The Accident at TEPCO's Fukushima Nuclear Power Stations and the IAEA Safety Standards

March , 2024
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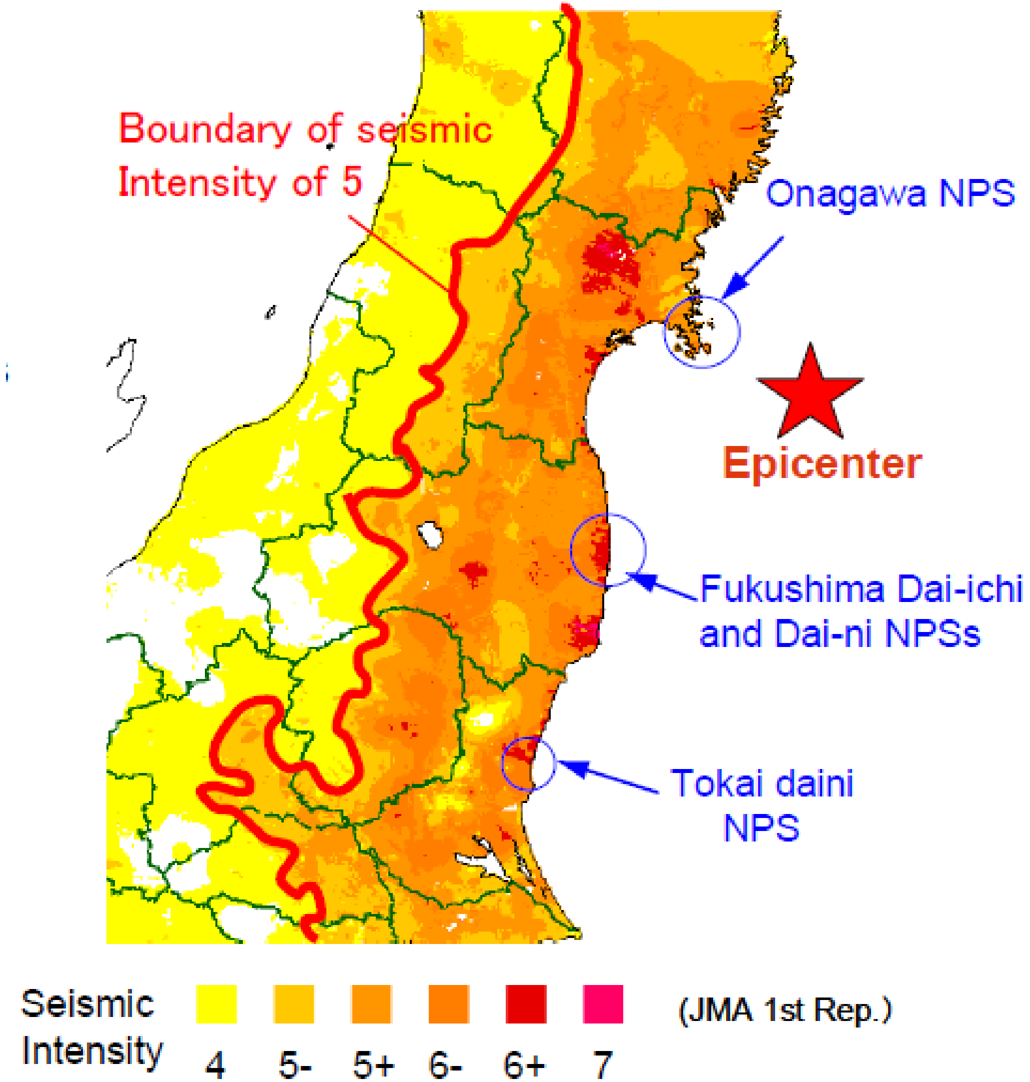
Contents

1. Occurrence and Development of the Accident

Tohoku District - off the Pacific Ocean Earthquake

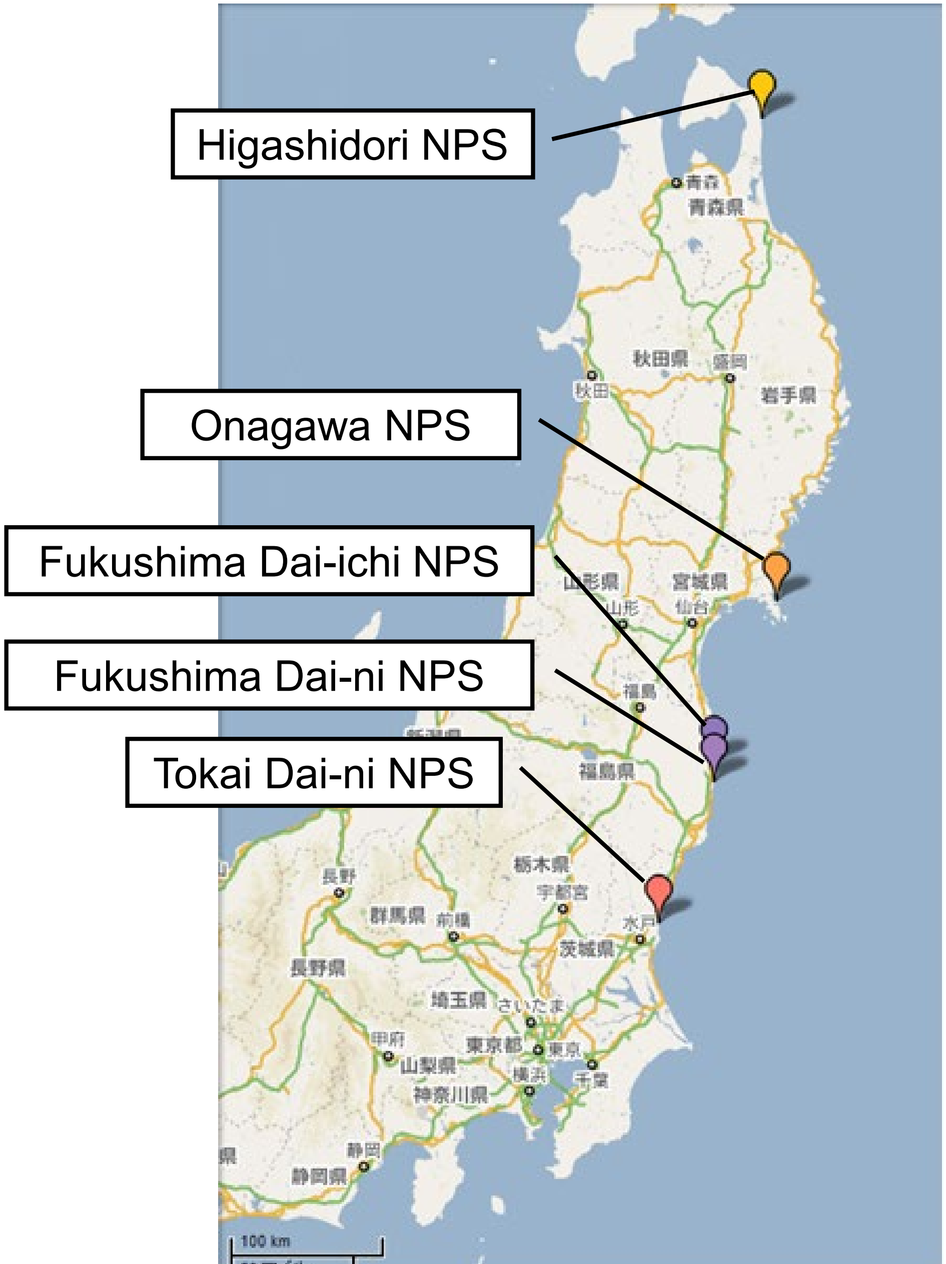


Reference: JMA Release [Online]. http://www.jma.go.jp/jma/index.html
Partially modified by JNES.

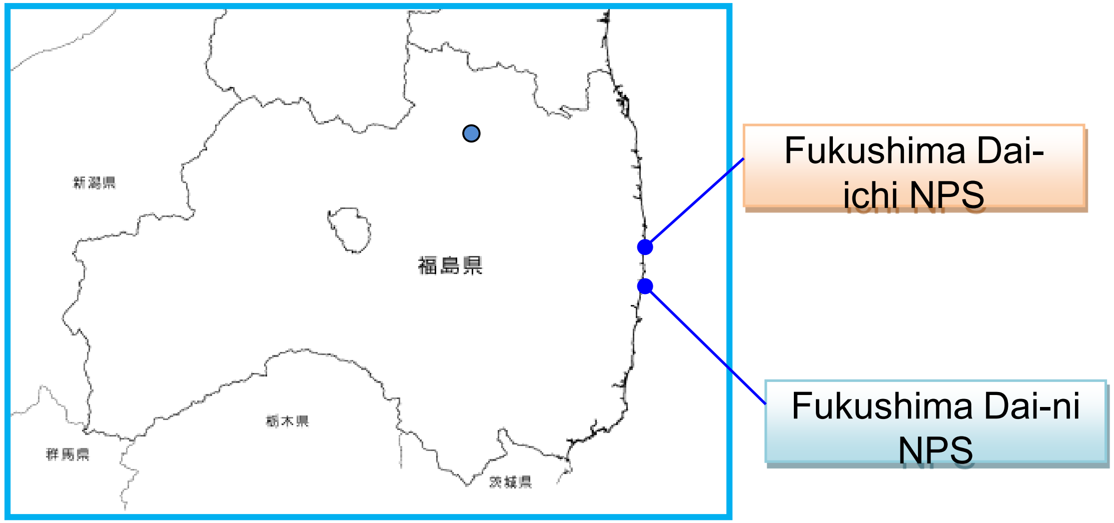
Map of JMA seismic intensities observed during the main shock.

- Occurrence: 14:46 March11, 2011
- Mw(moment magnitude): 9.0
- Epicenter: approximately 130km off the coast of Sanriku (at 38.10 degrees north latitude, 142.86 degrees east longitude and 23.7km deep)

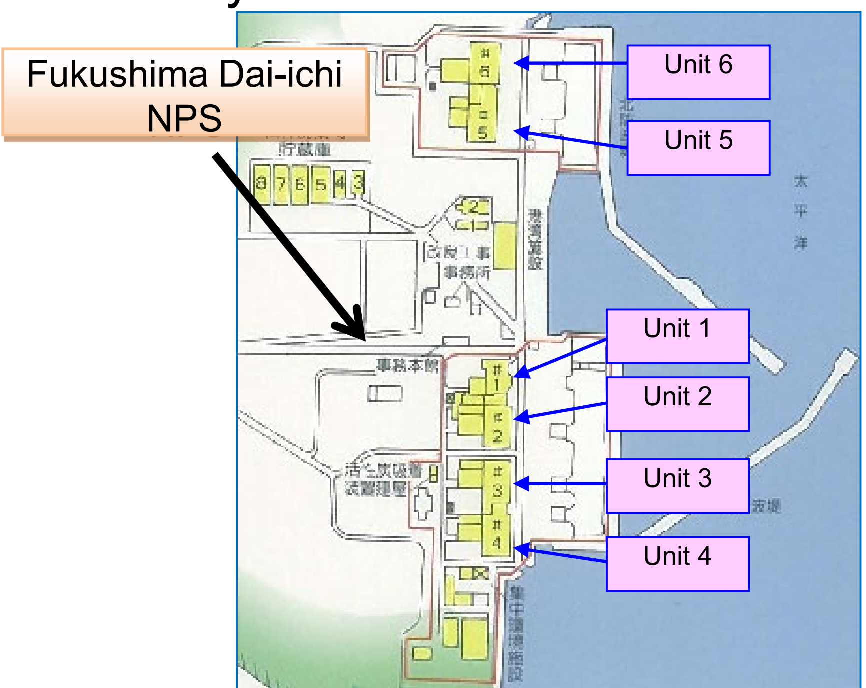
Location of NPSs in the Tohoku District

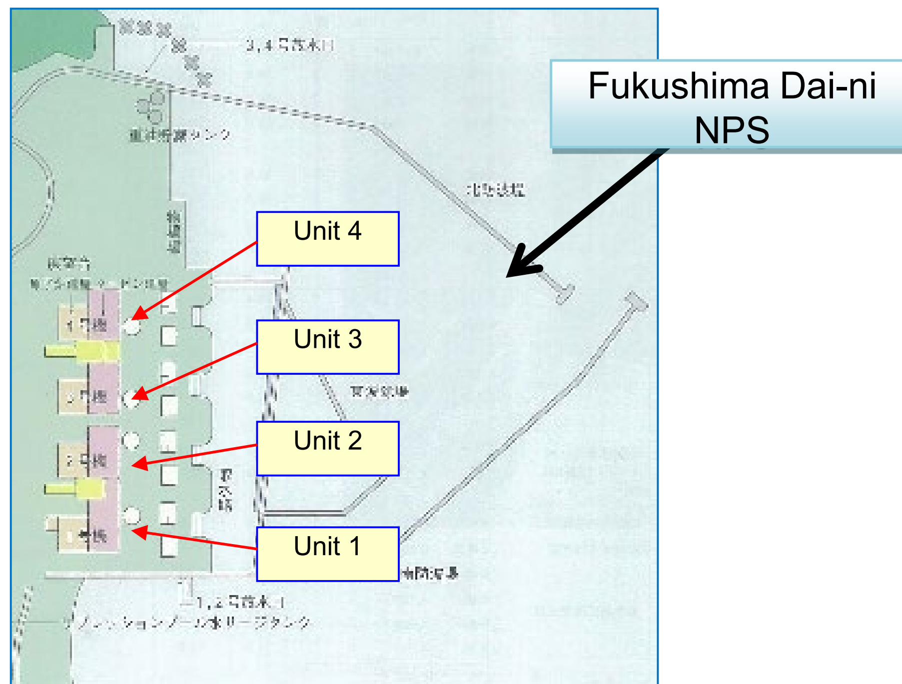


Location of NPSs within Fukushima



Layouts of Fukushima Dai-ichi NPS and Fukushima Dai-ni NPS





Yonomori Line(external power supply line) No.27 pylon was destroyed by the earthquake (source : TEPCO)

Source TEPCO

Huge tsunami attacked Minamisoma-shi on March 11, 2011.

(source : Tokyo Broadcasting System Television,TEPCO)

Tsunami getting over seawall at the Fukushima Dai-ichi NPS

Entire facilities at Fukushima Daiichi NPS were flooded by tsunami. (source : TEPCO)

Fukushima Dai-ichi NPS

(AC Power supply)

[External power supply] → [Emergency diesel generators]

X	Yonomori -line No.1
X	Yonomori- line No.2
X	Okuma- line No.1
X	Okuma-line No.2
X	Okuma-line No.4
X	TEPCO nuclear line

↑ earthquake

X	(Unit 1)
X	(Unit 1)
X	(Unit 2)
X	(Unit 2)
X	(Unit 3)
X	(Unit 3)
X	(Unit 4)
X	(Unit 5)
X	(Unit 5)
X	(Unit 6)
X	(Unit 6)
O	(Unit 6)

↑ Tsunami

Main Sequence of the accident of Unit1, Unit2 and Unint3 of Fukushima Dai-ichi NPS

Loss of external power supply due to earthquake

↓

Start-up of emergency power generation

↓

All emergency diesel power generators stopped except for one generator in Unit6 due to tsunami

(11 emergency diesel power generator stopped, and one generator(with air cooling)survived.)

↓

Loss of all AC power supply except for Unit6

(Unit 5 took power supply from Unit6 on 13 March).

→

Core cooling system not using AC power

(Unit1:IC(isolation condenser), Unit2 (RCIC(reactor core isolation cooling system), Unit3: RCIC and HPCI (high pressure core injection system)

↓

Stop of core cooling system not using AC power

↓

Water injection from a fire extinguishing line

(Unit1:pure water->sea water, Unit2: sea water Unit3: pure water-> sea water)

→

During this time without cooling, the fuel was exposed and core melt started, generating hydrogen

Hydrogen explosion occurred at the upper part of reactor building at Unit 1, Unit 3 and Unit 4. (source : TEPCO)

Total view

Unit4

Unit1

Unit2

Unit3

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Major issues in the Accident at TEPCO's Fukushima Nuclear Power Stations

1) Loss of power supply

2) Hydrogen explosion

3) Release of radioactivity

Ⅱ. IAEA Safety Standards
-Safety of Nuclear Power Plants: Design-

IAEA Safety Standards

- Safety of Nuclear Power Plants: Design（Specific Safety Requirements）
- Series No. SSR-2/1, published Monday, February 20, 2012

1. Requirement 17: Internal and external hazards

- All foreseeable internal and external hazards, including the potential for human induced events directly or indirectly to affect the safety of the nuclear power plant, shall be identified and their effects shall be evaluated. Hazards shall be considered for the determination of postulated initiating events and generated loadings for use in the design of relevant items important to safety for the plant.

Requirement 17:Internal and external hazards

5.17 Natural external events shall be addressed, Including meteorological, hydrological, geological, and seismic events. In the short term, the safety of the plant shall not be permitted to be dependent on the availability of off-site services such as electricity supply and fire fighting services. The design shall take due account of site specific conditions to determine the maximum delay time by which off-site services need to be available.

2.Requirement 20: Design extension conditions

- A set of design extension conditions shall be derived on the basis of engineering judgement, deterministic assessments and probabilistic assessments for the purpose of further improving the safety of the nuclear power plant by enhancing the plant's capabilities to withstand, without unacceptable radiological consequences, accidents that are either more severe than design basis accidents or that involve additional failures. These design extension conditions shall be used to identify the additional accident scenarios to be addressed in the design and to plan practicable provisions for the prevention of such accidents or mitigation of their consequences if they do occur.

Concept of Accident Management(1) (IAEA Standards No. NS-G-2.15)

- 2.6. At the top level, the objectives of accident management are defined as follows:

①Preventing significant core damage;

②Terminating the progress of core damage once it has started;

③Maintaining the integrity of the containment as long as possible;

④Minimizing releases of radioactive material;

⑤Achieving a long term stable state.

Concept of Accident Management(2) (IAEA Standards No. NS-G-2.15)

2.9. When developing guidance on accident management, consideration should be given to the full design capabilities of the plant, using both safety and non-safety systems, and including the possible use of some systems beyond their originally intended function and anticipated operating conditions, and possibly outside their design basis.

Four main steps for accident management programme(IAEA Standards No. NS-G-2.15)

3.7. Four main steps should be executed to set up an accident management programme:

(1) Plant vulnerabilities should be identified, to find mechanisms through which critical safety functions may be challenged. In the event that these challenges are not mitigated, the core may be damaged and the integrity of fission product barriers may be compromised;

(2) Plant capabilities under challenges to critical safety functions and fission product barriers should be identified, including capabilities to mitigate such challenges, in terms of both equipment and personnel;

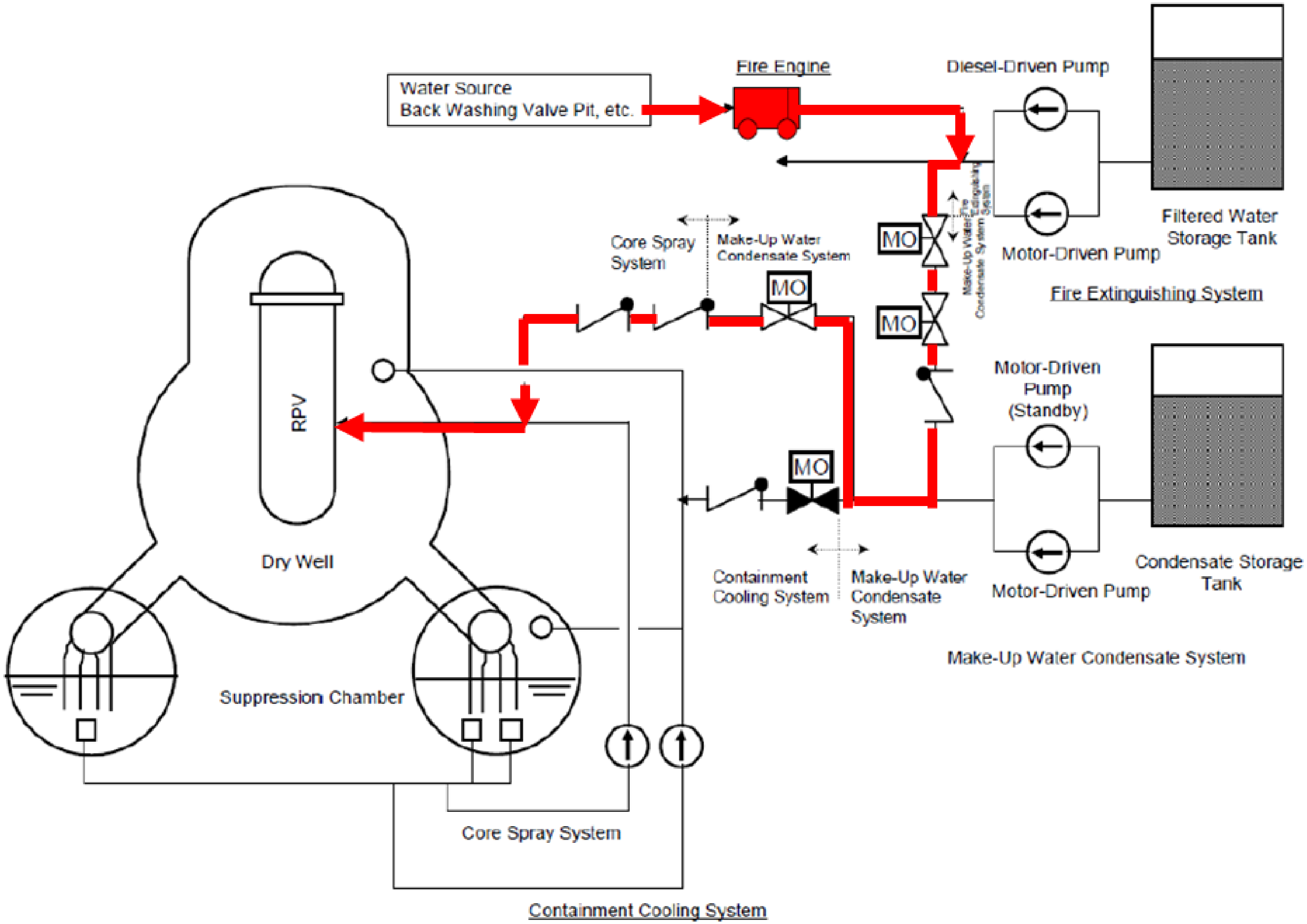
(3) Suitable accident management strategies and measures should be developed, including hardware features, to cope with the vulnerabilities identified;

(4) Procedures and guidelines to execute the strategies should be developed.

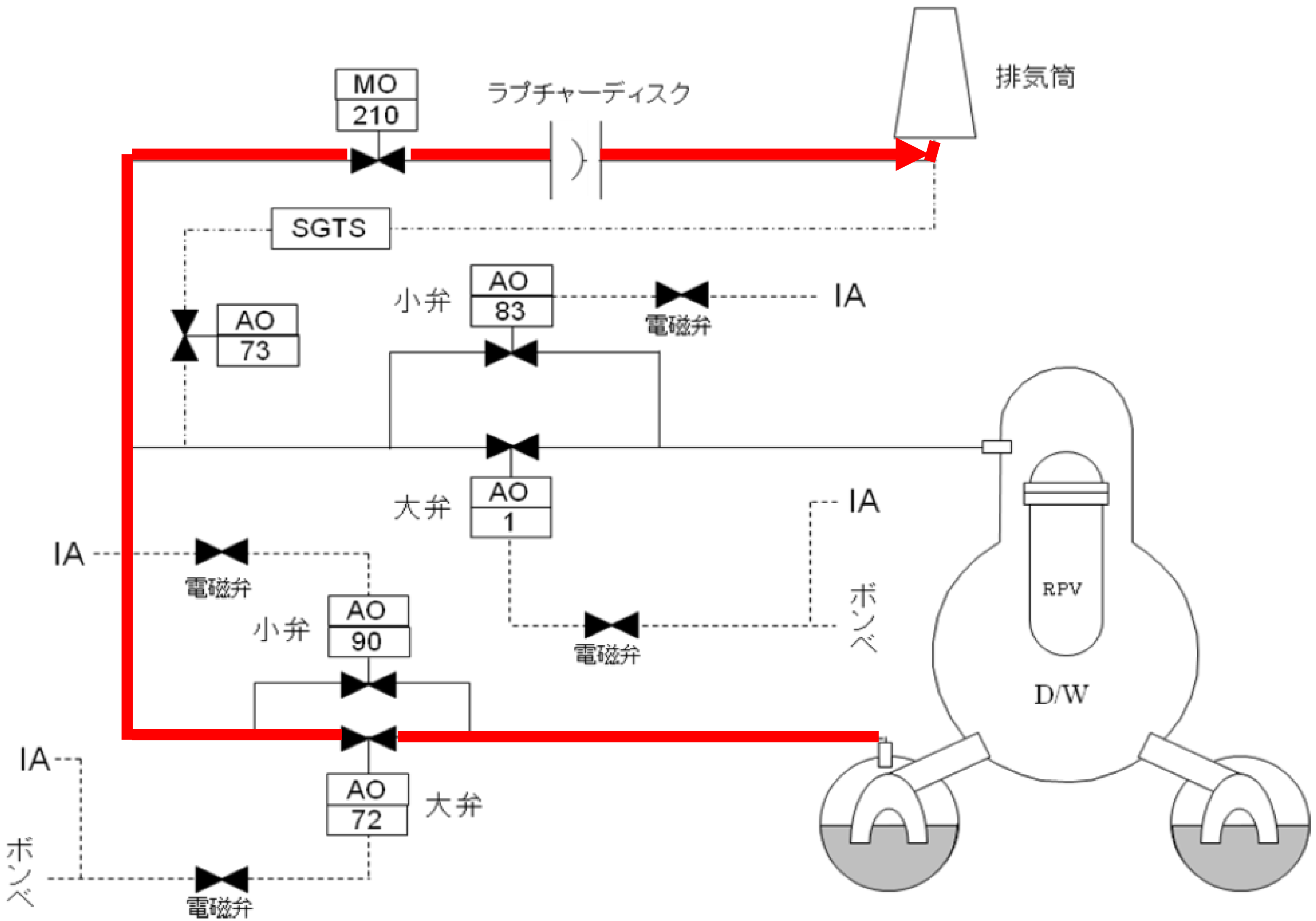
Accident Management Measures at Fukushima Dai-ichi Accident

Items	Contents
Alternative coolant injection	• Lines via condensate water makeup systems from the condensate storage tanks as the water sources • Lines via fire extinguishing systems and condensate water makeup systems from the filtrate tanks as the water sources
PCV vent facilities	• PCV vent facilities were installed to bypass the standby gas treatment system so that they can vent the PCV when the pressure is high.
Power interchange facilities	• Power interchange facilities have been installed such that the power supply of the alternating current source for power machinery (6.9kV) and the low voltage alternating current source (480V) can be interchanged between adjacent reactor facilities (between Units 1 and 2, between units 3 and 4, and between Unit 5 and 6).

Alternative coolant injection via a fire extinguishing line (Unit1)



PCV vent (Unit1)



3. Requirement 24: Common cause failures

- The design of equipment shall take due account of the potential for common cause failures of items important to safety to determine how the concepts of diversity, redundancy, physical separation and functional independence have to be applied to achieve the necessary reliability.

Main points in Requirement 24

- Diversity
- Redundancy
- Physical separation
- Functional independence

Fukushima Dai-ichi NPS

(AC Power supply)

[External power supply] → [Emergency diesel generators]

X	Yonomori -line No.1
X	Yonomori- line No.2
X	Okuma- line No.1
X	Okuma-line No.2
X	Okuma-line No.4
X	TEPCO nuclear line

↑ earthquake

X	(Unit 1)
X	(Unit 1)
X	(Unit 2)
X	(Unit 2)
X	(Unit 3)
X	(Unit 3)
X	(Unit 4)
X	(Unit 5)
X	(Unit 5)
X	(Unit 6)
X	(Unit 6)
O	(Unit 6)

↑ Tsunami

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Ensuring the independence and diversity of safety systems

- Almost all of the emergency diesel generators were destroyed by the tsunami.
  - Only one emergency diesel generator which had a air-cooling system* and was located at higher place survived to operate.

    *There is no sea water pump in case of air-cooling system.
  - Diversity of safety system is important to improve safety level.

One emergency generator in Unit 6 could survive because of diversification in design.

- The reason why one emergency diesel generator in Unit 6 was not flooded, because it located on a ground level in a building.

(Other diesel generators were located on underground level and were flooded by tsunami.)

- This survived emergency diesel generator in Unit 6 had an air-cooling system to which tsunami gave no damage.

(In case of other diesel generators installed water-cooling system, seawater pump was damaged by tsunami.)

- Consideration of diversification is important to secure safety.

4. Requirement 51: Removal of residual heat from the reactor core

- Means shall be provided for the removal of residual heat from the reactor core in the shutdown state of the nuclear power plant such that the design limits for fuel, the reactor coolant pressure boundary and structures important to safety are not exceeded.

Decay heat

(change of decay heat (ratio to power output) according to cooling time(seconds))

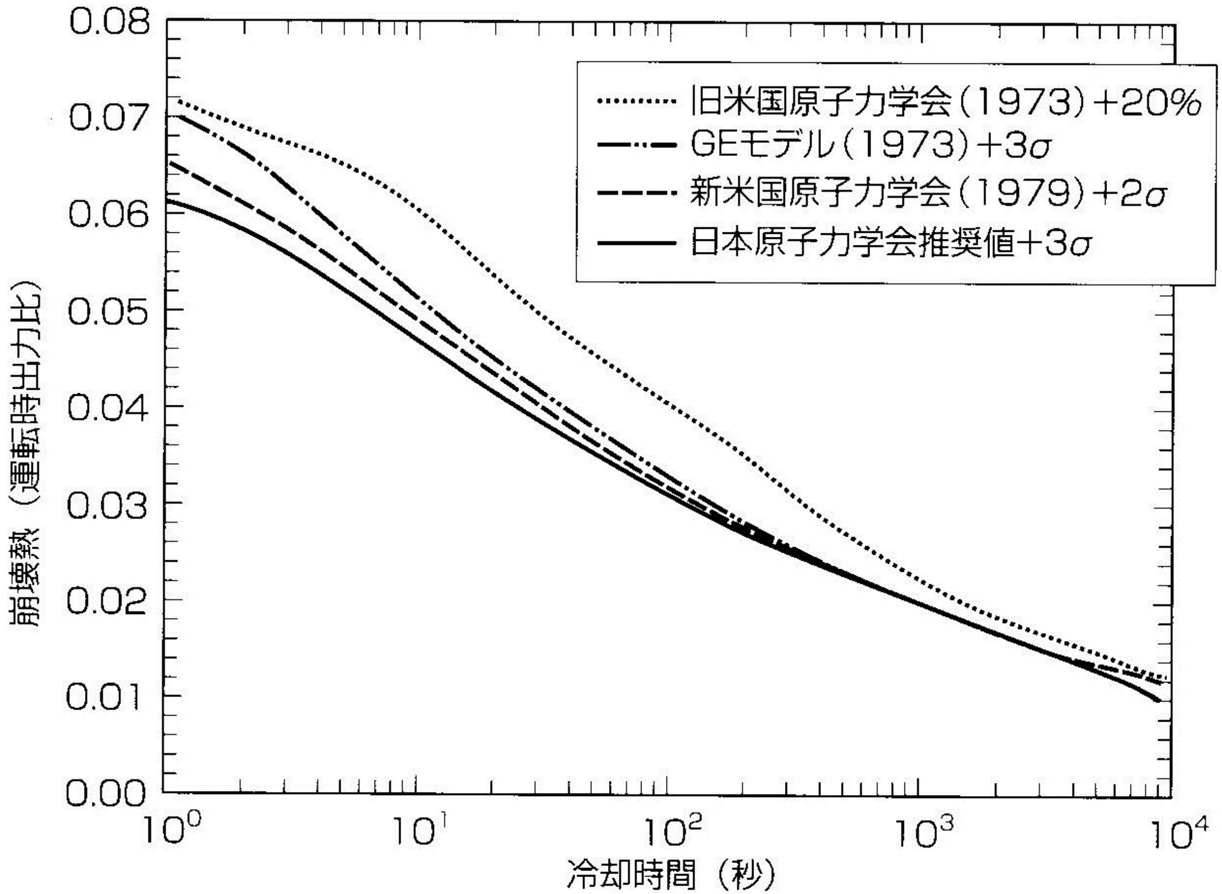


図9−3　軽水炉の崩壊熱曲線の例（ウラン235の無限時間照射）

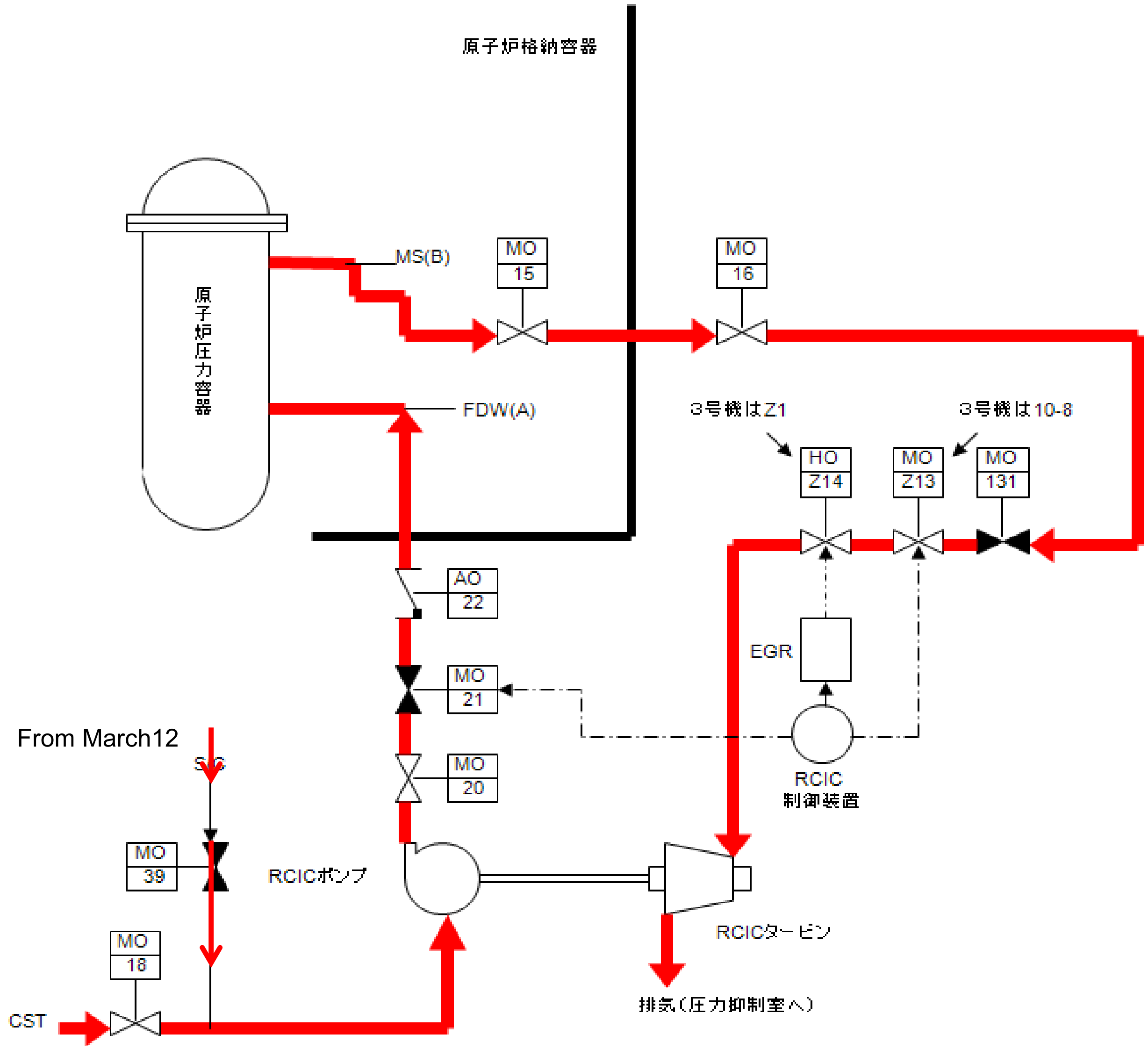
（出典：原子力安全委員会「軽水型動力炉の非常用炉心冷却系の性能評価に用いる崩壊熱データについて

Cooling systems without using AC power and alternative cooling system using fire extinguishing line were made use of after the loss of all the AC power.

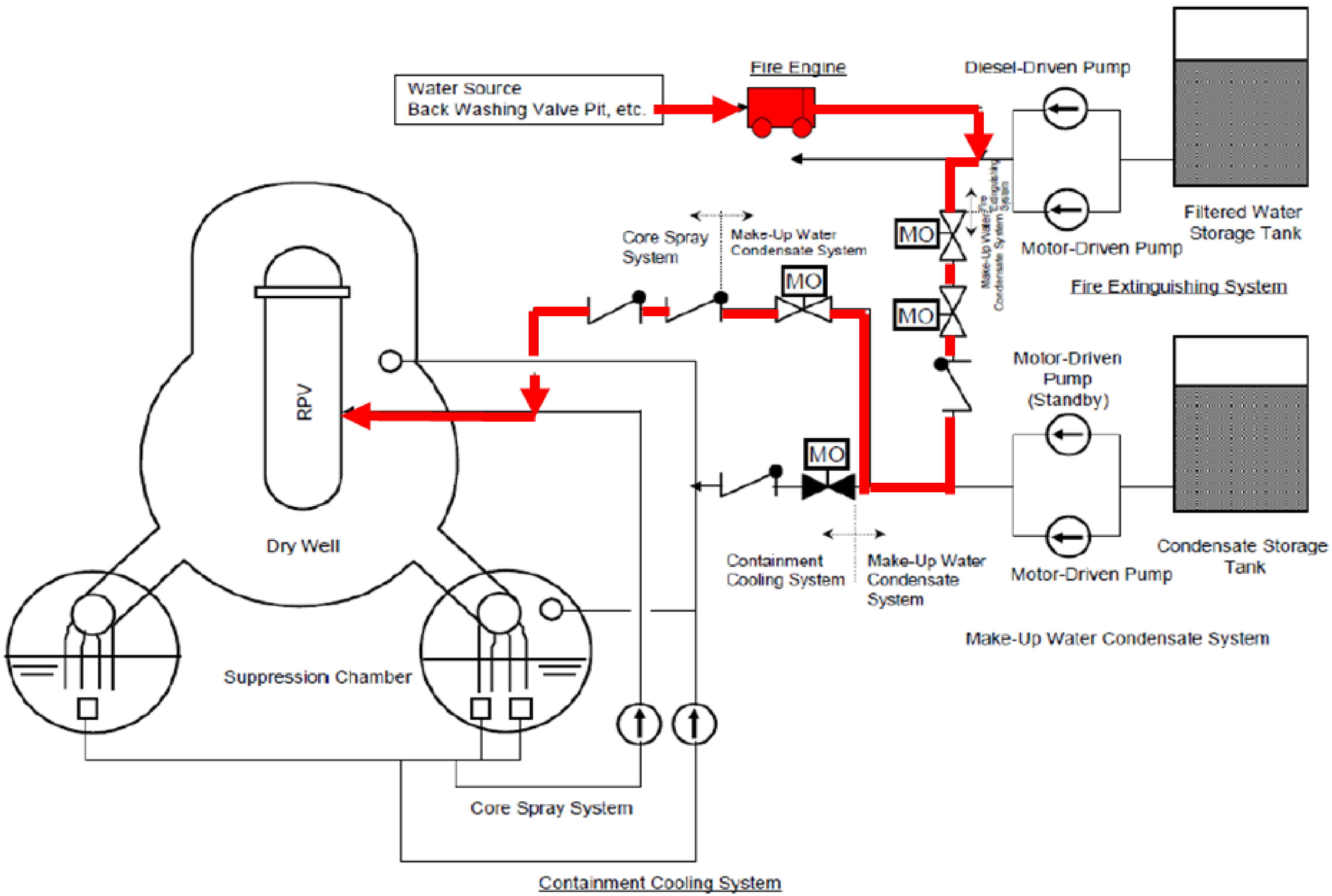
- After the loss of the all AC (alternating current) power supplies, cooling systems without using AC power were made use of at Unit 2 and Unit 3. But they were stopped due to depletion of DC battery.

- Alernative cooling using lines via fire extinguishing systems was made at Unit 1, Unit 2 and Unit 3.

At Unit 2 RCIC using DC power functioned from 14:50 March 11 until 13:25 March 14 for reactor cooling.



At Unit 1 from 05:46 March 12 water injection into the reactor was started via fire extinguishing line.



Water was injected into the reactors via fire extinguishing line using fire trucks as accident management. (source : TEPCO)

5. Requirement 58: Control of containment conditions

- Provision shall be made to control the pressure and temperature in the containment at a nuclear power plant and to control any buildup of fission products or other gaseous, liquid or solid substances that might be released inside the containment and that could affect the operation of systems important to safety.

Requirement 58: Control of containment conditions

6.29. Design features to control fission products, hydrogen, oxygen and other substances that might be released into the containment shall be provided as necessary:

(a) To reduce the amounts of fission products that could be released to the environment in accident conditions;

(b) To control the concentrations of hydrogen, oxygen and other substances in the containment atmosphere in accident conditions so as to prevent deflagration or detonation loads that could challenge the integrity of the containment.

Nuclear power plant is exposed to risk of hydrogen explosion both in case of normal operation and in case of severe accident.

- In case of normal operation, hydrogen is generated by water radiolysis.

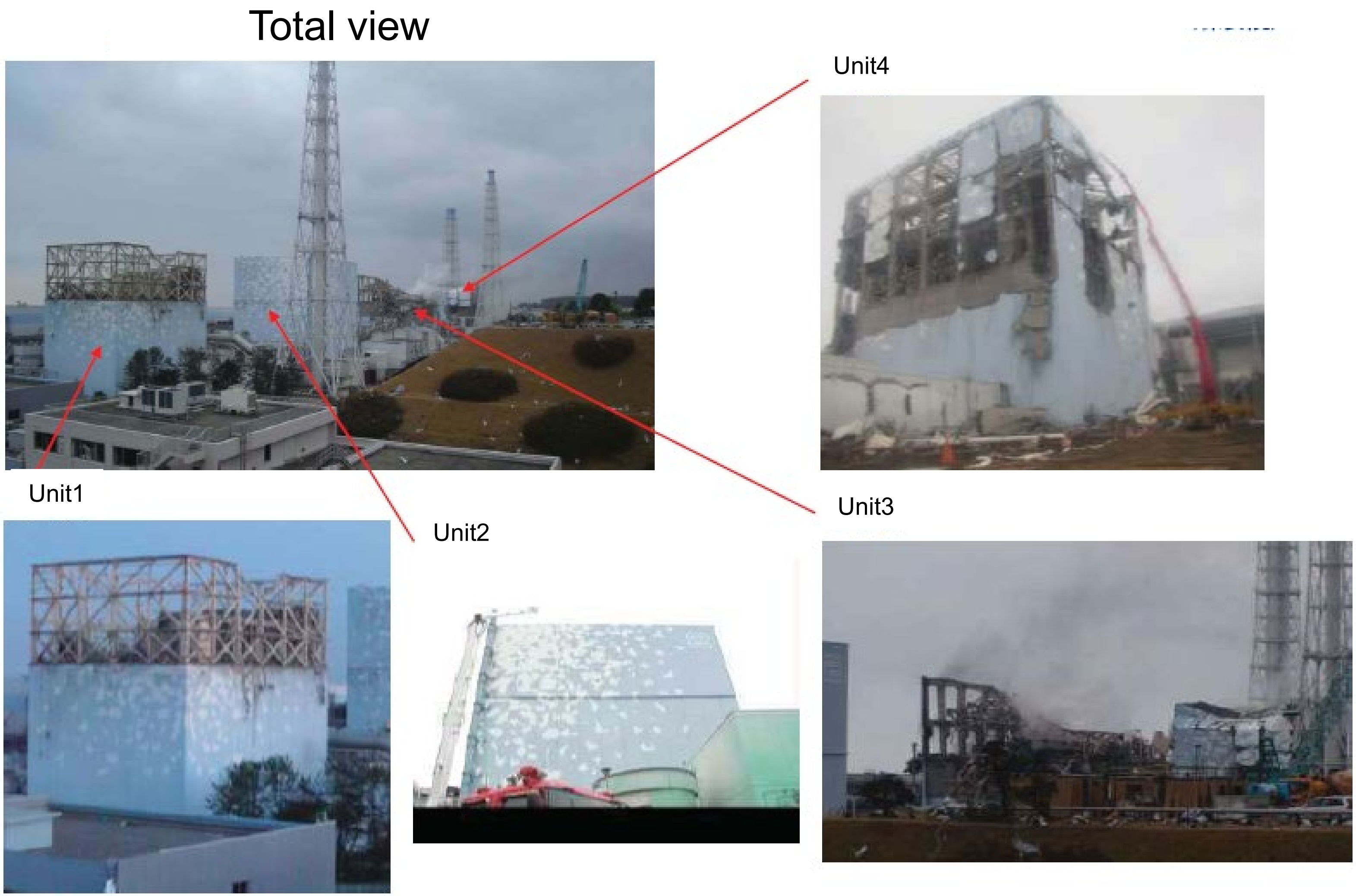
  $2H_20 \rightarrow 2H_2 + O_2$

- In case of severe accident hydrogen is generated by zirconium water reaction.

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

(reference) In normal operation residual heat removal system piping was ruptured by hydrogen explosion.(2001/07 Hamaoka Nuclear Power Station Unit 1)

Hydrogen explosion occurred at the upper part of reactor building at Unit 1, Unit 3 and Unit 4. (source : TEPCO)



6. Requirement 68:Emergency power supply

- The emergency power supply at the nuclear power plant shall be capable of supplying the necessary power in anticipated operational occurrences and accident conditions, in the event of the loss of off-site power.

The earthquake caused shutdown of all the external power supply lines at the Fukushima Dai-ichi Nuclear Power Station.

- The Fukushima Dai-ichi Nuclear Power Station had 5 available external power supply lines which could supply electric power to the nuclear plants at the time of shutdown.
- Yonomori-line No.1
- Yonomori-line No.2
- Okuma-line No.1
- Okuma-line No.2
- Okuma-line No.4

- The earthquake caused shutdown of all the five power supply lines at the Fukushima Dai-ichi Nuclear Power Station.

Yonomori Line(external power supply line) No.27 pylon was destroyed by the earthquake (source : TEPCO)

Source TEPCO

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Power supply car

Ⅲ． IAEA Safety Standards -Radiation Protection and Safety of Radiation Sources : International Basic Safety Standards-

Basic safety standards (BSS)

- Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards

(IAEA Series No. GSR Part 3 (Interim),2011)

Main points of BSS

- Basic concepts of radiation protection
  - Types of exposure situation
  - Dose limits
  - Justification
  - Optimization
  - Exemption level of each radionuclide

Types of exposure situations

- For the purpose of establishing practical requirements for protection and safety, these Standards distinguish between three different types of exposure situation: planned exposure situations, emergency exposure situations and existing exposure situations. Together, these three types of exposure situation cover all situations of exposure to which these Standards apply.

(a)A planned exposure situation

- A *planned exposure situation* is a situation of exposure that arises from the planned operation of a source or from a planned activity that results in an exposure from a source. Since provision for protection and safety can be made before embarking on the activity concerned, the associated exposures and their likelihood of occurrence can be restricted from the outset.

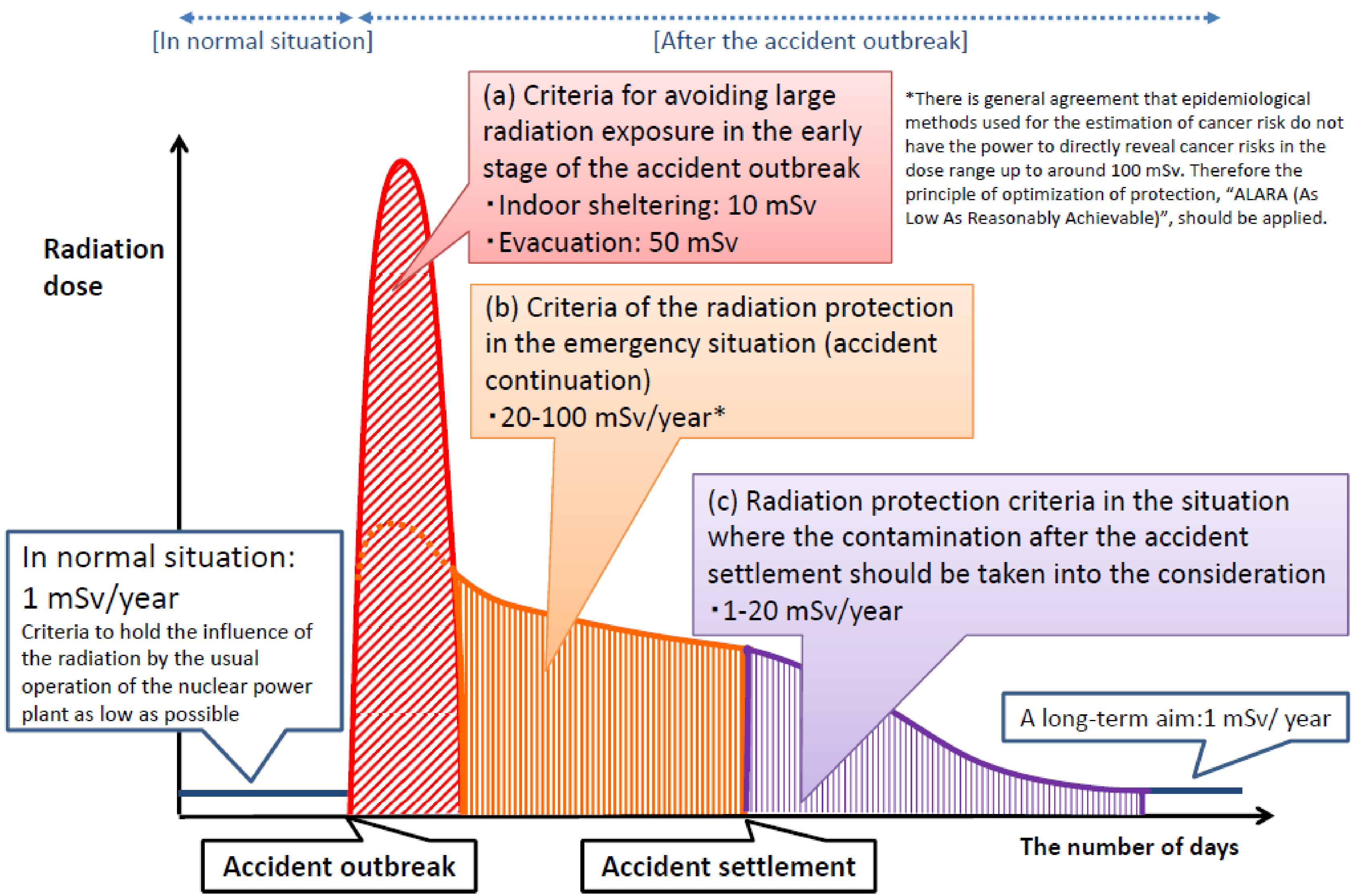
(b)An emergency exposure situation

- An emergency exposure situation is a situation of exposure that arises as a result of an accident, a malicious act, or any other unexpected event, and requires prompt action in order to avoid or to reduce adverse consequences. Preventive actions and mitigatory actions have to be considered before an emergency exposure situation arises. However, once an emergency exposure situation actually occurs, exposures can be reduced only by implementing protective actions.

(c)An existing exposure situation

- An existing exposure situation is a situation of exposure which already exists when a decision on the need for control needs to be taken. Existing exposure situations include situations of exposure to natural background radiation. They also include situations of exposure due to residual radioactive material that derives from past practices that were not subject to regulatory control or that remains after an emergency exposure situation.

The idea of the criteria of the radiation dose for the radiation protection



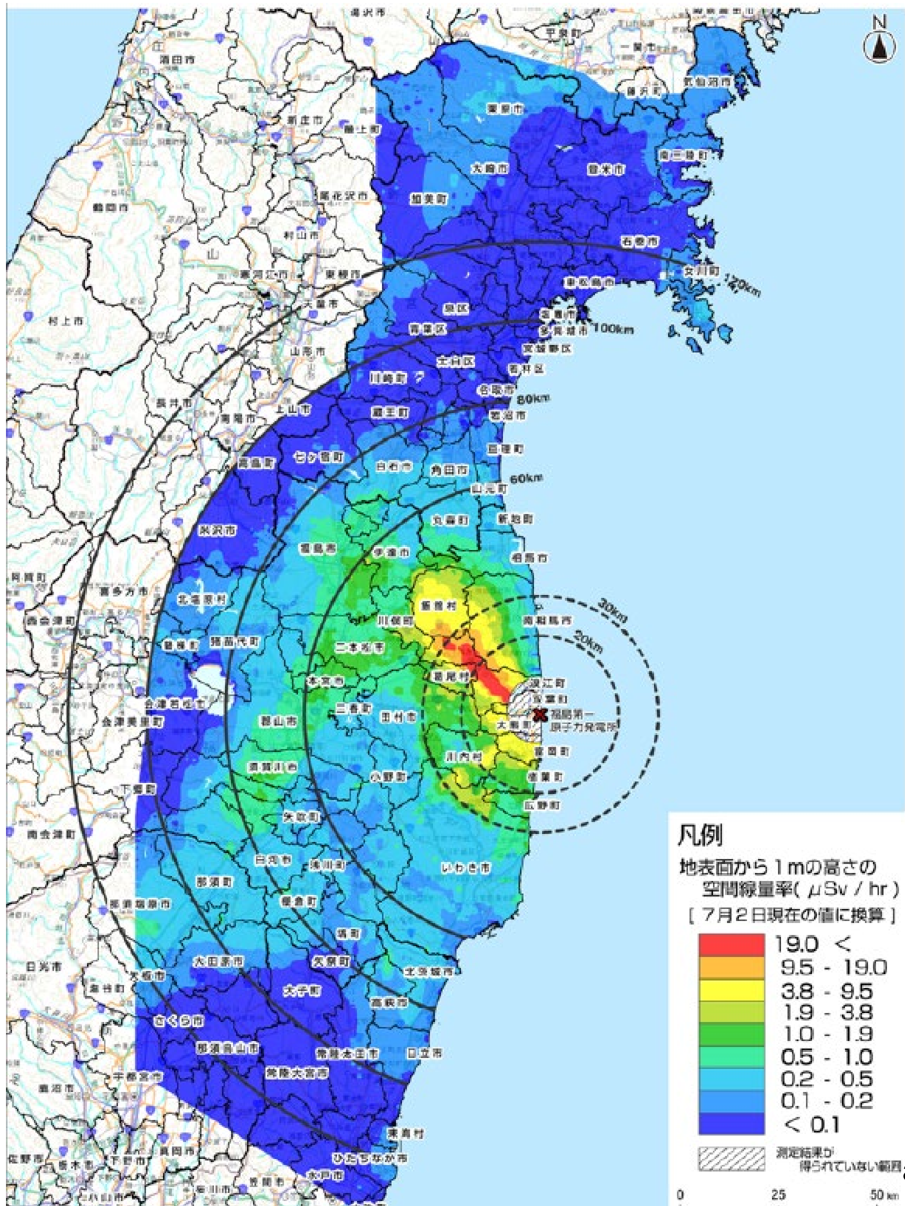
The policies for dose criteria for radiation protection

Integrated dose in accident

Radiation protection criteria for public in accident	Contents
(a) Criteria to prevent large exposure in the early stage of the accident	As for the criteria to be used for protection measures in the early stage of accidents(indoor sheltering/evacuation), the regulatory guide by the Nuclear Safety Commission, “Emergency Preparedness for Nuclear Facilities”, provide criteria for projected dose as **effective dose from external exposure “10-50 mSv (indoor sheltering)” and “over 50mSv(evacuation)”.** These criteria were determined by reference to the IAEA safety requirementGS-R-2 “Preparedness and Response for a Nuclear or Radiological Emergency”(2002)
(b) Criteria in the emergency situation(accident continuation)	In this accident, if people would continue to live the area with high level dose by local accumulation of radioactive materials released from the plant, integrated dose to the people might become high level. Therefore, the Prime Minister, who is the Chief of the Nuclear Emergency Response Headquarters, considering the opinion of the Nuclear Safety Commission into account, established “deliberate evacuation area”. The deliberate evacuation area was set by reference to **the recommendation 2007 of ICRP in which 20-100mSv is suggested as a reference level to protect public in the emergency exposure situation and IAEA safety guidance GSG2 “Preparedness and Response for a Nuclear or Radiological Emergency”(2011) in which the countermeasures for protection in the emergency situation are described to be optimized under 100 mSv/year,** and in consideration of basic principle “Radiation exposure should be kept as low as reasonably achievable”. Predicted integrated dose of 20 mSv in one year from the accident outbreak is adopted as the criteria for the deliberate evacuation area.
(c) Radiation protection criteria in the situation where contamination from past accidents should be taken into the consideration	**In the 2007 recommendation of ICRP, a standard of “1-20 mSv/year” is provided as a reference level for protecting the public from contamination after accidents(existing exposure situation).** And also, the principle of optimization of protection, “ALARA(As Low As Reasonably Achievable)” is to be applicable to the existing exposure situation.

Result of airborne monitoring by MEXT and DOE

Readings of air dose monitoring inside 100km,120km zone of FukushimaDai-ichi NPS and NorthernMiyagi Prefecture



as of July 2,2011

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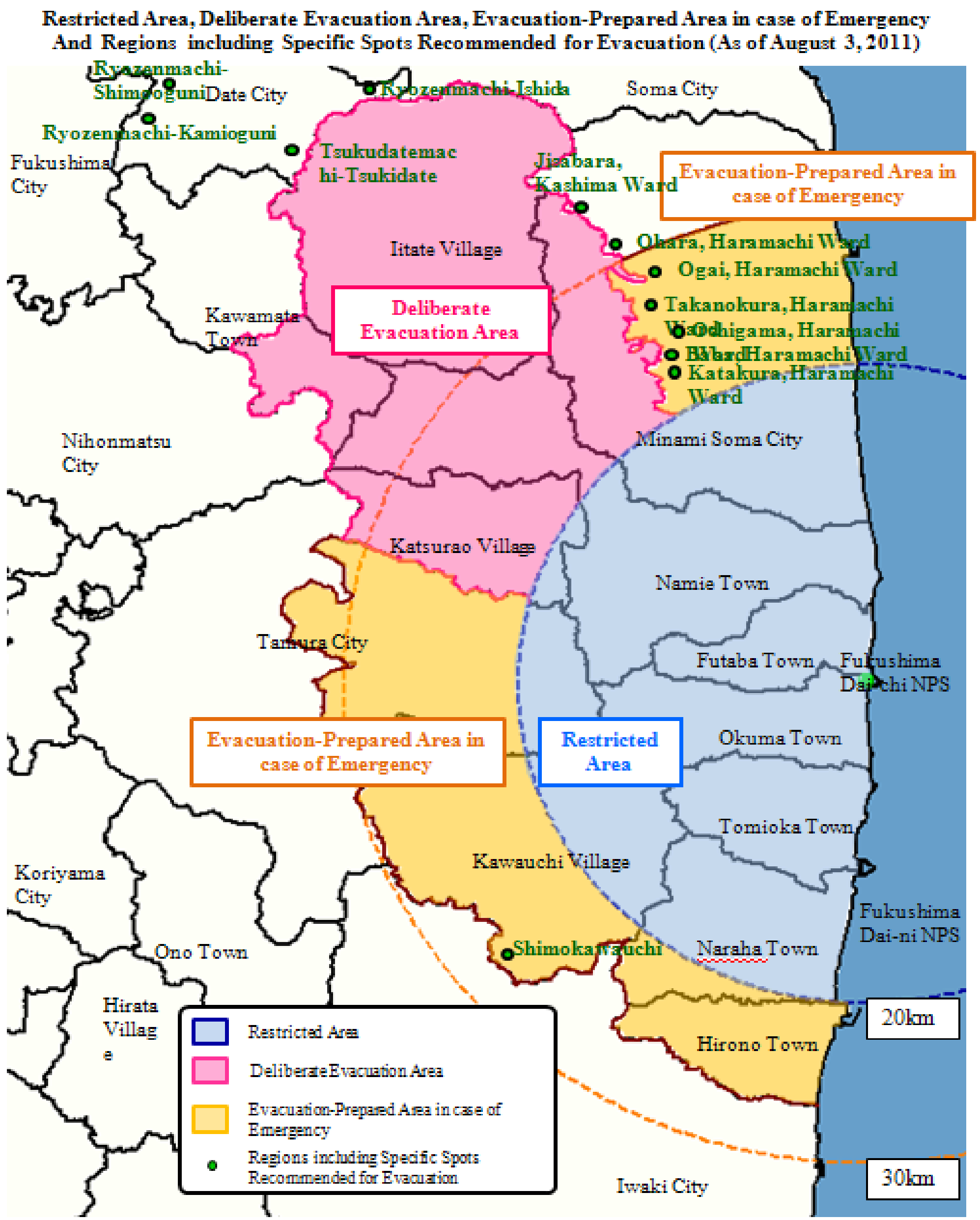
Map of Restricted Area, Deliberate Evacuation Areas, Evacuation-prepared Areas in Case of Emergency, Specific Areas Recommended for Evacuation

(As of August 3, 2011)



Ⅳ. Lessons Learned from the Accident

Lessons Learned from the Viewpoint of Leadership

1.Lessons in category 1

- Strengthen preventive measures against a severe accident

2.Lessons in category 2

- Enhancement of response measures against severe accident

3.Lessons in category 3

- Enhancement of nuclear emergency responses

4.Lessons in category 4

- Reinforcement of safety infrastructure

5.Lessons in category 5

- Thoroughly instill a safety culture

Lessons in Category 1
Strengthen preventive measures against a severe accident

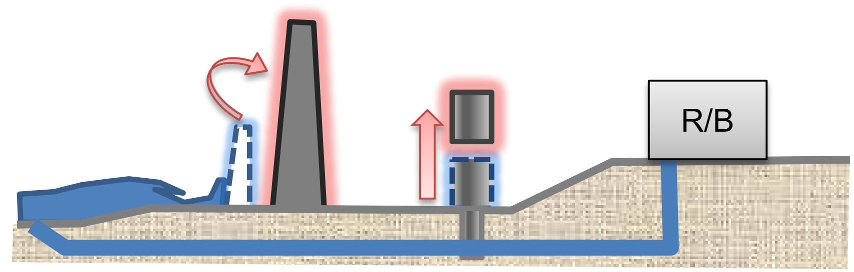
○Strengthen measures against earthquakes and tsunamis

- Measures against large-scale tsunamis were not prepared adequately.

- To assume appropriate frequency and adequate height of tsunamis in consideration of a sufficient recurrence period for attaining a safety goal
- To perform a safety design of structures, etc. to prevent the impact of flooding of the site caused by tsunamis of adequately assumed height


Photo: TEPCO


Watertight door



Sea wall Sea water pumps

Lessons in Category 1
Strengthen preventive measures against a severe accident

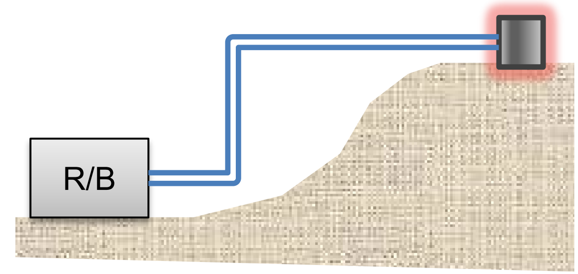
○Ensure power supplies

- Power supply sources were not diversified against common cause failures arising from an external event.

- To secure a power supply at sites for a longer time set forth as a goal, even severe circumstances, through diversification of power supply

Power supply car

Power generator for disaster preparedness



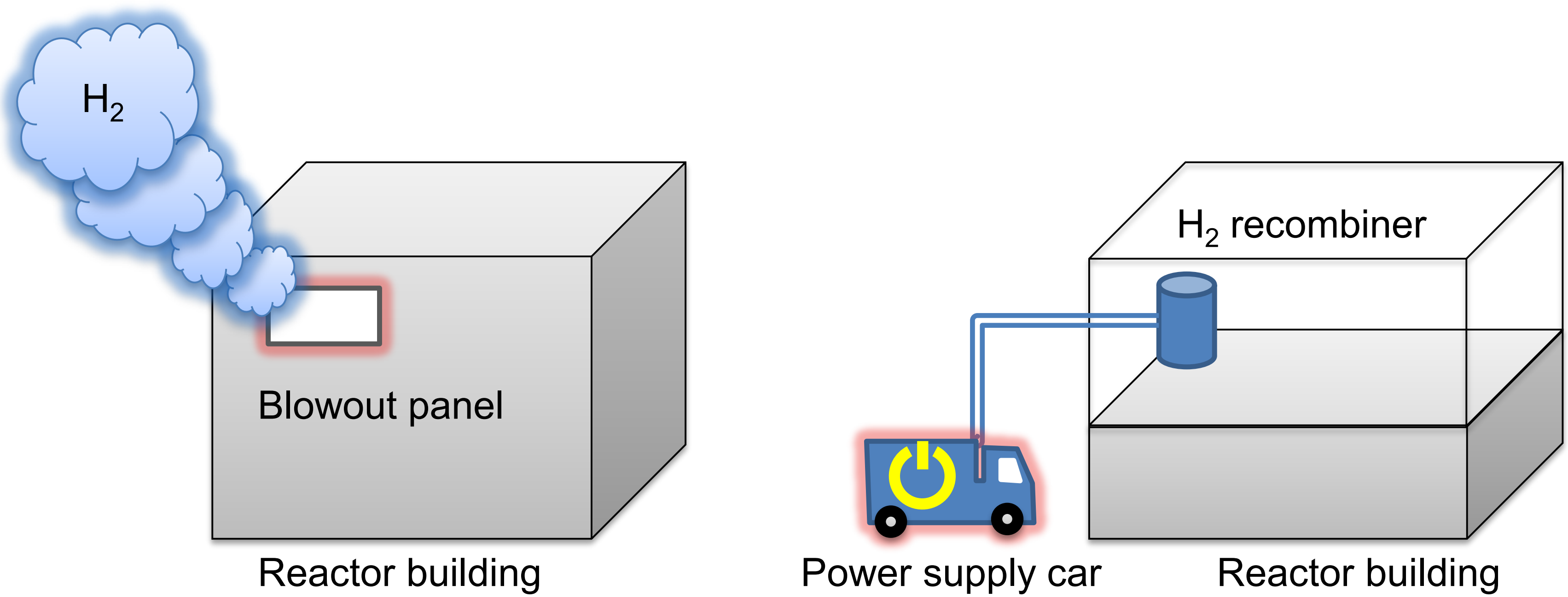
Location of power generator for disaster preparedness

Lessons in Category 2
Enhancement of response measures against severe accidents

○ Enhancement of measures to prevent hydrogen explosions

- Hydrogen measures for reactor building were not taken.

- To enhance measures to prevent hydrogen explosions in the event of a severe accident in reactor buildings



Lessons in Category 3
Enhancement of nuclear emergency responses

○Response to combined emergencies of both large-scale natural disasters and prolonged nuclear accident

- Tremendous difficulty in communication, mobilizing human resources and procuring supplies when addressing the nuclear accident that coincided with a massive natural disaster

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- To prepare the structures and environments where appropriate communication tools and devices and channels to procure supplies in the case of both a massive natural disaster and a prolonged nuclear accident

Photo: TEPCO

Lessons in Category 4
Reinforcement of safety infrastructure

○Reinforcement of safety regulatory bodies

- It was not clear where the primary responsibility lies in ensuring citizens' safety in an emergency.

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- The Japanese Government will separate NISA from METI and start to review implementing frameworks, including the NSC and relevant ministries, for the administration of nuclear safety regulations and for environmental monitoring.

Lessons in Category 5
Thoroughly instill a safety culture

○Thoroughly instill a safety culture

- Have the operators been serious in introducing appropriate measures for improving safety, when they are not confident that risks concerning the public safety of the plant remain low?

- Have the regulators been serious in addressing new knowledge in a responsive and prompt manner, not leaving any doubts in terms of safety?

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- To establish a safety culture by going back to the basics, namely that pursuing defense-in-depth is essential for ensuring nuclear safety, by constantly learning professional knowledge on safety, and by maintaining an attitude of trying to identify weaknesses as well as room for improvement in the area of safety