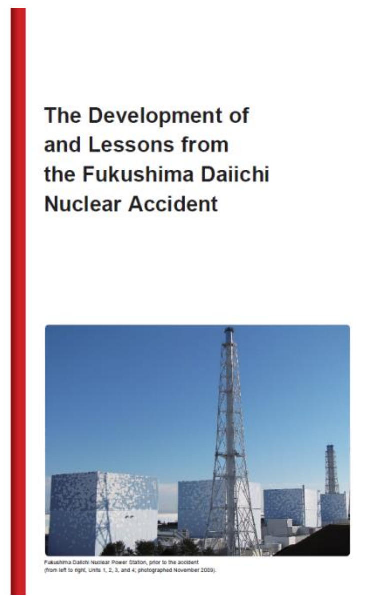
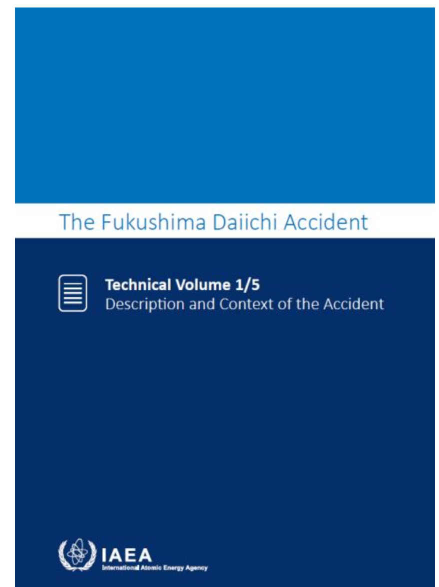
2. BOILING WATER REACTOR
AND FUKUSHIMA DAIICHI NUCLEAR DISASTER

References
1. The Development of and Lessons from the Fukushima Daiichi Nuclear Accident
2. The Fukushima daiichi accident Technical volume 1: description and context of the accident





Nuclear Thermal Hydraulic Engineering Lab.

❖ **Overall**

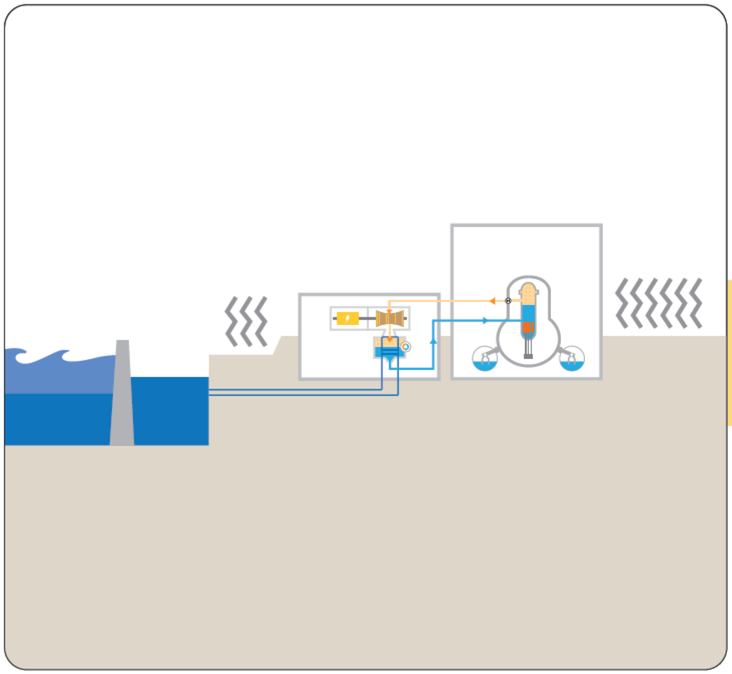

IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE
Enhancing nuclear safety

Fukushima Daiichi Nuclear Disaster

Safety Philosophy

- Nuclear reactors are designed to maintain safety based on a philosophy of
  - Shutting down, Cooling down, Confining inside

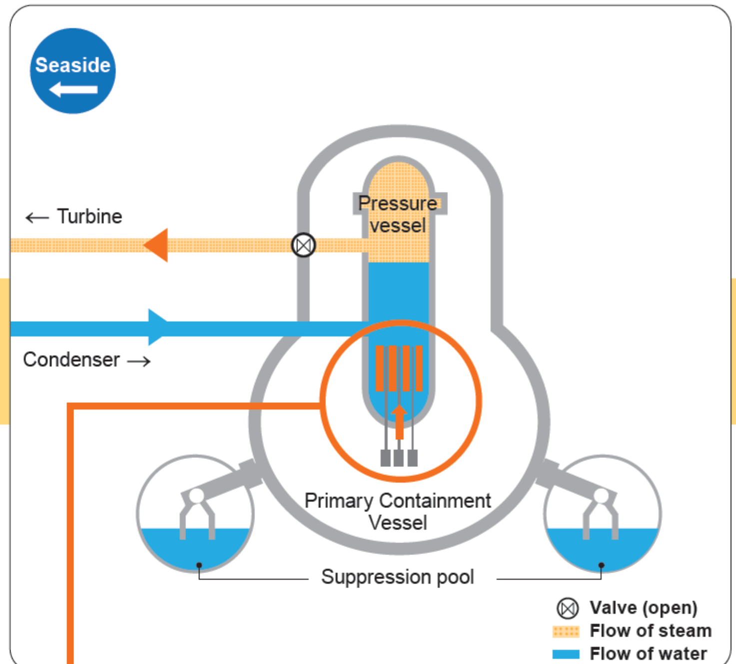
0. Protect



Design mindful of the height of tsunami and strength of earthquakes

Elements on the site of a power station are designed with provisions for the onslaught of conceivable earthquakes and tsunami.

1. Shutting down



Emergency shutting down through insertion of control rods

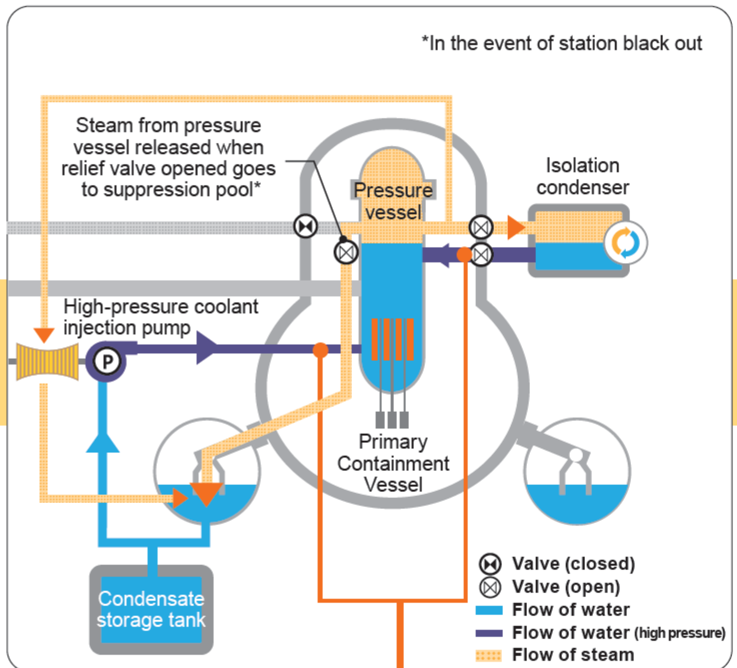
Control rods are swiftly inserted in emergencies such as major earthquakes and the reactor undergoes an emergency shutting down.

Fukushima Daiichi Nuclear Disaster

Safety Philosophy

- Nuclear reactors are designed to maintain safety based on a philosophy of
  - Shutting down, Cooling down, Confining inside

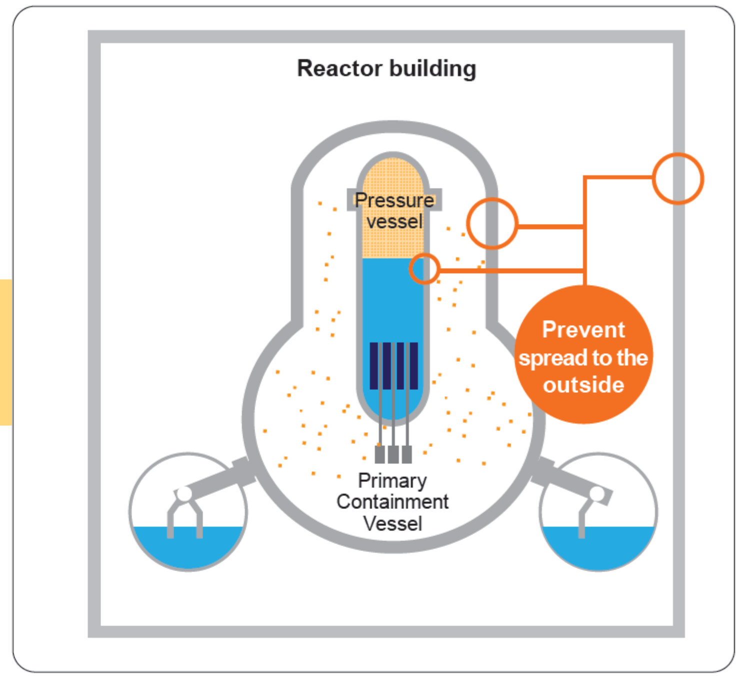
2. Cooling down



Cooling of the pressure vessel
through injection and circulation of water

Equipment for sending a large amounts of water into the reactor is installed so that the fuel does not rise to high temperatures and the reactor core is not heating while empty.

3. Confining inside



Radioactive materials are confined inside
with pressure vessels,
primary containment vessels, and the like

Protective walls are installed to confine inside radioactive materials so that they do not get outside even in an accident.

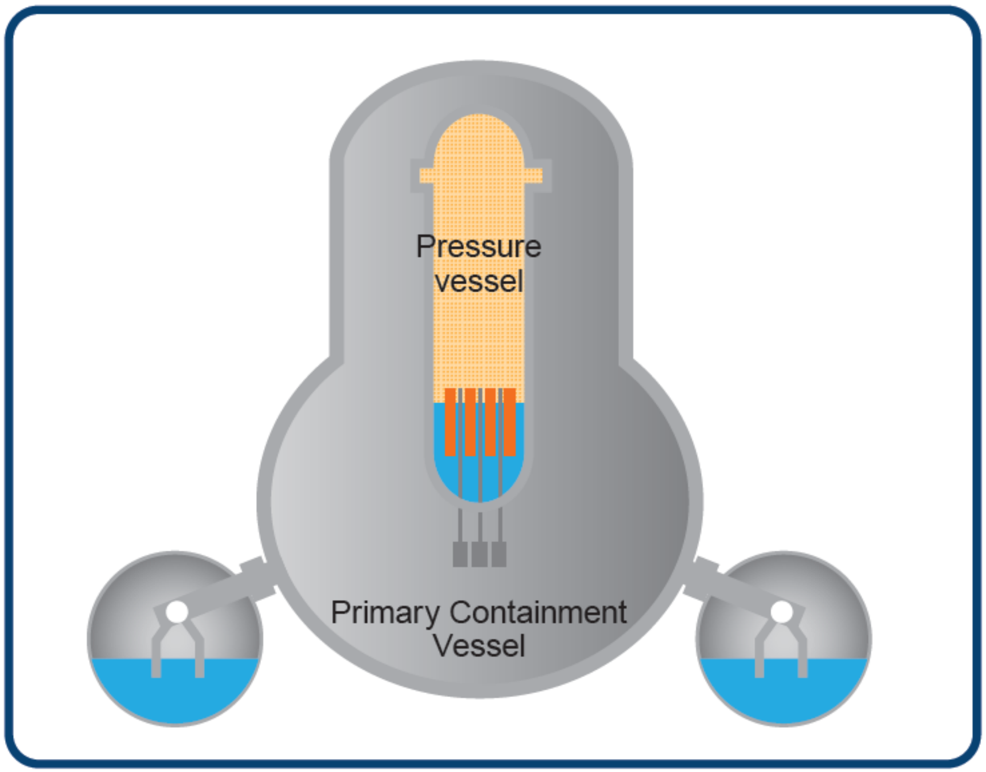
Safety Philosophy

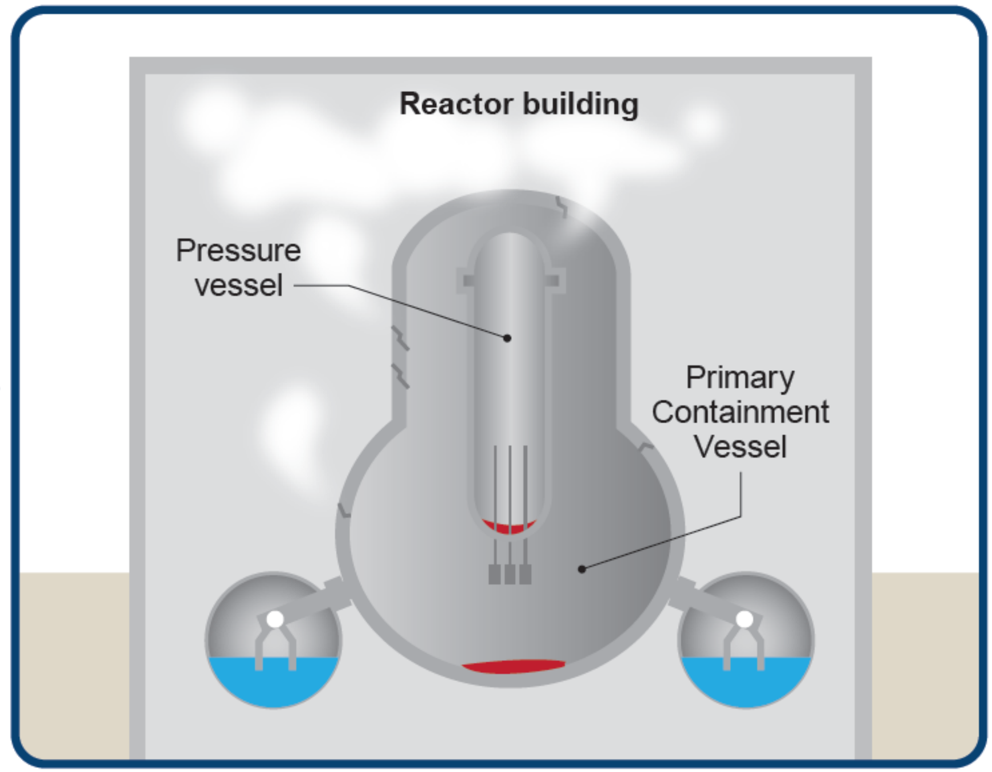
- If cooling fails

If cooling fails...

Water level in the pressure vessel falls, leading to core damage.

If cooling cannot be performed, it becomes difficult to continue keeping material confined inside.
When confining inside fails, it leads to the release of hydrogen and radioactive materials to the outside.





Cooling system of Fukushima Daiichi Units 2 and 3

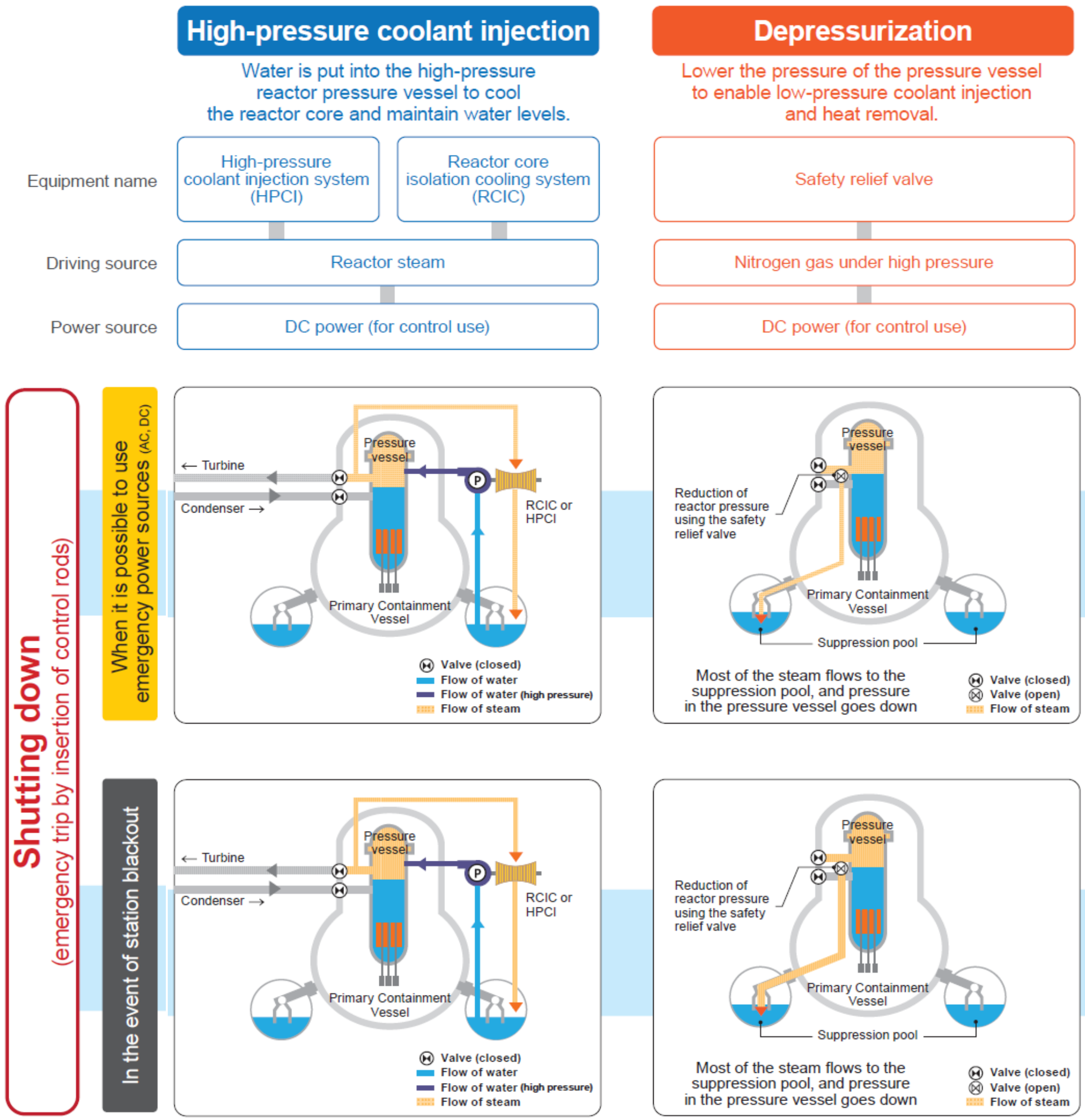
- The cause of the accident at Fukushima was the failure to “Cooling Down”.

- What does it mean to "cool" a nuclear reactor?
  - The objective of "cooling" a reactor is
    - To achieve a state wherein the reactor is stabilized at "cold shutdown“
  - Cold shutdown
    - Condition in which the temperature of the water within the reactor is below 100°C

- Decay heat removal capability should be provided with
  - Coolant injection
  - Depressurization
  - Heat removal

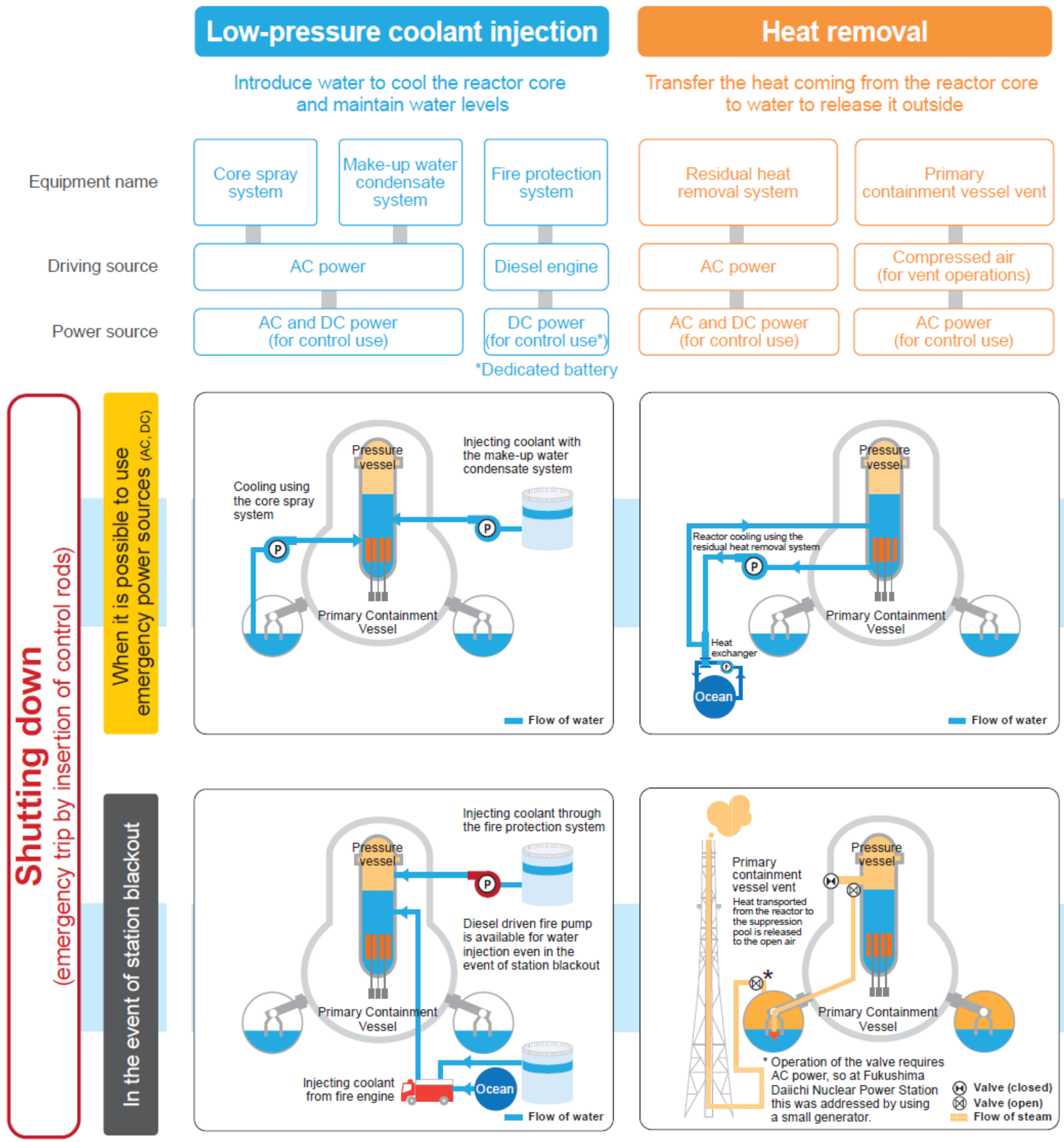
Cooling system of Fukushima Daiichi Units 2 and 3

- HPCI/RCIC
  - Passive cooling system
  - Available in the event of SBO
- ADS
  - Passive system
  - Available in the event of SBO



Cooling system of Fukushima Daiichi Units 2 and 3

- LPCI/LPCS
  - Active system
  - Not available in the event of SBO
  - Fire protection system was prepared.
- RHRS
  - Active system
  - Not available in the event of SBO
- PCV Vent
  - AC power is required.



Review

- **Protection measures**
  - Shut-down system
  - Cooling system
    - Coolant injection
  - Containment system

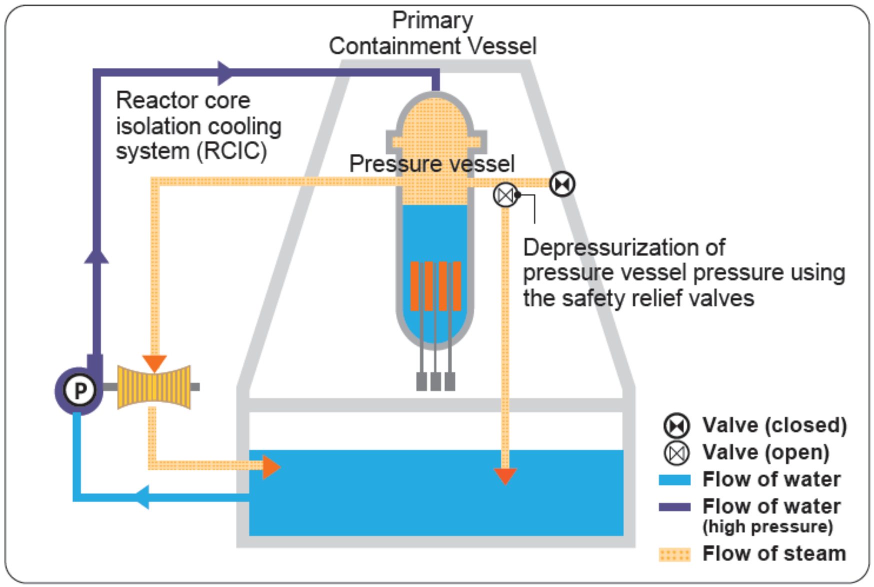
- **Normal shut-down**
  - High pressure cooling:
  - Low pressure cooling:

- **Emergency shut-down**
  - High pressure cooling:
  - Depressurization:
  - Low pressure cooling:

Operation of cooling system in Fukushima Daiini Power Station

High-pressure coolant injection

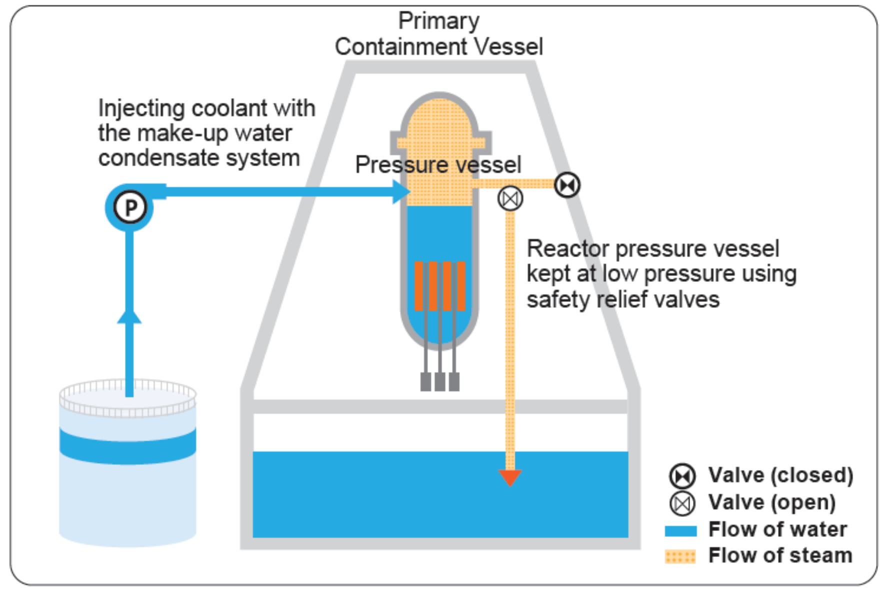
Depressurization



Water level is maintained by the HPCI system (or RCIC system), and pressure in the pressure vessel is lowered using the safety relief valve.

Low-pressure coolant injection

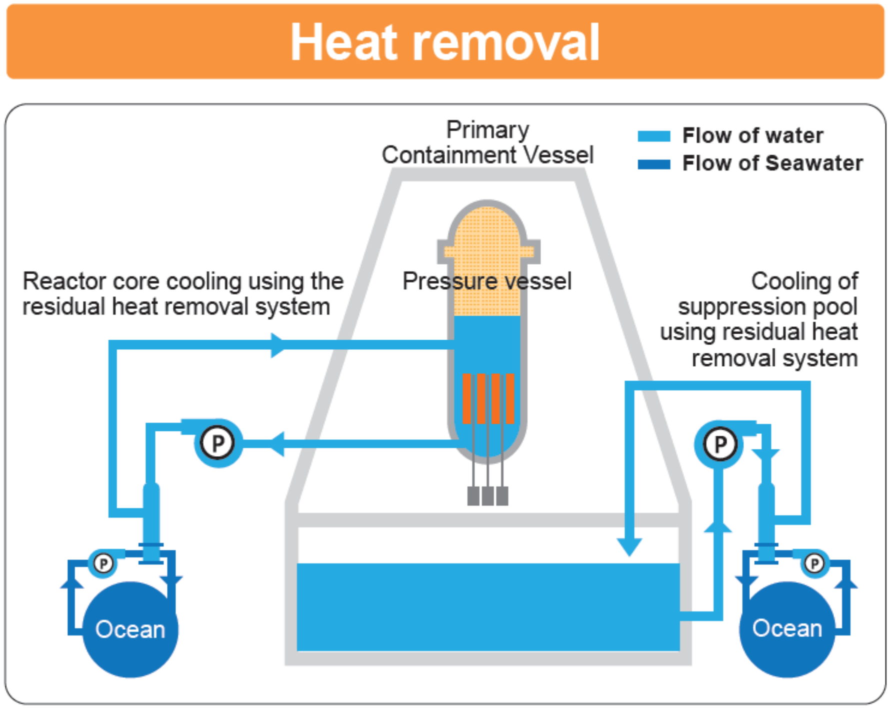
Depressurization



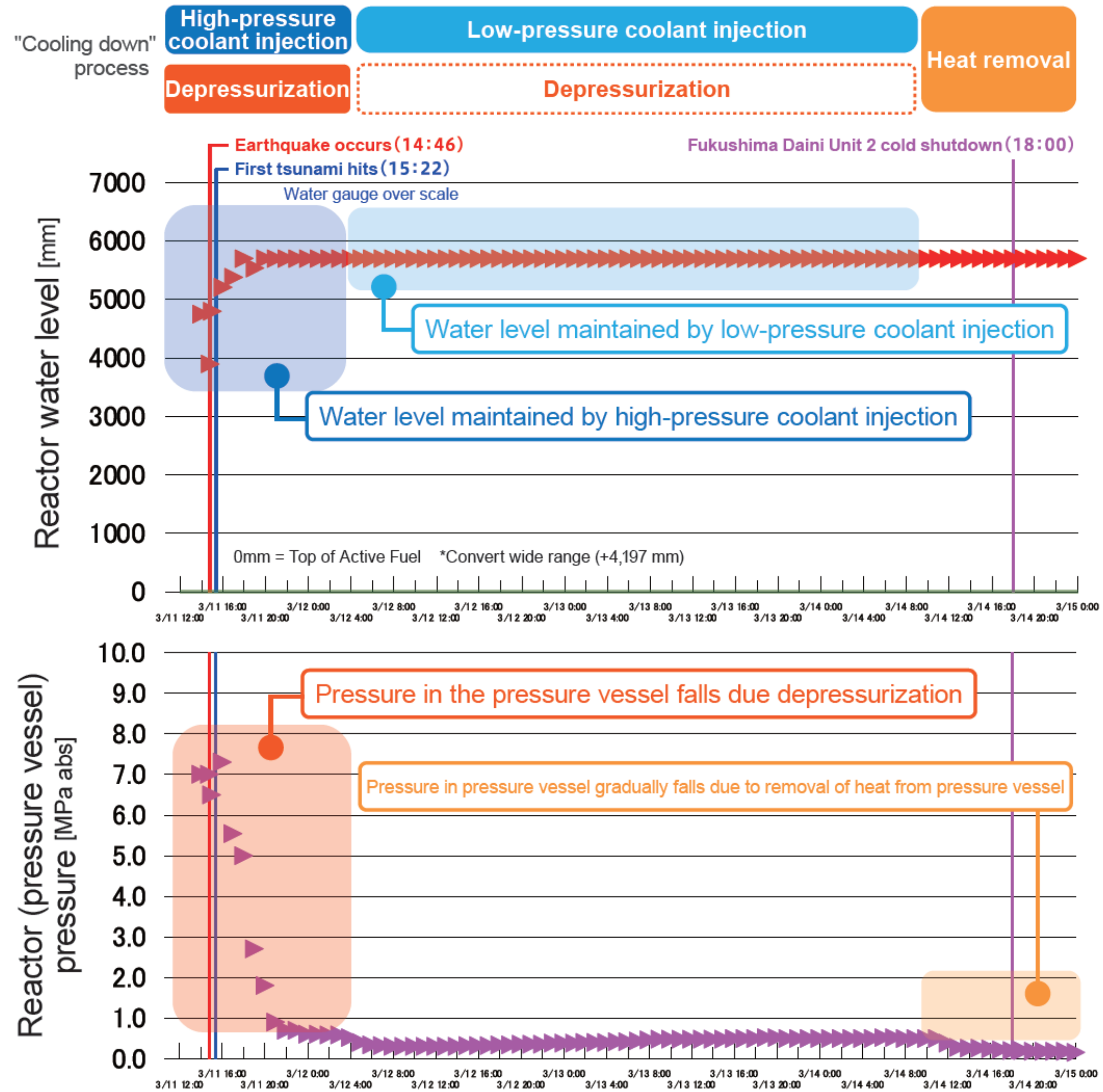
Water level is maintained through low-pressure coolant injection (make-up water condensate system), and pressure in the primary containment vessel is raised by transferring steam from the pressure vessel to the primary containment vessel.

Fukushima Daiichi Nuclear Disaster

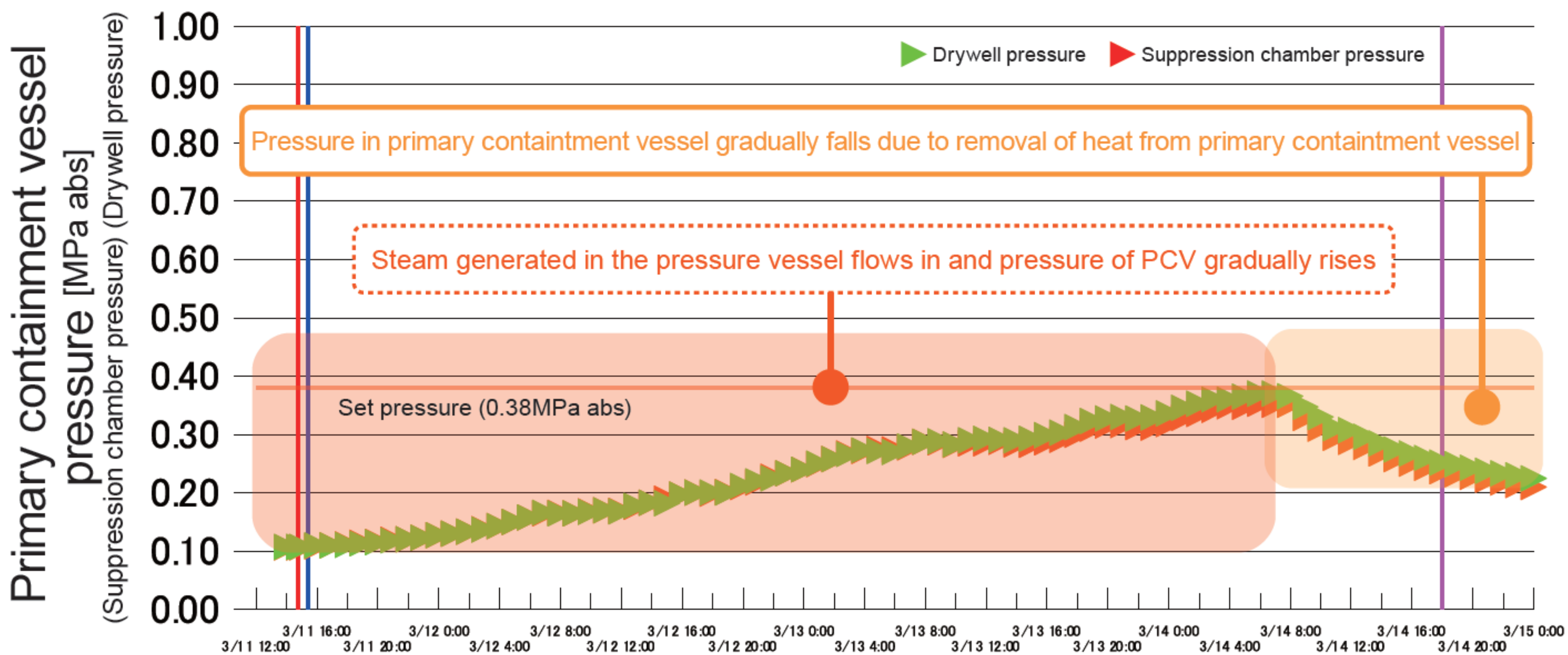
❖ Operation of cooling system in Fukushima Daiini Power Station



By starting heat removal, the flow of steam from the pressure vessel is halted while the primary containment vessel cools and its pressure gradually falls.



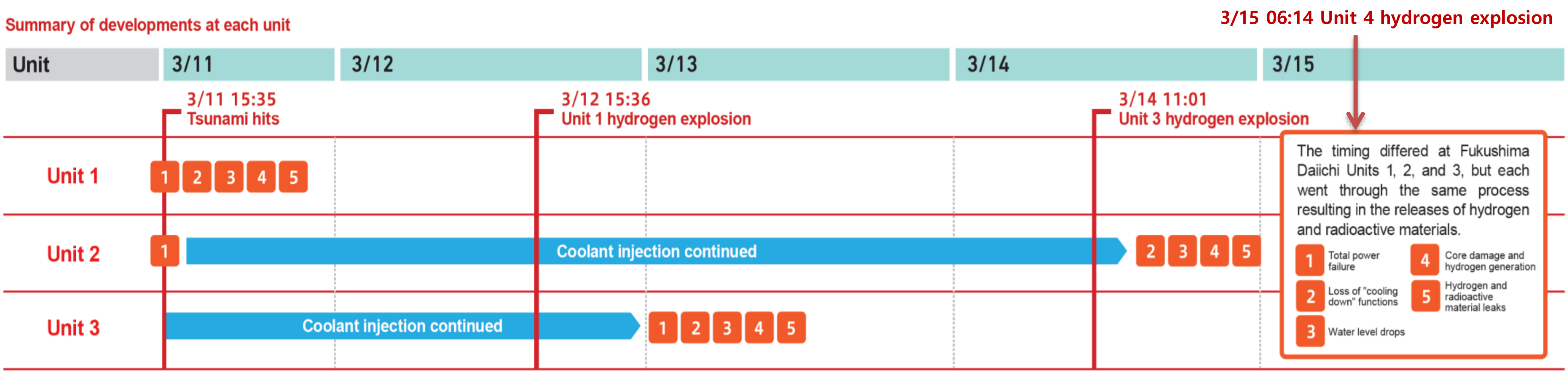
❖ Operation of cooling system in Fukushima Daiini Power Station



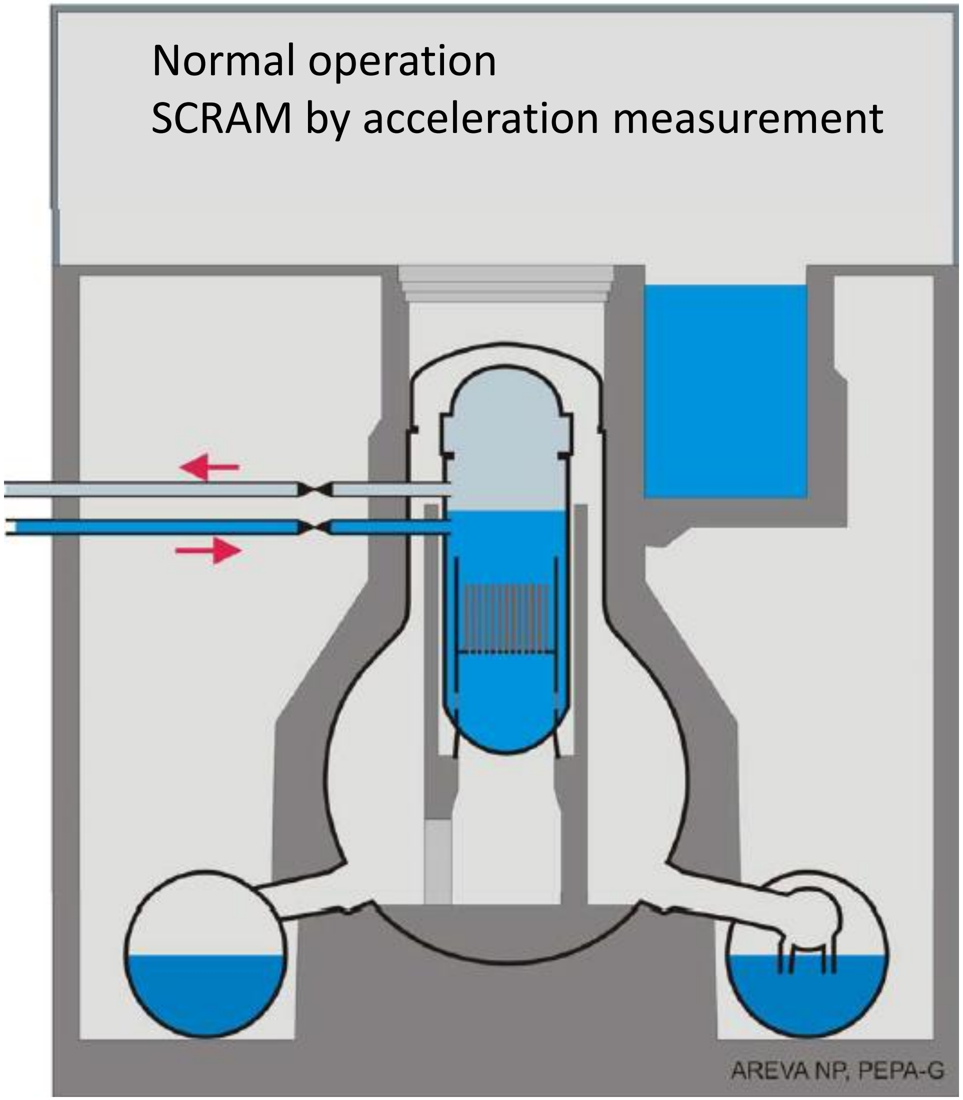
Fukushima Daiichi Nuclear Disaster

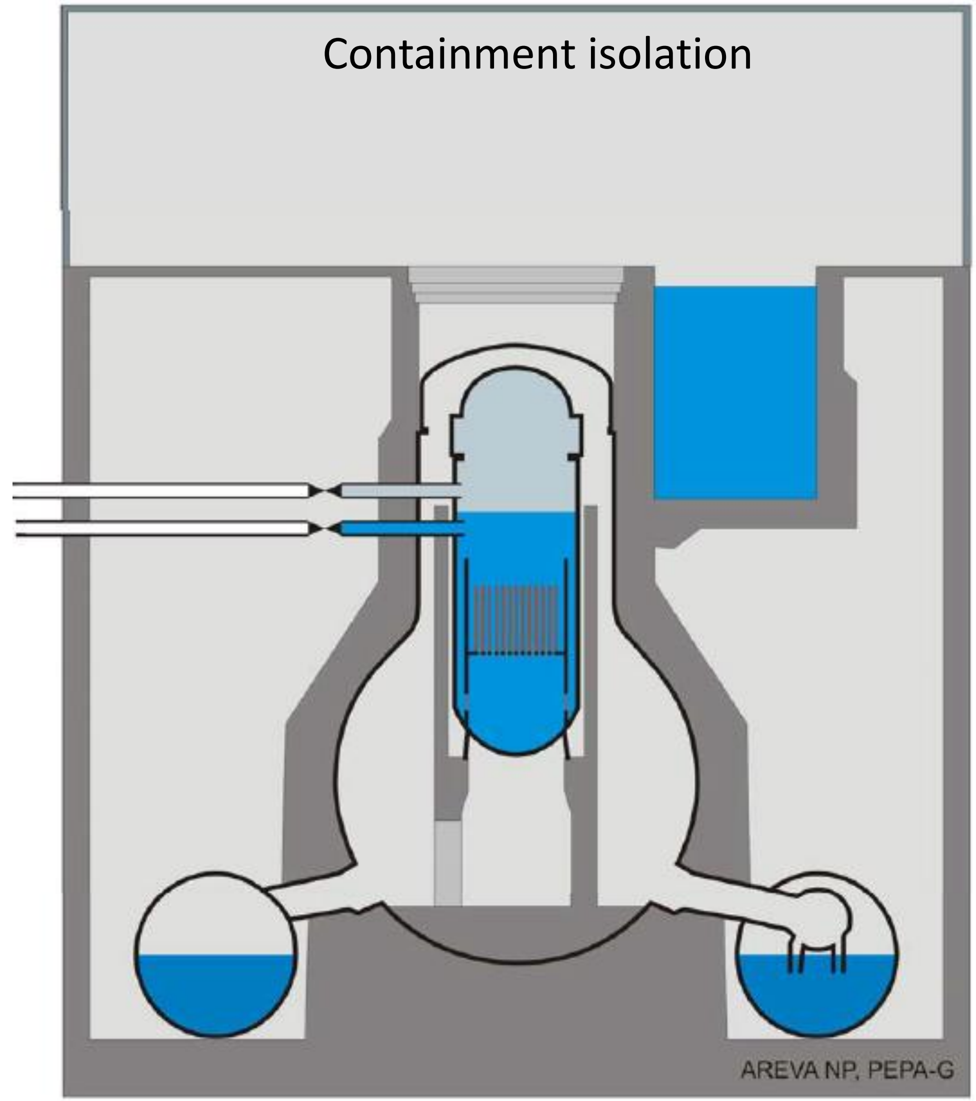
Development of the accident

- Loss of cooling function ⇐ loss of power sources
  - Water in RPV ran out.
  - Fuel temperature rose.
  - Hydrogen was generated in large quantities.
  - Fuel melted.
  - RPVs were damaged.
  - PCVs were damaged.
  - Both hydrogen and radioactive materials were released into the reactor buildings.



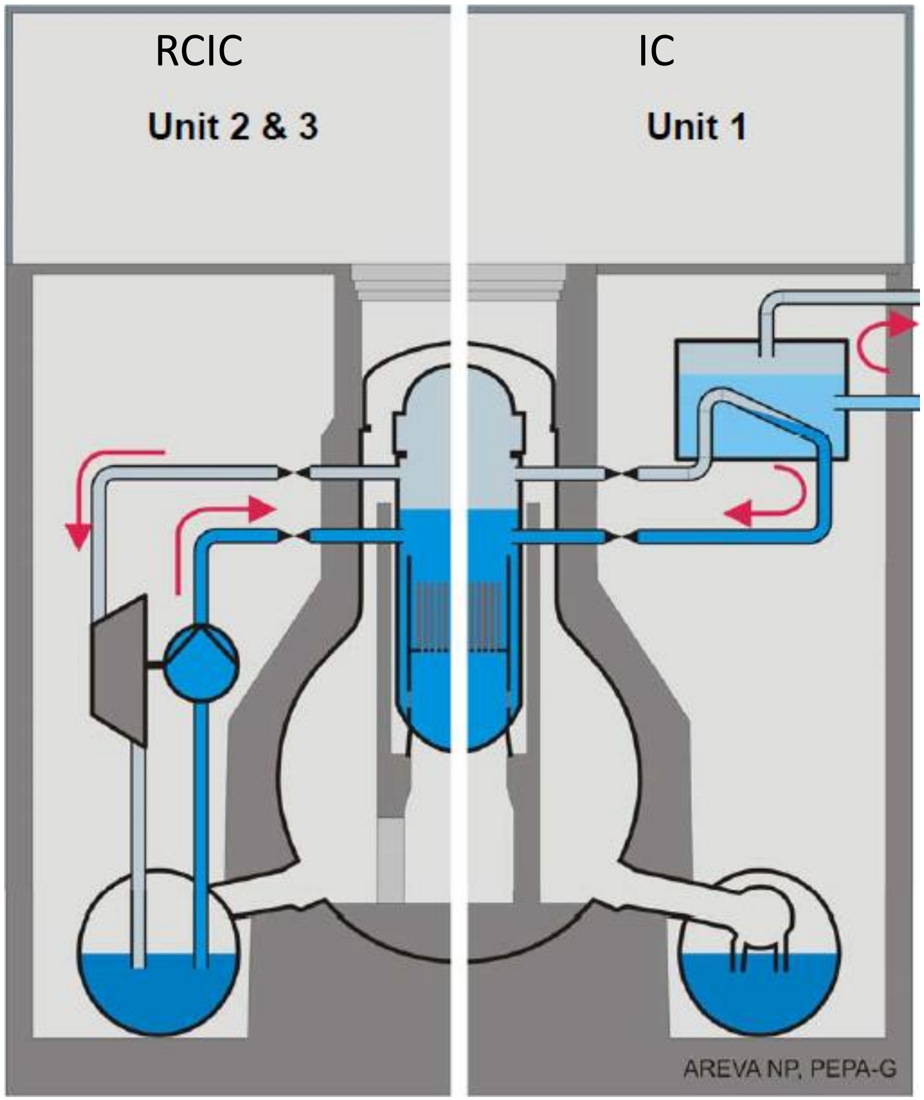
Development of the accident





Fukushima Daiichi Nuclear Disaster

❖ Development of the accident

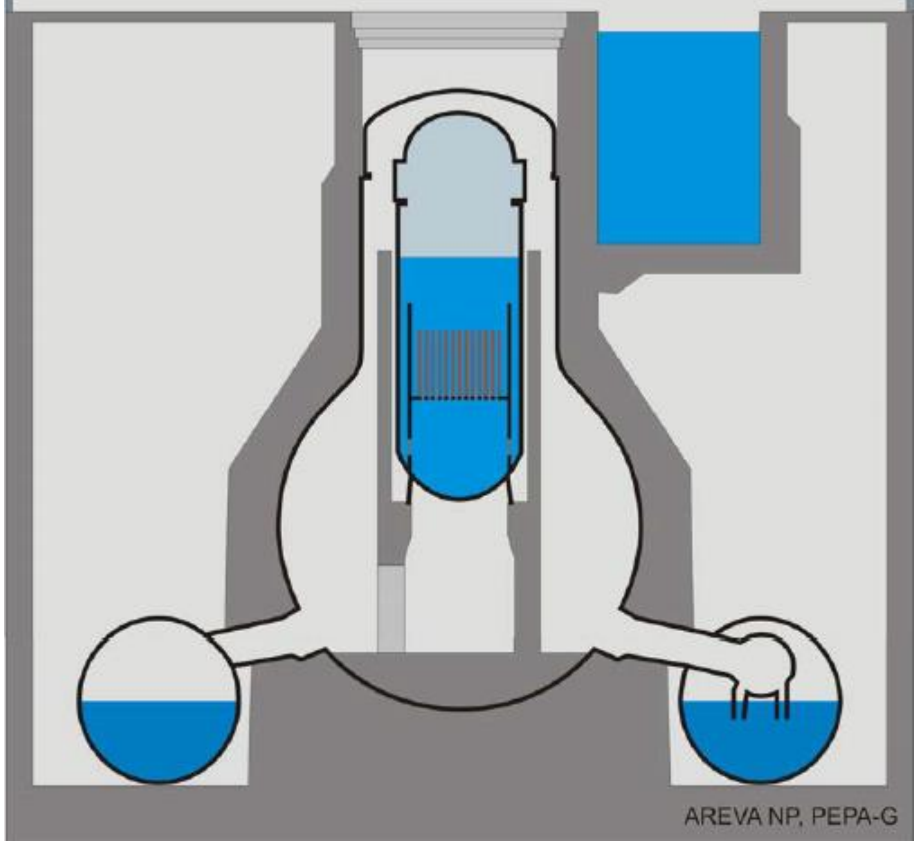


Tsunami waves

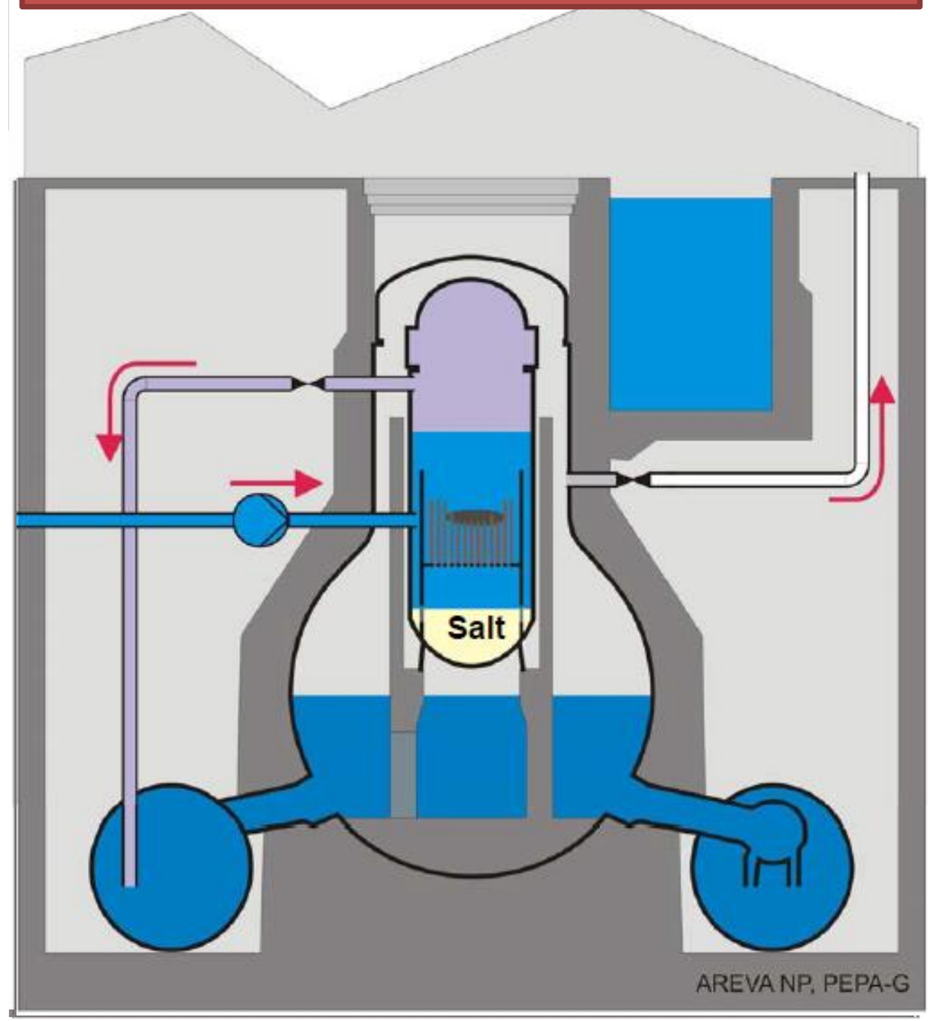
Fukushima Daiichi Nuclear Disaster

Development of the accident

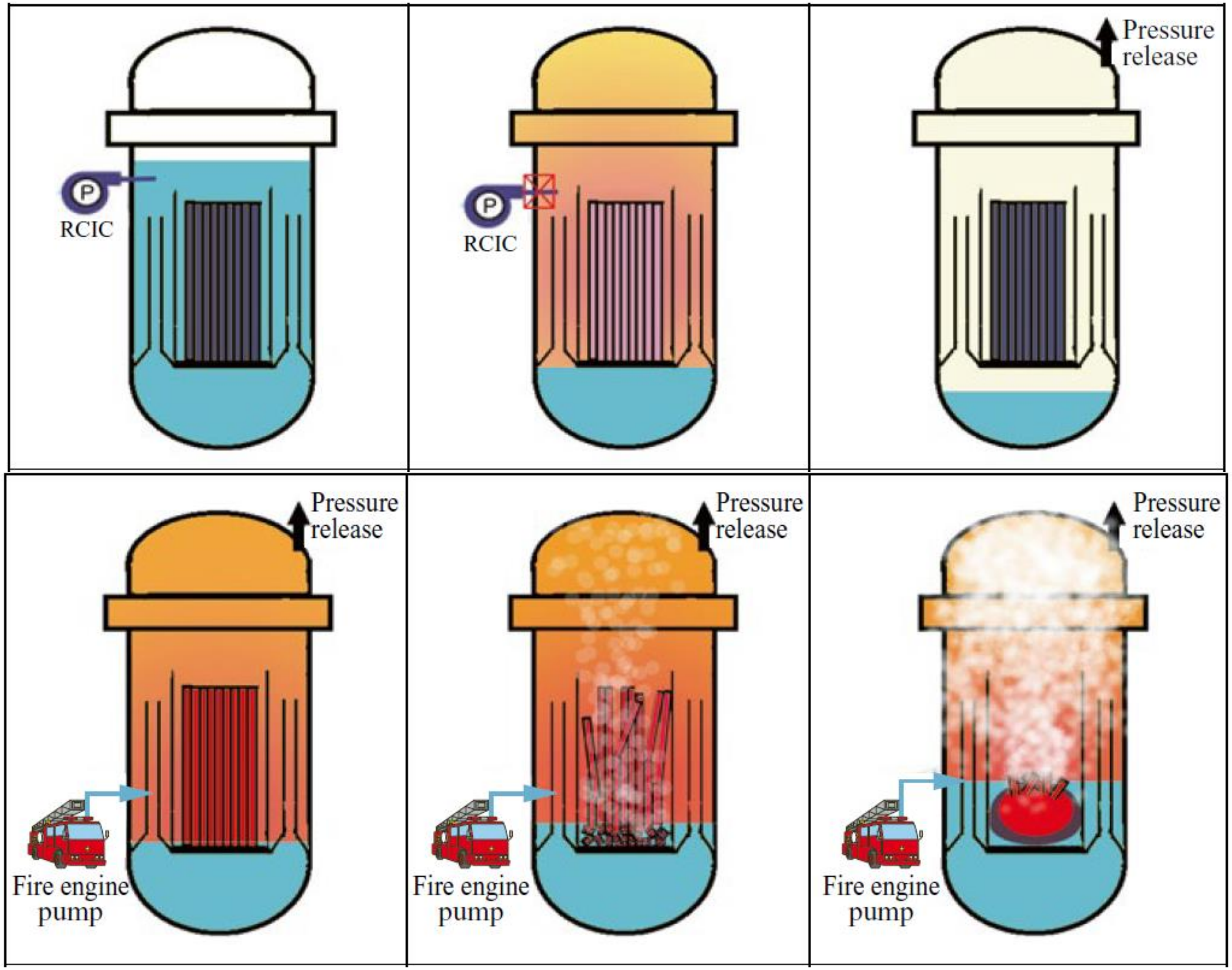
- Decay Heat produces steam in Reactor pressure Vessel
- Pressure increase



Core degradation stopped by sea water injection.



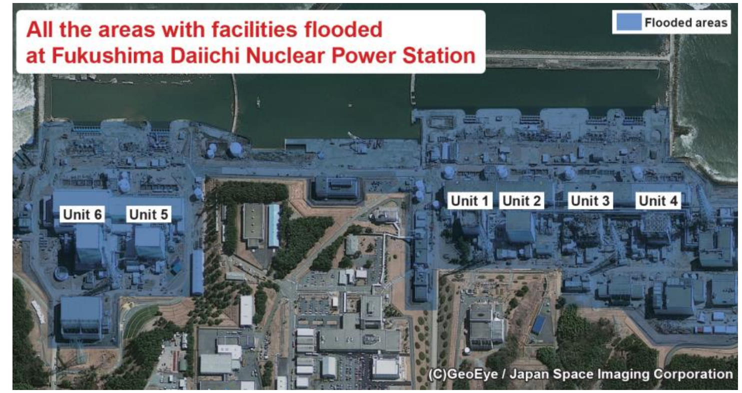
❖ Development of the accident



Fukushima Daiichi Nuclear Disaster

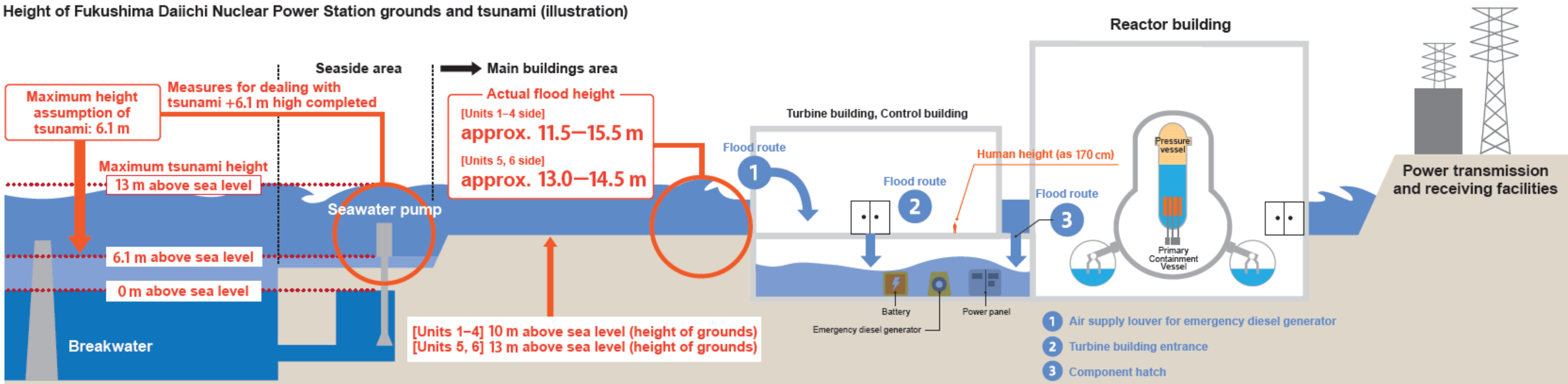
Earthquake and Tsunami

- No damage from the earthquake to key safety features
  - Emergency trips were made.
  - Emergency diesel generators started up.
- Tsunami arrived about 50 minutes after the earthquake.
- Coolant injection and heat removal were lost.
- A variety of damage was inflicted
  - Spread of debris by the tsunami that prevented people from moving around site.



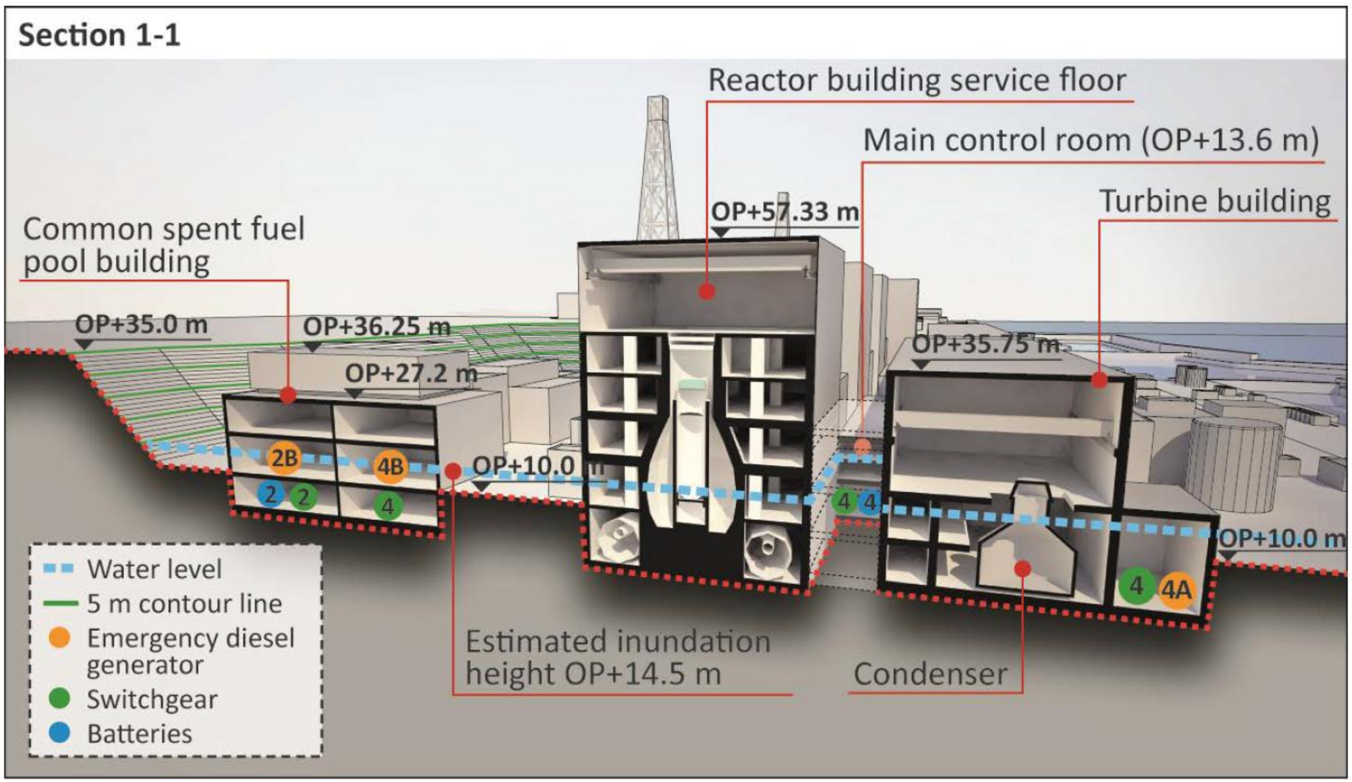
1. Air supply louver for emergency diesel generator
2. Turbine building entrance
3. Component hatch

Height of Fukushima Daiichi Nuclear Power Station grounds and tsunami (illustration)



Earthquake and Tsunami

The wave flooded and damaged the unhoused seawater pumps and motors of all six units at the seawater intake locations on the shoreline, resulting in loss of ultimate heat sink events for all units. This meant that essential plant systems and components, including the water cooled EDGs14, could not be cooled to ensure their continuous operation.



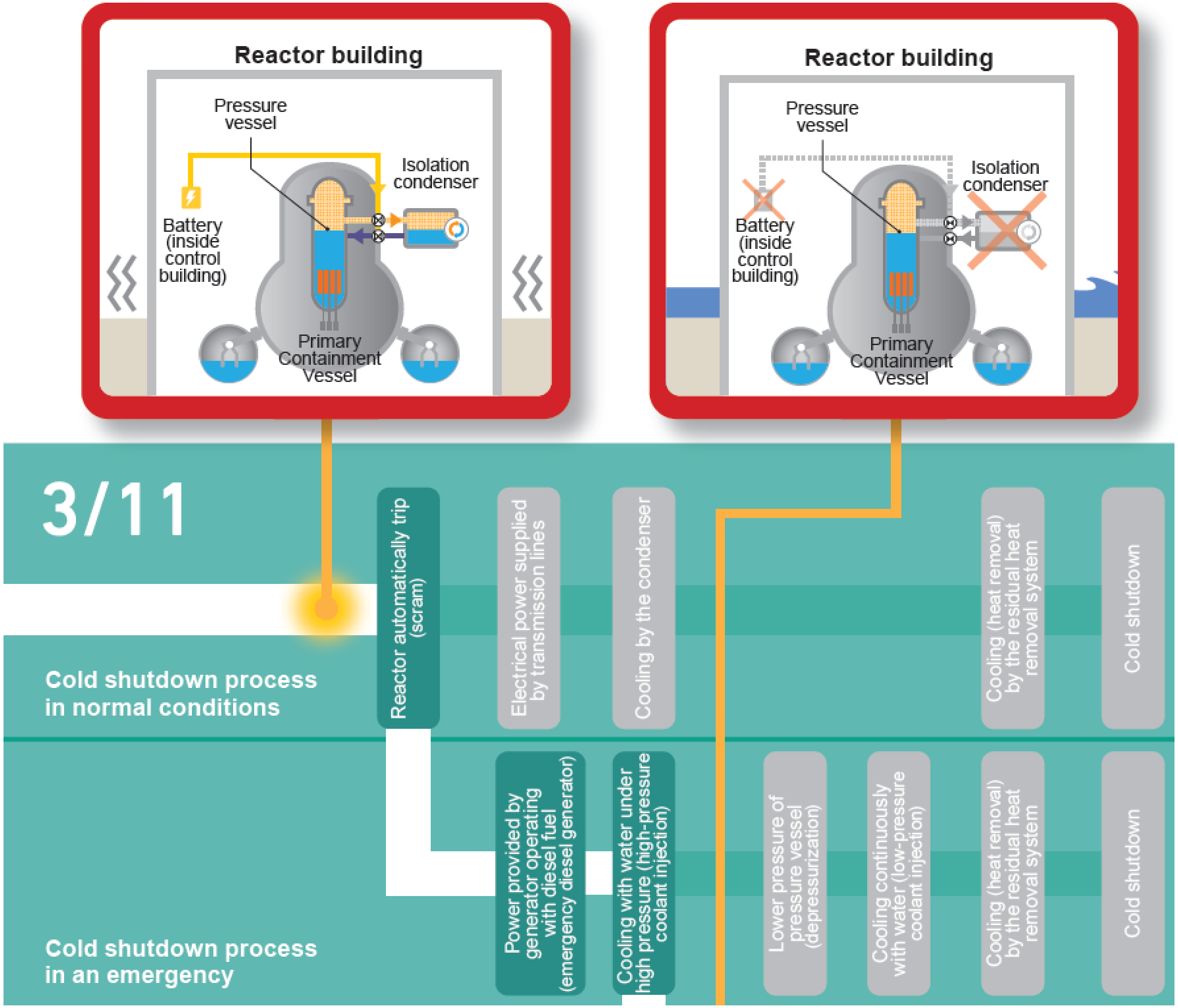
Each unit had a pair of EDGs, and Unit 6 had an additional generator. Of those 13 EDGs, Units 2, 4 and 6 each had one that was air cooled. Since they were air cooled, operability of these generators was not directly affected by the loss of cooling water caused by the damage to the seawater pumps.

Fukushima Daiichi Nuclear Disaster

Severe accident at Unit-1

14:46 Earthquake occurred

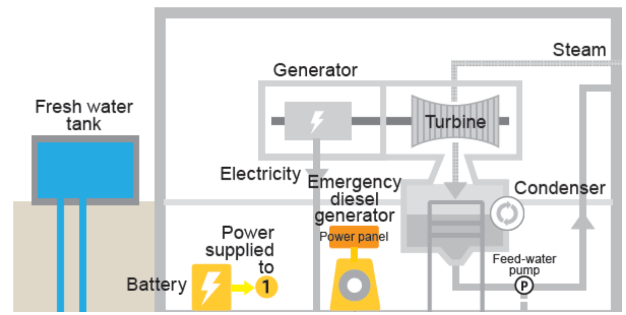
15:35 Tsunami hits



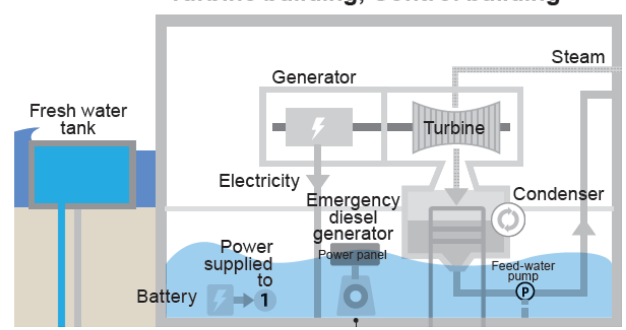
Isolation condenser became unusable due to the tsunami

The isolation condenser can perform cooling just by opening and closing a valve. The valve on the isolation condenser was opened and closed to slowly cool the reactor core after the earthquake. However, this valve was closed when all power was lost due to the tsunami. It could not be reopened for that reason, and the isolation condenser lost its cooling function.

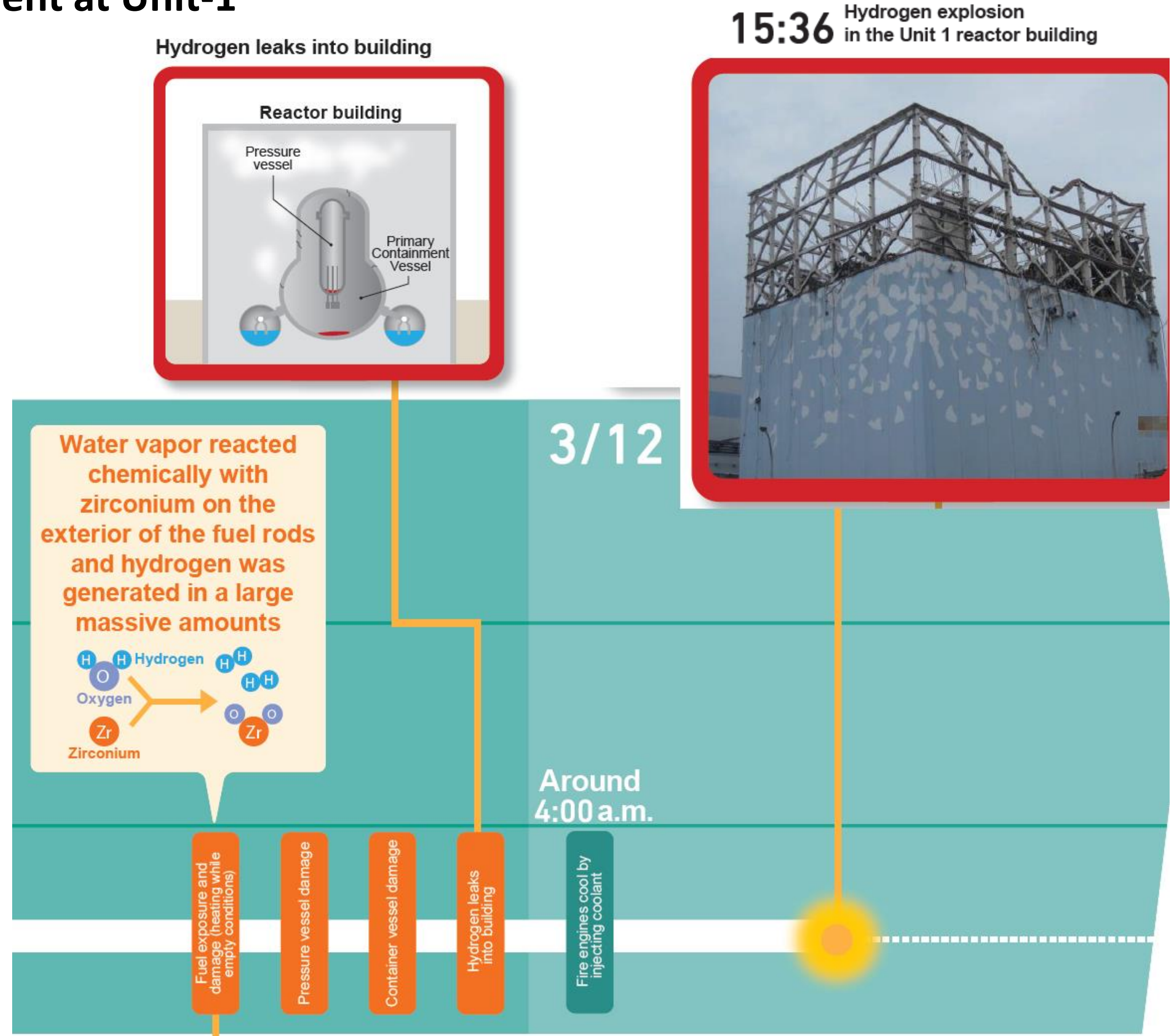
Turbine building, Control building



Turbine building, Control building

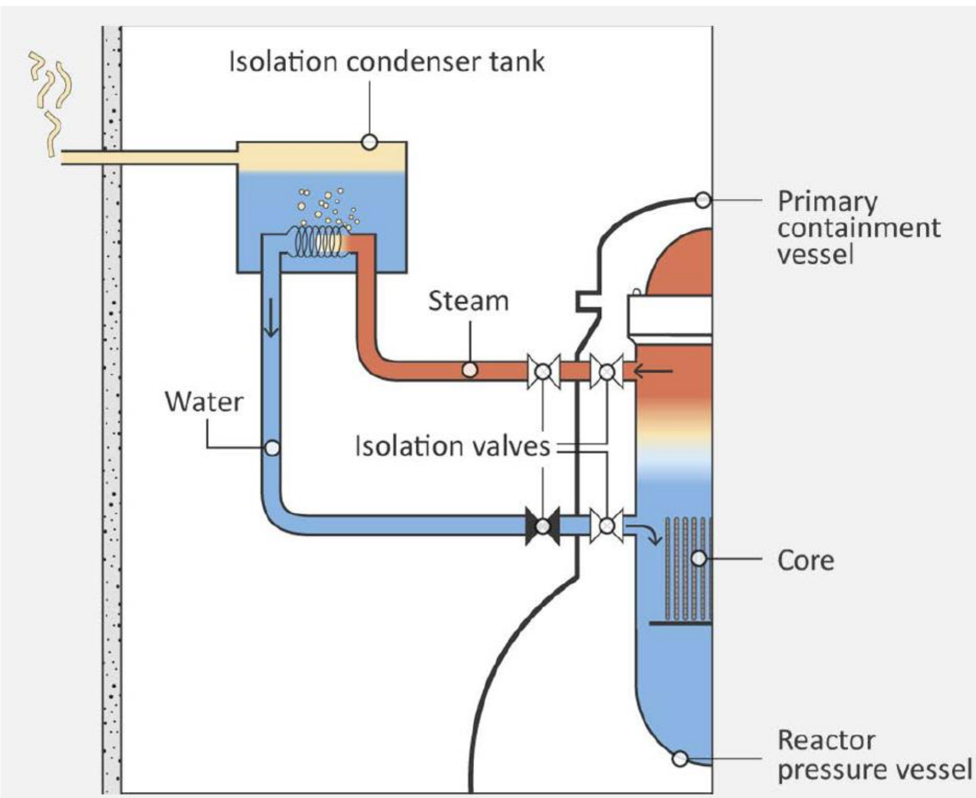


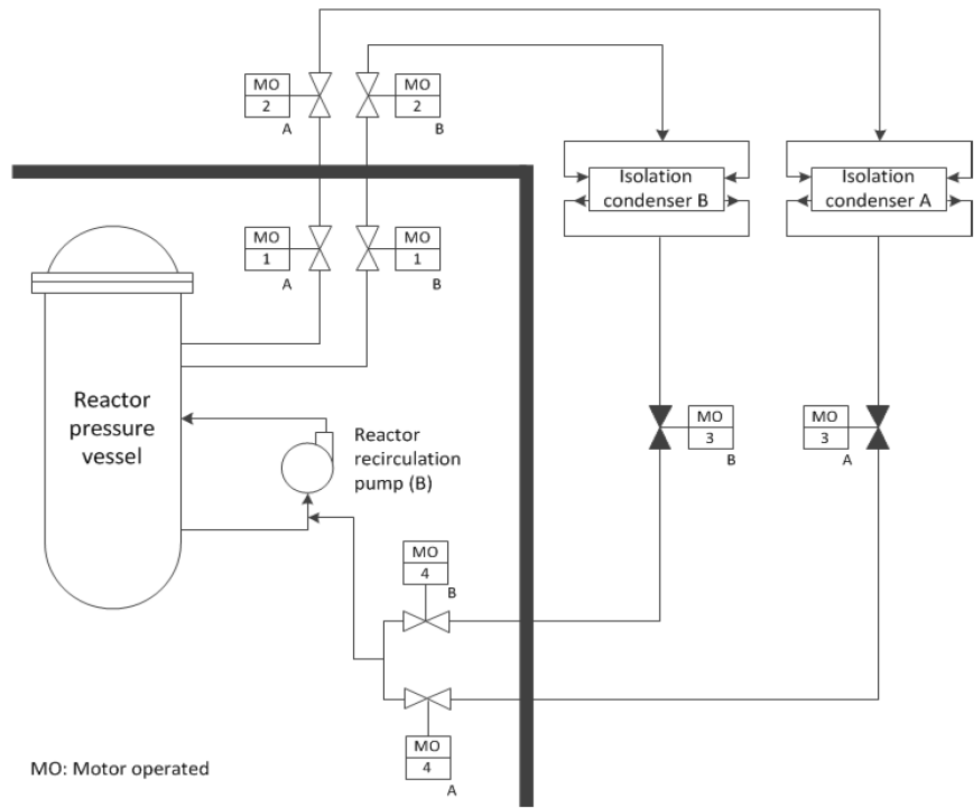
Severe accident at Unit-1



❖ Severe accident at Unit-1

<u>All the inside containment isolation condenser valves (AC operated) would keep their position when the AC power was lost, but they would close, by design, if the control power (i.e. DC power) was lost to the protection system — for the line break situation — that would have sent ‘close signal’ signals to those valves.</u> The position of AC-powered isolation valves has not yet been confirmed by post accident investigations.





Severe accident at Unit-1

The shift team opened the outboard isolation valves from the MCR (remote-manually) at 18:18, taking the chance that the other isolation valves were in an open position. After opening the outer isolation valves of Train A, a small amount of steam was observed above the RB of Unit 1, suggesting the onset of IC operation. However, these indirect signs of an operating IC disappeared after a short time. As there were questions concerning the soundness of the IC system, and as it was not operating as expected, the outboard isolation valve in the condensate leg of the IC was remote-manually closed again at 18:25, which was not reported to the ERC.

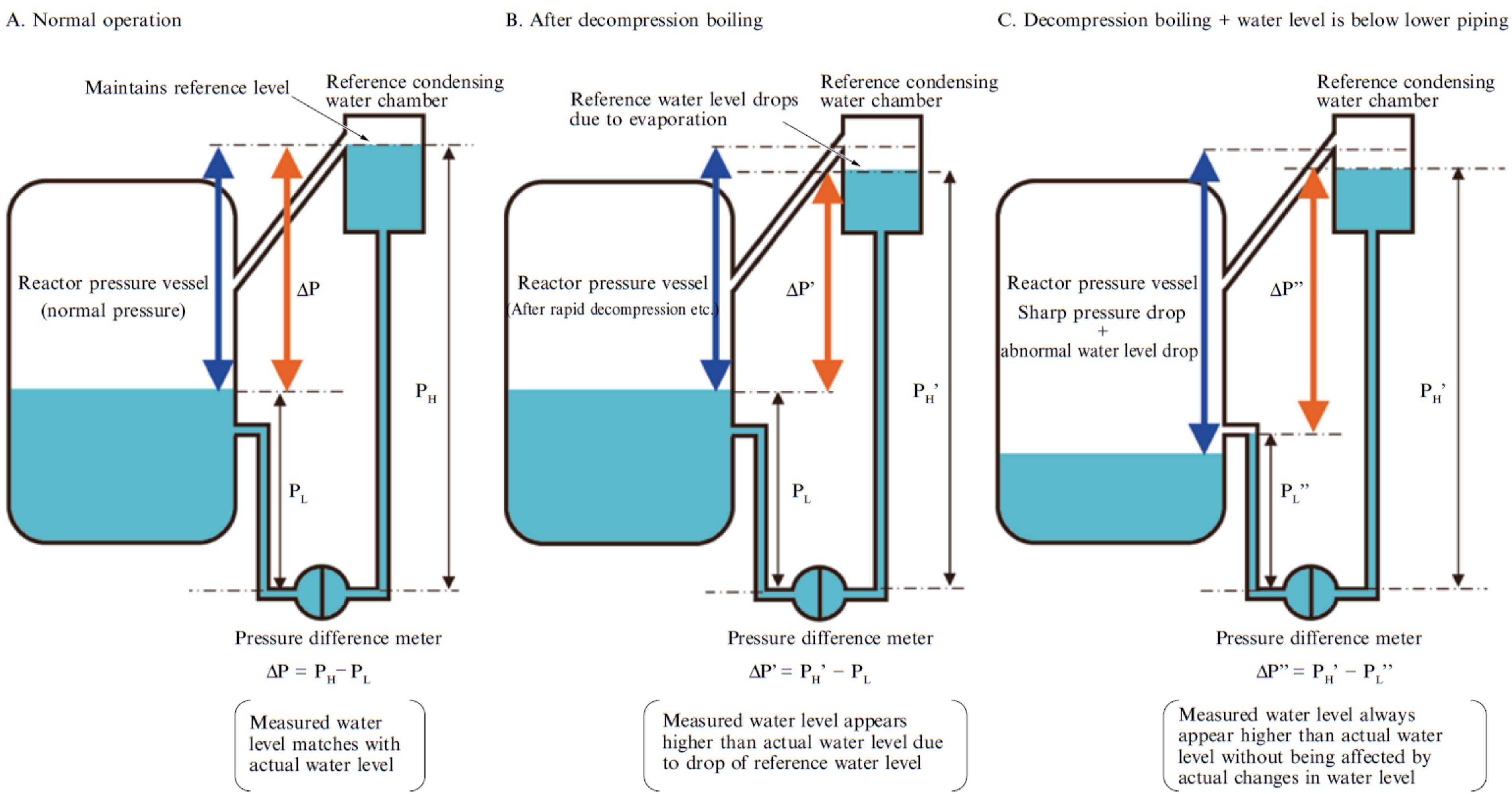
2011-03-11 18:18	03 h 32 min	Indications show both outboard IC valves closed.	Operators found that the valve indicator lamps were lit sometime before 18:18. Not only MO-3A, which was controlled by operators for IC activation/deactivation and was left closed before the second wave of the tsunami, but also the IC supply piping containment isolation valve (MO-2A), which was normally open was closed. Thus, operators inferred that an IC isolation signal was generated during the loss of control (DC) power, possibly by the IC pipe rupture detection circuit. It was corroborated that they were closed at the time of DC failure; thus, there was no shutdown heat removal since then.	02 h 41 min
2011-03-11 18:18	03 h 32 min	Operator started IC by opening the motor operated IC valves MO-3A and MO-2A.	Outboard (outside containment) valves of Train A, assuming that the inboard valves (which cannot be controlled without power) were open since they would fail as-is in the case of loss of AC power. They failed open since they were open at the time of the SBO.	02 h 41 min
2011-03-11 18:18	03 h 32 min	IC observed to be operating.	Steam was observed from the IC exhaust area for a short duration. It was reported to the station ERC that IC is operating.	02 h 41 min
2011-03-11 18:25	03 h 39 min	IC operation cannot be confirmed.	Steam that was observed from the IC exhaust area ceased. There was a doubt regarding the integrity of the IC system. Possible causes were: inboard valves closed, IC tank inventory depleted, line break, etc.	02 h 48 min
2011-03-11 18:25	03 h 39 min	Operator closed the motor operated IC valves MO-3A, securing IC.	—	02 h 48 min

Fukushima Daiichi Nuclear Disaster

Severe accident at Unit-1

2011-03-11 20:07	05 h 21 min	High reactor pressure.	Reading of the gauge in the reactor building. This pressure reading further suggested that the IC was not working.	04 h 30 min
2011-03-11 20:30	05 h 44 min	Established alternative water injection line from the fire protection system to the core spray began operation, sending crew to the reactor building.	By manual alignment of injection line in the reactor building. No unusual exposure is observed from APDs.	04 h 53 min
2011-03-11 20:40	05 h 54 min	DDFP started.	DDFP operation switch was moved from the shutdown position in the MCR, having been manually held since placing the DDFP in standby earlier to prevent unintended start.	05 h 03 min
2011-03-11 20:40	05 h 54 min	DDFP failed to start.	Operators in the reactor building kept resetting the fault trip.	05 h 03 min
2011-03-11 20:50	06 h 04 min	DDFP started continuous operation.	DDFP stopped tripping on fault.	05 h 13 min
2011-03-11 20:50	06 h 04 min	Water injection not achieved.	The pump head of the DDFP is 7.9 bar.	05 h 13 min
2011-03-11 22:00	07 h 14 min	Increased reactor water level.	An earlier reading was TAF + 450 mm.	06 h 23 min
2011-03-11 22:10	07 h 24 min	Reactor water level above TAF reported to government officials.	TAF + 450 mm.	06 h 33 min
2011-03-11 23:00	08 h 14 min	High dose rate reading in front of the north door of the reactor building on the 1st floor of the TB.	The dose rate inside the reactor building was extrapolated to be ~300 mSv/h.	07 h 23 min
2011-03-11 23:00	08 h 14 min	High dose rate reading in front of the south door of the reactor building on the 1st floor of the TB.		07 h 23 min
2011-03-11 23:05	08 h 19 min	Entry to the reactor building restricted. 1.2 mSv/h 0.5 mSv/h	Due to the rising radiation levels, ordered by the Site Superintendent. Radiation zone (restricted entry) signs were posted at 23:33 and 23:50 on the north and south air lock doors, respectively.	07 h 28 min
2011-03-11 23:50	09 h 04 min	Temporary generator powered the dry well pressure instrument.	Small generator used for temporary MCR lighting was connected to DW pressure instrumentation.	08 h 13 min
2011-03-11 23:50	09 h 04 min	Dry well pressure high. 6 bar	The first measurement since loss of DC power.	08 h 13 min

Severe accident at Unit-1



Severe accident at Unit-1

2011-03-12 00:06	09 h 20 min	The Site Superintendent directed preparations to vent the PCV.		In the MCR, operators assembled piping and instrumentation drawings, accident management procedures, valve drawings, and a white board. The operators began to develop a procedure for venting, including how to manually operate the valves, and the associated sequence. Operators collected the equipment needed to perform the evolution, including fire-fighting turnout gear, SCBAs, dosimeters, survey meters, and flashlights.	08 h 29 min
2011-03-12 00:30	09 h 44 min	Evacuation of the 3 km zone completed.	PCV pressure (DW) > design pressure (5.28 bar)	Government confirmed the completion of evacuation. Evacuation for residents within a 3 km radius of Futaba and Okuma Towns was confirmed as being completed, reconfirmed at 01:45. Completion of evacuation to start the venting was agreed with the Fukushima Prefecture authorities.	08 h 53 min
2011-03-12 02:30	11 h 44 min	Reactor water level reading taken.	TAF+ Ch. A 1300 mm, Ch. B 530 mm	The reliability of these readings are questionable.	10 h 53 min
2011-03-12 02:30	11 h 44 min	Maximum (recorded) containment (DW) pressure.	8.4 bar	Subsequently, the pressure decreased.	10 h 53 min
2011-03-12 02:45	11 h 59 min	DW pressure decreased.	8 bar	Pressure stabilized between 7 and 8 bar (700–800 kPa) afterwards.	11 h 08 min
2011-03-12 04:00	13 h 14 min	Water injection into the reactor by one fire engine.		One fire truck's inventory was pumped through the FP line.	12 h 23 min
2011-03-12 06:50	16 h 04 min	METI issued the order for containment venting.		Venting of both Units 1 and 2 containments was issued in accordance with the Act on Special Measures Concerning Nuclear Emergency Preparedness.	15 h 13 min
2011-03-12 07:11	16 h 25 min	The Prime Minister arrived at the site.		—	15 h 34 min
2011-03-12 08:04	17 h 18 min	The Prime Minister left the site.		—	16 h 27 min

Severe accident at Unit-1

2011-03-12 09:04	18 h 18 min	Start of venting.	—	17 h 27 min
2011-03-12 09:04	18 h 18 min	Team 1 (of 3) was dispatched to manually open containment vent valves (motor and air operated).	The control room operators formed three teams to perform the venting, with two operators on each team (one to perform actions and the other to assist by holding flashlights and monitoring dose rates and for other safety concerns, such as ongoing aftershocks). Because there was no means of communicating with the field teams, the decision was made to dispatch one team at a time, with the next team leaving only after the preceding team returned.	17 h 27 min
2011-03-12 09:05	18 h 19 min	Commencement of venting conveyed to the public through the press.	—	17 h 28 min

Effort for suppression chamber venting

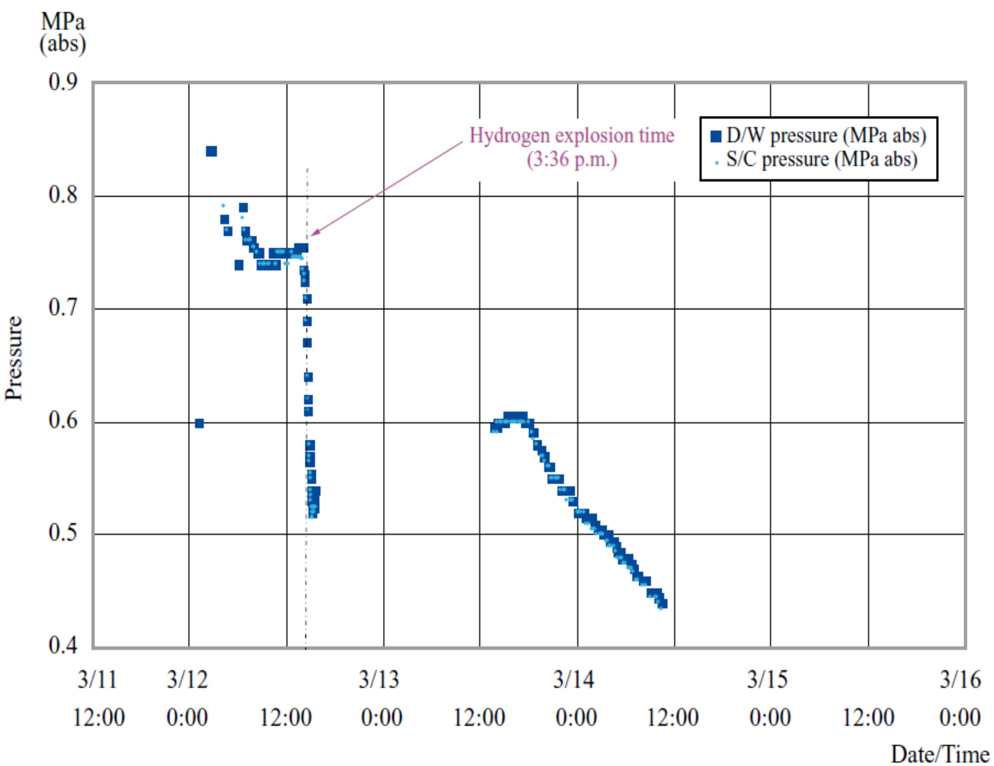
2011-03-12 09:24	18 h 38 min	Team 2 (of 3) dispatched to manually open the suppression chamber vent valve for containment venting.	The control room operators formed three teams to perform the venting, with two operators on each team.	17 h 47 min
2011-03-12 09:32	18 h 46 min	Attempt to manually open the air operated suppression chamber vent by-pass valve failed.	The second team of operators was unsuccessful in the attempt to manually open the suppression chamber air operated vent valve. The operators entered the torus room but had to turn back because they expected they would exceed the 100 mSv dose limit.	17 h 55 min
2011-03-12 10:17	19 h 31 min	The first attempt to remotely open smaller (bypass) air operated suppression chamber vent valve failed.	Operators attempted to open the suppression chamber AOV remotely from the MCR utilizing residual air pressure in the instrumentation air system and temporary DC power supplied by batteries.	18 h 40 min
2011-03-12 10:23	19 h 37 min	The second attempt to remotely open air operated suppression chamber vent bypass valve failed.		18 h 46 min
2011-03-12 10:24	19 h 38 min	The third attempt to remotely open air operated suppression chamber vent bypass valve failed.		18 h 47 min
2011-03-12 14:30	23 h 44 min	The large (isolation) suppression chamber venting valve (AO) was opened.	Inferred from the following PCV pressure drop (sometime between 14:00 and 14:30).	22 h 53 min
2011-03-12 14:30	23 h 44 min	Venting commenced.	The venting and release of radioactive material were confirmed through an indicated decrease in containment pressure.	22 h 53 min
2011-03-12 14:50	01 d 00 h 04 m	Containment pressure decreased.	Due to successful venting.	23 h 13 min

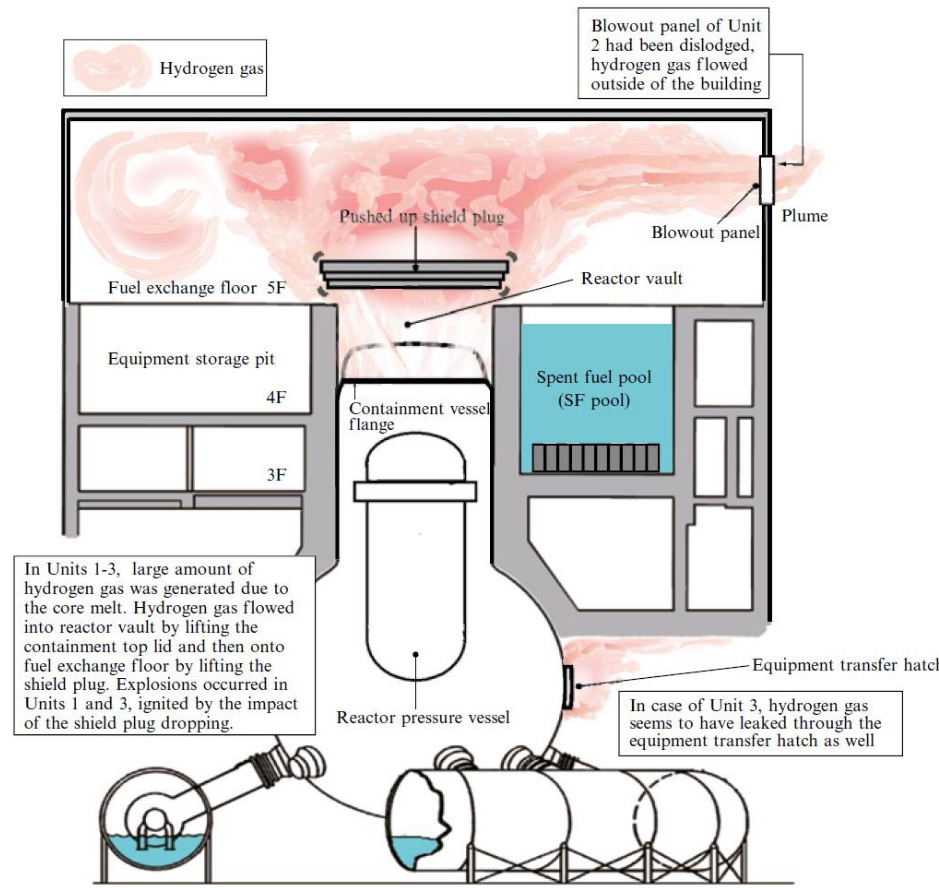
Explosion in Unit 1

2011-03-12 15:36	01 d 00 h 50 m	Explosion in Unit 1.	The explosion damaged seawater injection and 480 V grid setup.	23 h 59 min

Fukushima Daiichi Nuclear Disaster

❖ Severe accident at Unit-1





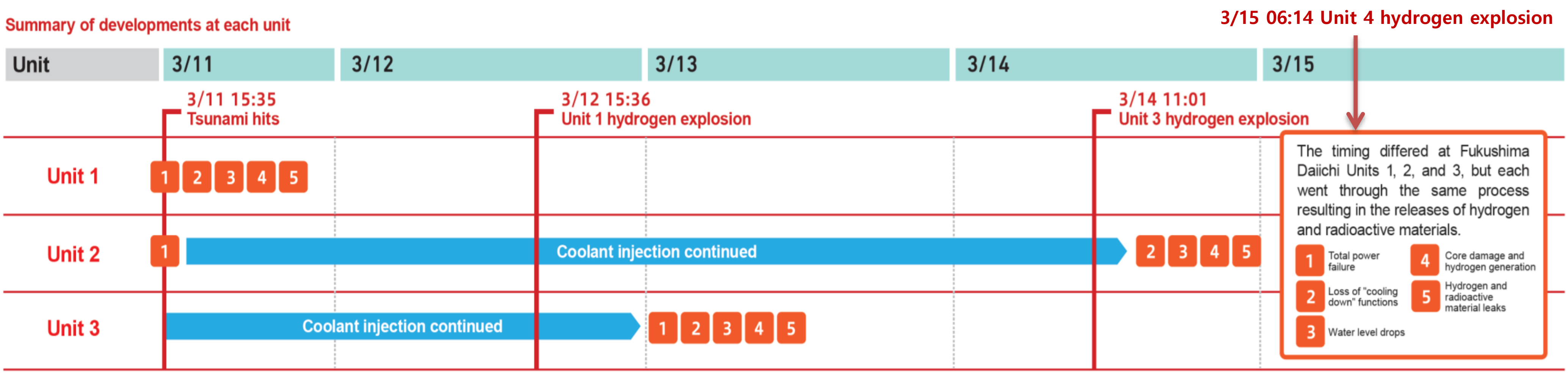
Severe accident at Unit-1

After explosion in Unit 1

2011-03-12 15:36	01 d 00 h 50 m	Explosion in Unit 1.
2011-03-12 15:36	01 d 00 h 50 m	480 V low voltage grid connection damaged from explosion.
2011-03-12 15:36	01 d 00 h 50 m	Seawater injection lineup damaged from explosion.
2011-03-12 15:36	01 d 00 h 50 m	MCR lighting lost.
2011-03-12 15:36	01 d 00 h 50 m	PCV pressure measurement lost

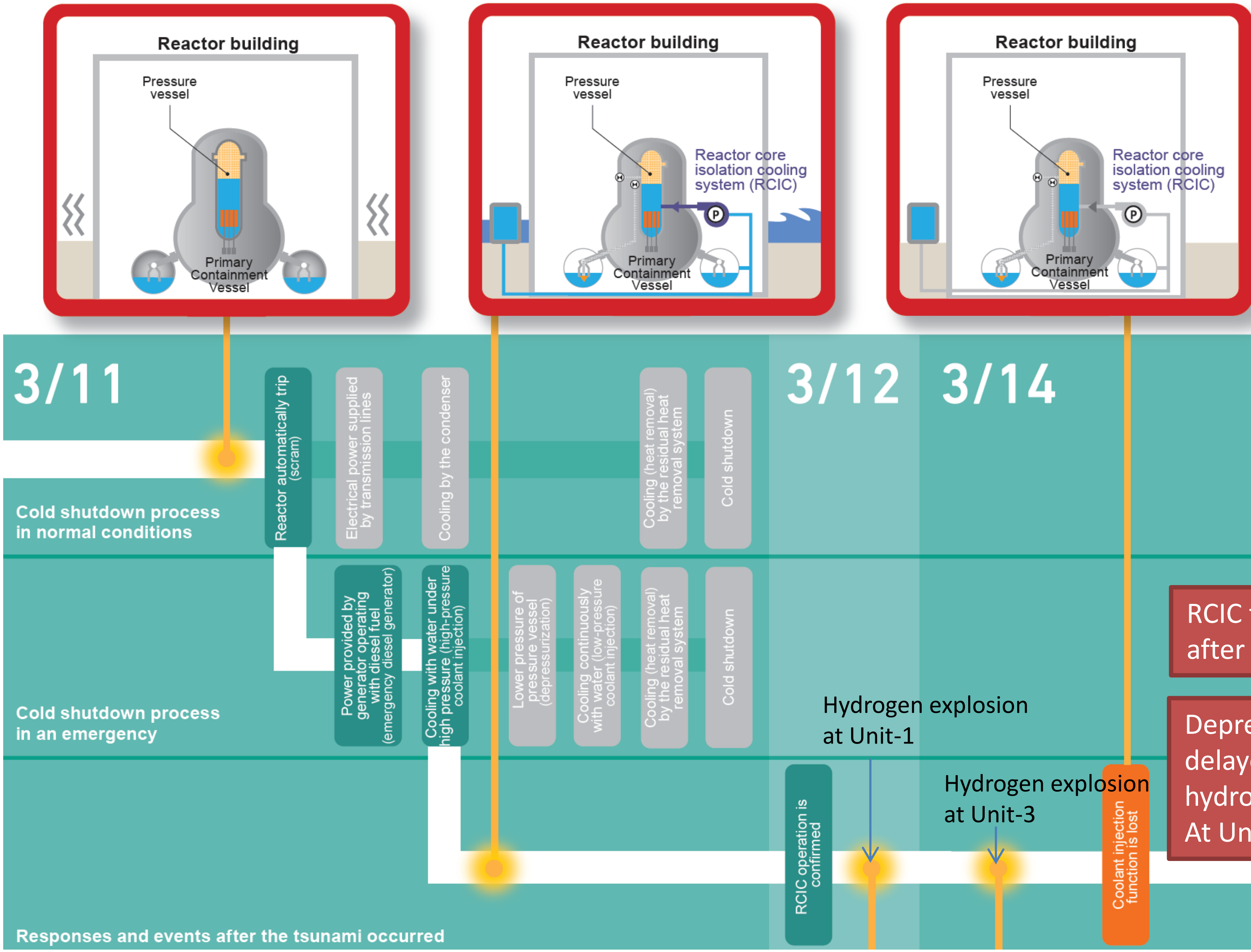
2011-03-13 13:37	01 d 22 h 51 m	PCV pressure measurement re-established.	—
2011-03-13 13:37	01 d 22 h 51 m	SC pressure reading.	0.590 MPa
2011-03-13 13:37	01 d 22 h 51 m	DW pressure reading.	0.595 MPa

2011-03-12 19:04	01 d 04 h 18 m	Damaged hoses for water injection repaired.
2011-03-12 19:04	01 d 04 h 18 m	Seawater injection into reactor started upon start of the fire engine.
2011-03-12 20:45	01 d 05 h 59 m	Boric acid added to the seawater injection.



Fukushima Daiichi Nuclear Disaster

Severe accident at Unit-2

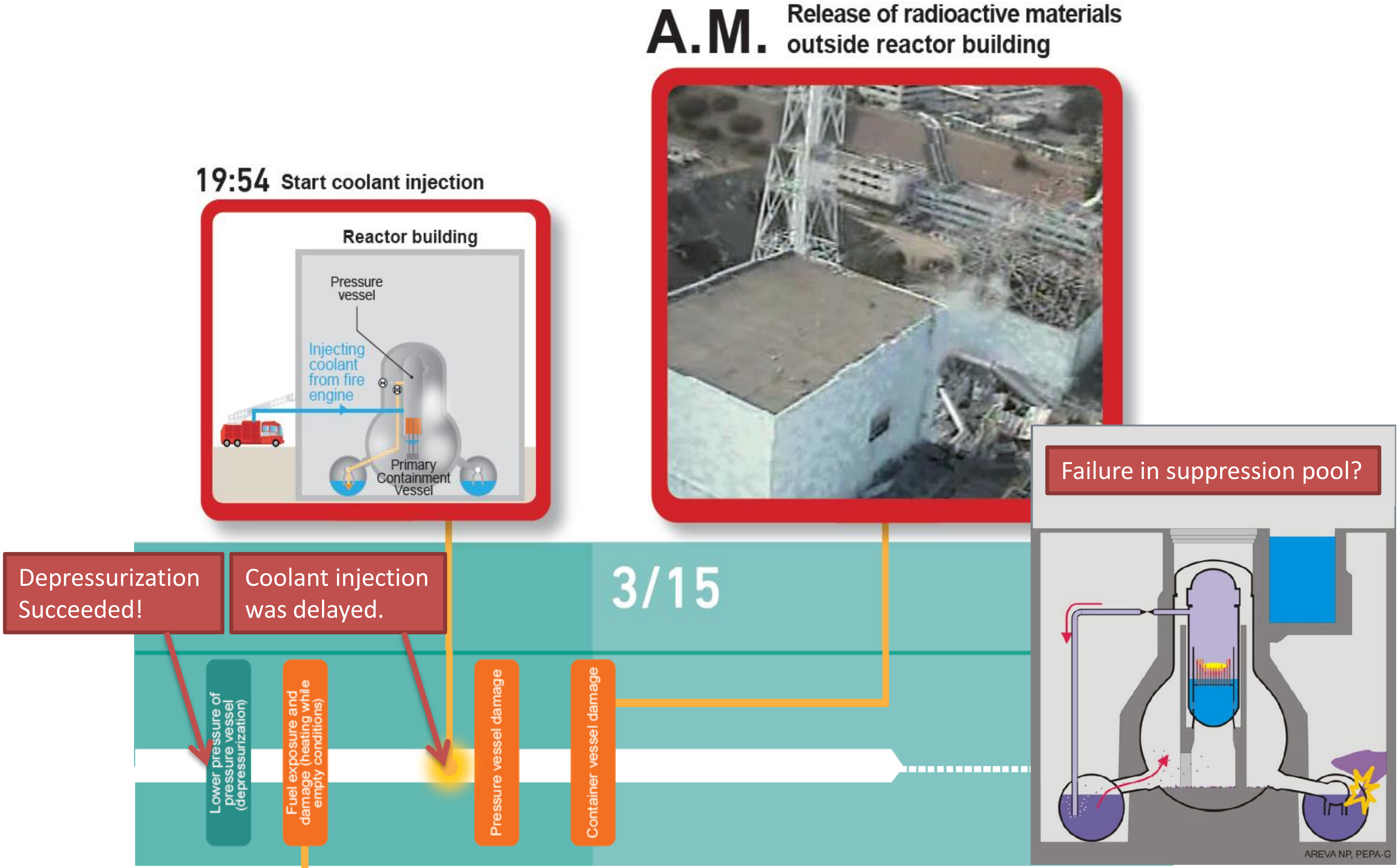


RCIC tripped after 3 days

Depressurization delayed by the hydrogen explosion At Units 1 and 3

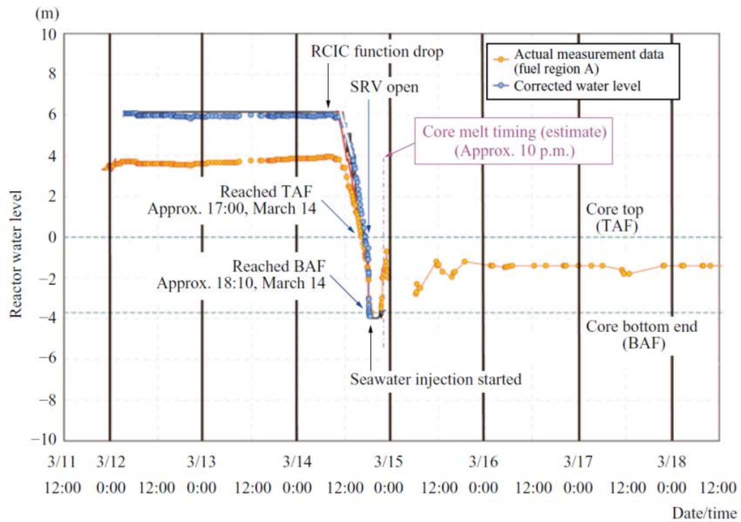
Fukushima Daiichi Nuclear Disaster

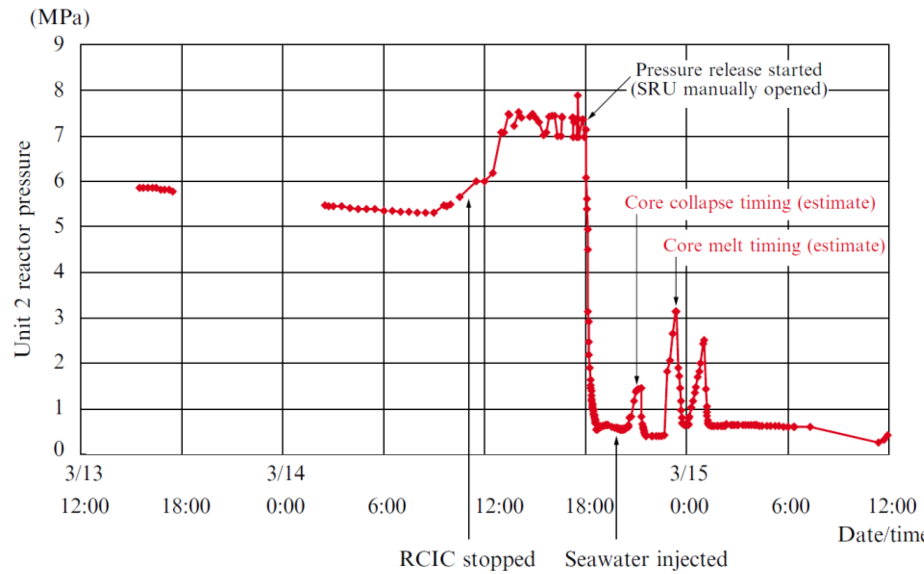
- Severe accident at Unit-2

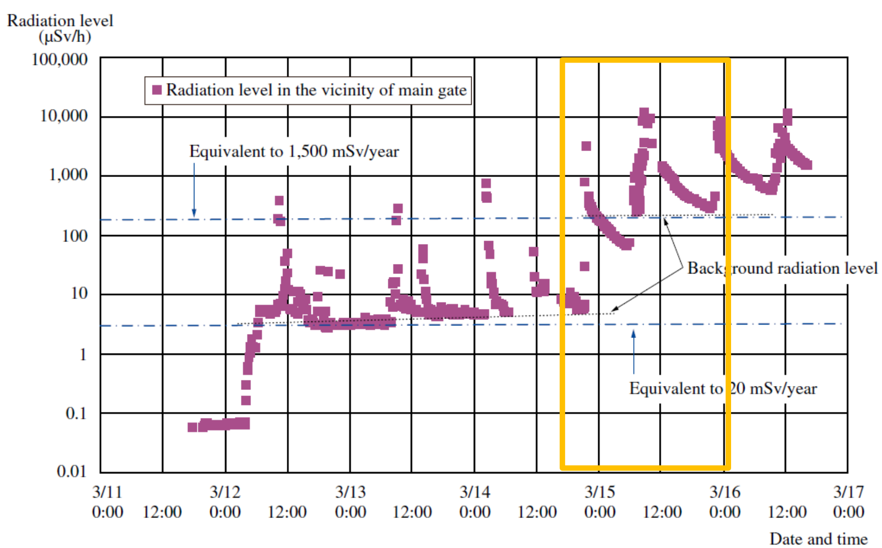


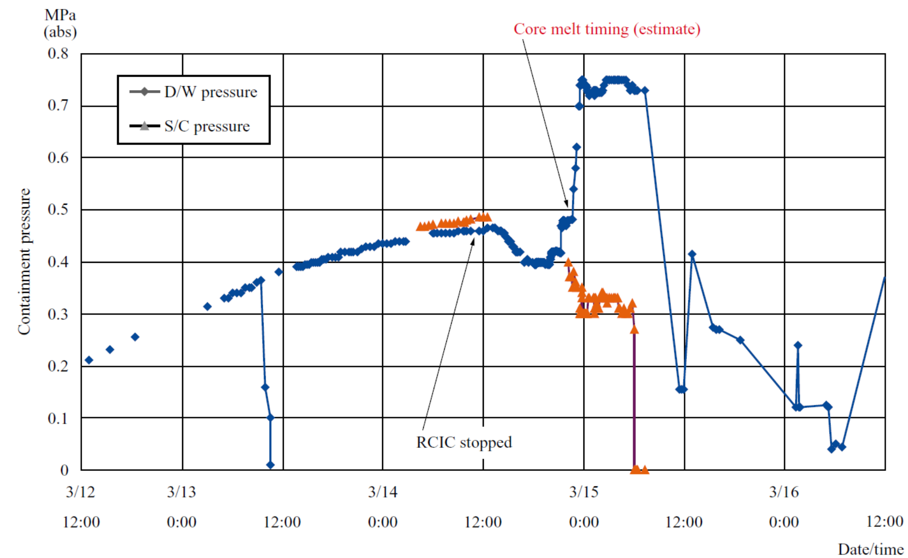
Fukushima Daiichi Nuclear Disaster

❖ Severe accident at Unit-2









Fukushima Daiichi Nuclear Disaster

Severe accident at Unit-2

2011-03-11 15:41	55:00 (min)	SBO
2011-03-11 15:41	55:00 (min)	DC power panel flooded and failed.
2011-03-11 15:41	55:00 (min)	Loss of DC power.
2011-03-11 15:41	55:00 (min)	Loss of DC distribution systems resulted in the loss of control room indications and alarms.
		Control room lighting lost, with only emergency lighting remaining.
		Control panel indications for HPCI barely visible, but slowly faded away. Operators determined that HPCI was not operable because indicators on the control panel were lost.
		RCIC manipulation lost.
2011-03-11 21:13	6 h 27 min	TEPCO informed Government on estimated time for uncovering of the core at 21:40.
2011-03-11 22:10	07 h 24 min	Reactor water level above TAF reported to government officials.
2011-03-11 22:10	07 h 24 min	Radiation monitor data around plant monitoring points reported to government.
2011-03-11 23:00	08 h 14 min	High dose rate reading in front of the Unit 1 reactor building north door on the 1st floor of the TB.
2011-03-11 23:00	08 h 14 min	High dose rate reading in front of the Unit 1 reactor building south door on the 1st floor of the TB.
2011-03-11 23:25	08 h 39 min	DW pressure reading. 1.41 bar
2011-03-12 00:06	09 h 20 min	The Site Superintendent directed preparations to vent the PCV.
2011-03-12 00:30	09 h 44 min	3 km zone evacuation completed.
2011-03-12 01:00	10 h 14 min	Operators sent to the RCIC room.
2011-03-12 02:55	12 h 09 min	RCIC declared operating.
2011-03-12 02:56	12 h 10 min	CST water level low.
2011-03-12 03:06	12 h 20 min	Plans to vent Unit 1 and 2 PCV announced to the public.

2011-03-12 04:20	13 h 34 min	A team was dispatched to the RCIC room to manually open 3 MOVs to switch the RCIC source to SC from CST.
2011-03-12 05:00	14 h 14 min	RCIC water intake line up to SC complete.

Restoration work for power supply and water injection

2011-03-12 15:36	01 d 00 h 50 min	Explosion in Unit 1 occurred.
2011-03-12 15:36	01 d 00 h 50 min	MCR lighting was lost.
2011-03-12 15:54	01 d 01 h 08 min	Site ERC ordered the evacuation of the staff from two MCRs (Units 1 and 2 and Units 3 and 4), except for the most senior staff.
2011-03-13 11:00	01 d 20 h 14 min	Large SC AOV is opened for venting. 3.7 bar | Less than rupture disk pressure. No venting.
2011-03-14 11:00	02 d 20 h 14 min	Alternative seawater injection line assembly completed.
2011-03-14 11:01	02 d 20 h 15 min	Explosion in Unit 3.
2011-03-14 11:01	02 d 20 h 15 min	Unit 3 explosion damaged seawater injection setup.
2011-03-14 11:01	02 d 20 h 15 min	Large isolation AOV in the SC venting line closed.

The valve could not be reopened

2011-03-14 13:00	02 d 22 h 14 min	Reactor pressure reading. 75.4 bar
		Reactor water level reading. TAF+2400 mm
2011-03-14 13:00	02 d 22 h 14 min	RCIC declared inoperable.
2011-03-14 13:25	02 d 22 h 39 min	Time for core uncovering estimated at 16:30.
2011-03-14 14:43	02 d 23 h 57 min	Seawater injection though core spray line re-established.

Vent for RV and SC was critical. SC temp. ~ Tsat

2011-03-14 16:21	03 d 01 h 35 min	Unsuccessful attempt to open large isolation SC vent AOV.

Severe accident at Unit-2

2011-03-14 16:28	03 d 01 h 42 min	Operators decided to depressurize RPV via SRV. regardless of the concerns for PCV integrity (saturated/solid SC)
2011-03-14 19:05	03 d 04 h 19 min	Seawater injection via fire engines commenced.
2011-03-14 19:20	03 d 04 h 34 min	Water injection stops. Fire engines ran out of fuel
2011-03-14 19:54	03 d 05 h 08 min	Seawater injection into RPV via FP system began.
2011-03-14 21:00	03 d 06 h 14 min	Attempt to open small (bypass) SC vent AOV.
2011-03-14 22:50	03 d 08 h 04 min	RPV (DW) pressure reading 540 kPa (5.4 bar) > design pressure
2011-03-14 23:25	03 d 08 h 39 min	Discovery of small (by-pass) SC vent AOV being closed
2011-03-14 23:25	03 d 08 h 39 min	Decision making to vent PCV directly from DW began 700 kPa
2011-03-15 00:01	03 d 09 h 15 min	Commence opening DW vent (bypass) AOV venting did not occur

DW pressure maintained at ~ 750 kPa until after 6 hours.

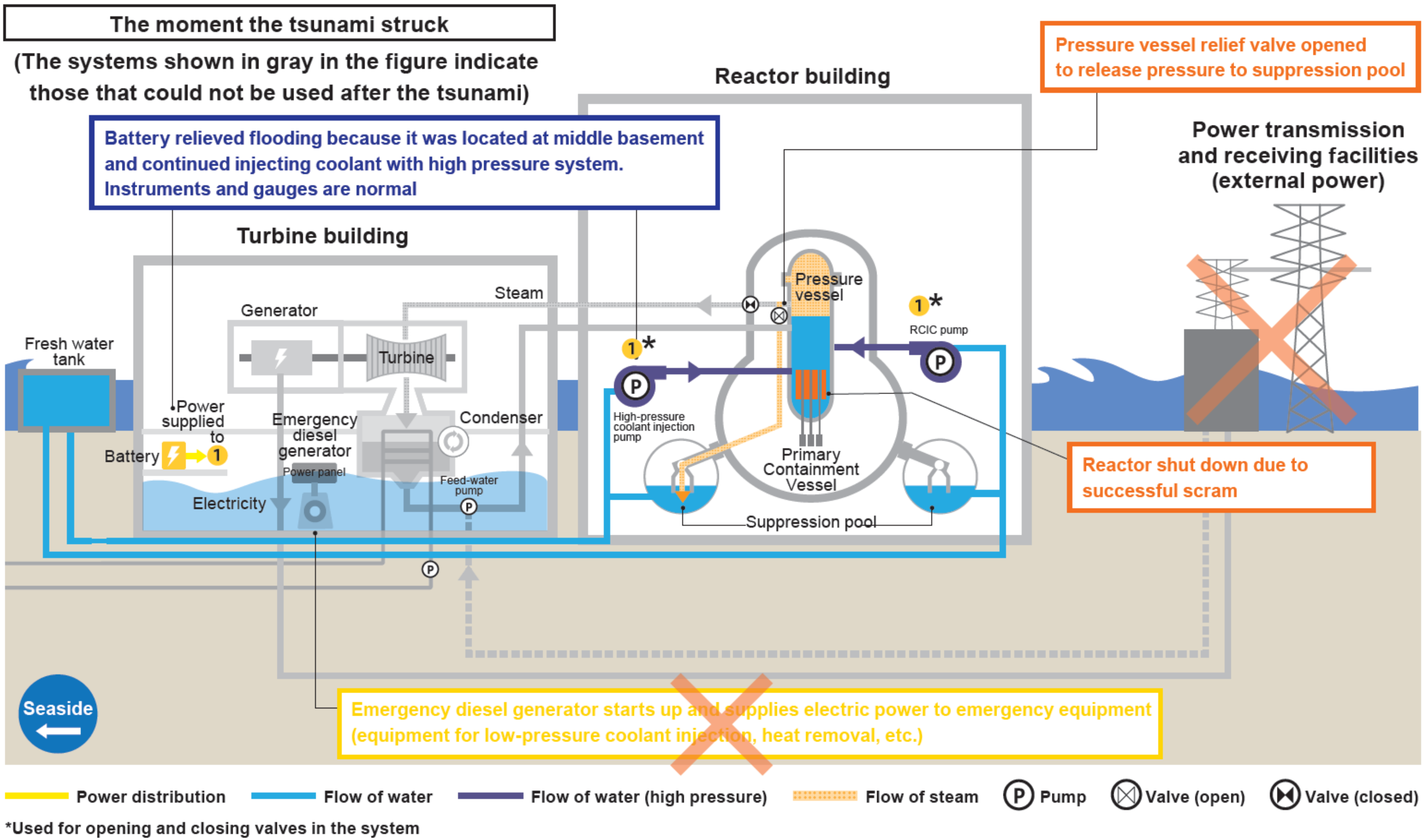
2011-03-15 06:14	03 d 15 h 28 min	Sound of explosions at site and tremors felt in the MCR.
2011-03-15 06:14	03 d 15 h 28 min	SC pressure dropped to atmospheric pressure.
2011-03-15 06:14	03 d 15 h 28 min	Explosion reported in Unit 4.
2011-03-15 06:30	03 d 15 h 44 min	SC pressure reading. 0.0 bar

[138] Later seismic analyses by TEPCO showed that there had been no explosion inside Unit 2 and ascribed the noise to the explosion in Unit 4.

Fukushima Daiichi Nuclear Disaster

❖ Severe accident at Unit-3

- Battery relieved flooding!



Severe accident at Unit-3

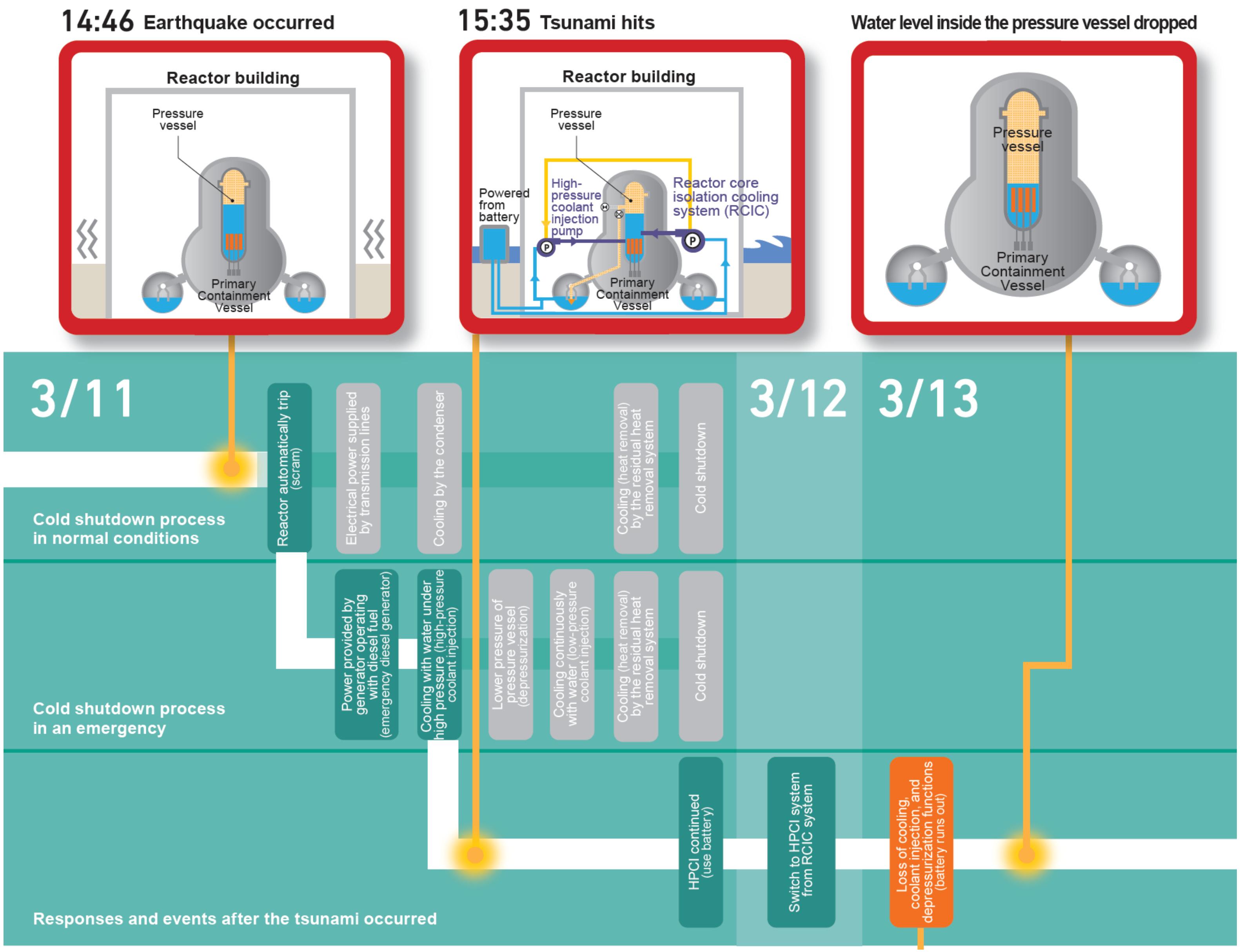
- Battery relieved flooding!
- Operation and control of the RCIC and HPCI could be maintained.
- It was also possible to continue monitoring reactor status using meters and gauges.

- Coolant injection continued for approximately a day and a half, after which the HPCI system was tripped to change over to injecting coolant at low pressure (with a diesel driven fire pump).
  - RPV pressure was 0.58 MPa.
  - Safety relief valve did not work due to battery run-out.

- However, **depressurization after this took time**, the water level dropped, and the result was the generation of hydrogen and damage to the core.

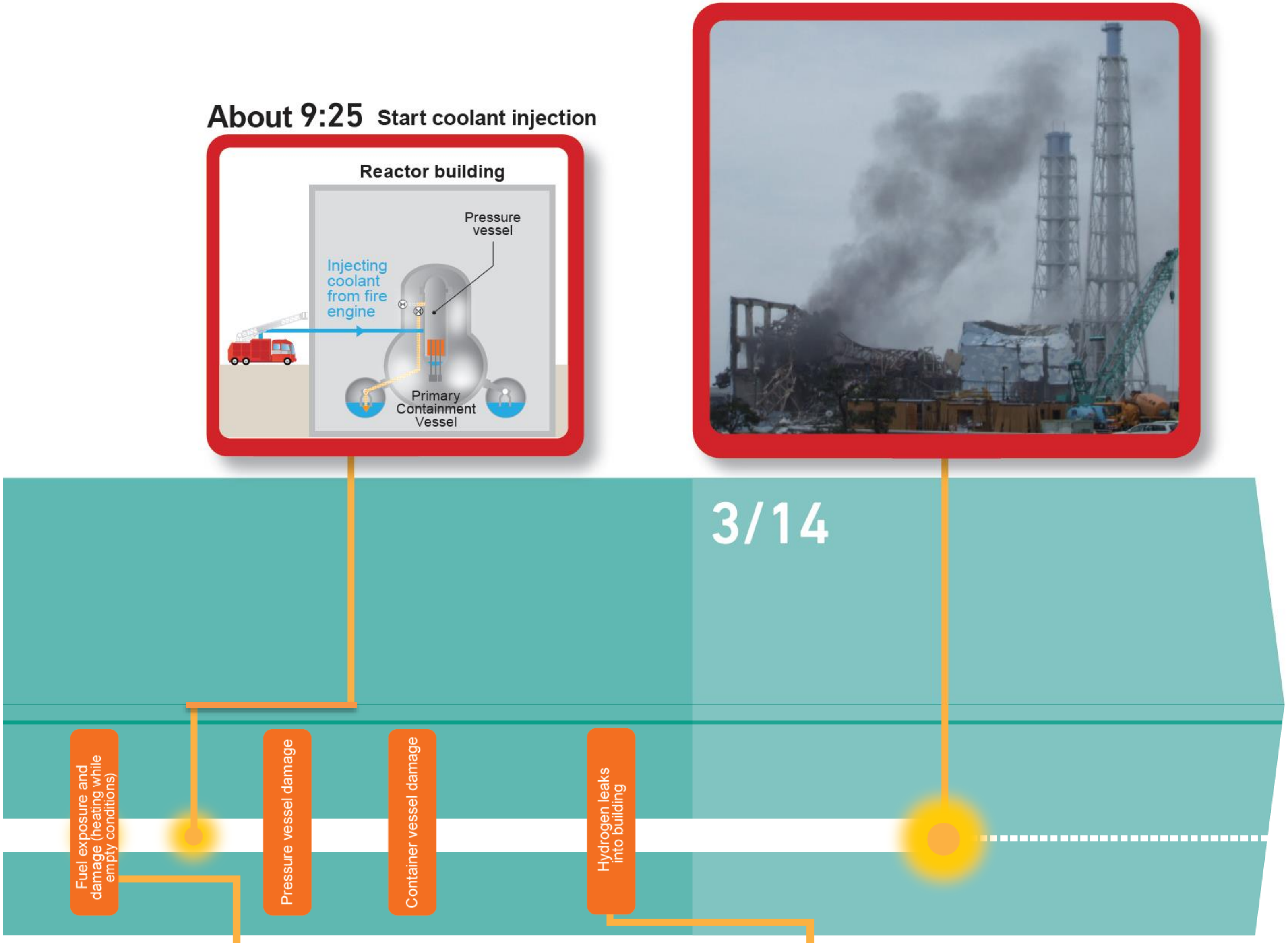
Fukushima Daiichi Nuclear Disaster

Severe accident at Unit-3



Fukushima Daiichi Nuclear Disaster

❖ Severe accident at Unit-3



Severe accident at Unit-3

2011-03-12 11:36	20 h 50 min	RCIC tripped.
2011-03-12 11:40 2011-03-12 12:35	20 h 54 min 21 h 49 min	Attempts to restart RCIC unsuccessful. HPCI started.
2011-03-12 12:45	21 h 59 min	Reactor pressure. 5.6 MPa
2011-03-12 17:00	01 d 02 h 14 min	Reactor pressure. 2.9 MPa
2011-03-12 19:00	01 d 04 h 14 min	Reactor pressure reading. 0.95 MPa
2011-03-13 02:30	01 d 11 h 44 min	Reactor pressure reading.

0.79 Mpa, Below the set point of the automatic isolation of the HPCI.

2011-03-13 02:30	01 d 11 h 44 min	HPCI fails to auto stop.
2011-03-13 02:30	01 d 11 h 44 min	Decision to switch core cooling function from HPCI to DDFP.
2011-03-13 02:30	01 d 11 h 44 min	Team dispatched to reactor building to switch DDFP line up to RPV injection from SC spray.
2011-03-13 02:42	01 d 11 h 56 min	DDFP line up was changed from SC spray to RPV injection.
2011-03-13 02:42	01 d 11 h 56 min	HPCI stopped.

Due to the possibility of reactor pressure drop causing a further slowing of HPCI turbine revolution speed, which would increase turbine vibrations and ultimately result in reactor steam release due to equipment damage.

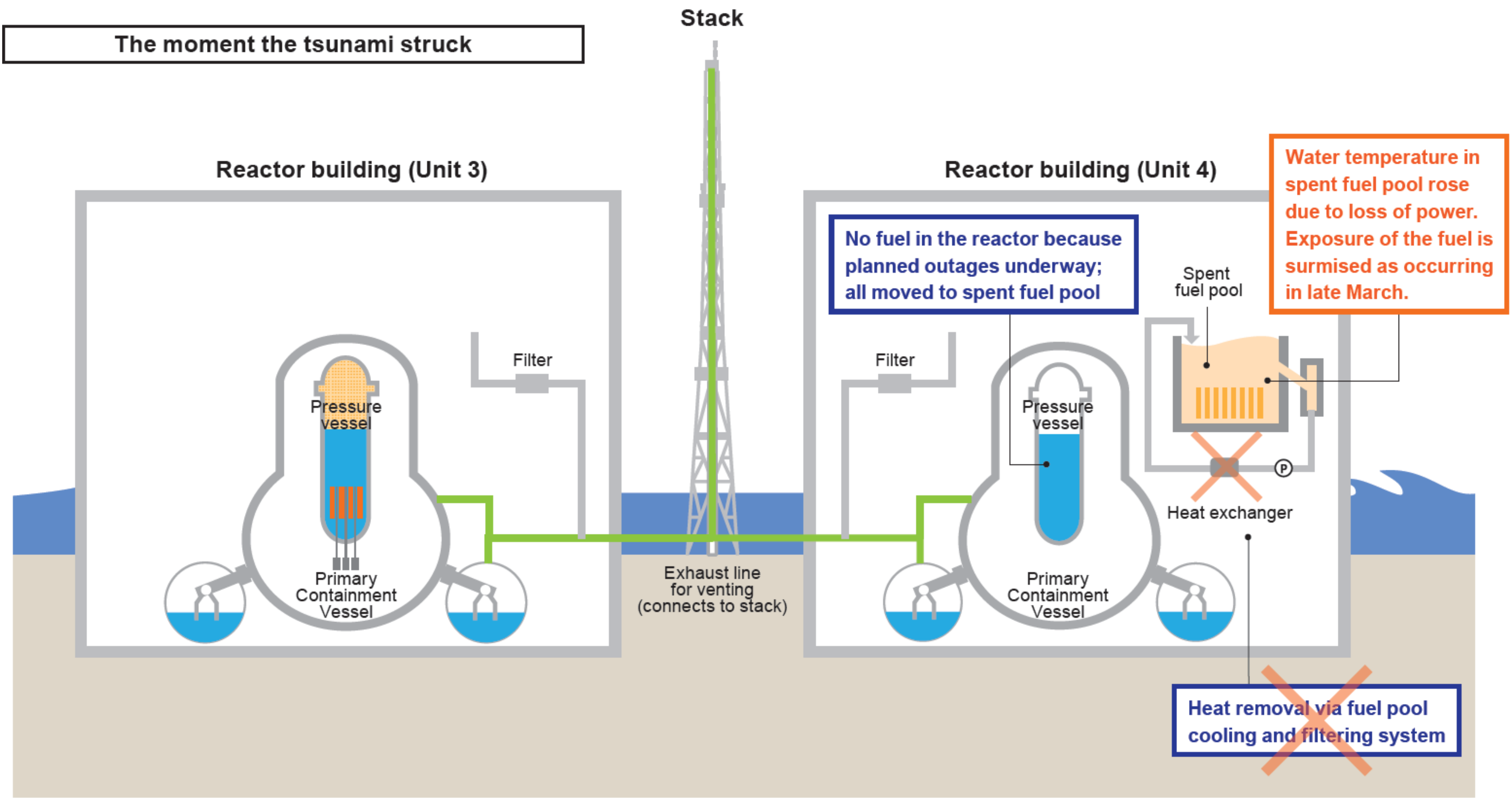
Fukushima Daiichi Nuclear Disaster

Severe accident at Unit-3

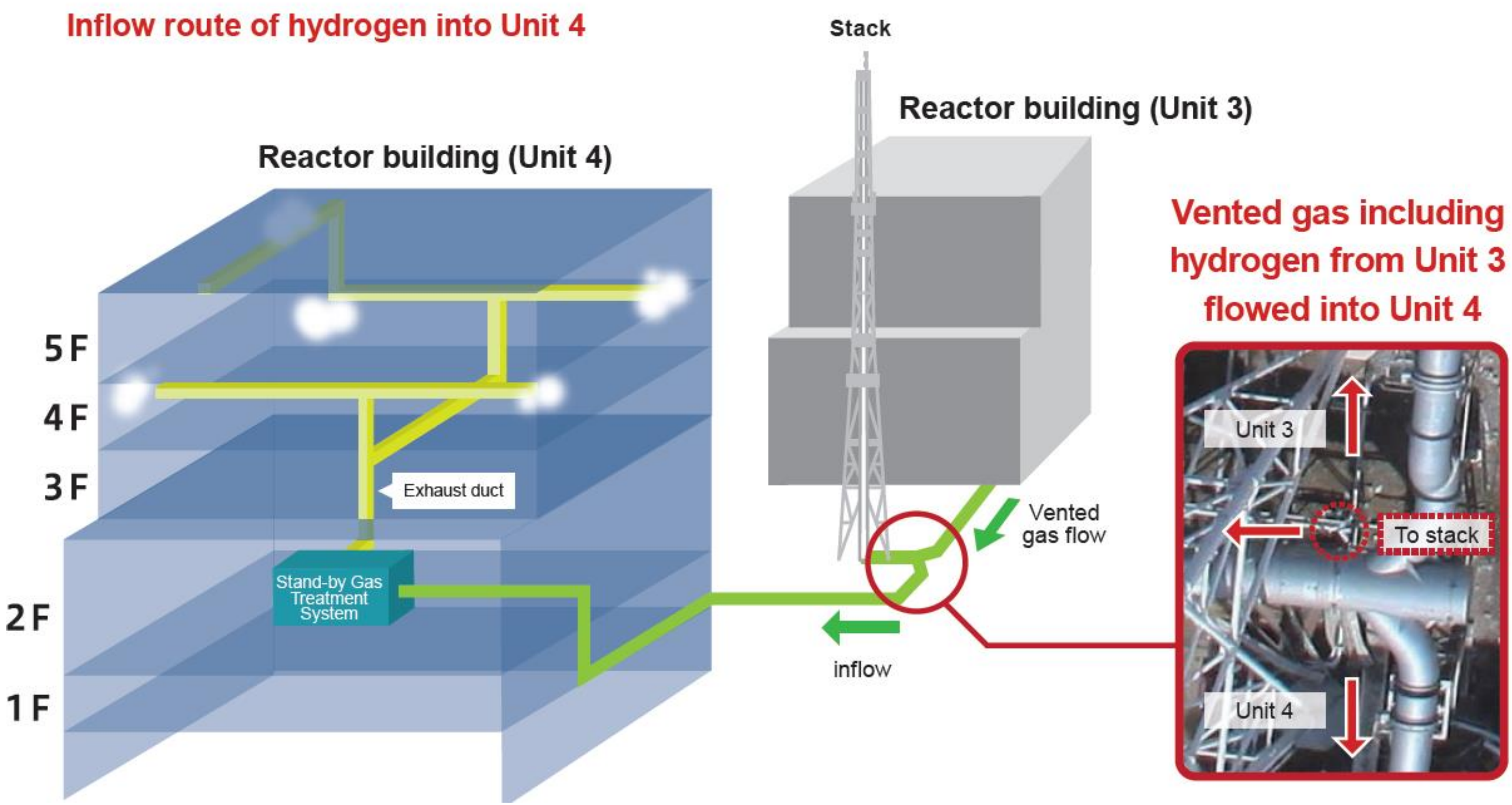
2011-03-13 02:44	01 d 11 h 58 min	Reactor pressure reading. 0.58 MPa
2011-03-13 02:45	01 d 11 h 59 min	Attempt to open SRV unsuccessful.
2011-03-13 03:00	01 d 12 h 14 min	Reactor pressure reading. 0.87 MPa
2011-03-13 03:05	01 d 12 h 19 min	Attempt to inject water via DDFP unsuccessful.
2011-03-13 03:35	01 d 12 h 49 min	Attempt to restart HPCI.
2011-03-13 03:37	01 d 12 h 51 min	Attempt to restart RCIC.
2011-03-13 03:37	01 d 12 h 51 min	Team dispatched to HPCI room to local manual start of HPCI.
2011-03-13 03:38	01 d 12 h 52 min	Attempt to open SRV unsuccessful.
2011-03-13 03:39	01 d 12 h 53 min	Operators start load shedding of HPCI equipment to preserve DC power.
2011-03-13 03:44	01 d 12 h 58 min	Reactor pressure reading. 4.1 MPa
2011-03-13 03:51	01 d 13 h 05 min	Reactor water level monitor restored.
2011-03-13 03:51	01 d 13 h 05 min	Reactor water level reading.
2011-03-13 04:30	01 d 13 h 44 min	Reactor pressure reading. 7.0 MPa
2011-03-13 05:08	01 d 14 h 22 min	Attempted to restart RCIC.
2011-03-13 09:08	01 d 18 h 22 min	Reactor pressure decreased.
2011-03-13 09:10	01 d 18 h 24 min	Increased SC pressure.
2011-03-13 09:20	01 d 18 h 34 min	Unit 3 PCV venting.
2011-03-13 09:25	01 d 18 h 39 min	Borated freshwater injection into the reactor started though the FP line.

The SRVs did not open, although the valve status in the MCR displayed them as functional. It is considered that the **battery capacity was enough to display the status indicator lamps, but not enough to operate the SRVs**.

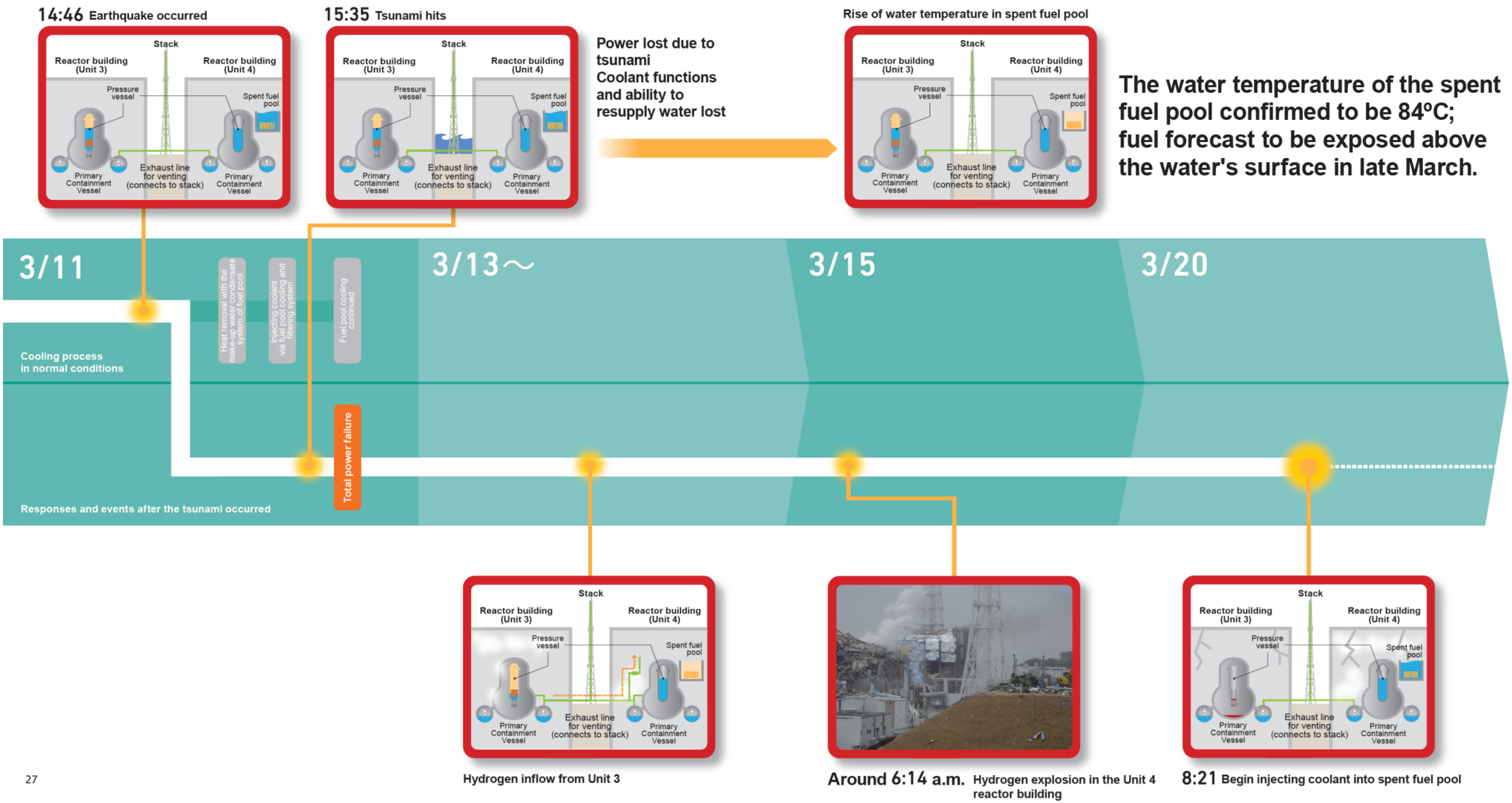
Hydrogen explosion at Unit-4



❖ Hydrogen explosion at Unit-4



Hydrogen explosion at Unit-4

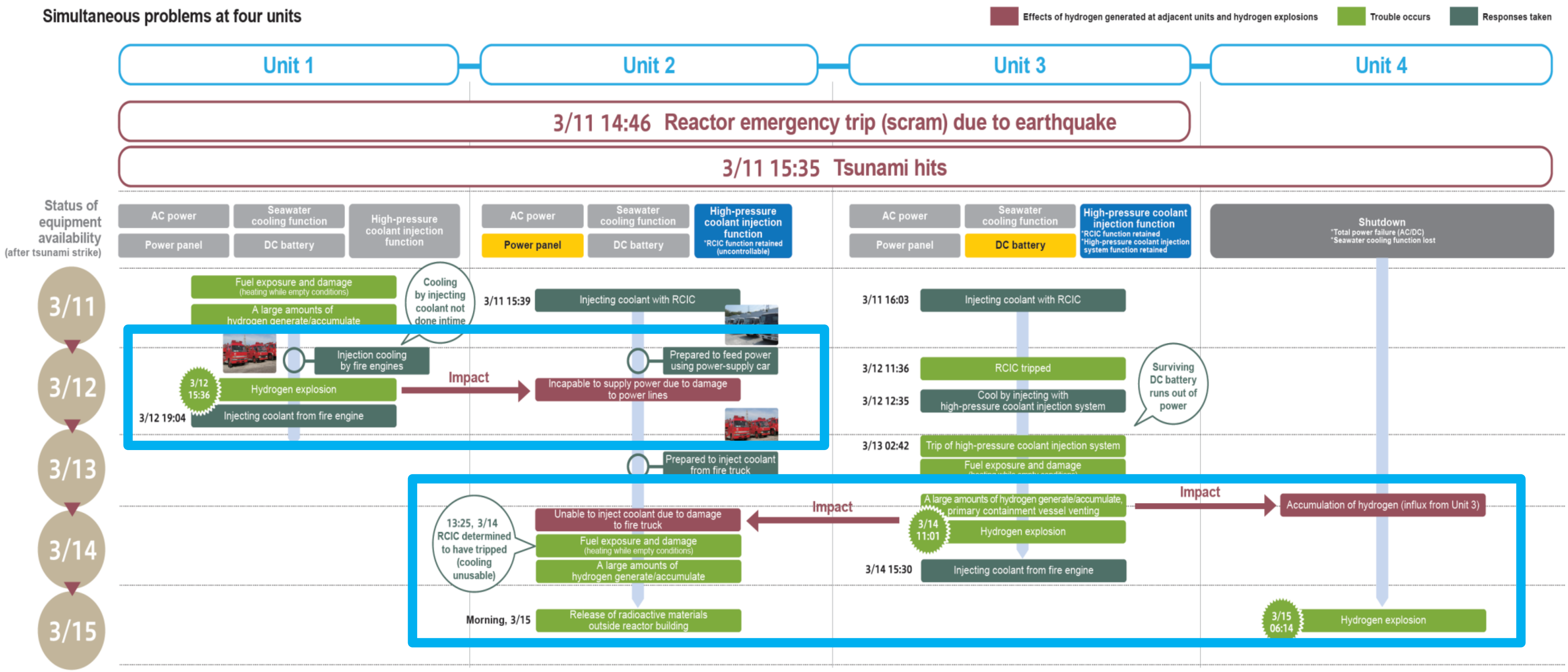


What if?

- Easy to say “if IC were not terminated”; “if RCIC and HPCI were not stopped manually”, … , etc.
- These afterthoughts are not totally correct.
- True that the reactor core seemed to have survived as long as IC or RCIC/HPCI were operating but this does not mean that the core could avoid core damage and melting w/o heat sinks.

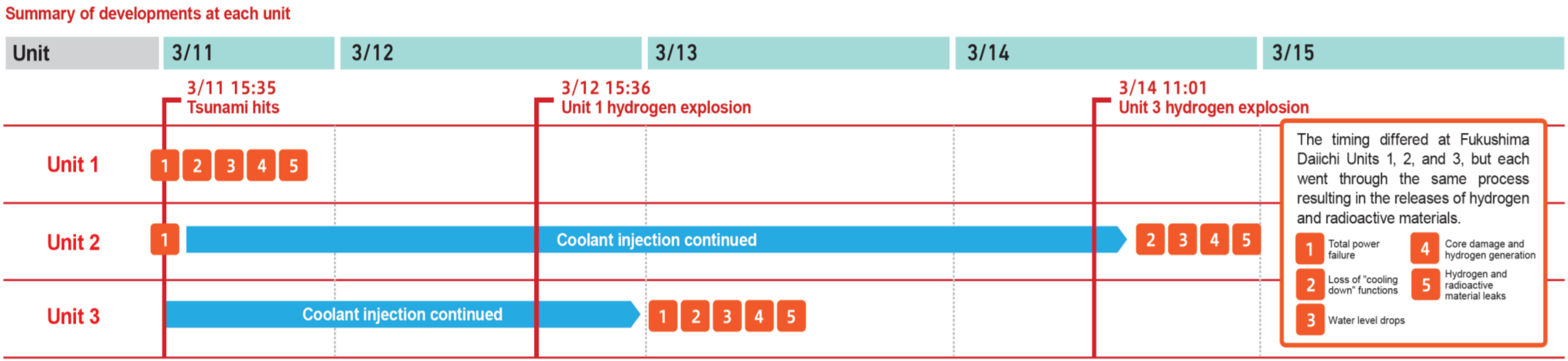
Magnification of damage

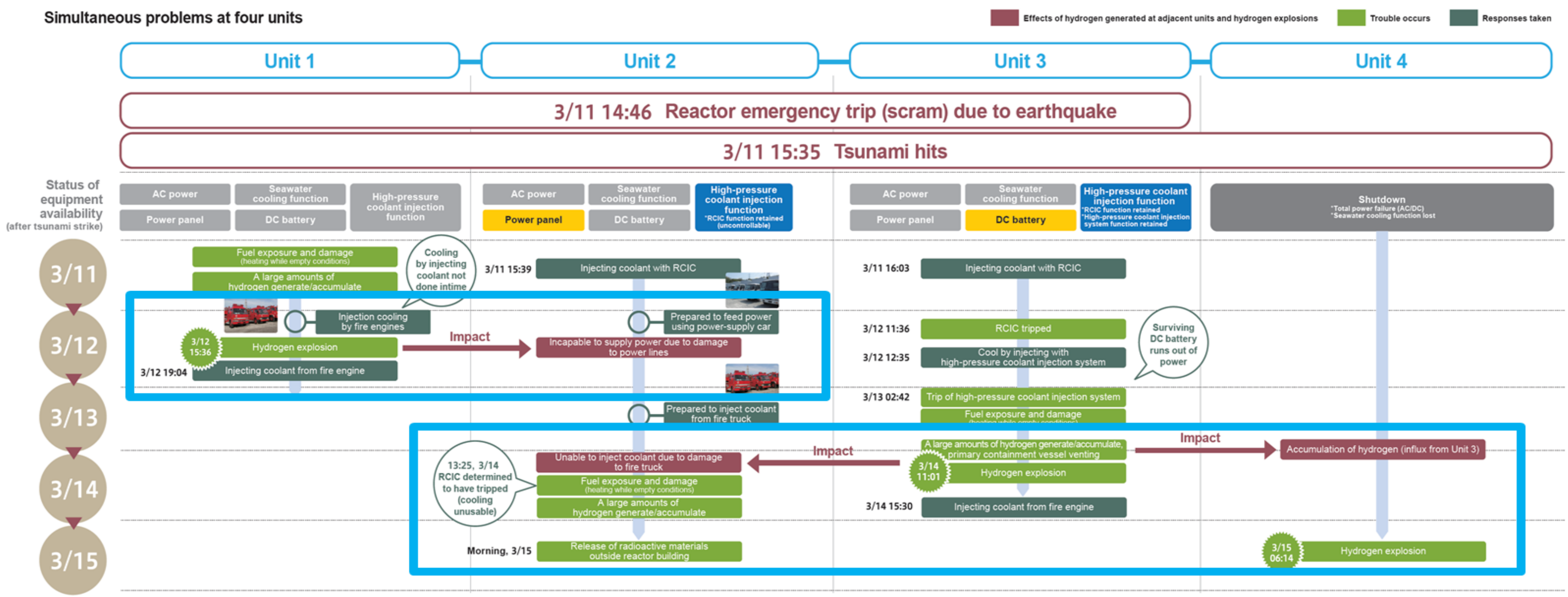
- Due to simultaneous accidents at Units 1~4



In this way, one of the lessons learned from the events is that the progression of the accident at one unit had a big impact on restoration work at the other units.

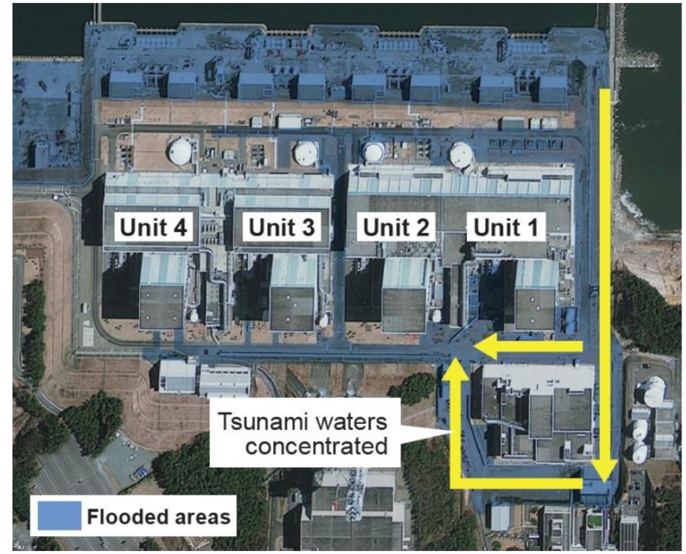
Development of Fukushima Daiichi accident





Fukushima Daini vs. Daiichi

	Unit 1	Unit 2	Unit 3	Unit 4
	3/11 14:48 Reactor emergency trip (scram) due to earthquake			
	3/11 15:22 Tsunami hits			
Status of equipment availability (after tsunami strike)	Offsite power (only one line) Emergency diesel generators (0 of 3 units)	Offsite power (only one line) Emergency diesel generators (0 of 3 units)	Offsite power (only one line) Emergency diesel generators (2 of 3 units)	Offsite power (only one line) Emergency diesel generators (1 of 3 units)
3/11	3/11 15:34 All emergency power supply tripped by tsunami 3/11 15:36 RCIC started manually (start injecting coolant into pressure vessel) 3/11 15:55 Depressurization using relief valve	3/11 15:34～15:41 All emergency power supply tripped by tsunami 3/11 15:41 Depressurization using relief valve 3/11 15:43 RCIC started manually (start injecting coolant into pressure vessel)	3/11 15:35 One emergency power source tripped by tsunami 3/11 15:46 Depressurization using relief valve 3/11 16:06 RCIC started manually (start injecting coolant into pressure vessel) 3/11 22:53 Start injecting coolant using make-up water condensate system 3/11 23:58 Trip RCIC by manual operation	3/11 15:34 Two emergency power sources tripped by tsunami 3/11 15:46 Depressurization using relief valve 3/11 15:54 RCIC started manually (begins injecting coolant into reactor) 3/12 0:16 Start injecting coolant using make-up water condensate system RCIC tripped
3/12	3/12 0:00 Start injecting coolant using make-up water condensate system 3/12 4:58 Trip RCIC by manual operation	3/12 4:50 Start injecting coolant using make-up water condensate system 3/12 4:53 RCIC tripped	3/12 9:37 Cooling mode started with residual heat removal system 3/12 12:15 Reactor in state of cold shutdown	3/12 12:32 Coolant injection begun using high-pressure core spray system 3/12 22:14 Coolant injection by make-up water condensate system tripped
3/13	Temporary power lines installed, and replaced on residual heat removal system cooling pumps and motors, etc.	Temporary power line installed		Power received through temporary lines, motors of residual heat removal system cooling pumps replaced, etc.
3/14～15	3/14 1:24 Residual heat removal system (in suppression pool cooling mode) started 3/14 10:05 Residual heat removal system (in low-pressure coolant injection [heat removal] mode) started 3/14 17:00 Reactor in state of cold shutdown	3/14 7:13 Residual heat removal system (in suppression pool cooling mode) started 3/14 10:48 Residual heat removal system (in low-pressure coolant injection [heat removal] mode) started 3/14 18:00 Reactor in state of cold shutdown		3/14 15:42 Residual heat removal system (in suppression pool cooling mode) started 3/14 18:58 Residual heat removal system (in low-pressure coolant injection [heat removal] mode) started 3/15 07:15 Reactor in state of cold shutdown



12 m above sea level

Future responses

Mid-and-Long Term Roadmap for Fukushima Daiichi Nuclear Power Station

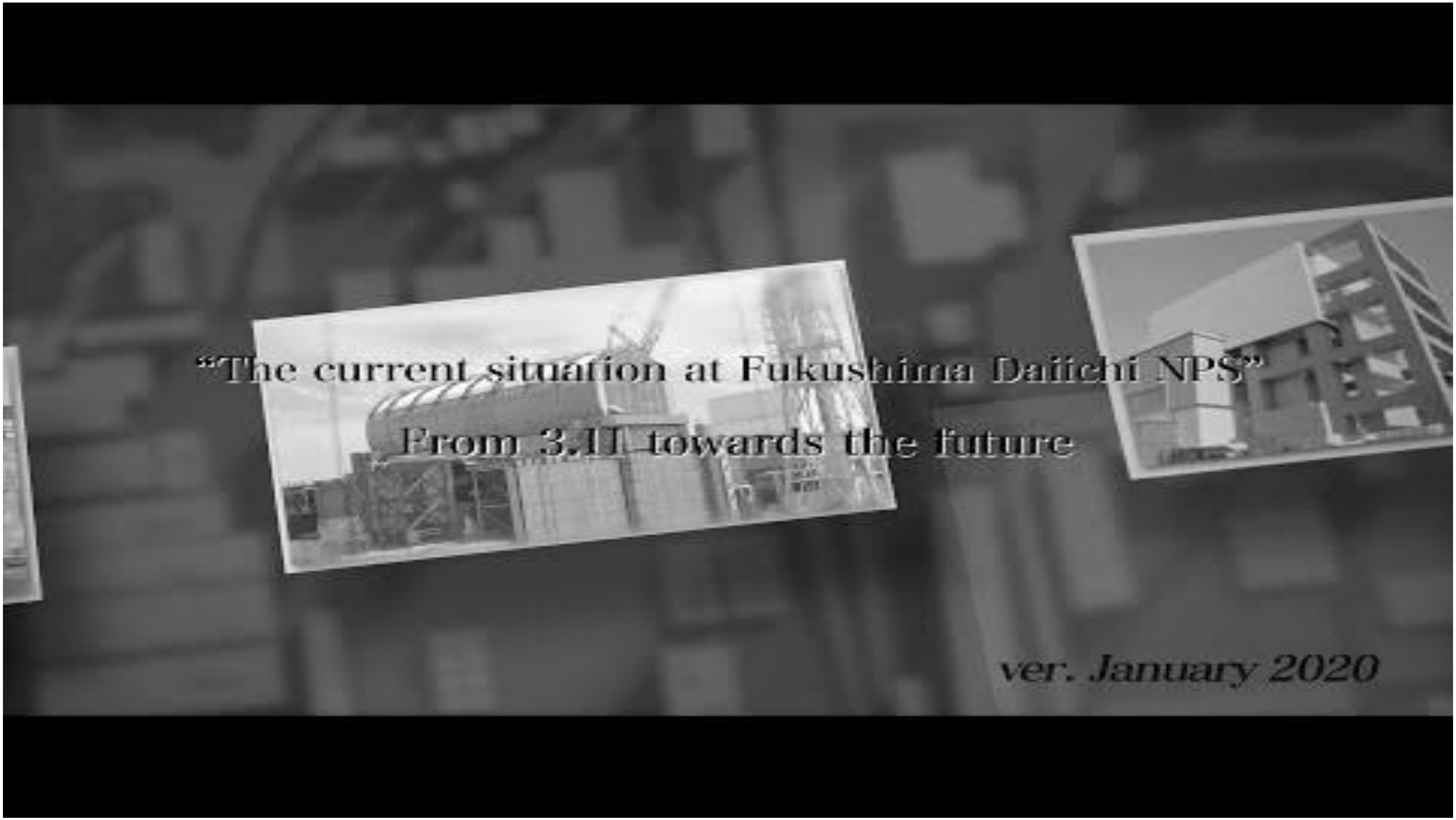
(announced December 2011)

Step 2 completed, December 16, 2011	Within 2 years of completing Step 2	Within 10 years of completing Step 2	30 to 40 years after completing Step 2
Step 1 Step 2	**1st Phase**	**2nd Phase**	**3rd Phase**
● Cold shutdown situation ● Broad control of release of radioactive materials	● Until removal of fuel from spent fuel pool begun	● Time until removal of fuel debris* is begun *Debris: Materials made of fuel, cladding tubes, etc. that have fused and re-solidified	● Time until decommissioning completed

Current status

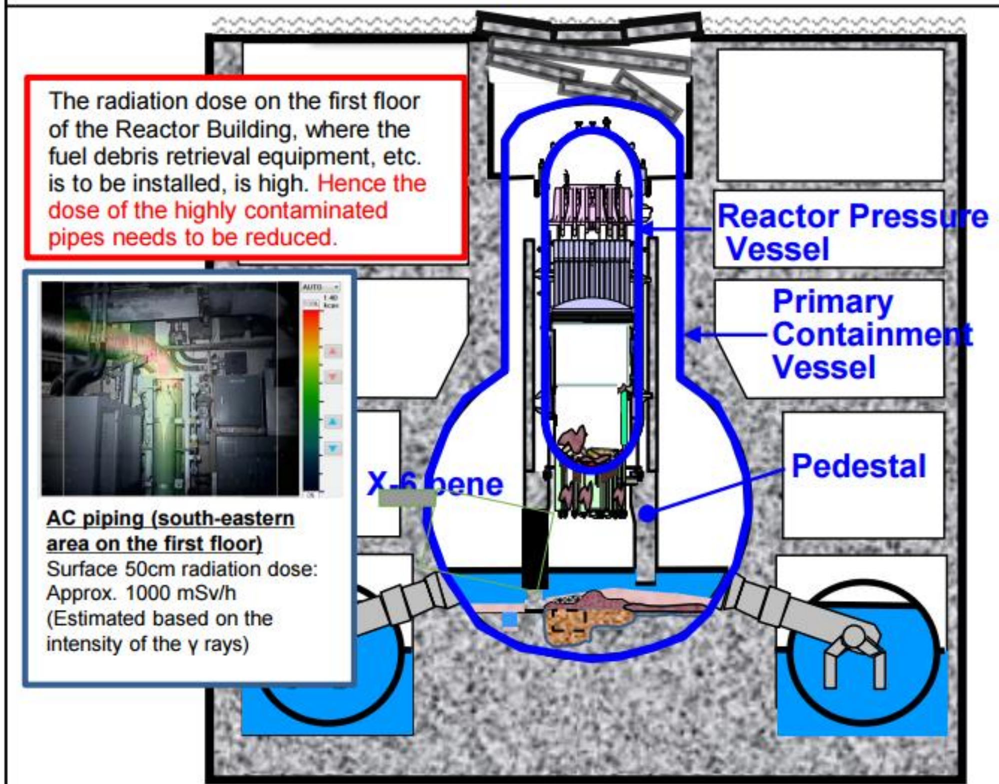
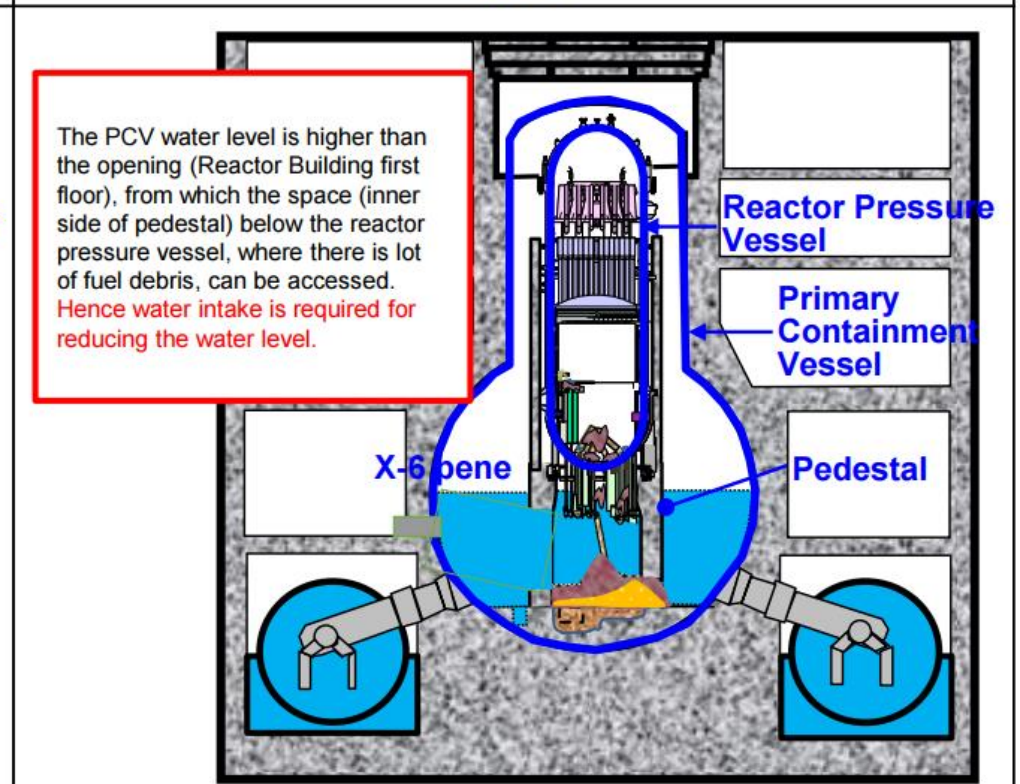
- https://www.tepco.co.jp/en/insidefukushimadaiichi/index-e.html

Future responses

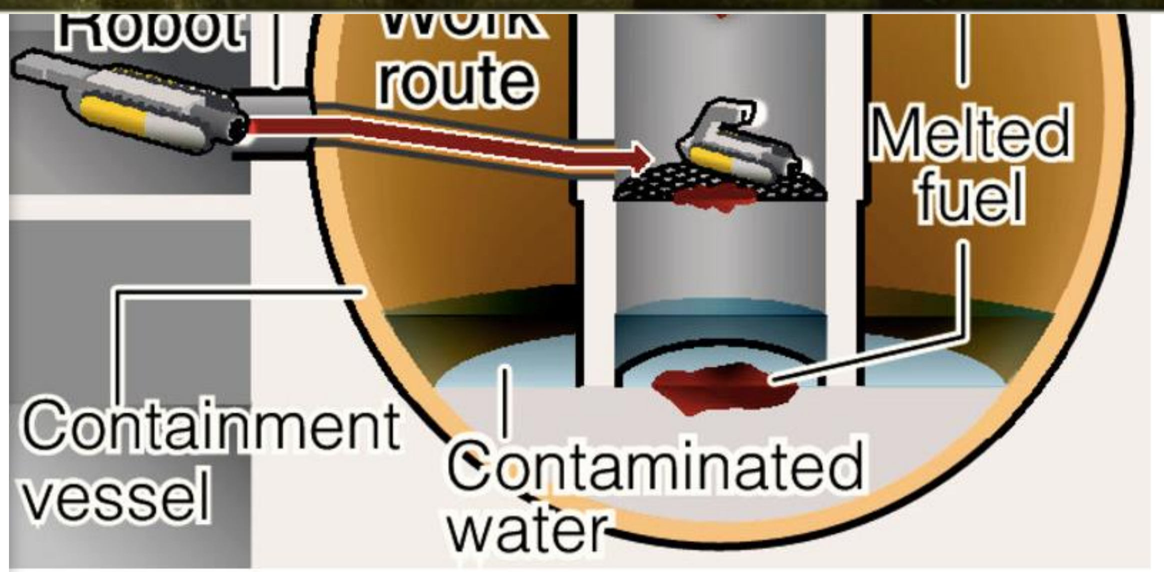


Fukushima Daiichi Nuclear Disaster

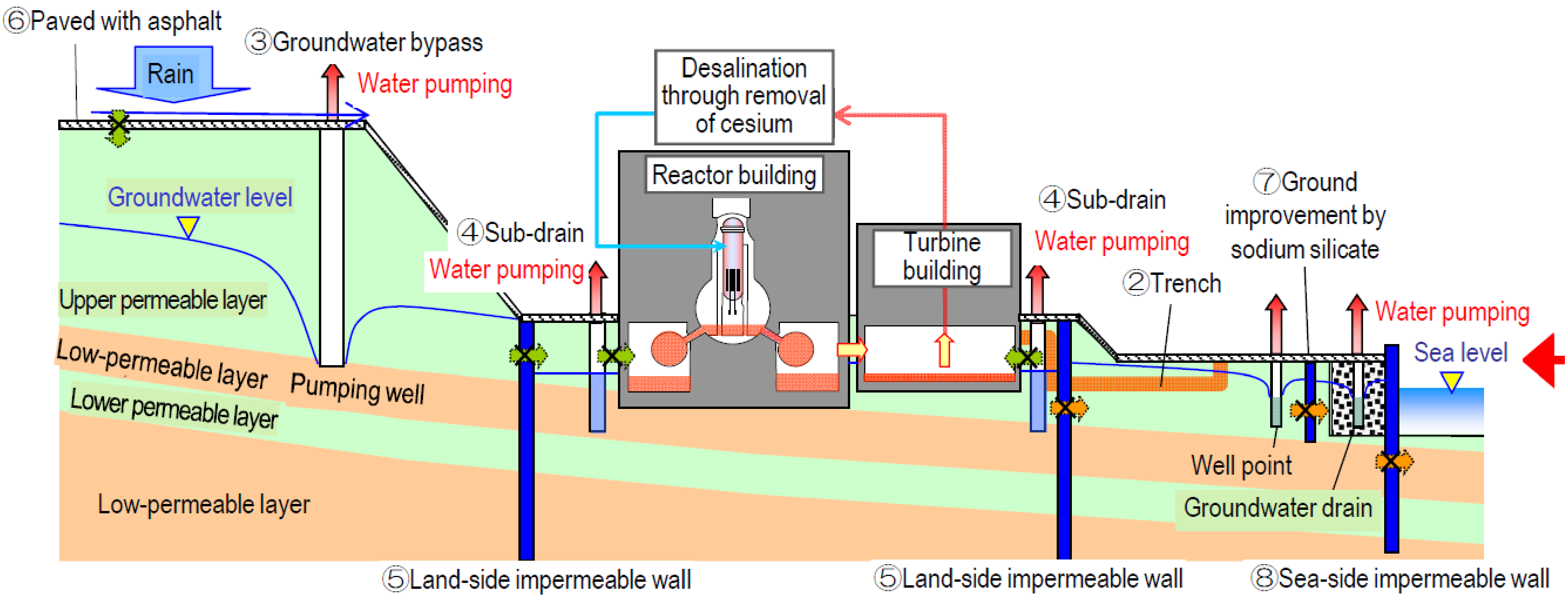
❖ Current status

Unit 1	Unit 3
	

- Current status

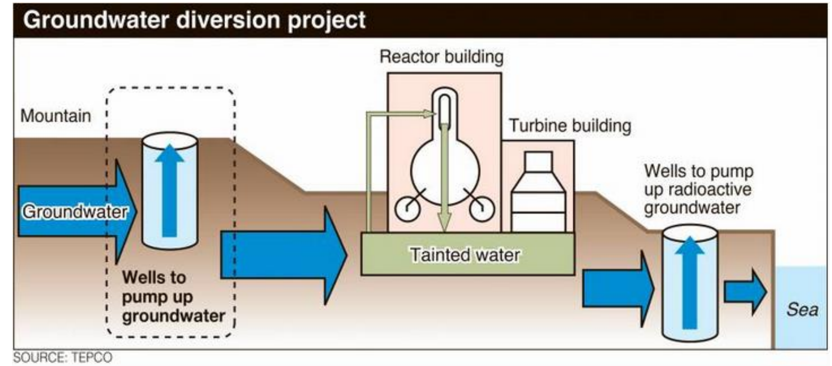


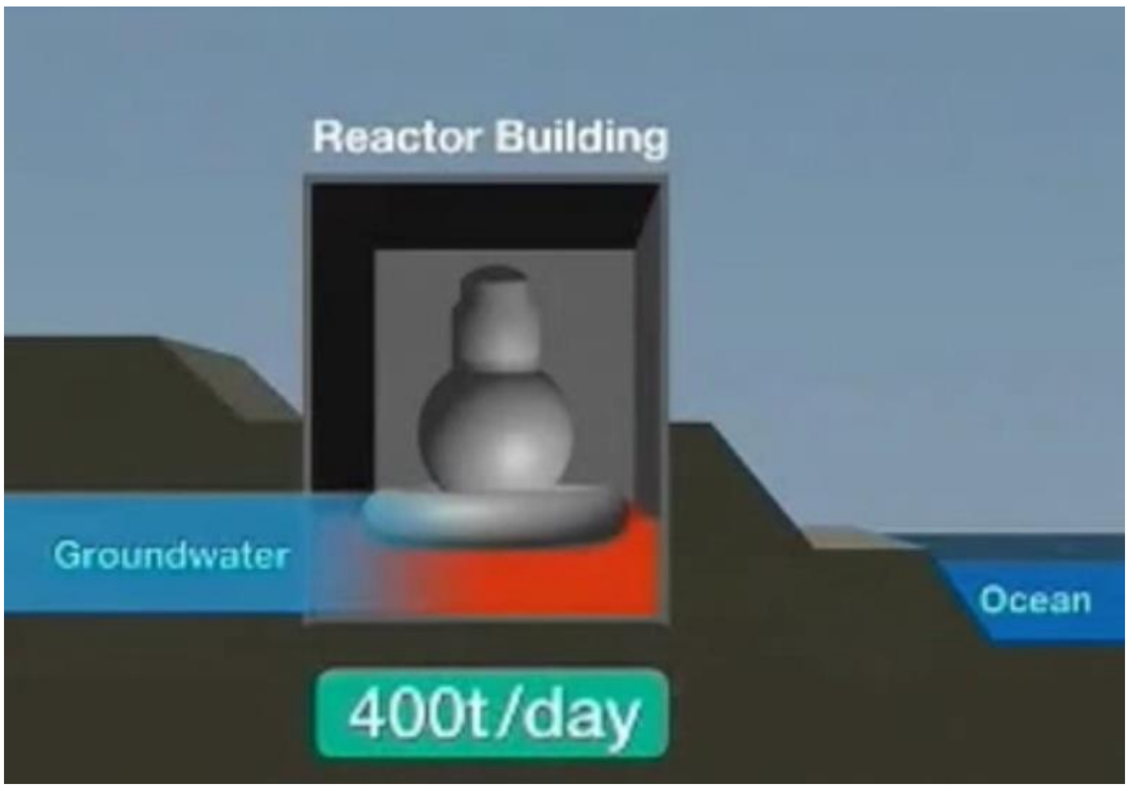
Reactor Circulation Cooling

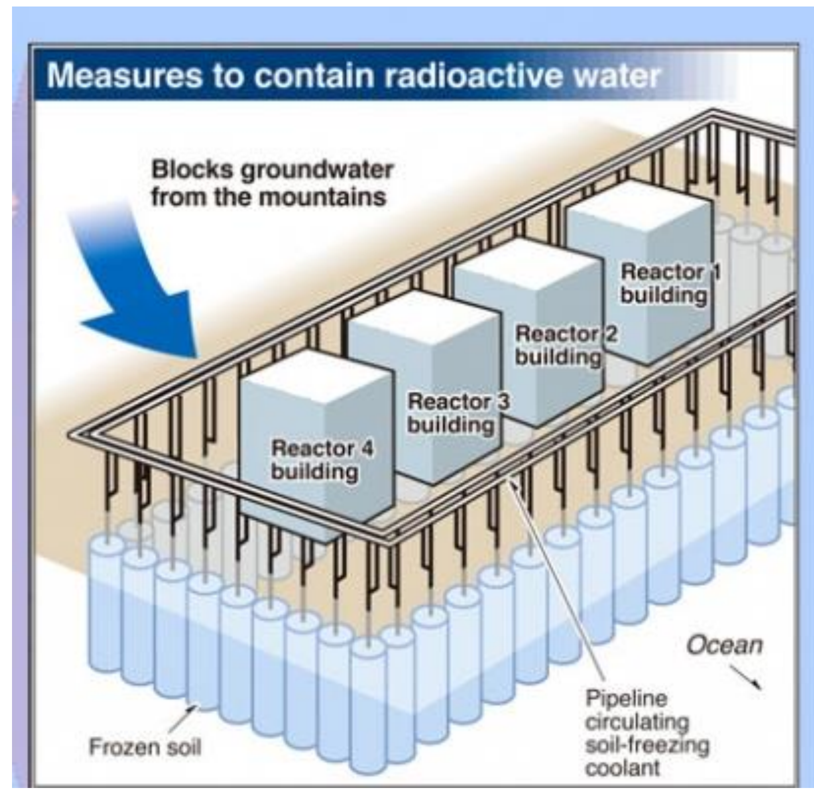


Fukushima Daiichi Nuclear Disaster

❖ Ground water

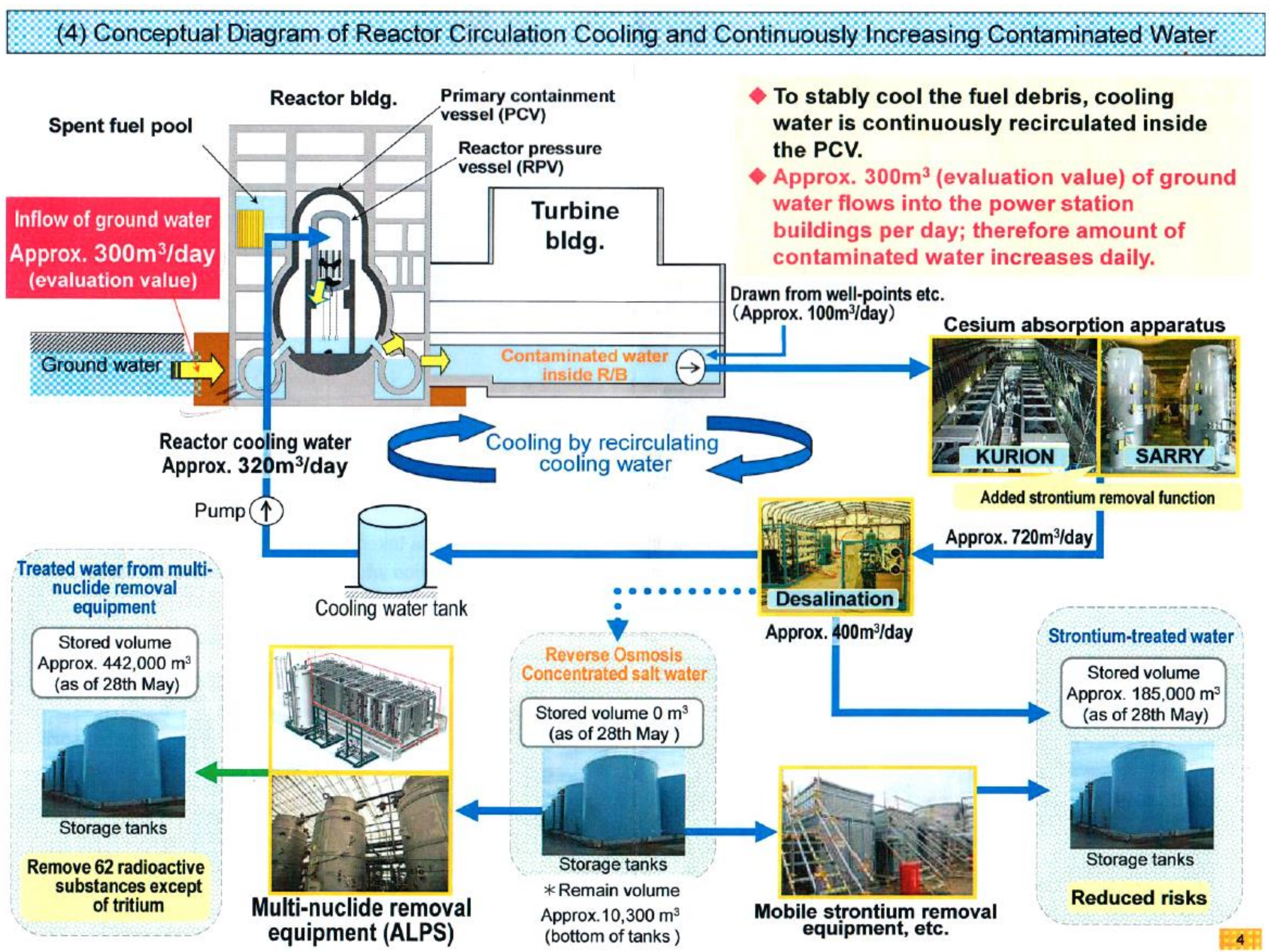






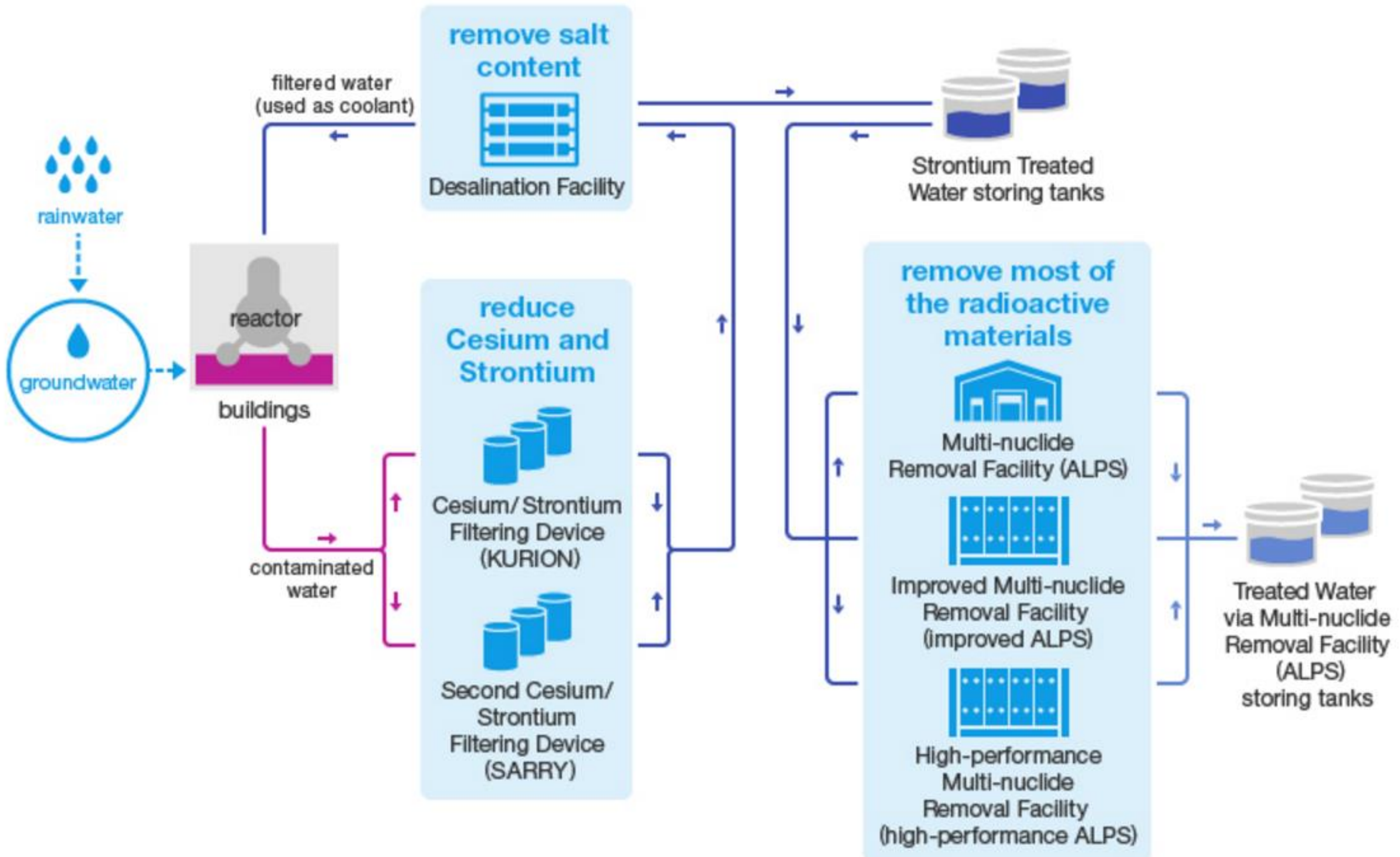
Fukushima Daiichi Nuclear Disaster

❖ Reactor Circulation Cooling



Fukushima Daiichi Nuclear Disaster

❖ Reactor Circulation Cooling



Fukushima Daiichi Nuclear Disaster

- Reactor Circulation Cooling https://www.youtube.com/watch?v=o0cwp-d5BSU