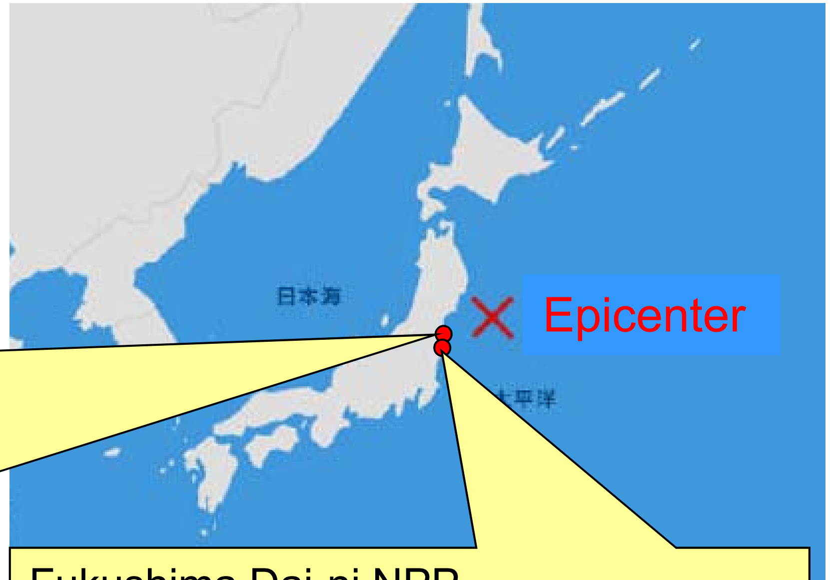
Fukushima Accident : An overview

Icapp2011, 3 May 2011 Akira OMOTO, University of Tokyo, JAPAN

1-1. 2011 off Tohoku Pacific Earthquake

Fukushima Dai-ichi NPP

Source: www.tepco.co.jp

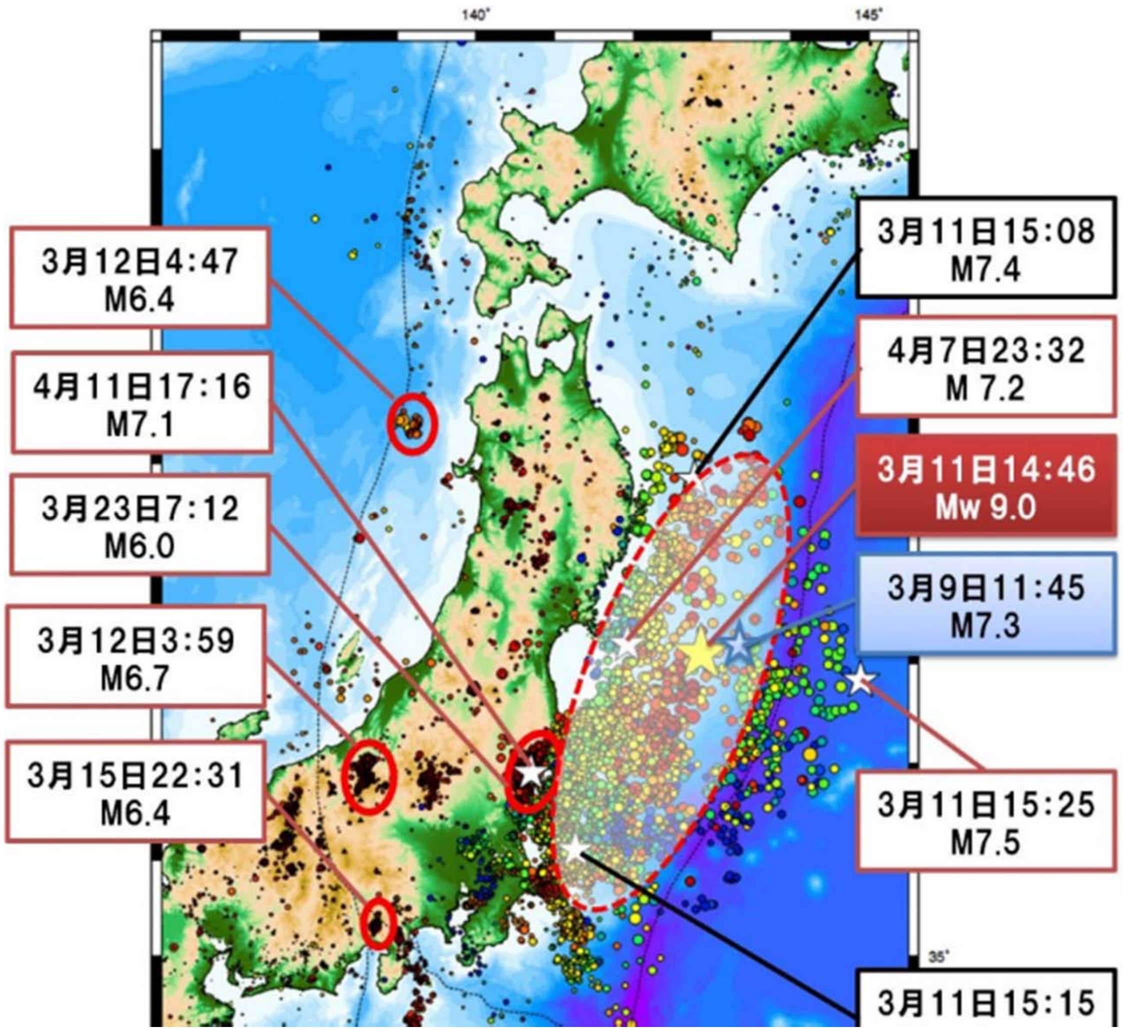


Fukushima Dai-ni NPP

Source: www.tepco.co.jp

- **Occurred 14:46 March 11, 2011**
- **Magnitude:9.0 Mw**
- **Epicenter location: 38° 6''N and 142° 51''E, and 24km in depth**
- **It is said that the height of tsunami attacked Fukushima NPP was more than 14m**

3.11 Earthquake and aftershocks



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

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

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

http://outreach.eri.u-tokyo.ac.jp/eqvolc/201103_tohoku/eng/#mesonet
"Earthquake Research Institute, University of Tokyo, Prof. Takashi Furumura and Project Researcher Takuto Maeda"

3.11 Earthquake

Design basis earthquake and observed acceleration (Basement of Reactor/B)

Nr.	MWe	3.11 Observed (max. gal)			Design (Ss) (max. gal)		
		N-S	E-W	Vertical	N-S	E-W	Vertical
1Fuku1	460	460	447	258	487	489	412
1Fuku2	784	346	550	302	441	438	420
1Fuku3	784	322	507	231	449	441	429
1Fuku4	784	281	319	200	447	445	422
1Fuku5	784	311	548	256	452	452	427
1Fuku6	1100	298	444	244	445	448	415

Note 1: **Damage by the earthquake**: Not fully inspected but maybe not significant considering the KK earthquake (2007) where no damage to safety functions even though the observed acceleration exceeded design basis by factor 2-3
(Acceleration will not necessarily be damages indicators)

Note 2: **Scram set points** by acceleration (Basement of Reactor Building)
Horizontal=135-150 gal, Vertical=100 gal

3.11 Tsunami

1F1-3 Plant response immediately after the earthquake

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

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

http://outreach.eri.u-tokyo.ac.jp/eqvolc/201103_tohoku/eng/#mesonet
"Earthquake Research Institute, University of Tokyo, Prof. Takashi Furumura and Project Researcher Takuto Maeda"

1-2. Tsunami after the earthquake

- **East coast of northern area in the main island of Japan is seriously damaged**
- **As of April 4, 12,175 people are dead and 15,489 people are missing**

Fukushima Daiichi Nuclear Power Station

Units 5 &6

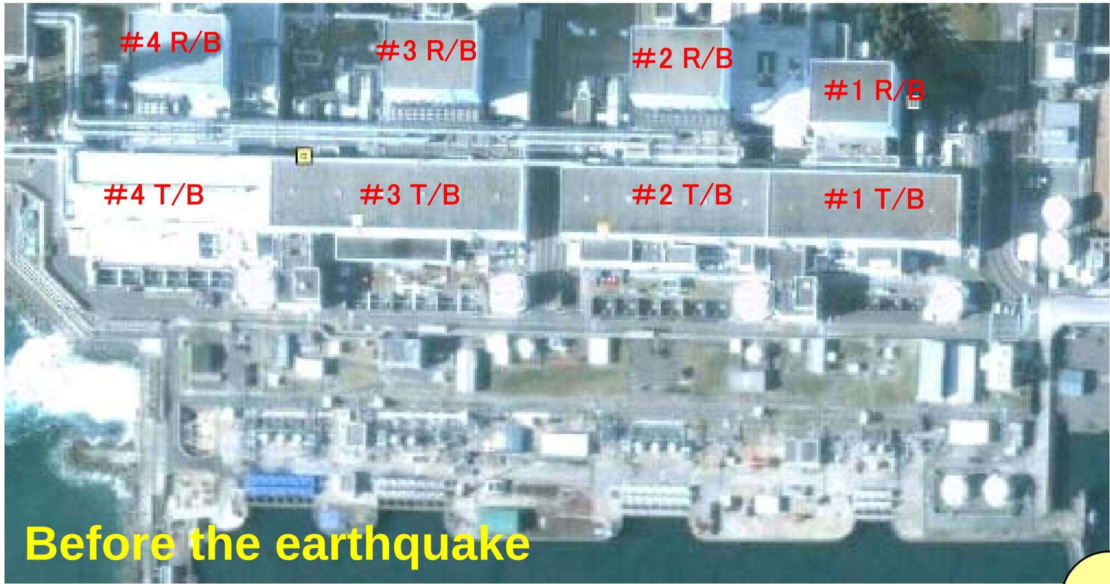
Dry SNF Storage

Common
Spent Fuel
Pool

Units 1-4

Tsunami Waves

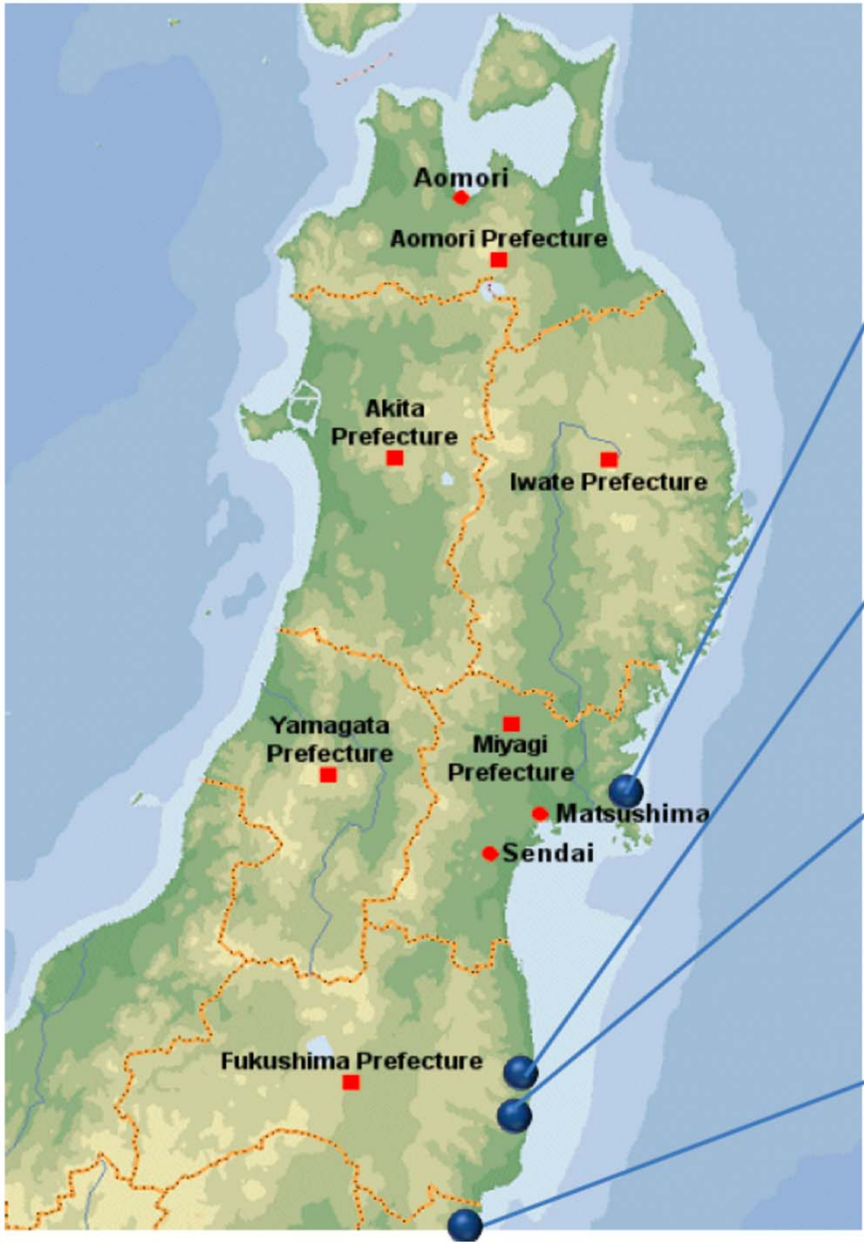
3-1. Satellite view of Fukushima Dai-ichi NPP



Many structures facing the bay are destroyed

Source: Google Earth

14 NPPs along the coastal line affected by Tsunami



Onagawa
- Unit1: 524 MW, 1984-
- Unit2: 825 MW, 1995-
- Unit3: 825 MW, 2002-

Fukushima Ⅰ
- Unit1: 460 MW, 1971-
- Unit2: 784 MW, 1974-
- Unit3: 784 MW, 1976-
- Unit4: 784 MW, 1978-
- Unit5: 784 MW, 1978-
- Unit6: 1,100 MW, 1979-

Fukushima Ⅱ
- Unit1: 1,100 MW, 1982-
- Unit2: 1,100 MW, 1984-
- Unit3: 1,100 MW, 1985-
- Unit4: 1,100 MW, 1987-

Tokai Ⅱ (1,100 MW, 1978-)

1-4. Automatic shut-down of nuclear reactors

● **11 reactors were automatically shut-down**

- Onagawa Unit 1,2,3
- Fukushima Dai-ichi (I) Unit 1,2,3
- Fukushima-Dai-ni (II) Unit 1,2,3,4
- Tokai Dai-ni (II)

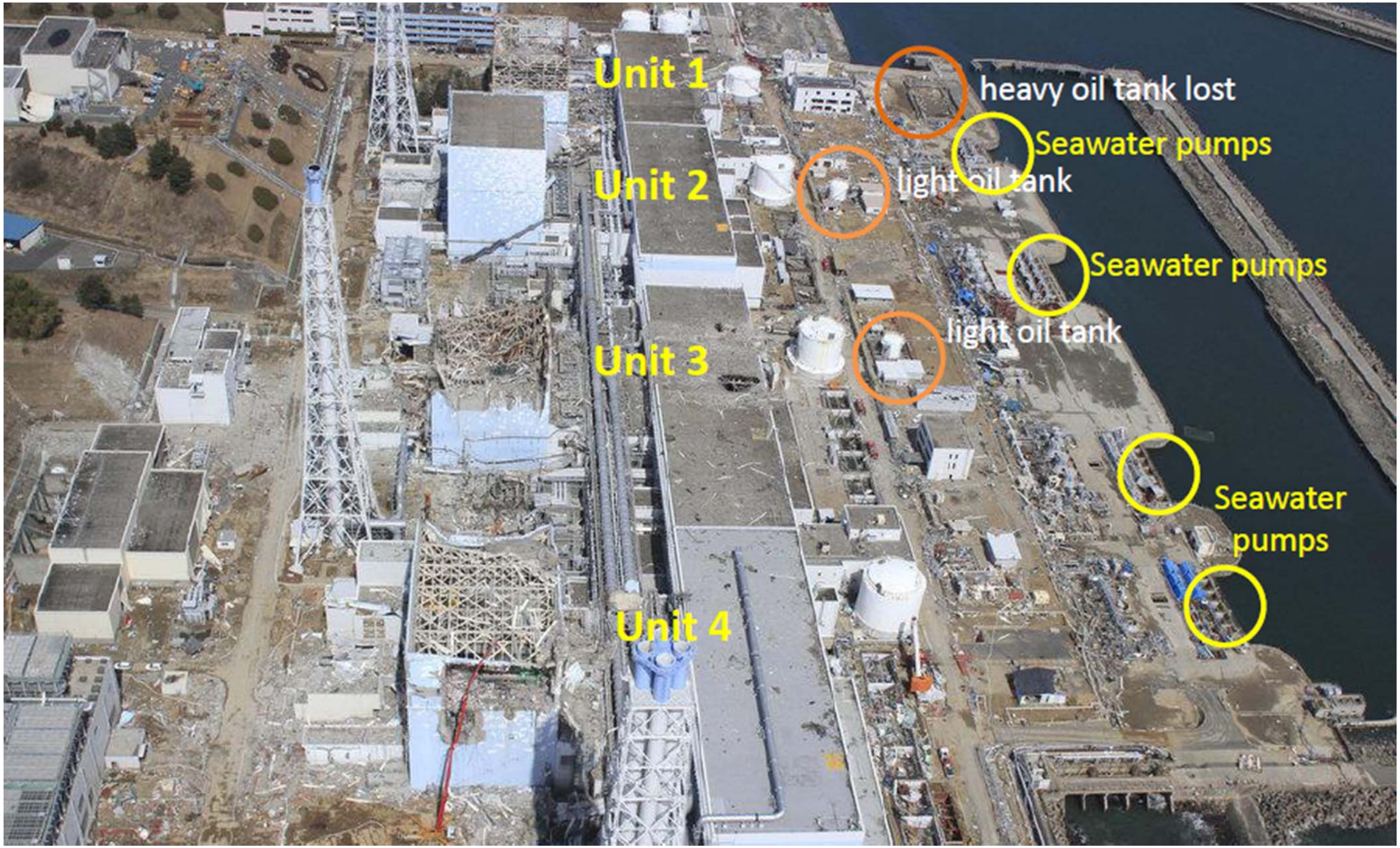
● **3 reactors were under periodic inspection**

- Fukushima Dai-ichi (I) Unit 4,5,6

-After the automatic shut-down, the Unit 1-3 at Onagawa Nuclear Power Station, the Unit 3 at Fukushima II Nuclear Power Station, and the Unit at Tokai II Nuclear Power Station have been cold shut down safely.

-As for the unit 1,2,4 at Fukushima II Nuclear Power Station, the operator of the station reported NISA nuclear emergency situation because the temperature of the suppression pools became more than 100 ℃, but afterward the three units have been cold shut down.

Fukushima Dai-ichi Unit 1-4



Fuel damage or not ---- *What made the difference?*

(1) *Elevation vs. Tsunami height*

- *Site ground level* → *saved Onagawa units*
- *Elevation of air intake/exhaust of EDG*
- *Location of EDG/EE room/battery*

(2) Availability of power

- *Offsite power* → *saved 2F site*
- *Air-cooled EDG coupled with the above 1) location/height*
  → *saved 1F6*

  \- *Air-cooled EDG was added for 1F2,4,6 respectively in the 1990's as a part of SAM modifications.*
- *1F3/5/6 battery located at a higher elevation, escaped flooding*

(3) Implementation of AMG by using then-available resources

→ *saved 1F5, SFPs (makeup water)*

NOTE: Availability of UHS commensurate to decay heat level supports quick recovery but does not seem to be a decisive factor.

- 1F5/6 : Use of temporary seawater pump for RHR (units were in refueling outage)

- 2F4 : continued Rx water makeup under isolation from UHS until March 14th

Tsunami: NPP Design guidelines and probabilistic study

- ***Safety Design Guide (NSC) Nr. 2 [footnote]***
  - *"….Anticipated natural hazard includes flood, Tsunami …."*
- ***Japan Society of Civil Engineers (JSCE) on Tsunami***
  - *Renewed concern over Tsunami by 1983, 1993 Tsunami experiences*
  - *2002 guidelines for NPPs from the Nuclear Civil Engineering Committee of JSCE http://committees.jsce.or.jp/ceofnp/system/files/JSCE_Tsunami_060519.pdf*

  1) Consideration of Tsunami sources along the plate boundary, uncertainty analysis and verification by the use of historical record;

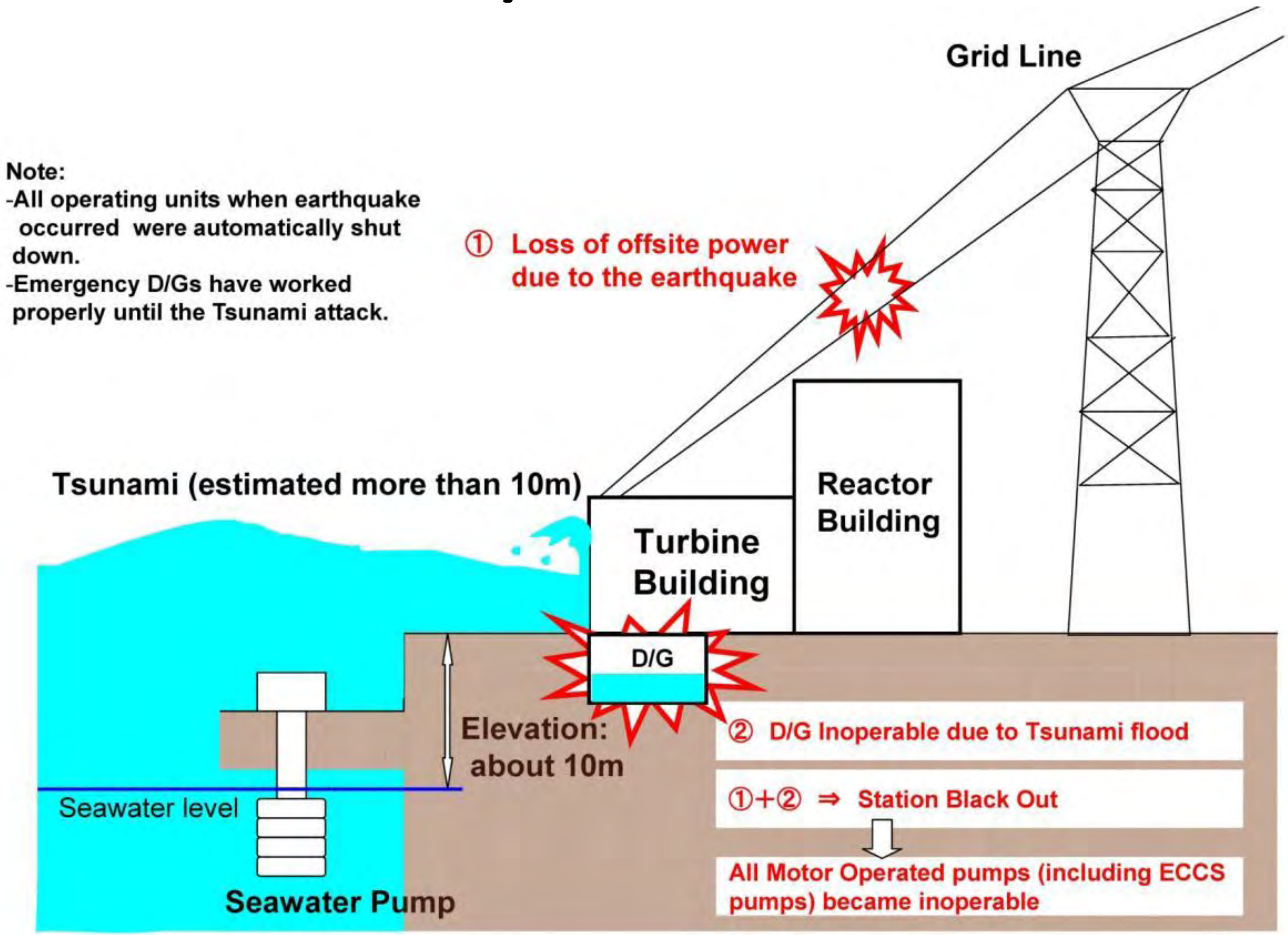
  …. At the target site, <u>the height of the design tsunami should exceed all the calculated historical tsunami heights.</u>

  2) "….the design tsunami is compared with the historical records …. it is confirmed the height of the design tsunami that is obtained in this paper is <u>twice</u> that of historical tsunamis on an average"

  - *Modification in 2002 based on this guideline*
- ***Tsunami Probabilistic Hazard study***
  - *Probabilistic Tsunami hazard analysis (TEPCo, ICONE-14, 2006)*
  - *Methodology guide from JSCE Nuclear Civil Engineering Com. (2009)*
- ***IAEA DS417 (draft)***
  - *Includes guide on Tsunami analysis*

Tsunami Size Was Accident Cause

3/11 15:45



1. Design of Fukushima NPP

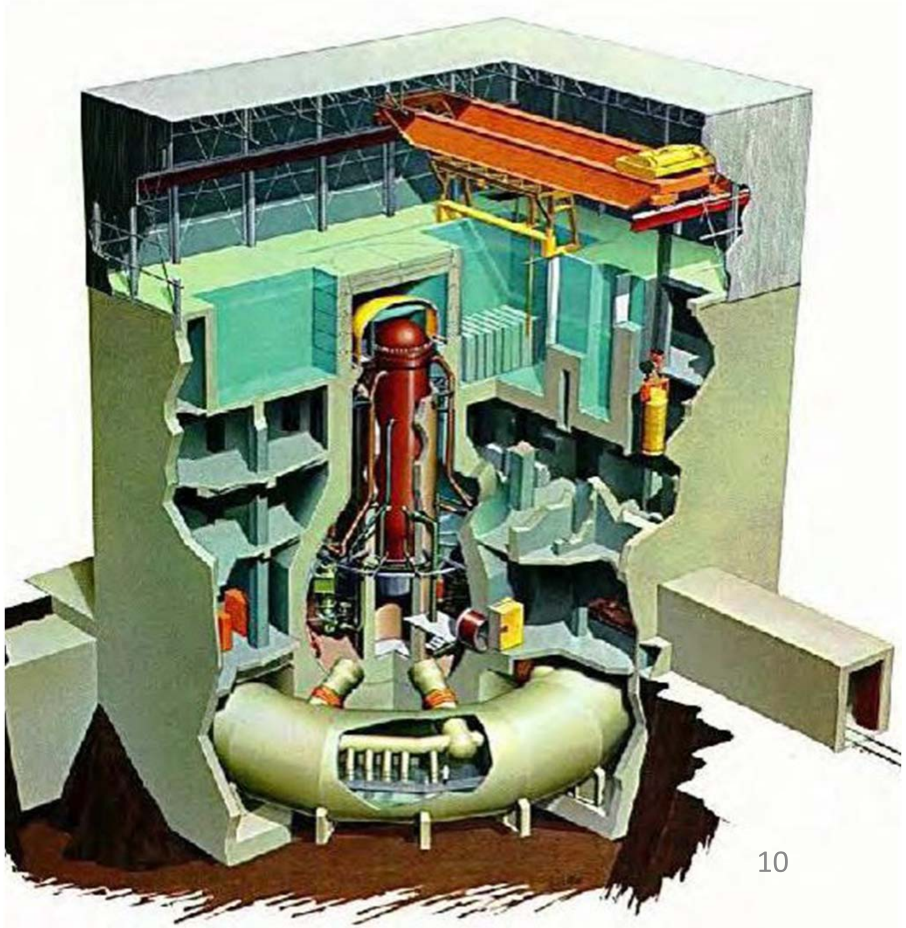
BWR/3,4 generation plant

BWR/3 (460MWe, 1Fuku1)

- Mark I Containment (Drywell + Torus-type Suppression Pool)
- SFP on top floor of the R/B
- Isolation condenser for passive core cooling (@Hi Pressure)
- Core Spray system (@Lo Pressure) after depressurization by SRV

BWR/4 (784MWe, 1Fuku 2,3,4 &5)

- Mark I Containment (Drywell + Torus-type Suppression Pool)
- SFP on top floor of the R/B
- RCIC (Reactor Core Isolation Cooling) & HPCI (High Pressure Core Injection) (@Hi Pressure)
- CS (Core Spray) & RHR/LPCI (@Lo Pressure) after depressurization by SRV



2-1. Summary of Fukushima Dai-ichi NPS

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
PCV Model	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-2
Electric Output (MWe)	460	784	784	784	784	1100
Max. pressure of RPV	8.24MPa	8.24MPa	8.24MPa	8.24MPa	8.62MPa	8.62MPa
Max. Temp of the RPV	300℃	300℃	300℃	300℃	302℃	302℃
Max. Pressure of the CV	0.43MPa	0.38MPa	0.38MPa	0.38MPa	0.38MPa	0.28MPa
Max. Temp of the CV	140℃	140℃	140℃	140℃	138℃	171℃(D/W) 105℃(S/C)
Commercial Operation	1971,3	1974,7	1976,3	1978,10	1978,4	1979,10
Emergency DG	2	2	2	2	2	3*
Electric Grid	275kV×4				500kV×2	
Plant Status on Mar. 11	In Operation	In Operation	In Operation	Refueling Outage	Refueling Outage	Refueling Outage

* One Emergency DG is Air-Cooled

Major Design Parameter of Fukushima1-1~4

	Unit 1	Unit 2	Unit 3	Unit 4
Commercial Operation	1971	1974	1976	1978
Reactor Design	BWR-3	BWR-4	BWR-4	BWR-4
Rated Power (MWe)	460	784	784	784
Thermal Power (MWt)	1,380	2,381	2,381	2,381
Isolation Cooling system	IC	RCIC	RCIC	RCIC
ECCS Configuration	HPCI (1) ADS CS (4)	HPCI (1) ADS CS (2) LPCI (2)	HPCI (1) ADS CS (2) LPCI (2)	HPCI (1) ADS CS (2) LPCI (2)
Primary Containment Vessel	Mark-I	Mark-I	Mark-I	Mark-I
Operation Status at the earthquake occurred	In Service ↓ Shutdown	In Service ↓ Shutdown	In Service ↓ Shutdown	Outage

ECCS: Emergency Core Cooling System, HPCI: High Pressure Core Injection System, ADS: Automatic Depressurization System, CS: Core Spray System, LPCI: Low Pressure Core Injection System
IC: Isolation Condenser, RCIC: Reactor Core Isolation Cooling System

Evolution of BWR Design

Improvement Safety

Improvement Economy

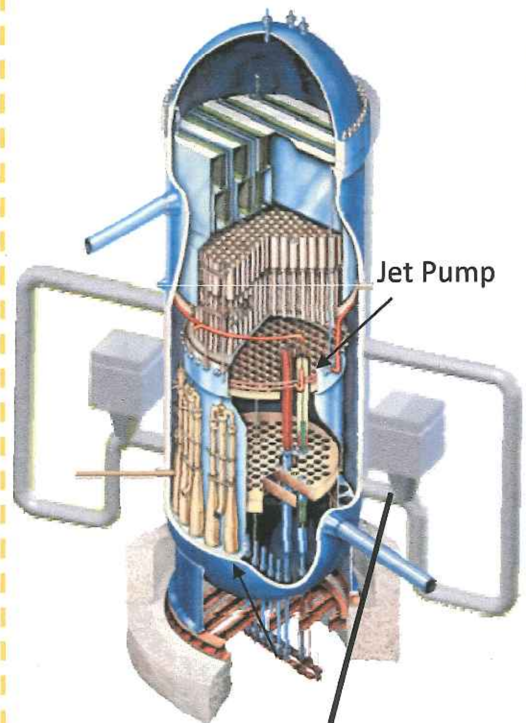
BWR-1

Dual cycle
(with separator)

BWR-2

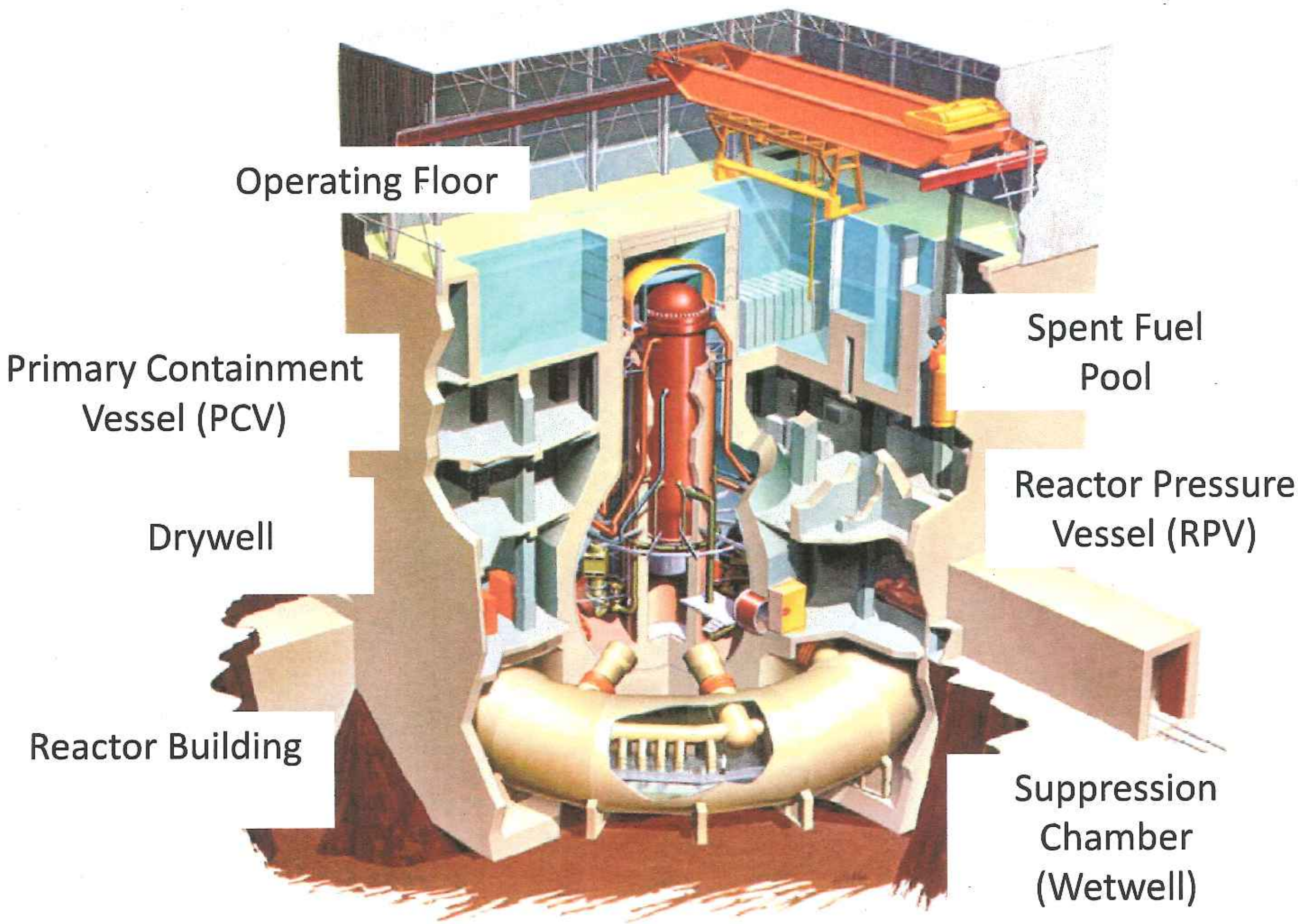
External Recirculation pump
With built-in separator

Standardized BWR
(BWR-3/4/5)
Fukushima 1-1~6



Reactor coolant
Recirculation pump

Mark-I Containment & Surrounding Structures



Browns Ferry Primary Containment

Mark-I Containment: design and improvement

	Technical Issues	Concept/Countermeasures
Basic Design	-	•Achieve compact design by having pressure suppression chamber
Hydrodynamic Load during LOCA	•Pool swell (short term), Condensation Oscillation (mid term), Chugging (long term) were identified as possible hydrodynamic loads to containment after LOCA •SRV quencher issue (condensation during transient)	•Comprehensive experimental and analytical studies were conducted, then individual plant evaluation was conducted based on these studies. •Actual implementation was different from plant by plant (implementation of modifications, or evaluation of design)
Integrity against Severe Accident	•Loss of integrity could be foreseen for possible beyond DBA	•Hardened Containment Venting capability was added per Generic Letter 89-16 by USNRC in USA •Same countermeasures were implemented in Japan

Important Systems coping with SBO

	Unit 1	Unit 2, 3	Remarks
Number of EDG	2	2	•1 DG was added to Unit 2, 4, and 6 in 1990's as part of SAMG implementation
DC Battery Capacity	10 hrs	8 hrs	•Based on SBO coping evaluation (using different system, U1: IC, U2/3: RCIC/HPCI) •Compliant with NSC's regulatory requirement for short term SBO (Guide 27: see below)
Non-AC dependent Systems	IC, HPCI	RCIC, HPCI	•Only DC battery power needed to operate
Containment Venting	HVS installed	HVS installed	•In 1990s, Hardened Venting Systems were installed in each units

NSC Safety Design Guide 27: Design considerations against loss of power ...shall be designed that safe shutdown and proper cooling of the reactor after shut-down can be ensured in case of **a short term total AC power loss**.

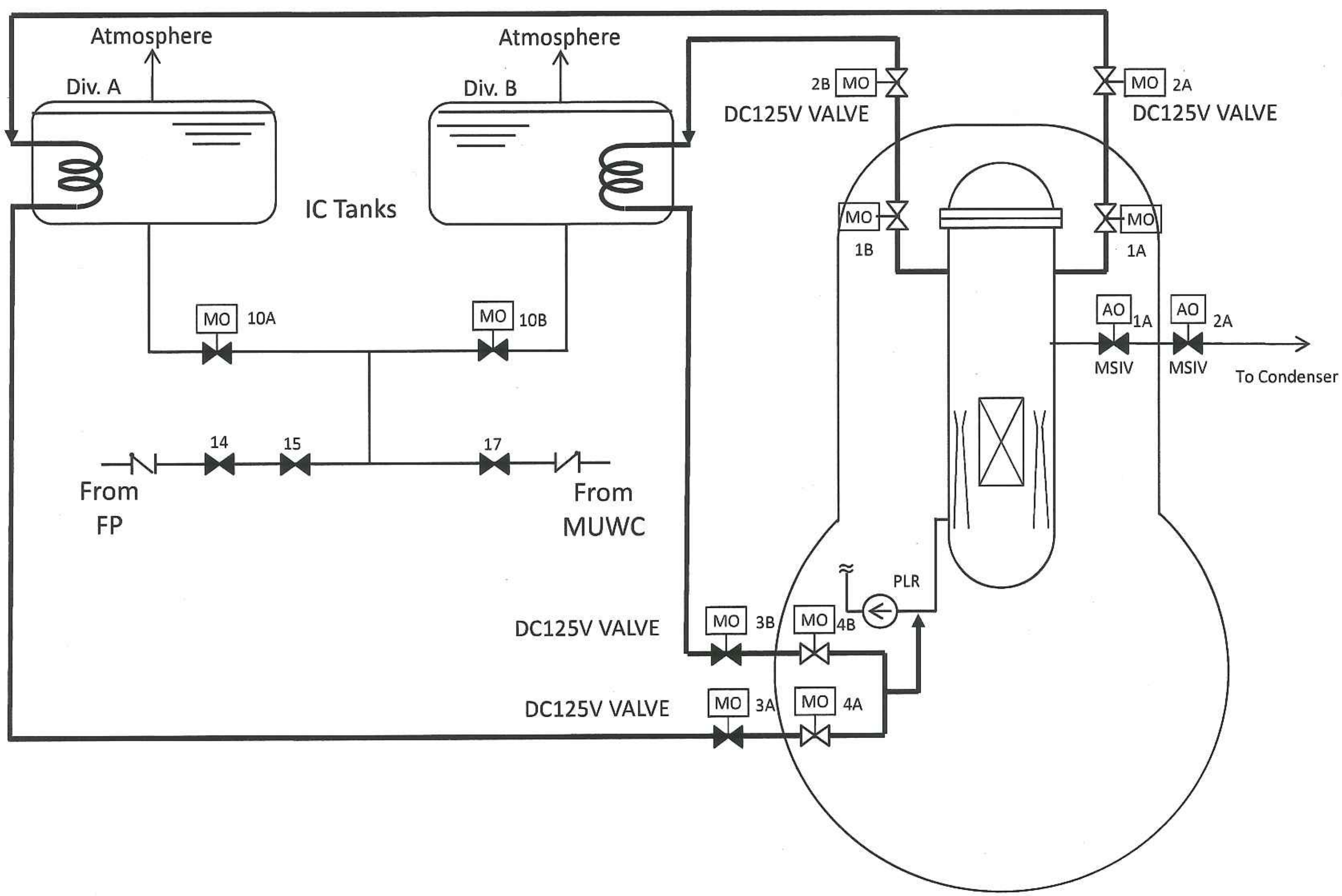
Commentary to Guide 27: No particular considerations are necessary against a long-term total AC power loss because of repair of transmission line or emergency power system can be expected in such a case.

HPCI: High Pressure Core Injection System, IC: Isolation Condenser
RCIC: Reactor Core Isolation Cooling System, HVS: Hardened Venting System

Design Feature of Isolation Condenser (Unit 1)

Item	Description
Purpose	•Cool down RPV water during isolation event (MSIV closure) without losing RPV water inventory
Function	•After reactor isolation, sends reactor steam into condenser •After heat exchange at condenser, returns condensed water into reactor
System configuration	•Two division systems with Condensers, isolation valves, piping [see next slide] •NOFO isolation MO valves in steam lines •NCFC isolation MO valve in return lines •All valves can be operated by DC power
Capacity	•Two ICs can remove heat load of 6% of rated power •IC Pool capacity is good enough for 10 hour operation without AC power for makeup water into IC tank

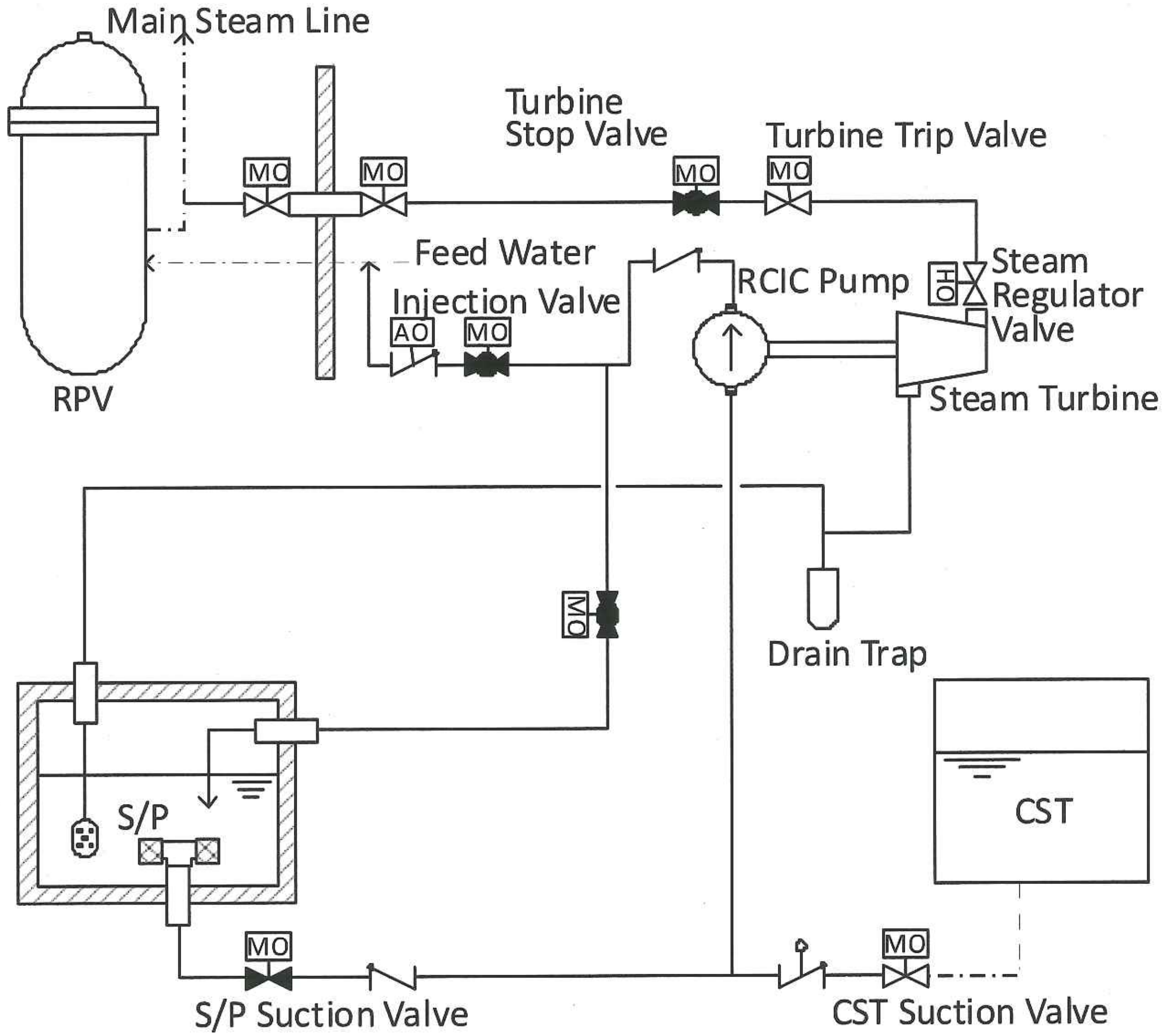
Schematic of Isolation Condenser (Unit 1)



Design Features of RCIC (Unit 2, 3)

Item	Description
Purpose	•Inject water into RPV during isolation event (MSIV closure)
Function	•After reactor isolation, sends reactor steam to RCIC Turbine, which injects water into RPV •Condensed reactor steam (drained water from RCIC Turbine) is discharged to Suppression Pool
System configuration	•Turbine, Pump, piping, valves, water sources (CST and S/P) [see next slide] •Auto start at RPV low water level (L2), then stop at RPV high water level (L8) •Primary water source is CST then switch to S/P when reaching high water level (+5 cm NWL) in S/P •All valves and governor in turbine pump can be operated by DC power
Capacity	•RCIC can operate without AC power using DC power only for 8 hours depending on load reduction in an SBO

Schematic of RCIC*



*HPCI (High Pressure Core Injection System) was also available as AC independent system

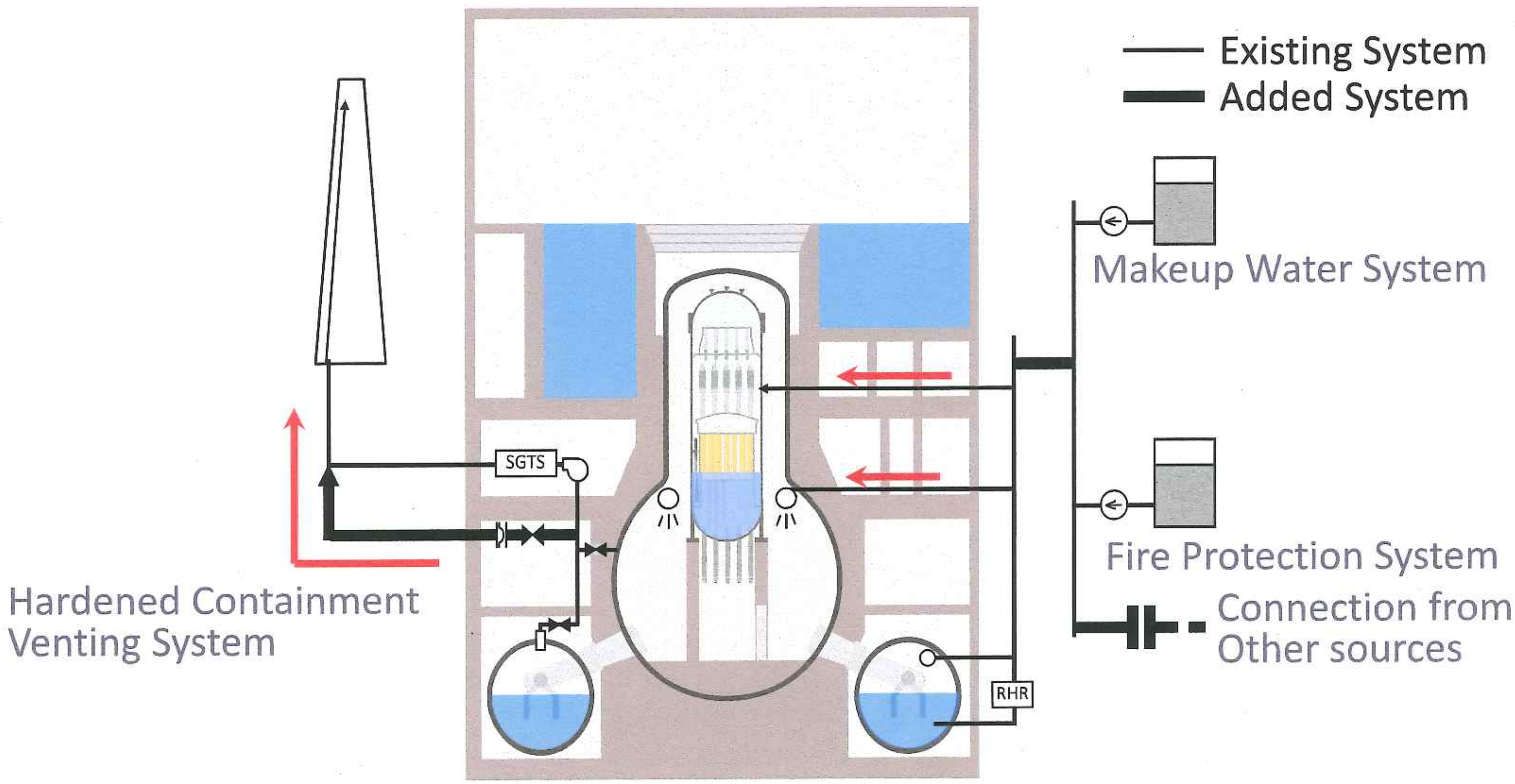
Overview of Severe Accident Countermeasures

Severe Accidents	Countermeasures
Anticipated Transient Without Scram (ATWS)	Alternative Reactivity Control System (Alternative Rod Insertion System and Recirculation Pump Trip System)
SA events with loss of core cooling and/or loss of molten core cooling	Alternative Water Injection System (Utilizing Fire Protection System etc.)
Hydrogen Generation	Inerting Primary Containment Vessel by nitrogen
Loss of decay heat removal	Hardened Containment Venting System
Station Blackout	Alternative Electric Supply System (Inter-connections with adjacent unit)

In Japan, all units installed SA Countermeasures in late 1990s

SA Countermeasures in Fukushima

- Alternative Water Injection System did provide water into either RPV (or PCV) by using existing systems (RHR/LPCI, MUWC, FP) from several water sources
- Hardened Containment Venting System did remove decay heat from containment either from Wetwell or Drywell



2. Earthquake and Tsunami

Capability of each units for each events

Event	Category	Unit 1	Unit 2	Unit 3	Unit 4
Seismic	Design Basis	180 Gal	180 Gal	180 Gal	180 Gal
	Max. Beyond DB Capability	489 Gal	441 Gal	449 Gal	447 Gal
	Max. Actual Seismic	460 Gal	550 Gal	507 Gal	319 Gal
Tsunami	Initial Design Basis	3.1 m	3.1 m	3.1 m	3.1 m
	Revised Design Basis	5.7 m	5.7 m	5.7 m	5.7 m
	Actual Tsunami	14 m	14 m	14 m	14 m
SBO	Design Basis	N/A	N/A	N/A	N/A
	Beyond DB Capability	10 hrs	8 hrs	8 hrs	8 hrs
	Actual SBO	Days	Days	Days	Days

Damages by earthquake and Tsunami

Incident	Major Damages	Remarks
Earthquake	• Collapsed pylons – leading to Loss of Off-site Power	• Automatic shut down and hot stand-by achieved in all units, even having SBO after Tsunami hit the site
Tsunami	• Washed out many structures along bay - sea water pumps, intake structures and several tanks – leading to loss of all ECCS • Water penetrated Turbine Buildings – leading to damaging DGs and Switchgears (SBO) • Moved many debris and rubbles onto site road – leading to unavailability of access to units • Damaged local roads – made it difficult to approach Fukushima site from outside	• Transition from hot stand-by to cold shut down is not yet to be achieved due to unavailability of many important equipments after Tsunami hit the site, besides unavailability of transportation to the site

Tsunami caused huge damages, while Earthquake caused LOPA

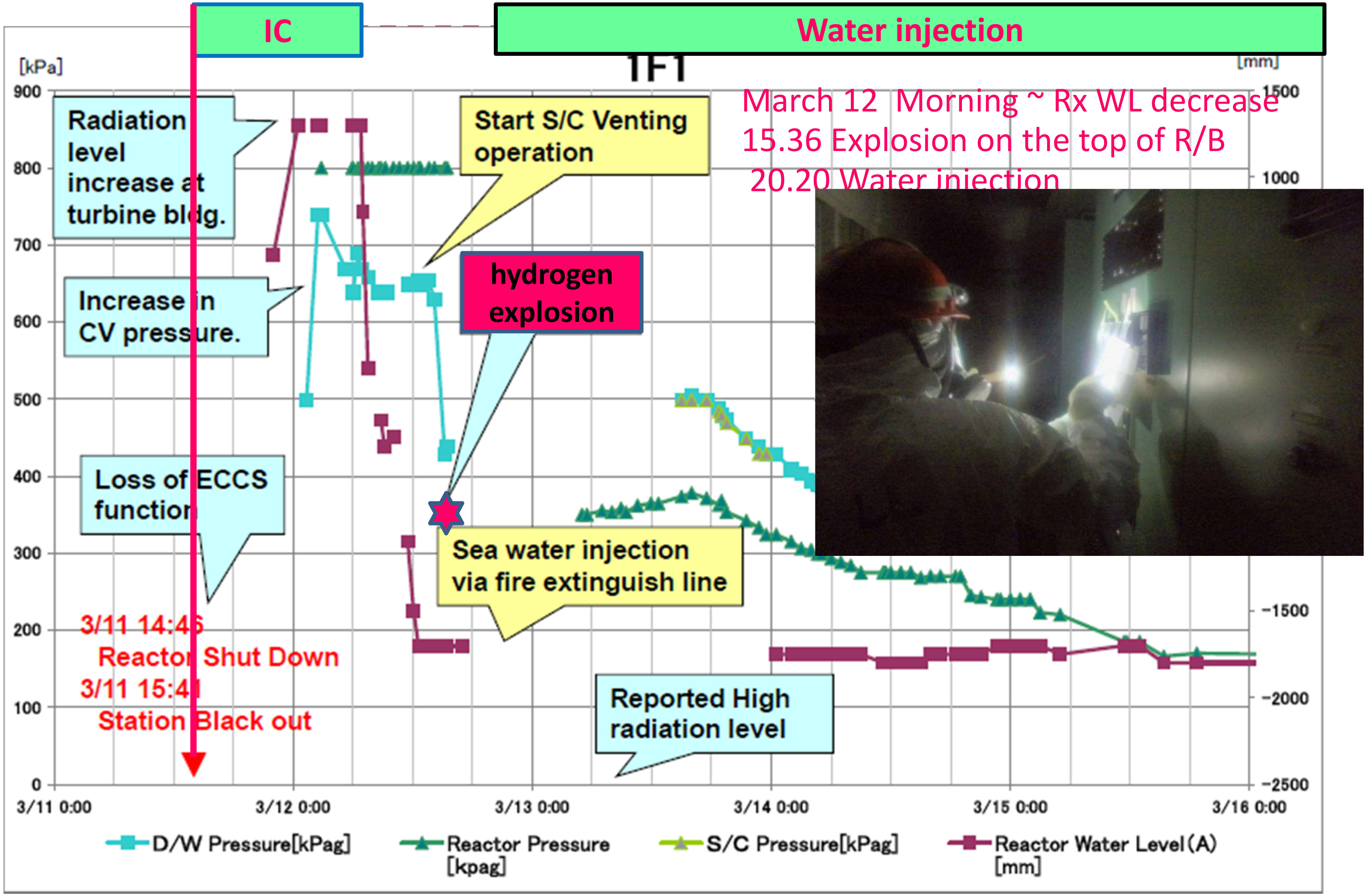
SBO - comparison of assumptions and reality

	Presumed SBO	Fukushima Accidents
AC Power Recovery	• AC Power can be restored by either off-site power (OSP) or DG restoration within about few hours	• OSP restoration was not available due to damages (believed to be mainly by Tsunami - even local train station was washed out by Tsunami) • DGs could not be restored because of heavy damages mainly by submergence of Tsunami water • Tsunami washed away entire sea water cooling capability for good
DC Power	• No extended loss of DC was assumed	• DC power management was necessary to control plant for days
Operating Actions	• SAMG actions was assumed	• Damage (believed to be mainly by Tsunami) made it very difficult to access systems and components, which delayed actions
Control Room	• Habitability should be maintained even in SBO • Many plant parameters should have been available to monitor	• Unable to control in extended SBO condition from Main Control Room • Only a few plant parameters available to monitor

Tsunami exceeded design assumption led to a severe SBO beyond control

3. Event Progression

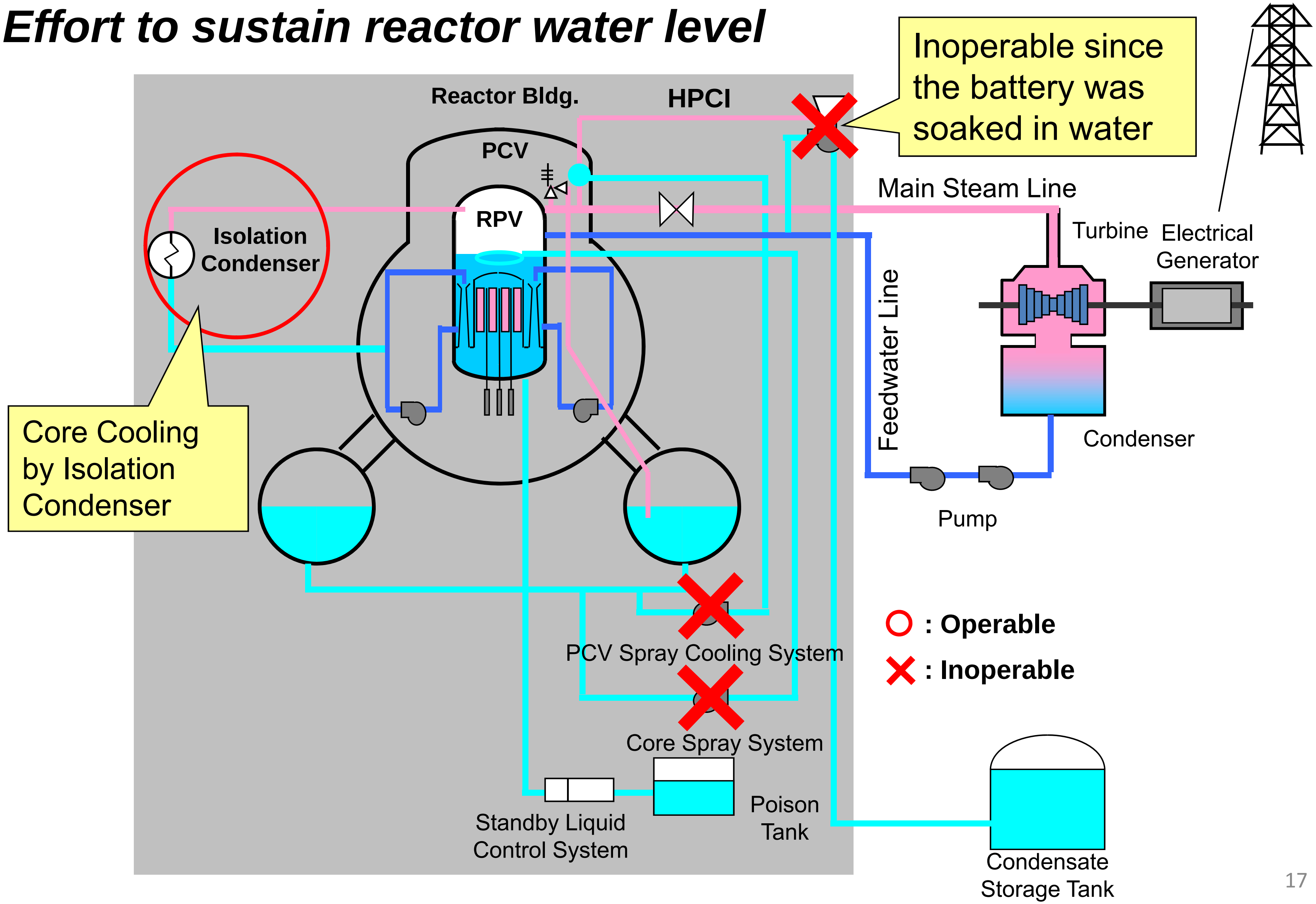
1Fuku1



[Based on NISA slide, IAEA Safety Convention Meeting, 2011April4]

3-7. Major event progression at Unit 1 (1/4)

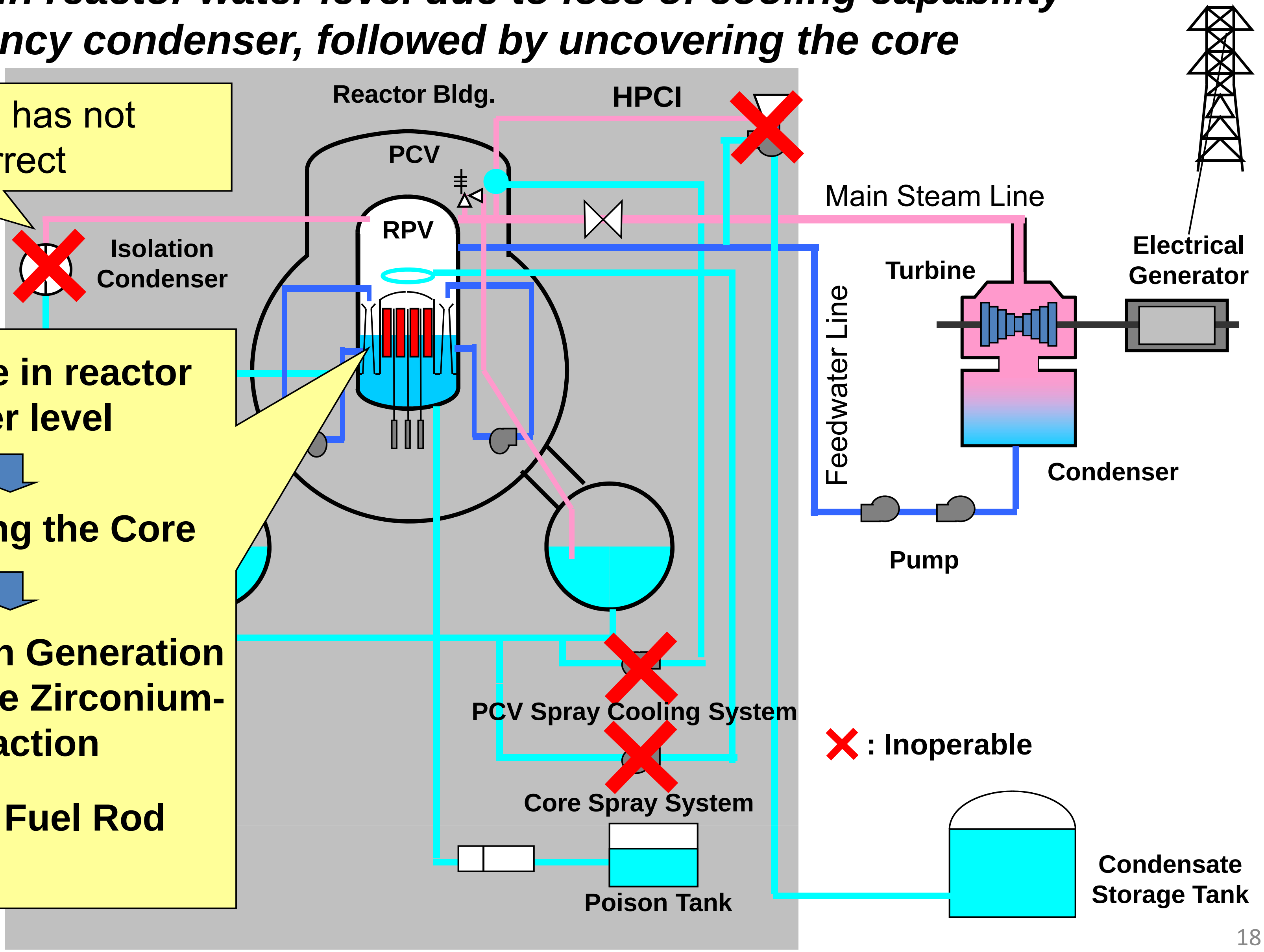
Effort to sustain reactor water level



3-7. Major event progression at Unit 1 (2/4)

Decrease in reactor water level due to loss of cooling capability of emergency condenser, followed by uncovering the core

Function has not been correct



Decrease in reactor water level

⬇

Uncovering the Core

⬇

-Hydrogen Generation due to the Zirconium-Water reaction

-Possible Fuel Rod damage

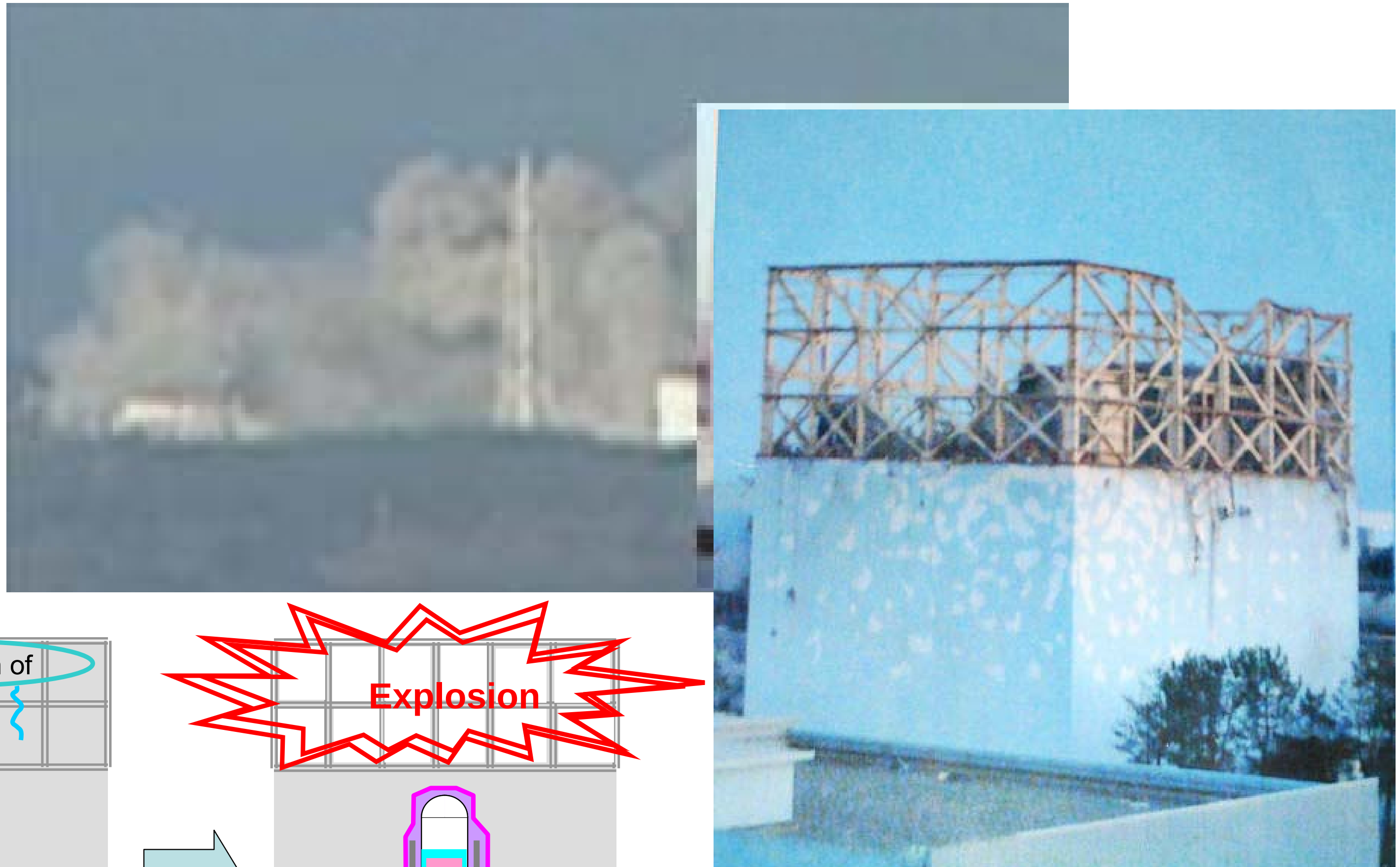
0

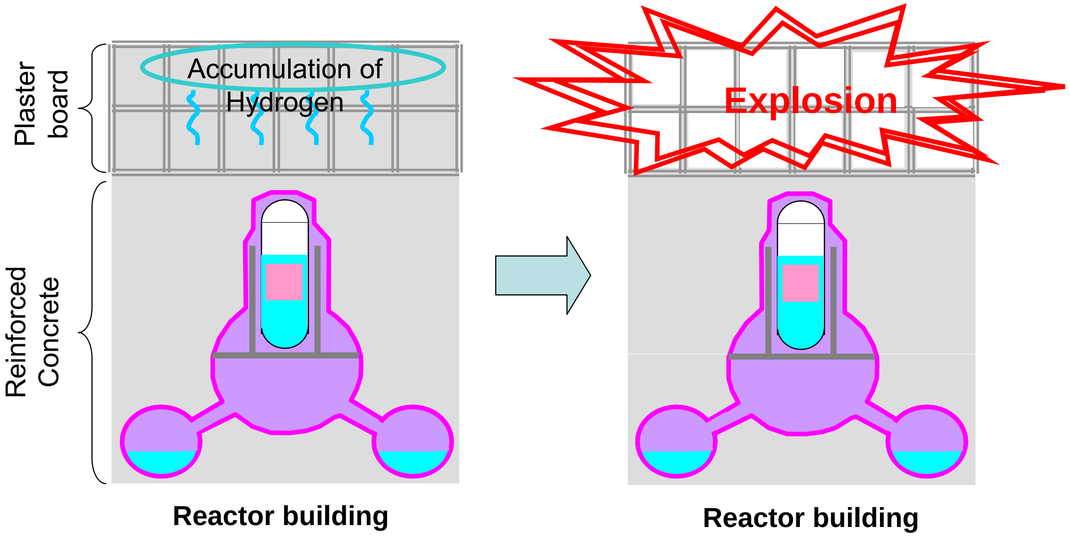
Unit 1 Explosion

3/12 15:31

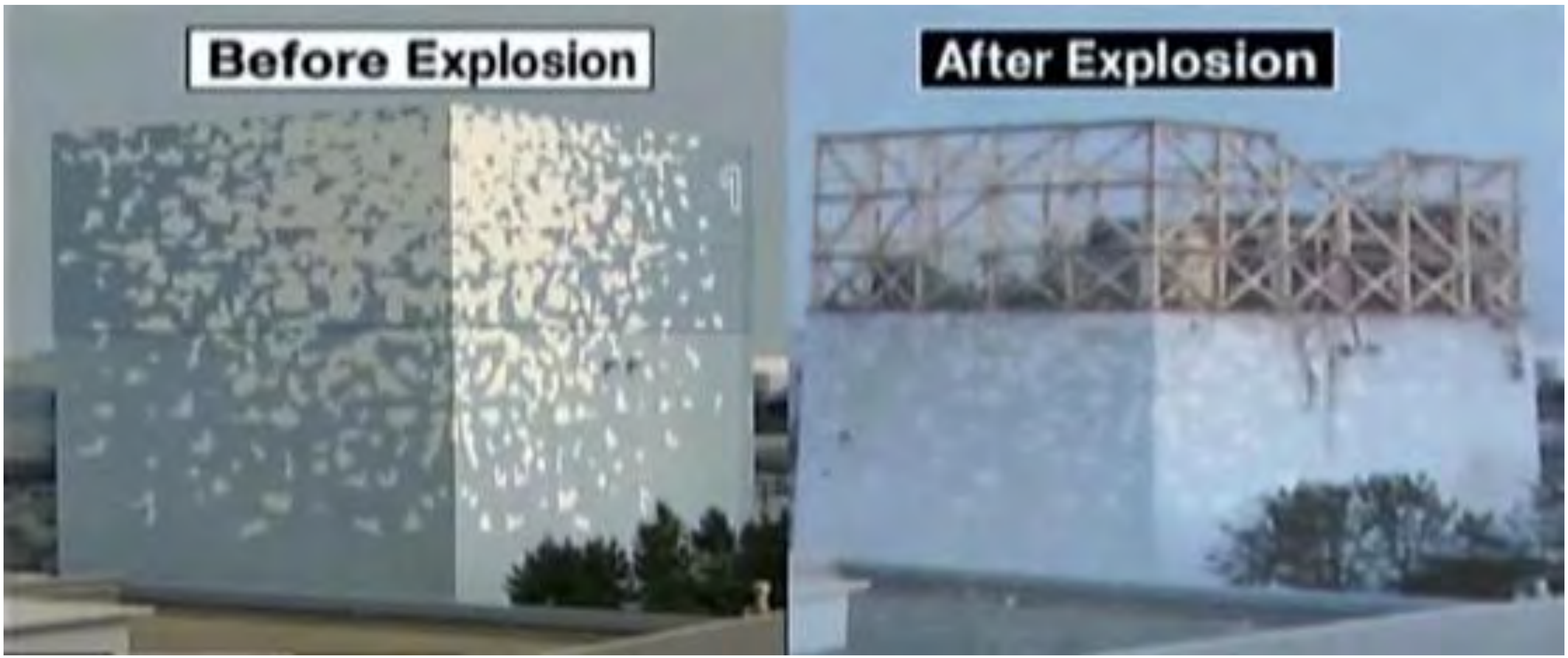
3-7. Major event progression at Unit 1 (3/4)

Hydrogen explosion in the operation floor

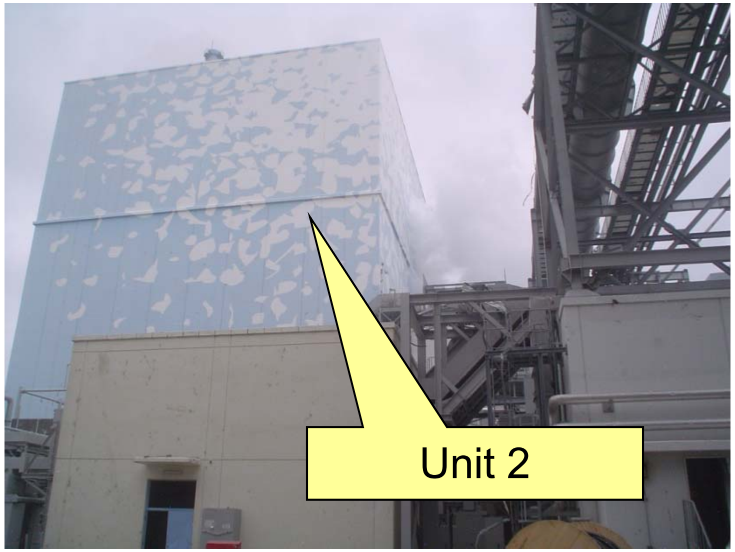


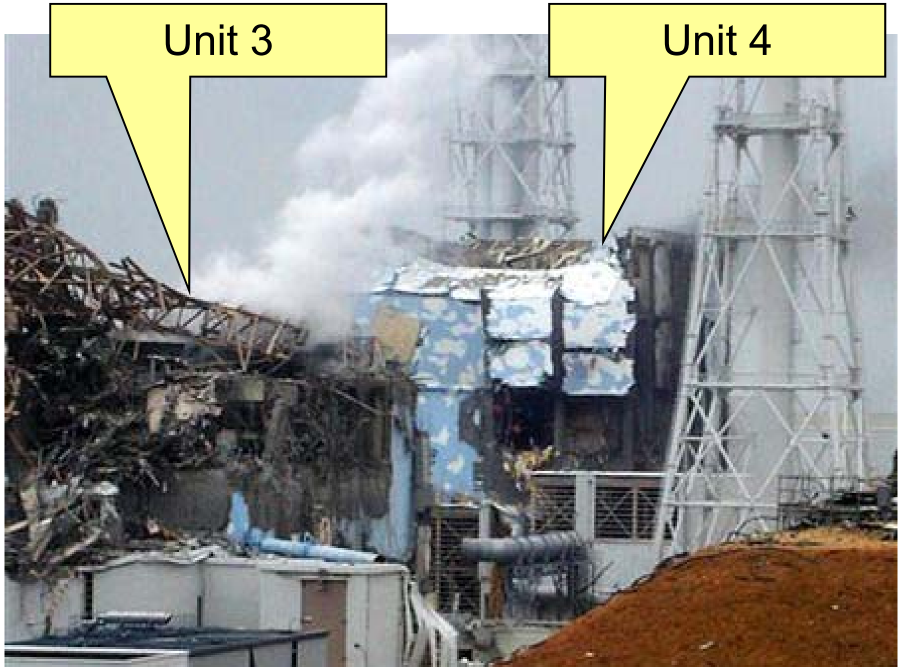


Unit 1 Reactor Building

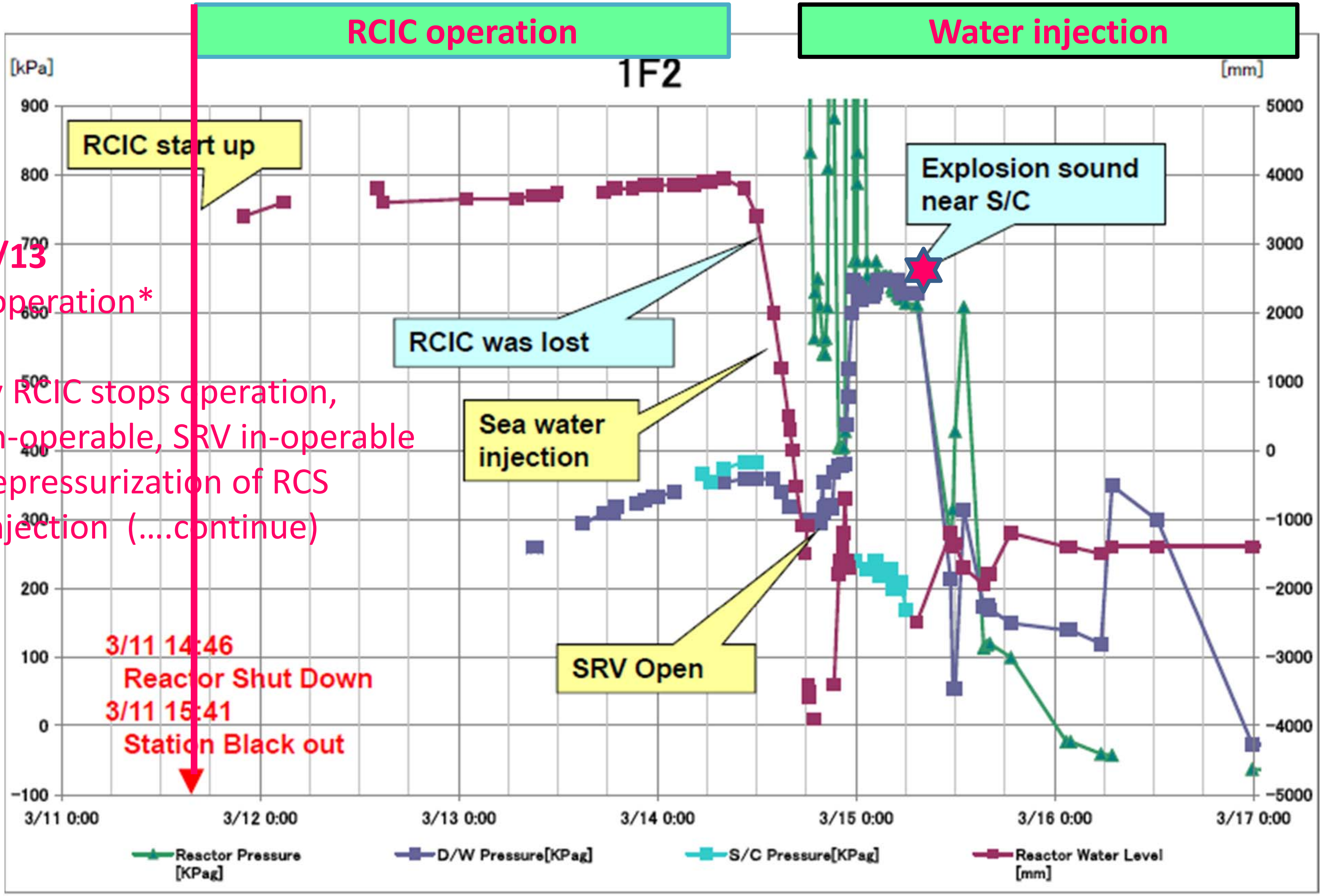


3-8. Accident Progression at Unit 2 through 4 reactors





1Fuku2



March 12/13

RCIC in operation*

March 14

~midday RCIC stops operation,
HPCI in-operable, SRV in-operable

16.34 Depressurization of RCS
start injection (….continue)

[Based on NISA slide, IAEA Safety Convention Meeting, 2011April4]

3-9. Chronology of Unit 2 after the earthquake (1/2)

● *Unit 2*

11th ●Under operation, Automatic shutdown by the earthquake
- Loss of A/C power
- Loss of water injection function

14th
- Loss of water cooling function
- Unusual increase in PCV pressure

15th
- Sound of explosion
- Possible damage of the suppression chamber

20th
- Injection of about 40 tons of seawater into SFP through fire extinguishing system.
- Injection of seawater to the Spent Fuel Pool (SFP)

21st
- White smoke generated

22nd
- Injection of seawater to the Spent Fuel Pool (SFP)

25th
- Injection of seawater to SFP

3-9. Chronology of Unit 2 after the earthquake (2/2)

● *Unit 2(Continued)*

26th ●Lighting in the Central Control Room was recovered

27th ●Switched to the water injection to the core using a temporary motor-driven pump.

29th ●The Seawater injection to the Spent Fuel Pool using the Fire Pump Truck was switched to the fresh water injection using the temporary motor-driven pump

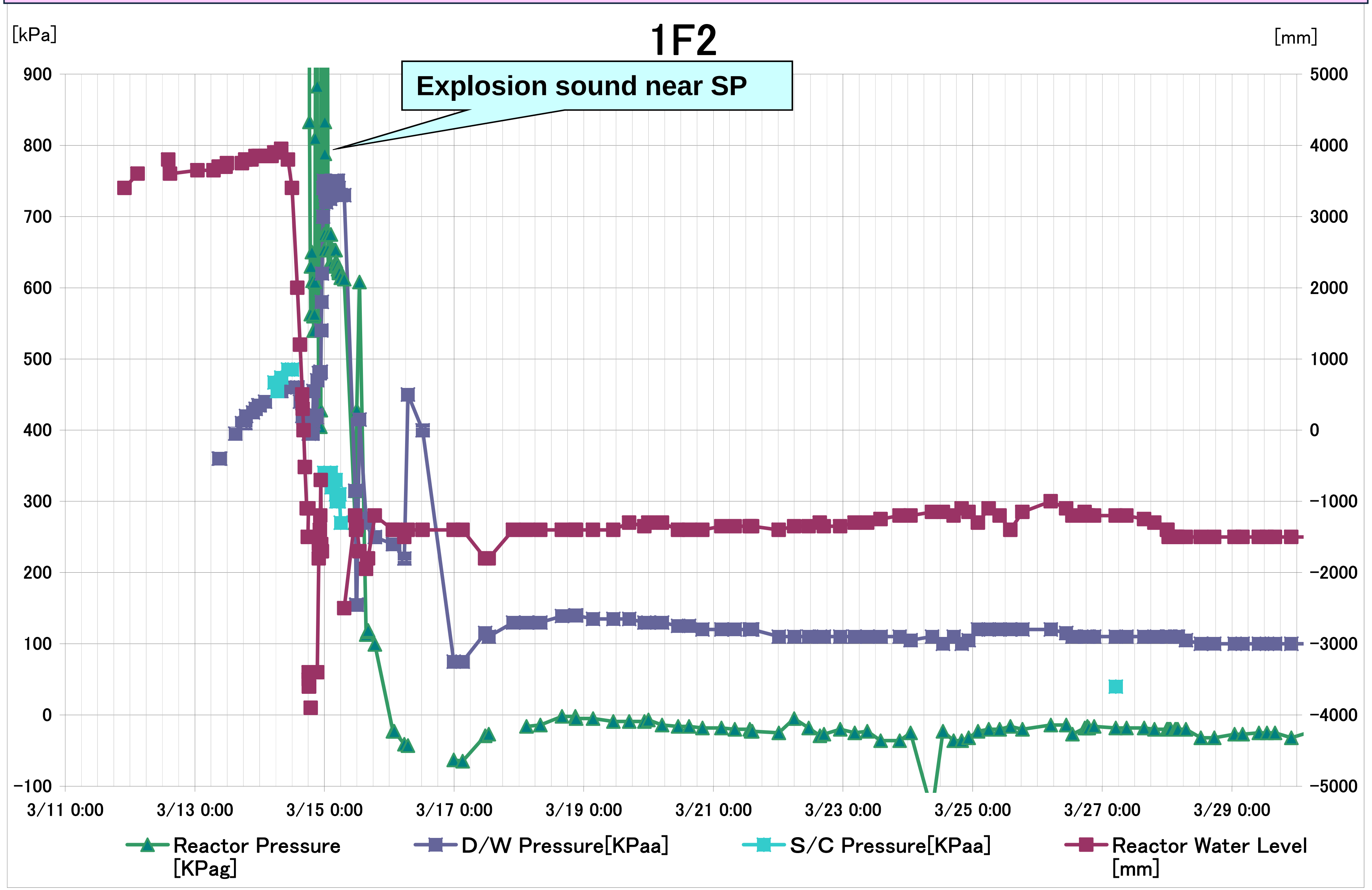
●In order to prepare for transferring the stagnant water on the basement floor of turbine building to the Condenser, the water in the Condensate Storage Tank is being transferred to the Surge Tank of Suppression Pool Water.

30th ●The injection pump was switched to the Fire Pump Truck. However, because cracks were confirmed in the hose (12:47 and 13:10 March 30th), the injection was suspended. The injection of fresh water resumed at 19:05 March 30th.

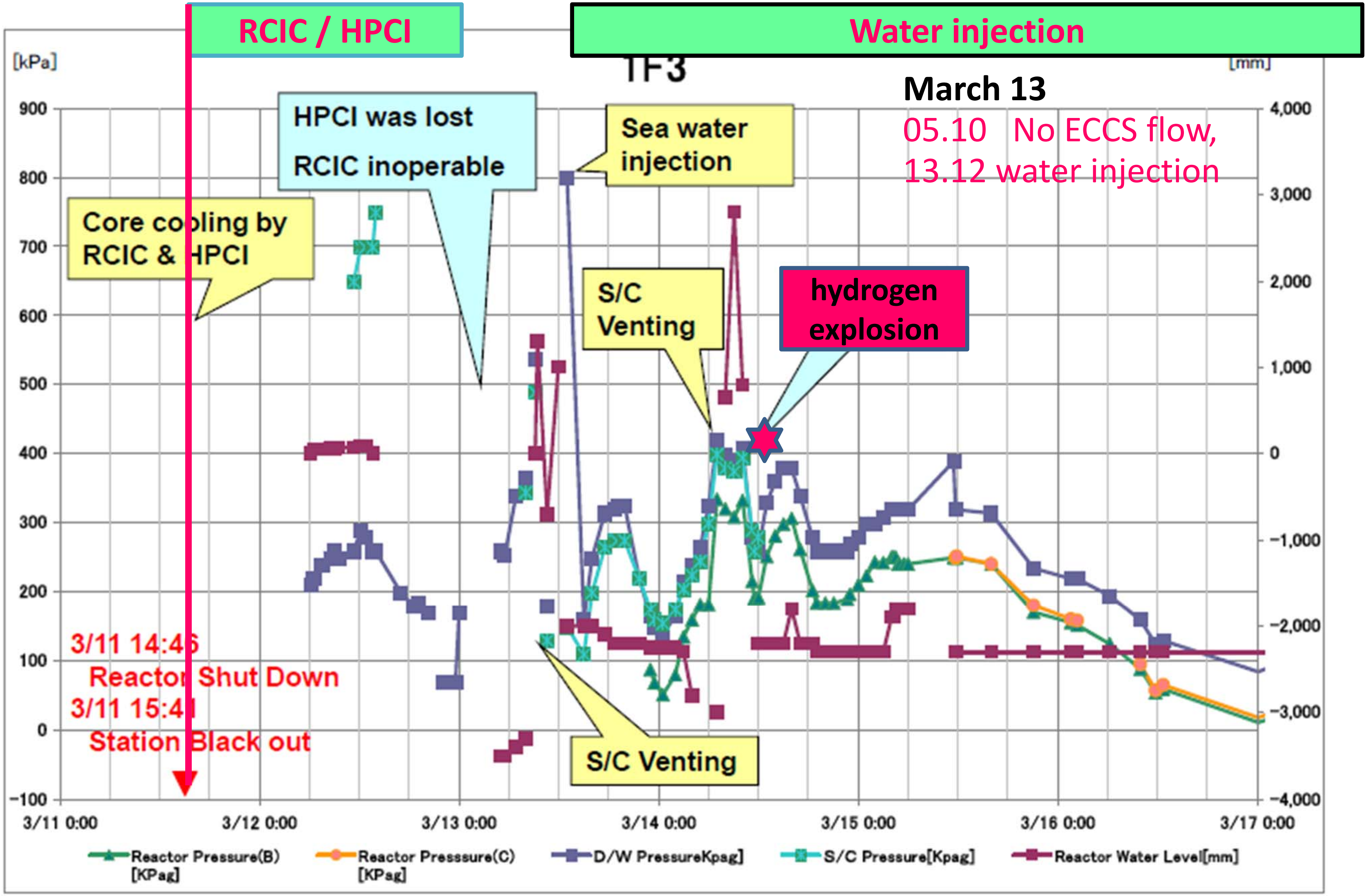
31st ●White smoke was confirmed to generate continuously.

●Fresh water is being injected to the spent fuel pool and the RPV

3-11. Trend data of Unit 2 until March 30



1Fuku3



[Based on NISA slide, IAEA Safety Convention Meeting, 2011April4]

3-12. Chronology of Unit 3 after the earthquake (1/2)

●*Unit 3*

11th ●Under operation, Automatic shutdown by the earthquake
● Loss of A/C power

13th ● Loss of water injection function
● Started to vent

14th ●Unusual increase in PCV pressure
●Sound of explosion

16th ●White smoke generated

17th ●Water discharge by the helicopters of Self-Defense Force(4 times)
●Water spray from the ground by High pressure water-cannon trucks
(Police: once, Self-Defense Force: 5 times)

18th ●Water spray from the ground by same trucks (Self-Defense Force: 6 times)
Water spray from the ground by US water-cannon trucks
(US armed force:1 time)

19th ●Water spray from the ground by High pressure water-cannon trucks by Hyper Rescue Unit of Tokyo Fire Department.

3-12. Chronology of Unit 3 after the earthquake (2/2)

● ***Unit 3(Continued)***

20th ●Sprayed by Hyper Rescue Unit of Tokyo Fire Department

22nd ●Lighting in the Central Control Room was recovered.

23rd ●Injection of seawater to the SFP

24th ●Injection of seawater to the SFP

25th ●Water spray (Emergency fire support team
●Started fresh water injection

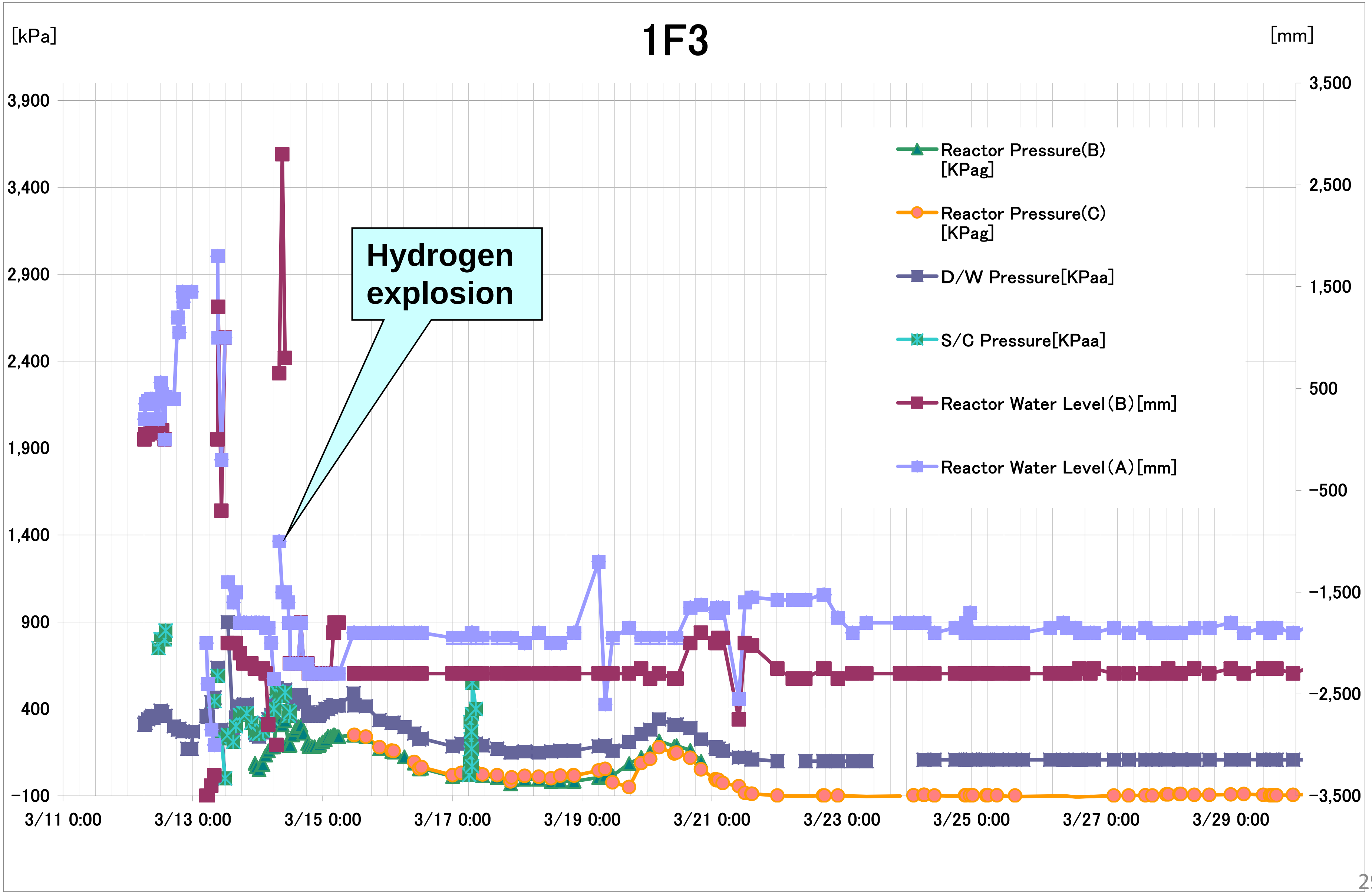
27th ●Water spray by Concrete Pump Truck

28th ●Switched to the water injection to the core using a temporary motor-driven pump
●In order to prepare for transfer the stagnant water on the basement floor of turbine building to the Condenser, the water in the Condensate Storage Tank is being transferred to the Surge Tank of Suppression Pool Water

29th ●Started to spray freshwater by Concrete Pump Truck

31st ●White smoke was confirmed to generate continuously
●Fresh water is being injected to the spent fuel pool and the RPV

3-14. Trend data of Unit 3 until March 30



Unit 3 Reactor Building Explosion

3/14 11:15

Unit 3 Reactor Building

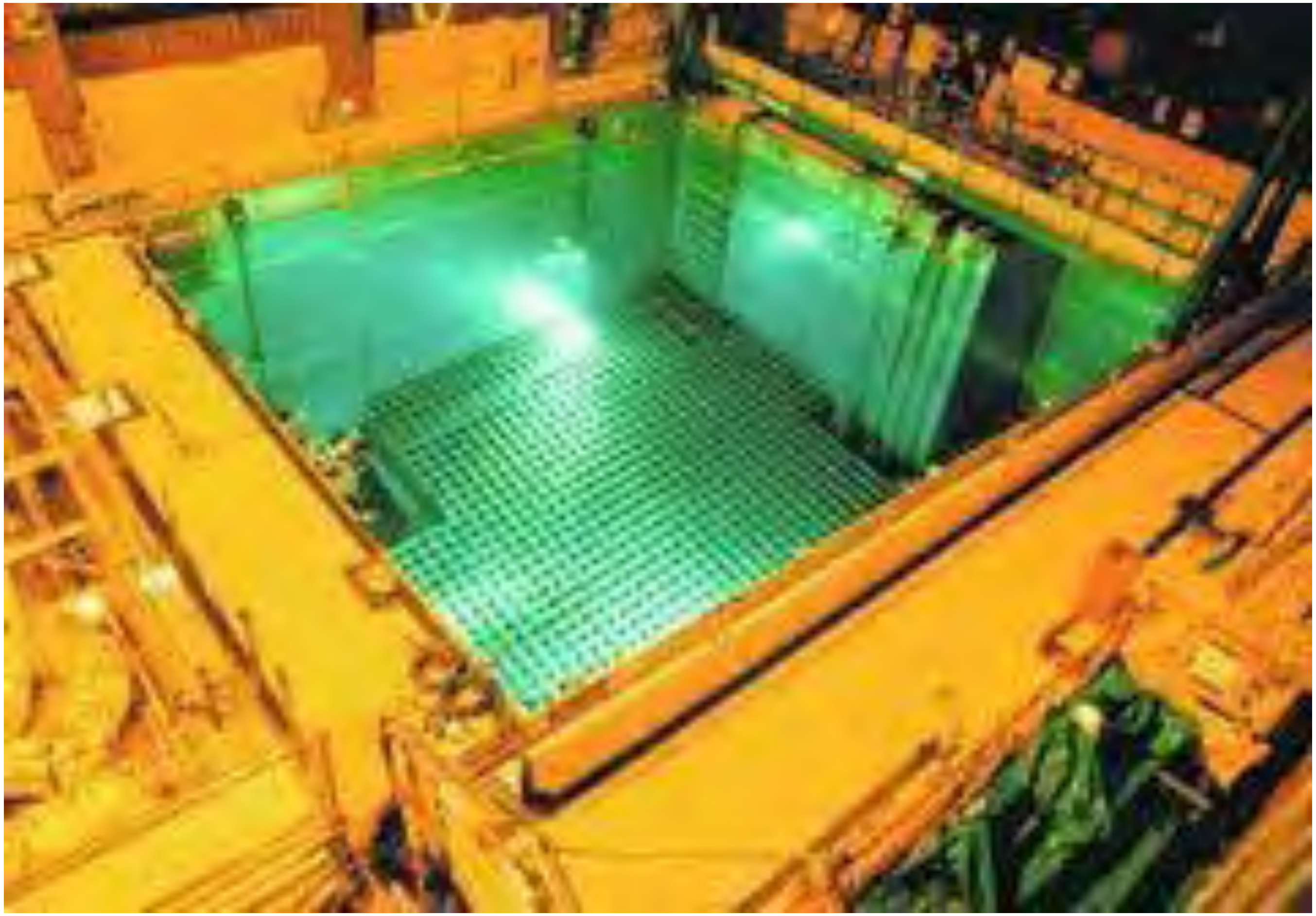
Before

Reuters

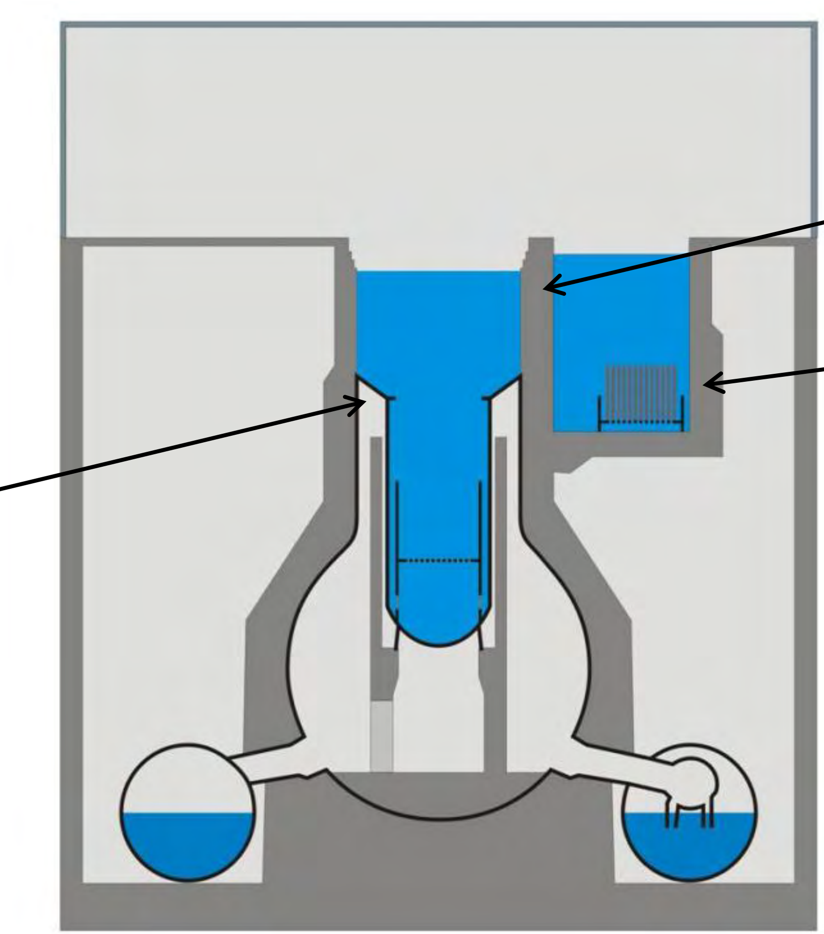
After

TEPCO

Empty Spent Fuel Pool



Unit 4 Refueling Configuration?



Unit 4 Reactor Building

Reuters TEPCO

3-16. Chronology of Unit 4 after the earthquake

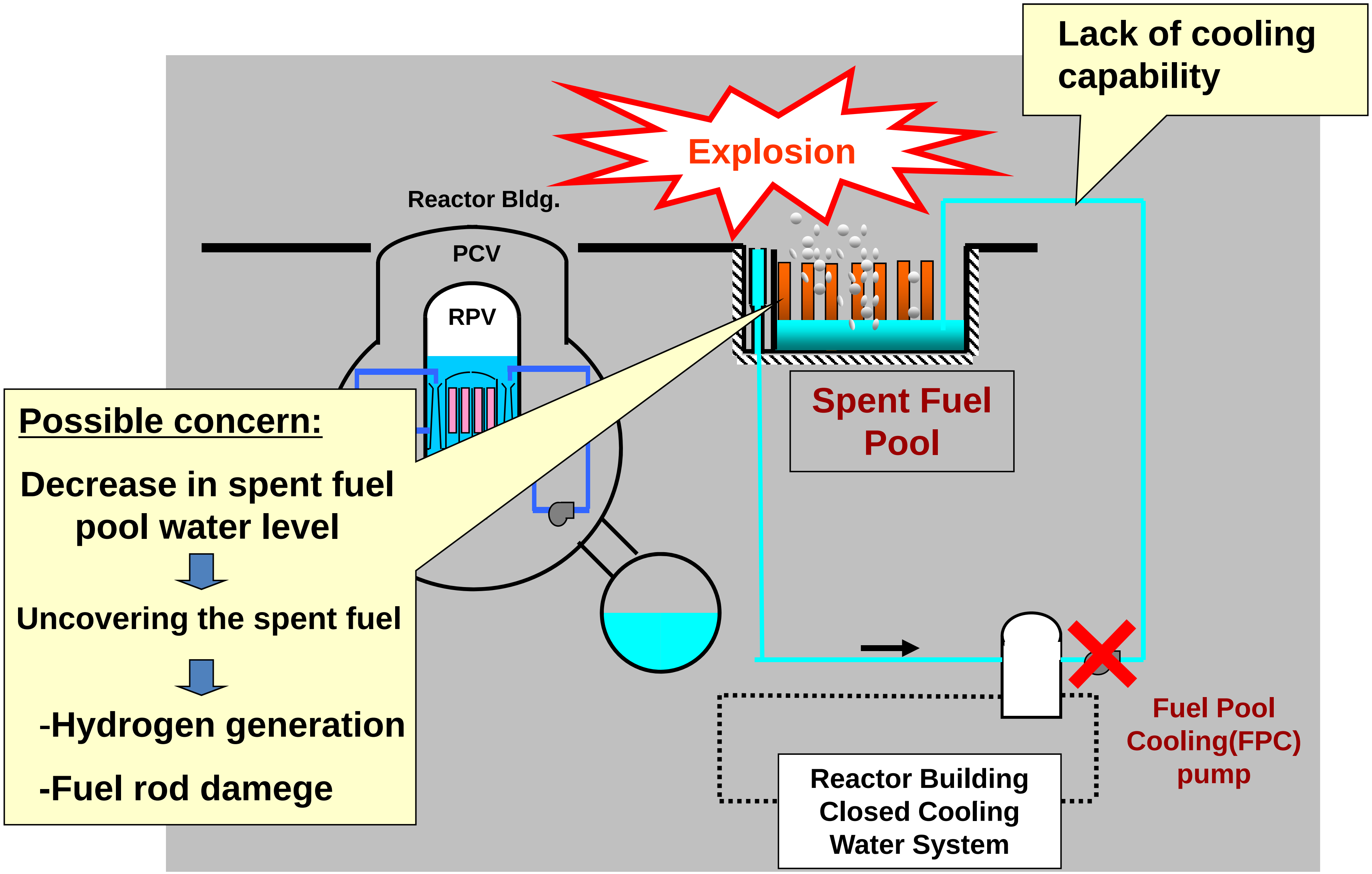
● *Unit 4*

14th	● Water temperature in the Spent Fuel Pool, 84℃
15th	● Damage of wall in the 4th floor confirmed ● Fire occurred in the 3rd floor (12:25 extinguished)
16th	● Fire occurred. TEPCO couldn't confirm any fire on the ground.
20th	● Water spray over the spent fuel pool by Self Defense Force
21st	● Water spray over the spent fuel pool by Self Defense Force
22nd-24th	● Water spray (Concrete Pump Track (3 times)
25th	● Injection of seawater to SFP via the Fuel Pool Cooling Line (FPC) ● Water spray (Concrete Pump Truck)
27th	● Water spray (Concrete Pump Truck)
29th	● Lighting in the Central Control Room was recovered.
3oth	● White smoke was confirmed to generate continuously. ● Spray of fresh water (Around 140t) over the Spent Fuel Pool using Concrete Pump Truck (50t/h) was carried out. ● Fresh water is being injected to the spent fuel pool

4. Report concerning incidents at spent fuel pools in the Fukushima Dai-ichi NPS

Photo: Water spray into the SFP in Unit 4 using concrete pump truck

4-1. Possible concerns about Spent Fuel Pool



4-2. Status of the Fuel as of March 11, 2011

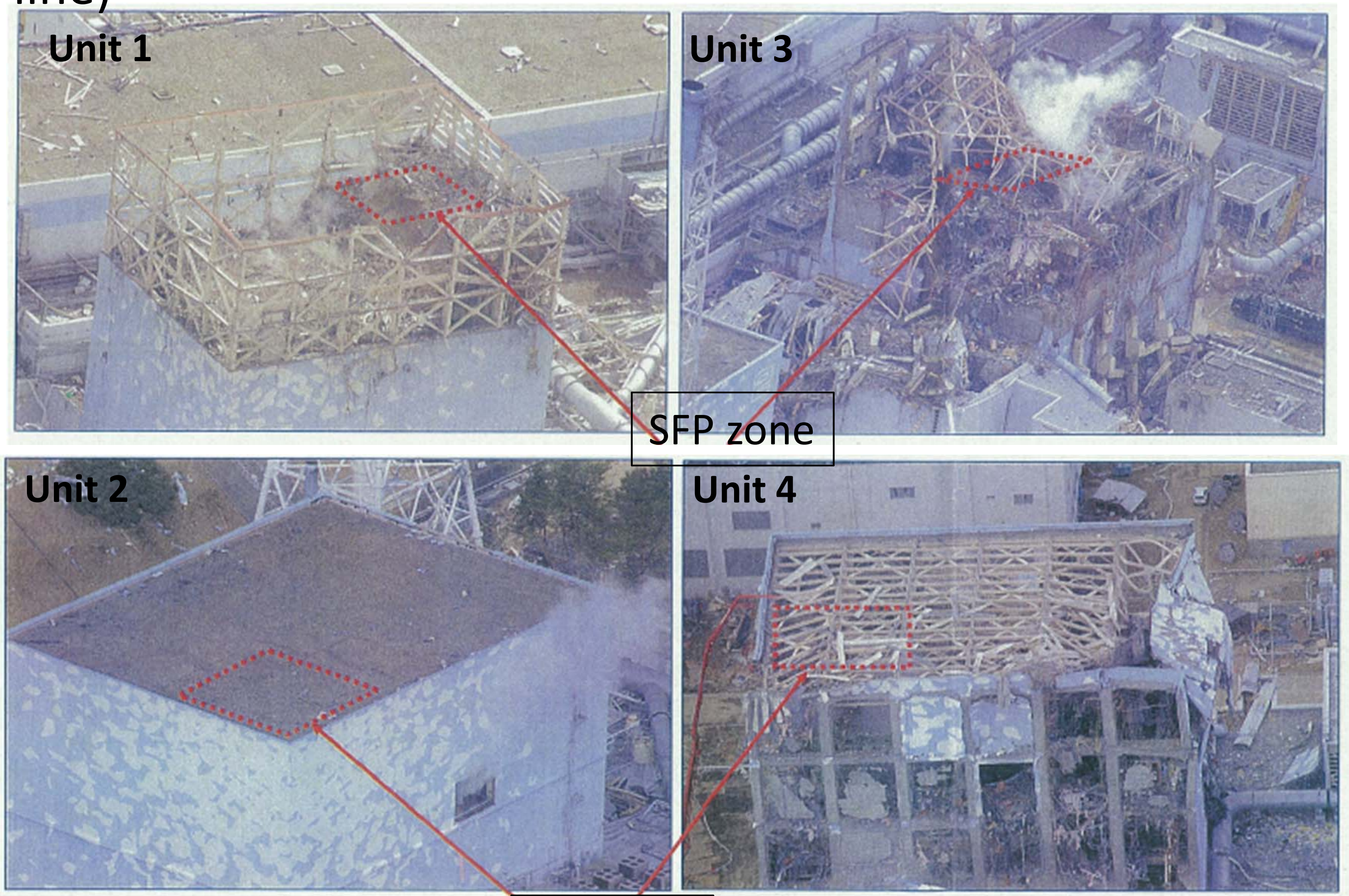
Unit	1	2	3	4	5	6
Number of Fuel Assembly in the Core	400	548	548	-	548	764
Number of Spent Fuel Assembly in the Spent Fuel Pool	292	587	514	1,331	946	876
Number of New Fuel Assembly in the Spent Fuel Pool	100	28	52	204	48	64
Water Volume (m^3)	1,020	1,425	1,425	1,425	1,425	1,497

Condition of the fuel in the Spent Fuel Pool

Unit 1	Unit 2	Unit 3	Unit 4
-Most recent shut down was on Sep.27,2010	- Most recent shut down was on Nov.18,2010	- Most recent shut down was on Sep.23,2010	-Most recent shut down was on Nov.29,2010 -All fuel assembly was removed from the core and located in the pool due to the core shroud replacement

Why H_2 explosion right after venting?

Possible Path 1 : Excessive leakage by over-pressure at CV flange/airlocks
Possible Path 2: Vent line→ SGTS→R/B (vent line merge with adjacent unit's line)

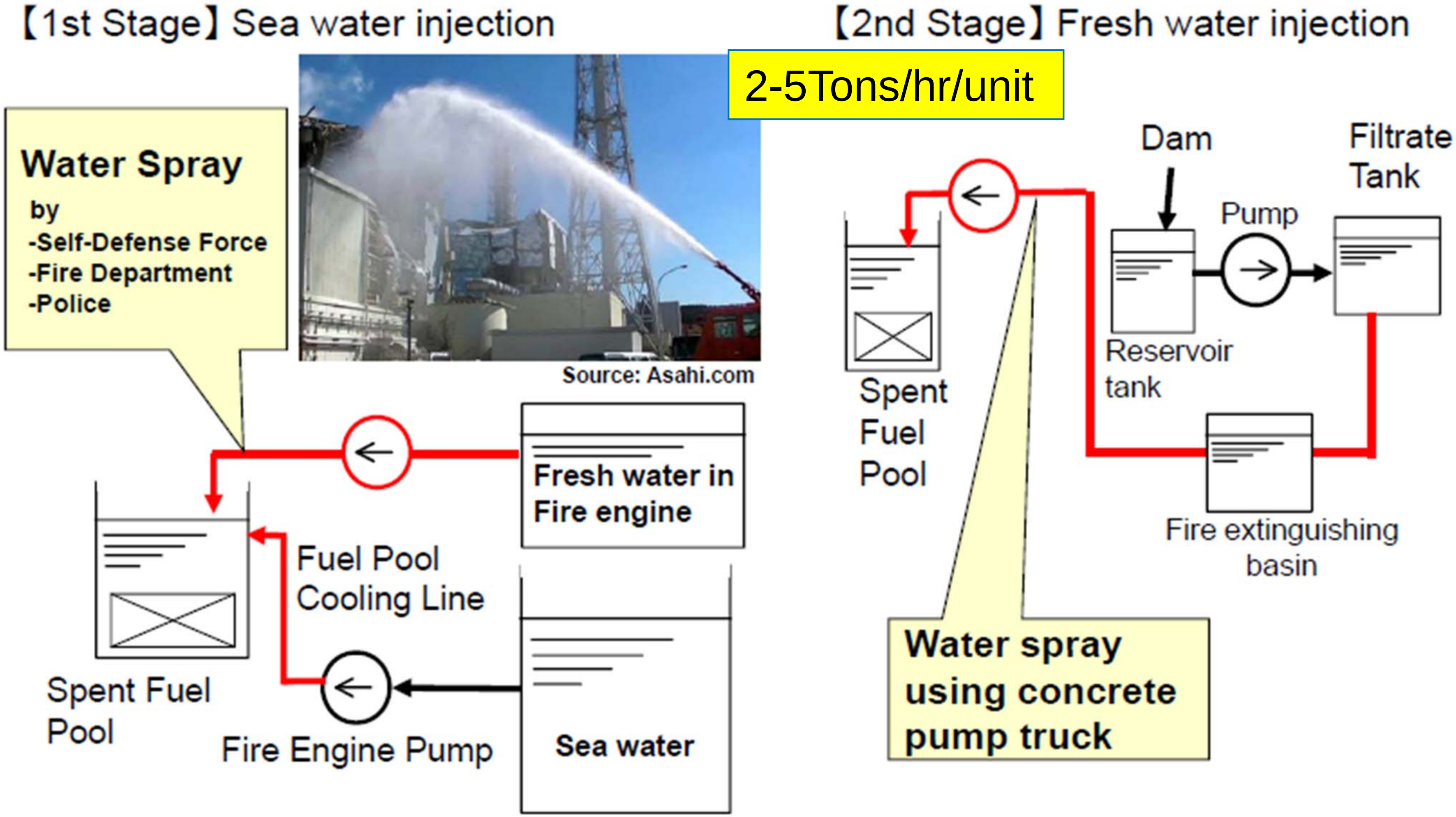


1F2 blowout panel opened by 1F3 blast, which released H_2

SFP zone

Water sample from SFP and photo indicate SFs in 1F4 most probably remain intact

Current : Water Injection to SFP (Spent Fuel Pool)

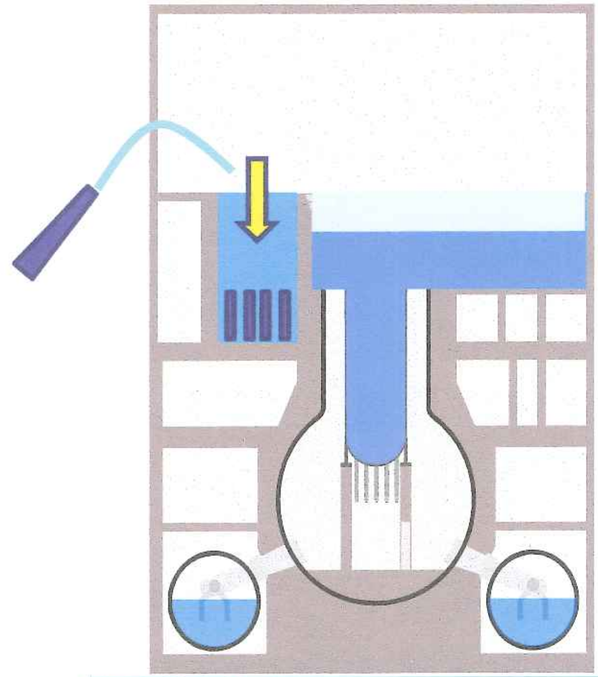


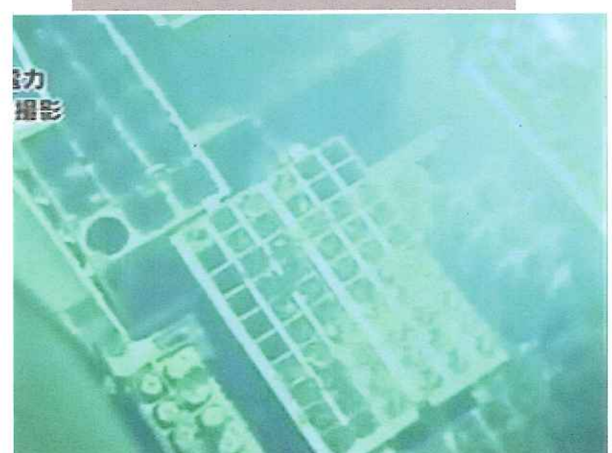
1F1,3, 4: Similarly by occasional spray from above
1F2: Using FPC-MUW (w/o overhead spray)

[SOURCE] NISA, IAEA Safety Convention Meeting, 2011April4

Unit 4 Situation

- Spent Fuel Pool has about 2 MW heat load but water level is maintained (filled up on 4/27) to keep the pool cooled
- Pool water samples were taken and it has been confirmed that there should be no severe fuel damage
- Rather, "Fukushima Background" was measured (short lived Fission Product, which should have never been existing in Unit 4 Spent Fuel after four months of shut down)





Source: TBS (provided by TEPCO)

3-17. Chronology of Unit 5 & 6 after the earthquake

● *Unit 5&6*

20th ●Unit 5 under cold shutdown (Water temperature of reactor water is less than 100℃)

●Unit 6 under cold shutdown (Water temperature of reactor water is less than 100℃)

21st ●Water spray over the Common Spent Fuel Pool started

22nd ●Recovering power supply of unit 5 and 6 is completed.

24th ●The power was started to be supplied. Cooling also started

30th ●Bach up power of Unit 6 is in working condition and external power was supplied to Unit 5 as of March 30th

Units 1-6 After U4 Spent Fuel Pool Explosion

Units 1-4 After U4 Spent Fuel Pool Explosion
3/16

Units 3, 2, & 1 Looking Down

Units 4 & 3 Looking Down

Unit 4 Fuel Pool-Side

Unit 3 & Unit 4

Unit 3 Spent Fuel Pool

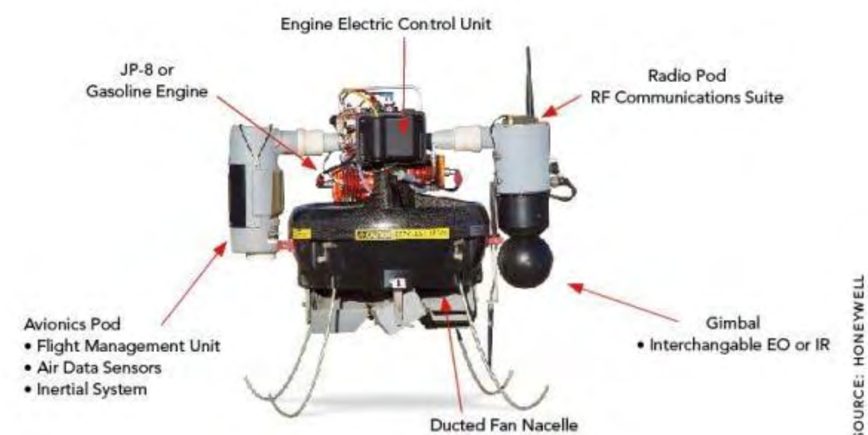
3/16

福島第一原子力発電所 3号機(3/16 PM撮影)

Water Spray to Unit 3 Pool Area

Unit 4 Reactor Building
Water Injection Boom To Spent Fuel Pool

Gather Data Inside Reactor Buildings



Adapted Military Drones With Thermal & Radiation Capabilities

Inside Unit 1 Reactor Building 04-18

Unit 4 Spent Fuel Pool Water Sampling

Boom Inserting Probe
~11-04-11

400ml Sample Probe
~11-04-11

Likely Future
Underwater Robot
Deep Drilling Technology

Clearing Wreckage To Inject U4 SFP Cooling Water

Debris Was Blocking
Pumper Access to SFP

Debris Cleared For Pumper
By Manual Tank-Bulldozer

Working Conditions are Challenging

Restoring Power In High Radiation & Contaminated Areas

Control Room Power Restoration

Before Power Restored

After Power Restored

Working In Contaminated Buildings

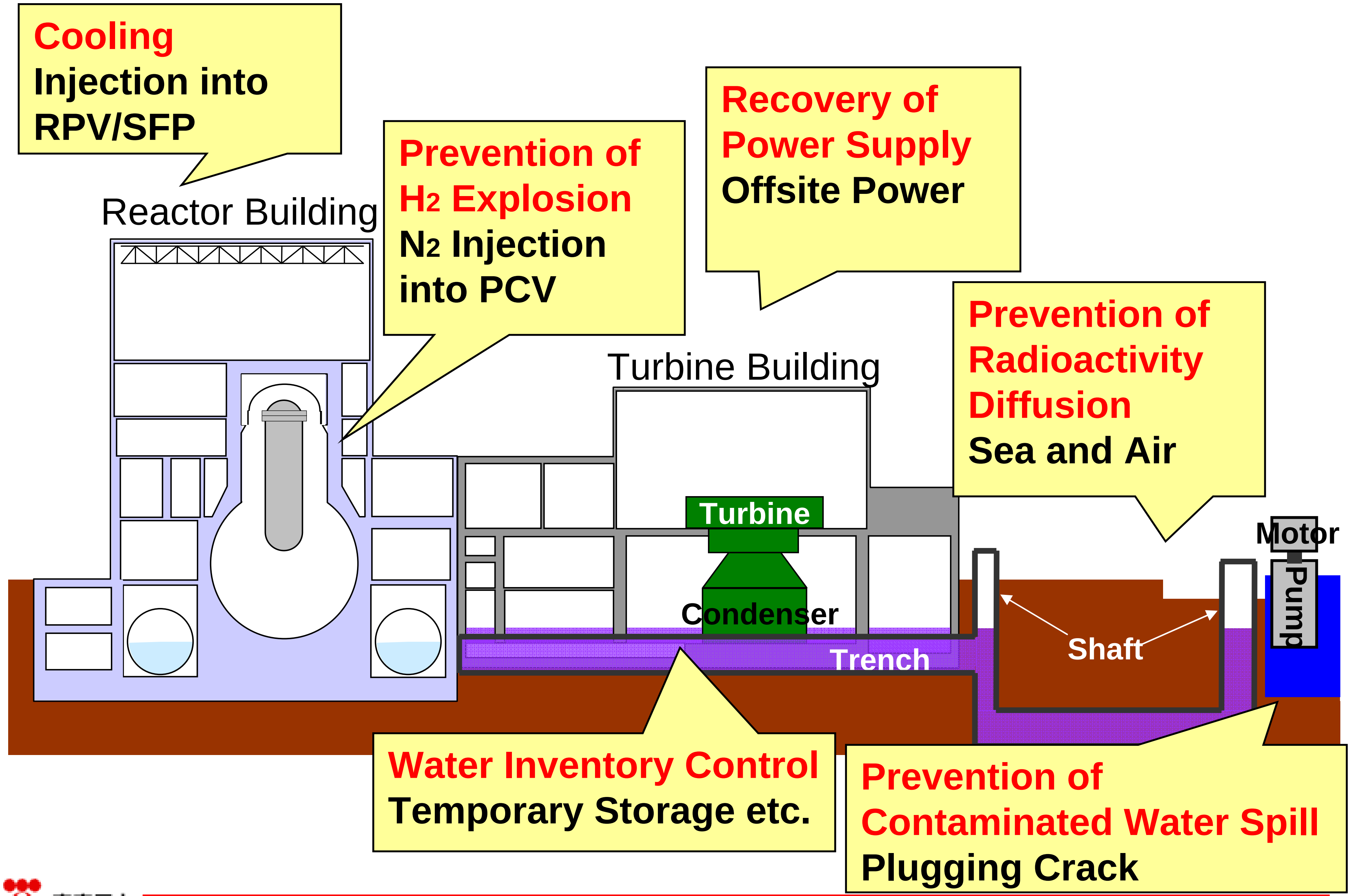
Entering Waste Processing Building

Worker Showing TB Basement Floor Water Level

Soil/Dust Suppression Resin Application

1. Recovery Actions

Overview of Recovery Actions



東京電力 TEPCO

Recovery of Power Supply

Recovery of Offsite Power

- Unit 5/6: Mar.20-21
- Unit 1: Mar.22
- Unit 2: Mar.20
- Unit 3: Mar.22
- Unit 4: Mar.22

Cable Laying Operation

Installation of Transportable Switch Gear

東京電力

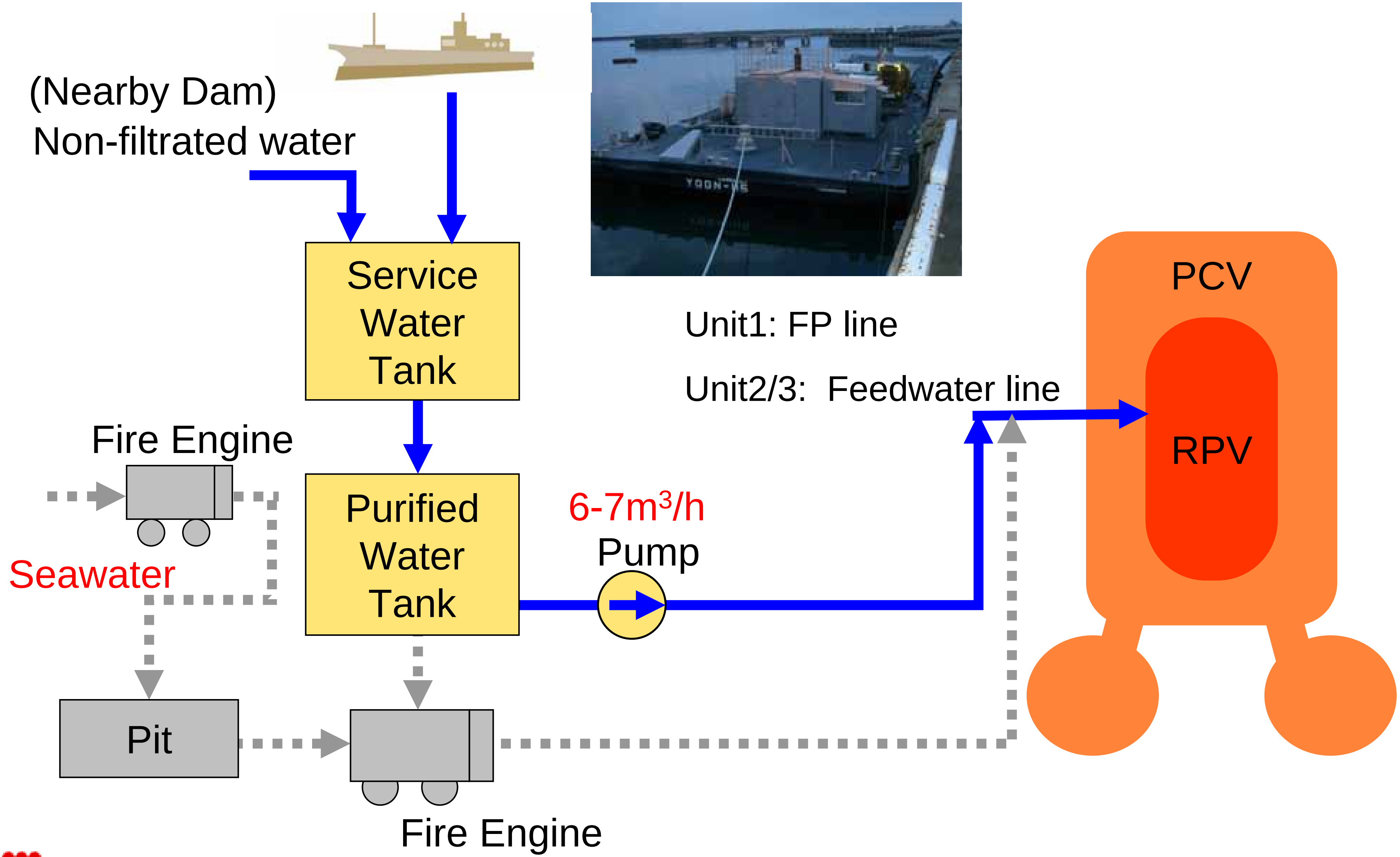
Recovery of Main Control Room Light

- Unit 3 : March 22
- Unit 1 : March 24
- Unit 2 : March 26
- Unit 4 : March 29

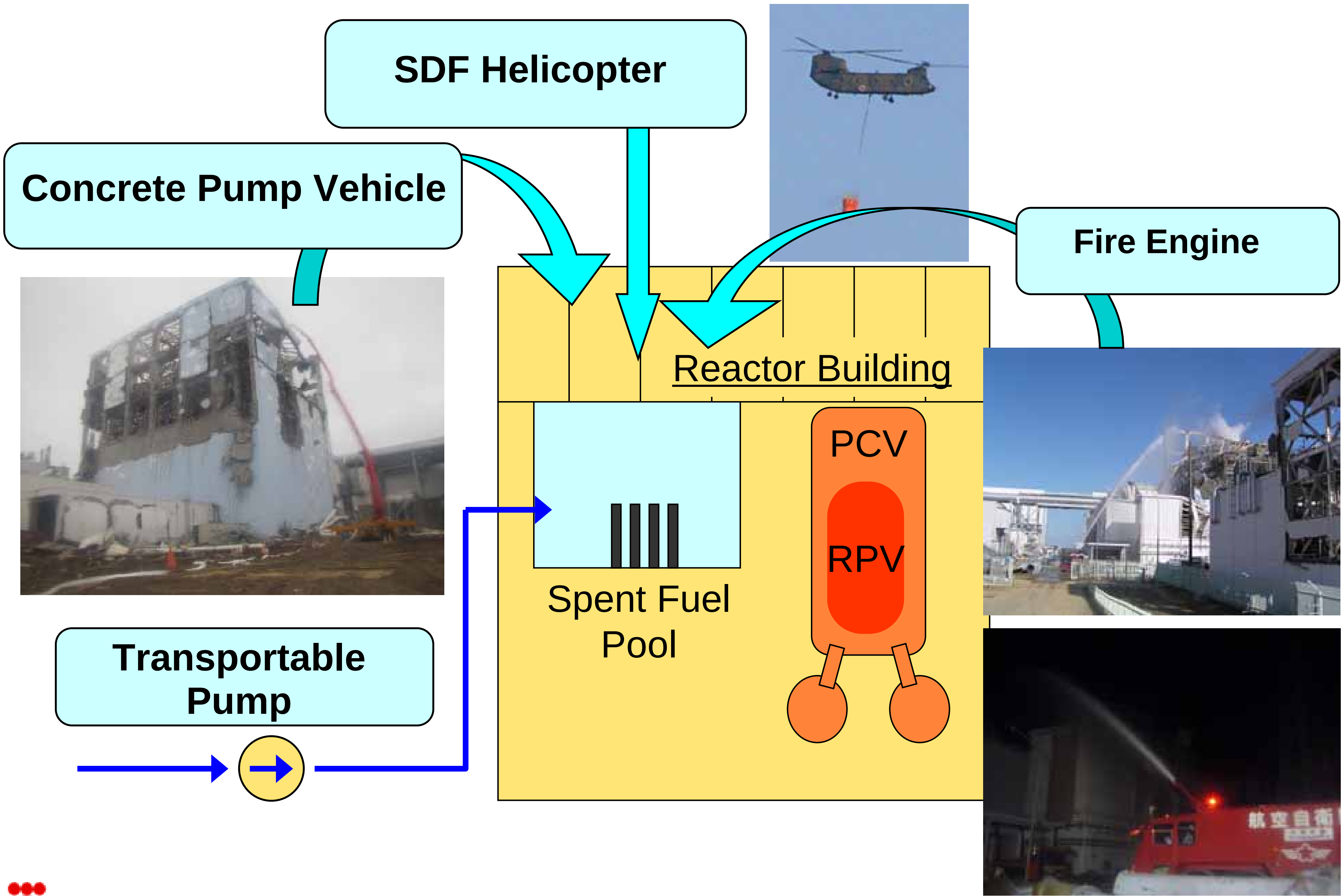
Unit 1

Cooling – Water Injection into RPV

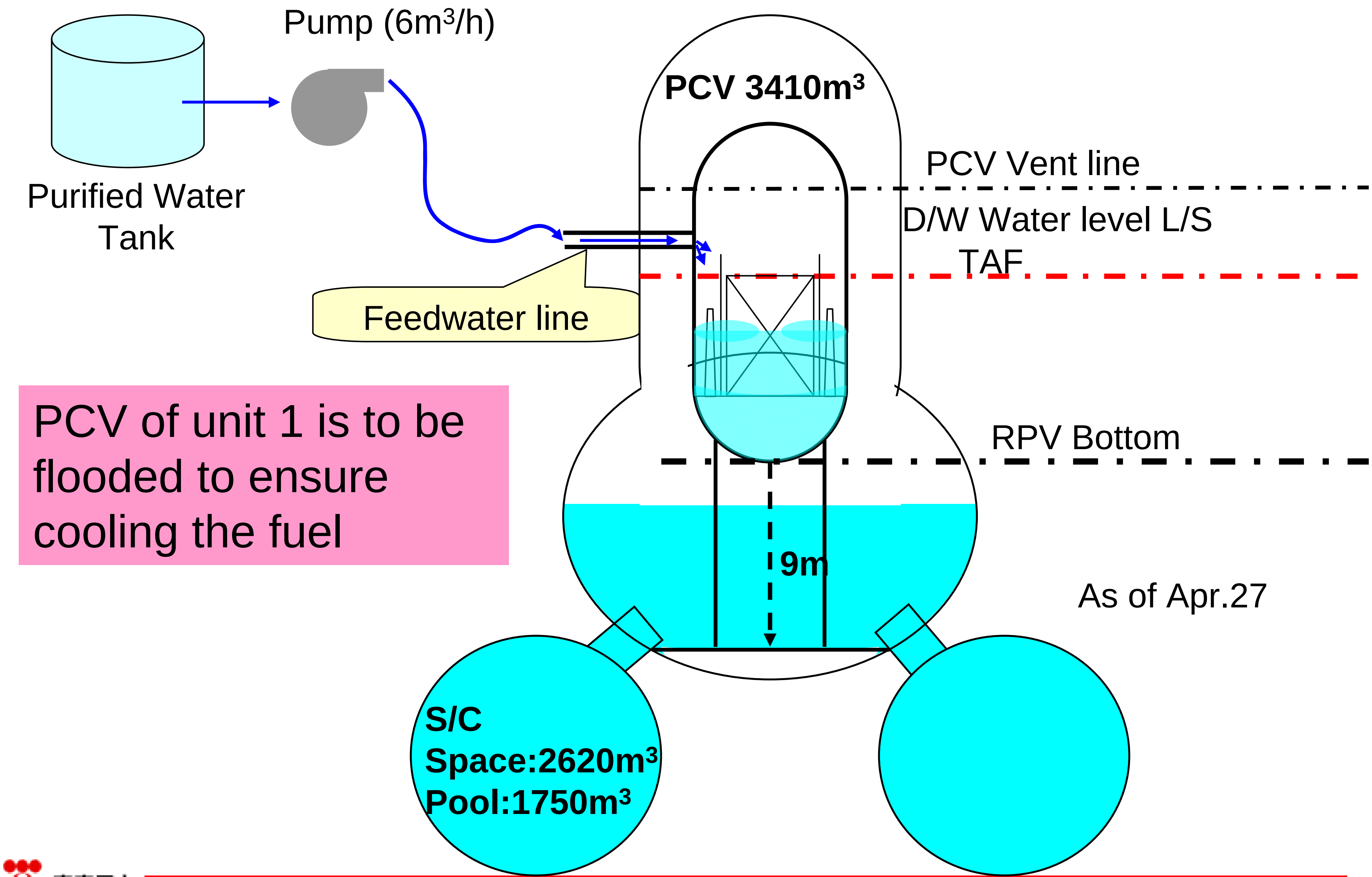
Freshwater carried by Barge Ship (Courtesy of US force)



Water Injection into Spent Fuel Pool



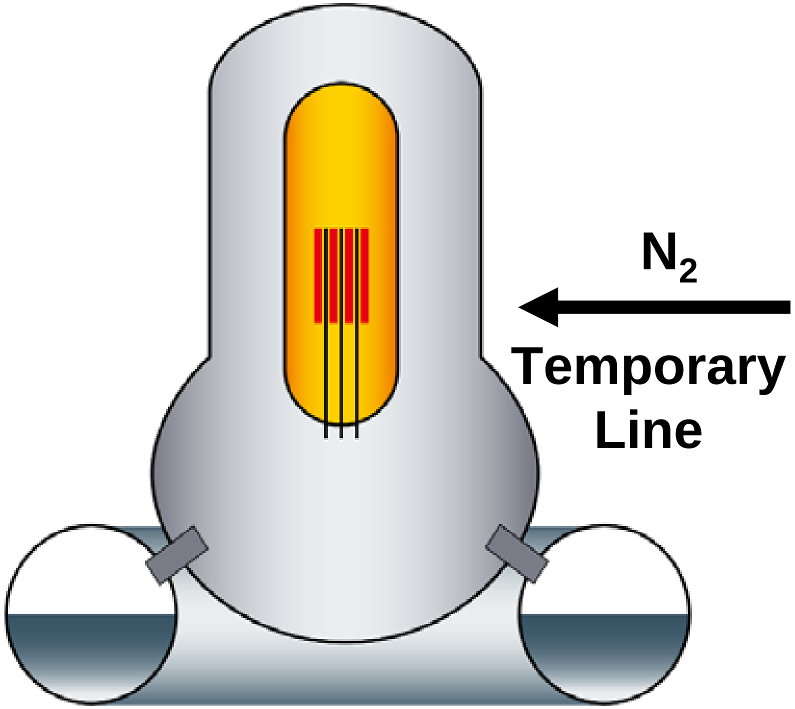
PCV Flooding (unit 1)



PCV of unit 1 is to be flooded to ensure cooling the fuel

Prevention of Hydrogen Explosion

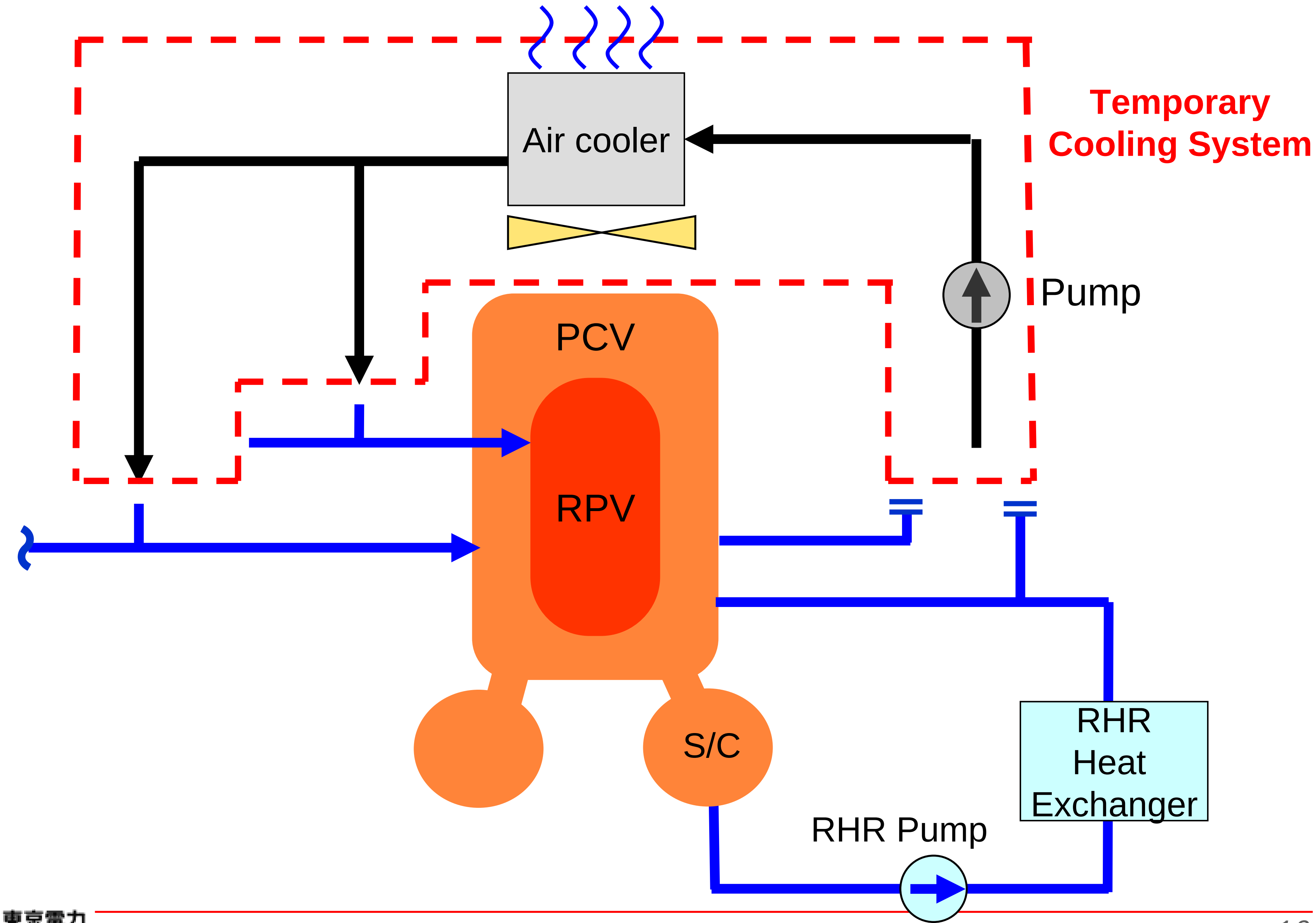
N_2 gas has been injected into unit 1 PCV to reduce the risk of a hydrogen explosion since Apr.7.



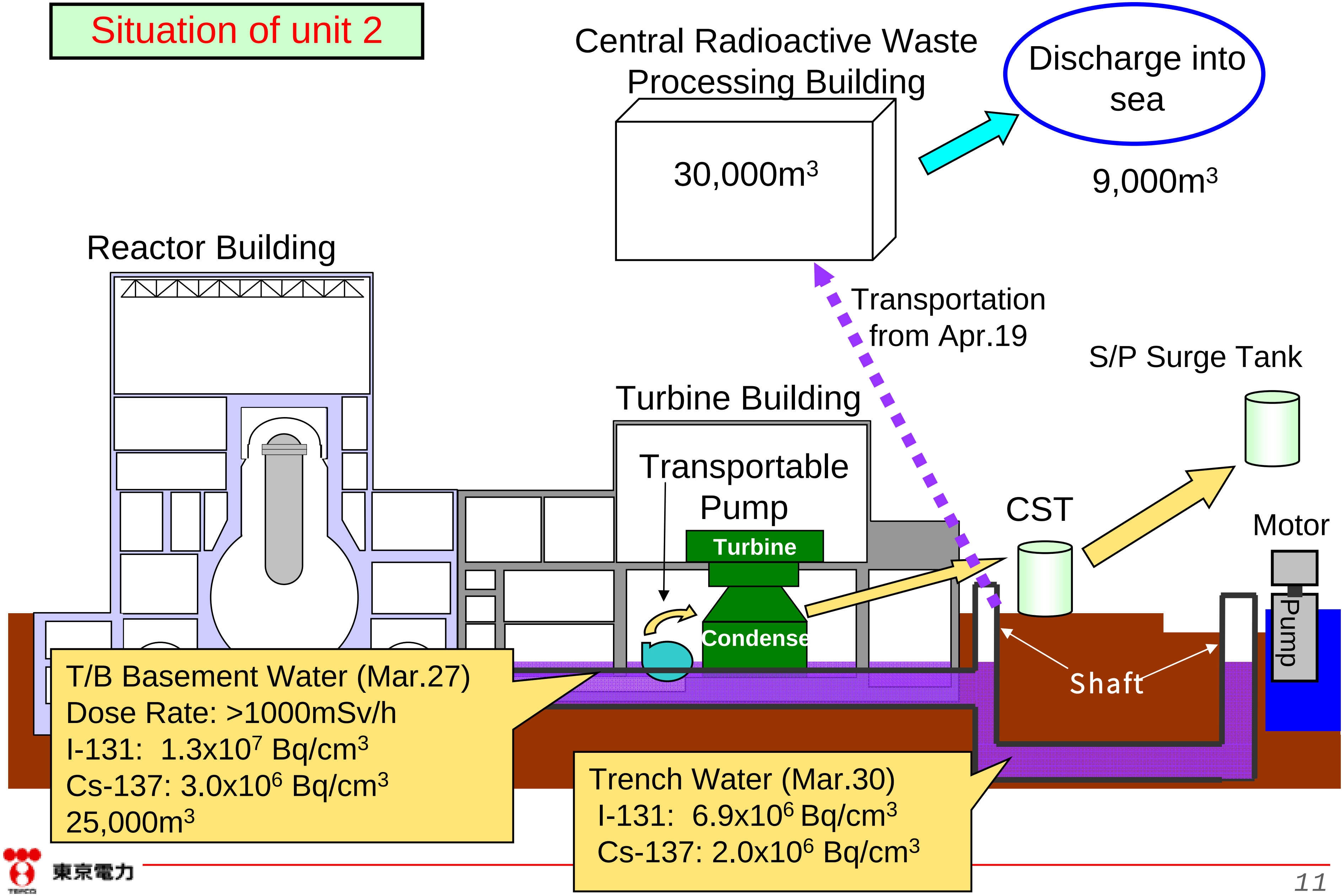
N_2 Generator

Max 14m^3/h, 0.6MPa

Temporary External Cooling System



Water Inventory Control



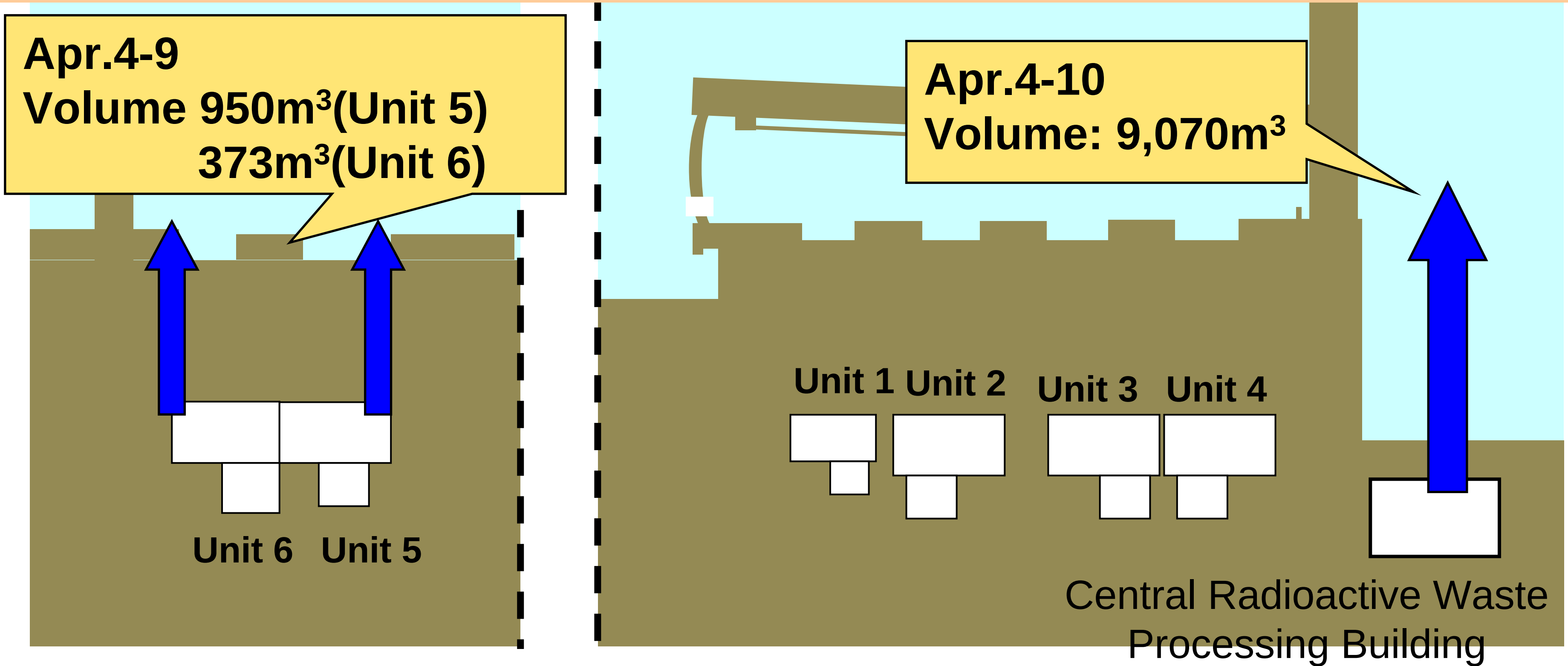
Emergency Discharge of Low Contaminated Water

Low contaminated water was discharged with authorization of the regulator.

- to avoid spill-over of highly contaminated water (more significant risk)
- to prevent sub drain leakage into unit 5 and 6

Total radioactivity was 1.5×10^{11}Bq and within planned yearly release under licensing (2.2×10^{11}Bq)

No significant change was recognized in seawater radiation during discharge.



Securing Storage Capacity

Mega Float: Vast Floating Structure
(currently under modification)
10,000m^3

Temporary Storage Tank

Radioactive Water Retention
New Water Storage Tanks

US Fresh Water Barge On Site

Japanese ship hauling US Navy water barge

Japanese Tow Operators

New Water Barge Under Construction

2.5 Million Gallon Capacity Barge

Russian Rad Water Processing Ship

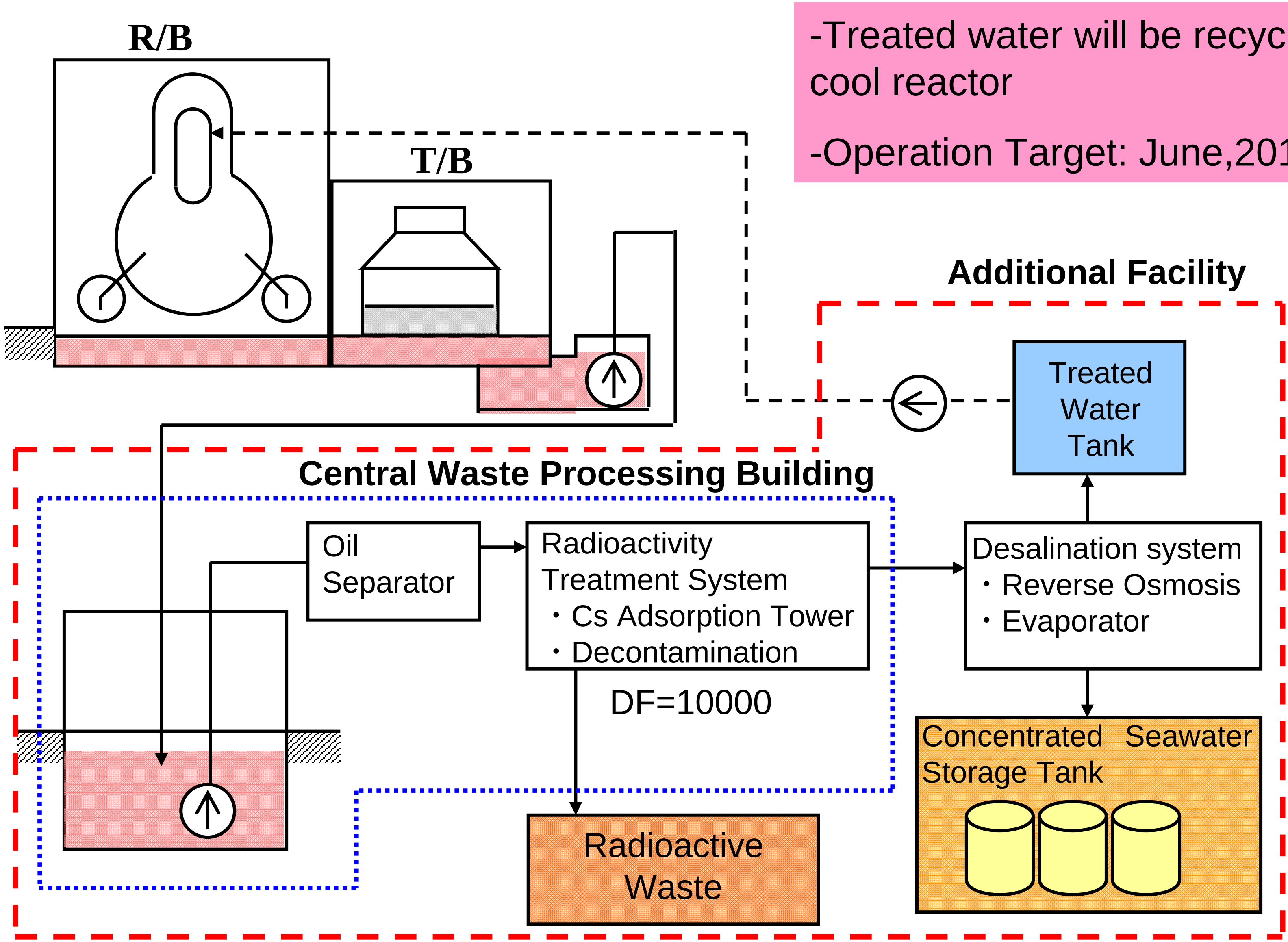
From Russia This Month

Landysh Waste Water Treatment Ship-Japan bought for Russian Navy

Installation of Water Treatment Facility

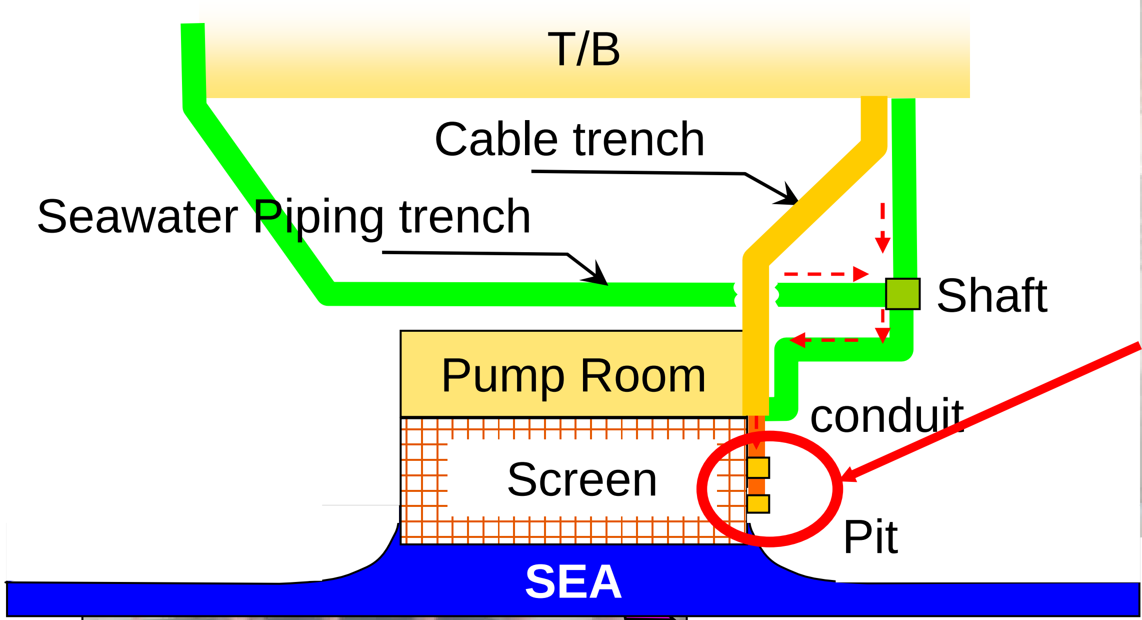
-Treated water will be recycled to cool reactor

-Operation Target: June,2011



Prevention of Contaminated Water Spill

Highly contaminated water was found to leak into the sea through crack in the cable pit on Apr.2.



Dose rate：more than1,000mSv/h

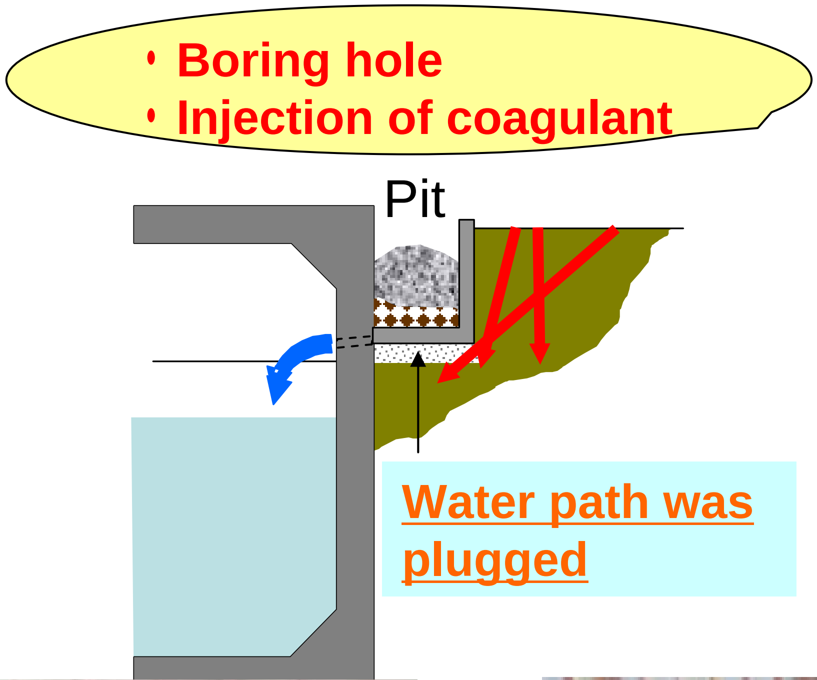
Radioactivity：

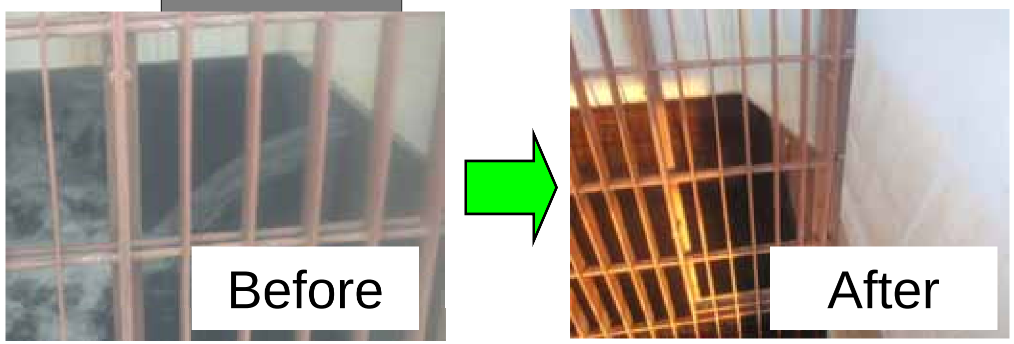
I-131	**$5.4X10^6$**	**[Bq/cc]**
Cs-134	**$1.8X10^6$**	**[Bq/cc]**
Cs-137	**$1.8X10^6$**	**[Bq/cc]**

Prevention of contaminated water spill

Injection of coagulant successfully plugged water path on Apr.6.

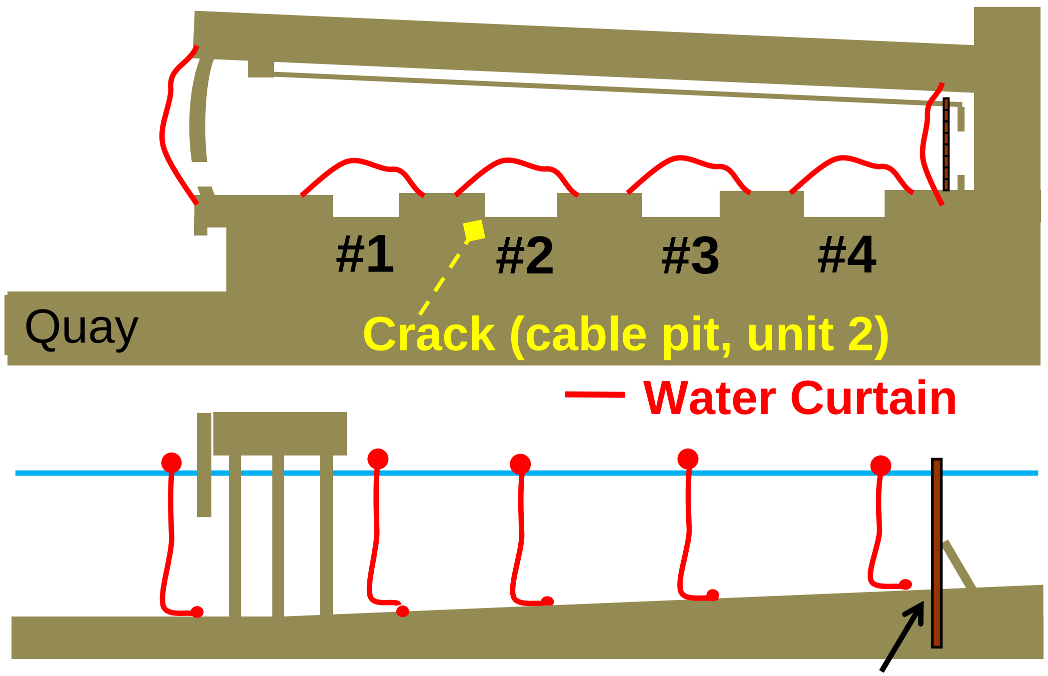
Total radioactivity released was estimated to be **4.7X10**^{15} Bq





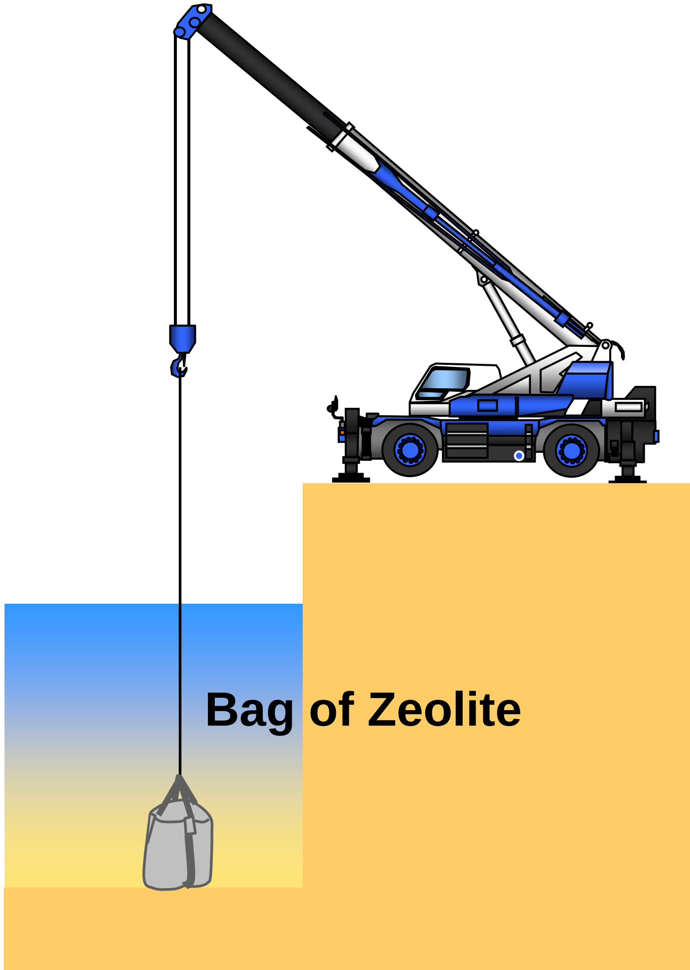
Prevention of Radioactivity Diffusion into sea

Water curtains and steel plates were installed into breakwater to prevent the contaminated water into the sea.



Prevention of Radioactivity Diffusion into sea

Bags of zeolite were placed in front of water intake screen to estimate absorption capability

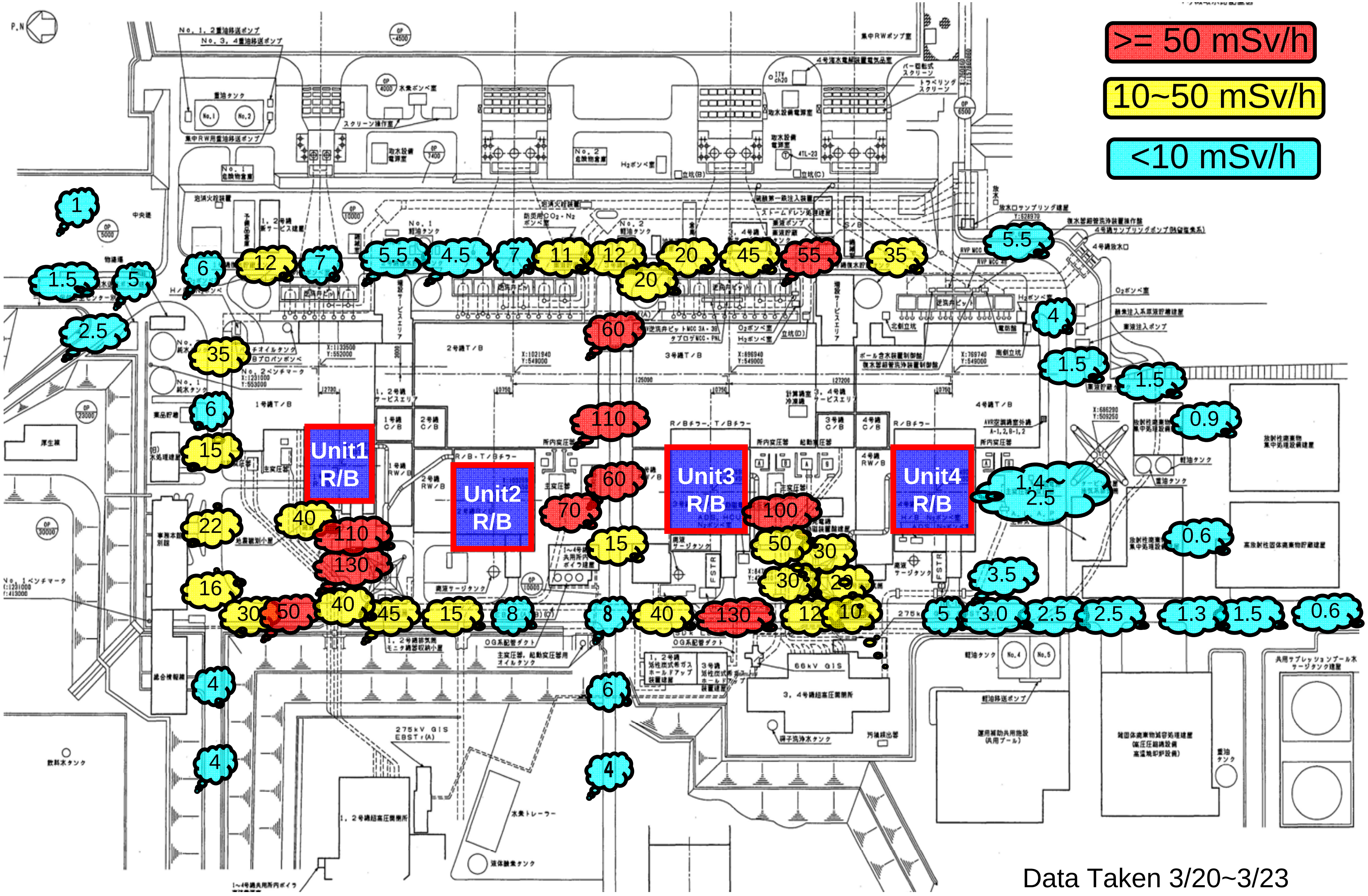


Remote-controlled Heavy Machinery

Unmanned excavator to remove rubbles

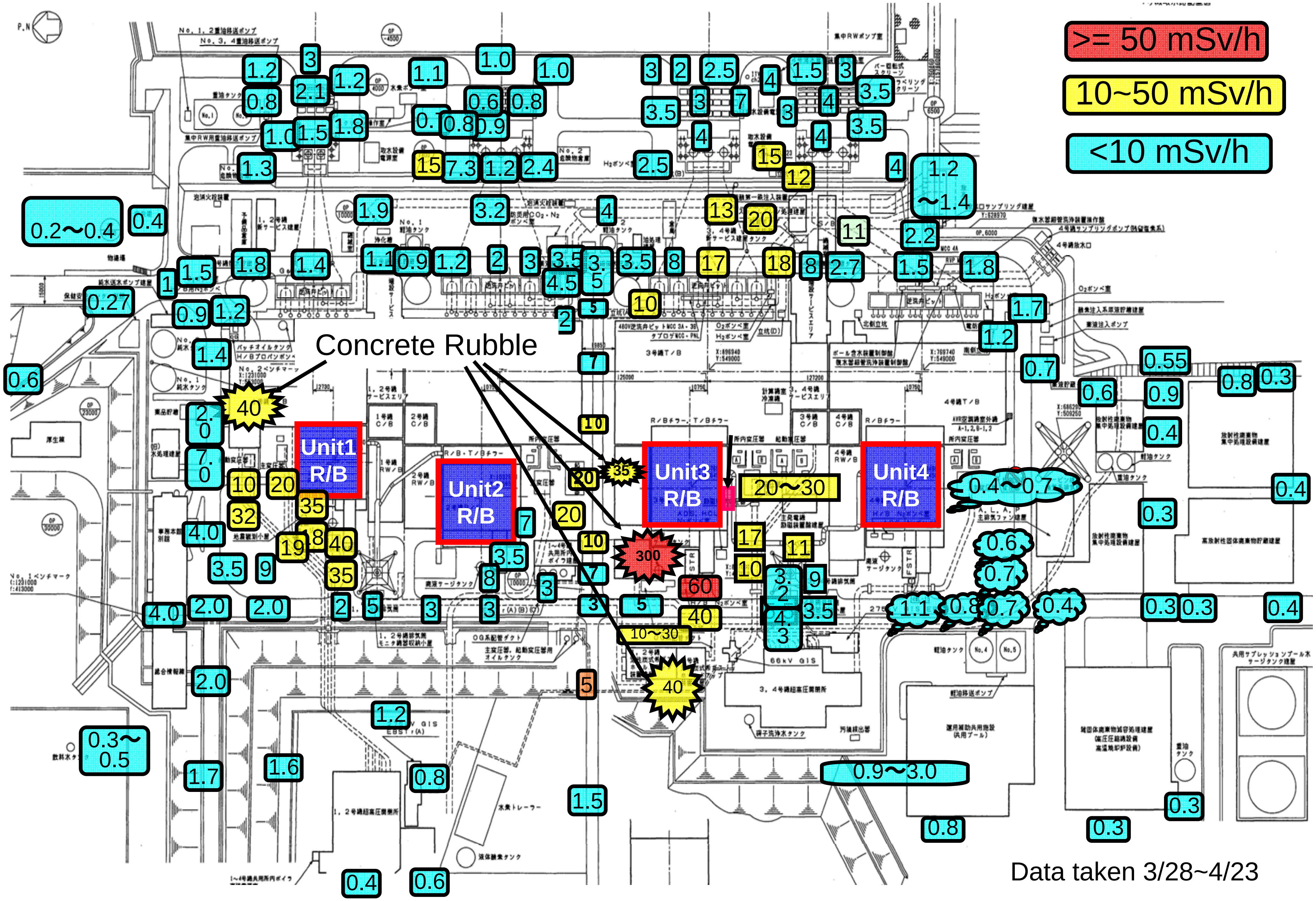
Operation Console

Radiation Survey Map (As of Mar.23 , 2011)



Data Taken 3/20~3/23

Radiation Survey Map (As of Apr.23 , 2011)



Robot Investigation of Reactor Building

Packbot
(courtesy of i-robot corporation)

Observed Dose Rate at R/B

Unit 1: 10-49 mSv/h,

1120mSv/h (around SHC pp)

Unit 2: 4mSv/h

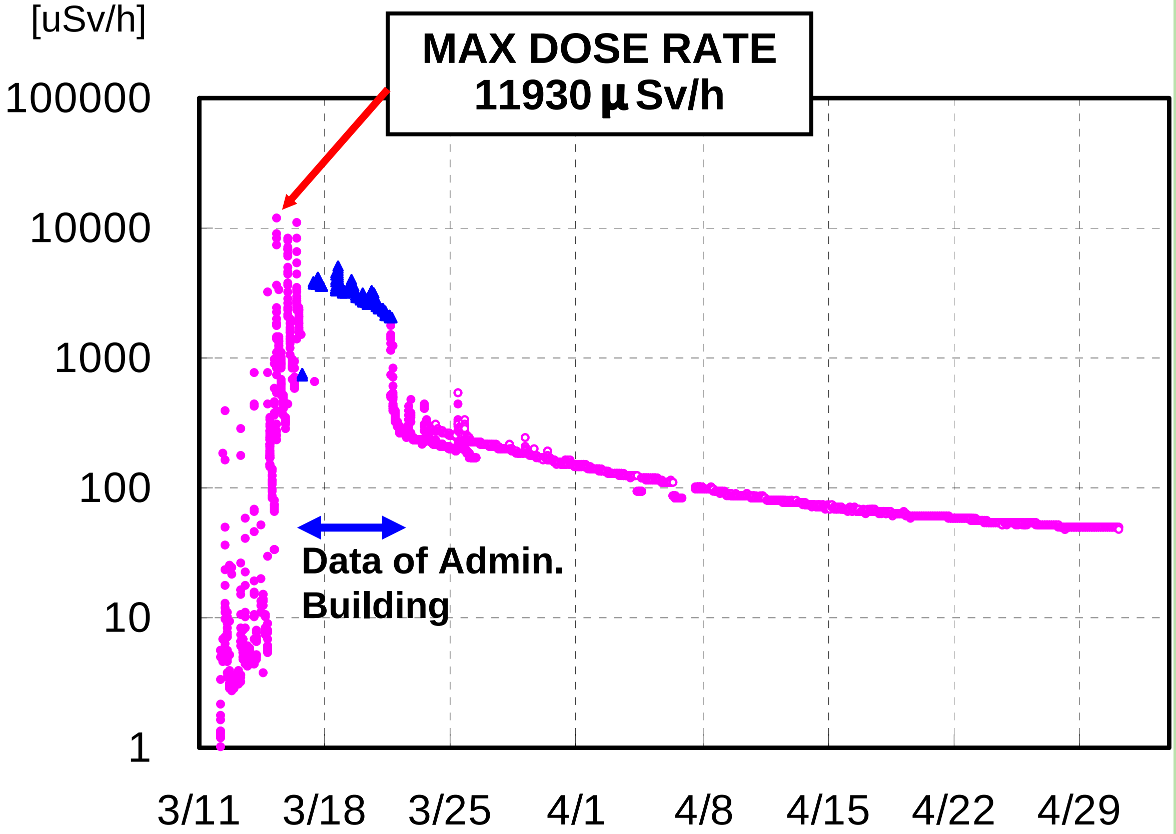
Unit 3: 28-57mSv/h

Inside Reactor Building

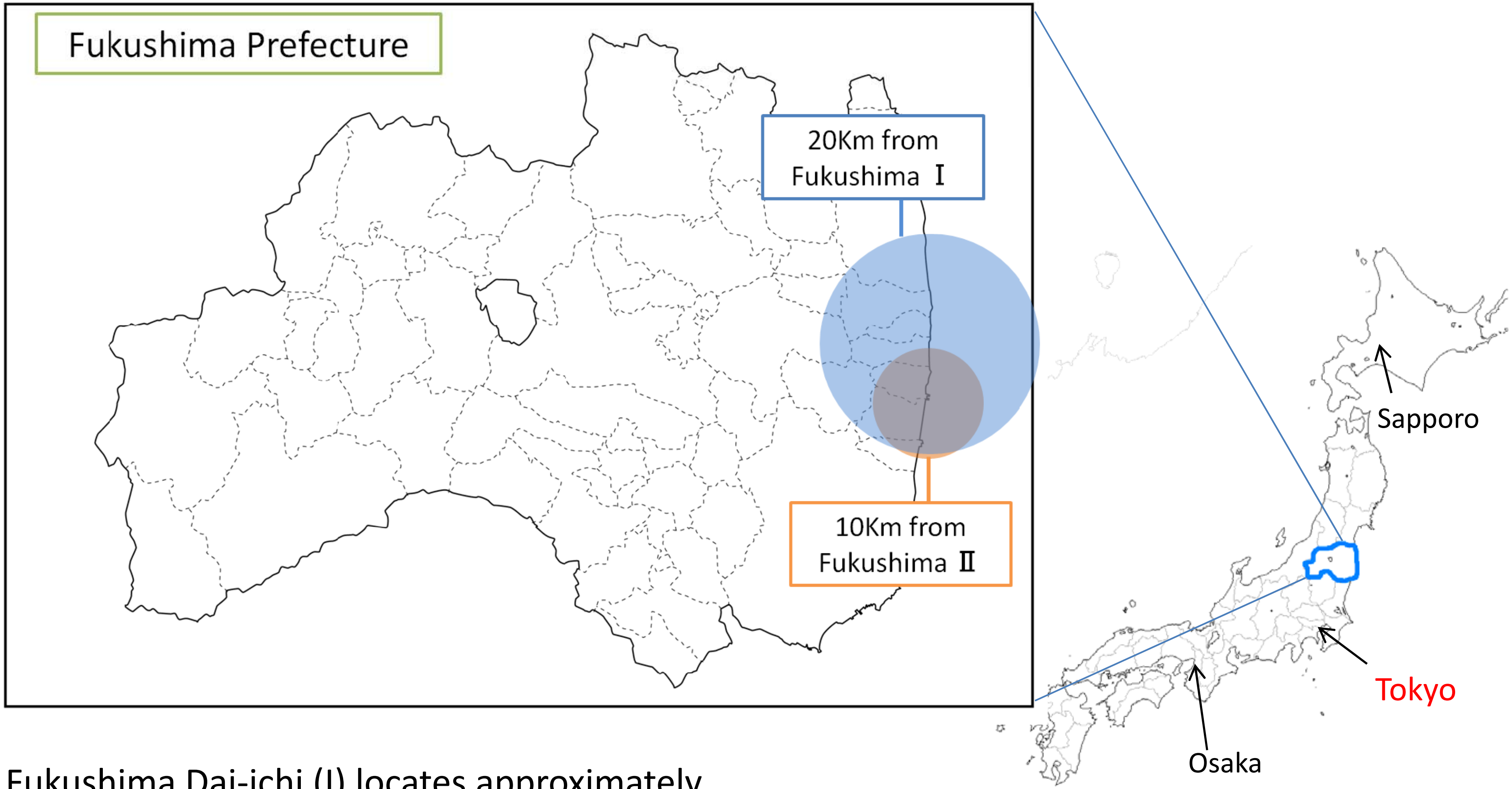
3. Environmental Impact

Monitoring Result at Site Boundary

Dose rate (Main Gate)



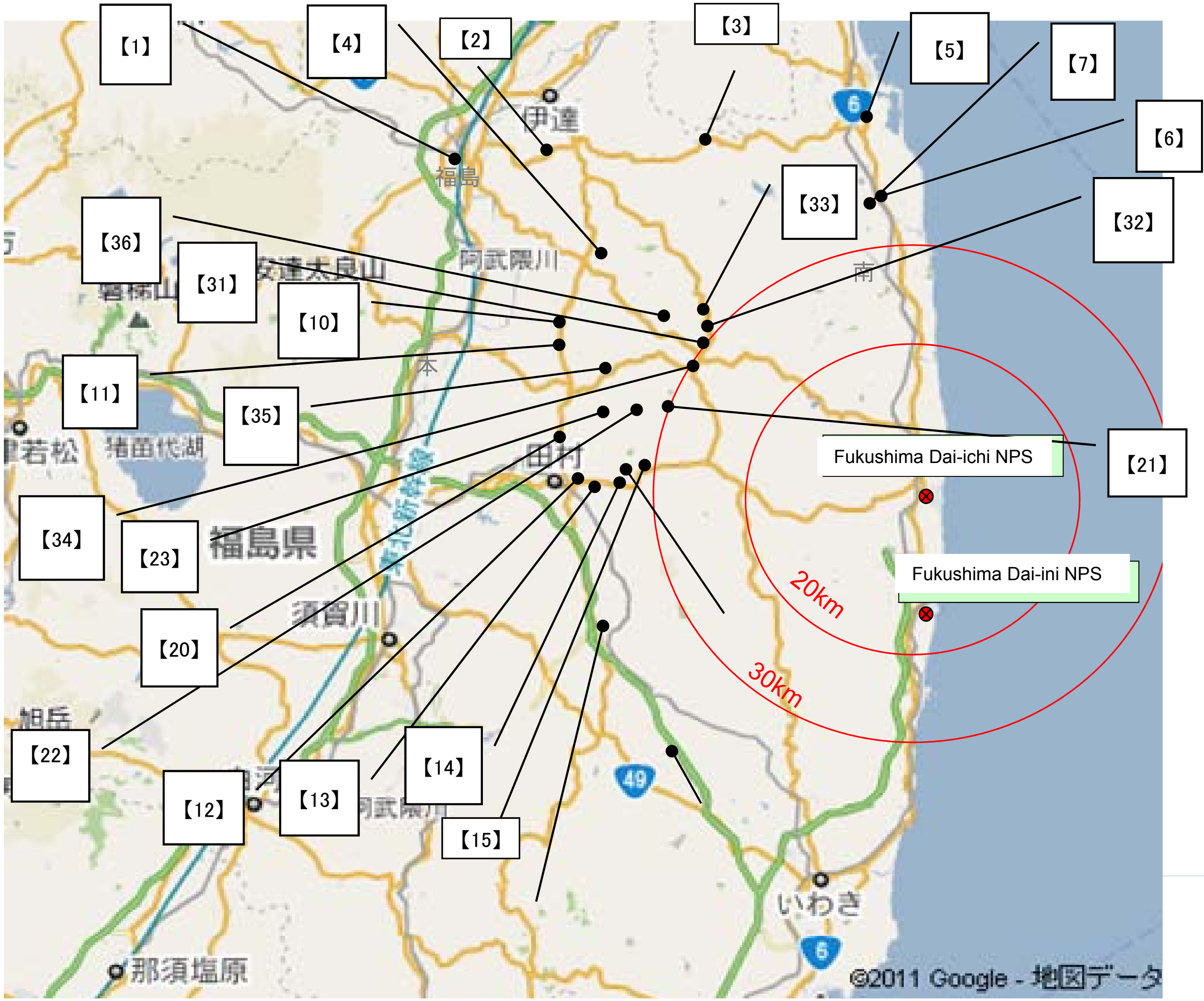
6-1. Current Situation on Resident Evacuation(2/2)



Fukushima Dai-ichi (I) locates approximately

- 230 km from Tokyo
- 580 km from Osaka
- 600 km from Sapporo

① Air Dose Rate Measuring Locations Using Monitoring Vehicles



Internal Accident Recovery Phases Per Basic Four Elements

1. <u>Energy</u> Heat Rejection Control
   1. **Open Feed & Bleed: Cools but Vents Radioactive Steam**
   2. **Closed Residual Heat Removal Operation**
2. **<u>Gas</u> Release Control/Mitigation**
   1. **Containments**
   2. **Filtration**
3. **<u>Liquid</u> Release Control/Mitigation**
   1. **10+ Millions Of Gallons of Highly Radioactive Water in Basements**
   2. **Containments**
   3. **Purification**
4. **<u>Solids</u>/Contamination Control Materials Management**
   1. **Contain/package**
   2. **Store/transport**
   3. **Dispose**

External Phases Of Accident

- **Plant Accident Recovery Period**
  - Impossible Information Demands
  - Stabilize/Remediate/Recover
  - Hours-Days-Weeks-Months-Years-Decades
- **Environmental Impact Period**
  - Public Perception/Impacts/Remediation (Offsite)
  - Weeks-Months-Years
- **Societal/Institutional Reactions Period**
  - Cultural
  - Political
  - Policy
  - Financial
  - Days-Weeks-Months-Years-Decades

Human Feelings & Reactions

Personal Fukushima Observations

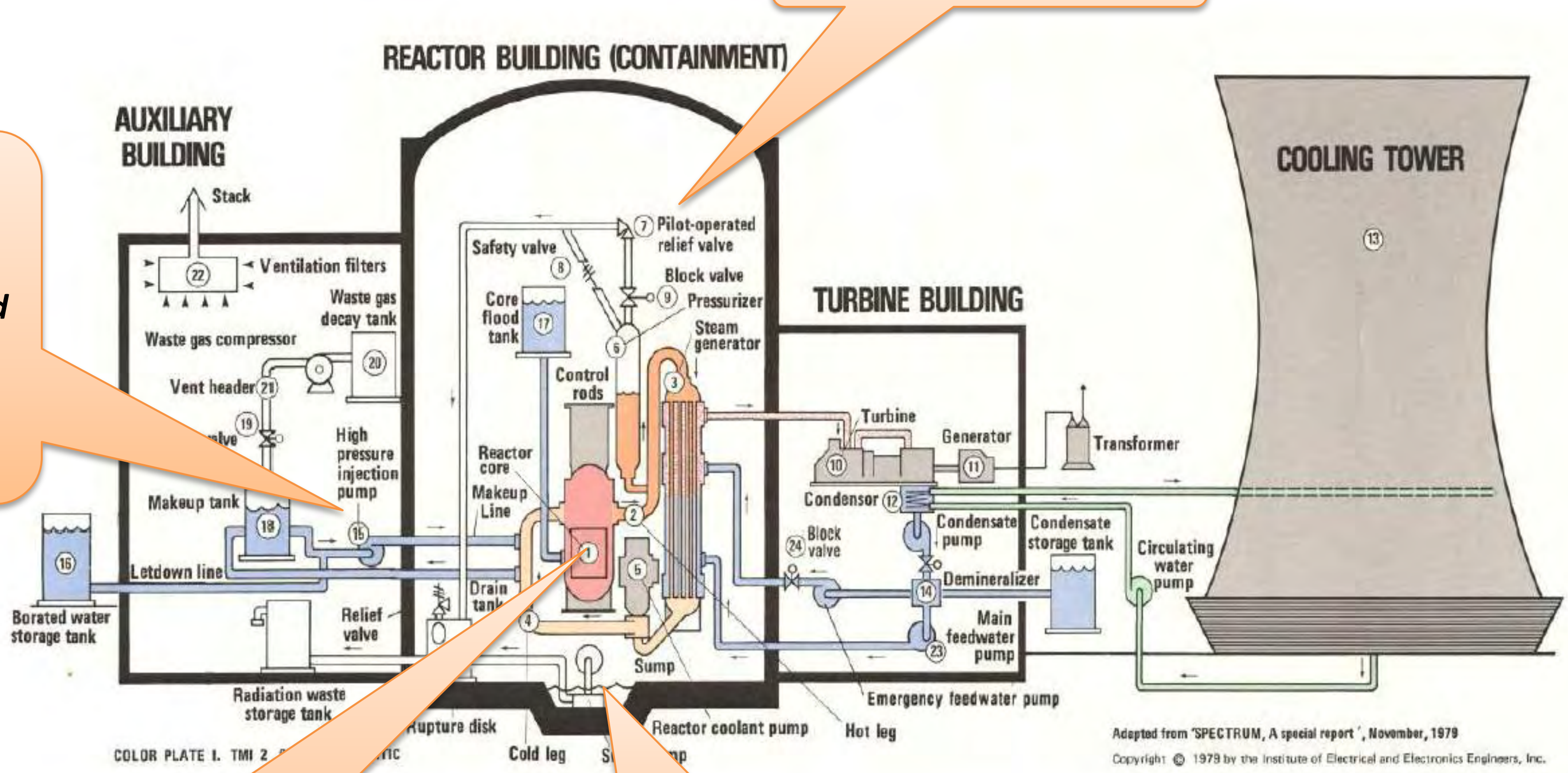
- **Not a Public Health Catastrophe**
  - Inconsequential Compared to Earthquake/Tsunami Impacts
  - US Evacuation Decision-Poor Judgment With Net Negative Public Good
- **Is An Industrial Plant Catastrophe**
  - Three Severely Damaged Cores and Two Severely Damaged Spent Fuel Pool inventories
  - Units 1-4 Complete Loss, Units 5 &6 Technically Recoverable
  - Cleanup Long, Expensive & Technically Achievable (But Much Larger than TMI)
- **Energy Dissipation is Getting Better, but Challenging**
  - Salt Cake Dissolution Concerns
  - Primary Containment Oxygen Intrusion Explosion Concern
  - Need Closed Cooling to Stop Venting: Barge Mounted Solution Likely
- **Environmental Release Mitigation is a Growing Challenge**
  - Technically at Plant With Continued Feed & Bleed Vapor/Water Effluents
  - Environmental/Social Impact
  - Institutionally Challenging Infrastructure Ahead
- **Lessons Learned Ahead**
  - TMI Lessons Learned Improved US Nuclear Safety and Productivity
  - Most Painful Lessons are the Most Teachable
  - Hopefully the Fukushima Lessons Will Strengthen Nuclear Energy As TMI Did

Three Mile Island Units 1 &2

March 28, 1979

Three Mile Island Unit-2 Accident

March 28, 1979



Relief Valve fails to close

Operators Believe Reactor Overfilled and Turn Off Injection Pumps

Core is uncovered Fuel overheats/fails/~50% Melt

650,000 gallons of highly radioactive water collects

Three Mile Island History

- Reactor Scram: 04:00 3/28/79
- Core melt and relocation: ~ 05:00 – 07:30 3/28/79
- Hydrogen Deflagration: 13:00 3/28/79
- Recirculation Cooling: Late 3/28/79
- Phased Water Processing: 1979-1993
- Containment Venting 43KCi Kr-85: July 1980
- Containment Entry: July 1980
- Reactor Head removed and core melt found: July 1984
- Start Defuel: October 1985
- Shipping Spent Fuel: 1988-1990
- Finish Defuel: Jan 1990
- Evaporate ~2.8M gallons Processed Water: 1991-93
- Cost: ~$1 Billion

What English information on web from Japan?

<Earthquakes and Tsunami>
Japan Meteorological Agency
http://www.jma.go.jp/jma/indexe.html
http://www.jma.go.jp/jma/en/2011_Earthquake.html
http://www.jma.go.jp/en/tsunami/
Geospacial Information Authority of Japan(partially in Japanese)
http://www.gsi.go.jp/ENGLISH/index.html

<Radiation Levels>
http://www.mext.go.jp/english/radioactivity_level/index.htm
http://www.bousai.ne.jp/eng/index.html
U.S. Department of Energy Releases Radiation Monitoring Data from Fukushima Area
http://www.energy.gov/news/10194.htm

Food and Water
http://www.mhlw.go.jp/english/topics/2011eq/index.html
Radioactive material level in tap water in Tokyo/day
http://ftp.jaist.ac.jp/pub/emergency/monitoring.tokyo-eiken.go.jp/monitoring/w-past_data.html

prepared by Shuichi IWATA(iwatacodata@mac.com) the University of Tokyo & Osamu MIZUTANI (osamumztn@aol.com) UAJC on April 21, 2011 for "Twenty-Five Years after Chernobyl Accident: Safety for the Future"

<Status of Nuclear Reactors>
Tokyo Electric Power:
http://www.tepco.co.jp/en/nu/fukushima-np/index-e.html#anchor02
-Radiation Levels measured by TEPCO
http://www.tepco.co.jp/en/nu/fukushima-np/f1/index-e.html
-TEPCO's explanation paper
http://www.tepco.co.jp/en/nu/fukushima-np/f1/images/f12np-gaiyou_e.pdf
-Influence of radioactive materials to the environment (prepared by TEPCO)
http://www.tepco.co.jp/en/nu/fukushima-np/f1/index2-e.html
-Photos for Press (TEPCO)
http://www.tepco.co.jp/en/news/110311/
Japan Atomic Industrial Forum
http://www.jaif.or.jp/english/
Japan Nuclear and Industrial Safety Agency
http://www.nisa.meti.go.jp/english/
Nuclear Safety Commission of Japan
http://www.nsc.go.jp/NSCenglish/geje/index.htm
Prime Minister's Office of Japan
http://www.kantei.go.jp/foreign/incident/index.html
NHK World in English
http://www3.nhk.or.jp/nhkworld/
NHK World TV
http://www3.nhk.or.jp/nhkworld/r/movie/

What English information on web from Japan?

<Assistances>

NHK Radio provides quake-related broadcast in 18 languages
http://www3.nhk.or.jp/nhkworld/english/radio/program/index.html

Assistance Manual for Foreigners in Times of Disaster by TICC
http://www.tokyo-icc.jp/english/information/howto.html

Transportation
http://www.mlit.go.jp/page/kanbo01_hy_001411.html

Ministry of Defense
http://www.mod.go.jp/e/index.html

National Police Agency
http://www.npa.go.jp/english/index.htm

National Institute of Radiological Sciences
http://www.nirs.go.jp/ENG/index.html

<Other Information Sources>

Atomic Energy Society of Japan
http://www.aesj.or.jp/en/

Japan Atomic Energy Agency
http://www.jaea.go.jp/english/index.shtml

International Atomic Energy Agency
http://www.iaea.org/newscenter/news/tsunamiupdate01.html

US Department of Energy Blog
http://blog.energy.gov/content/situation-japan

US Nuclear Regulatory Commission
http://www.nrc.gov/japan/japan-info.html

World Nuclear Association
http://world-nuclear.org/info/fukushima_accident_inf129.html

United States Environmental Protection Agency
http://www.epa.gov/japan2011/

Google Crisis Response
http://www.google.co.jp/intl/en/crisisresponse/japanquake2011.html

Photo Service
http://cryptome.org/eyeball/daiichi-npp/daiichi-photos.htm

American Nuclear Society
http://ansnuclearcafe.org/fukushima/