(1) Fukushima Accident and Current Status of NPPs in Japan

Follow-up Training Course (FTC) Indonesia

On Reactor Engineering (RE)

21 February 2025

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I. Outline of Fukushima Accident

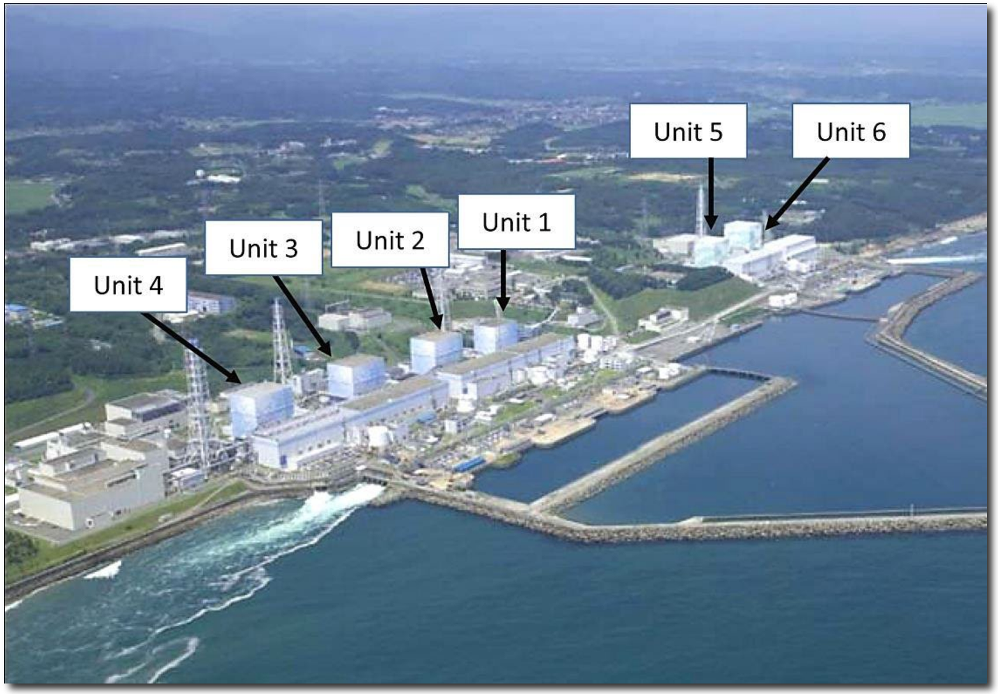
Understanding the accident of Fukushima Daiichi

Video by IRSN, France

source: Institute for Radiological Protection and Nuclear Safety (IRSN), France,

https://www.youtube.com/watch?v=YBNFvZ6Vr2U

Specification of Each Unit of the Fukushima Daiichi NPS



(11 March 2011)

* Primary Containment Vessel

	No.1	No.2	No.3	No.4	No.5	No.6
Output Power	**460 MWe (1971～)**	**784 MWe (1974～)**	**784 MWe (1976～)**	**784 MWe (1978～)**	**784 MWe (1978～)**	**1,100 MWe (1979～)**
Situation	Under Operation	Under Operation	Under Operation	Under Inspection	Under Inspection	Under Inspection
PCV* Type	**BWR Mark-Ⅰ**					**Mark-Ⅱ**

Epicenter of "Tohoku Pacific Earthquake" and Location of Fukushima Daiichi and Fukushima Daini NPSs

Fukushima Dai-ichi NPP

◆Distance from Epicenter: 180 km

Fukushima Dai-ni NPP

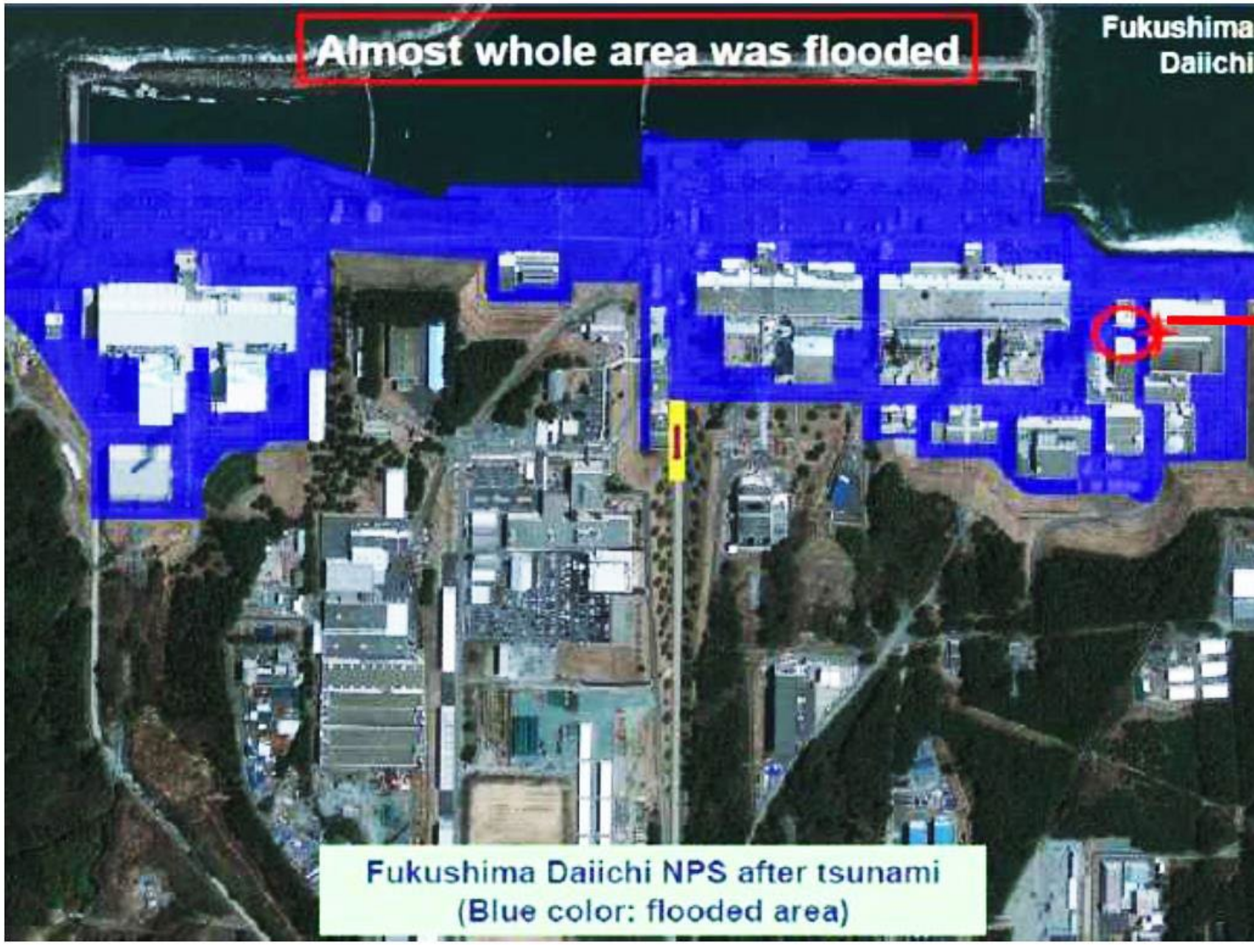
◆Occurrence: 14:46 March 11th , 2011
◆Magnitude: 9.0 Mw
◆Epicenter Location: 24km in Depth
<38º 6"N and 142º 51"E>
◆Height of Tsunami: Over 14m Height

Scene of Tsunami Attacking the Site (1/3)

Tsunami of 15m height easily overflowed the seawall of 10m height of the Fukushima Daiichi NPS 1hr after the big earthquake.

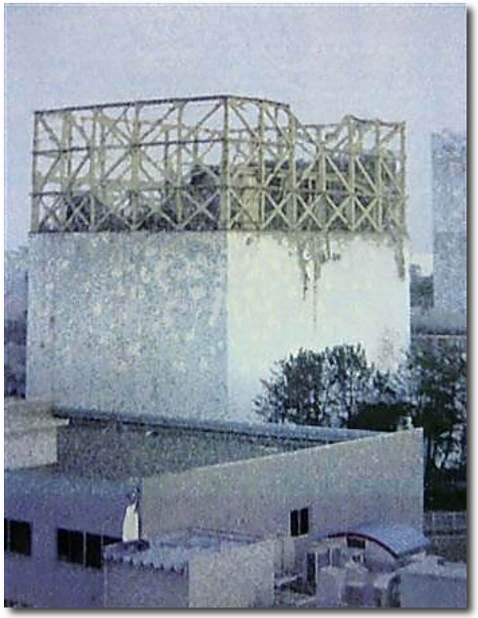
Scene of Tsunami Attacking the Site (2/3)

Fukushima Daiichi NPS was flooded about 5m due to the Tsunami of 15m height coming 1hr later of the earthquake. (for 5 min.)



Scene of Tsunami Attacking the Site (3/3)

Sky Photographs of Unit No.1-No.4 After the Accident



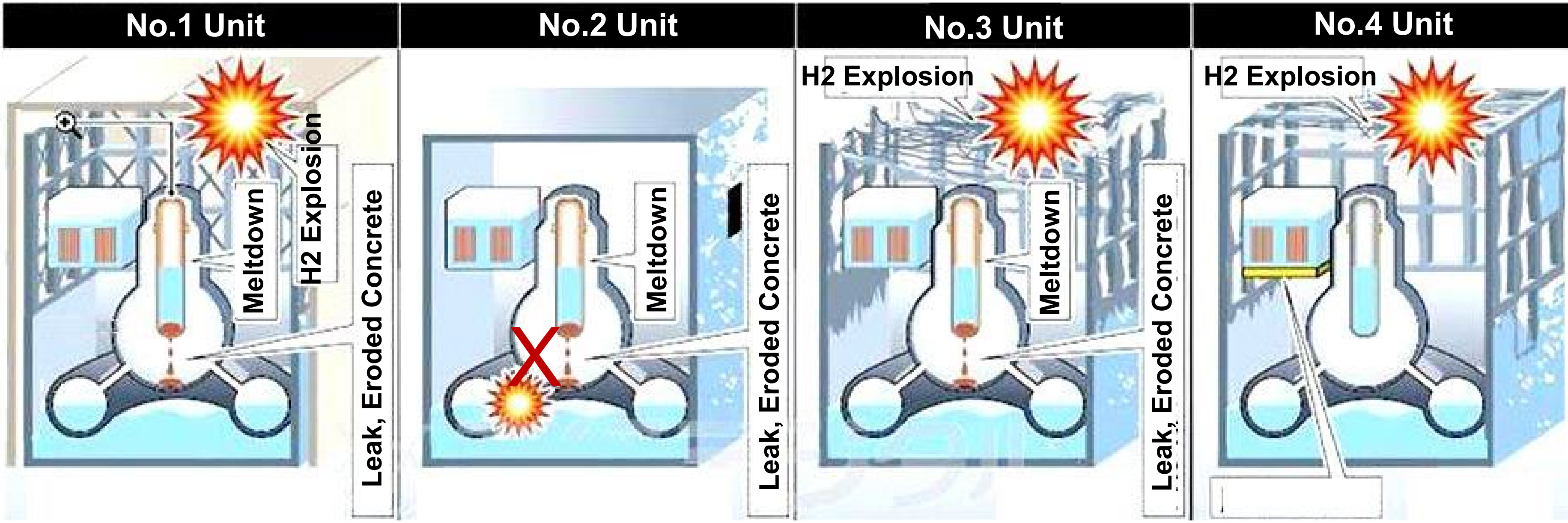
<Unit No.1>

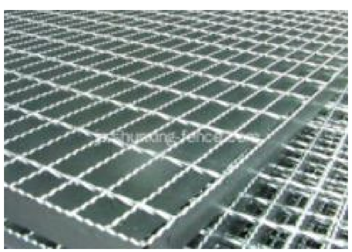
<Unit No.2>

<Unit No.3>

<Unit No.4>

Summarization of Each Unit's Damage (Unit No.1-No.4)

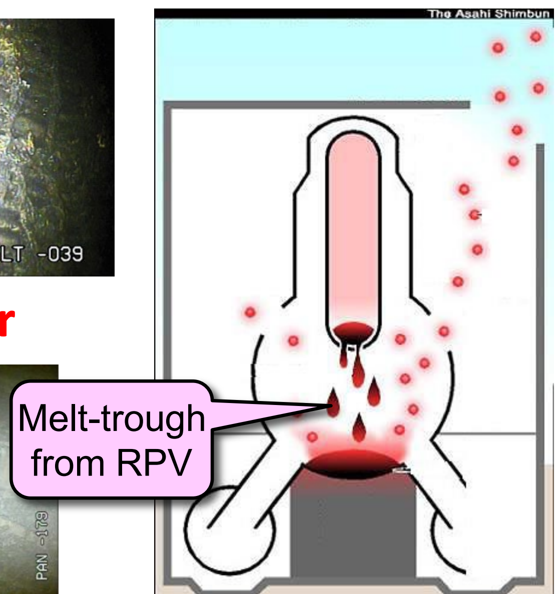




Grid

530 Sv/hr

2017.01.3
0



Fuel Meltdown

☞ Unit-1, Unit-2 and Unit-3

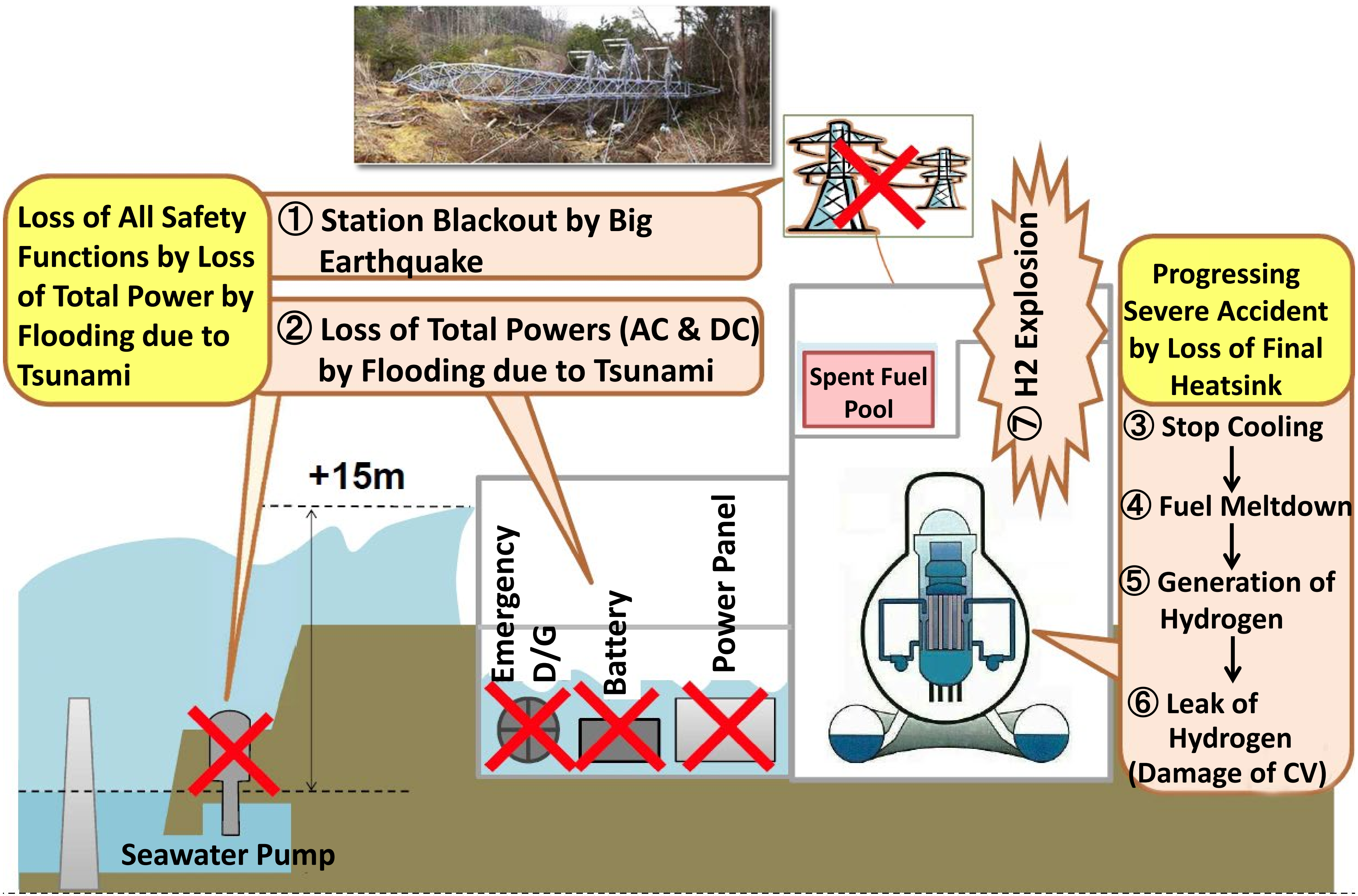
Hydrogen Explosion

☞ Unit-1, Unit-3 and Unit-4

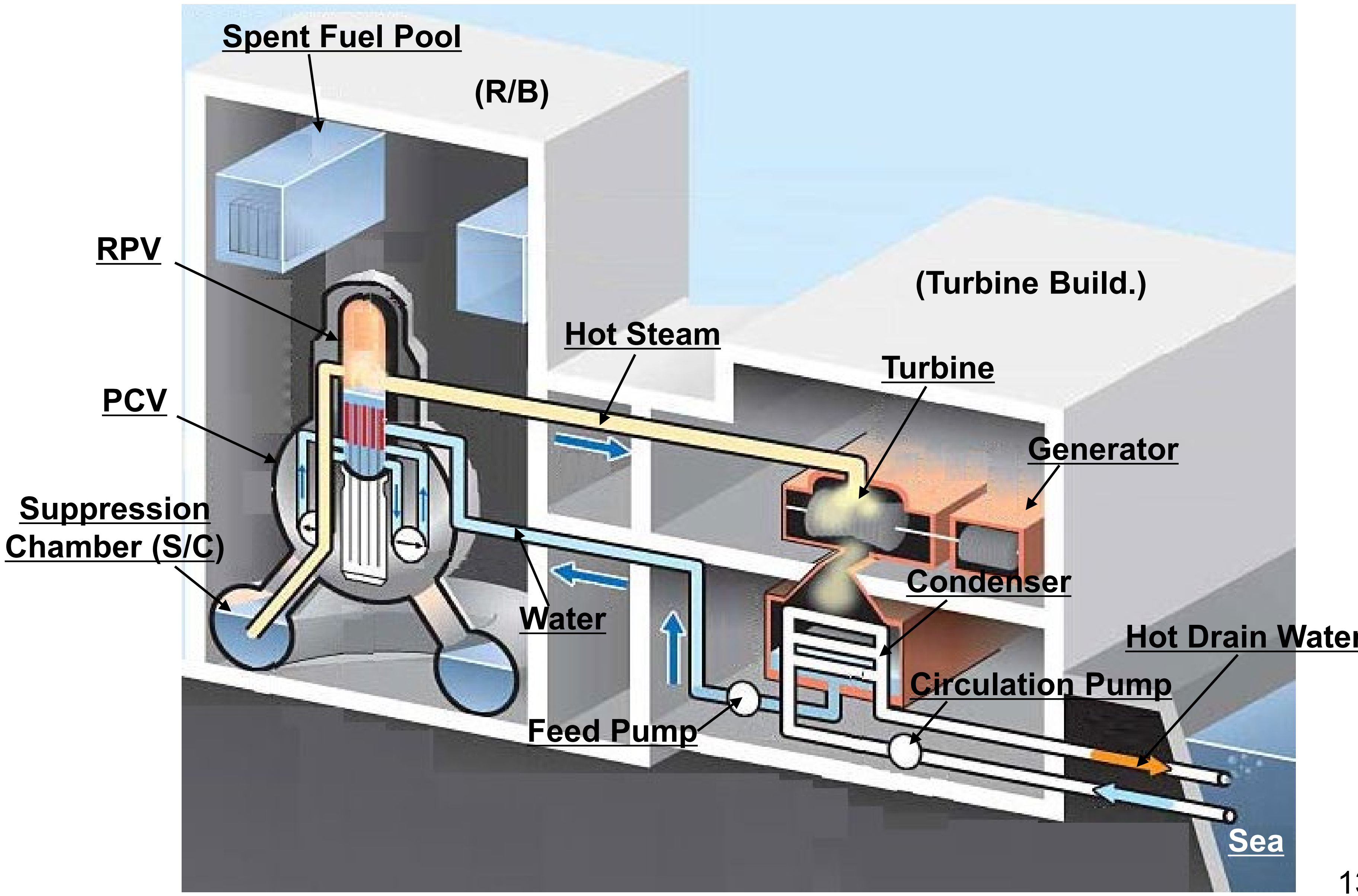
Broken of PCV

☞ Unit-2

Summarization of the Accident Progressing

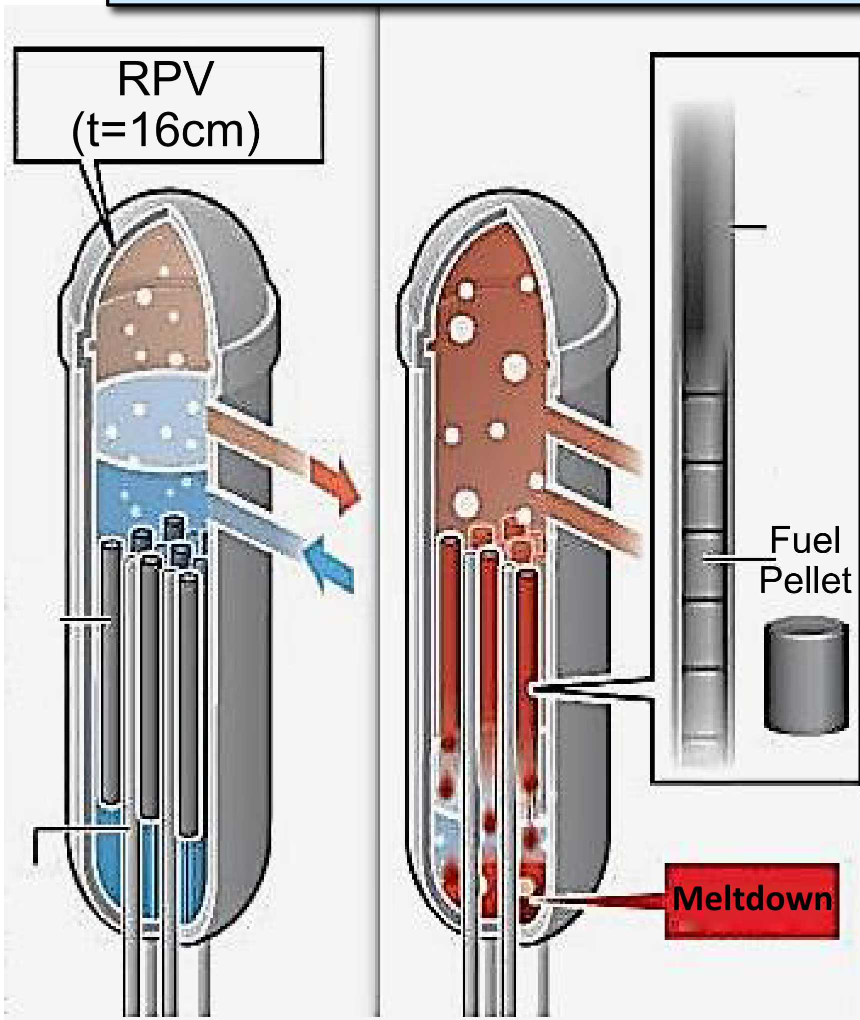


Side View of the BWR Type Power Plant



Fuel Meltdown due to LOCA (Loss of Coolant Accident)

A Core should be **cooled** even after Reactor Shutdown because of that **Decay Heat** remained in a core.



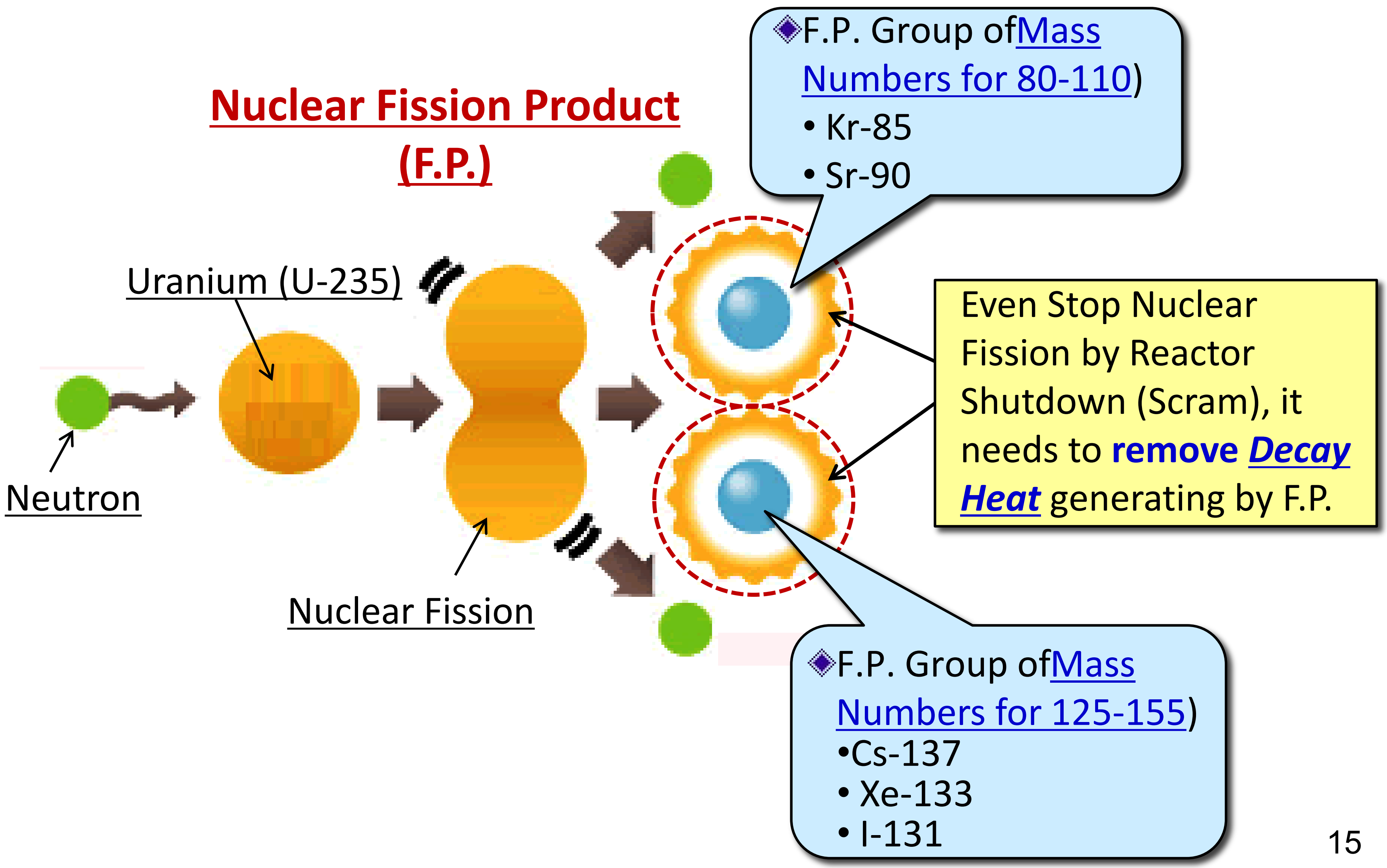
Normal State   LOCA State

Fuel Meltdown Time after Tsunami Flooding	
Unit-1	**After ~15h**
Unit-2	**After ~1011h**
Unit-3	**After ~60h**

(Reference)

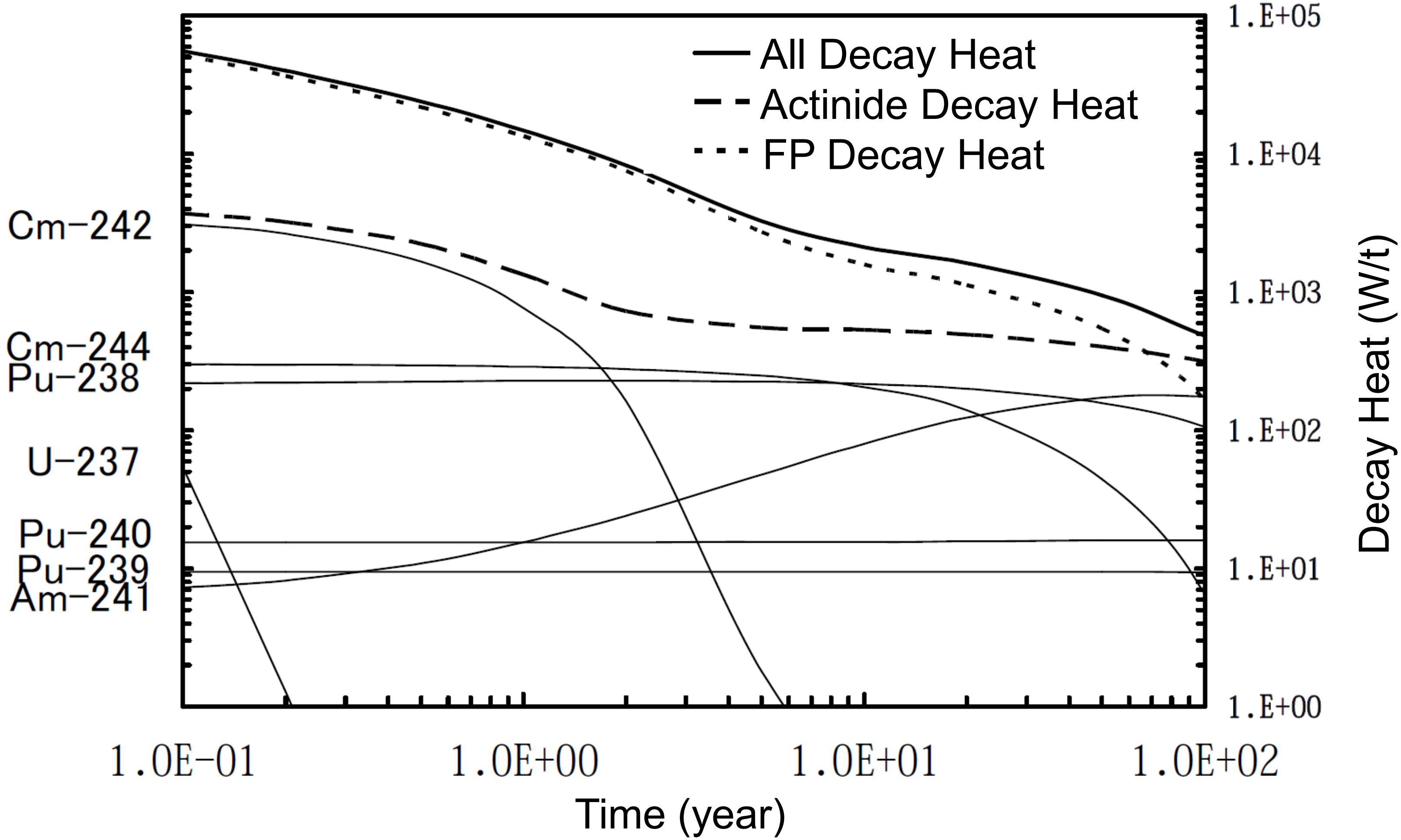
Fuel Pellet Temperature (U-235)	
Under Normal Operation	~1,740ºC
Melting Points under LOCA	
Fuel Pellet (U-235)	~2,400-2,860ºC
Fuel Cladding (Zircaloy)	~1,850ºC

What is "Decay Heat"? How to be produced…?



Decay Heat Curve of LWR (Uranium Fuel)

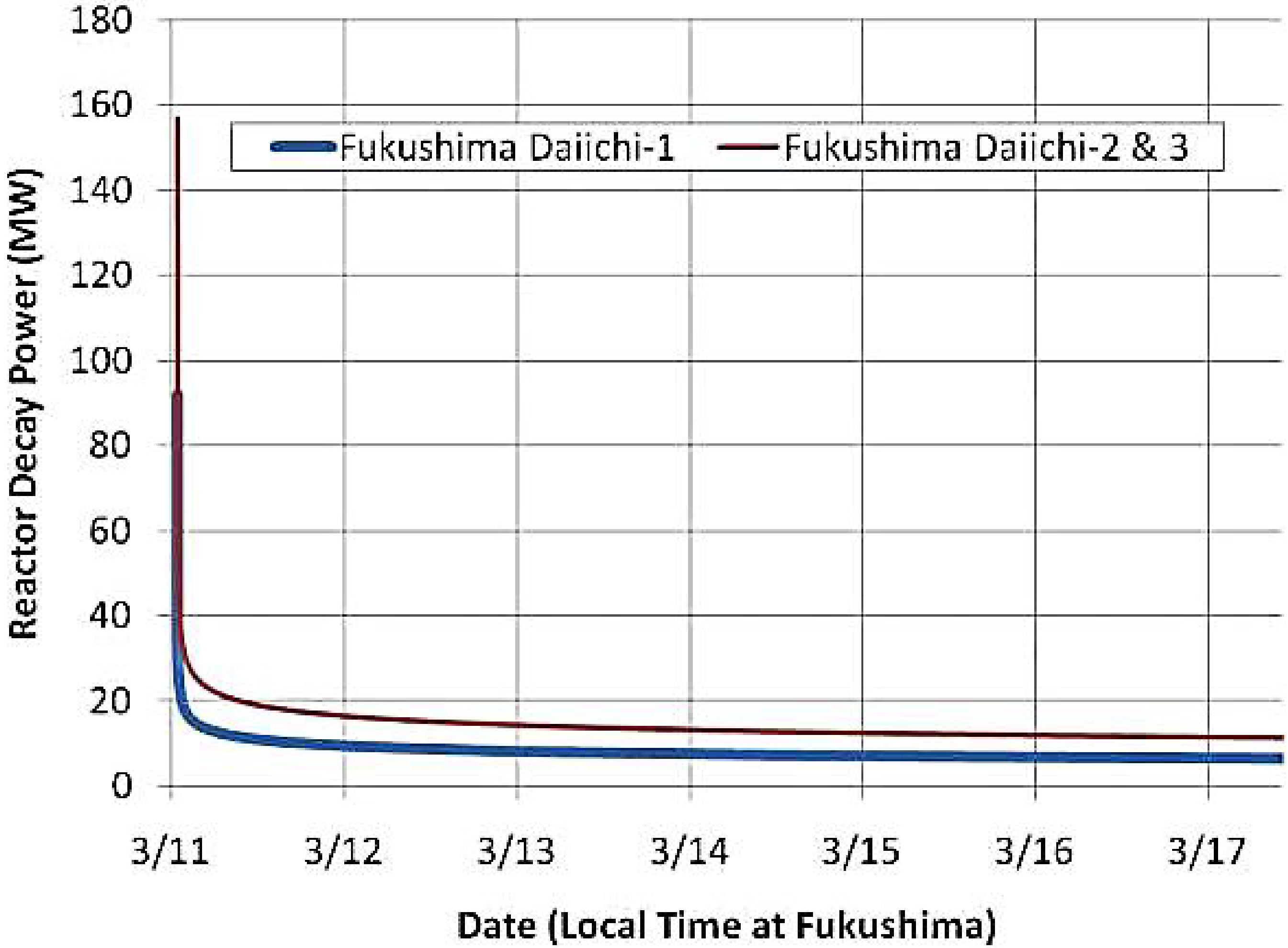
- Decay heat from Fission Products (FP) is dominant within several years.



Source: https://rpg.jaea.go.jp/else/rpd/annual_report/pdf64/No64-4.pdf

Decay Heat Curve of Fukushima Daiichi NPS (Unit No.1-No.3)

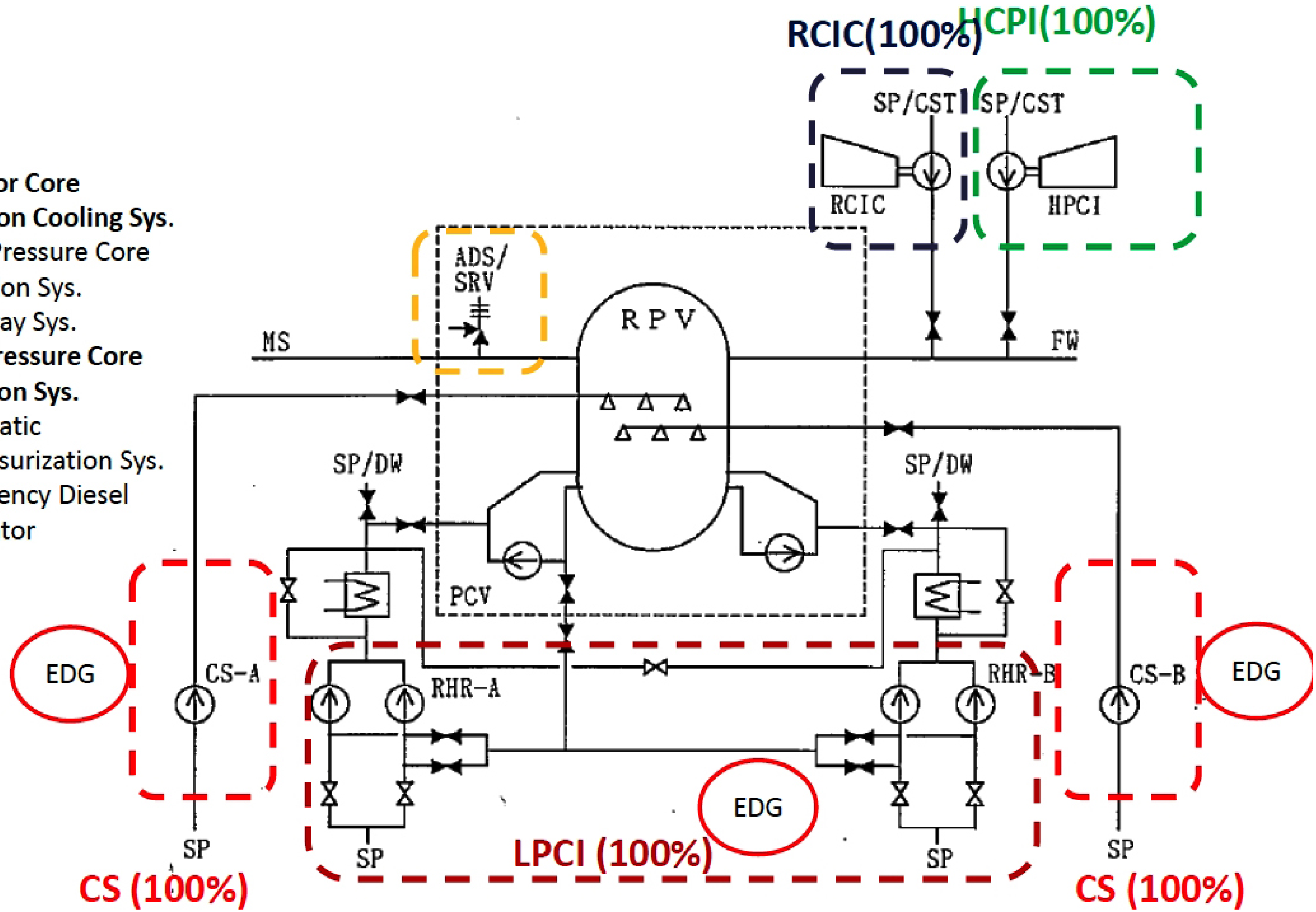
- The decay heat right after shutdown of nearly 7% of the rated power decreases very quickly, for example, it drops off to less than 1% after around 5 hours.
- However, it remains approximately 0.2% even one year later.



Source: http://mitnse.com/2011/03/16/what-is-decay-heat/

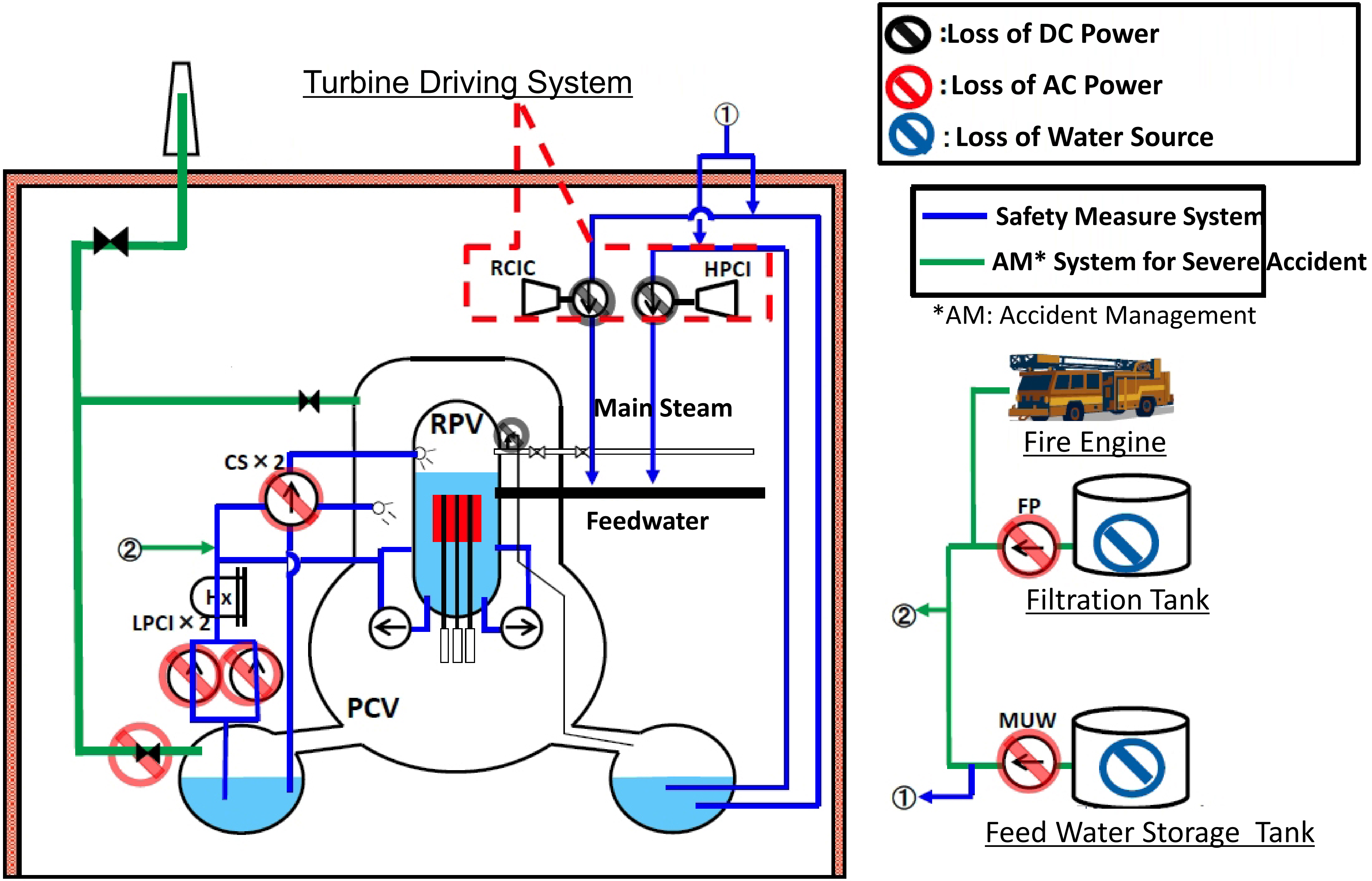
ECCS System of Fukushima Daiichi NPS (Unit No.2-4)

RCIC: Reactor Core Isolation Cooling Sys.
HPCI: High Pressure Core Injection Sys.
CS: Core Spray Sys.
LPCI: Low Pressure Core Injection Sys.
ADS: Automatic Depressurization Sys.
EDG: Emergency Diesel Generator



Source：https://www.nuc.tcu.ac.jp/wp-content/uploads/2014/11/1_moriya.pdf

Malfunction of ECCS System of Fukushima Daiichi NPS (Unit No.3)



Source: https://www.nuc.tcu.ac.jp/wp-content/uploads/2014/11/1_moriya.pdf

Why does Hydrogen Gas generate in LWR?

Hydrogen is produced from the following two reasons:

1) ***By Radiation Decomposition under Normal Operation***

Hydrogen is generated during normal operation by **Radiation Decomposition of Water Molecule**.

2) ***Chemical Reaction between Zirconium and Steam under High Temperature (Fuel Failure)***

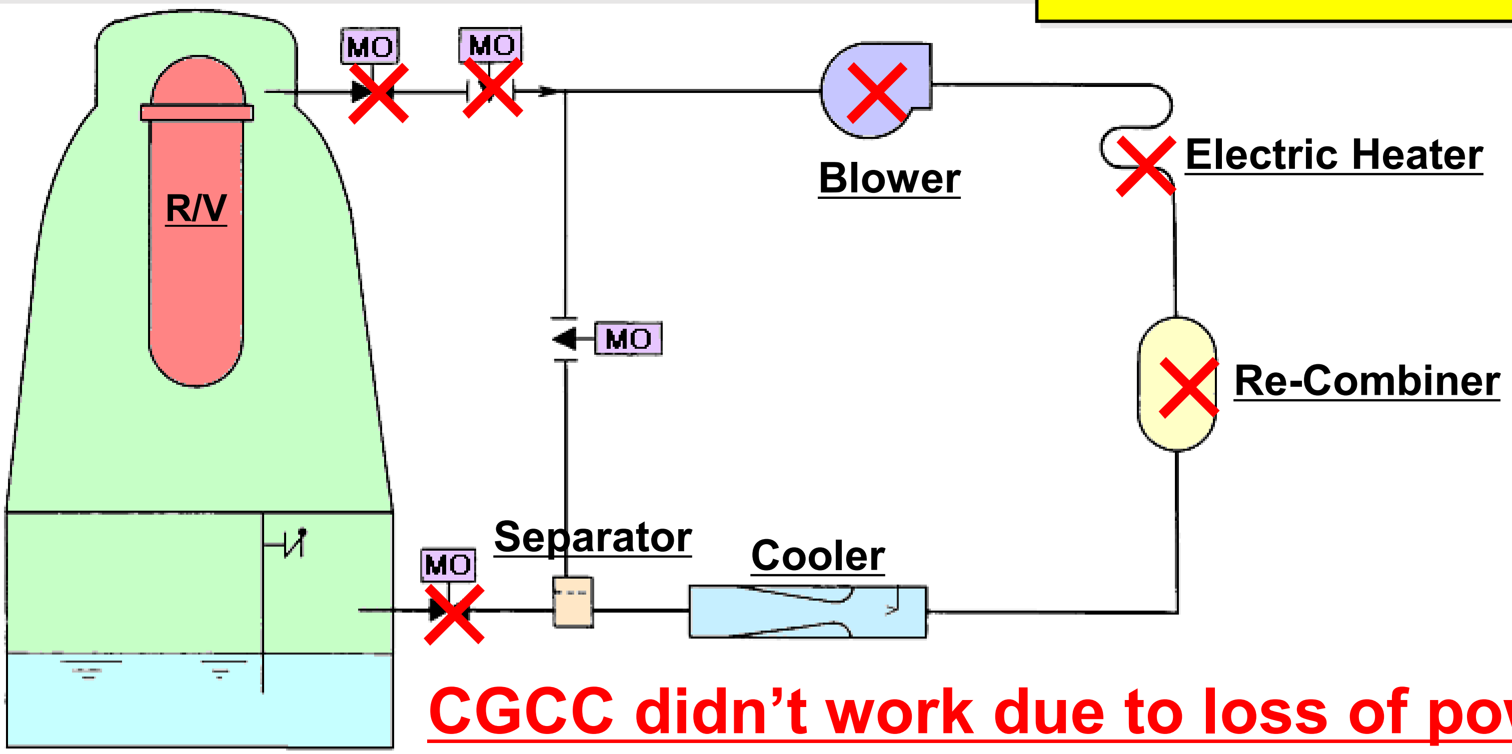
LWR uses Zirconium alloy (Zircaloy) as the material of fuel cladding tube. If the **temperature rises above 900ºC**, the following oxidation reaction of Zr becomes more pronounced. (Fuel cladding tube temp. exceeded **1,200ºC under the accident.**)

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

Malfunction of Combustible Gas Concentration Control System (CGCC) under the Accident

- The ***Concentration of Hydrogen*** produced in LOCA has to be controlled ***less than 4%*** which is the ***Explosion Limit Value***.
- By CGCC, Hydrogen is re-united with oxygen at a Re-combiner and then it is burned with an electric heater.

Function of CGCC

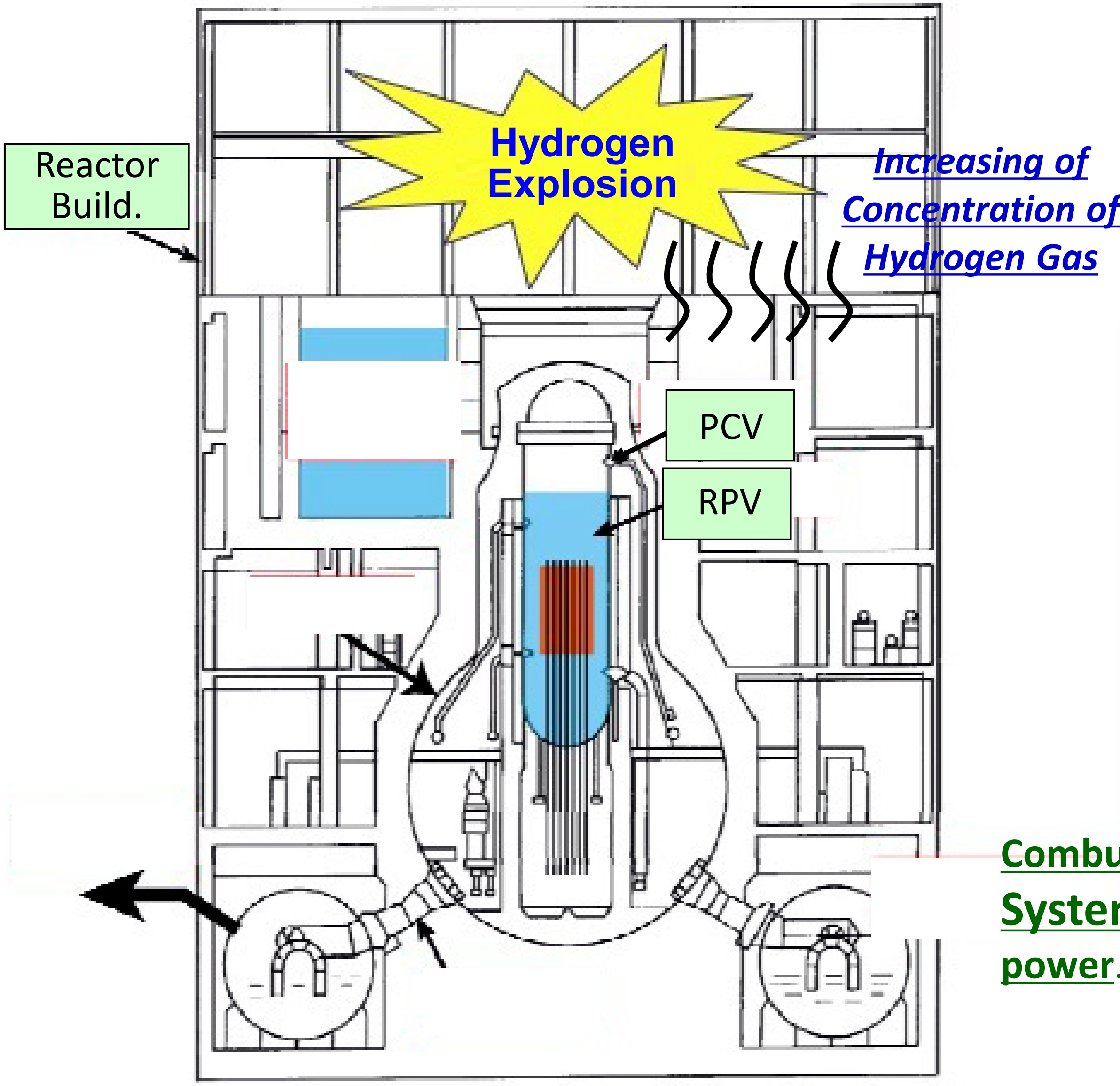


CGCC didn't work due to loss of power.

Source:http://www.rist.or.jp/atomica/data/dat_detail.php?Title_Key=02-03-04-01

Hydrogen Explosion at Unit-1

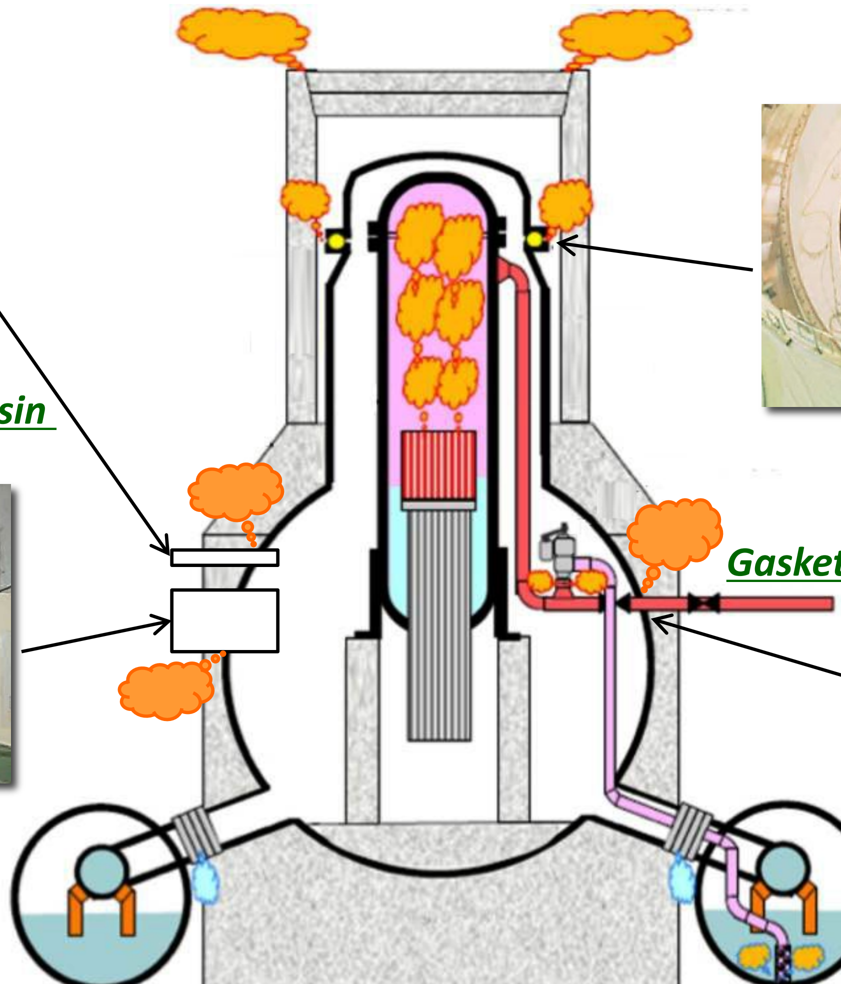
Hydrogen Gas Explosion occurred at Reactor Operating Floor (Outside of PCV)

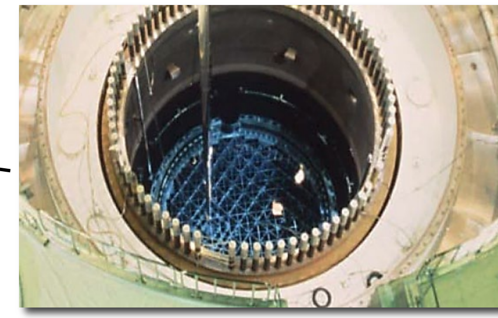


Combustible Gas Concentration Control System didn't work due to loss of power.

Why did Hydrogen leak from PCV?

<Cable Penetration>





<PCV Top Flange>

<Component Hatch>

<Pipe Penetration>

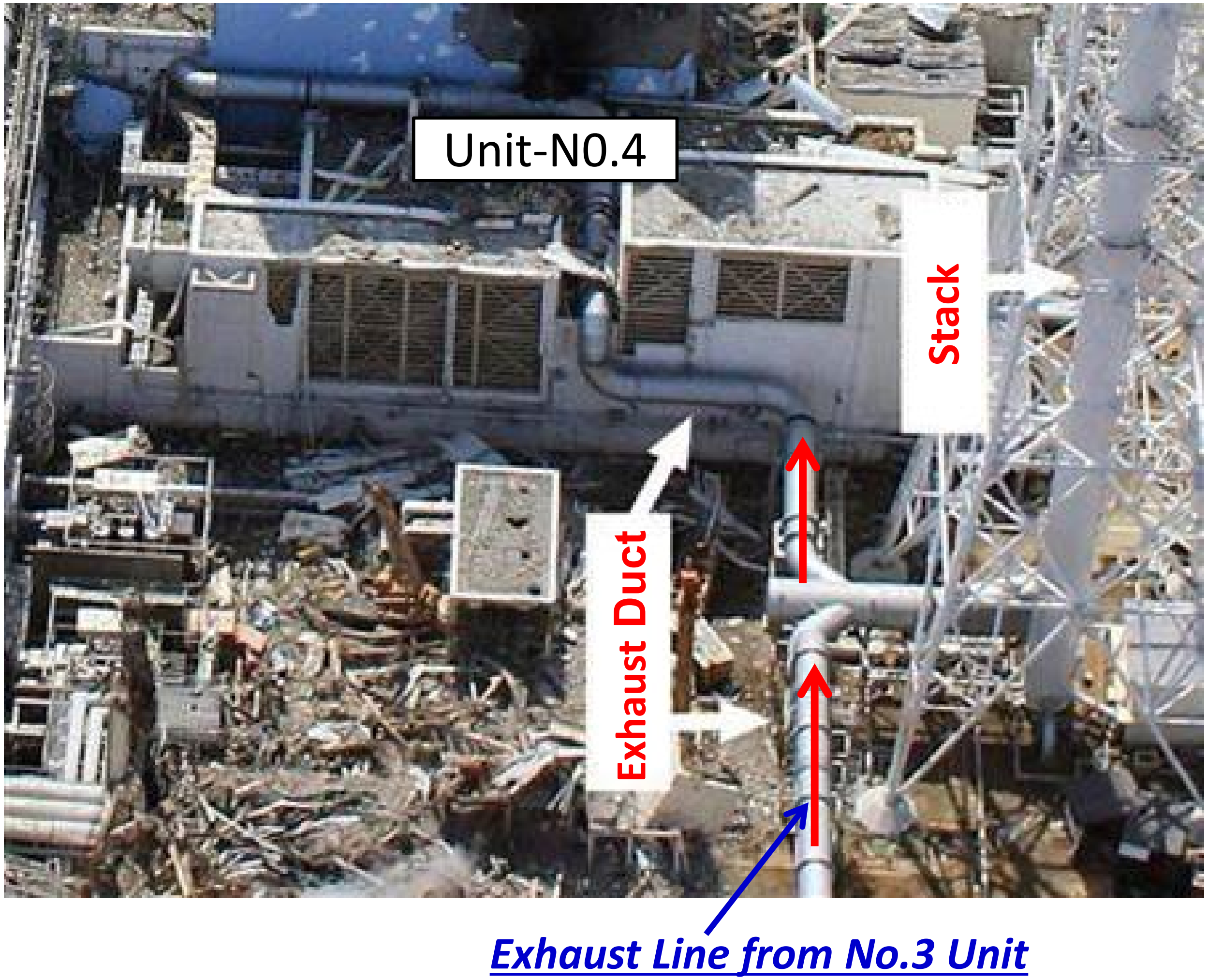
Cause of the Leak

Leak arose at some parts of PCV due to ***Degradation of Seal Materials of PCV Penetration***, which was caused by ***Overpressure and Heat Radiation from RPV***.

Hydrogen Explosion at Unit No.4 Causing by Careless Design

An Exhaust Stack Sharing by Unit No.3 and No.4

- As shown the right picture, a stack is shared by unit No.3 and No.4.
- When venting operation at unit No.3 have been carried out, it seemed that **hydrogen gas leaked into unit No.4 through a exhaust duct connecting with unit No.3's duct** due to a valve was opened by loss of driving power.



The Fact confirmed from the Accident

Influence by Earthquake

- A Reactor was shut downed automatically. ○
- All Emergency Diesel Generators worked automatically. ○
- All Equipment required for Cooling of a Reactor Core operated smoothly. ○
- The External Power lost by collapsing of the Power Transmission Steel Towers due to a landslide. ✕

Influence by Tsunami

- ☐ Important Equipment, such as Emergency Diesel Generators, Distribution Boards, Batteries, were flooded. ✕
- ☐ Total Power Loss (External Power + Emergency Diesel Generator + Battery) ✕
- ☐ Final Heat-sink lost caused by Seawater Pumps (Loss of Cooling Function) ✕

Resulted in Severe Accident due to ***LOCA*** (loss of coolant accident) caused by ***Total Loss of Power for Long Time*** and ***Loss of Final Heat-sink***

It is clear that ***Tsunami is the Direct Cause of the Accident***.

II. Radiation Exposure Situation of Radiation Workers in the Accident

Scenes of Radiation Work at Fukushima Daiichi NPS

Restoring Off-site Power and Water Circulation

1 week after

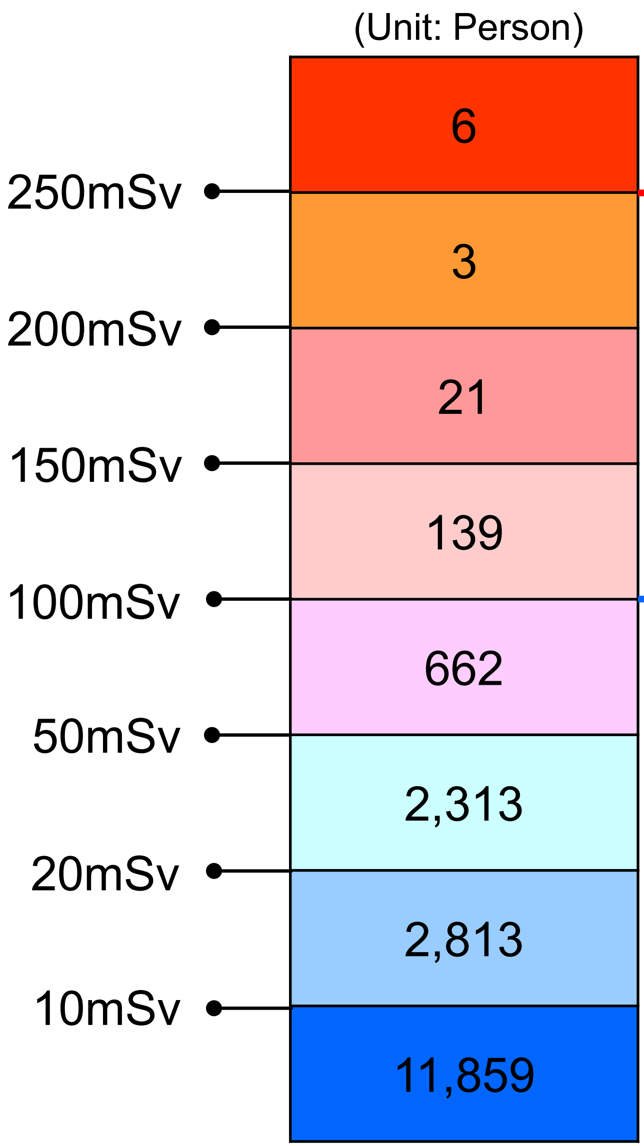

Restoration of External Power, installing portable power distribution board on March 18~19

Similar activities was performed in Fukushima Daini, too

Installing submersible pump for Unit 5 & 6

Restoring seawater pump in Fukushima Daini

Total Exposure Dose of Fukushima Daiichi NPS Radiation Workers in 2011



Allowable Dose Limit in Emergency Case (250mSv*)

*<u>***Temporary Standard***</u>:
This was firstly applied to the Fukushima accident.

Allowable Dose Limit in Normal Case (100mSv)

(Remark)
Although the National Institute of Radiological Sciences has conducted contamination inspection for about 2,300 workers working at Fukushima Daiichi NPS, ***nobody exceeded the standard value required decontamination****.

*Allowable Limit of Surface Density for Decontamination

- ◆<u>β-ray Emitter or γ ray Emitter: 40 Bq/cm^2</u>
- ◆<u>α-ray Emitter: 4 Bq/cm^2</u>

Source：https://www.tepco.co.jp/cc/press/betu11_j/images/111130s.pdf

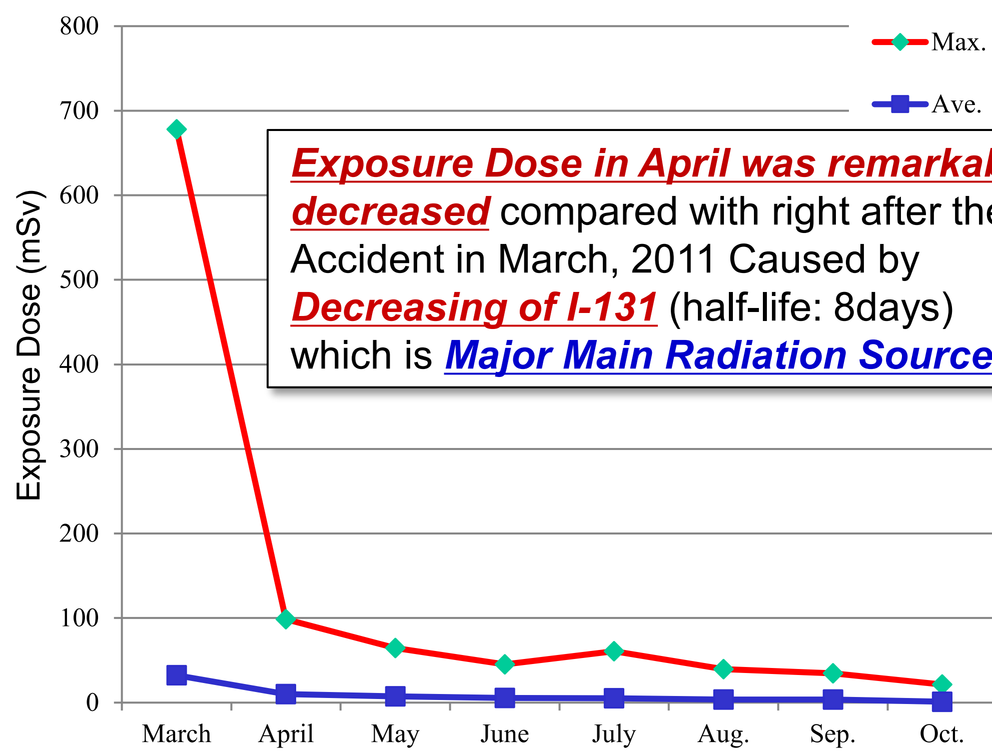
Total Exposure Dose of Fukushima Daiichi NPS Radiation Workers in 2011 (cont.)

	March	April	May	June	July	Aug.	Sep.	Oct.
Max. (mSv)	678.1	98.6	64.5	45.3	50.8	39.4	34.7	21.4
Ave. (mSv)	32.3	10.1	7.4	5.5	5.3	3.8	3.6	1.1

- Right after the Accident in March, Two workers were exposed ***over 650mSv*** exceeded greatly the ***Permissible Dose of 250mSv for Emergency Work*** (Provisional Value).

  ☞ **Mr. A: 678.1 mSv**
  Mr. B: 643.1 mSv

  They stuck their feet in the puddle.
- While, the *max. average vale is 32.3mSv* in March.
- From May, the average dose transitions under 10mSv.



Exposure Dose in April was remarkably decreased compared with right after the Accident in March, 2011 Caused by ***Decreasing of I-131*** (half-life: 8days) which is ***Major Main Radiation Source***.

Source: https://www.tepco.co.jp/cc/press/betu11_j/images/111130s.pdf

Evaluation of Fukushima Radiation Worker's Exposure Dose

Evaluation for Two Workers Exposed over 600mSv

◈As the result of a detailed diagnostic, the following points were revealed:

Breakdown of Exposure

- Mr. A: 678.1mSv = (External: 88.1mSv + ***Internal: 590mSv***)
- Mr. B: 643.1mSv = (External: 103.1mSv + ***Internal: 540mSv***)

☞ *Main Source of Internal Exposure*: ***I-131 (β-ray)***
Accumulated Part of Internal Exposure: Thyroid Gland mainly

◆Short-term Symptom: ***Acute Radiation Disease*** (alopecia, etc.)→ ***No Appear***

◆Long-term Symptom: ***Cancer Risk*** → Evaluation and Periodical Medical Check

☞One Worker has been attacked with ***Leukemia***, who was exposed to ***15.7mSv*** during 1year and 1mont from Oct. 2012 to Dec. 2013.

The Ministry of Health, Labor and Welfare accepted Occupational Injury on 10/20, 2015.

◈Exposure over 5mSv per year

◈Get sick after more over 1year after exposed

Source : http://www.tepco.co.jp/cc/press/11061010-j.html

Integrated dose during March 2011 to November 2015

Workers of TEPCO and related companies

Effective dose (mSv)	People
> 250	6
200 - 250	3
150 - 200	28
100 - 150	137
75 - 100	570
50 - 75	2020
20 - 50	6932
10 - 20	6248
5 - 10	5822
1 - 5	10389
1 <	13736
Total	45891
Max	678. 80 mSv
Average	12. 63 mSv

3.30 mSv in 2015 for 16,605 people

Residents

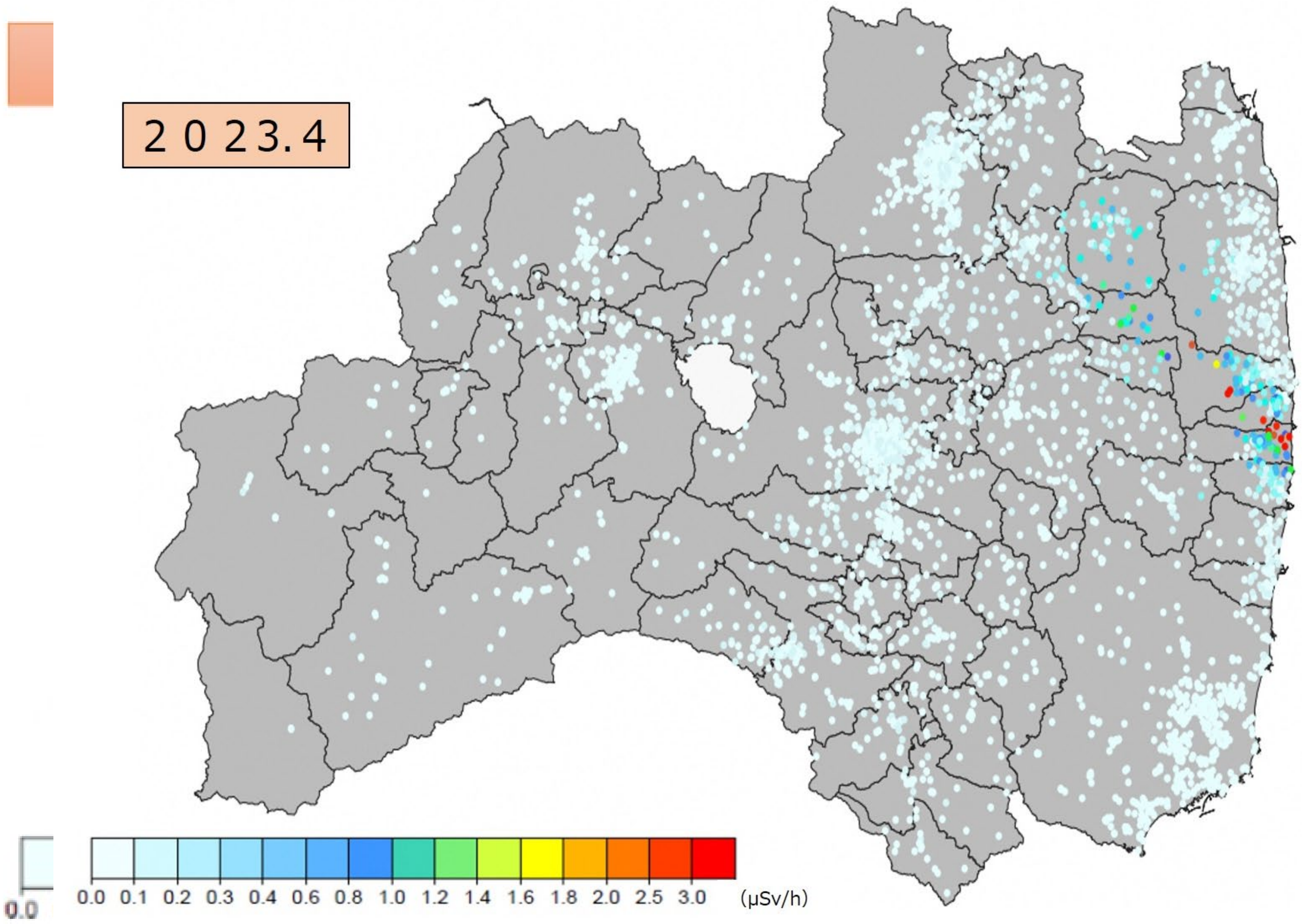
Effective dose (mSv)	People
Max	25mSv
> 15	11
14 - 15	6
13 - 14	12
12 - 13	13
11 - 12	31
10 - 11	33
9 - 10	39
8 - 9	73
7 - 8	114
6 - 7	225
5 - 6	373
4 - 5	494
3 - 4	1382
2 - 3	22600
1 - 2	134848
1 <	261140

Dose limit in Japanese standard

Radworker : 20 mSv/year, 100 mSv/5years → 250 mSv in the 1F accident (Emergency)
Resident : 1 mSv/year → 20 mSv/year (Existing exposure)

III. Present Ambient Dose Rate at Fukushima Area

Fukushima Prefecture Radioactivity measurement map



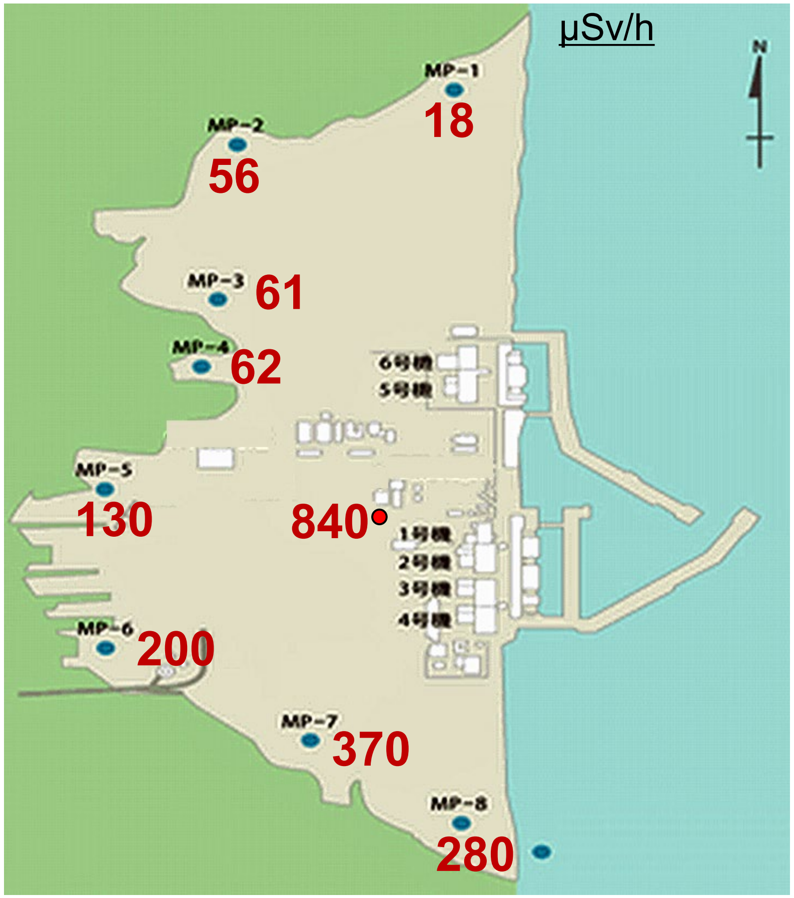
μSv/h

https://fukushima-radioactivity.jp/pc/?lang=en

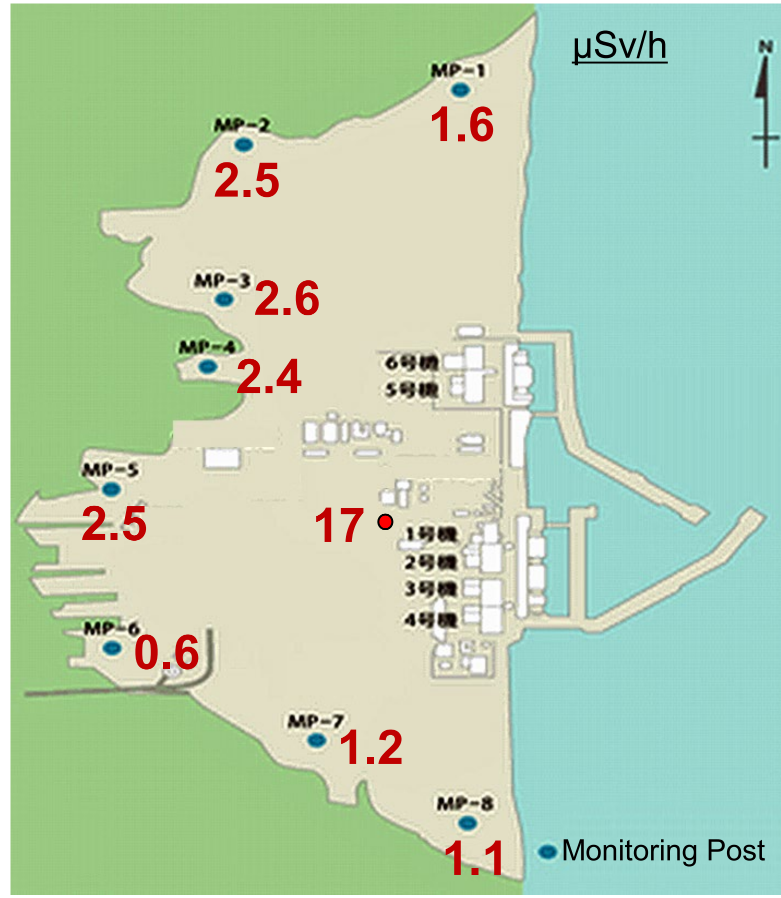
Present Ambient Dose Rate at the Fukushima NPS-1

Attenuation of Ambient Dose Rate

<April 2nd, 2011> *Starting Operation of Monitoring System



<As of June 1st, 2016>



(Max. Air Dose Rate)

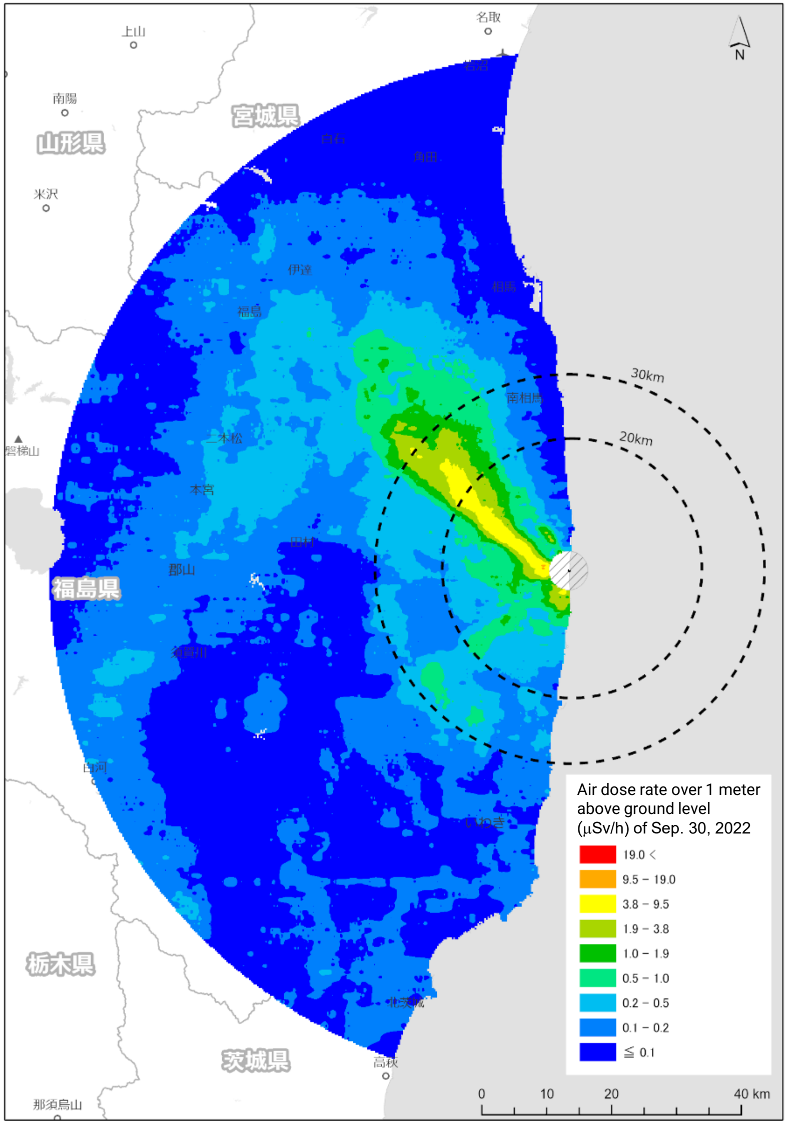
370 μSv/h	370x(8h+16hx0.4)x365= 1,944.7mSv/y
840 μSv/h	840x(8h+16hx0.4)x365= 4,415.0mSv/y

(Max. Air Dose Rate)

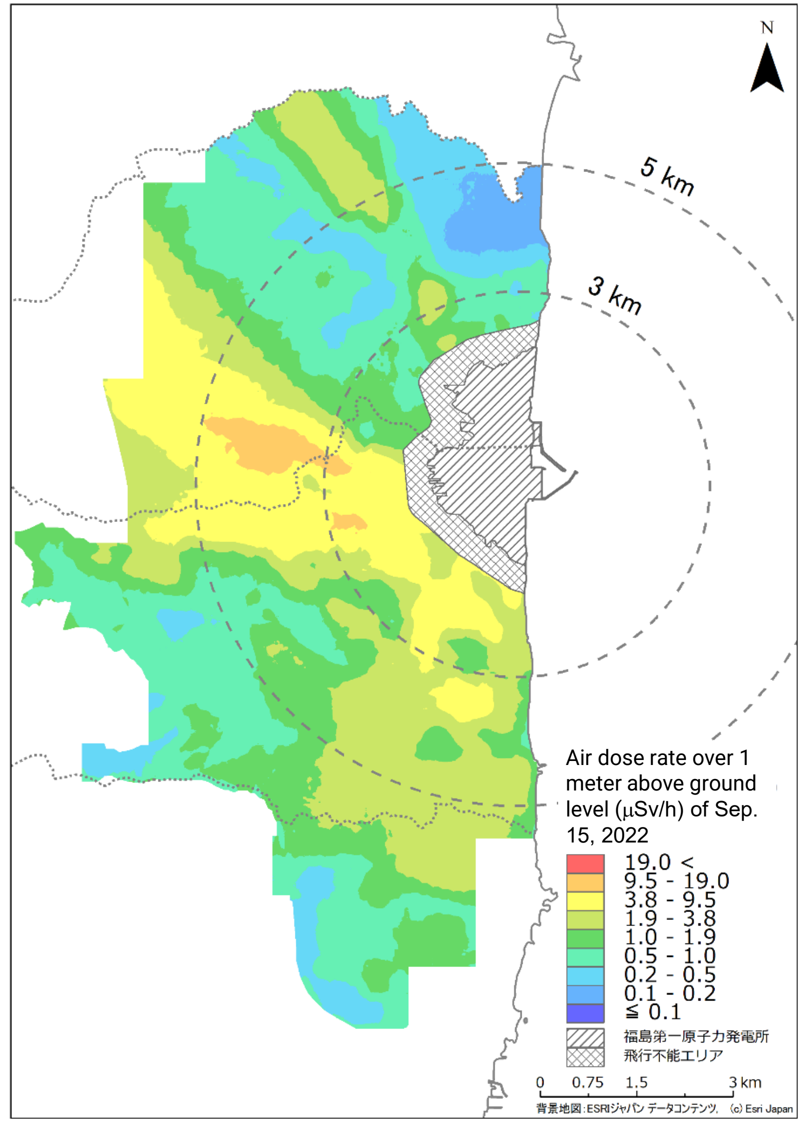
1.6 μSv/h	1.6x(8h+16hx0.4)x365= 8.4mSv/y
17 μSv/h	17x(8h+16hx0.4)x365= 89.4mSv/y

Latest radiation monitoring data (2022)

Manned heli survey



UAV survey



IV. Present Situation of Fukushima Daiichi NPPs

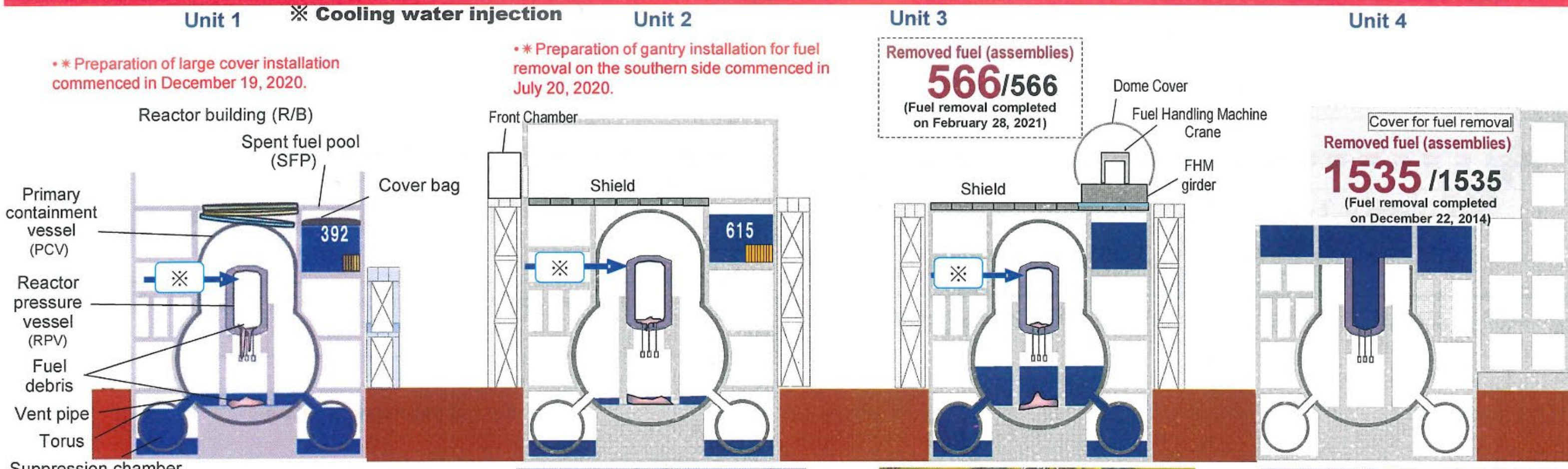
Current Status of Fukushima NPPs

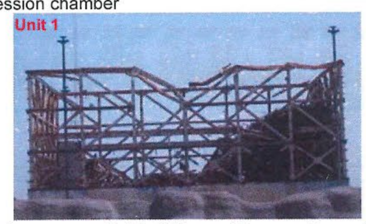
November 2023 R0
Tokyo Electric Power Company Holdings, Incorporated

TEPCO

(1) State of Units 1-4

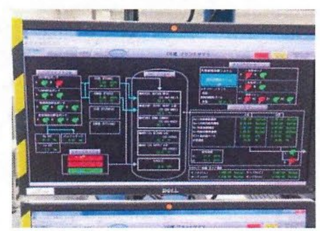
All reactors are in cold shutdown condition





Values as of 11:00 on November 8 2023

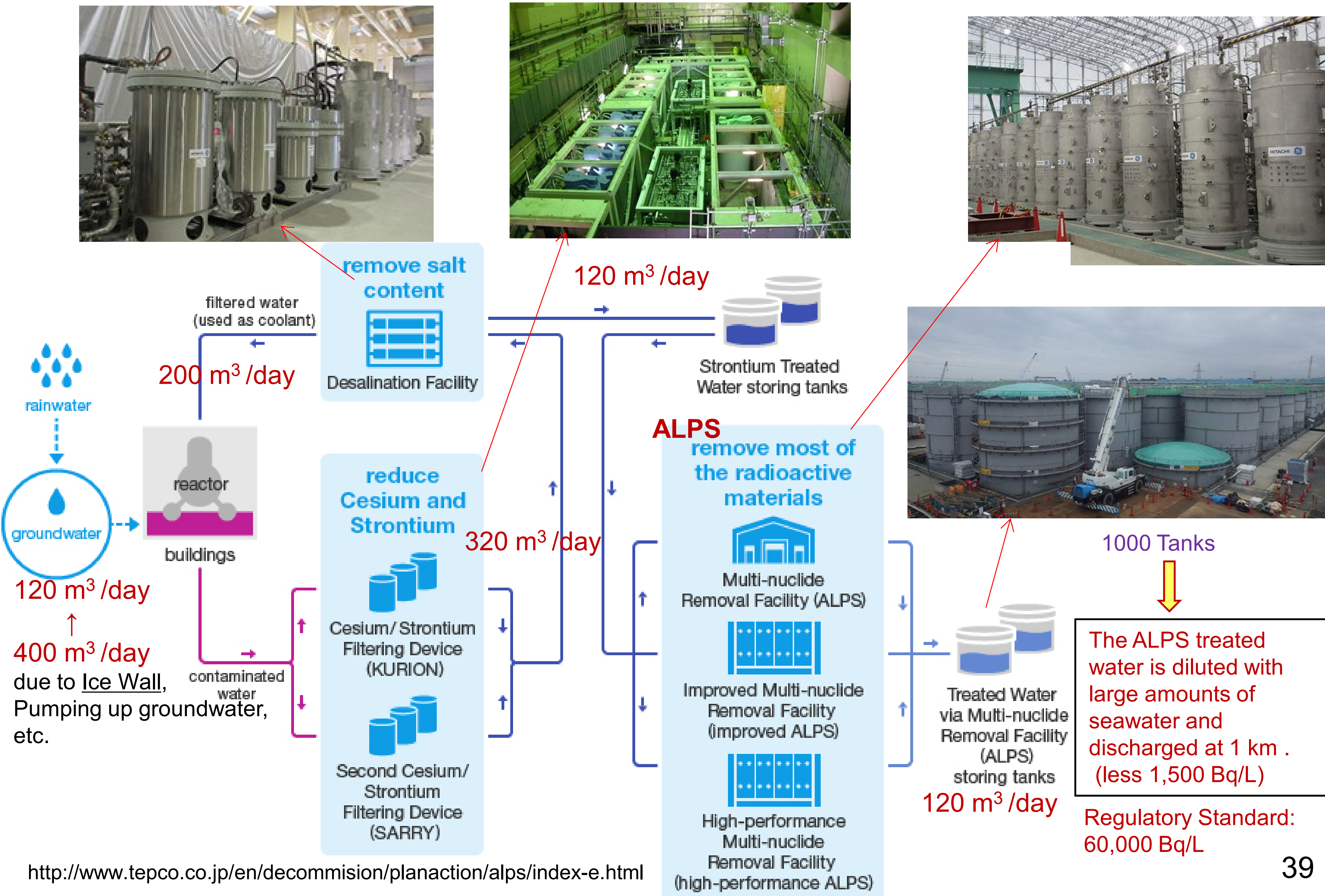
	RPV bottom temp.	PCV internal temp.	Fuel pool temp.	Water injection to the reactor
Unit 1	~26℃	~25℃	~27℃	3.7㎥/h
Unit 2	~35℃	~35℃	~27℃	1.5㎥/h
Unit 3	~29℃	~28℃	Not monitored as all fuel removal is complete.	3.8㎥/h



Plant parameters, including RPV and PCV temperatures, are monitored continuously 24 hours a day.

1

Treatment of Contaminated Water



http://www.tepco.co.jp/en/decommision/planaction/alps/index-e.html

Current Status of Fukushima NPPs

Unit-1

Unit-2

Unit-3

Unit-4

Current Status of Fukushima NPPs


Unit-5&6


ALPS


Tank Area


Ice-Wall (underground)

V. Current Status of Nuclear Energy in Japan

Current Status in Japan

(Before) 54 NPPs operated, 3 NPPs constructed and 2 NPPs decommissioned.

Mar. 2011: Tohoku Pacific Earthquake and 15m Tsunami
Fukushima Daiichi NPS Accident
All NPPs in Japan were stopped.

Jul. 2013: New Safety Regulation Standard by NRA

Sep. 2014: First NPP (Sendai-1) passed the review.
(Local government agreement)

Aug. 2015: First NPP (Sendai-1) restarted.

May 2023: “Return to Nuclear Power” by Prime minister Kishida
GX Decarbonization Electricity Act
(NPP life extension: more than 60 years)

Oct. 2023: 12 NPPs (PWR only) restarted.

Jan. 2025: 2 BWR (Shimane-2 and Onagawa-2) restarted.

Scheme of New Safety Regulation Standard

New Safety Regulation Standard was established in July 2013 after the Fukushima NPS accident.

DBA (Design-Based Accident) expected never resulted in Core Damage (Consider only Single Failure)

Before:

- Measure for Natural Phenomena (Volcano, Tornado, etc.)
- Measure for Facility Fire
- Measure for Reliability (Redundancy and Diversity Design)
- Measure for Securing of Power
- Capability of Heat Removal System
- Capability of Other Systems
- Capability for Earthquake-proof and Tsunami-proof

New Safety Regulation Standard:

New Addition (Countermeasure for Sever Accident):

- **Restriction of Dispersion of Radioactivity**
- **Measure for Prevention of PCV Damage**
- **Measure for Prevention of Core Damage**
- Measure for Aircraft Impact

Strengthening:

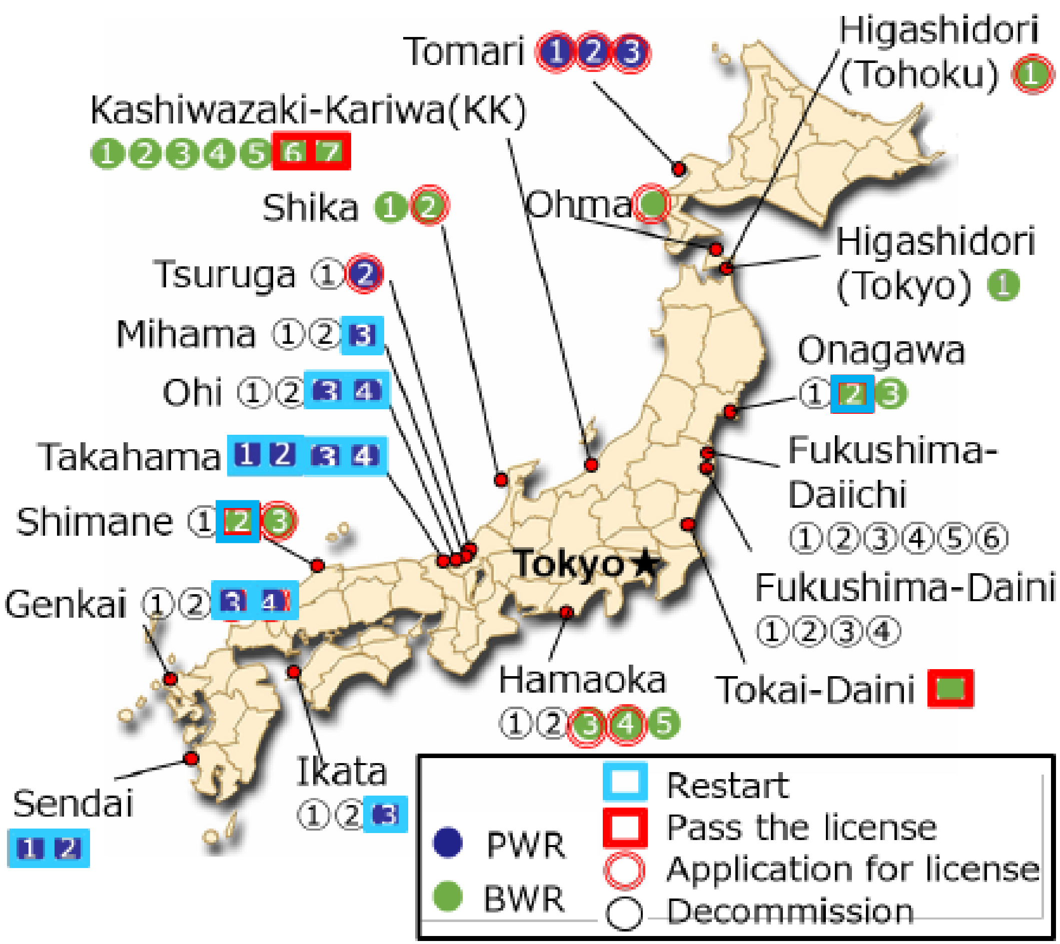
- Measure for Natural Phenomena (Volcano, Tornado, etc.)
- Measure for Facility Fire
- Measure for Reliability (Redundancy and Diversity Design)
- Measure for Securing of Power
- Capability of Heat Removal System
- Capability of Other Systems

Strengthening:

- Capability for Earthquake-proof and Tsunami-proof

Status of Nuclear Power Stations in Japan

January 2025



Status	PWR (●)	BWR (●)	Total
Restart(□)	12	2	14
Pass (□)	0	3	3
Application (◎)	4	6	10
Preparation	0	9	9
Total	16	20	36

Status	PWR	BWR	Total
Decommission (○)	8	15	23

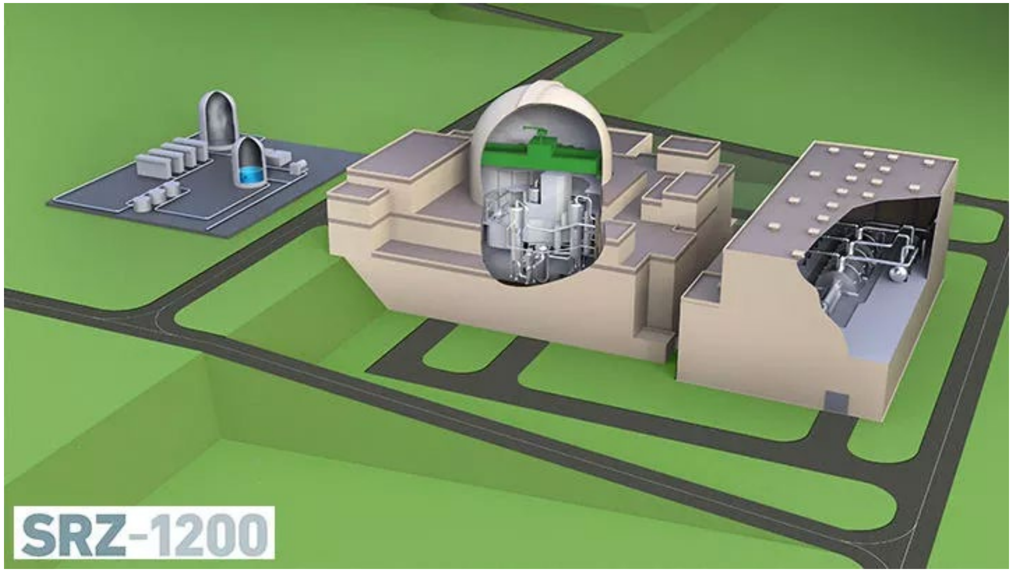
Nuclear Energy Policy in Japan

1. Restart of existing NPPs
    - Especially BWRs near Tokyo area (Kashiwazaki-Kariwa-6 and 7)
    - Start of new NPPs (Shimane-3, Ohma, Higashidori-1) under construction
2. Plant life extension
    - SSC (Structures, Systems & Components) ageing degradation
    - Non-physical ageing degradation (Safety design obsolescence)
3. Construction of large scale Advanced LWR (2030~)
    - Strong RV and CV
    - Integrated Components (less pipes, internal pumps, etc.)
    - Accident tolerant fuel (ATF)
4. Small Module Reactors (SMRs) and Micro reactors (2040~)

Features of SRZ-1200 (MHI)

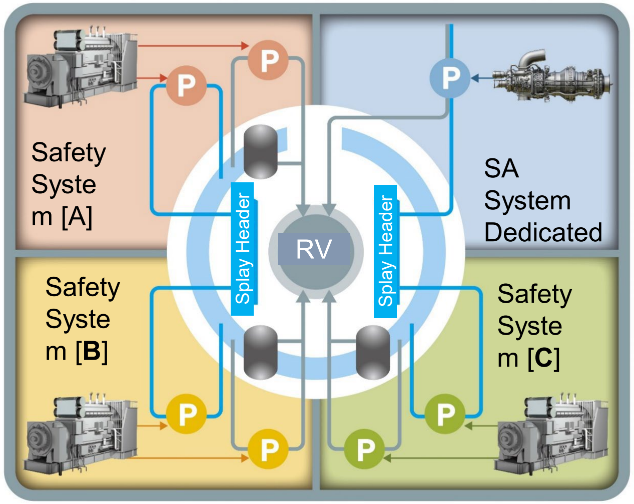
- Power: 1,200MWe class
- strengthening safety equipment
- security against terrorism and unforeseen event
- High resistance to external hazard. (earthquake, tsunami, airplane attack, etc.)
- Confine radioactive material in case of accident, and impact limited to inside of plant

https://youtu.be/KREpHHxc8Ek
https://www.mhi.com/products/energy/advanced_light_water_reactor.html

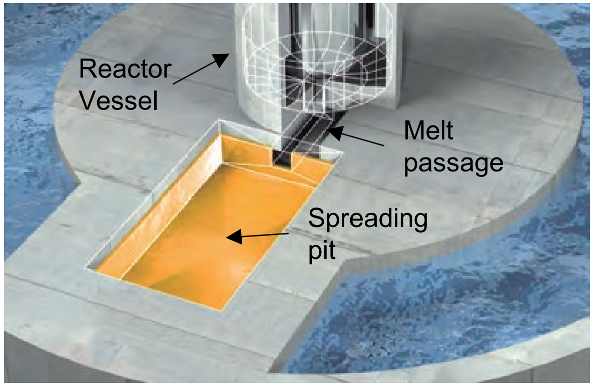


Features of SRZ-1200

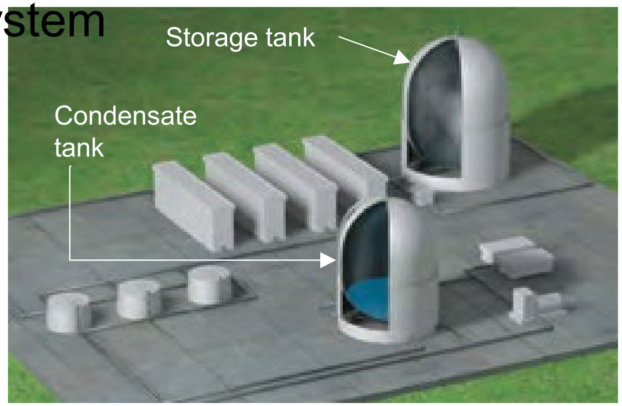
Adoption of new safety designs



Adoption of the core catcher



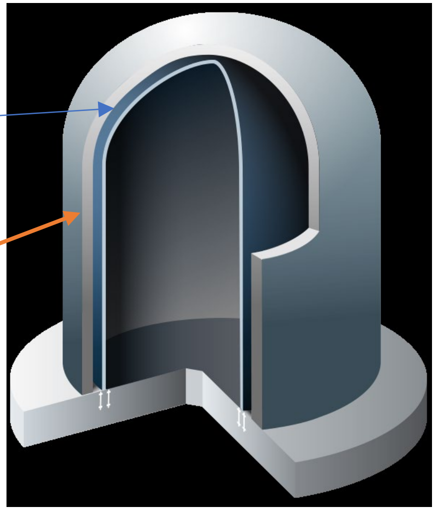
Materials release prevention system



Containment Vessel Damage Protection Measures

Inner containment vessel
(High tensile steel sheet)

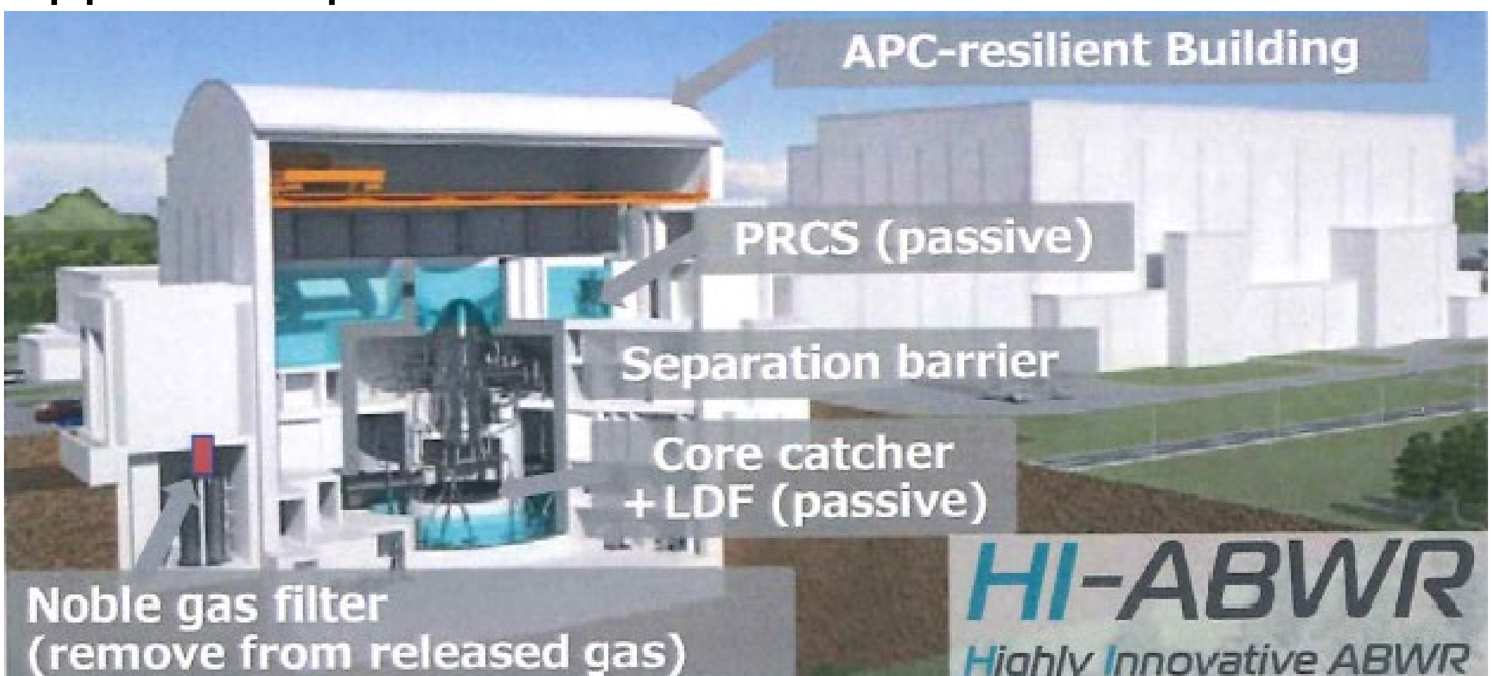
external shielding wall
(thickness about twice)



https://www.mhi.com/products/energy/advanced_light_water_reactor.html

Highly Innovative ABWR:HI-ABWR (Hitachi-GE)

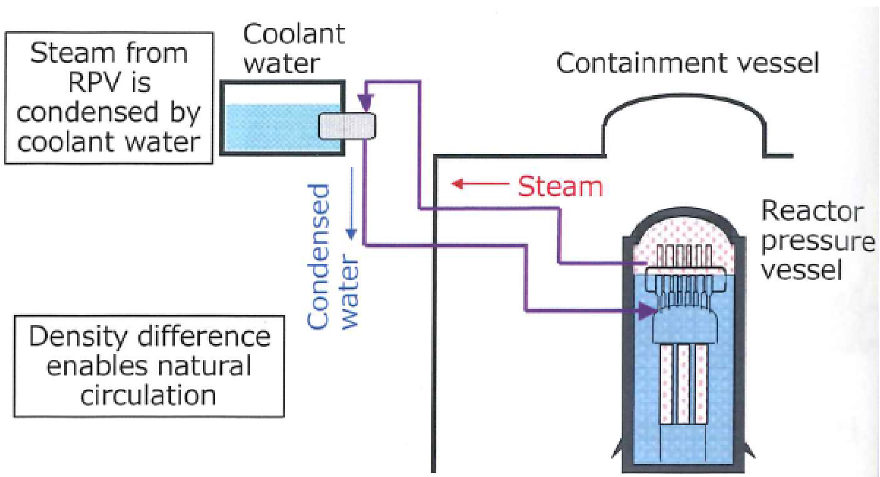
- Power: 1350~1500 MWe
- Reactor Pressure: 7.17 MPa
- Strengthened countermeasures for natural disasters, terrorism, internal hazards (APC: AirPlane Crash)
- Passive safety systems utilizing natural forces
- Suppress impact on the external environment



Enhanced Safety Systems for Severe Accident

Passive Reactor Cooling System (PRCS)

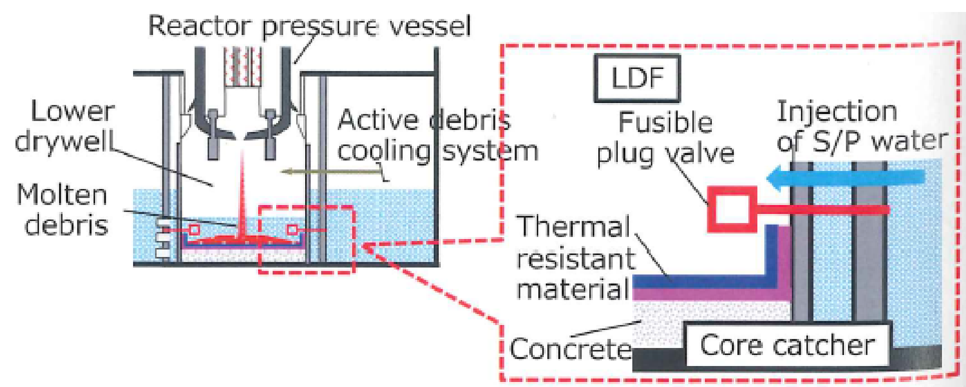
- Remove decay heat by natural circulation at BDBE*
- No operator actions required with automatic start
- Capacity to operate for 24 hours



* Beyond Design Basis Events

Core catcher + Lower Drywell Flooder (LDF)

- Core catcher placed at ABWR lower drywell.
- LDF: Fusible plug valve automatically injects the water of suppression pool (S/P) without operator actions. (S/P is large enough to enable debris cooling for 3 days)



Thank you for your Attention!!

20 November 2023