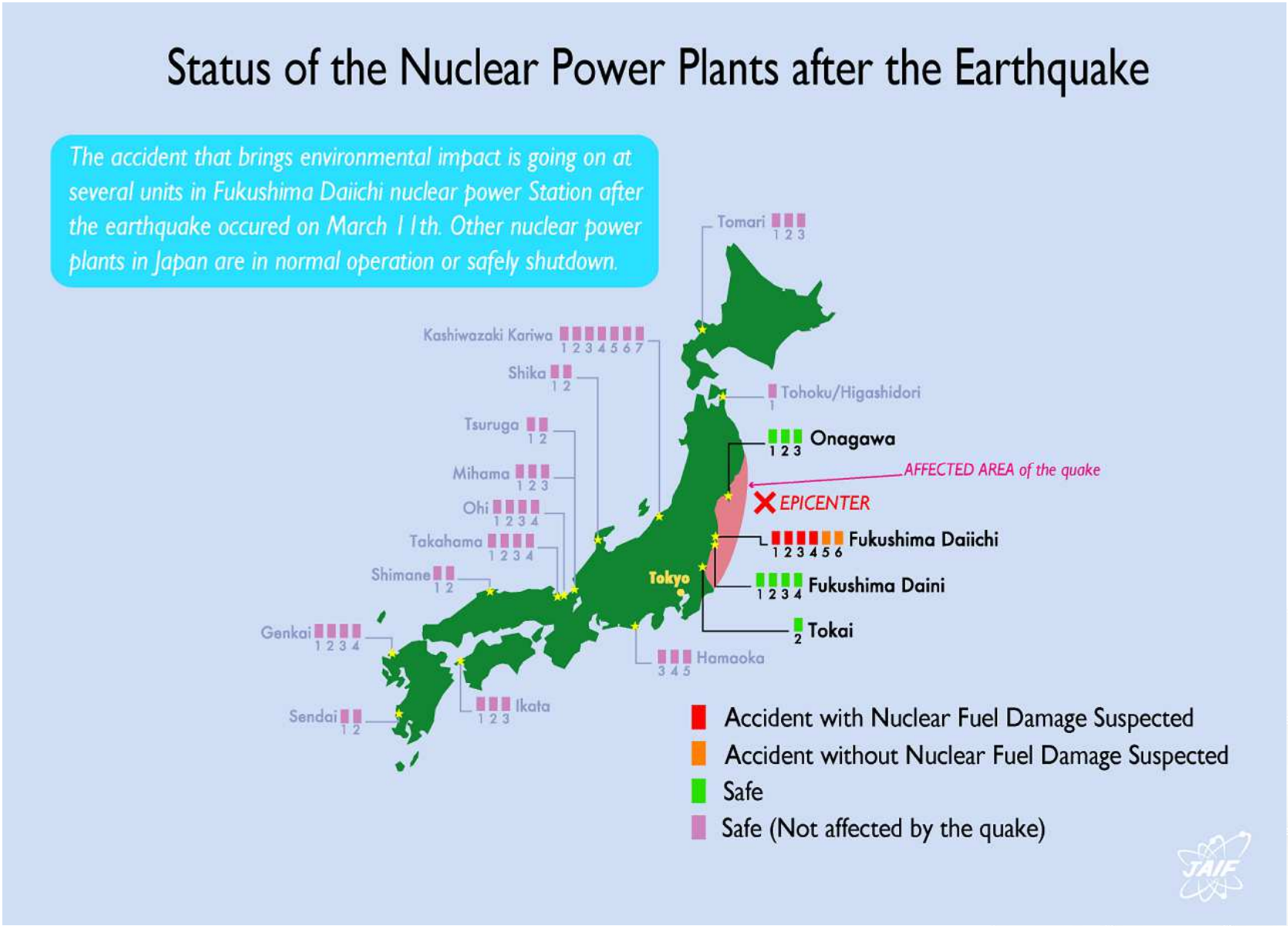
Fukushima Dai-ichi

Short overview of 11 March 2011 accidents and considerations

Marco Sangiorgi - ENEA

3rd EMUG Meeting – ENEA
Bologna 11-12 April 2011

NPPs affected by Earthquake

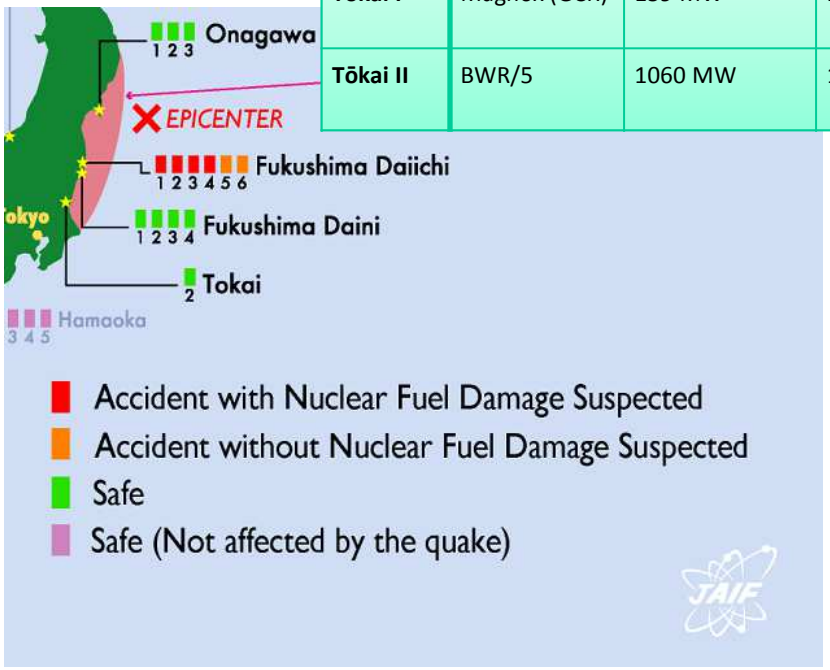


NPPs affected by Earthquake

Tōkai Nuclear Power Plant

The **Tōkai Nuclear Power Plant** (東海発電所 *Tōkai hatsudensho*, Tōkai NPP) was Japan's first nuclear power plant. It was built in the early 1960s to the British Magnox design, and generated power from 1966 until it was decommissioned in 1998. A second nuclear plant, built at the site in the 1970s, was the first in Japan to produce over 1000 MW of electricity, and still produces power as of 2009. The site is located in Tokai in the Naka District in Ibaraki Prefecture, Japan and is operated by the **Japan Atomic Power Company**.

Unit	Type	Average electric power	Capacity	Construction started	Construction completed	First criticality	Closure
Tōkai I	Magnox (GCR)	159 MW	166 MW	March 1, 1961	November 10, 1965	July 25, 1966	March 31, 1988
Tōkai II	BWR/5	1060 MW	1100 MW	October 3, 1973	March 13, 1978	November 28, 1978	



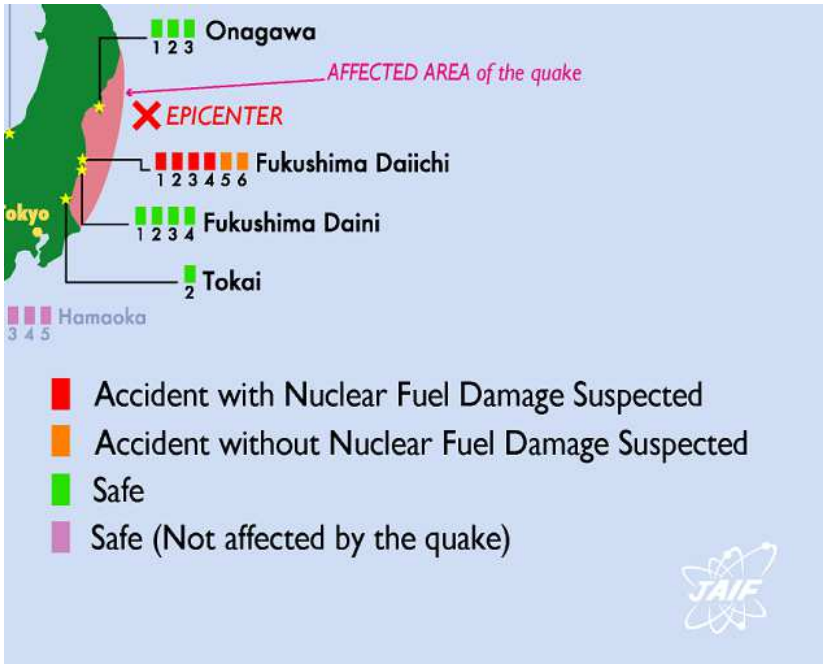
NPPs affected by Earthquake

Onagawa Nuclear Power Plant

The **Onagawa Nuclear Power Plant** (女川原子力発電所 *Onagawa genshiryoku hatsudensho*, Onagawa NPP) is a nuclear power plant in Onagawa in the Oshika District and Ishinomaki city, Miyagi Prefecture, Japan. It is managed by the **Tohoku Electric Power Company**. It was the most quickly constructed nuclear power plant in the world.

The Onagawa-3 unit was the most modern reactor in all of Japan at the time of its construction. It was used as a prototype for the Higashidori Nuclear Power Plant.

All the reactors were constructed by Toshiba.



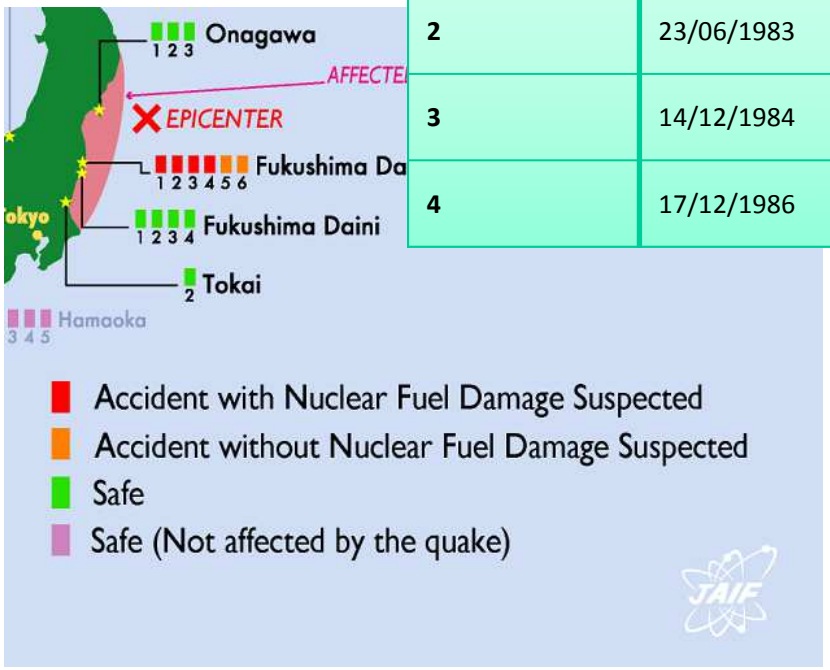
Unit	Type	Start of Operation	Electric Power
Onagawa - 1	BWR	June 1, 1984	524 MW
Onagawa - 2	BWR	July 28, 1995	825 MW
Onagawa - 3	BWR	January 30, 2002	825 MW

NPPs affected by Earthquake

Fukushima II Nuclear Power Plant

The **Fukushima II Nuclear Power Plant** (福島第二原子力発電所 *Fukushima Dai-Ni Genshiryoku Hatsudensho,* Fukushima II NPP, 2F), or **Fukushima Daini**, is a nuclear power plant located in the town of Naraha and Tomioka in the Futaba District of Fukushima Prefecture. Like the Fukushima I, 11.5 kilometres (7.1 mi) to the north, it is run by the **Tokyo Electric Power Company (TEPCO)**.

Unit	First criticality	Electric Power	Reactor supplier	Construction	Containment
1	31/07/1981	1.1 GW	Toshiba	Kajima	Mark 2
2	23/06/1983	1.1 GW	Hitachi	Kajima	Mark 2 advanced
3	14/12/1984	1.1 GW	Toshiba	Kajima	Mark 2 advanced
4	17/12/1986	1.1 GW	Hitachi	Shimizu Takenaka	Mark 2 advanced

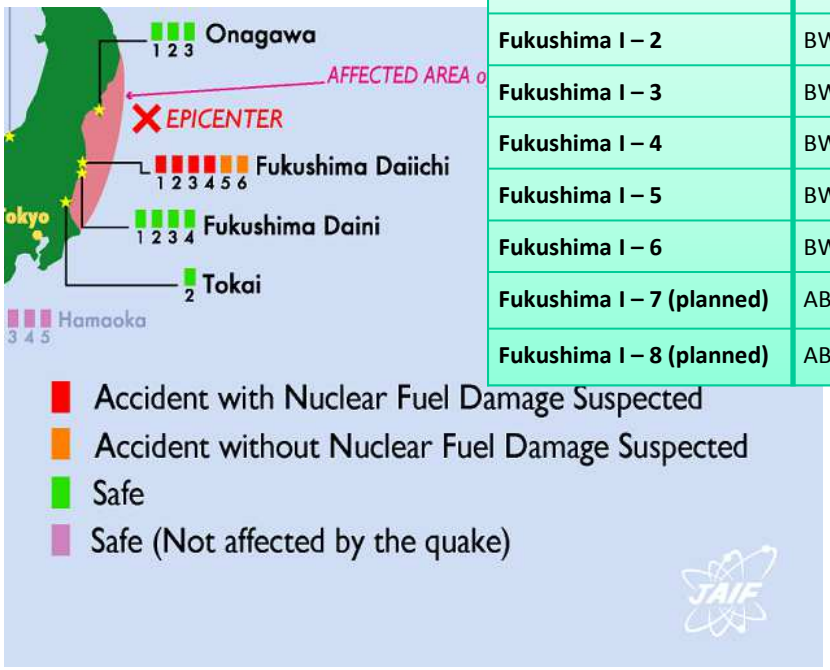


NPPs affected by Earthquake

Fukushima I Nuclear Power Plant

The **Fukushima I Nuclear Power Plant** (福島第一原子力発電所 *Fukushima Dai-Ichi Genshiryoku Hatsudensho*[?], Fukushima I NPP), often referred to as **Fukushima Dai-ichi**, is a nuclear power plant located in the town of Okuma in the Futaba District of Fukushima Prefecture, Japan. The plant consists of six boiling water reactors designed by General Electric. These light water reactors have a combined power of 4.7 GW, making Fukushima I one of the 25 largest nuclear power stations in the world. Fukushima I was the first nuclear plant to be constructed and run entirely by the **Tokyo Electric Power Company (TEPCO)**.

Units 1 to 5 use the BWR Mark I Containment Building design, and unit 6 uses the Mark II Containment Building design



Unit	Type	First criticality	Electric power	Reactor supplier	Construction
Fukushima I – 1	BWR-3	October 1970	460 MW	General Electric	Kajima
Fukushima I – 2	BWR-4	July 18, 1974	784 MW	General Electric	Kajima
Fukushima I – 3	BWR-4	March 27, 1976	784 MW	Toshiba	Kajima
Fukushima I – 4	BWR-4	October 12, 1978	784 MW	Hitachi	Kajima
Fukushima I – 5	BWR-4	April 18, 1978	784 MW	Toshiba	Kajima
Fukushima I – 6	BWR-5	October 24, 1979	1,100 MW	General Electric	Kajima
Fukushima I – 7 (planned)	ABWR	October 2016	1,380 MW		
Fukushima I – 8 (planned)	ABWR	October 2017	1,380 MW		

Fukushima Dai-ichi before the Earthquake

Fukushima Dai-ichi after the accidents

Fukushima Dai-ichi after the accidents

March 24, 2011 aerial photo taken by small unmanned drone

Unit 1

Unit 2

Unit 3

Unit 4

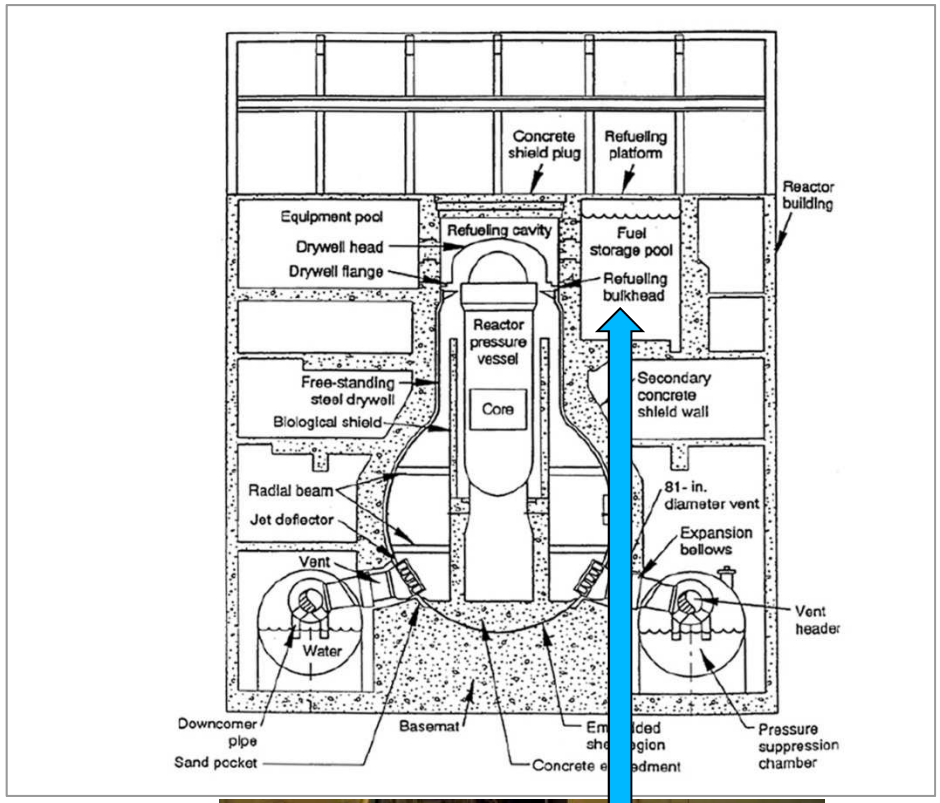
March 24, 2011 aerial photo taken by a small unmanned drone

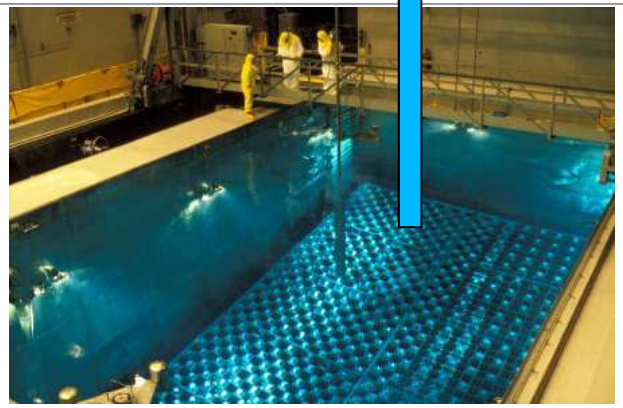

Unit 1
Unit 2
Unit 3
Unit 4

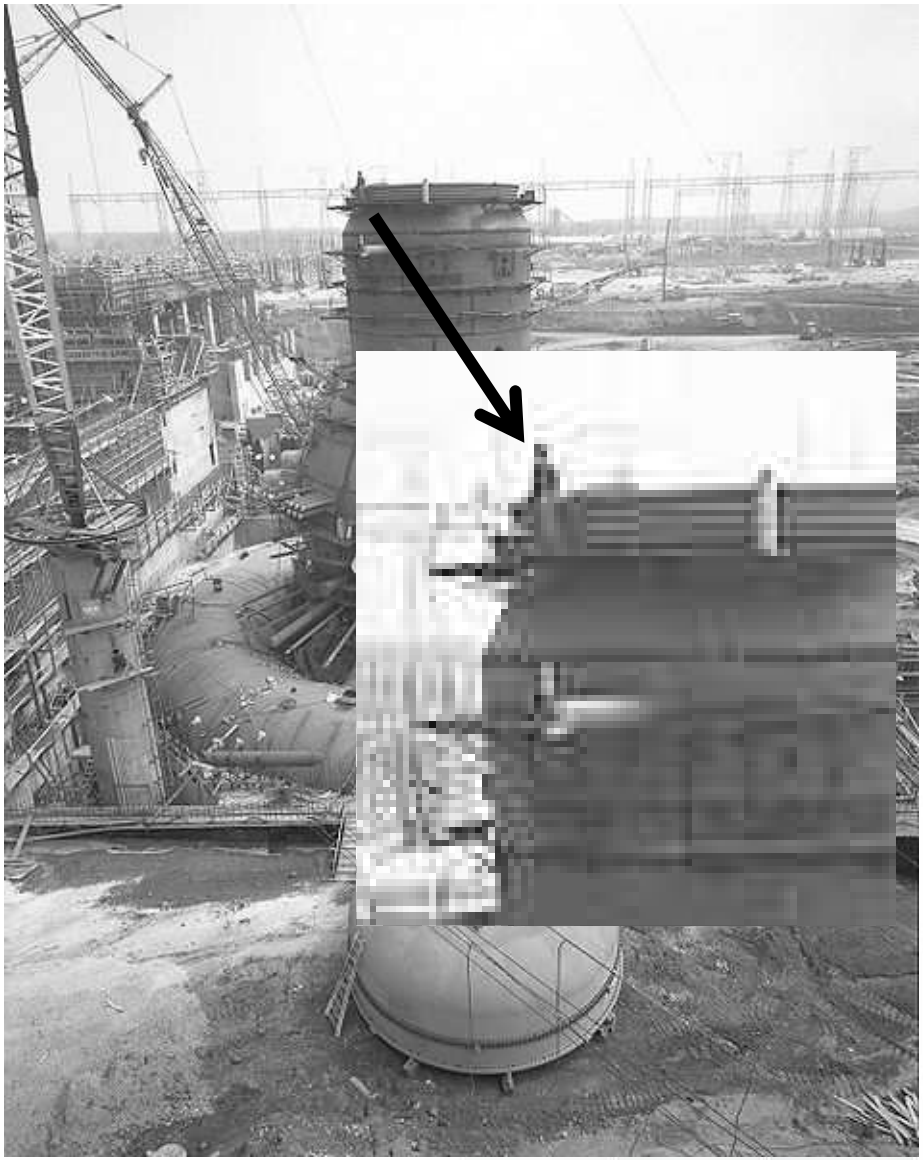
GE MARK-I containment

Wetwell
"torus"

GE MARK-I containment

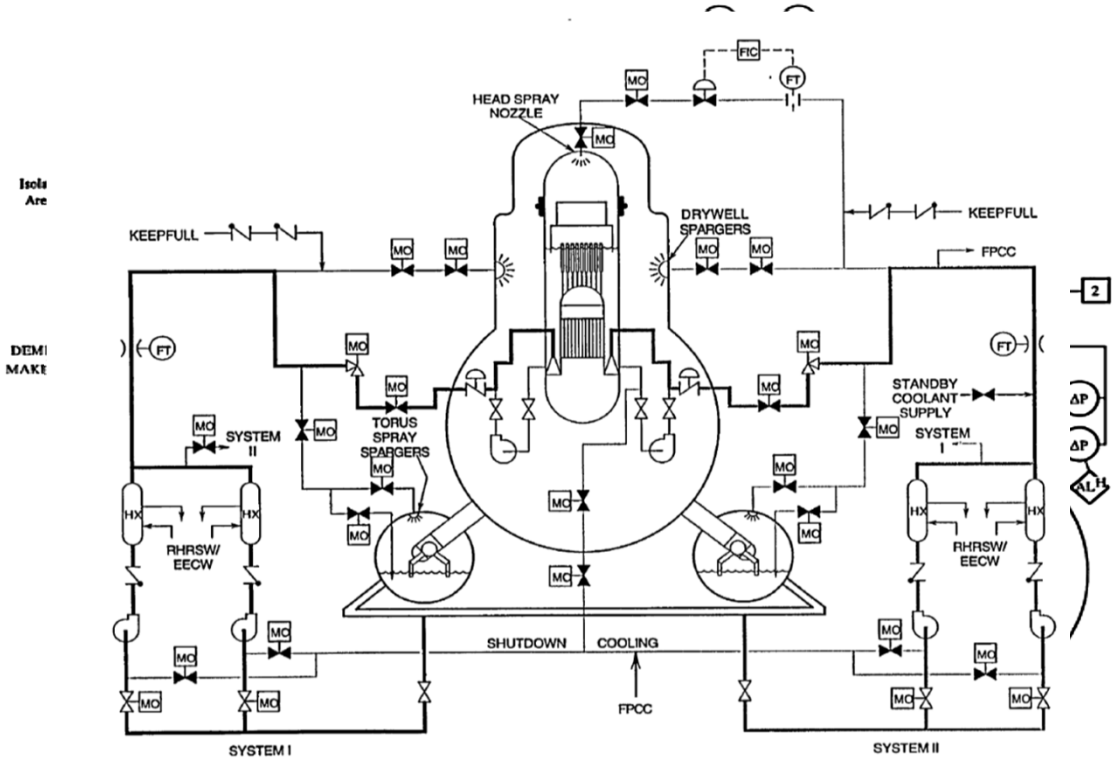






Timeline

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
11/3 14:46	Earthquake 9.0 magnitude strikes Japan			
	Automatic shut down	Automatic shut down	Automatic shut down	Outage
	Power plant to be cut off from the Japanese electricity grid			
	Back-up diesel generators start			

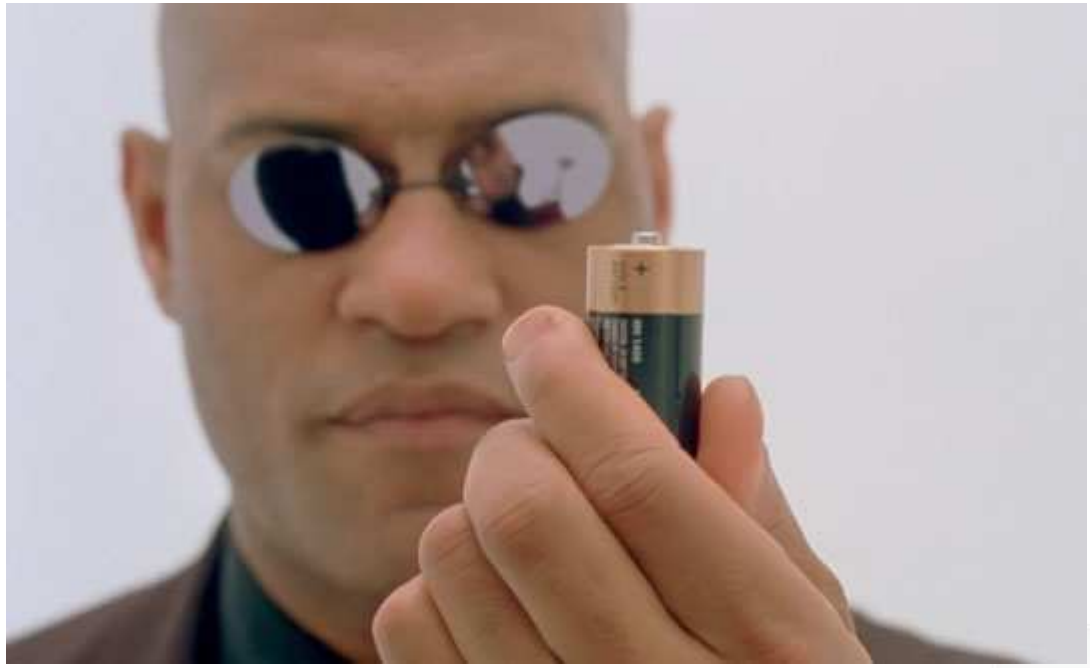


UNIT 1, 2, 3

Residual Heat Removal (RHR) System to cool down the reactor

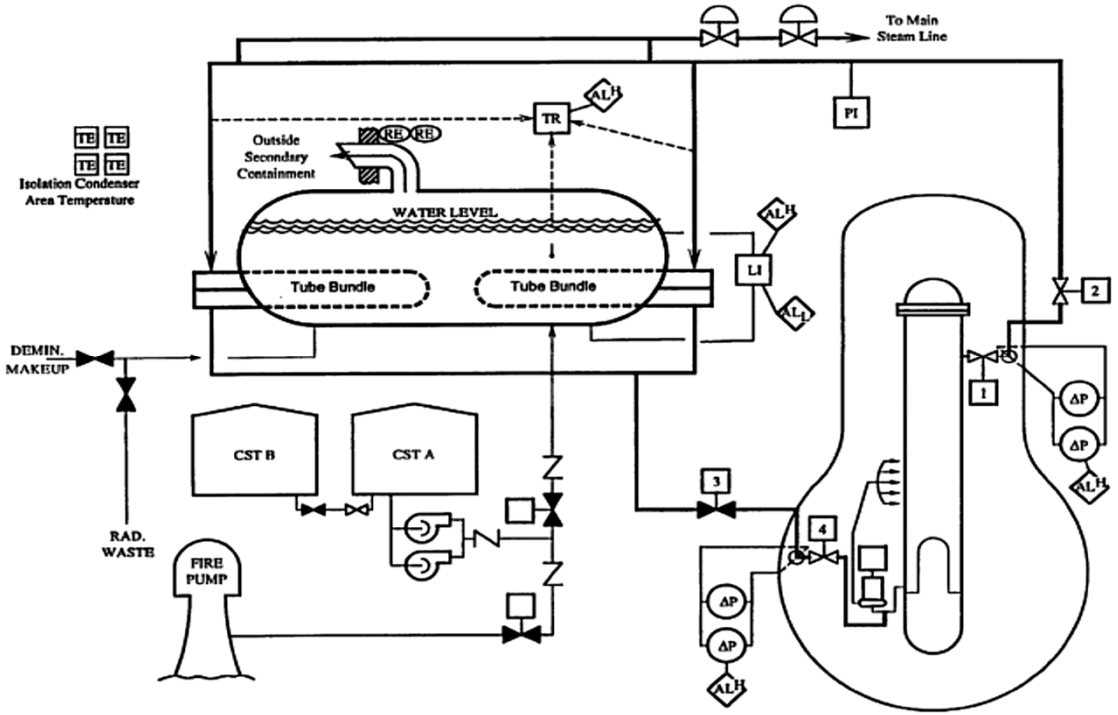
So far so good. but…

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
11/3 15:01	14 meters high tsunami wave strikes Fukushima Dai-ichi			
11/3 15:42	All AC power sources for Units 1 through 3 at Fukushima I were lost (Back-up diesel generators fail) / Report to “the Law” (Loss of power)			
	Oil tanks were washed away by tsunami			
	Loss of AC power (Station Black out) **Only DC batteries left**			



Things got bad

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
11/3 16:36	Water injection failed to function in the Emergency Core Cooling System (ECCS) at Fukushima Daiichi Units 1 and 2 (Incapability of water injection by core cooling function)			



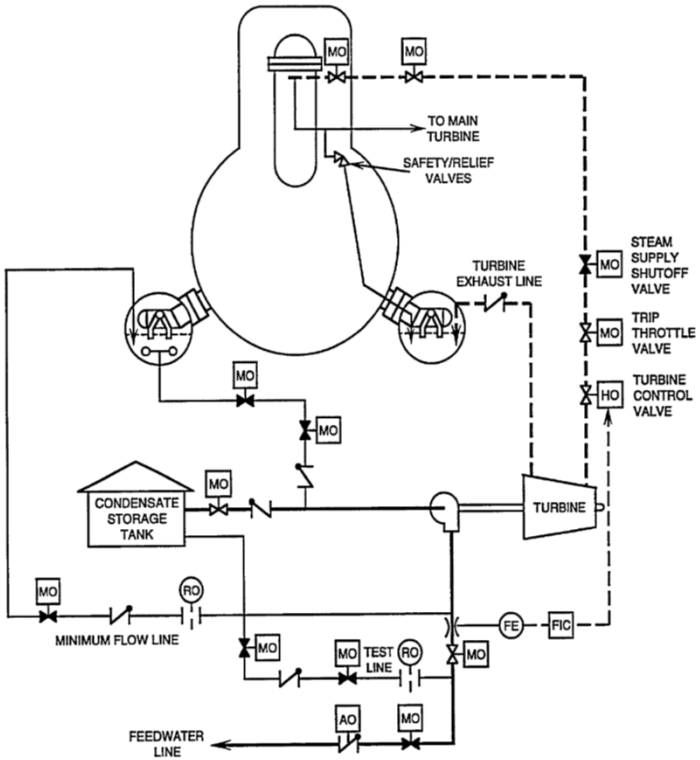
UNIT 1

Isolation Condenser: w/o feed water injection (AC power needed) it boils dry

… and it boiled dry!

Things got bad

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
11/3 16:36	Water injection failed to function in the Emergency Core Cooling System (ECCS) at Fukushima Daiichi Units 1 and 2 (Incapability of water injection by core cooling function)			



UNIT 2, 3

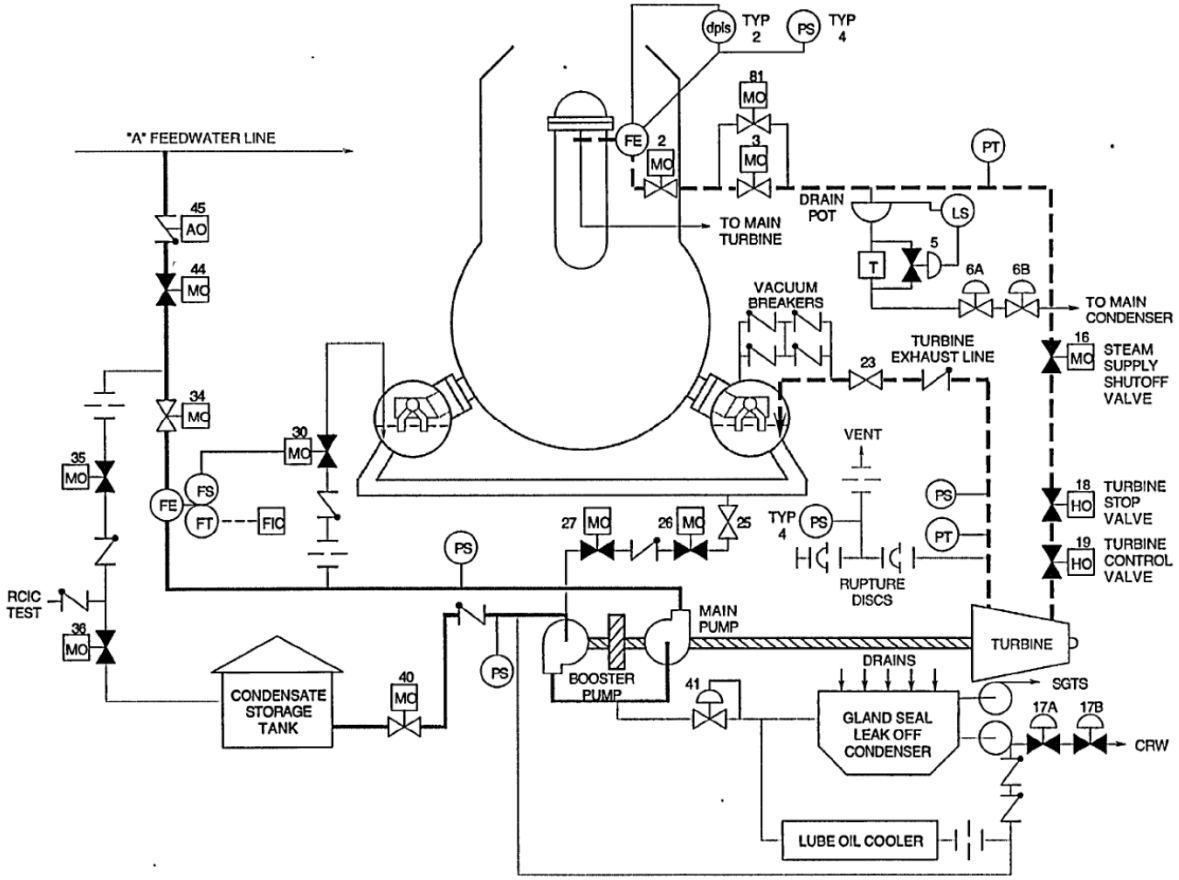
RCIC: steam turbine driven pump

W/o feed water injection (AC power needed) it boils dry

Needs DC power to operate.

Things got bad

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
11/3 16:36	Water injection failed to function in the Emergency Core Cooling System (ECCS) at Fukushima Daiichi Units 1 and 2 (Incapability of water injection by core cooling function)			



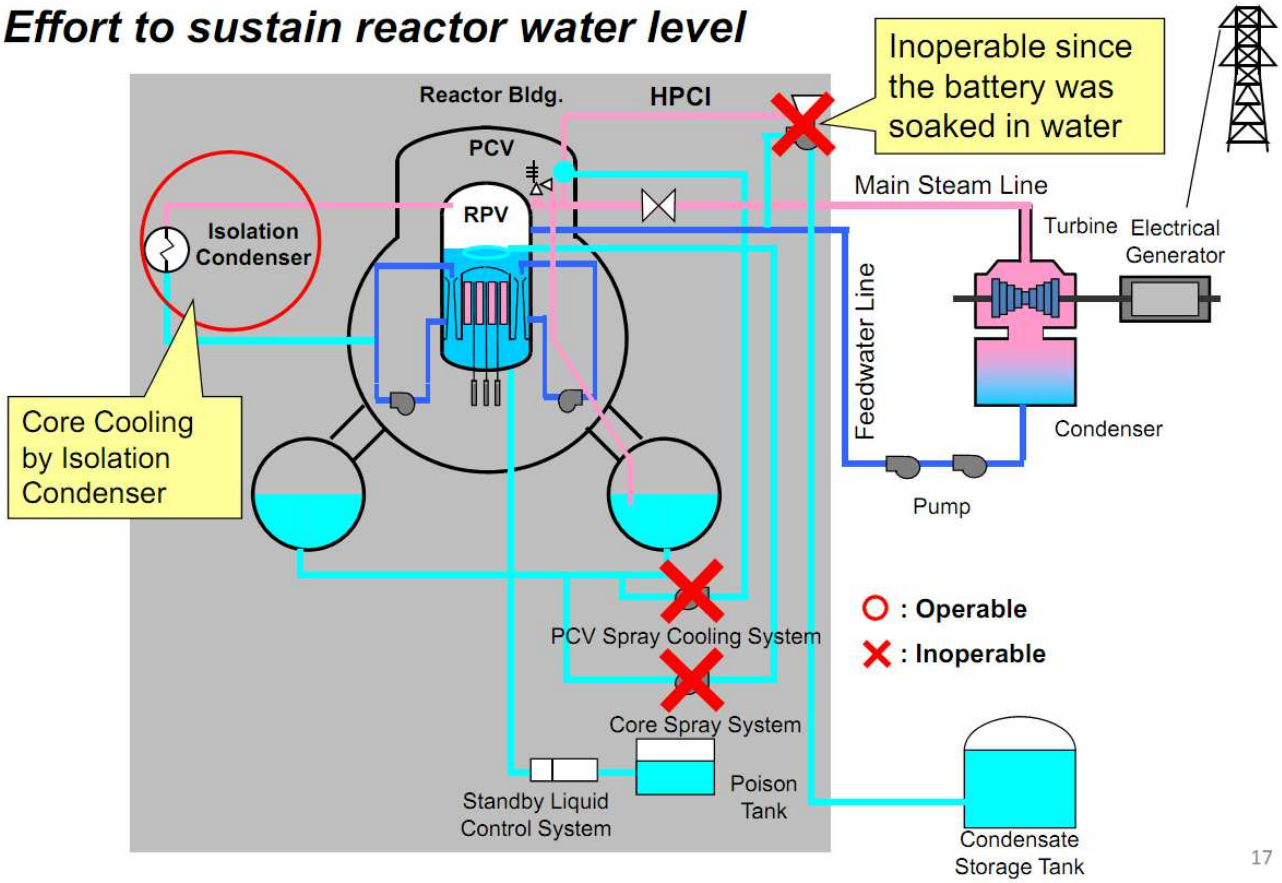
High **P**ressure **C**oolant **I**njection System to cool down the reactor.

Steam turbine driven pump, but needs DC power to operate.

Things got bad

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
11/3 16:36	Water injection failed to function in the Emergency Core Cooling System (ECCS) at Fukushima Daiichi Units 1 and 2 (Incapability of water injection by core cooling function)			

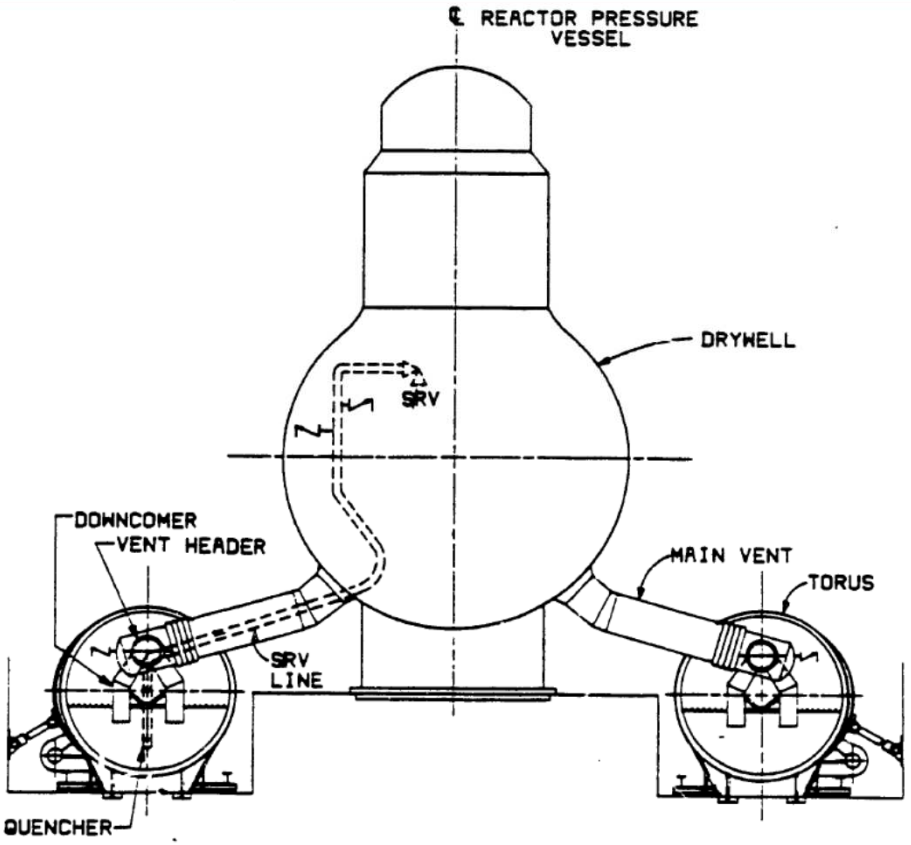
Effort to sustain reactor water level



DC batteries depleted or failed!

Things got worse

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
12/3 0:49	Abnormal rise of CV pressure			
	Back-up battery supplies are depleted. The ability to cool the reactors of units 1, 2 and 3 is significantly degraded or unavailable. Discharges to suppression chambers designed to control pressure within the reactor coolant system cause pressure within the primary containments to increase.			



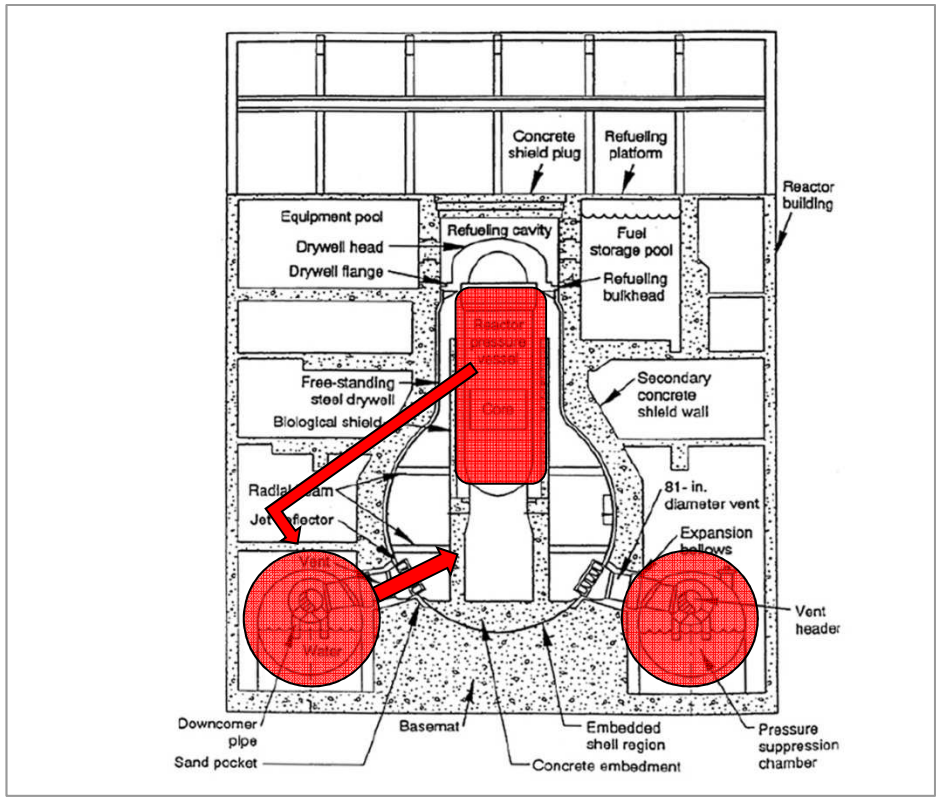
UNIT 1, 2, 3

Start dumping steam into the wet-well to release the pressure inside the RPV.

Cores uncover and suppression pools become saturated.

Things got worse

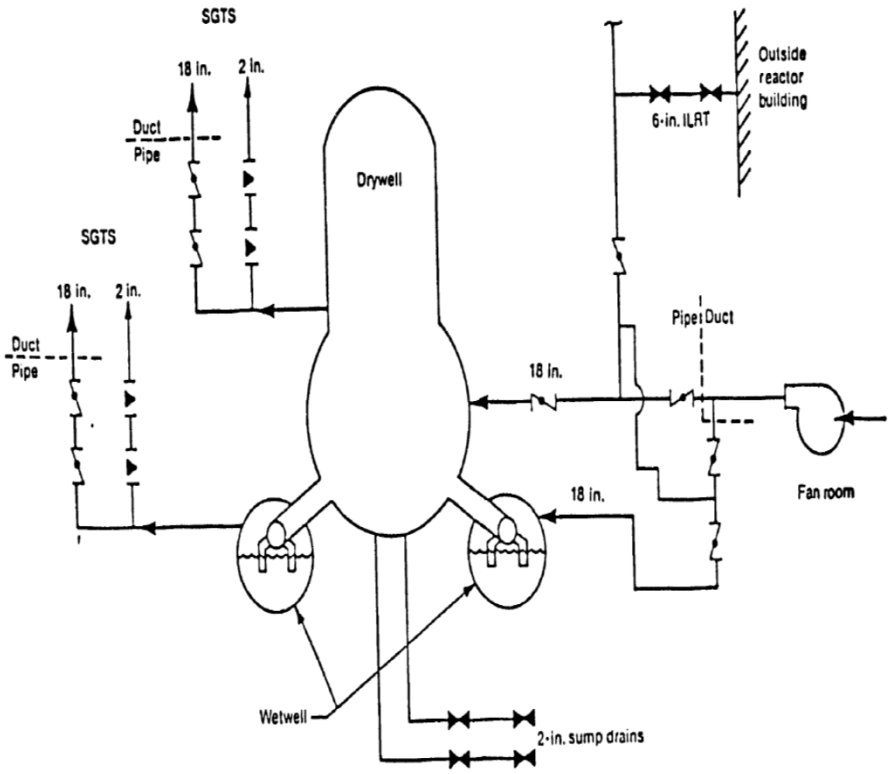
Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
12/3	Cores over heat and uncover			
12/3 9:07	A pressure relief valve on the pressure vessel at Unit 1 of Fukushima Daiichi was opened.			

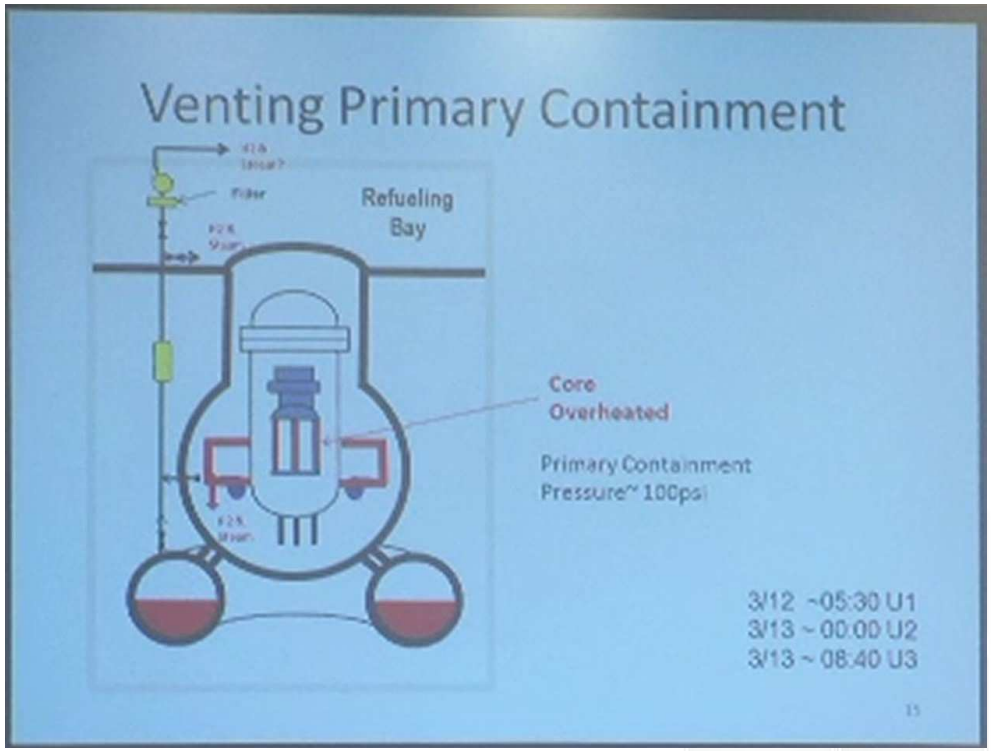


- Cores over heat and uncover
- Vent from RPV to wet-well
- Vent from wet-well to dry-well

Things got even worse

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
12/3 14:30	Vent from primary to…?			

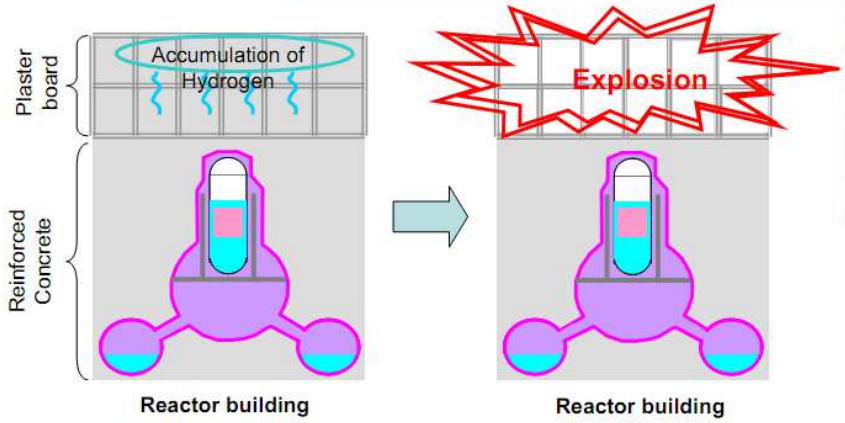




Things got even worse

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
12/3 15:36	An **(hydrogen) explosion** occurred at Unit 1			

Hydrogen explosion in the operation floor



Accident is unleashed

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
12/3 20:20	Seawater was injected into the reactor at Unit 1 of Fukushima Daiichi			
13/3 5:58	Water injection failed to function in the Emergency Core Cooling System (ECCS) at Unit 3			
13/3 9:20	A pressure relief valve on the pressure vessel at Unit 3 of Fukushima Daiichi was opened.			
13/3 13:12	Seawater was injected into the reactor at Unit 3 of Fukushima Daiichi.			
14/3 4:02	Water temperature of the spent fuel storage pool at **Unit 4** of Fukushima Daiichi increased to 84 degrees C.			
14/3 6:10	Pressure in the containment vessel at Unit 3 of Fukushima Daiichi rose to approx. 460 kPa beyond the design value.			
14/3 11:01	An **hydrogen explosion** occurred at Unit 3 of Fukushima Daiichi.			
14/3 13:25	The reactor water level at Unit 2 of Fukushima Daiichi was found to be low, from which it was concluded that the reactor cooling function had been lost.			
14/3 16:34	Seawater was injected into the reactor at Unit 2			
14/3 22:50	Abnormal rise of CV pressure at Unit 2			
15/3 0:02	Start venting at Unit 2			
15/3 6:10	An **explosive sound (hydrogen?)** was heard at Unit 2 of Fukushima Daiichi, which was judged to indicate an abnormality in the pressure suppression pool			
15/3 9:38	Fire occurred on Unit 4 3rd floor (**hydrogen explosion?**)			
16/3 8:37	An enormous amount of white steam going out of Unit 3			

Start taking control..

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
17/3	Injecting water to the spent fuel pool in unit 3 (Helicopters, truck)			
18/3	the common spent fuel pool was confirmed to be filled with water holes were made in the roof of the reactor building unit 5 and 6			
19/3	Power at Unit 5 and 6			
20/3	At Unit 3, the temperature inside the containment vessel remained high At Unit 2 and 4 TEPCO fire trucks began injecting water to Spent Fuel Pool			
21/3	Etc..			
22/3	Etc..			
23/3	Etc..			
24/4	Etc..			

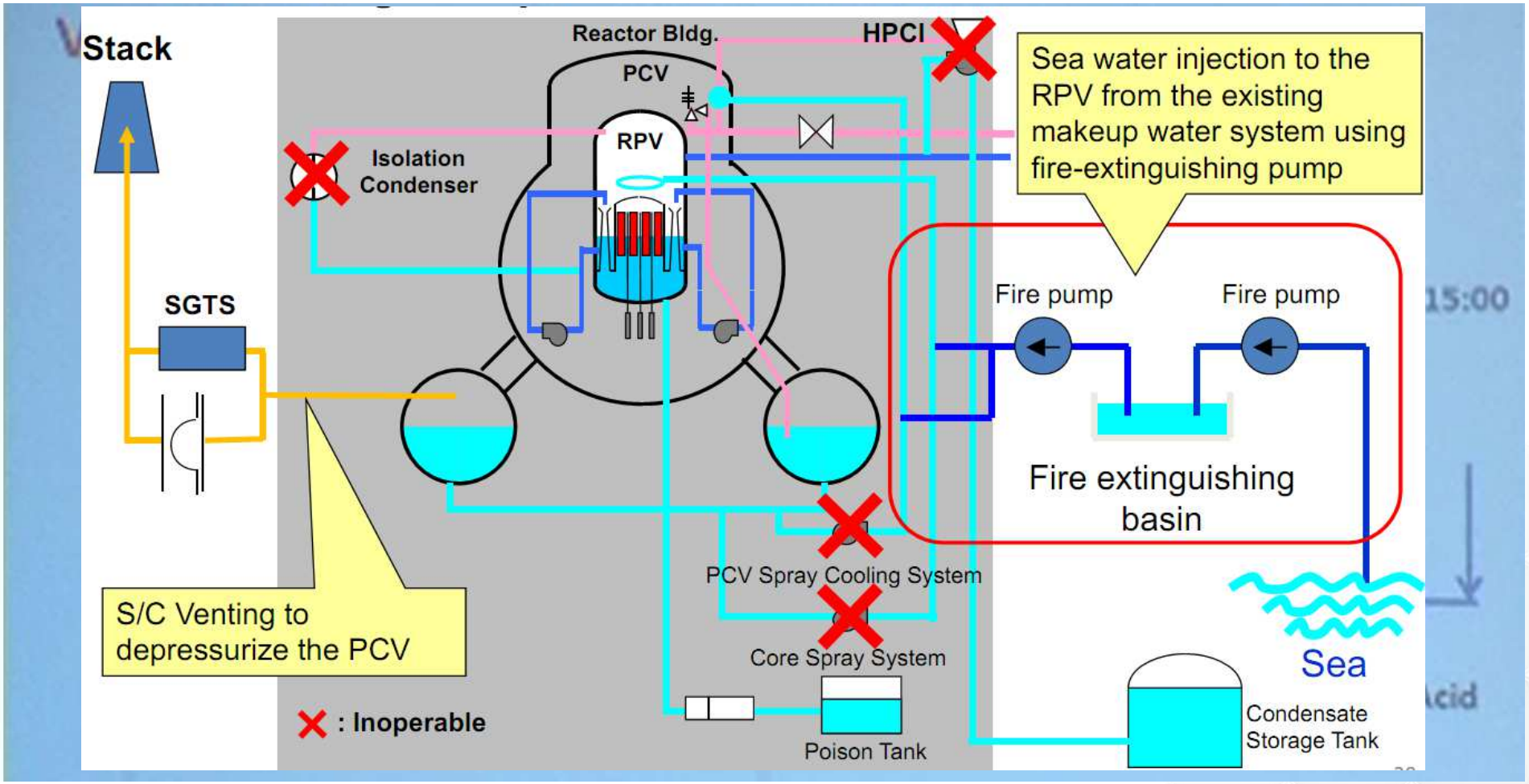
Start taking control..

The good news:

thermal control achieved

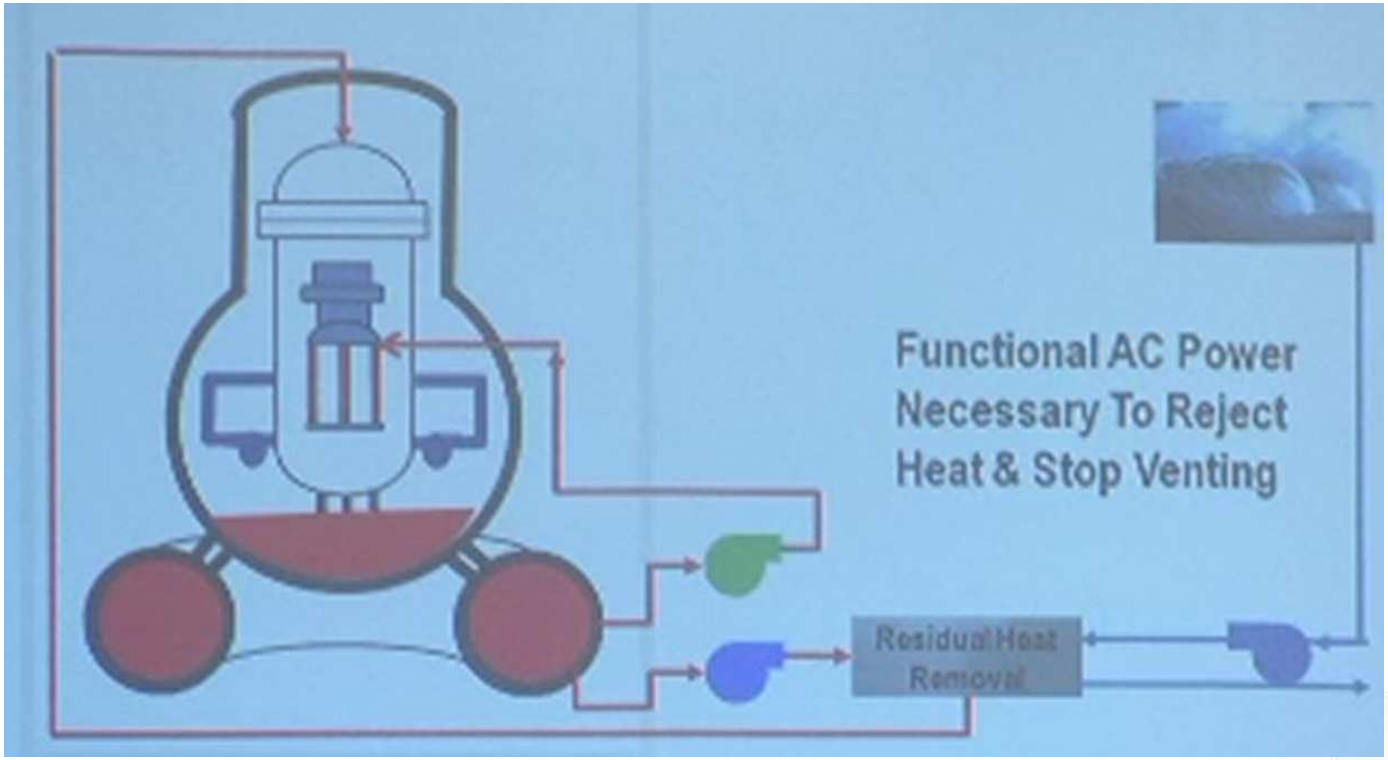
The bad news:

open loop, venting to the environment

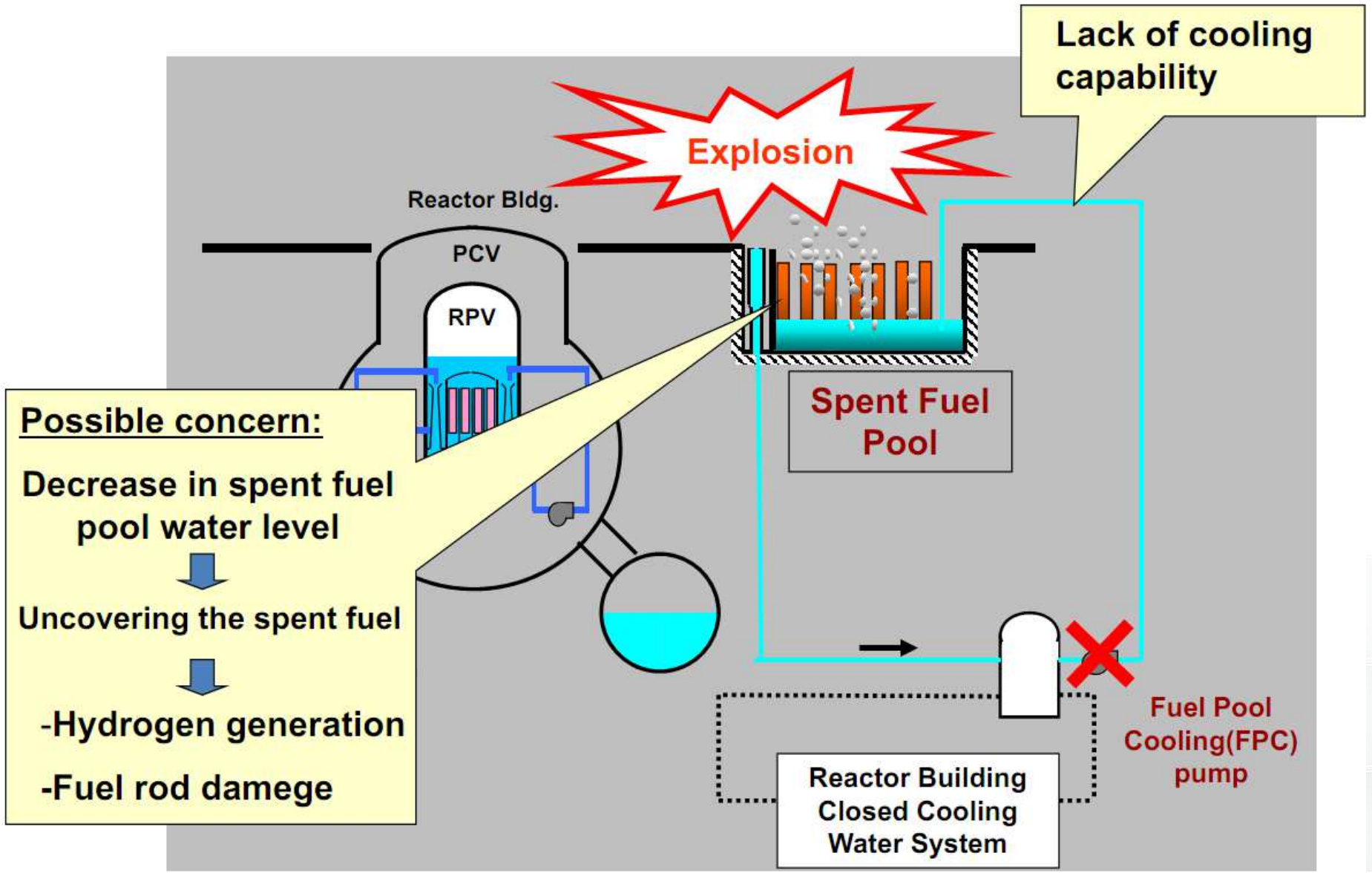


Start taking control..

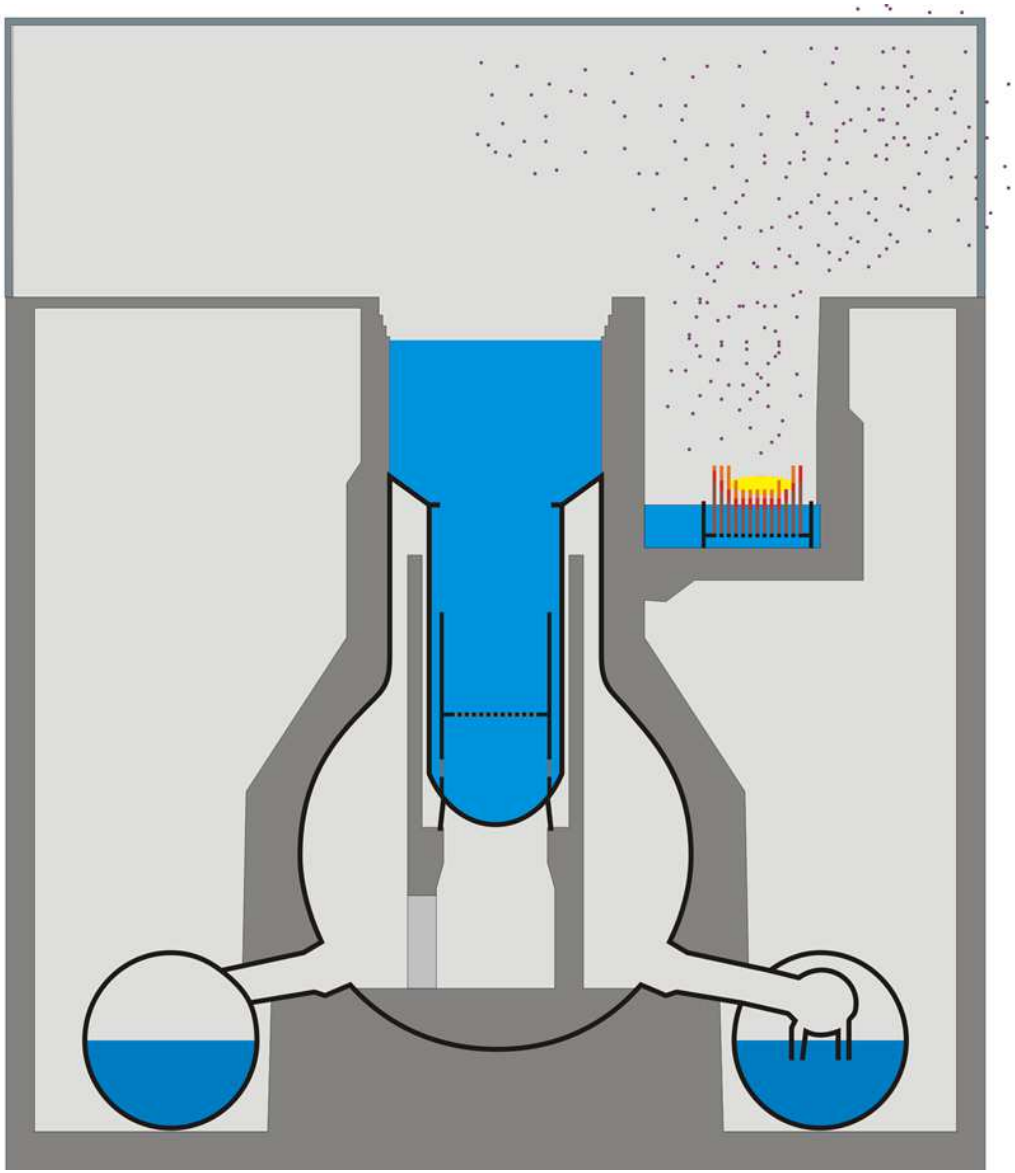
The cooling loop should be closed, but the RHR is damaged



What happened to Unit 4?



What happened to Unit 4?



Severe accident even outside a RPV?!?

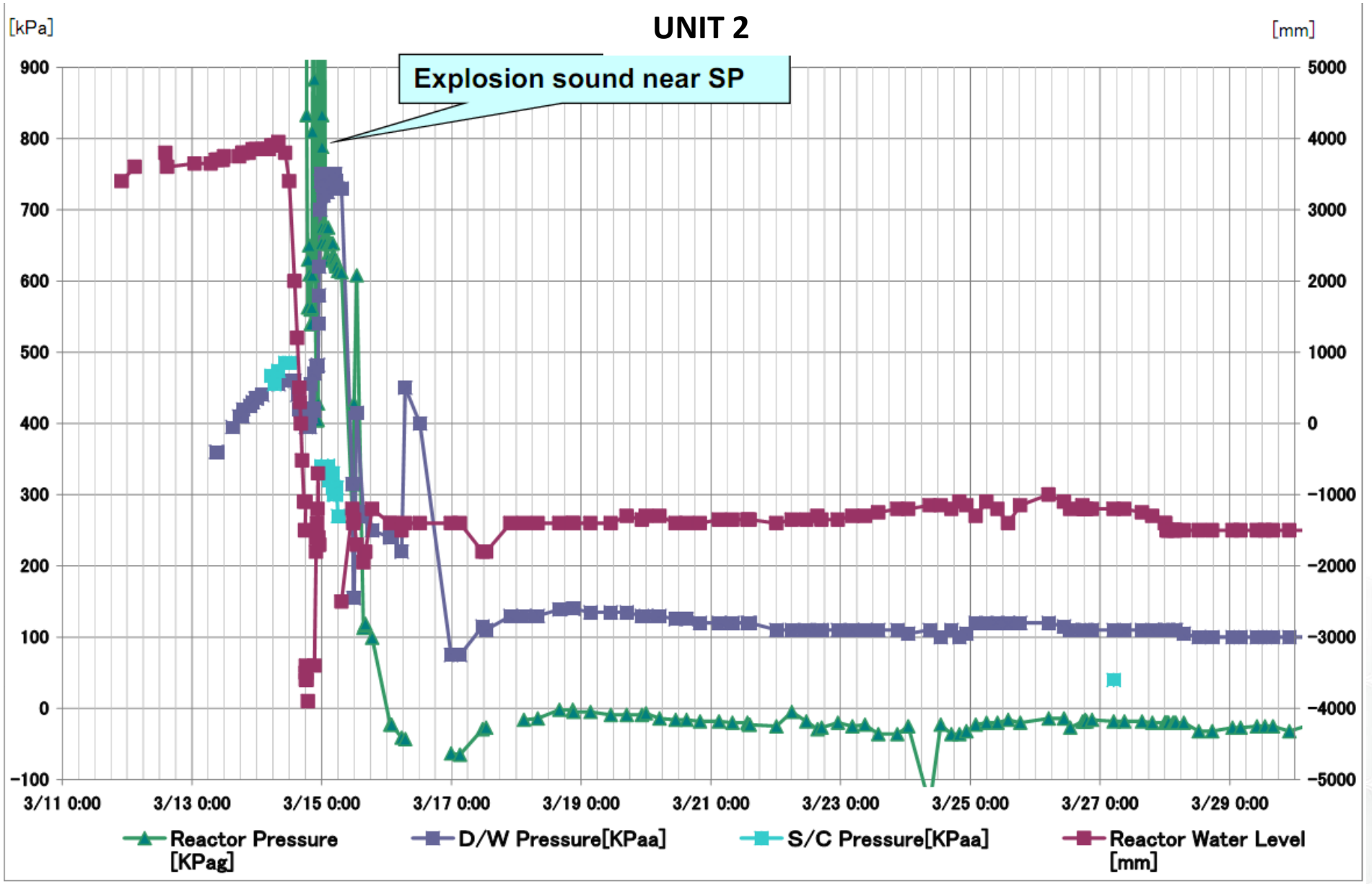
Situation today

Status of nuclear power plants in Fukushima as of 16:00, April 7th (Estimated by JAIF)

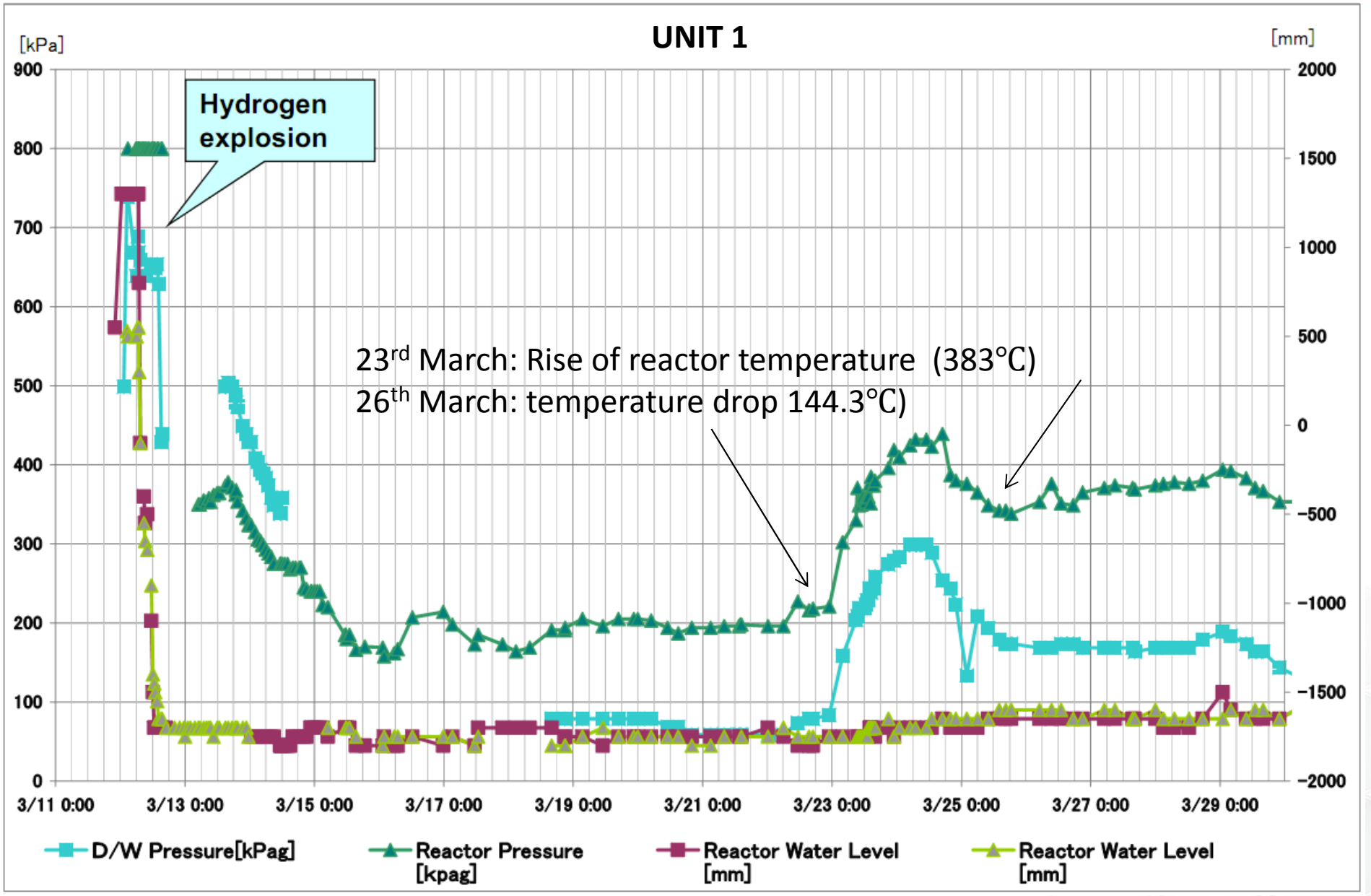
Power Station	Fukushima Dai-ichi Nuclear Power Station					
Unit	1	2	3	4	5	6
Electric / Thermal Power output (MW)	460 / 1380	784 / 2381	784 / 2381	784 / 2381	784 / 2381	1100 /3293
Type of Reactor	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Operation Status at the earthquake occurred	In Service -> Shutdown	In Service -> Shutdown	In Service -> Shutdown	Outage	Outage	Outage
Fuel assemblies loaded in Core	400	548	548	No fuel rods	548	764
Core and Fuel Integrity (Loaded fuel assemblies)	Damaged (70%*)	Damaged (30%*)	Damaged (25%*)	No fuel rods	Not Damaged	
Reactor Pressure Vessel structural integrity	Unknown	Unknown	Unknown	Not Damaged	Not Damaged	
Containment Vessel structural integrity	Not Damaged (estimation)	Damage and Leakage Suspected	Not damaged (estimation)	Not Damaged	Not Damaged	
Core cooling requiring AC power 1 (Large volumetric freshwater injection)	Not Functional	Not Functional	Not Functional	Not necessary	Functional	
Core cooling requiring AC power 2 (Cooling through Heat Exchangers)	Not Functional	Not Functional	Not Functional	Not necessary	Functioning (in cold shutdown)	
Building Integrity	Severely Damaged (Hydrogen Explosion)	Slightly Damaged	Severely Damaged (Hydrogen Explosion)	Severely Damaged (Hydrogen Explosion)	Open a vent hole on the rooftop for avoiding hydrogen explosion	
Water Level of the Rector Pressure Vessel	Fuel exposed partially or fully	Fuel exposed partially or fully	Fuel exposed partially or fully	Safe	Safe	
Pressure / Temperature of the Reactor Pressure Vessel	Gradually increasing / Decreased a little after increasing over 400℃ on Mar. 24th	Unknown / Stable	Unknown	Safe	Safe	
Containment Vessel Pressure	Decreased a little after increasing up to 0.4Mpa on Mar. 24th	Stable	Stable	Safe	Safe	
Water injection to core (Accident Management)	Continuing (Switch from seawater to freshwater)	Continuing (Switch from seawater to freshwater)	Continuing (Switch from seawater to freshwater)	Not necessary	Not necessary	
Water injection to Containment Vessel (AM)	(To be confirmed)	to be decided (Seawater)	(To be confirmed)	Not necessary	Not necessary	
Containment Venting (AM)	Temporally stopped	Temporally stopped	Temporally stopped	Not necessary	Not necessary	
Fuel assemblies stored in Spent Fuel Pool	292	587	514	1331	946	876
Fuel Integrity in the spent fuel pool	Unknown	Unknown	Damage Suspected	Possibly damaged	Not Damaged	
Cooling of the spent fuel pool	Water spray started (ffreshwater)	Continued water injection (Switch from seawater to freshwater)	Continued water spray and injection (Switch from seawater to freshwater)	Continued water spray and injection (Switch from seawater to freshwater) Hydrogen from the pool exploded on Mar. 15th	Pool cooling capability was recovered	
Main Control Room Habitability & Operability	Poor due to loss of AC power (Lighting working in the control room at Unit 1 and 2.)		Poor due to loss of AC power (Lighting working in the control room at Unit 3 and 4.)		Not damaged (estimate)	

- Core melt
- Thermal equilibrium reached
- Still open loop for cooling the cores?
- RPV integrity?
- CV integrity?
- Drywell flooded?

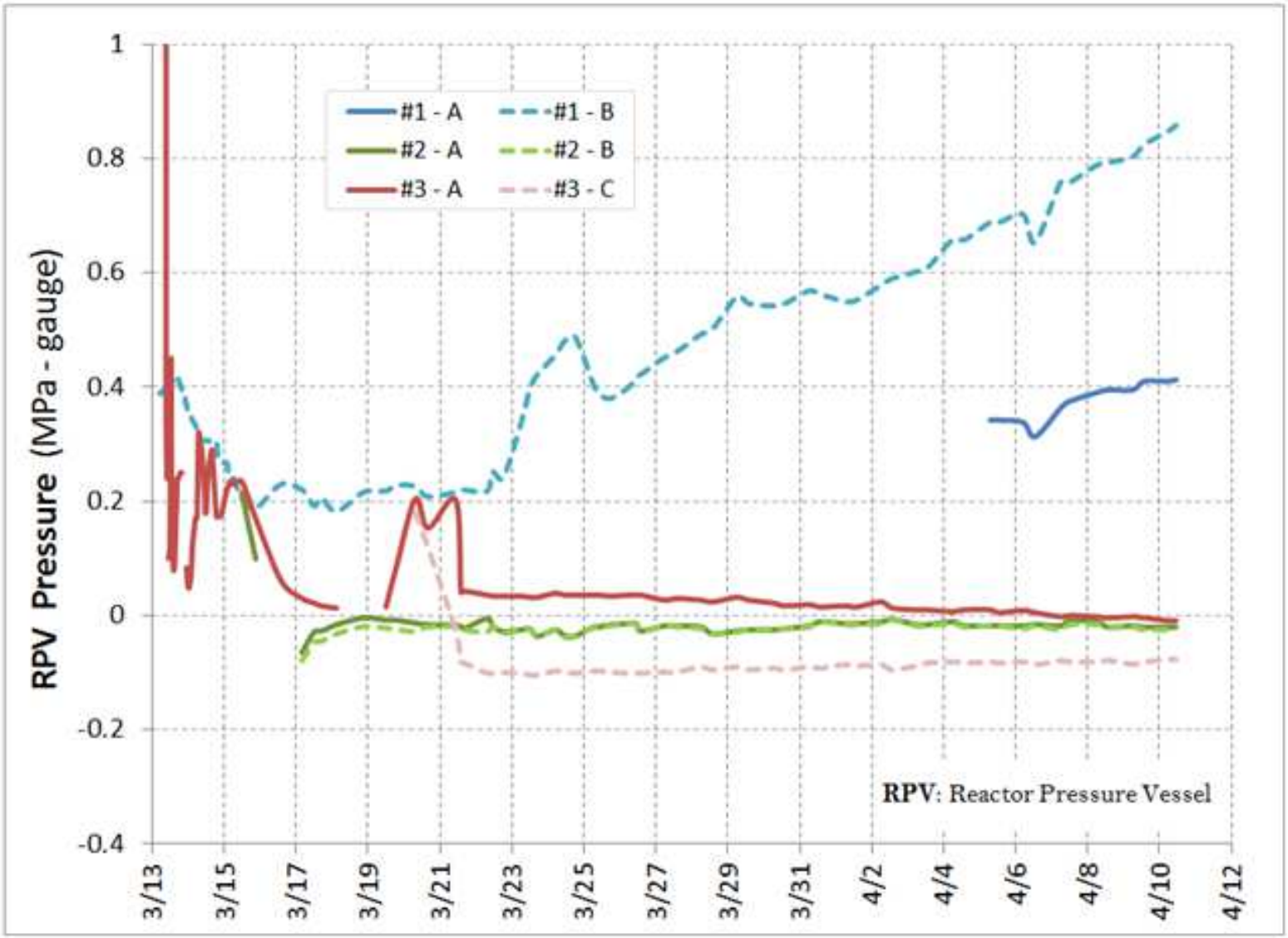
Situation today



Situation today

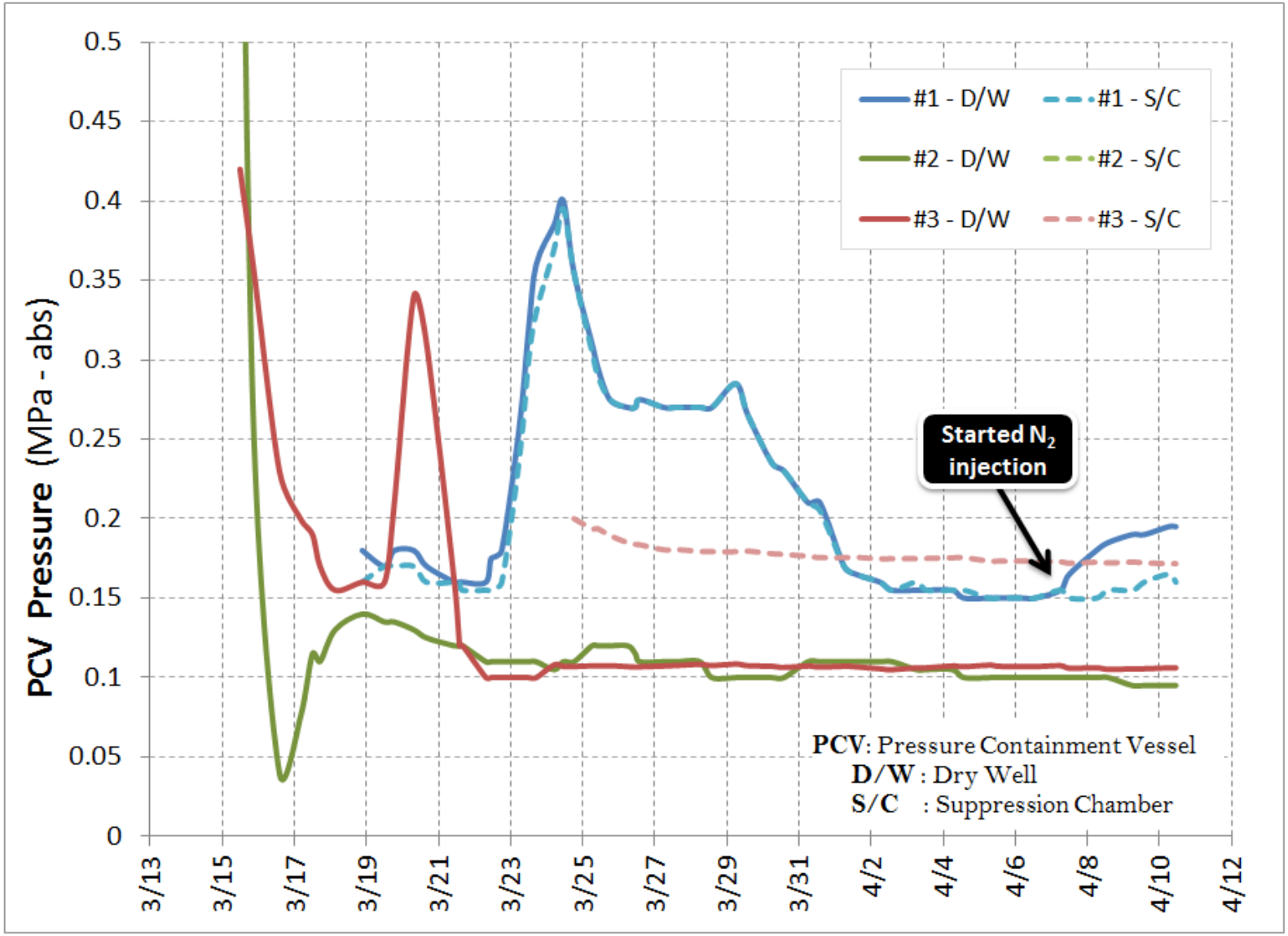


Situation today

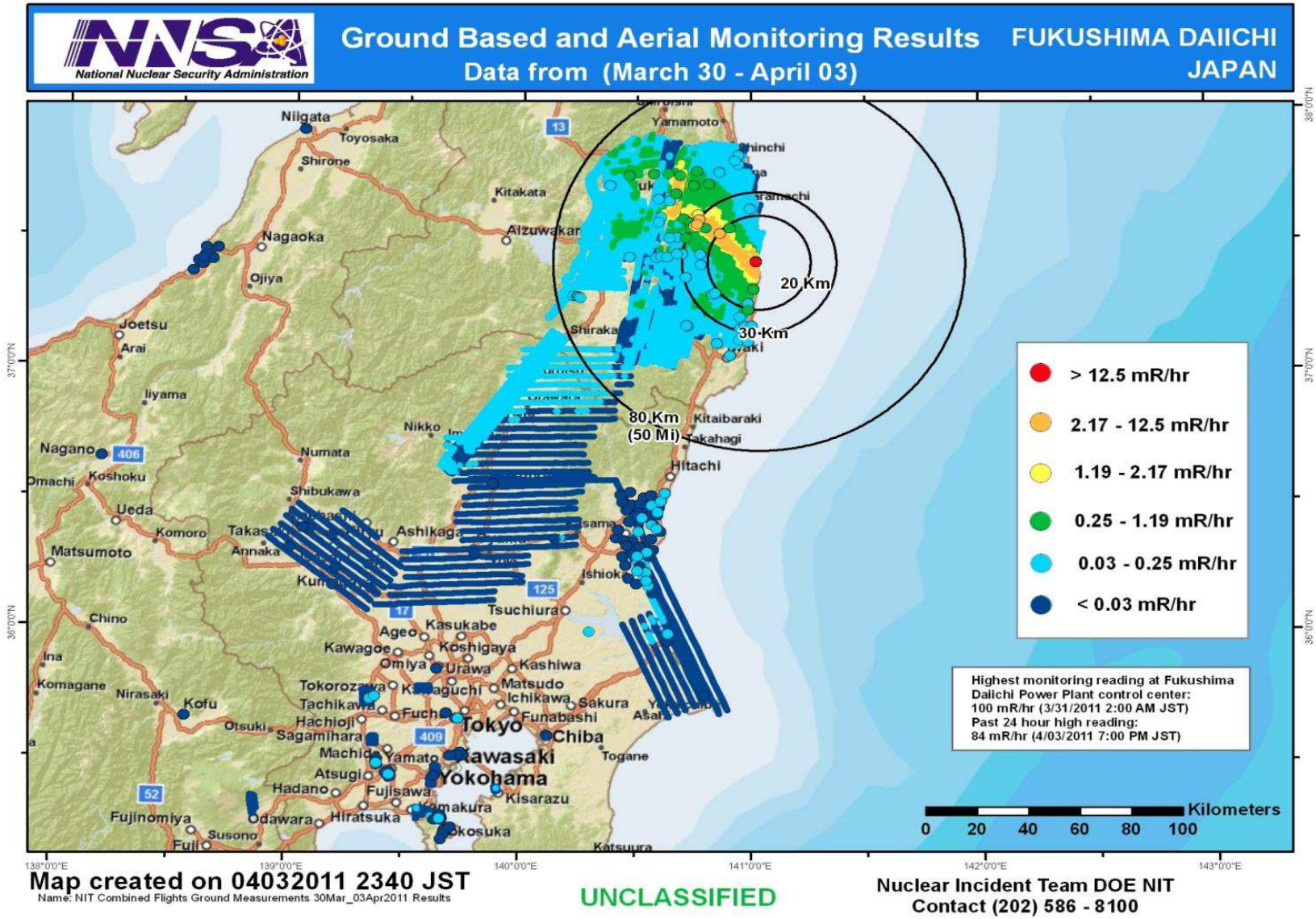


Situation today

Situation today



Situation today



Possibly observed phenomena

EARLY CORE DEGRADATION

- Core heat-up due to decay of Fission Products (PF)
- Core material oxidation by steam
- Liquefaction and melting of core materials
- Release and transport of Fission Products
- Loss of core geometry

LATE IN-VESSEL

- Massive melt formation in the core
- Relocation to the lower head
- Molten pool with crust
- Focusing effect
- Gap cooling
- Thermal attack on vessel wall
- Vessel failure ??

Possibly observed phenomena

DIRECT CONTAINMENT HEATING ??

- Vessel failure modes
- Discharge phenomena
- Cavity phenomena
- Debris transport
- Phenomena in the containment dome

HYDROGEN RISK OF EXPLOSION !!!

- It’s a real risk
- Generation, distribution, combustion
- Best mitigation methods

Possibly observed phenomena

EX-VESSEL ??

- Spreading
- Molten Core-Concrete Interaction
- Basement behaviour
- Coolability (Debris bed and Pools)

SOURCE TERM !!!!

- transport in the cooling system
- transport in the containment
- containment bypass
- chemistry

ENVIRONMENTAL IMPACT !!!!

SEVERE ACCIDENT MANAGEMENT AND MITIGATION

Lesson learnt

- Hydrogen drammatically confirmed to be a major issue.
- Severe accidents can happen even if there is no fuel inside the reactor
- The ultimate barrier to prevent a severe accident can’t just be a battery…
- Nuclear sector can’t go on just doing business as usual

Grazie

Accidents time line

Time (JST=UTC+9)	Unit 1	Unit 2	Unit 3	Unit 4
11/3 14:46	Earthquake 9.0 magnitude strikes Japan			
	Automatic shut down	Automatic shut down	Automatic shut down	Outage
	Power plant to be cut off from the Japanese electricity grid			
	Back-up diesel generators start			
11/3 15:01	14 meters high tsunami wave strikes Fukushima Dai-chi			
11/3 15:42	All AC power sources for Units 1 through 3 at Fukushima I were lost (Back-up diesel generators fail) / Report to “the Law” (Loss of power)			
	Oil tanks were washed away by tsunami			
11/3 16:36	Water injection failed to function in the Emergency Core Cooling System (ECCS) at Fukushima Daiichi Units 1 and 2 (Incapability of water injection by core cooling function)			
12/3 0:49	Abnormal rise of CV pressure			
	Back-up battery supplies are depleted. The ability to cool the reactors of units 1, 2 and 3 is significantly degraded or unavailable. Discharges to suppression chambers designed to control pressure within the reactor coolant system cause pressure within the primary containments to increase.			