak containment
  - Core and reactor building destroyed by critical disassembly
  - Release of substantial fraction of FPs including refractories during explosion/fire
  - Large contaminated zone (up to 100 km), reactor entombed
- Fukushima Dai-ichi – Unit 1, 2, 3, and 4
  - 3 BWR reactors and 4 spent fuel pools, SBO
  - 30-70% core damage to 3 reactors, suspect RPV and PCV damage
  - At least 4 hydrogen explosions, severe damage to reactor buildings
  - Spent fuel fire suspected
  - Plant highly contaminated, substantial release of volatile FP
  - Extent of contaminated zone 20 km

Information on the www

- http://www3.nhk.or.jp/nhkworld/

- http://www.nisa.meti.go.jp/english/
- http://www.tepco.co.jp/en/index-e.html
- http://www.jnes.go.jp/english/index.html
- http://www.jaif.or.jp/english/

- http://www.iaea.org/
- http://www.unscear.org/

- http://www.zamg.ac.at/

- http://www.world-nuclear-news.org/
- http://www.nei.org/
- http://www.new.ans.org/
- http://www.nucleartourist.com/

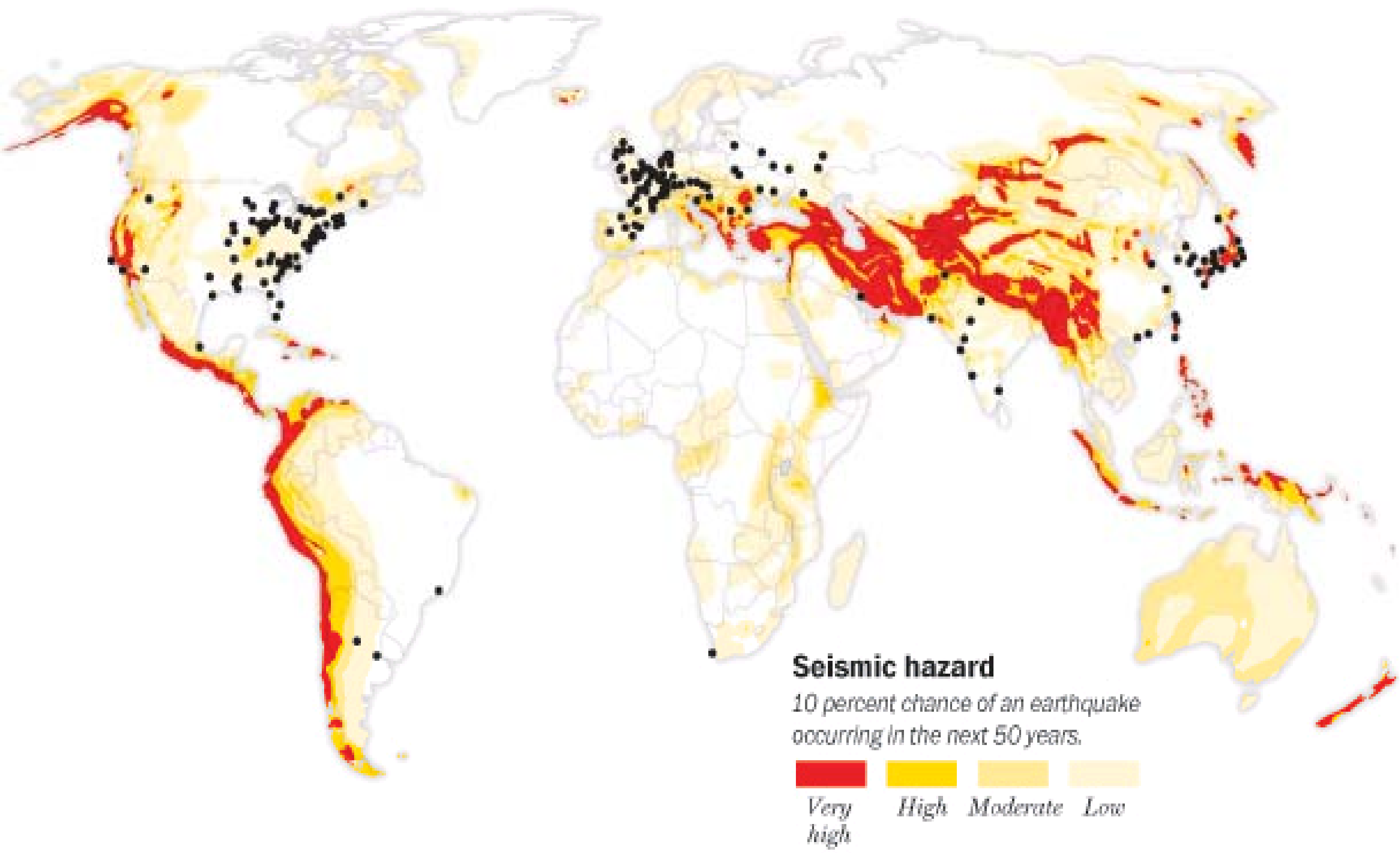
- http://www.nrc.gov/
- http://blog.energy.gov/content/situation-japan/
- http://www.epa.gov/radiation/
- http://www.ncrponline.org/

- http://en.wikipedia.org/wiki/Timeline_of_the_Fukushima_I_nuclear_accidents
- http://en.wikipedia.org/wiki/Fukushima_I_nuclear_accidents

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

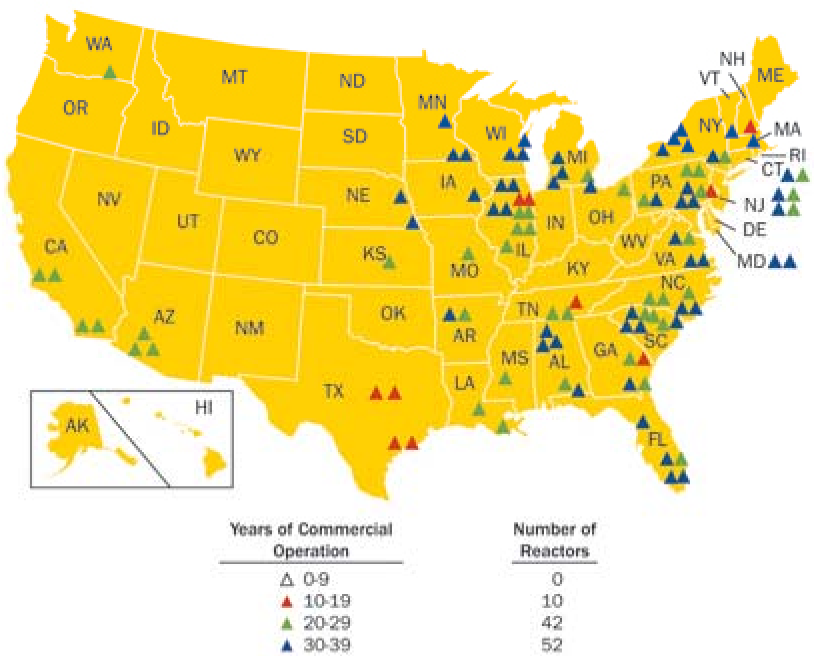


NY Times

104 Operating Reactors in US

- 23 are BWR Mark 1 containment type

U.S. Commercial Nuclear Power Reactors—Years of Operation



Source: U.S. Nuclear Regulatory Commission

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		3/21/2012

US NRC