

Lessons Learned from the Fukushima Daiichi Accident

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References

IAEA : The Fukushima Daiichi Accident : Report by the Director General
STI/PUB/1710, ISBN 978-92-0-107015-9

TEPCO : Press Release (Jun 20,2012)
Release of the Fukushima Nuclear Accidents Investigation Report
-Fukushima Nuclear Accidents Investigation Report (Attachment) (PDF 28.1MB)
https://www4.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120620e0106.pdf

IRSN: [Understanding the accident of Fukushima Daiichi](#)

https://www.youtube.com/watch?v=ZJwg_McDGSI (70 min.)

<https://www.youtube.com/watch?v=YBNFvZ6Vr2U> (13 min.)

YouTube by Institut de Radioprotection et de Sûreté Nucléaire - IRSN (2013)

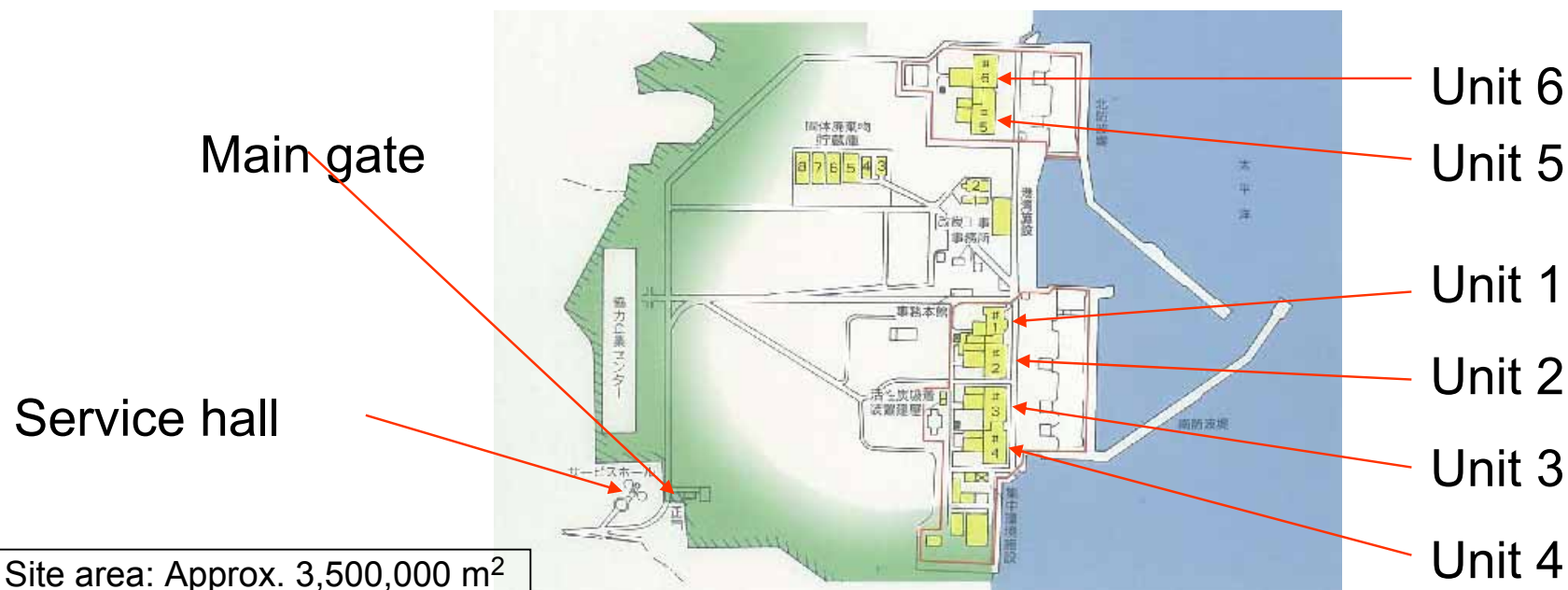
This film presents the sequence of the accident at the Fukushima Daiichi plant in March 2011. It explains how the boiling water reactor (BWR) operated in Japan, describes the

L'ASNR rassemble depuis 2025 les missions et les activités de l'ASN et de l'IRSN



Ministry of the Environment
Government of Japan

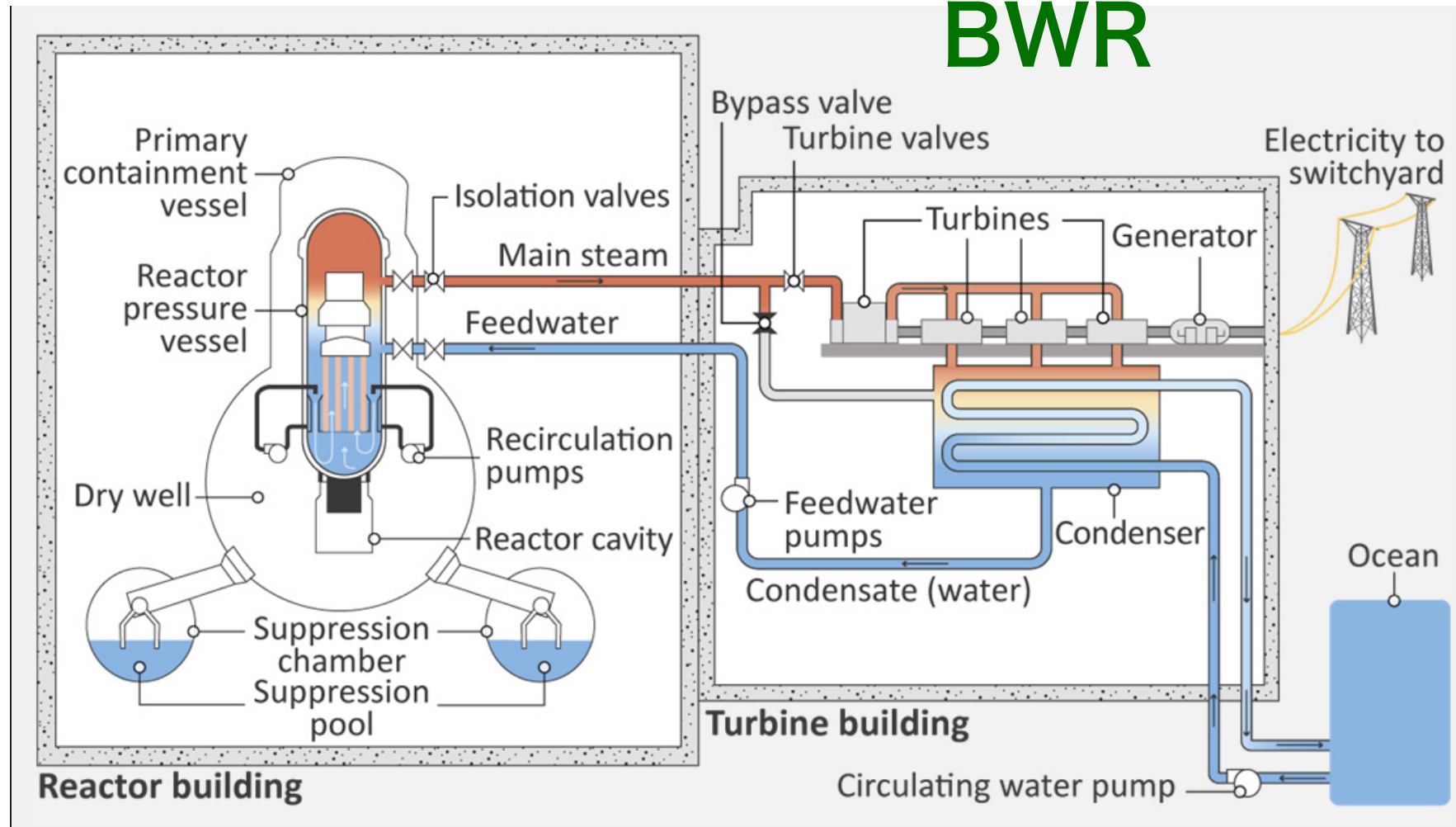
Summary of Fukushima Daiichi Nuclear Power Station



Address	Unit	Start of operation	Type	Output (x 10,000 kW)	Main contractor	Status when the earthquake struck	
Okuma Town	Unit 1	March 1971	BWR3	46.0	GE	In rated output operation	
	Unit 2	July 1974	BWR4	78.4	GE/Toshiba	In rated power operation	
	Unit 3	March 1976	BWR4	78.4	Toshiba		
	Unit 4	October 1978	BWR4	78.4	Hitachi	Outage	All fuel removed, pool gate closed (core shroud replacement work under way)
Futaba Town	Unit 5	April 1978	BWR4	78.4	Toshiba		Reactor pressure vessel top lid closed
	Unit 6	October 1979	BWR5	110	GE/Toshiba		

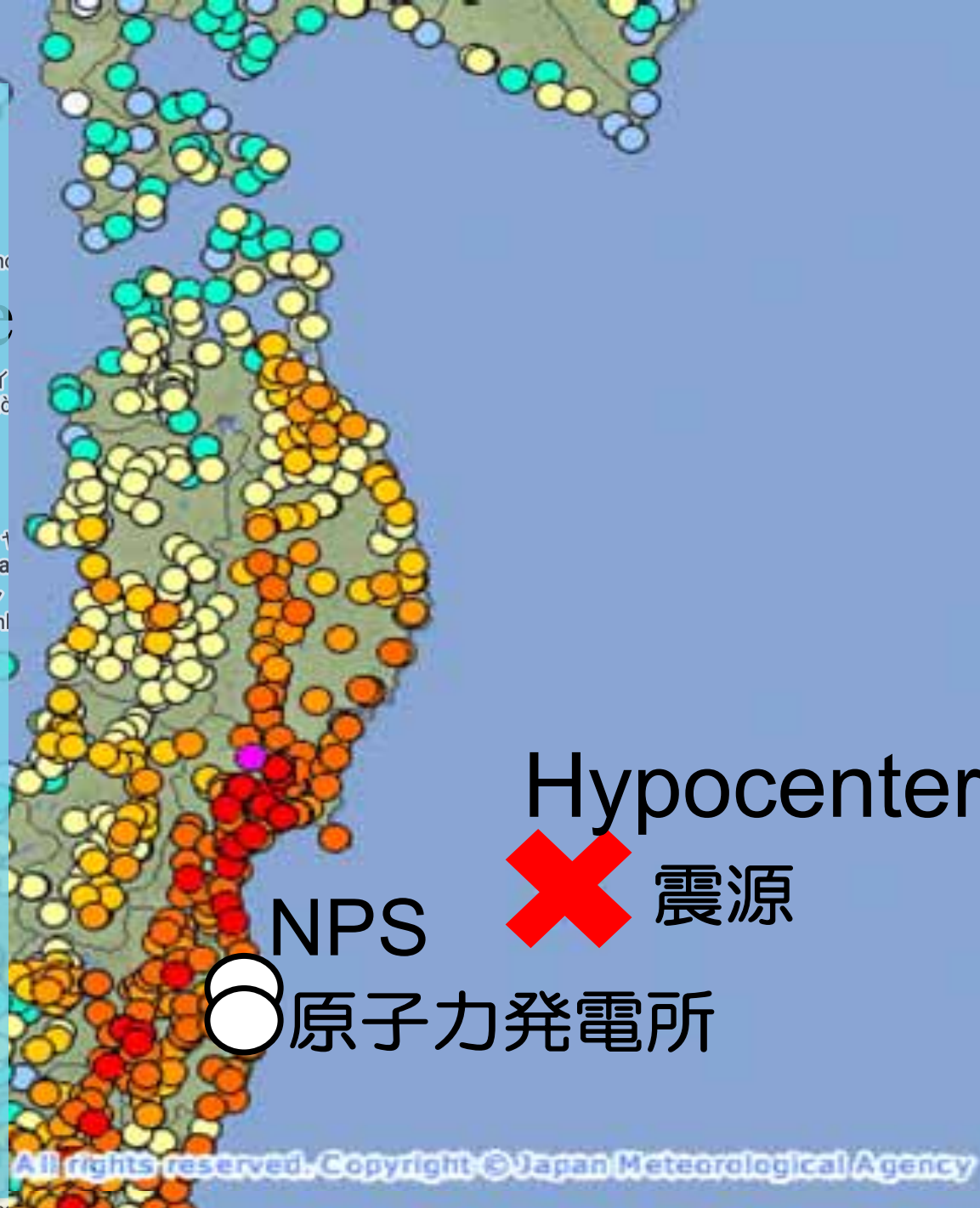
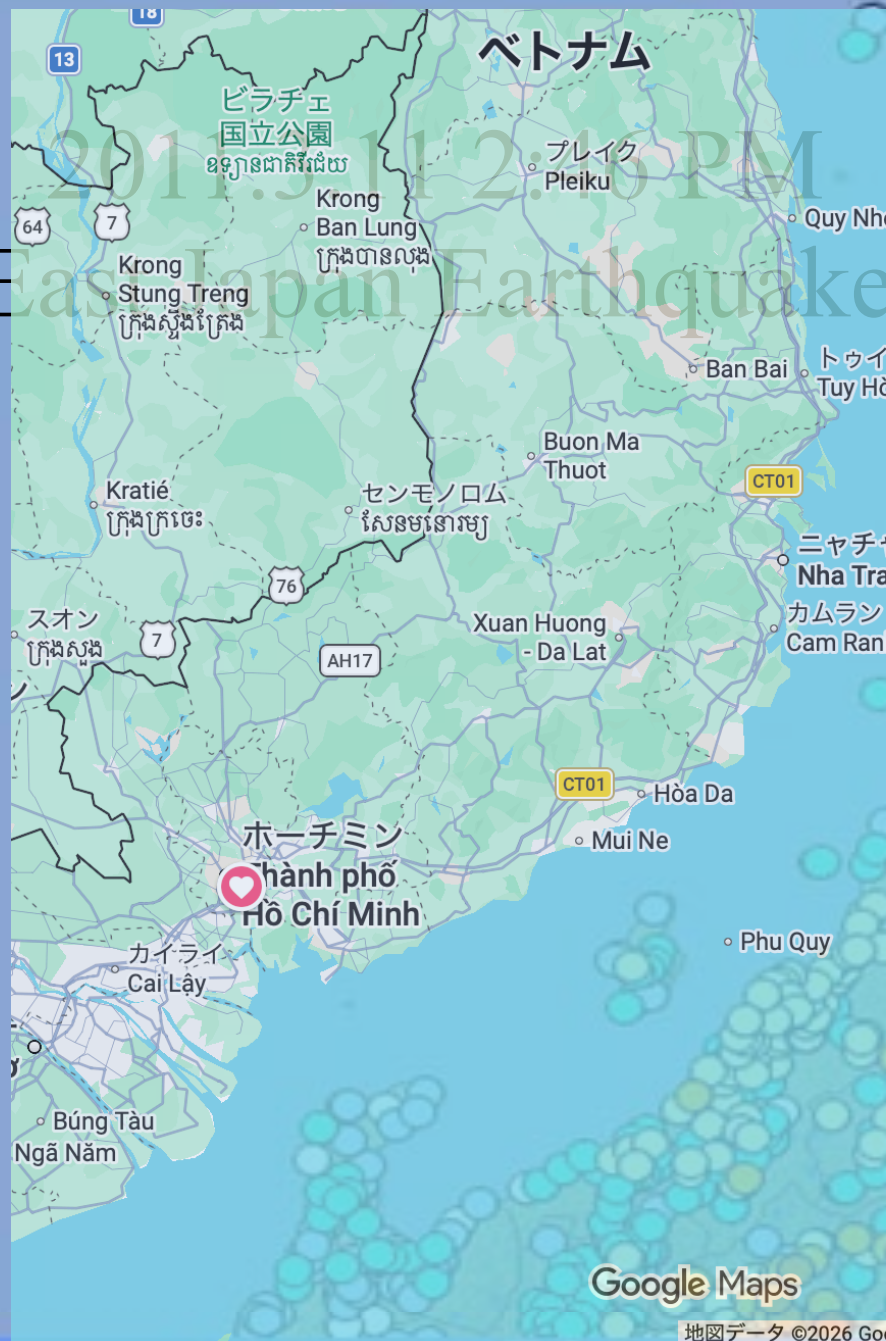
Fukushima Dai-Ichi

BWR



Pressure: 7 MPa / ~ 285°C

2011.3.11 2:46 PM East Japan Earthquake



Hypocenter

震源

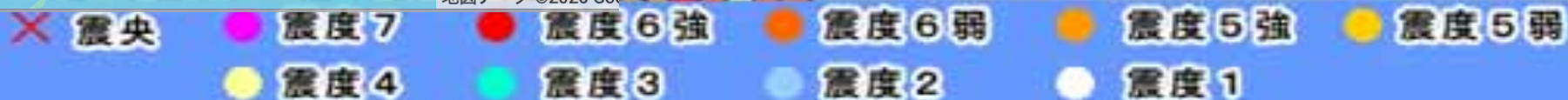
NPS

原子力発電所

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凡例



Tsunami at Fukushima Dai Ichi

The tsunami waves started reaching the Fukushima Daiichi NPP about 40 minutes after the earthquake.



Automatic shutdown

Reactor Scram

The operating reactors of Units 1–3 were shut down automatically when sensors at the plant detected the ground motion and triggered reactor protection systems in accordance with the design. This automatic action achieved control of reactivity.

The insertion of reactor control rods by the control rod drive systems terminated the nuclear chain reaction in the nuclear fuel and brought the reactors to a shutdown condition.

In Japan, we often experience earthquakes.

They are trained to respond to earthquakes.

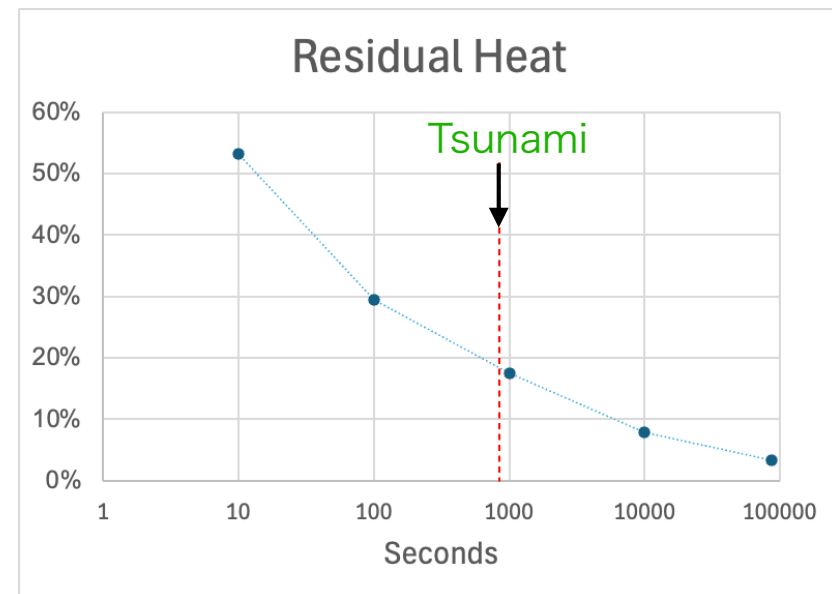


Residual Heat

When a reactor shuts down, the decay heat is **about 6%** of the thermal power during operation. It decreases rapidly. However, when the tsunami struck, the residual heat was still about **22 MW** in Reactor 1 and about **37 MW** in Reactors 2 and 3.

Table 17. Major contributors to total decay heat at 1 day-

#	Nuclide ID	Decay heat (W)
1	¹⁴⁰ La	6.18E+04
2	¹³² I	4.95E+04
3	⁹⁷ Zr	1.90E+04
4	¹³³ I	1.53E+04
5	⁹⁷ Nb	1.31E+04
6	⁹⁹ Mo	1.28E+04
7	¹⁴³ Ce	1.22E+04
8	¹⁴⁰ Ba	1.06E+04
9	⁹³ Y	7.62E+03
10	¹³¹ I	6.88E+03
11	⁹¹ Sr	6.54E+03
12	⁹⁵ Zr	6.42E+03



OAK RIDGE
NATIONAL LABORATORY
MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2010/318

*** Accumulated heat is huge**

Low Enriched Uranium Fuel Design
with Two-Dimensional Grading
for the High Flux Isotope Reactor

How to cool down

Pressure: 7 MPa / ~ 285°C

20~40 MW heat generation

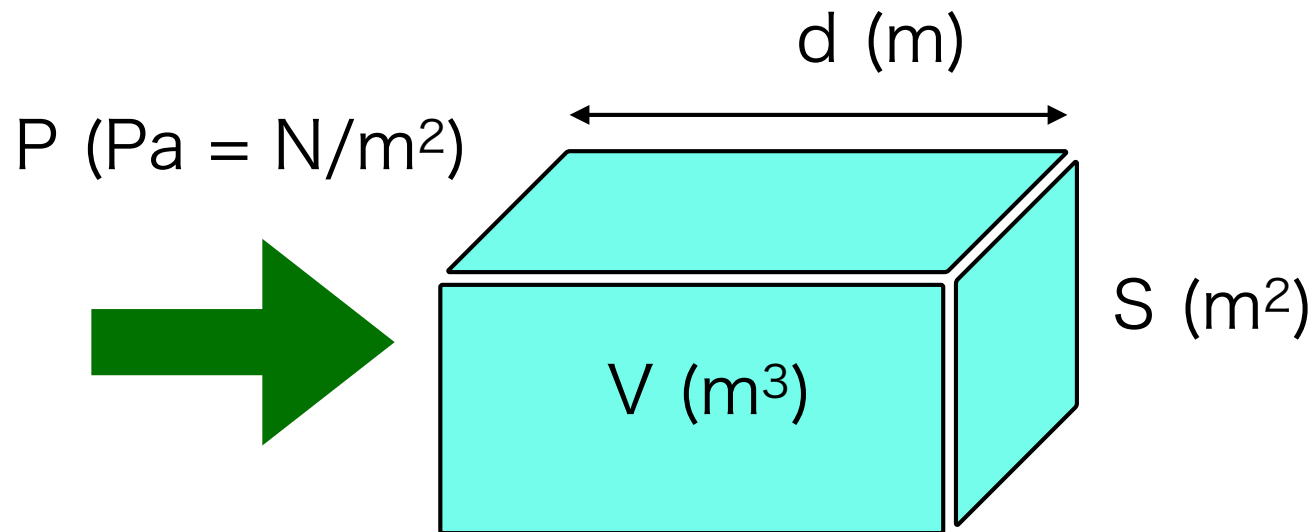
When shut down, the reactor cores continued to generate heat (known as decay heat). To prevent the nuclear fuel from overheating, this heat had to be removed by cooling systems that were mainly run or controlled by electrical power.

Reduce the Pressure by extracting steam

It causes bumping

Need to feed water in to the pressure vessel

How to push water in against 7 MPa of pressure.



$$V = d \times S$$

$$W \text{ (J = Nm)} = F \text{ (N)} \times d \text{ (m)} = P \times S \times d = P \times V$$



$$1.6\text{MPa} \times 500\text{L/s} = 800\text{kW}$$

Two 500kW pumps work at 2,400 V.

$$7\text{MPa} \times 100\text{ L/s} = 700\text{ kW}$$

The Jet d'Eau shoots 140 meters high from Lake Geneva into the sky in 500 L/s.



0.85 MPa (typical in Japan)

AC power to high pressure pump

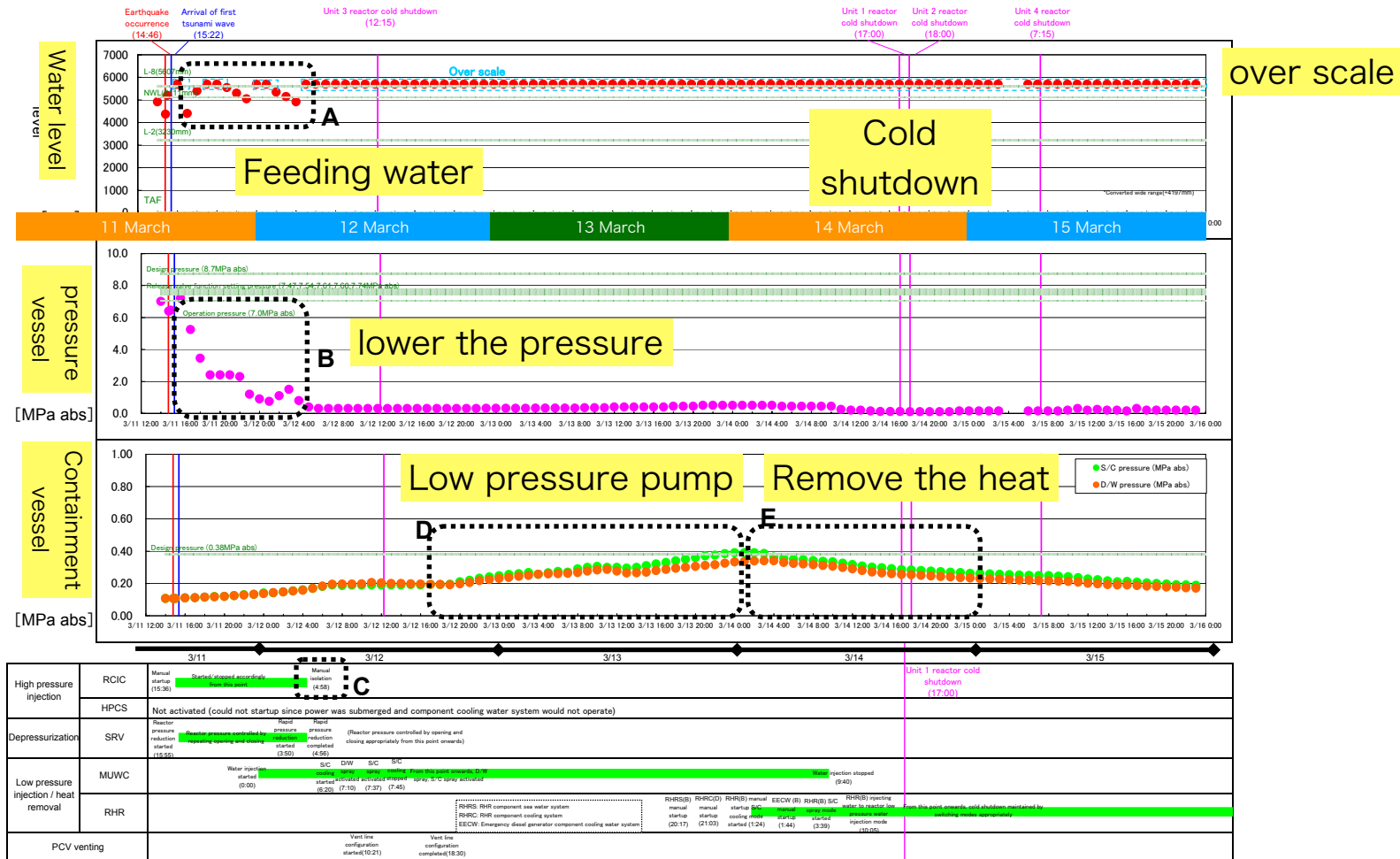
off-site AC power is lost by the earthquake

==> on-site power generator started.

They are trained to respond to the off-site power loss.

Case of Fukushima DaiNi (No. 2)

Attachment 8-17



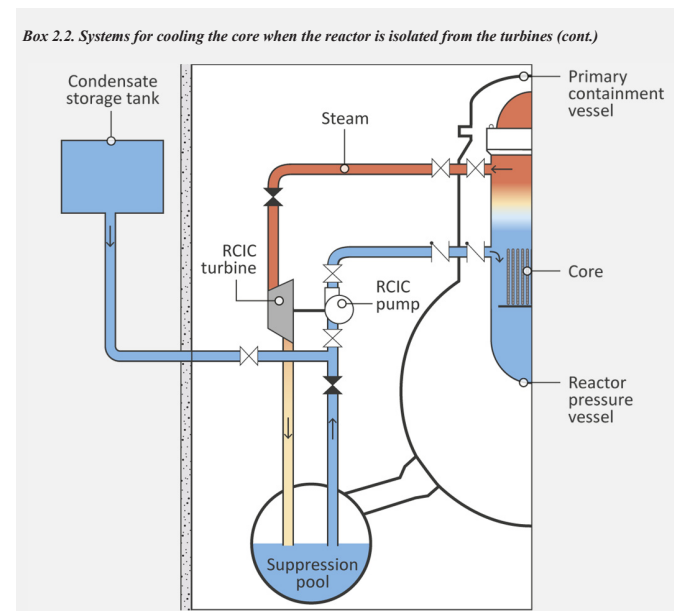
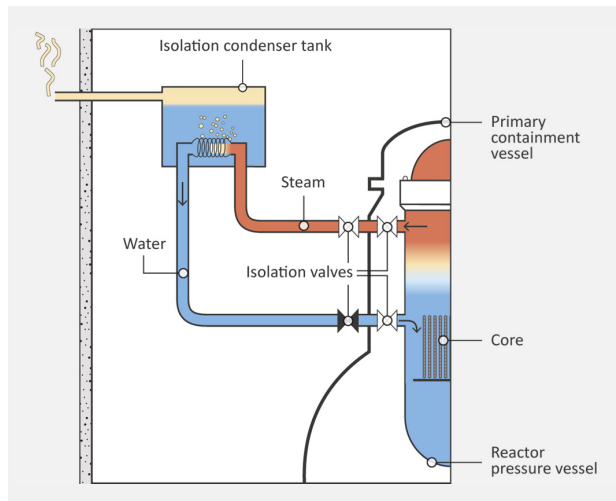
How to cool down

Pump for high pressure should be operated by off-site power or in-site power generator.

In Fukushima Dai Ichi, power generator for unit 1,2,3,4,5 were lost by Tsunami

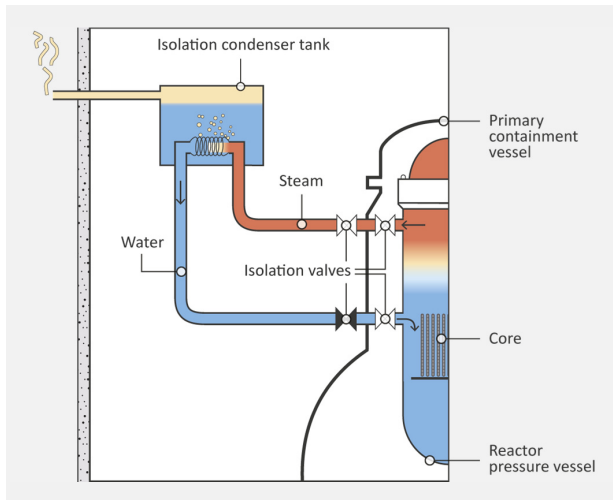
Emergency system

Reactor core isolation cooling system



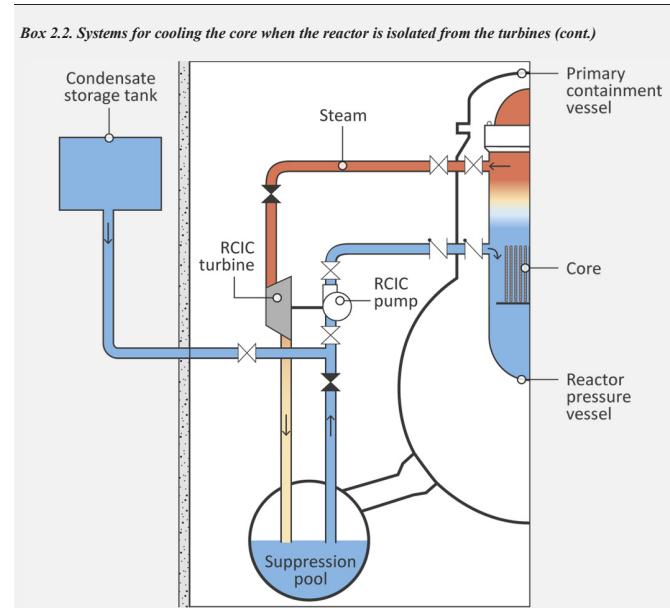
How to cool down

Reactor core isolation cooling system



Isolation condenser system (IC)

Steam is liquidized and is pushed back by the pressure of the steam.



Reactor core isolation cooling system (RCIC)

RCIC turbine generate electricity.
RCIC pump push water back to the pressure vessel.

What has happened in the NPP

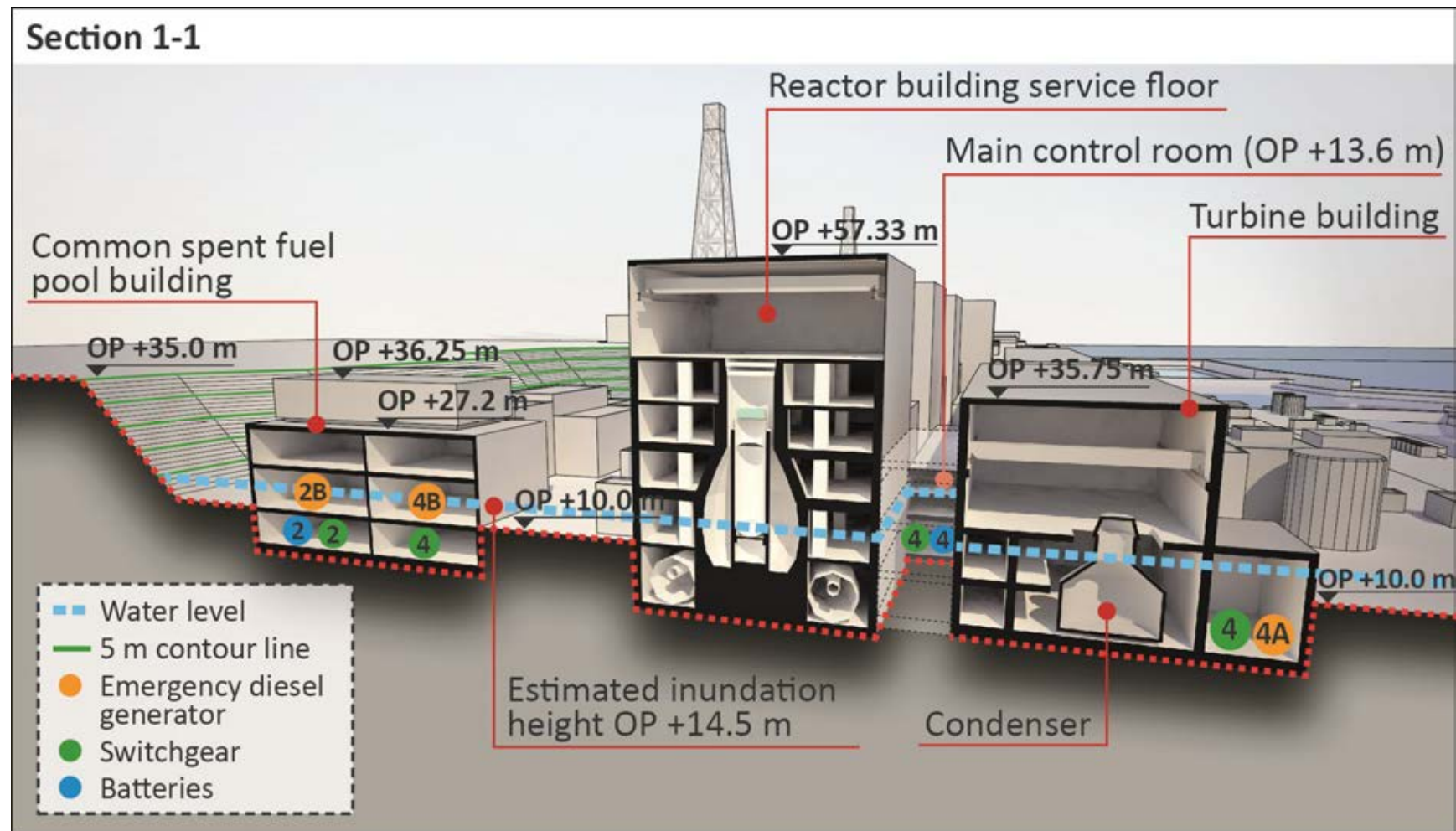


FIG. 2.4. The elevations and locations of structures and components at the Fukushima Daiichi NPP [20].

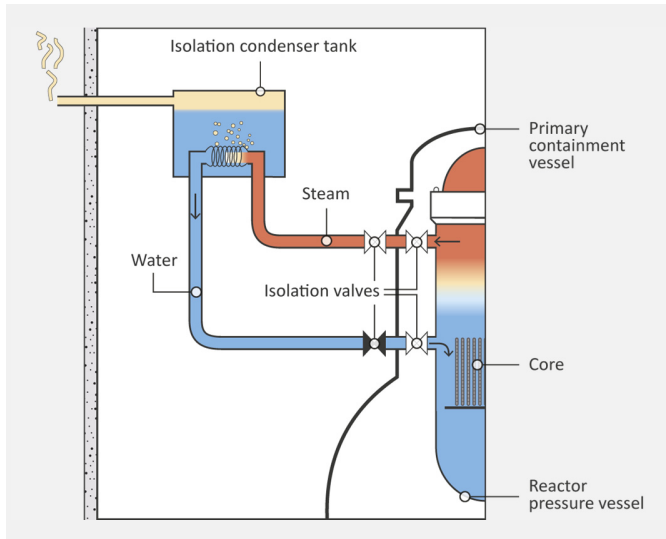
DC power (Battery)

Batteries for the reactor 1, 2 and 4 were lost by the tsunami.
Batteries for the reactor 3 survived.

Monitoring system
Control the valves.

They could not know the status of valves.

Unit-1



- 1) Duplicate IC system.
 - 2) Valves works either AC power or DC power.
- But, Both AC and DC were lost.**

Operation of IC (valve status) was not monitored.
..... They were not working.

It is simulated that water level is at TAS (Top of Active Fuel) approx. 3 hours after Tsunami.

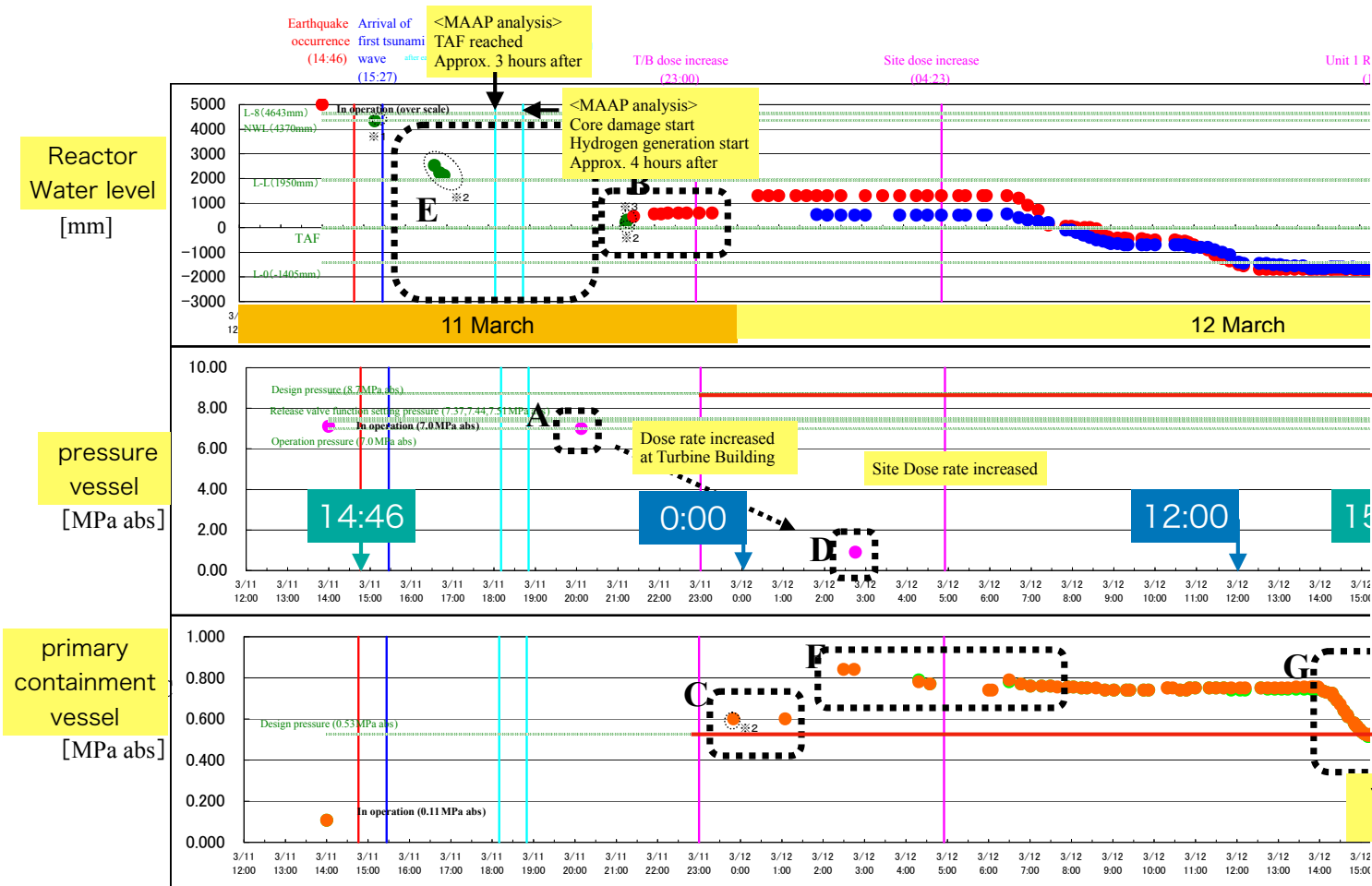
Design pressure of vessels should not be exceeded.

8.4MPs (Pressure vessel) / 0.53 MPs (Containment vessel)

Explosion of vessels causes sever ejection of radio activities.

Fukushima Daiichi Unit 1 Plant Parameters Transient

Attachment 8-5

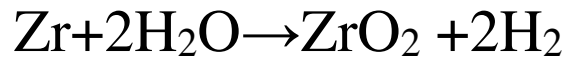


Reactor cooling	IC	3/11										3/12									
		Automatically activated (14:52)	Subsystem A	Subsystem B	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A	MOX-3A, 2A
HPCI	HPCI	Not activated (reactor water level did not drop to automatic activation levels in the time period between earthquake occurrence and SBO; no record of activation, including manual activation)																			
Depressurization	SRV	Not manually operated																			
LPCI	FP/Fire engine	DDFP field check began (16:53)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)	DDFP shut down after check (17:30)
PCV venting		Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)	Superintendent orders venting preparation (09:06)

Low pressure core injection system (LPCI) was activated

Hydrogen

Uranium fuel pellets are encased in metal tube made from zirconium alloys.

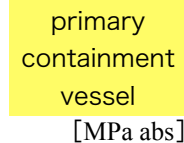


At high temperatures ($>1,200\text{ }^{\circ}\text{C}$), zirconium reacts with steam to form zirconium dioxide and hydrogen. This is an exothermic reaction, so it generates additional heat. In a severe nuclear reactor accident, the zirconium fuel cladding can react rapidly with steam, producing a large amount of hydrogen. The accumulation of this hydrogen can lead to **hydrogen explosions**.

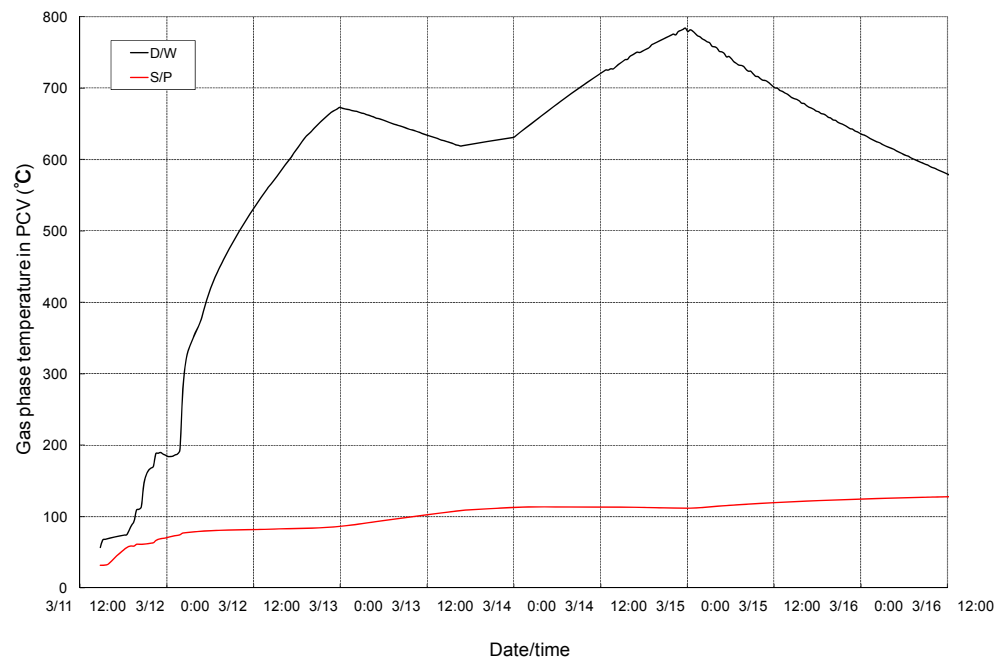
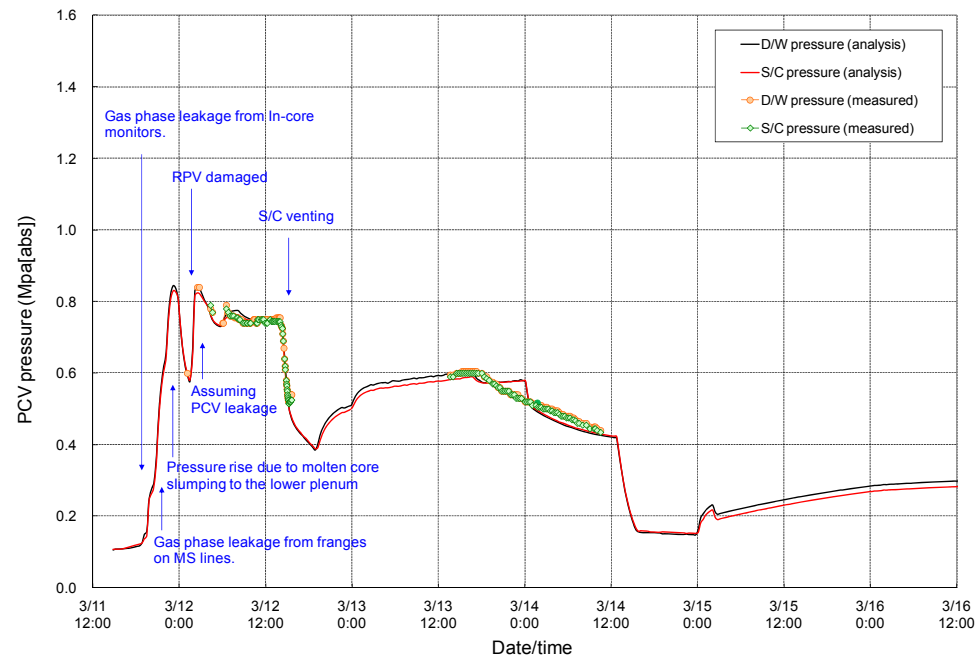


Fukushima Chuo TV

Attachment 8-5

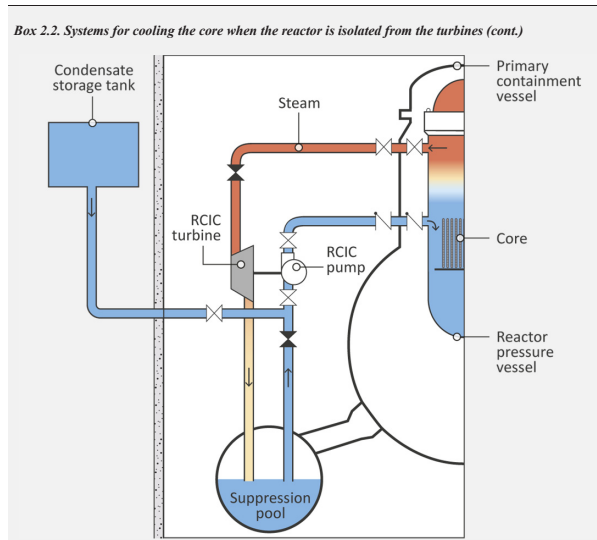


Reactor cooling	IC	Automatically activated Subsystem A (14:52) Subsystem B (15:03) MS-A, 2A opening operators confirmed (18:18) MS-A, 2A closing operation confirmed (18:25) MS-A, 2A opening operation confirmed (21:30)									
HPCI	HPCI	Not activated (reactor water level did not drop to automatic activation levels in the time period between earthquake occurrence and SRBO; no record of activation, including manual activation)									
Depressurization	SRV	Not manually operated									
LPCI	FP/Fire engine	DRFP field check began (18:55) DRFP shut down after automatic activation (17:30) Alternate injection line up began (18:35) Alternate injection line up completed (Around 20:30) DRFP activation confirmed in field (20:56) DRFP deliberation confirmed on fire engine (01:48) Deliberation on fire engine use began (02:05) Fire engine reactor fresh water injection complete (Around 04:00) Fire engine reactor fresh water injection halted (04:22) Fire engine reactor fresh water injection restarted (05:46) Injection completed and approved (14:53) Superintendant orders scawater injection (14:54) Reverse scawater injection via fire engine began (19:04) Brown injection into reactor starts (20:05)									
PCV venting		Method (17:12) Superintendant orders venting preparation (00:06) Superintendant/Kuma low orders venting, evacuation confirmed (08:03) Operators Kuma for field to perform venting operation (09:04) S/C MO valve field opening performed (09:15) S/C bypass valve field opening halted (09:32) S/C bypass valve opened from MCR (10:17 to 10:24) Temporary compressor activated (Around 14:00) D/W pressure down confirmed (14:36)									



TEPCO: Fukushima Nuclear Accident Analysis Report

Unit-3



DC power was available for about two days
The reactor core isolation cooling and the high pressure coolant injection systems using **steam driven pumps** were available.

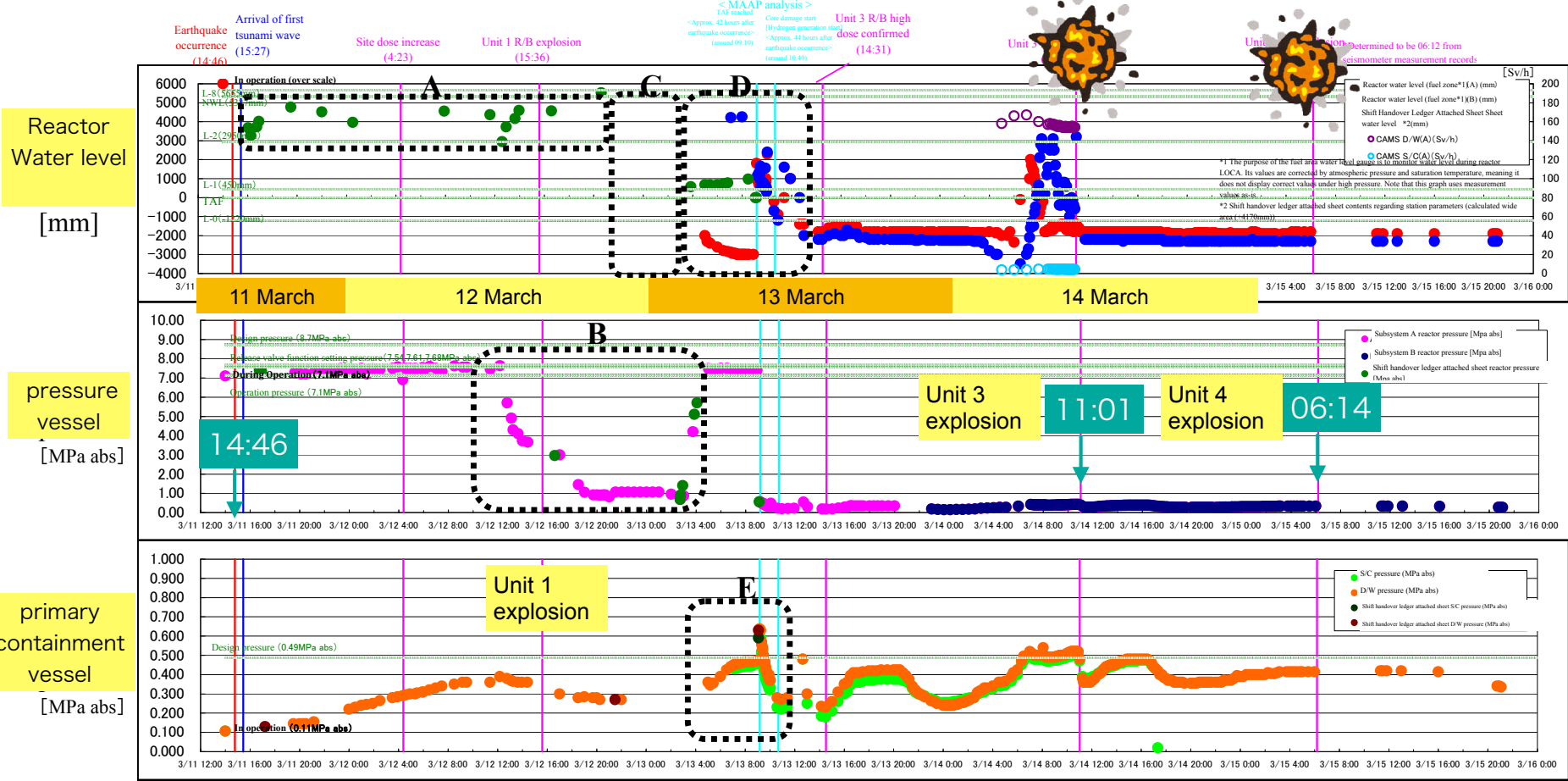
This system was very effective in reducing pressure.
Inlet steam pressure to the pump turbine dropped below the pump's specifications.
The operators decided to shut down the system after about 14 hours.

operators prepared to inject sea water into the reactor vessel.
However, **due to the high reactor pressure**, it was not possible to inject sea water until the reactor was depressurized.
Because of the delay in injecting sea water into the reactor vessel, the water level continued to drop close to the top of the fuel.

**Unit 1 explosion disturbed the water injection work.
Too low for turbine but too high for water injection**

Fukushimda Daiichi Unit 3 Plant Parameters Transient

Attachement 8-15



HPCI	RCIC	Manual AutomaticManual shutdown (15:05) (15:25) (16:03)	Automatic shutdown (11:36)
	HPCI	Automatic shutdown (12:35)	Manual shutdown (02:42)
Depressurization	SRV	SRV rapid depressurization start (around 09:08) SRV opened, depressurization continued	
LPCI	FP/DDFP	Automatic Manual start shutdown (11:13) (11:36)	S/C spray start (05:00) D/W spray (07:43) stopped (08:00) D/W spray (08:40) stopped (09:10)
	FP/Fire engine	Superintendent orders deliberation (17:12)	Injection line assembly complete reported (03:40) Broom-added freshwater injection start (9:25) stopped (12:20) Seawater injection start (11:15) stopped (01:10) Seawater injection (03:20) Seawater injection (around 15:30)
PCV venting		Superintendent orders venting preparation (17:30)	Superintendent orders venting (06:10) MO valve assembly complete (08:35) S/C isolation valve open, venting line confirmed (8:41) D/W isolation valve confirmed (around 09:20) closed (11:17) S/C isolation valve confirmed (12:30) Temporary S/C isolation valve installed, deemed open (around 19:00) (21:10) S/C bypass valve S/C bypass valve opening (05:20) continued open (8:10)
			S/C spray valve S/C spray valve opening (16:00) and bypass valve isolation valves from here onward opening (16:05) Opening operation performed multiple times from here onward

Unit-4

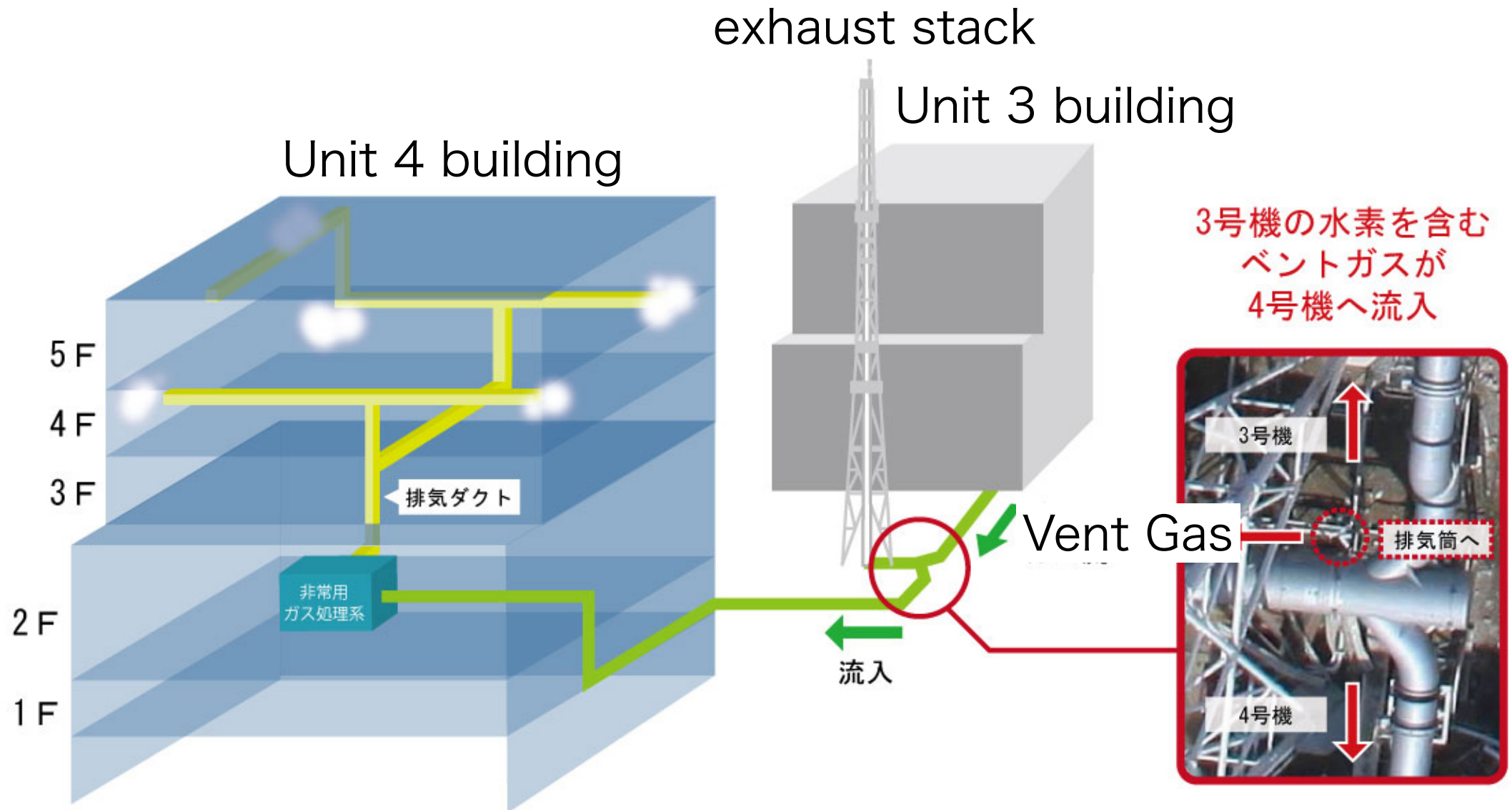
Pressure vessel was empty for maintenance.
All fuels were temporary at the **spent fuel pool**.

Unit-4 building also caused **explosion**.

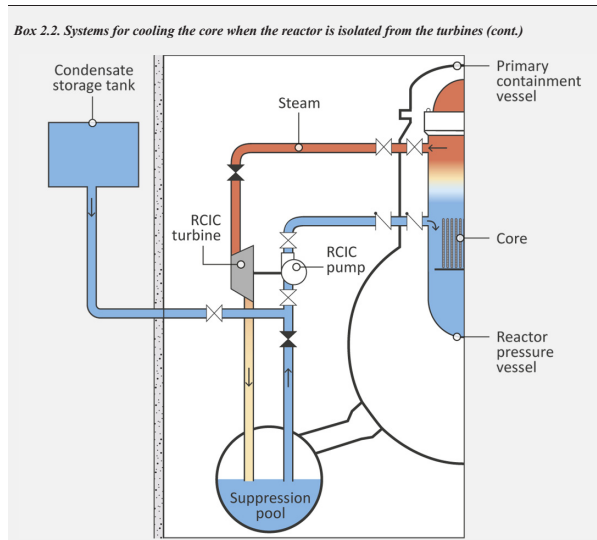
Why?



Unit-4



Unit-2



DC power was not available. However, the reactor core isolation cooling and the high pressure coolant injection systems using **steam driven pumps** were working.

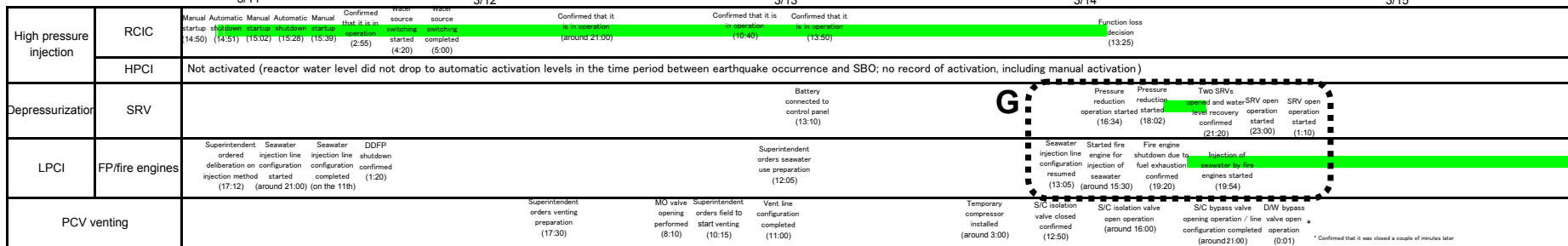
It worked three days and lost.

Water injection and venting were prepared but lost by explosion of unit 3.

No vent

**Pressure of Containment vessel was more than 0.7 MPa
(Design pressure is 0.47 MPa)**

Reference 8-12



Unit-2

Danger of explosion of containment vessel.

Direct ejection of Radio Activities

Pressure decreased

=> direct Leak from containment vessel

As the result, unit 2 ejected more RI than the others.

**No Hydrogen explosion.
Blowout panel was opened by
unit-1 explosion.**



Spent Fuel Pool

Table 1 SFP Fuel Storage Conditions

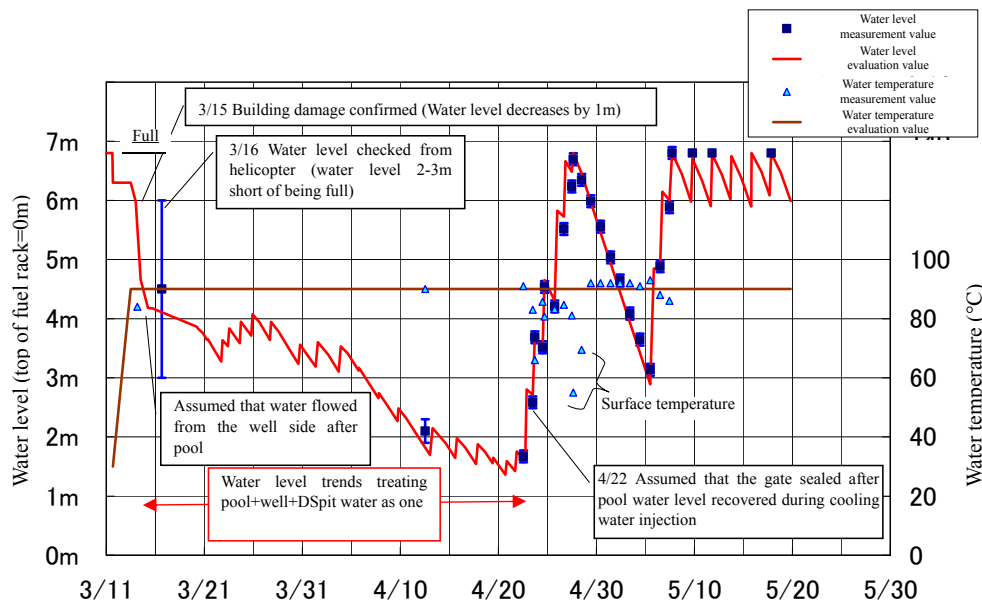
	Number of fuel assemblies stored (numbers in parenthesis indicate new fuel assemblies)	Storage capacity
Unit 1 SFP	292 (100)	900
Unit 2 SFP	587 (28)	1240
Unit 3 SFP	514 (52)	1220
Unit 4 SFP	1331 (204)	1590

Table 2 SFP Decay Heat

	Decay Heat (MW)	
	When the accident occurred (3/11)	3 months after the accident (6/11)
Unit 1 SFP	0.18	0.16
Unit 2 SFP	0.62	0.52
Unit 3 SFP	0.54	0.46
Unit 4 SFP	2.26	1.58

Spent Fuel Pool

**It became urgent problem.
It has no containment vessel. Damage of spent fuel causes
huge amount of RI ejection.
In the worst case, millions of people must evacuate.....**



*Water level evaluation considers that water flowed from the well/DSPit side to the pool side since the reactor well side was completely full of water at the time the earthquake occurred.

Figure 2 Unit 4 SFP evaluation results

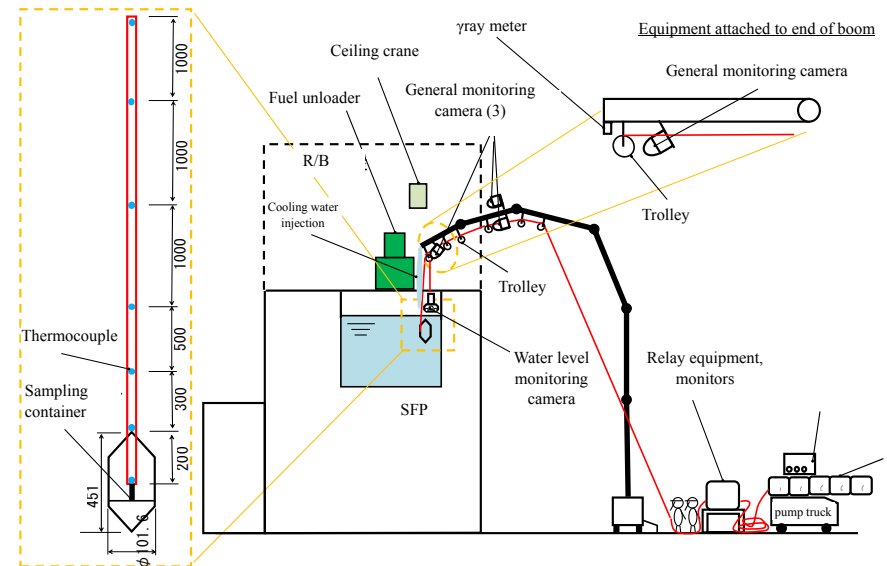
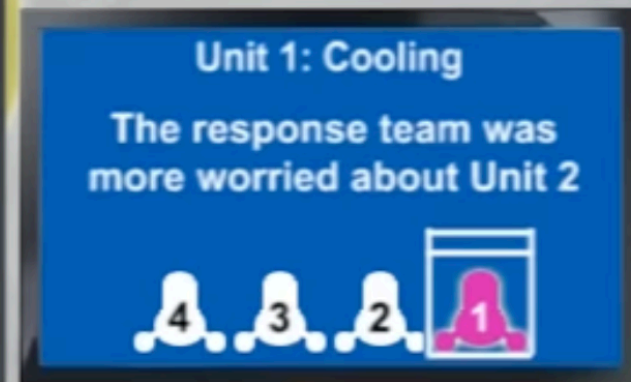
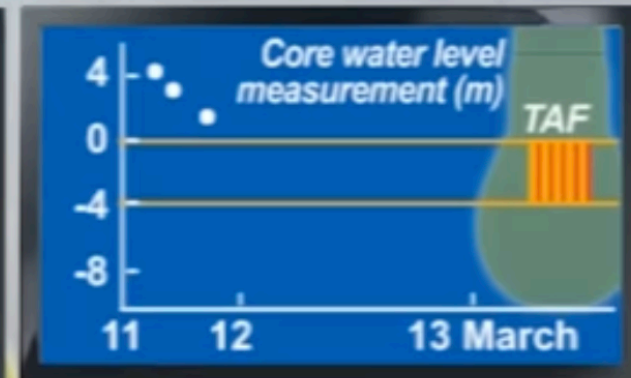
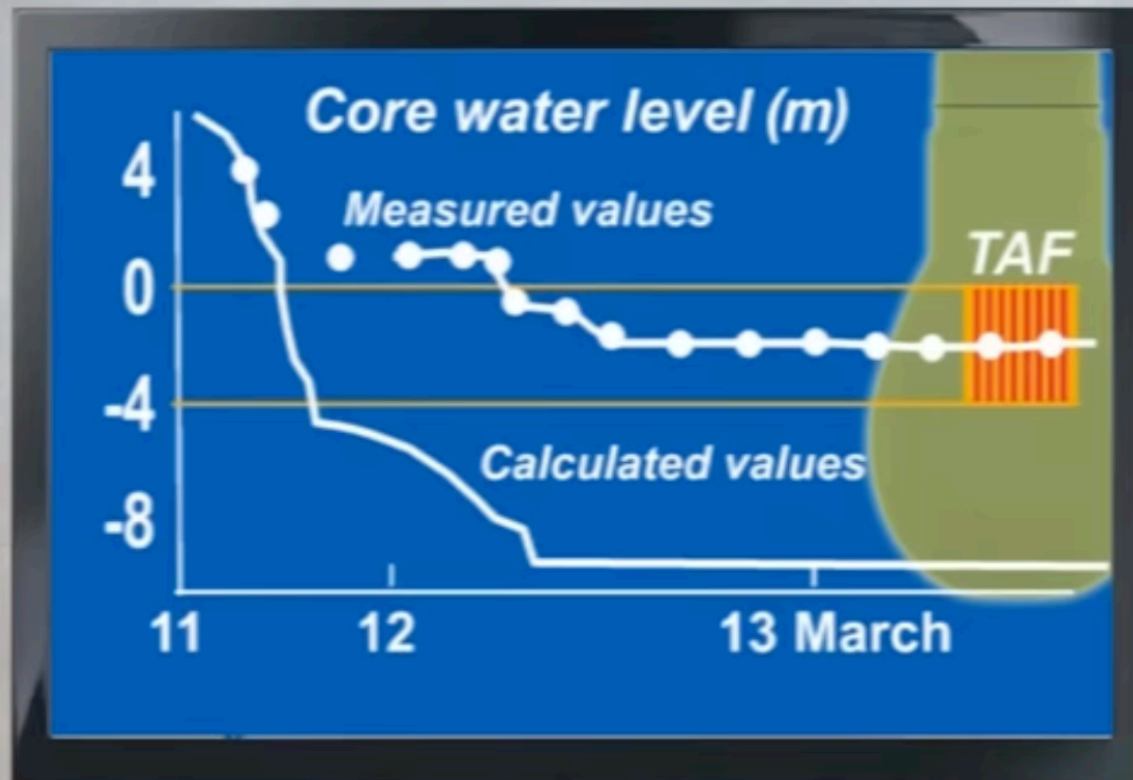
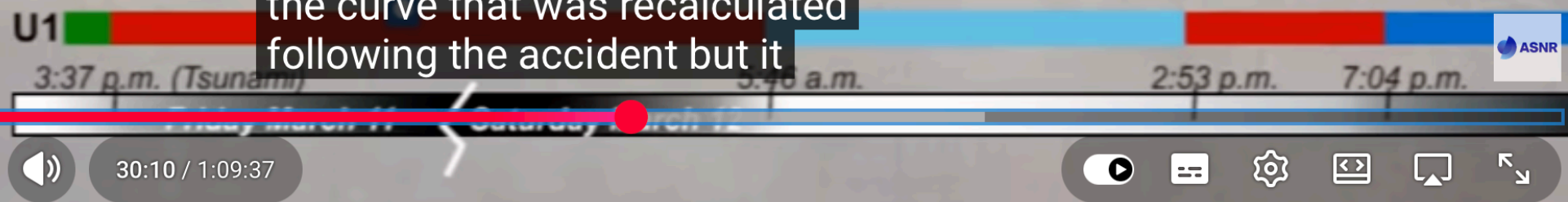


Figure 10 Method for measuring SFP water level and water temperature using a concrete pump truck

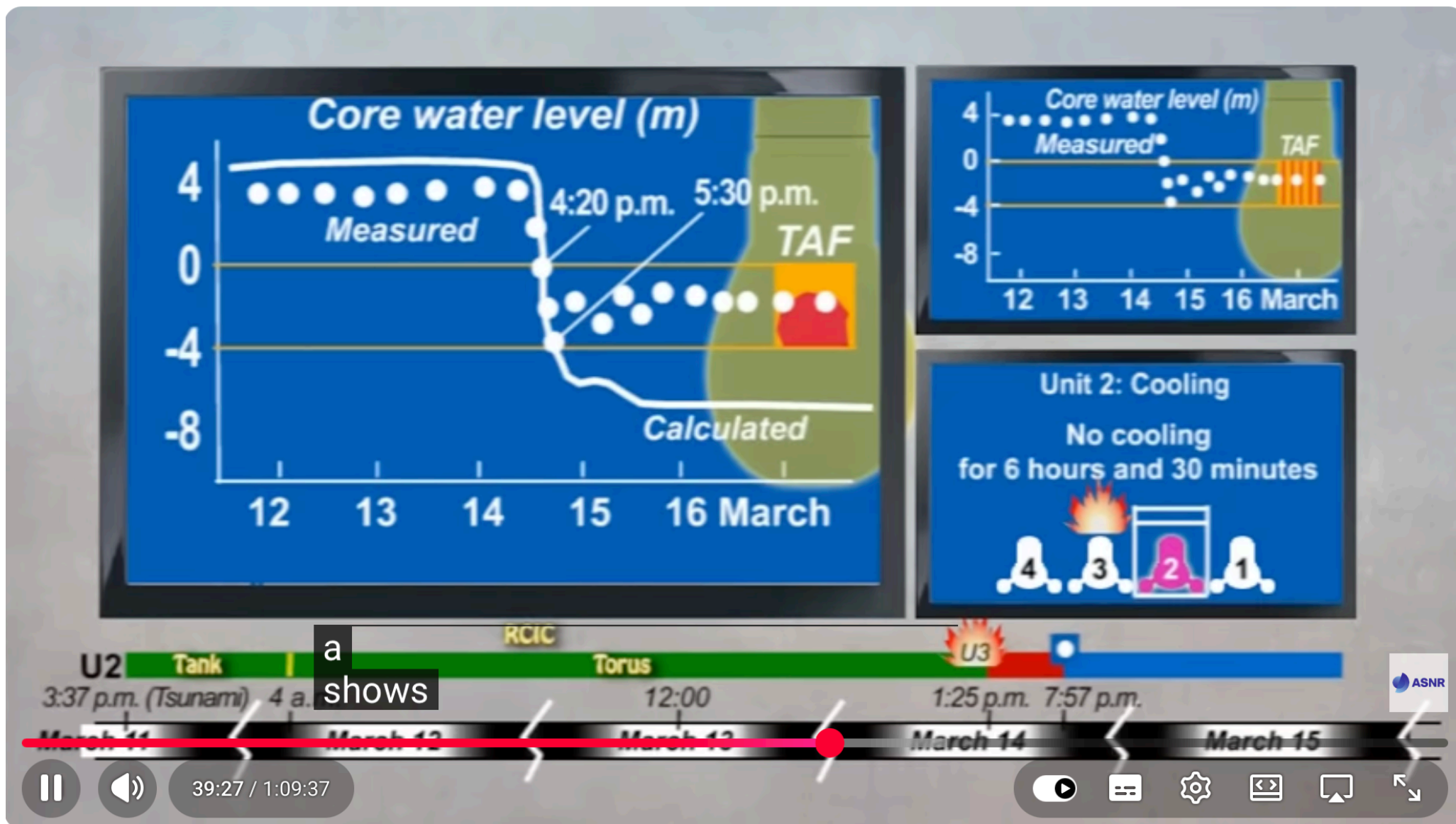


the curve that was recalculated following the accident but it



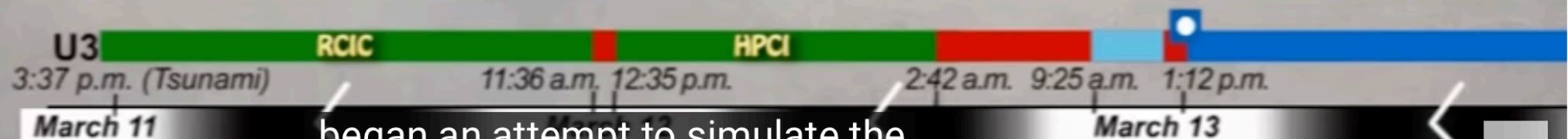
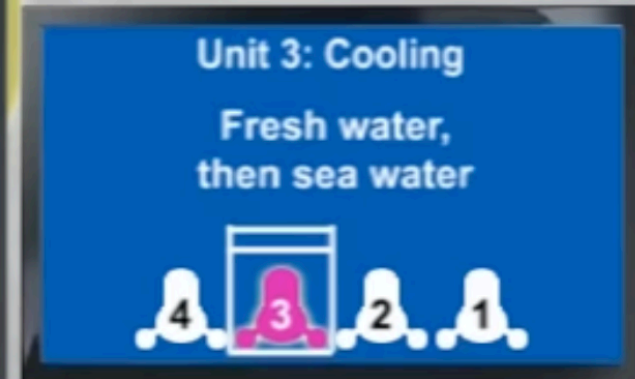
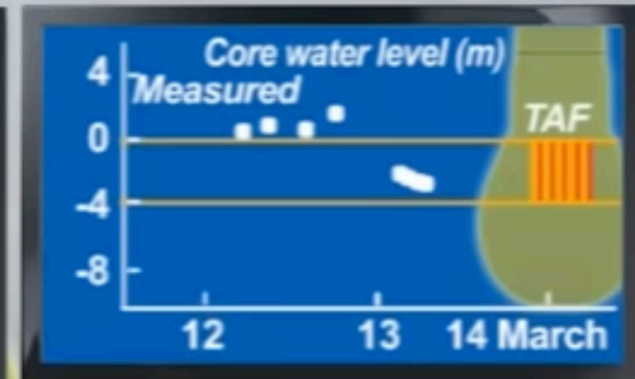
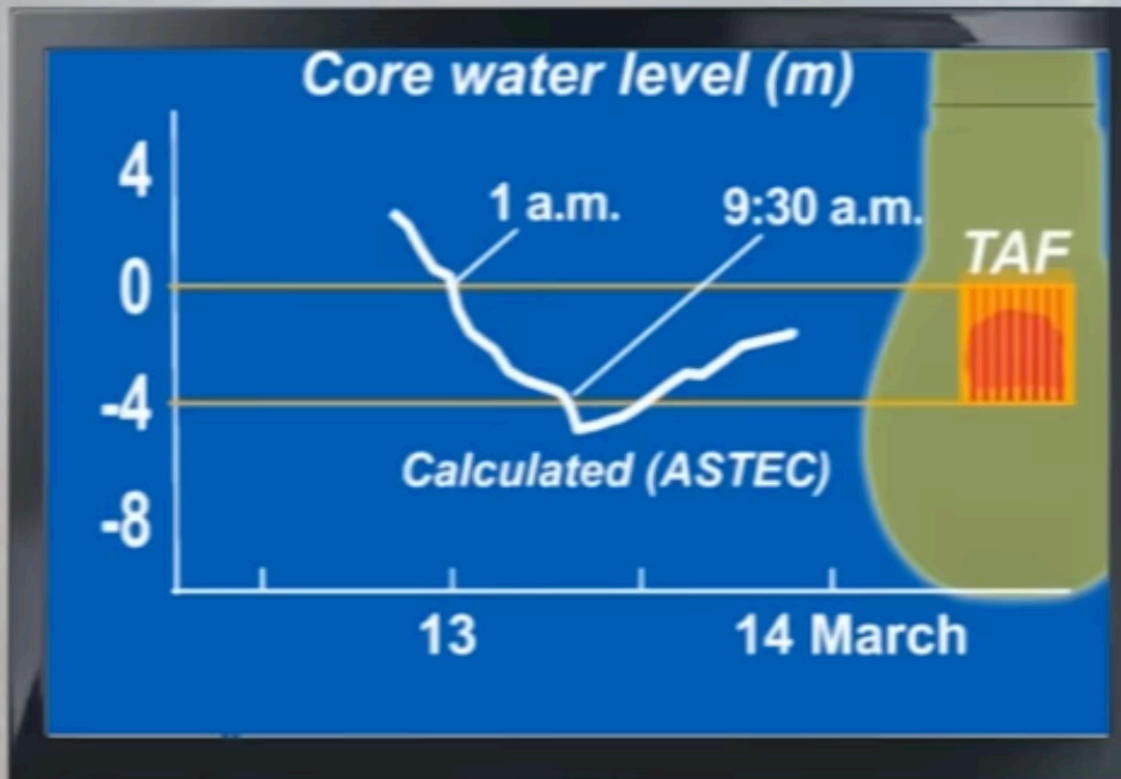
IRSN: [Understanding the accident of Fukushima Daiichi](https://www.youtube.com/watch?v=ZJwg_McDGSi)

https://www.youtube.com/watch?v=ZJwg_McDGSi (70 min.)



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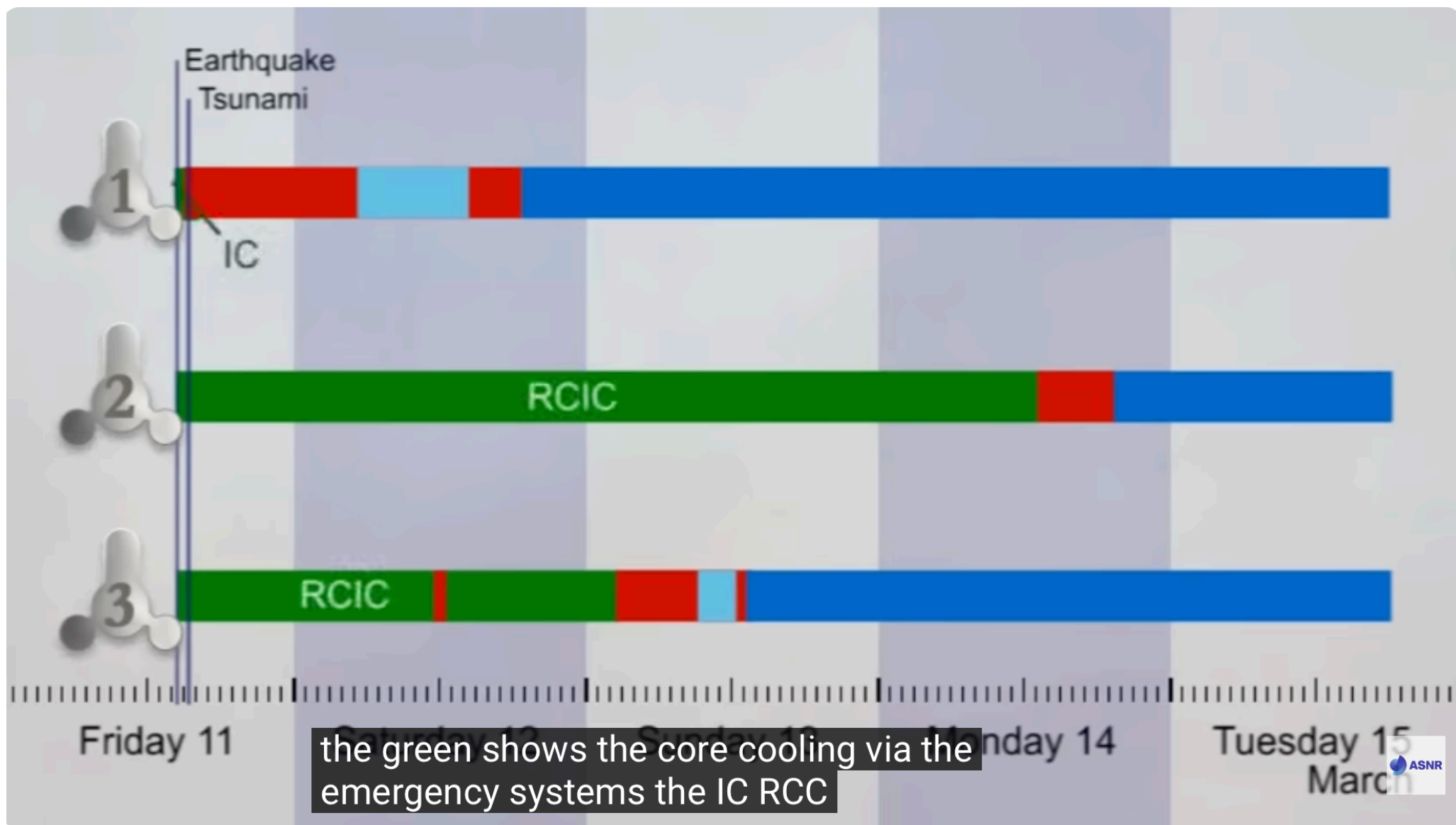
https://www.youtube.com/watch?v=ZJwg_McDGSI (70 min.)



began an attempt to simulate the accident scenario at

IRSN: [Understanding the accident of Fukushima Daiichi](https://www.youtube.com/watch?v=ZJwg_McDGS1)

https://www.youtube.com/watch?v=ZJwg_McDGS1 (70 min.)



IRSN: [Understanding the accident of Fukushima Daiichi](https://www.youtube.com/watch?v=ZJwg_McDGS1)

https://www.youtube.com/watch?v=ZJwg_McDGS1 (70 min.)

What we should learn

Probability of an error

= System failure probability

× Backup system failure probability

× Second backup system failure probability

× Third backup system failure probability

It should be extremely small

However it is not independent

the emergency diesel generators, battery rooms and switchgear were damaged by Tsunami.

Situation of neighboring units made the situation worse.

They are too close each other.