東京大学
THE UNIVERSITY OF TOKYO

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CSN, Spain

Fukushima Daiichi Nuclear Accident;

based on the Final Report of Atomic Energy Society of Japan

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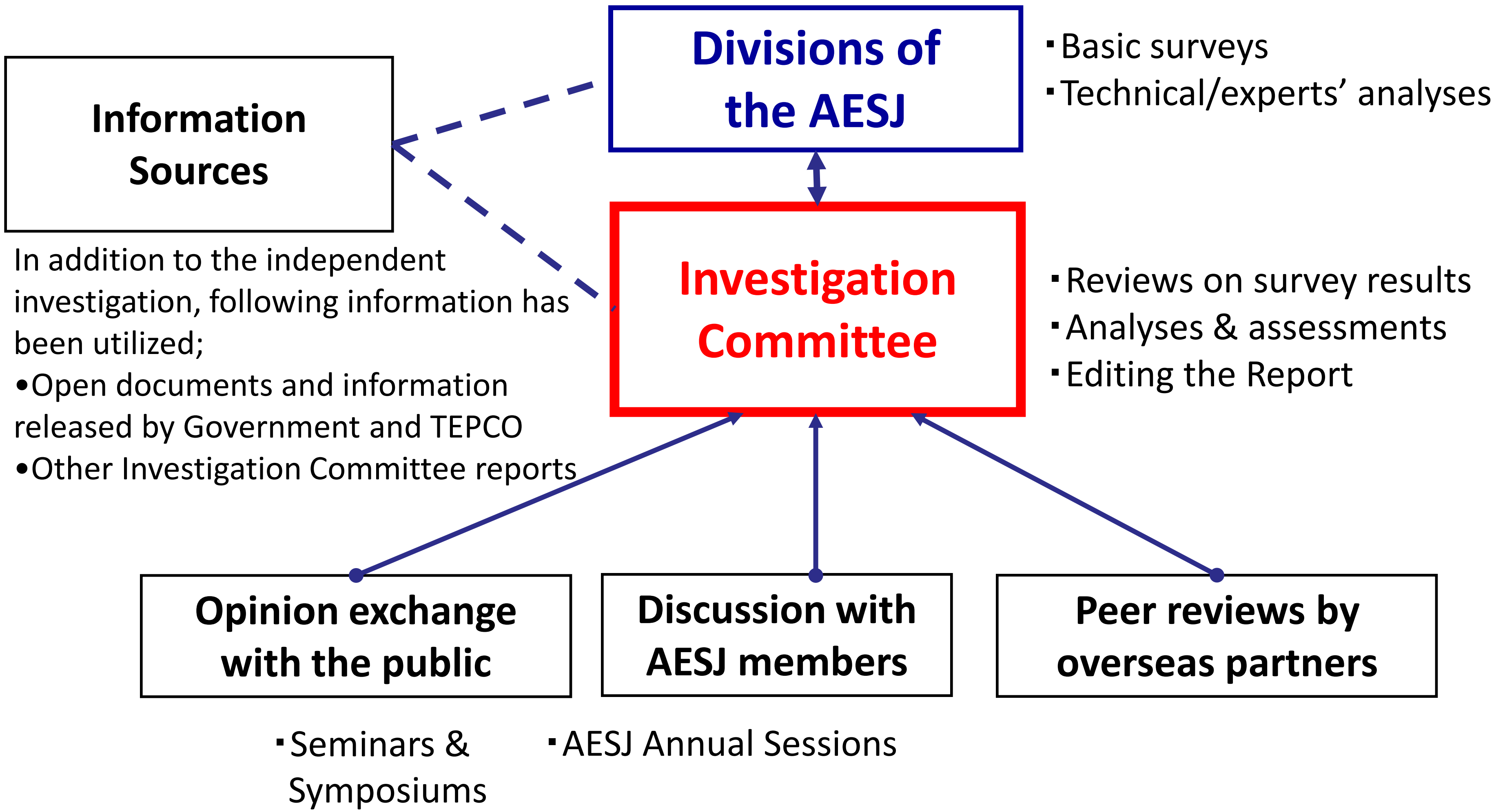
Contents

Objectives of the AESJ Investigation Committee on the Fukushima Daiichi Accident

- **The AESJ, as a professional and academic organization of nuclear experts and scientists, is responsible to identify the underlying and root causes of the TEPCO's Fukushima Daiichi NPS accident through technical surveys and analyses, and to offer solutions for ensuring and enhancing nuclear safety.**
  - **The Fundamental Concept on Nuclear Safety has also been developed to meet this objective.**
  - **Factors on why this nuclear disaster could not be prevented in connection to the organizational issues of the AESJ have also been discussed.**
  - **The AESJ is committed to promote organizational and operational reforms of the nuclear community in Japan and to enhance nuclear safety research, etc., on the basis of the recommendations in the Final Report.**

Survey Methods of the Investigation Committee



Structure of the AESJ Final Report

Chapter	Contents	Notes
1	Introduction	
2	Overview of Nuclear Power Stations	Confirmation of facts
3	Overview of the Accident at the Fukushima Daiichi Nuclear Power Station	
4	Overview of Events at Other Nuclear Power Stations	
5	Off-site Response	
6	Accident Analysis and Issues	Accident analysis
7	Analysis & Issues on Nuclear Safety System	
8	Root Causes of the Accident and Recommendations	Root cause analysis and recommendations
9	Post-Accident Management in Progress	Analysis of issues related to decommissioning
Appendix	1) List of the Committee Members; 2) List of the Committee activities; 3) List of Abbreviations	Others
Web Page	Glossary of terms, links to related reference sources (Japanese)	

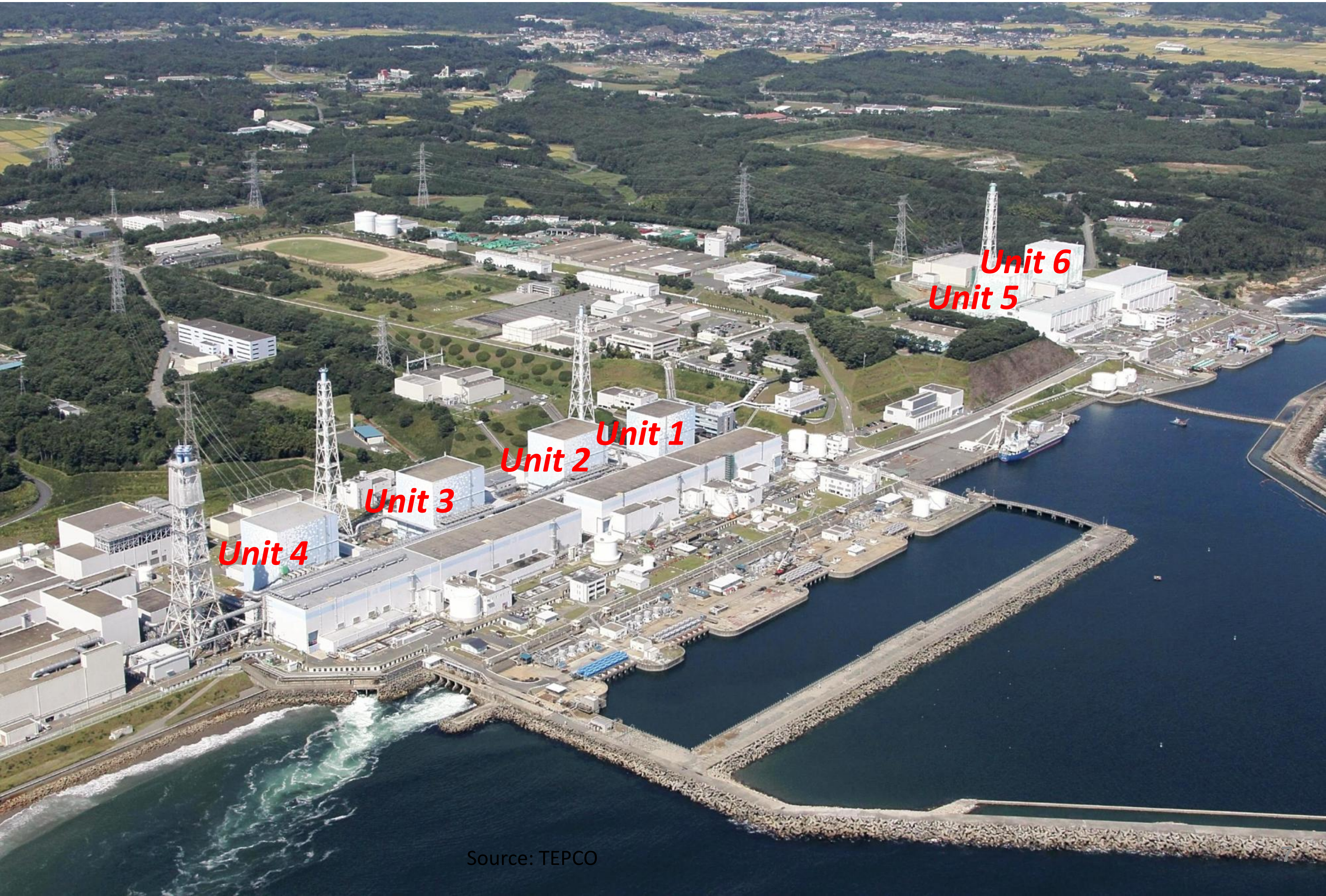
Key Approaches for the AESJ Surveys

- **The primary purpose of ensuring safety of nuclear facilities is "The Protection of People and the Environment" from radiation consequences.**
- From this perspective, surveys on the causes for radioactive material release from nuclear facilities and issues in accident management for the protection of local residents from exposure have been conducted.

- <u>Multi-disciplinary analyses have been made for clarifying the root causes of the accident in a typical huge and complex system.</u>

- In addition to technical & professional approach, reformation of the AESJ organization has been discussed.

Fukushima Daiichi Nuclear Power Plant operated by TEPCO

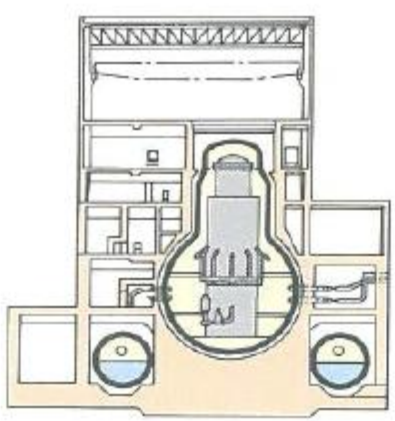


Source: TEPCO

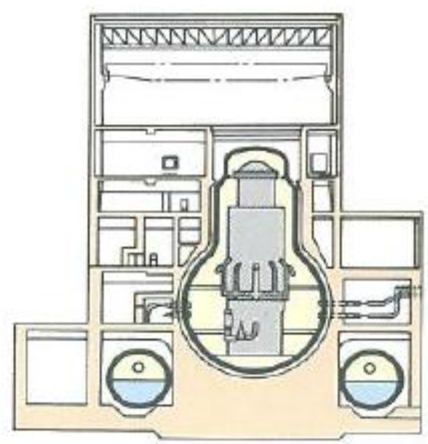
Status of Fukushima Daiichi Units 1-6

<table>
<tr><th></th><th>Unit 1</th><th>Unit 2</th><th>Unit 3</th><th>Unit 4</th><th>Unit 5</th><th>Unit 6</th></tr>
<tr><td>Reactor Type</td><td>BWR-3</td><td colspan="4">BWR-4</td><td>BWR-5</td></tr>
<tr><td>PCV Type</td><td colspan="5">Mark-I</td><td>Mark-II</td></tr>
<tr><td>Start of Operation</td><td>1971</td><td>1974</td><td>1976</td><td>1978</td><td>1978</td><td>1979</td></tr>
<tr><td>Electric Output (MW)</td><td>460</td><td colspan="4">784</td><td>1100</td></tr>
<tr><td>Thermal Output (MW)</td><td>1380</td><td colspan="4">2381</td><td>3293</td></tr>
<tr><td rowspan="2">Status on March 11 before the Earthquake</td><td colspan="3" rowspan="2">Full Power Operation</td><td colspan="3">Outage</td></tr>
<tr><td>All fuel removed</td><td colspan="2">RPV top lid closed</td></tr>
</table>

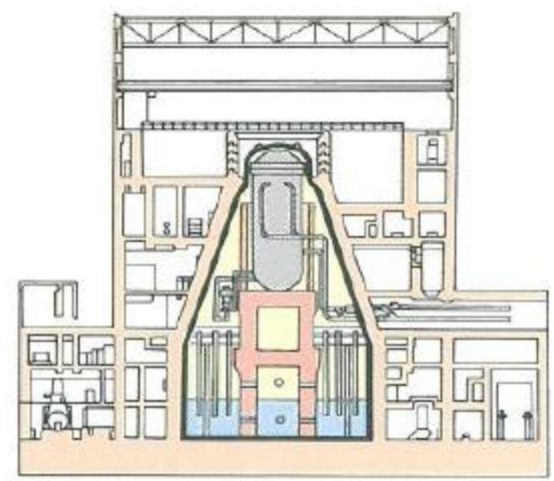
BWR-3



BWR-4



BWR-5

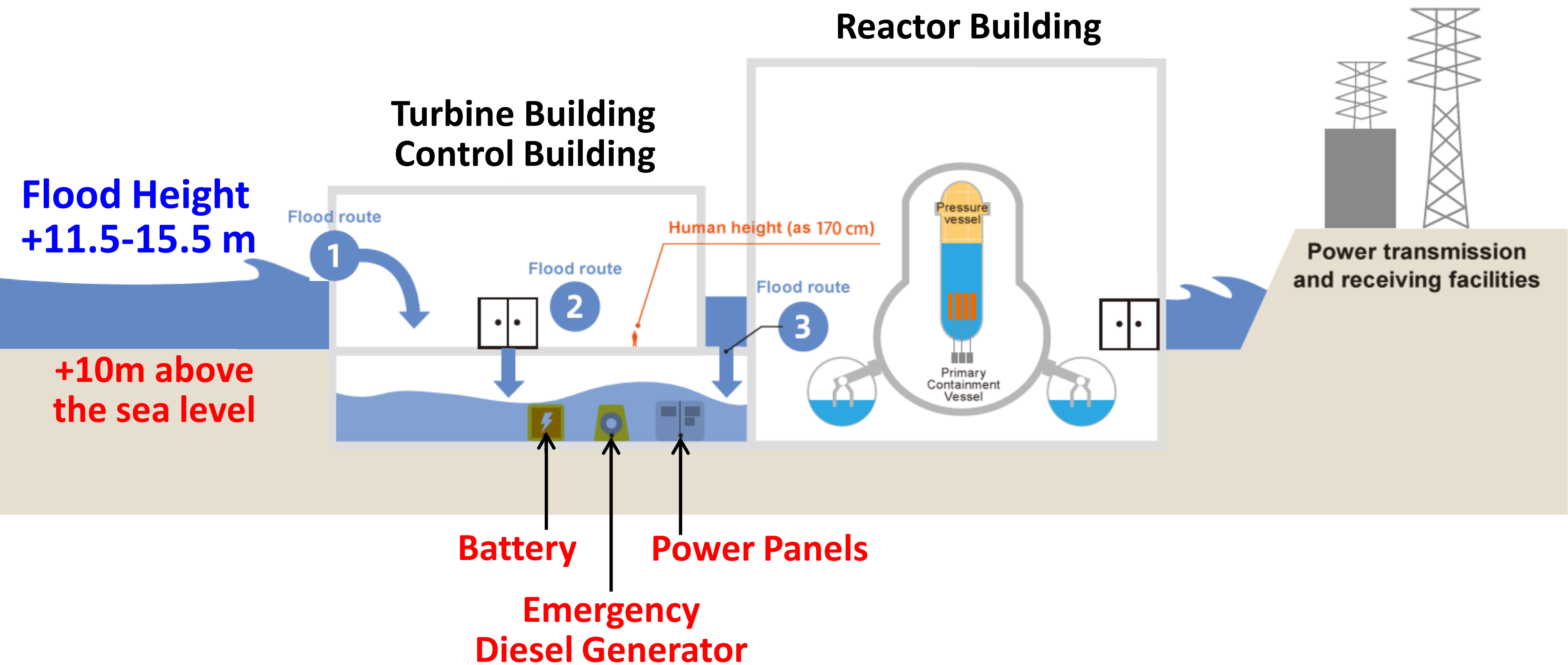


TEPCO, Fukushima Nuclear Accidents Investigation Report, Reference 2-3 (1),

Summary of Damages in NPSs

Site	Units	Off-site ac Power	E. D/G	dc Power	Heat Sink	Switchyard	Nuclear Fuels
Fukushima Daiichi	1	275kV, All Lost 66kV, All Lost	All Lost	Lost	Lost	Lost	Melt-down
	2		All Lost	Lost	Lost	Lost	Melt-down
	3		All Lost	Shortly L.	Lost	Lost	Melt-down
	4		All Lost	Lost	Lost	Lost	Sound
	5		All Lost	Available	Lost	Lost	Sound
	6		1/3 Available	Available	Lost	Available	Sound
Fukushima Daini	1	500kV, 1/2 Available 66kV, All Lost.	All Lost	Available	Lost	Available	Sound
	2		Available	Available	Lost	Available	Sound
	3		Available	Available	1/2 Usable	Available	Sound
	4		Available	Available	Lost	Available	Sound
Onagawa	1	275kV, 1/4 Available 66kV, All Lost	Available	Available	Usable	Available	Sound
	2		Available	Available	1/2 Usable	Available	Sound
	3		Available	Available	Usable	Available	Sound
Tokai-Daini	1	275kV/154kV, All Lost	Availabe	Available	Usable	Available	Sound

Tsunami Flood in Units 1-4



Assumption of Tsunami Height was Max. 6.1 m before the Accident.

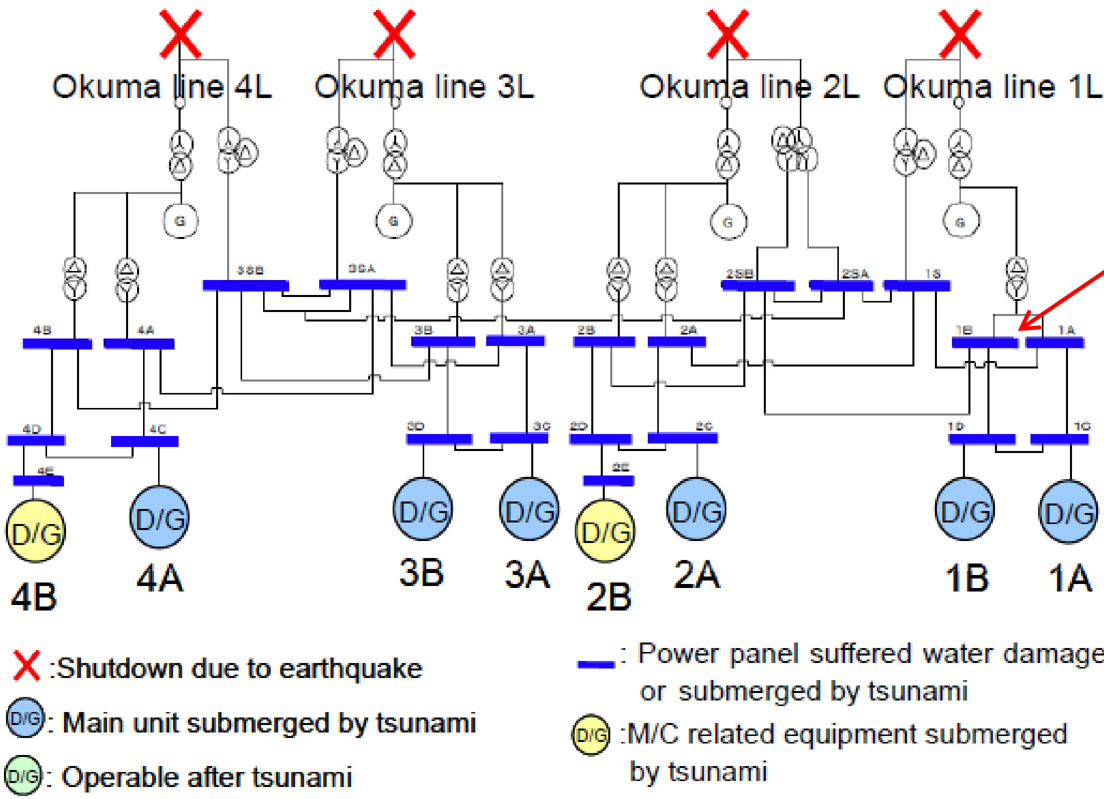
Flood Route to the Basement of Turbine Building

① Air Supply Louver for Emergency Diesel Generator

② Turbine Building Entrance

③ Component Hatch

Influence of the Tsunami Flooding on Electric Power Distribution Systems



TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 7-3.

Source: TEPCO

- All AC power (high voltage line of 6.9kV, low voltage line of 480 V and 120 V) were lost in Units 1, 2, 3, 4 and 5.
- Main DC bus (125 V) was lost in Units 1, 2 and 4.

Influence of Tsunami on Ultimate Heat Sink

- ✓ Seawater Pumps for Ultimate Heat Sink were lost in all the 6 units.

TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 7-2,

Possibility of Damage of Components by the Earthquake

Key points discussed in the Diet Investigation Report

Likelihood that SR valves in Unit 1 was not functioning at the time earthquake occurred - if so, a minor LOCA may have occurred in Unit 1 by the seismic ground motion.

Results of Data Analysis by the AESJ Investigation Committee

(1) Reactor pressure was maintained below SR valve pressure by IC activation in Unit 1.
(2) Insignificant increase in PCV internal pressure verified by suspended drywell cooler.
(3) No leakage exceeding predetermined limit stipulated in safety regulations; no LOCA.

Fundamental Safety Functions for Light Water Reactors

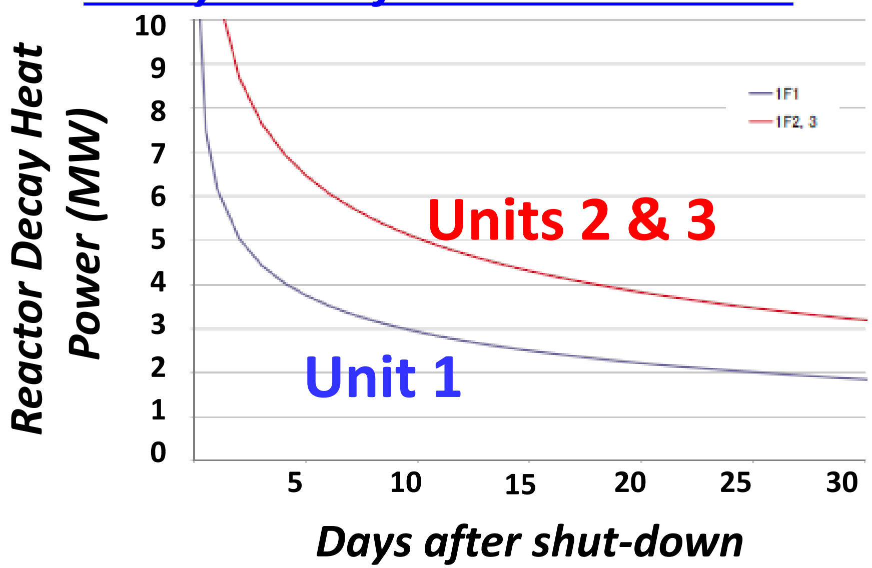
Shutting Down by interrupting fission chain reaction through insertion of control rods

Cooling Down the core through continuous water injection and circulation

Confining radio-active materials inside the boundary (RPV and PCV)

Decay Power and Radioactive Materials in Units 1, 2 and 3

Decay Heat after the Shut-down



Source Term just after the Shut-down

Unit 1

I-131 : 1.9×10^{18} Bq

Cs-137 : 2.0×10^{17} Bq

Unit 2

I-131 : 2.7×10^{18} Bq

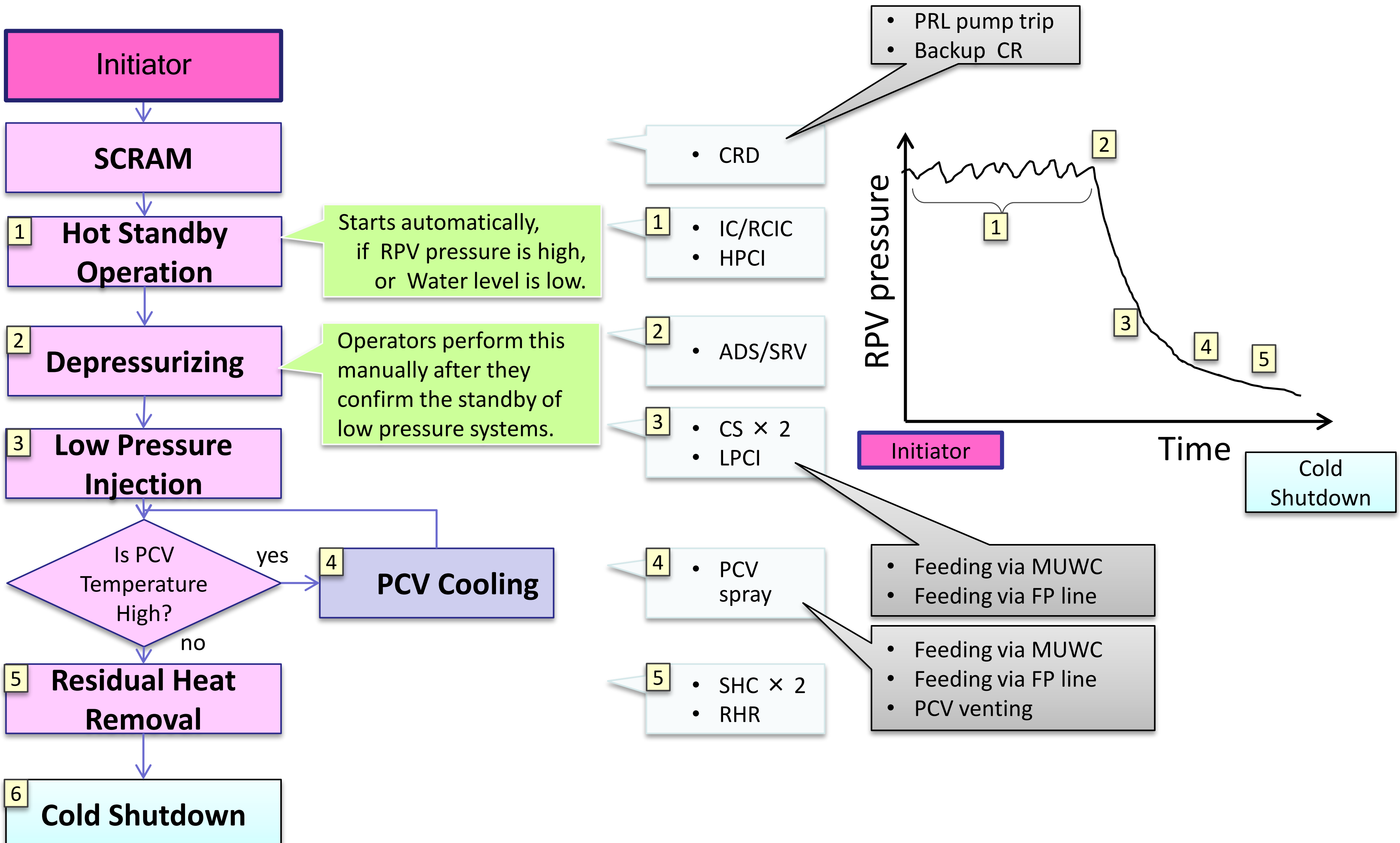
Cs-137 : 2.4×10^{17} Bq

Unit 3

I-131 : 2.7×10^{18} Bq

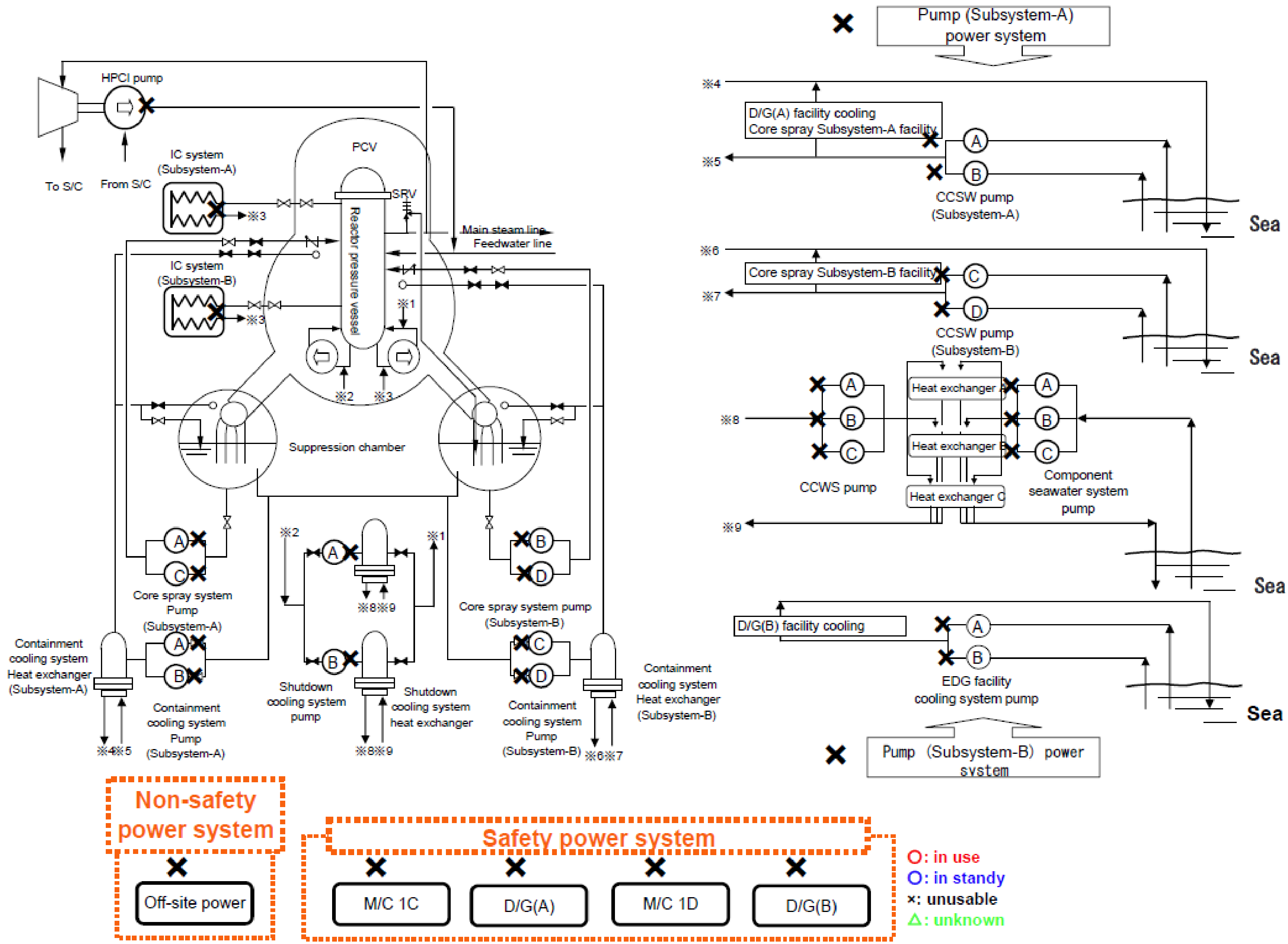
Cs-137 : 2.4×10^{17} Bq

Operational Procedure of BWR under Emergency



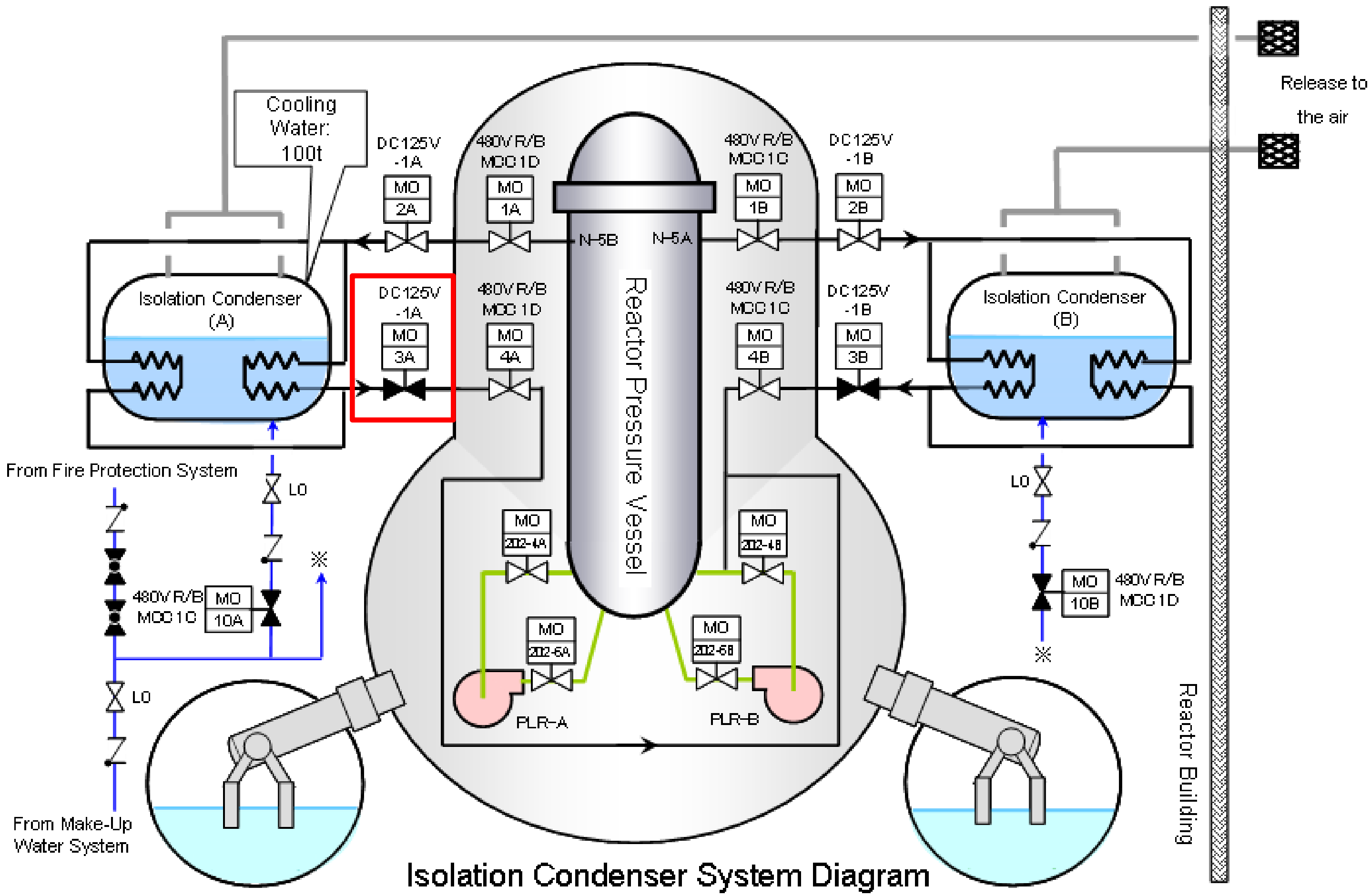
Based on the report of Nuclear Safety Division, Atomic Energy Society of Japan

Available Safety Systems after the Tsunami in <u>Unit 1</u>



TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 7-8,

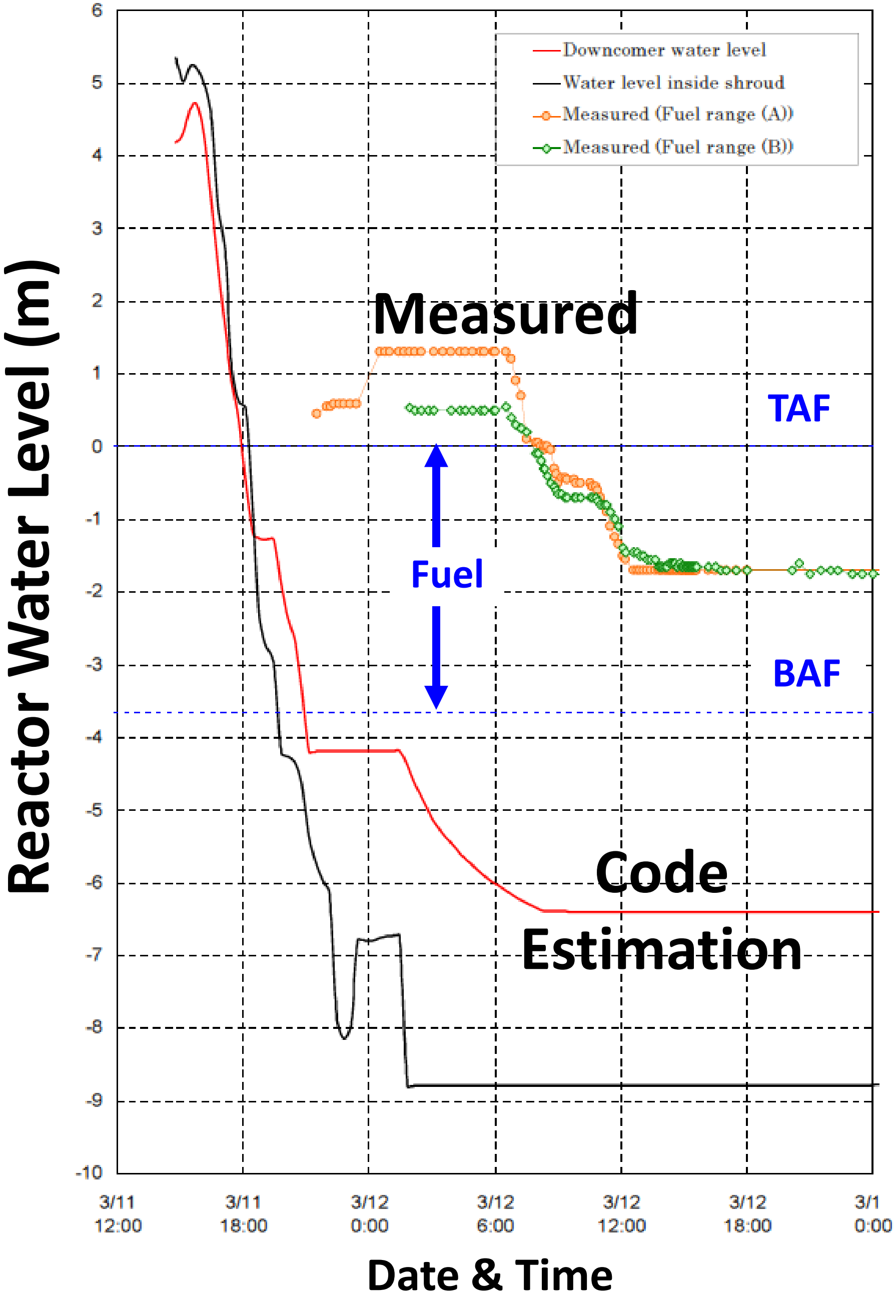
Isolation Condenser (IC) in Unit 1



Isolation Condenser System Diagram

Core damage in Unit 1 progressed in a short period of time after the tsunami. The status of the IC, which is used to cool the reactor in the initial stages after shutdown, have affected the event progression.

Water Level in Unit 1



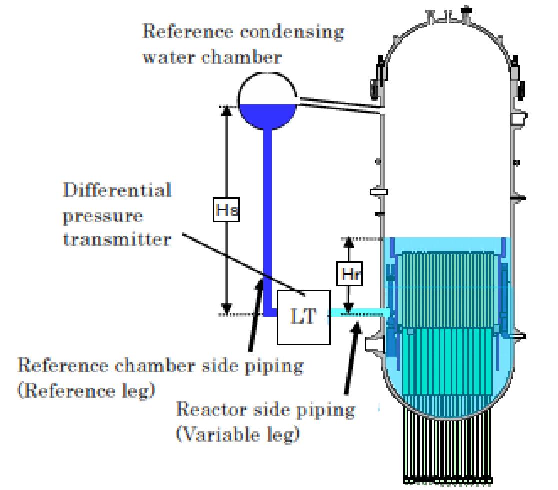
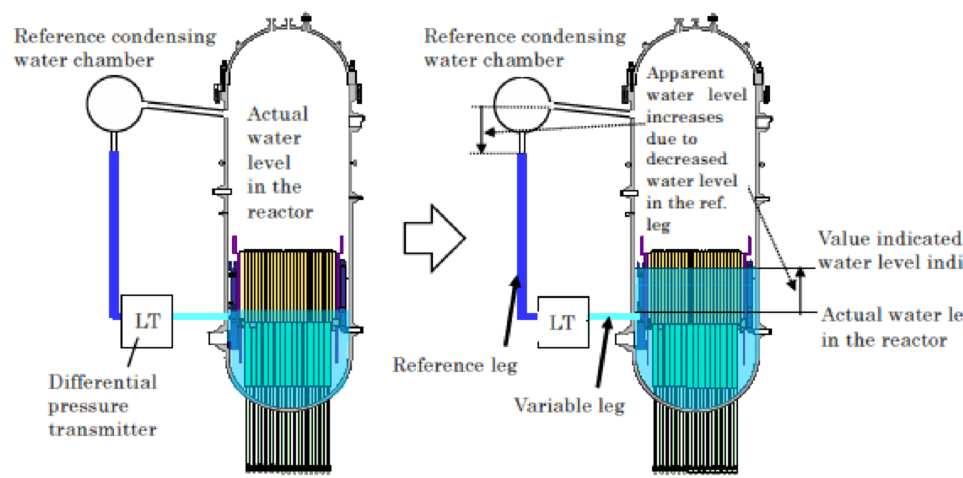
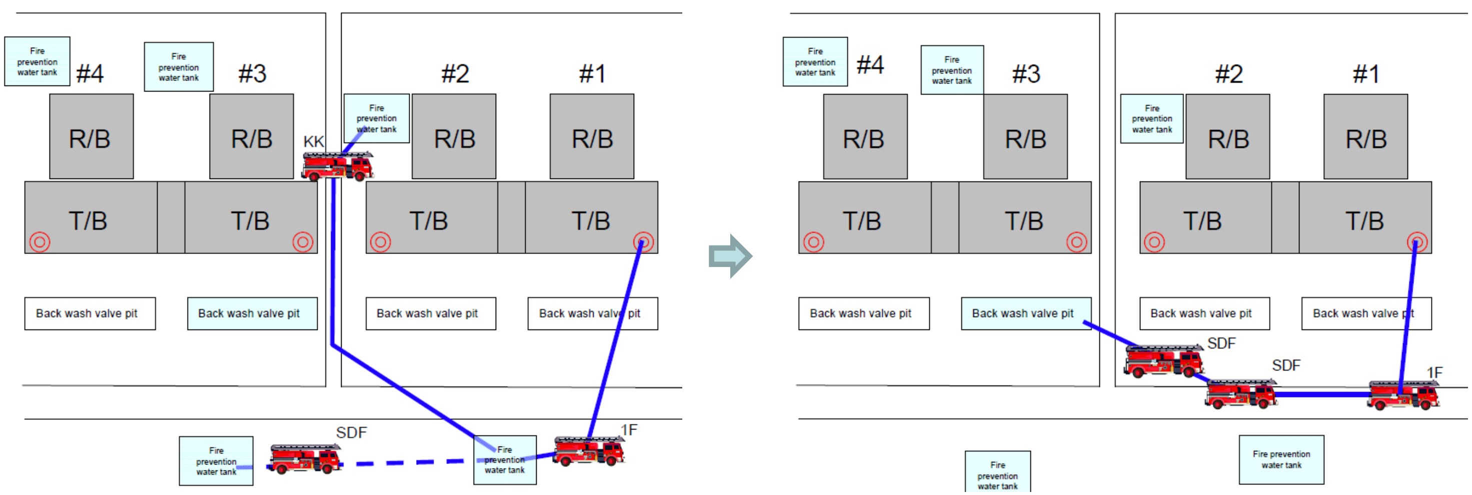


Figure 1 Fuel range water level indicator



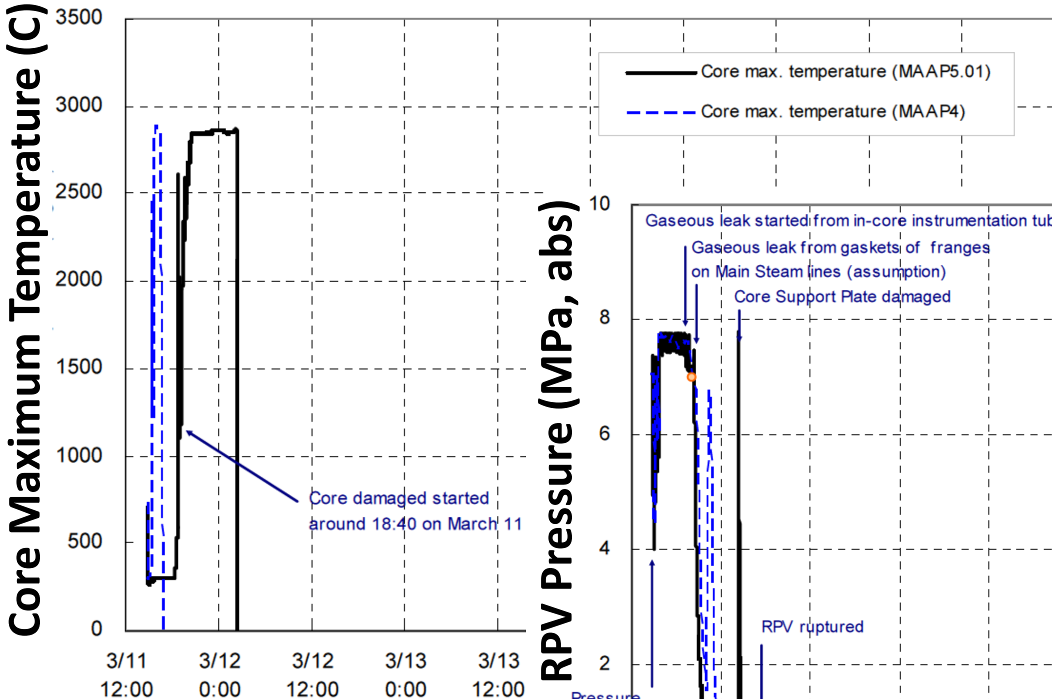
Cooing Reactor Core in Unit 1

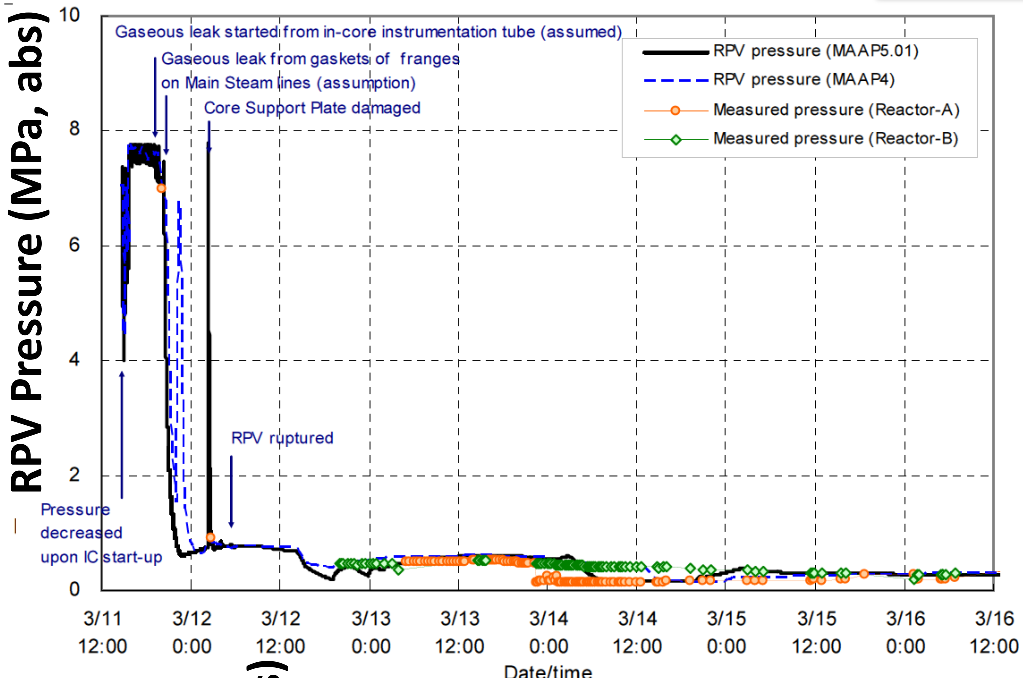
- At 2:45 on March 12, RPV pressure was determined to be 0.8 Mpa
- Around 4AM on March 12, fire engine brought fresh water and injected water into reactor core though Fire Prevention (FP) line.
  - The connection between FP line and reactor core was installed for accident management on 1990’s.
  - The connector between FP line and fire engine was prepared to enhance fire prevention capacity after Chuetsu-oki earthquake.
- Two fire engine was used to pump water directly from water tank, and 80 t of fresh water was injected until 14:53 on March 12.
- At 19:02, after the tank dried off, seawater in back wash valve pit for Unit 3 was injected into Unit 1 reactor core

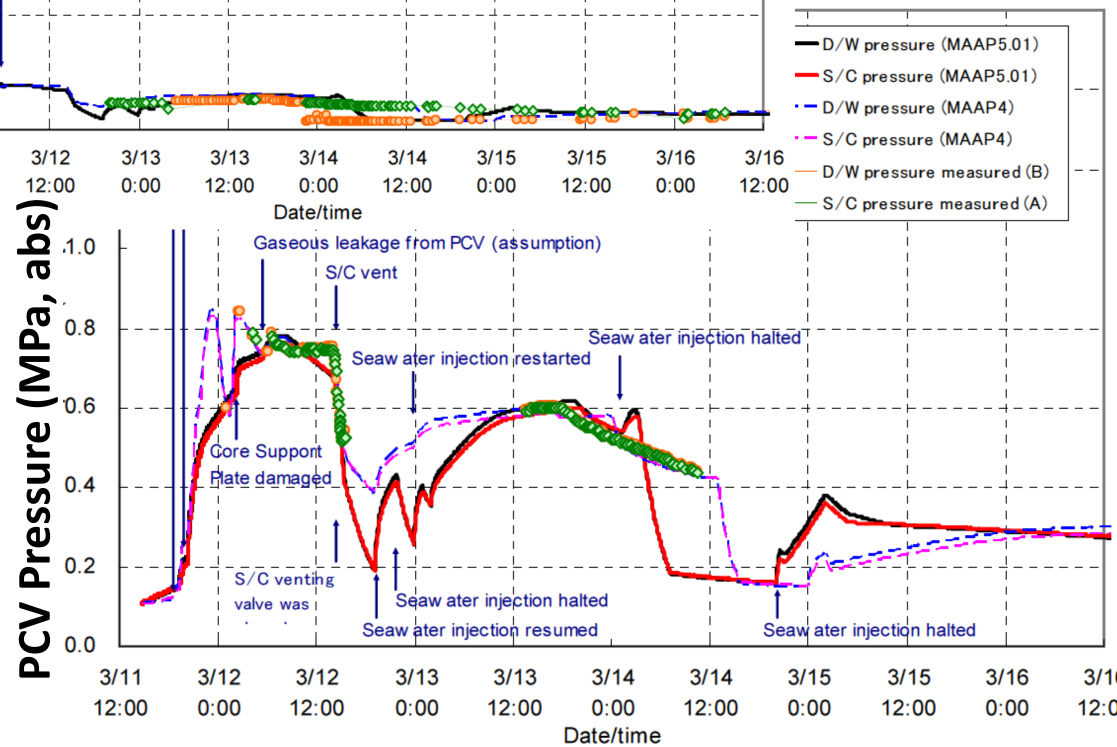


TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 10-4,

Estimated Parameters in Unit 1

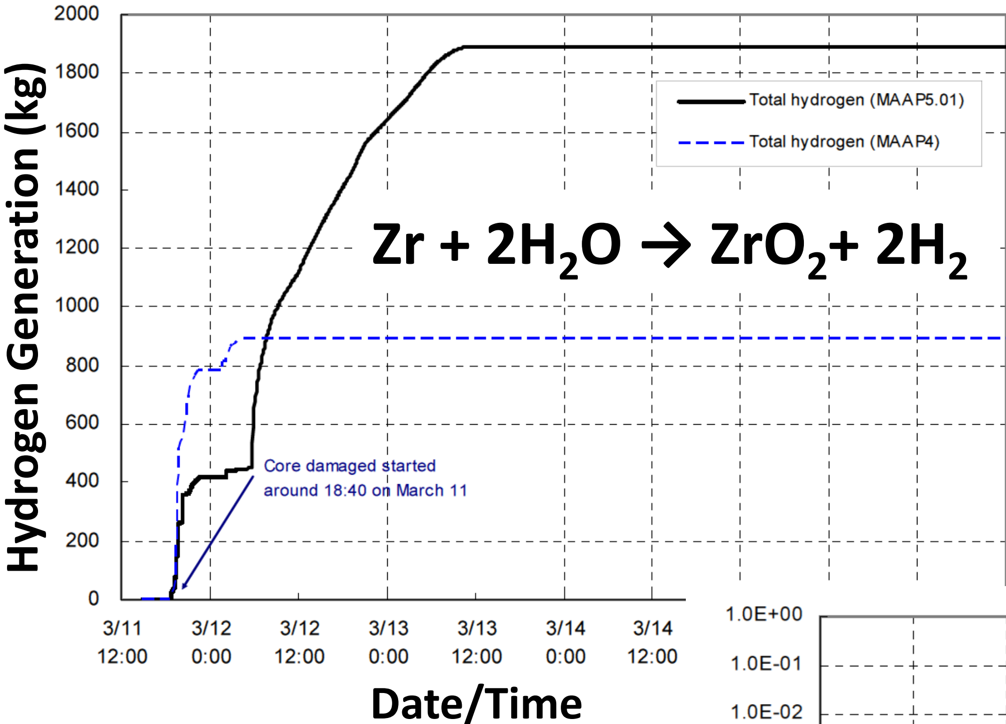






Some measured values used for model justification are also shown.

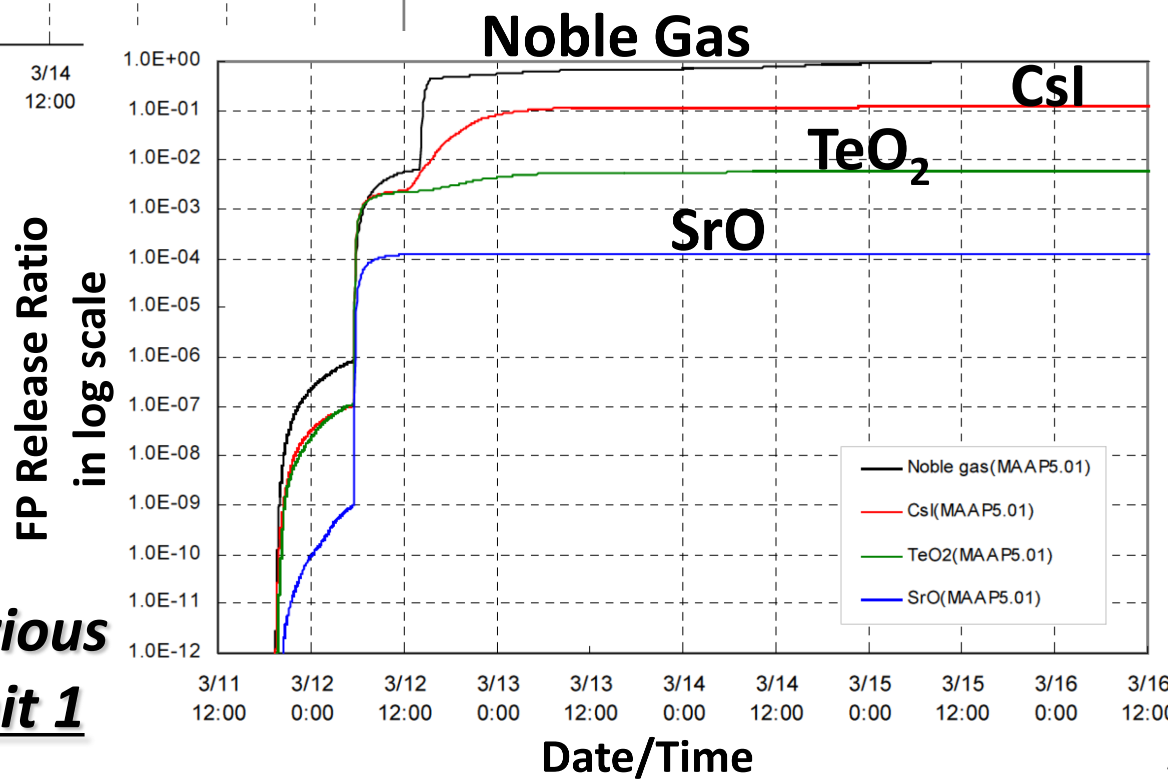
Generation of Hydrogen in Unit 1



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

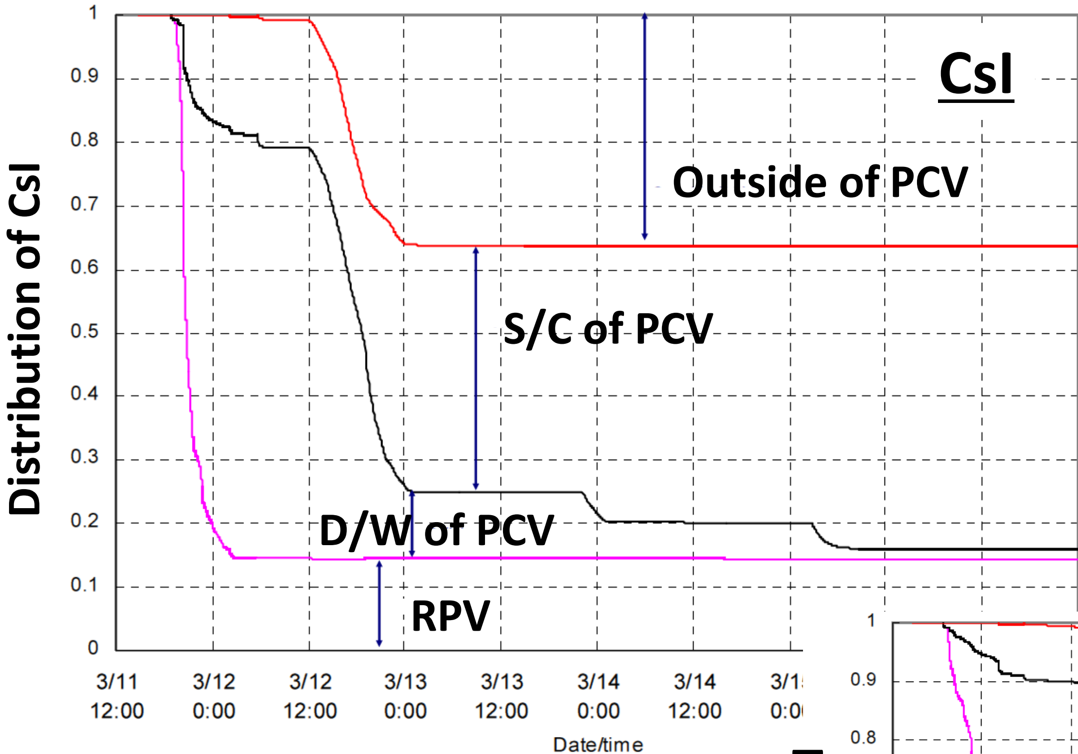
Zr-H_2O reaction at high temperature is main source of H_2.

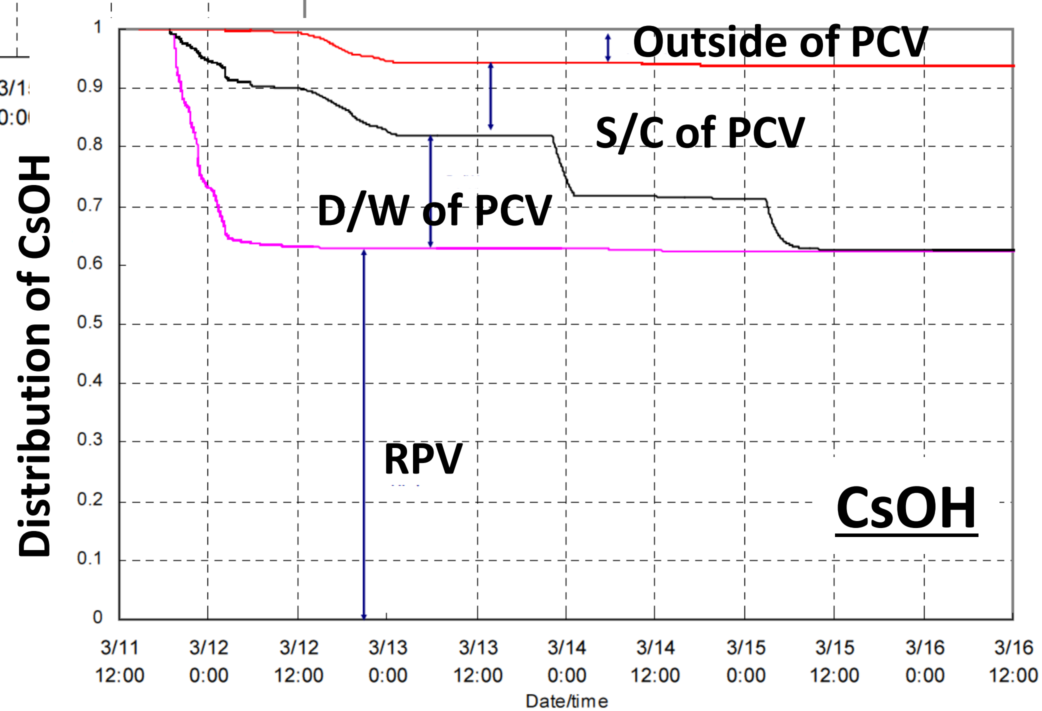
Release Rates of Fission Products in Various Chemical Forms in Unit 1

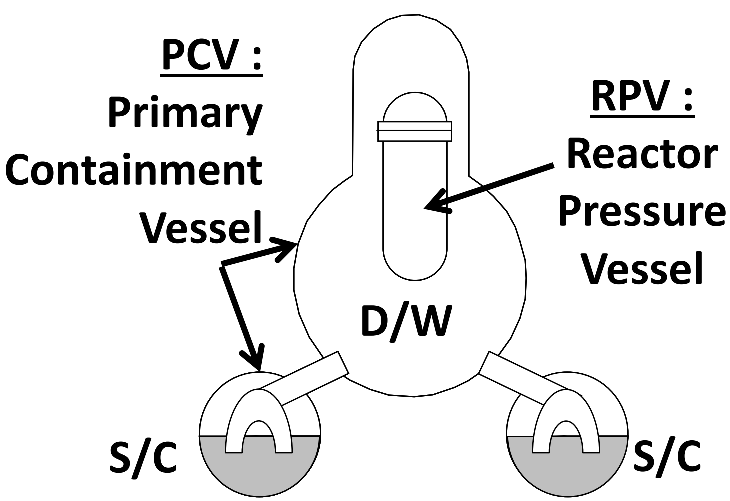


TEPCO, Fukushima Nuclear Accidents Investigation Report,

Distribution of CsI and CsOH in Various Location in Unit 1 (MAAP code)







D/W : Drywell of PCV

S/C : Suppression Chamber of PCV

Groups of Radionuclides from Nuclear Fuel

Group #	Designation	Elements
1	**Noble Gases**	Xe, Kr
2	**Halogens**	I, Br
3	**Alkali Metals**	Cs, Rb
4	**Tellurium Group**	Te, Sb, Se
5	**Barium, Strontium**	Ba, Sr
6	**Noble Metals**	Ru, Rh, Pd, Mo, Tc, Co
7	**Lanthanides**	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am
8	**Cerium Group**	Ce, Pu, Np

NUREG-1465

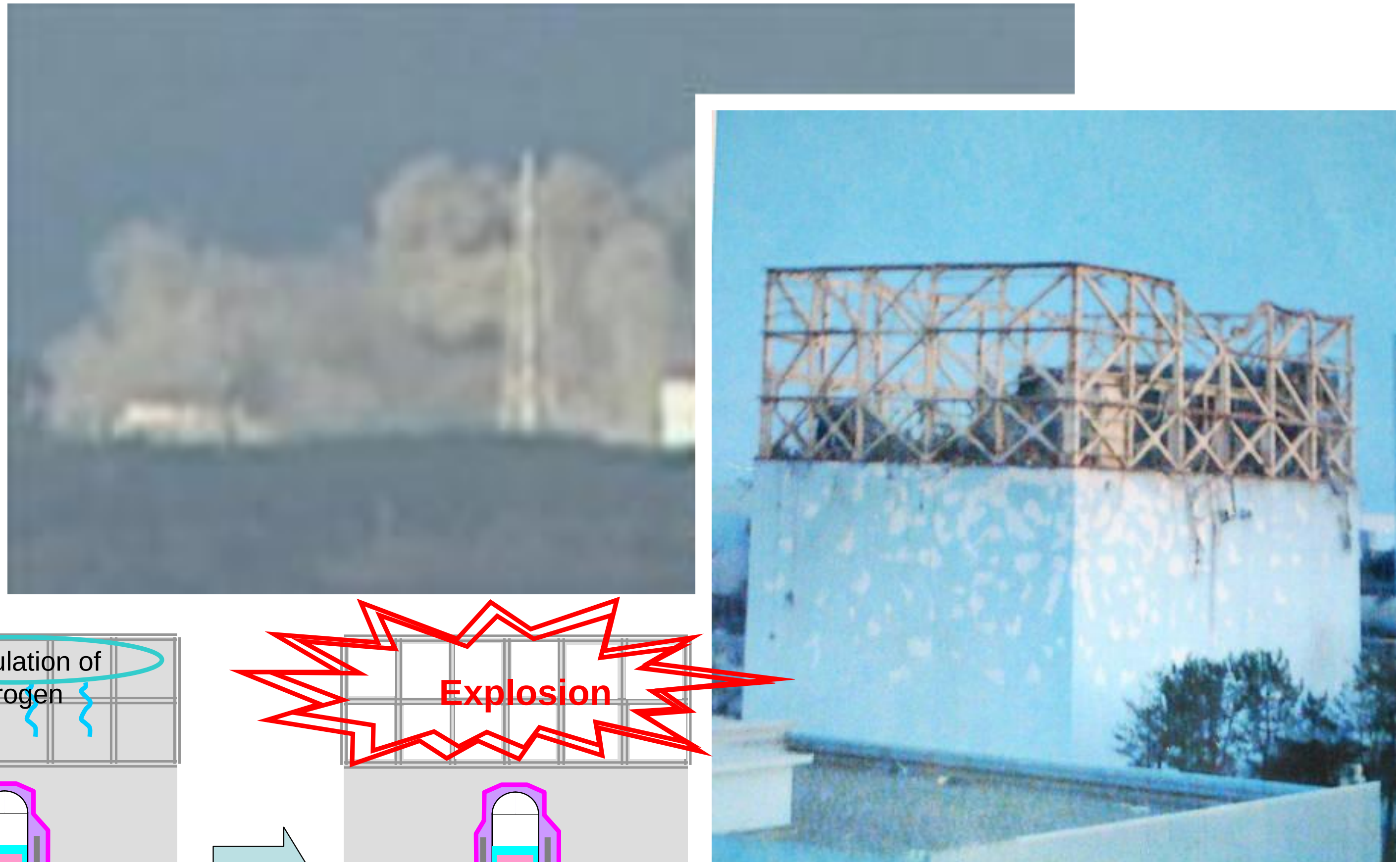
Released Amount of Radio-active Nuclide Estimated by the MELCORE code

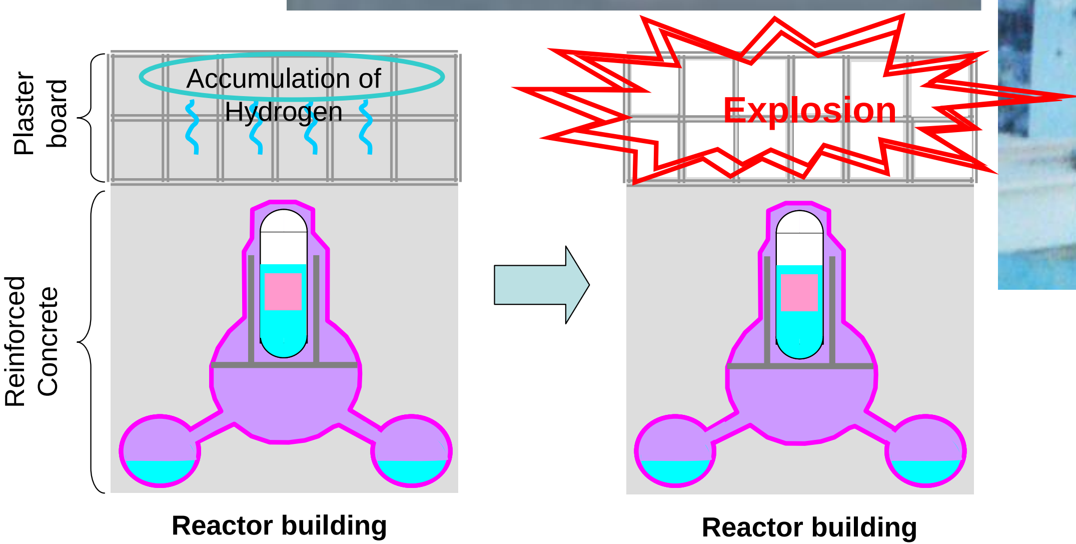
(Bq)

Nuclide	Unit 1	Unit 2	Unit 3
Xe-133	1.6×10^{18}	3.3×10^{18}	4.3×10^{18}
I-131	4.8×10^{16}	1.9×10^{17}	1.4×10^{16}～1.0×10^{17}
Cs-134	1.2×10^{15}	7.1×10^{15}	2.22×10^{13}～6.7×10^{15}
Cs-137	9.7×10^{14}	6.3×10^{15}	1.3×10^{12}～5.8×10^{15}
Sr-89	6.9×10^{14}	1.2×10^{16}	4.5×10^{13}～2.2×10^{14}
Ba-140	1.0×10^{15}	1.9×10^{16}	2.7×10^{14}～3.55×10^{14}
Te-132	4.6×10^{16}	8.3×10^{16}	2.8×10^{16}～3.3×10^{16}
Ru-103	8.82×10^{7}	6.8×10^{10}	3.2×10^{9}～4.0×10^{9}
Pu-241	6.3×10^{6}	3.0×10^{8}	3.0×10^{5}～2.6×10^{7}
Cm-242	2.4×10^{8}	7.51×10^{9}	2.1×10^{9}～6.7×10^{9}

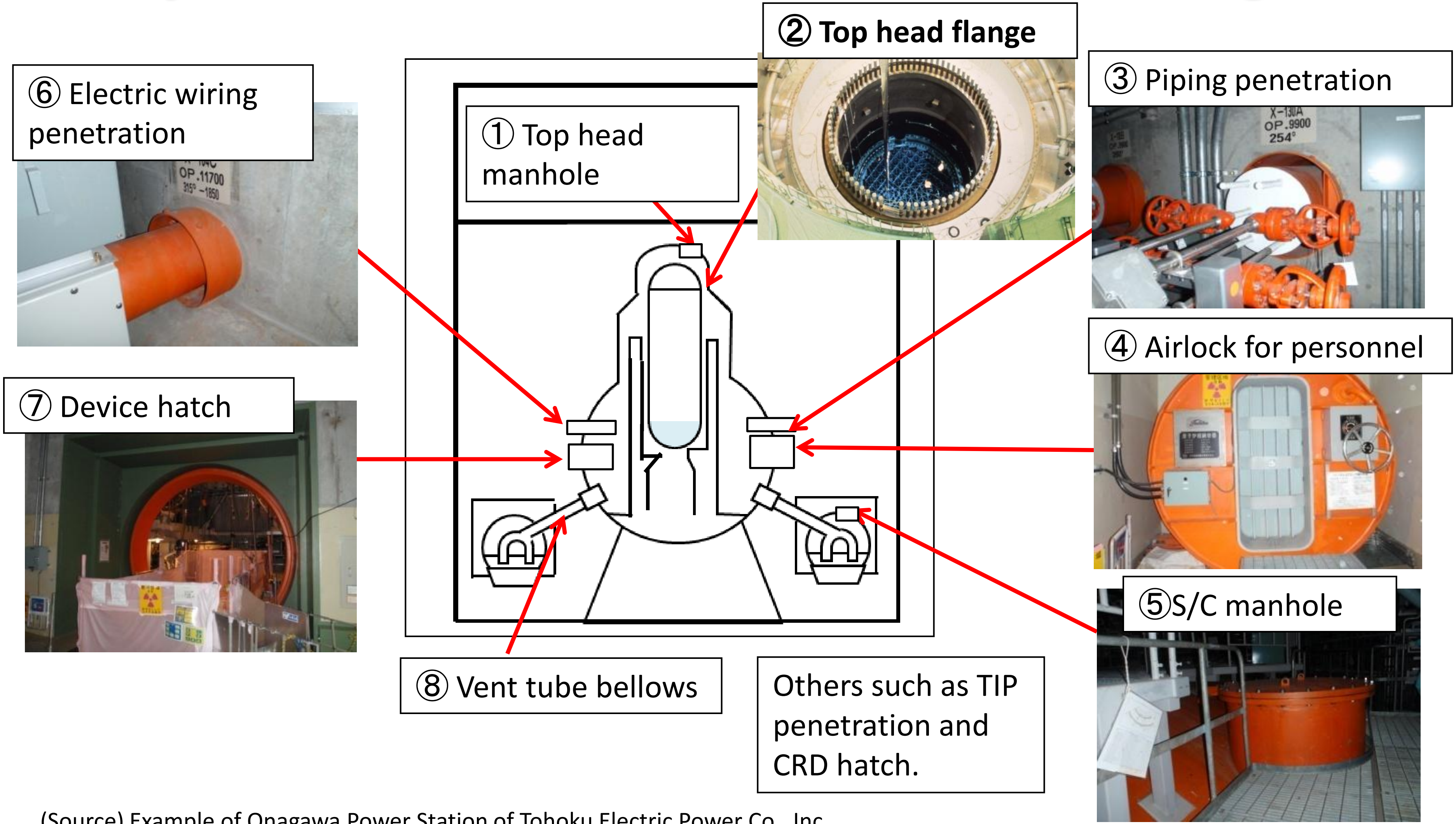
Hoshi et al (2012)

Hydrogen Explosion in <u>Unit 1</u> at 15:36 on March 12, 2011



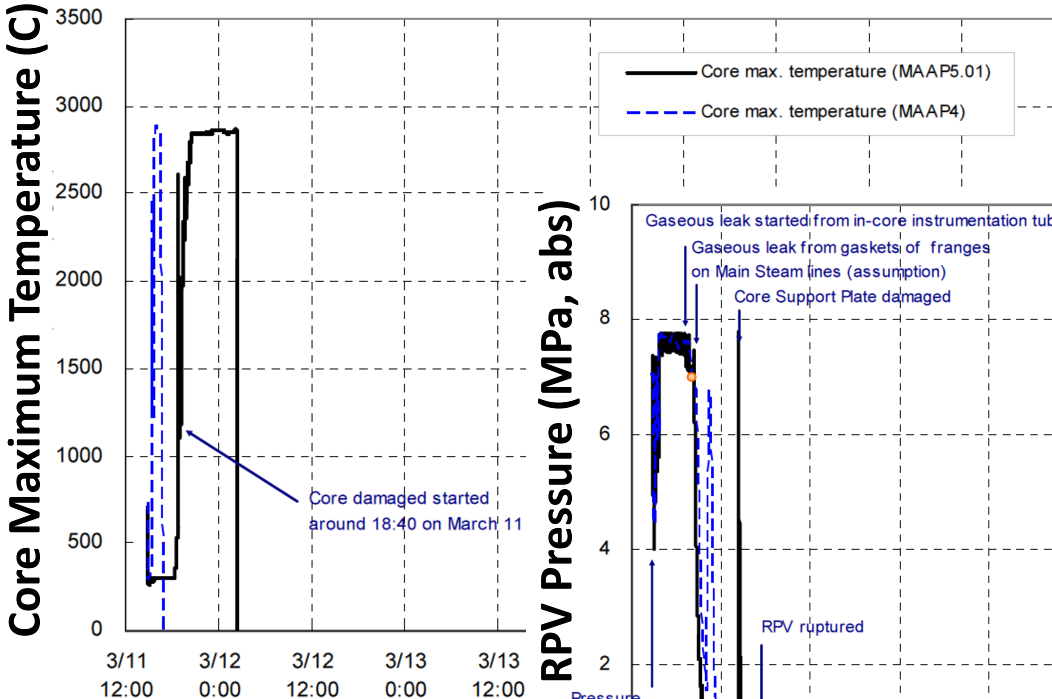


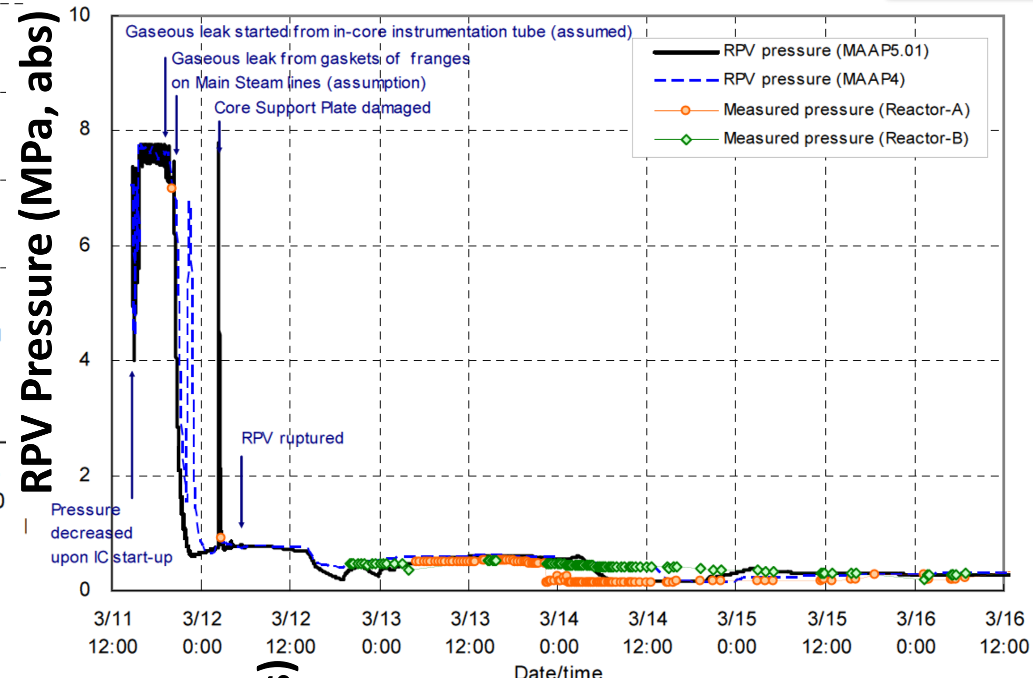
Location of Possible Gas Release from Mark-I PCV to the Reactor Building

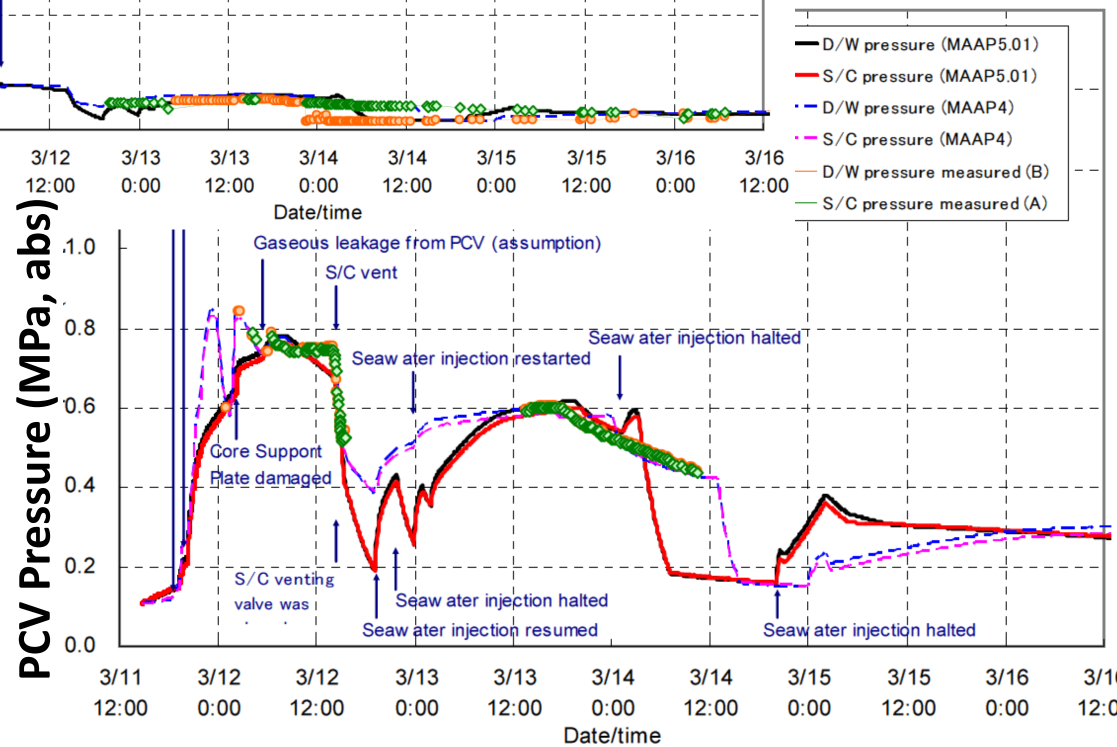


(Source) Example of Onagawa Power Station of Tohoku Electric Power Co., Inc.
(The photo of the top flange is from Tokyo Electric Power Co., Inc.)

Estimated Parameters in Unit 1

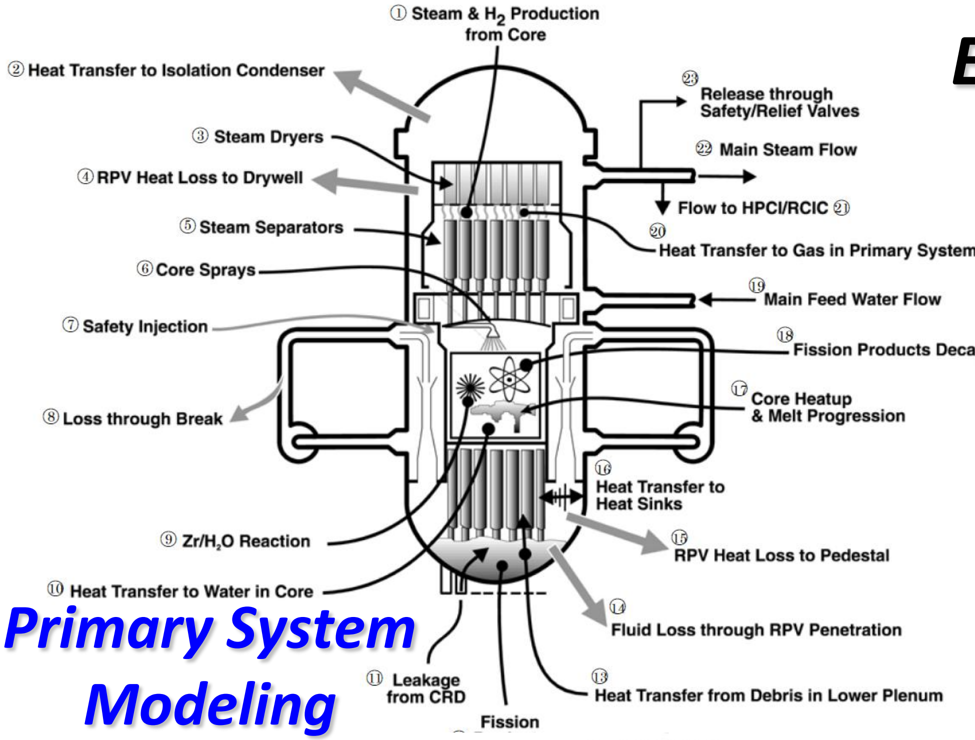




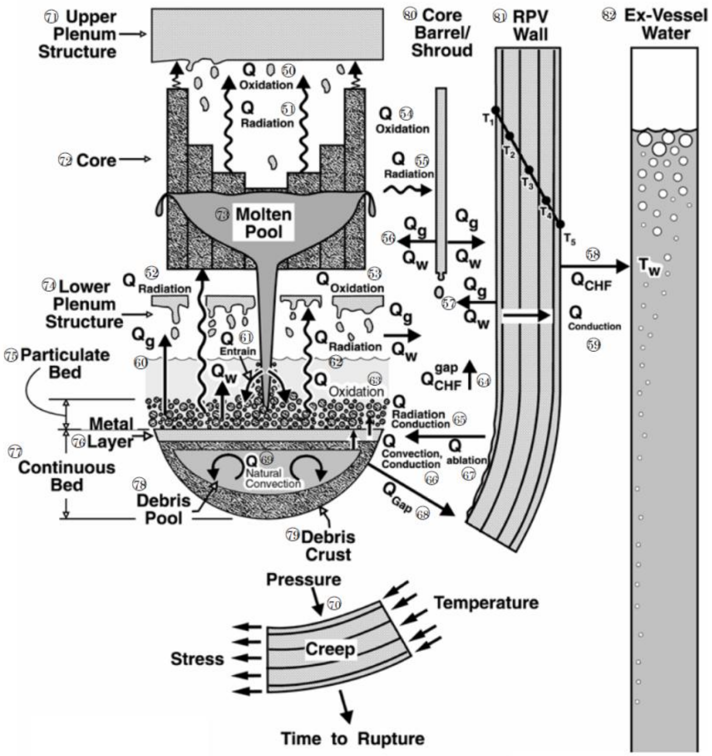


Some measured values used for model justification are also shown.

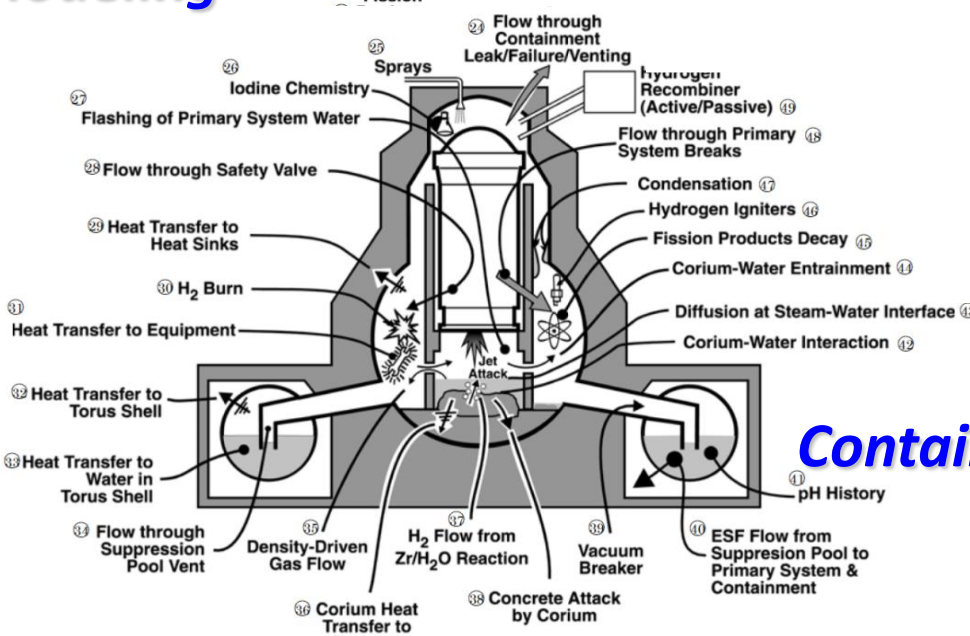
Elementary Models in the Accident Analysis Code



Primary System Modeling



Lower Plenum Modeling



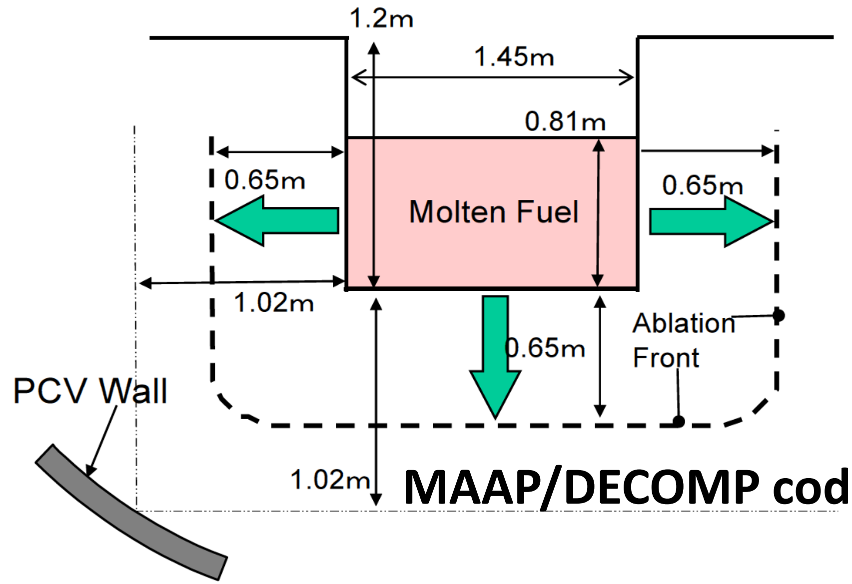
Containment Modeling

Example of the MAAP code

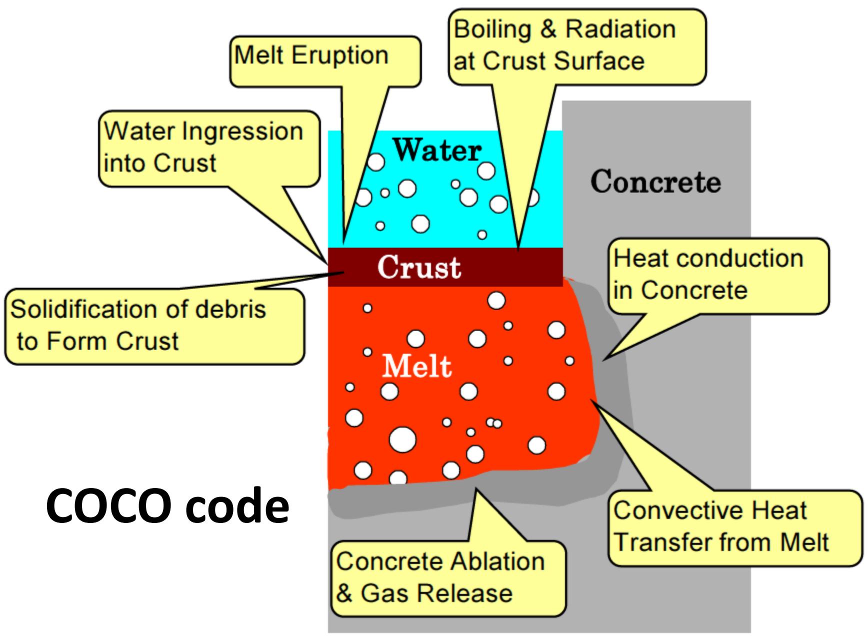
MCCI: Molten Core Concrete Interaction in Unit 1

Estimated Ablation Depth

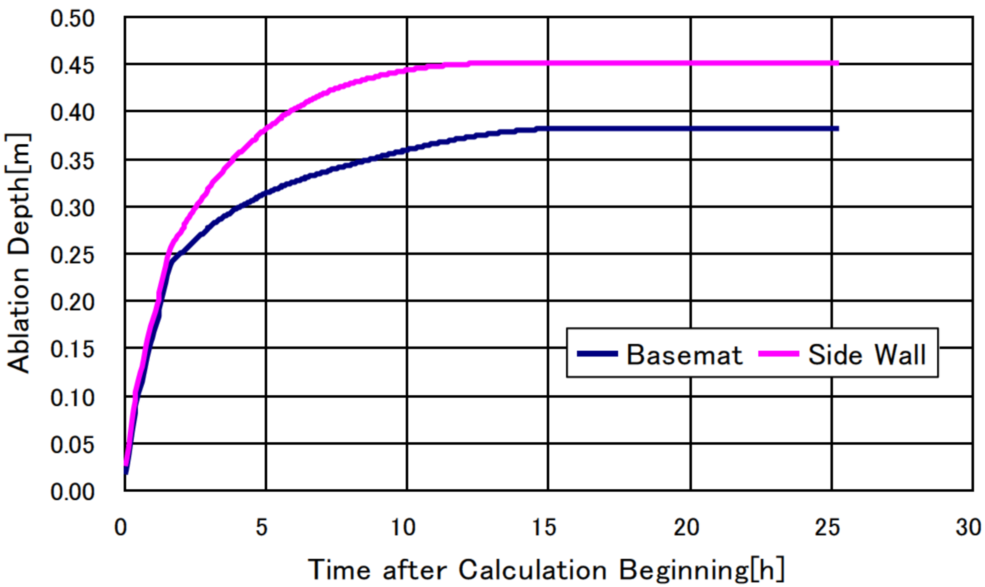
- ✓ MAAP/DECOMP code
  0.65 m
- ✓ COCO code
  0.45 m : Basement
  0.38 m : Side Wall



MAAP/DECOMP code

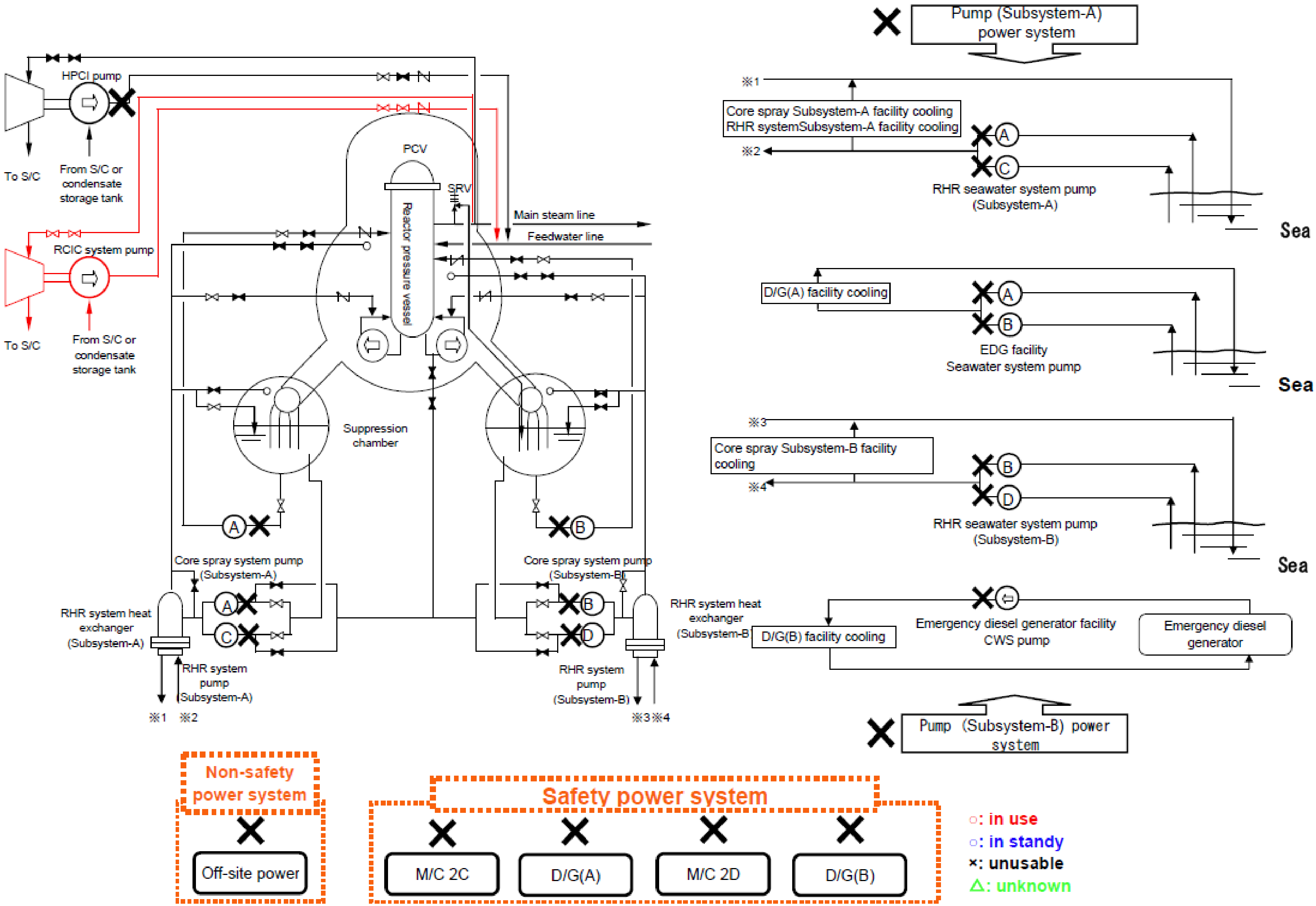


COCO code



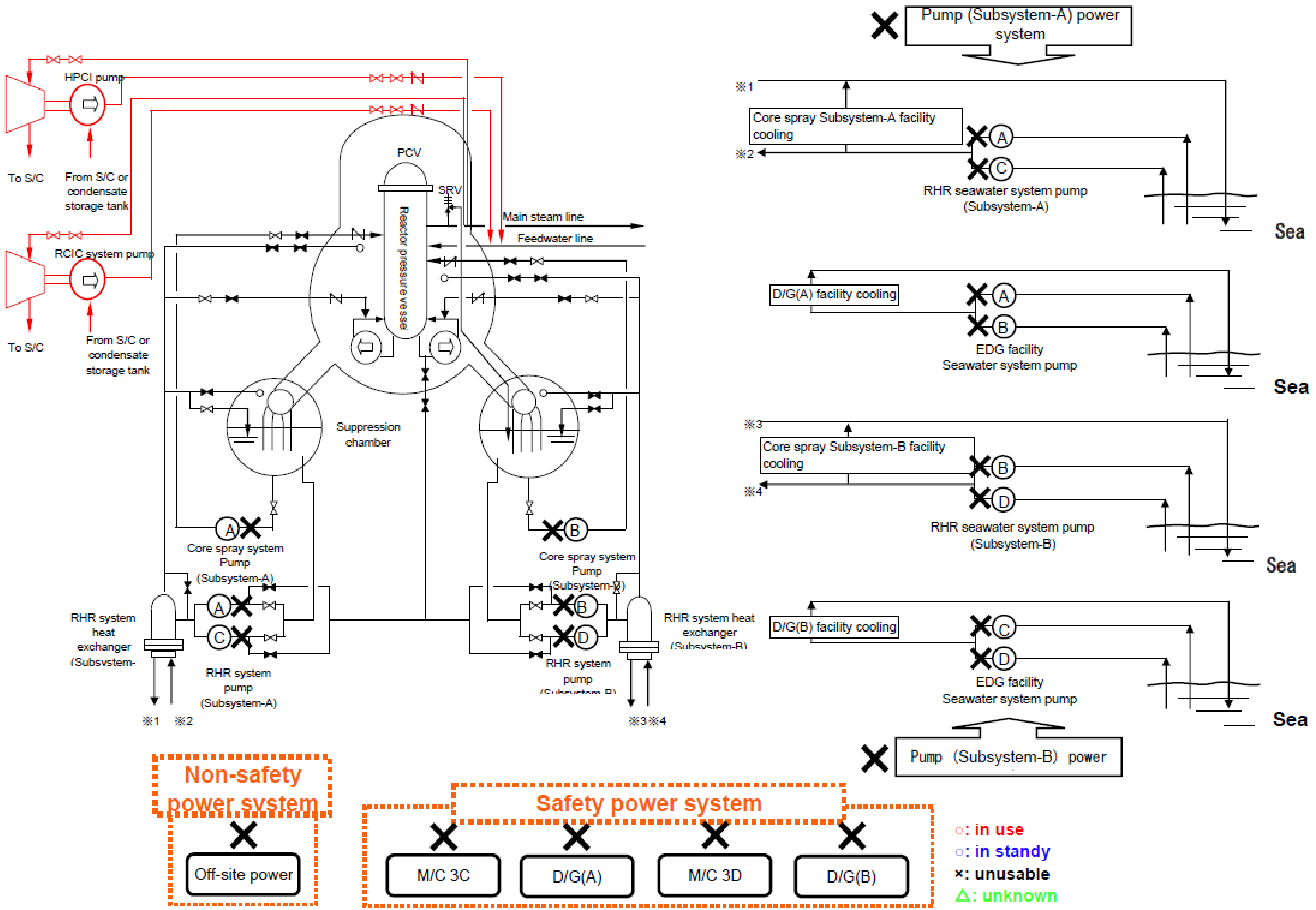
M. Fukasawa, S. Tamura, M. Hasebe, J. Nucl. Sci. Technol., Vol. 42, No. 8, pp.706-716 (2005) “Development of Thermodynamic Database for U-Zr-Fe-O-B-C- FPs System,”

Available Safety Systems after the Tsunami in Unit 2



TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 7-8,

Available Safety Systems after the Tsunami in Unit 3



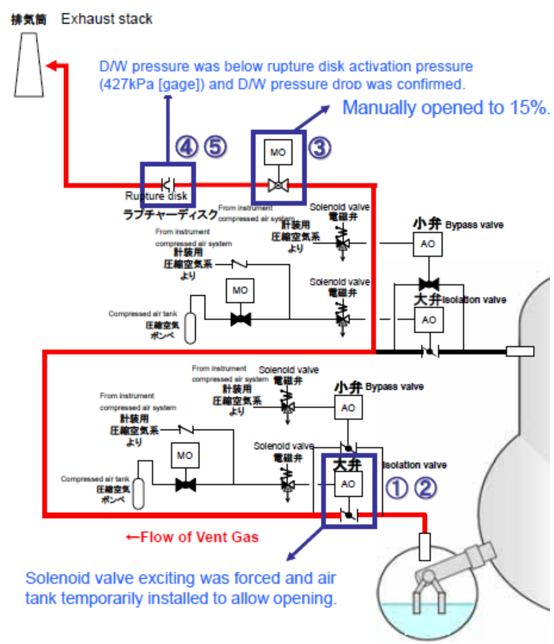
TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 7-8,

Cooling Reactor Core in Unit 3

- DC power was available in Unit 3, so that RCIC and HPCI could be used for high pressure water injection. In addition, diesel driven fire pump (DD/FP) was active, so that FP system could be used for low pressure injection after depressurizing.
- At 11:36 on March 12, RCIC automatically shut down.
- At 12:35, HPCI automatically started up.
- Then, Operator headed to the site to switch DD/FP to injection line.
- At 2:42 on March 13, operator manually shut down HPCI and tried to depressurize RPV since reactor pressure got lower than operational limit of HPCI, but･･･
  - SRV could not be opened due to the loss of batteries.
  - Reactor pressure increased 4MPa, and could not inject water with DD/FP
  - RCIC and HPCI could not be restarted again
  - While water injection stopped, water level decreased and core was exposed
- Around 9:08, rapid depressurization after SRV was forcibly opened.
- At 9:25, fresh water injection was commenced by fire engines.
- At 13:12, seawater injection commenced.

Protecting Containment Vessel in Unit 3

- To decrease PCV pressure, alternative S/C spray and PCV venting were performed
- Two valves must have been opened to perform PCV venting
  - To open S/C vent valve, AC power and instrumentation air was required.
  - PCV vent valve can be opened manually
  - If the pressure exceeded designed value, rapture disk gets break and venting commences.
- Since the morning of March 12, D/W pressure exceeded 400 kPa, so that operator performed alternative S/C spray at 12:06 on March 12, 5:08 and 7:39 on March 13.
- At 17:30 on March 12, site superintendent ordered the preparation of PCV venting.



Rupture disk activation pressure: 427kPa [gage]

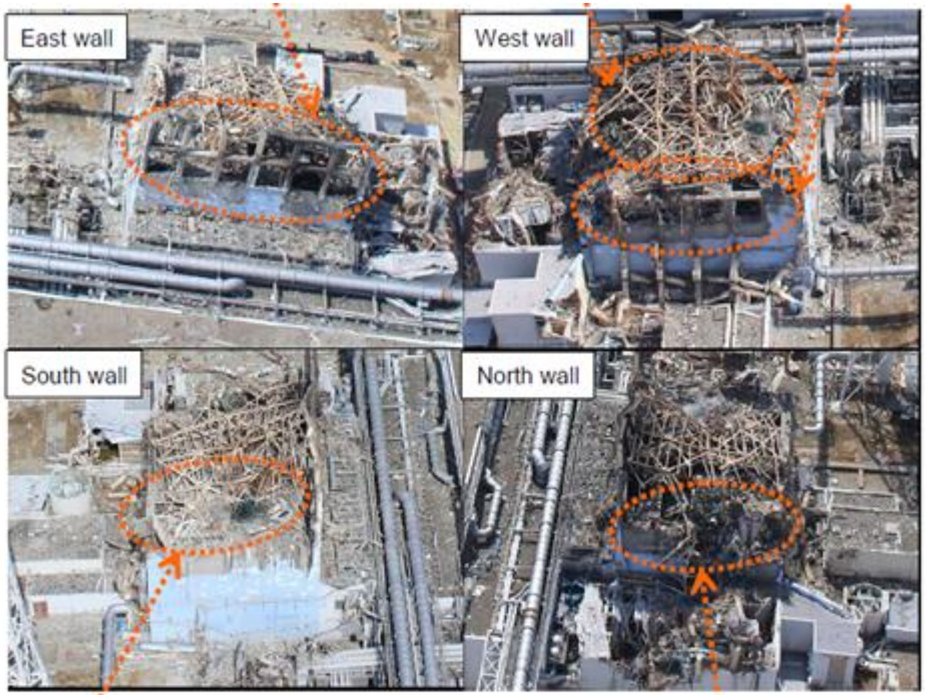
- At 4:52 on March 13, AC power was supplied using small generator.
- At 5:23, air supply was commenced
- At 8:35, PCV vent valve was manually opened.
- Around 9:20, it deemed that venting was implemented.
- S/C vent valve closed at 11:17, then restoration of air supply was performed at 12:30.
- D/W pressure increased again at 15:05, and air compressor was connected around 19:00.

TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 8-13, 8-14,

Hydrogen Explosion in Unit 3

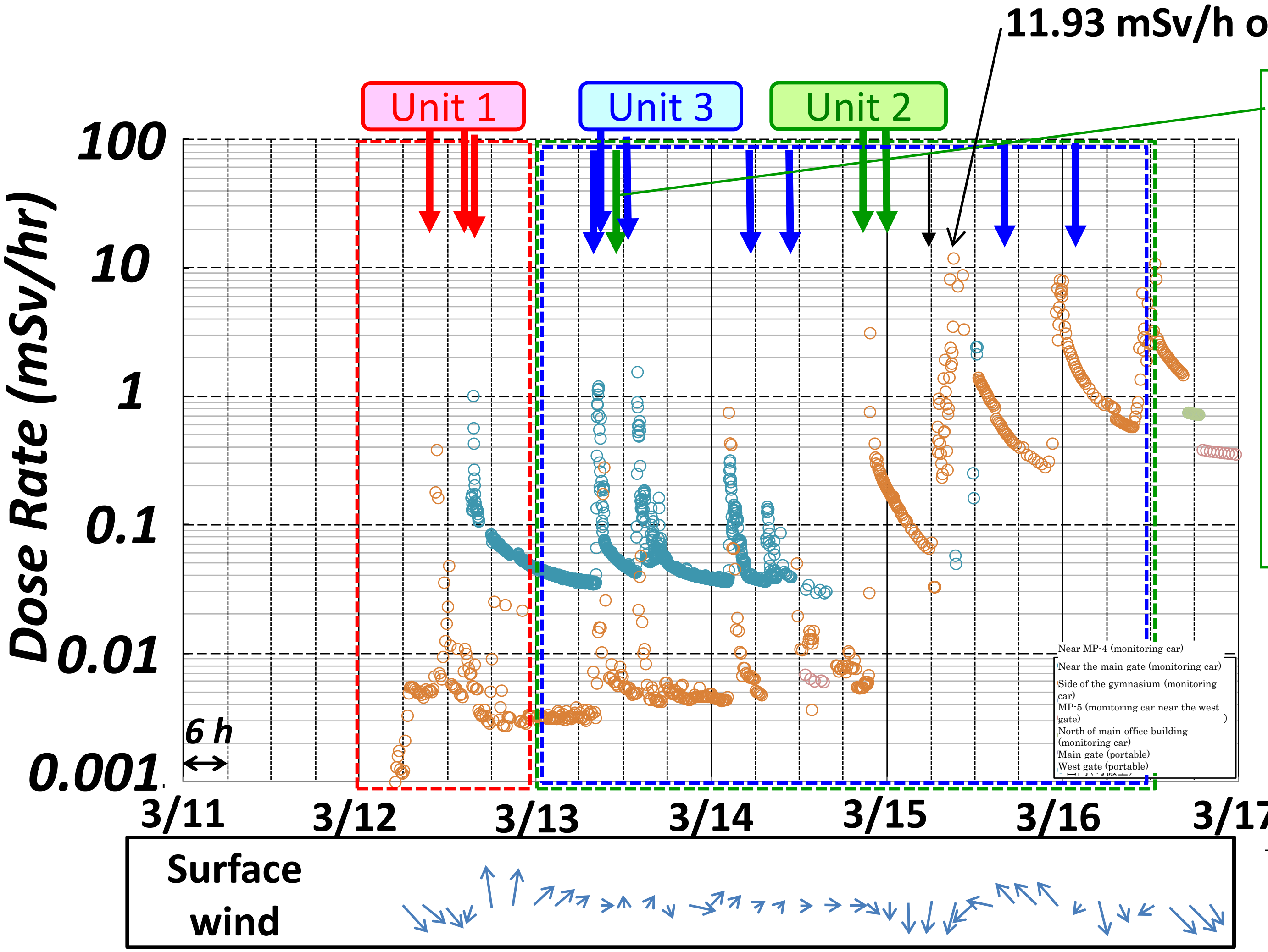
- At 11:01 on March 14, explosion occurred in Unit 3 R/B
- Hydrogen was generated due to core damage and leaked from PCV to R/B
- The hydrogen explosion injured 7 employees of TEPCO and its affiliated companies, 4 officers of Self-Defense Force that brought fresh water from off-site
- Seawater injection lines for Units 1, 2 and 3, was damaged by debris
- Circuit to control Unit 2 PCV venting that was temporary restored was also damaged.

Source: TEPCO



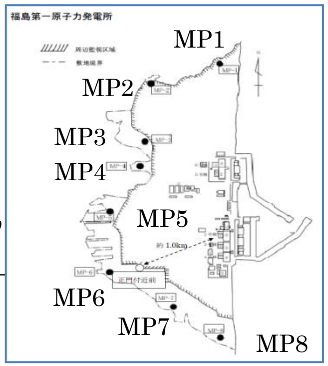
AESJ-NSD, Report of the Seminar to investigate the Accident at the Fukushima-Daiichi Nuclear Power Station, p. 40

On-site Radiation Monitoring in Fukushima Daiichi Site From March 11 to 17, 2011

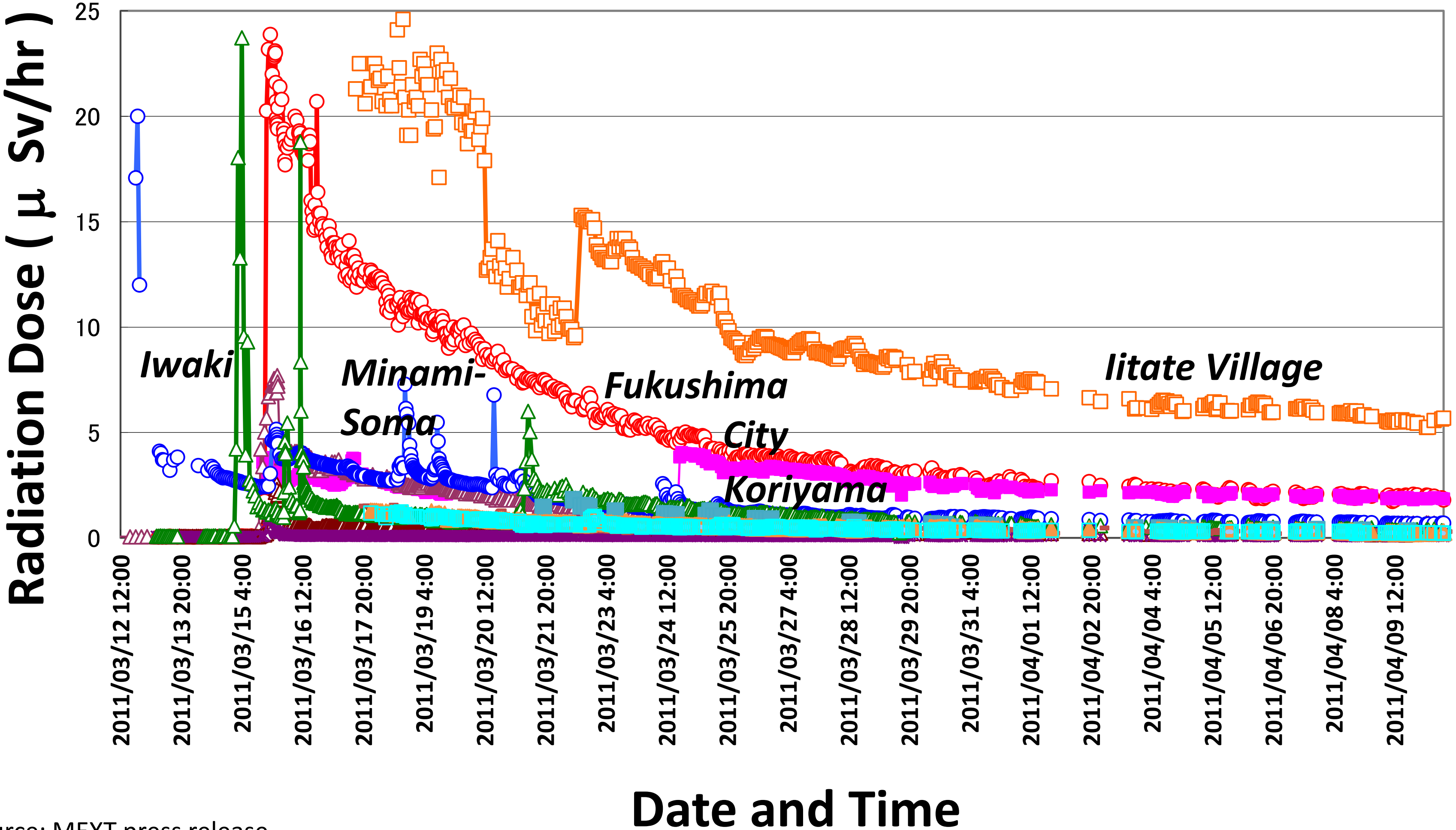


March 13 11:00
Unit 2's large S/C vent valve (AO valve) was opened and open operation of the valves in the PCV vent line other than the rupture disks was completed.

(D/W pressure did not reach to the operation pressure of 0.427MPa for the rupture disk)



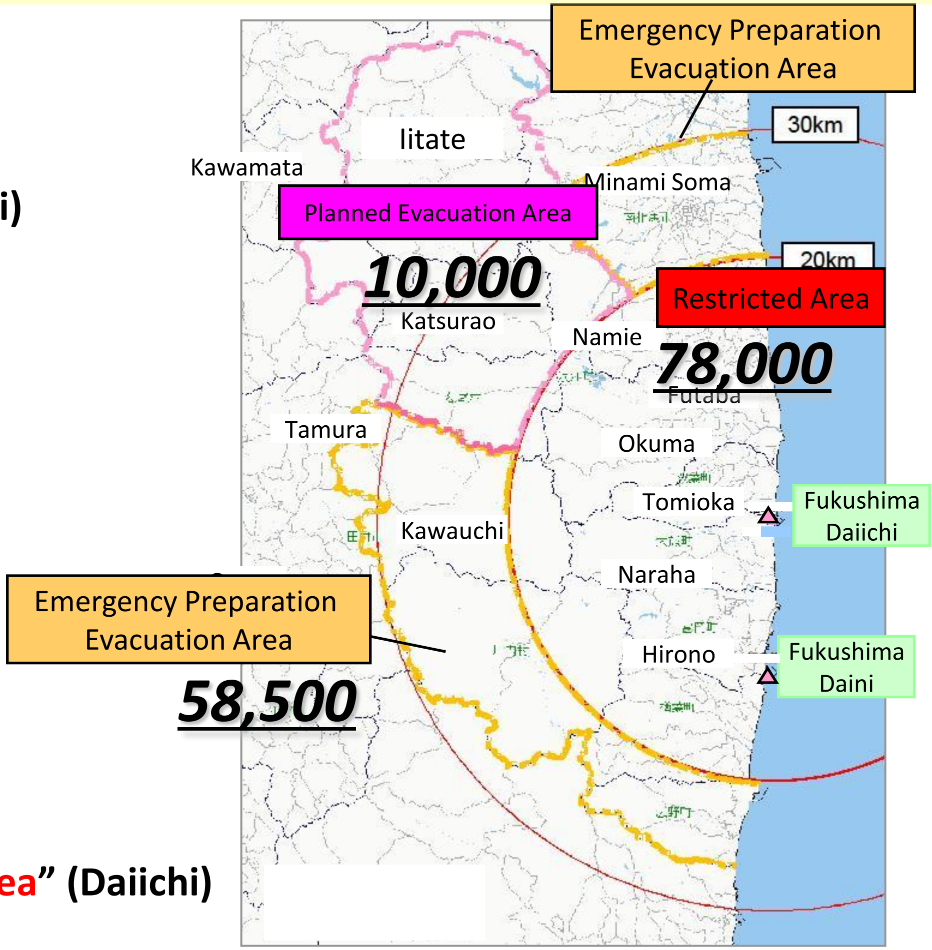
Monitoring Radiation Dose in Fukushima Prefecture



Source: MEXT press release

Evacuation of Residents

➢The government took measures such as taking shelters or evacuation as follows based on the reports from Fukushima Daiichi & Daini.



Source: NISA website

Fri, 11 March

14:46 The Earthquake

19:03 Emergency Declaration by the Gov't (Daiichi)

21:23 3 km radius evacuation (Daiichi)

10 km radius taking shelter (Daiichi)

Sat, 12 March

5:44 10 km radius evacuation (Daiichi)

7:45 3 km radius evacuation (Daini)

10 km radius taking shelter (Daini)

17:39 10 km radius evacuation (Daini)

18:25 20 km radius evacuation (Daiichi)

Tue, 15 March

11:00 20-30 km radius taking shelter (Daiichi)

Thu, 21 April

11:00 20 km radius is designated as "Restricted Area" (Daiichi)

Fri, 22 April

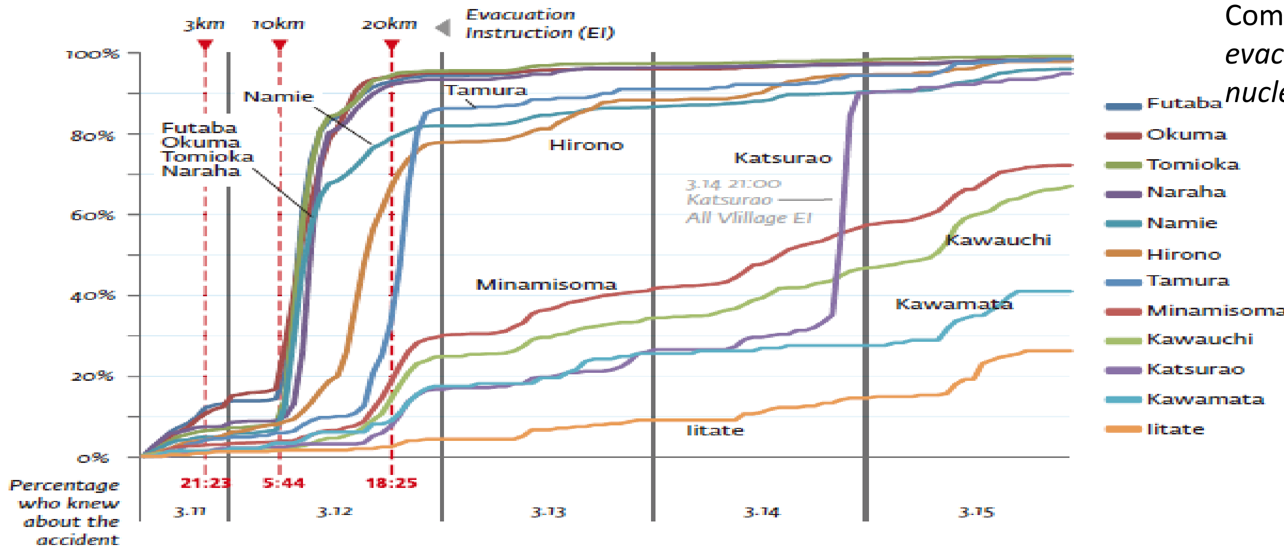
9:44 20-30 km radius taking shelter has been lifted (Daiichi)

Establishment of "Planned Evacuation Area" and "Emergency Preparation Area"

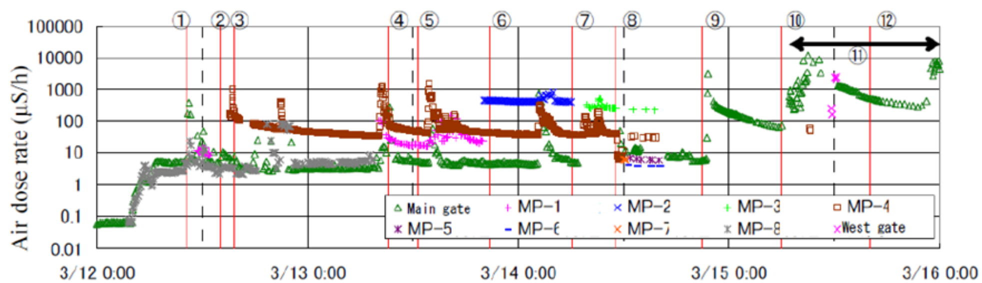
Evacuation of the Resident (2)

- About 78,000 resident was evacuated from 20 km area almost effectively, but…
  - Some evacuee had to move several time along with the extension of evacuation area.
  - 853 persons in 7 hospitals were evacuated. More than 50 inpatients died in a few month.

Ratio of resident who started evacuating



National Diet of Japan Nuclear Accident Independent Investigation Commission, "*Survey of the evacuees from the Fukushima nuclear power plant accident*"

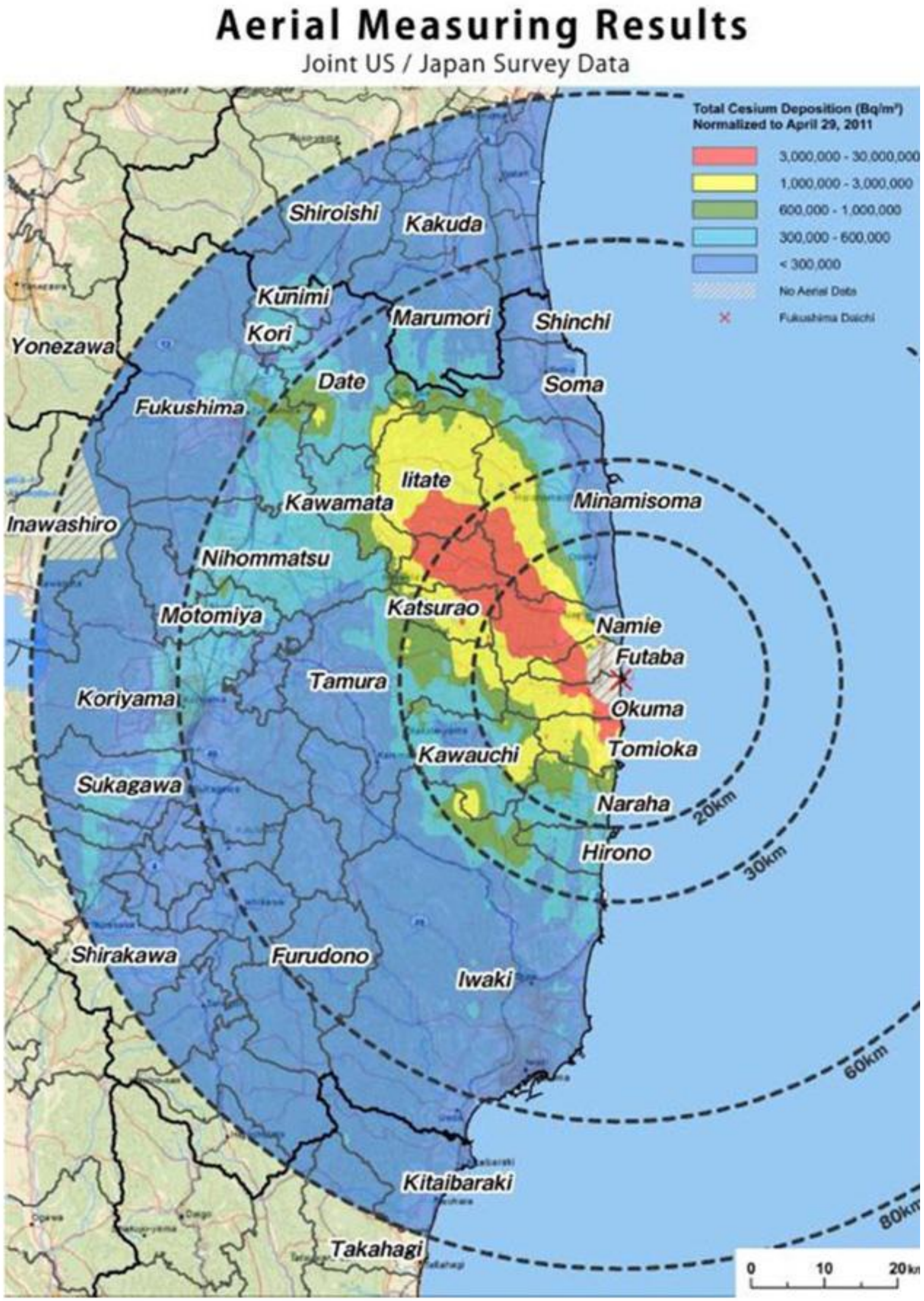


Air dose rate observe in Fukushima Daiichi NPS

AESJ-NSD, Report of the Seminar to investigate the Accident at the Fukushima-Daiichi Nuclear Power Station

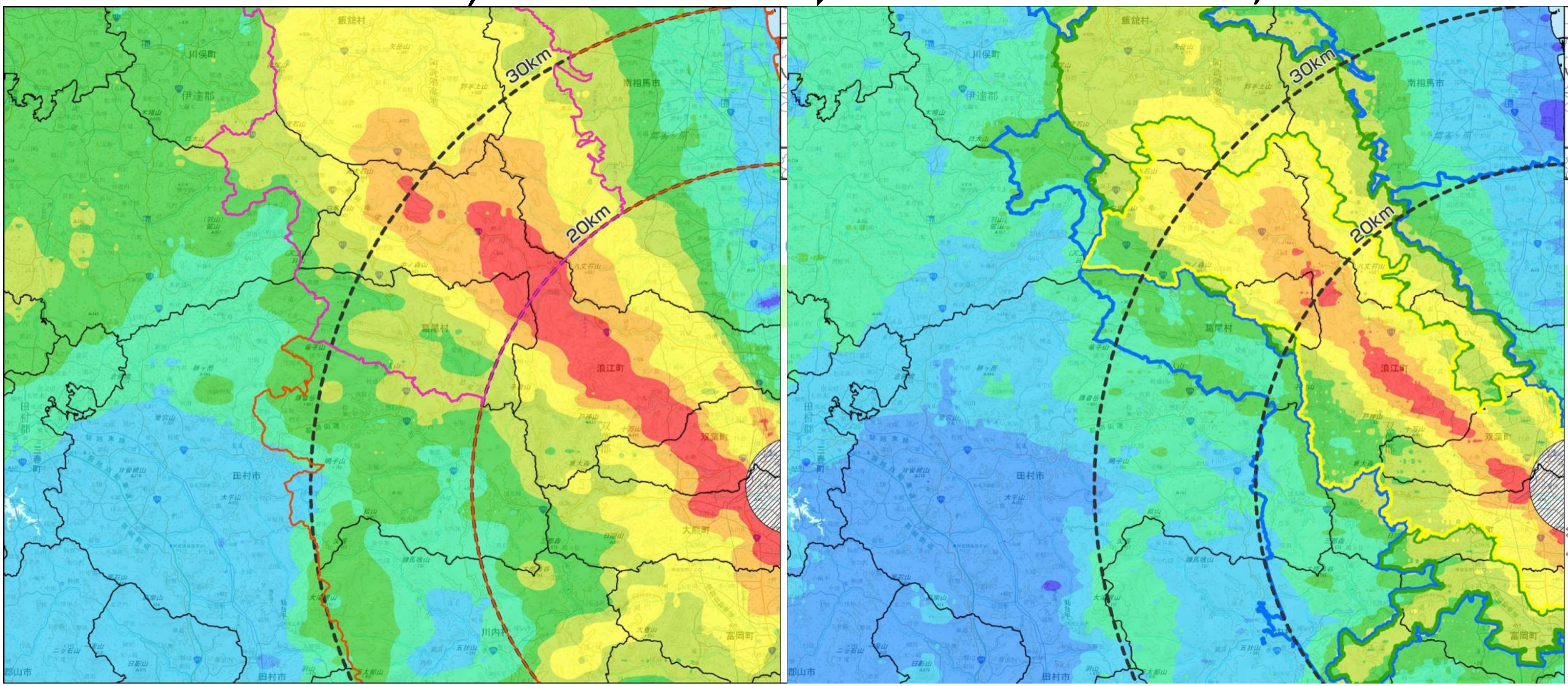
Cesium Deposition

April 29, 2011

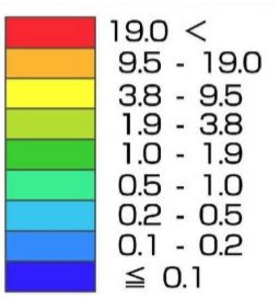


Monitoring of Radiation Dose Change in 2 Years

November 5, 2011 → November 19, 2013



Decrease of Dose Rate through
(1)Radioactive decay
(2)Reduction by natural dispersion
(3)Decontamination action



μ Sv/hr

Overview of Chapter 6 on Accident Analysis and Issues in the AESJ Final Report

The overviews of the following sections in Chapter 6 of the AESJ Final Report;

- ✓ **6.2 Fundamental Concept on Nuclear Safety**
- ✓ **6.3 Defense-in-Depth**
- ✓ **6.4 Accident Management**
- ✓ **6.5 External Events**

Fundamental Concept on Nuclear Safety (1)

- **Objective of Nuclear Safety;**
  "Protection of people and the environment from radiation risk arising from facilities and activities"

- **To achieve the objective, it is essential to establish;**
  - **awareness by all parties on the overriding priority of ensuring safety, even though owner or operators of nuclear facilities has prime responsibility for safety;**
  - **shared understanding on, and utilization of quantified risk; and continuous process of discussions on safety goal;**
  - **framework founded on defense-in-depth in managing uncertainties for preventing accidents and controlling risk.**

Fundamental Concept on Nuclear Safety (2)
Fundamental Safety Principles

- **Principles of Fundamental Nuclear Safety have been clarified by the Standard Committee members of the AESJ**

• Responsibility for safety • Role of the government • Role of the regulatory body • Leadership & management for safety	Responsibility & Management
• Fostering safety culture • Justification of nuclear facilities and activities • Continuous efforts on controlling radiation consequences on people and the environment	Nuclear Safety Goal
• Prevention and mitigation of accidents • Emergency preparedness & response • Protection measures on existing radiation risks, etc.	Controlling of Radiation Risk

- **Promoting development of a structured codes and standards that begins with Fundamental Safety Principles at the top.**

Defense in Depth (1)
Approach and Lessons Learned

➢ Lessons learned on Defense in depth

- Defense in depth has been introduced into nuclear safety system in Japan with the ultimate goal to prevent severe accidents.
- In other words, <u>measures so far had relied excessively on protective barriers (Levels 1 to 3) laid out for conditions before a severe accident.</u>
- However, this was not approach of defense in depth which extends to the realm of level 5 in managing unanticipated events.
- Enhancing mitigation of severe accident consequences (level 4) and emergency response(level 5), including management of extensive radioactivity release, are critical.
- The defense in depth approach prevails as the effective, founding basis for ensuring nuclear safety, that include the management of external and human events.
- All related parties must have deep understanding on defense-in-depth, and to take actions to ensure safety based on the defense in depth approach.
- The framework on codes and standards with defense in depth as the underlying safety concept should be formulated and documented.

Defense in Depth (2)
Approach and Lessons Learned

- **Defense in depth : Provisions against uncertainties**

✓**Since safety measures are generally laid out on the basis of specific assumptions to the exclusion of other possible scenarios or unexpected events, the effectiveness of a measure contains uncertainties to fully achieve nuclear safety goal on the protection of people and the environment.**

✓**Fundamental approach on defense in depth is the graded approch against the uncertainties by means of successive and independent safety measures to ensure and enhance reliability (independent effectiveness).**

✓**Defense in depth is an effective means for preventing and controlling severe accidents such as the Fukushima Daiichi accident.**

Accident Management
Lessons Learned from the Fukushima Daiichi Accident

- Accident management that was limited to internal events PRA (Probabilistic Risk Assessment)
  - ✓ **Scenarios should be extended to cover <u>external events</u>, internal events and combined events (internal & external).**
- Small probability events had not been included in the AM scope regardless of the magnitude of the source term.
  - ✓ **<u>Consideration of multi-unit sites, large-scale disasters impacting social infrastructure</u>, etc.**
- Absence of measures in case of the loss of critical safety functions
  - ✓ **Consideration of, and measures for extensive dependent failures, such as extended SBO and loss of final heat sink induced by the tsunami.**
- Inadequacies in education and training on accident management
  - ✓ **Need to establish flexible management that includes measures on intangible/human aspects, such as <u>education and training</u>, for complimenting tangible/ hardware aspects.**
- Codes & standards on severe accident management had not been established
  - ✓ **Need to establish <u>codes and standards</u> that satisfy the above requirements**

Accident Management Framework

Accident Management

Management considering tangible/hardware aspects

✓Identification of vulnerabilities based on PRA & stress tests
✓Combined use of permanent & transportable measures
✓Utilization of existing SSCs

Management considering software/human aspects

✓Development of organization & system Development of procedure manuals & related software
✓Maintaining/enhancing management competence by training & exercise
✓Operational maintenance management

Other Measures

✓Maintenance management of SSCs classified by management class
✓Management of availability of resources, fuel, etc.
✓Quality management activities, etc.

Knowledge and Management for External Events

History of Measures for Earthquake & Tsunami in Other Plants

Site	Ground Height of Major Buildings	Construction Permit	Chronology of tsunami scenarios after construction permit approval				
			2002 Tsunami Scenario by Japan Society of Civil Engineers	2007 Tsunami scenario for Ibaraki Prefecture	2007 Tsunami scenario for Fukushima Prefecture	2009 Updating submarine topography & tide level conditions	2011 Great East Japan Earthquake observed tsunami heights
Fukushima Dai-ichi	Unit 1-4 O.P. +10m *1 Unit 5 & 6 O.P. +13m	O.P. +3.122m 1966 (Unit 1)	O.P.+5.7m Largest tsunami/w wave source off the coast of Fukushima Implementing measures as elevating seawater intake pumps, etc.	O.P.+4.7m Measures not required	Approx. O.P.+5m Measures not required	O.P.+6.1m Implementing measures as elevating seawater intake pumps, etc.	Tsunami height O.P.+13.1m Inundation height O.P.+15.5m
Fukushima Dai-ni	O.P. +12m	O.P.+3.122m 1972 (Unit 1) O.P.+3.705m 1978 (Unit 3,4)	O.P.+5.2m Implementation of watertightness measures for buildings	O.P.+4.7m Measures not required	O.P.+5m Measures not required	O.P.+5.0m Measures not required	Tsunami height O.P.+7～8m Inundation height O.P.+14.5m
Onagawa	O.P. +14.8m	O.P.+2～3m: 1970 (Unit 1; per document search) O.P.+9.1m 1987 (Unit 2, numerical calculation)	O.P.+13.6m Largest tsunami/w wave source off the coast of Sanriku Measures not required	— —	— —	— —	Tsunami height O.P.+13.8m
Tokai Dai-ni	H.P. +8.9m Installation height of seawater intake pump ＋4.2m	H.P.+2.35m 1971	H.P.+5.75m Measures not required	H.P.+6.61m Implementing measures as elevating seawater intake pumps, etc. (H.P.:+7m）	— —	— —	Tsunami height H.P.+5.5m Inundation height H.P.+6.2m

Direct Causes of the Fukushima Daiichi Accident

Final Report of the AESJ Investigation Committee

- **Inadequacies in Tsunami Measures**
  - Critical incidents and related knowledge have not been utilized for developing effective prevention measures. Ex. Jogan Off the Coast Sanriku Tsunami Earthquake

- **Inadequacies in Severe Accident Management Measures**
  - No reinforcement of severe accident management measures after 2002.
  - No severe accident management measures for external events as earthquakes and tsunamis.
  - Japan did not adopt reinforcement of terrorist measures taken by many countries after 9.11.

- **Inadequacies in Emergency Responses, Post-accident Management and Other Mitigation/Recovery Measures**
  - The setting of a 10-kilometer radius emergency evacuation zone was not sufficient.
  - Emergency offsite center was damaged by the earthquake and could not be used.
  - Municipal/government directions on Iodine intake was not communicated sufficiently, resulting in the intake by only a few of the local population.

Underlying Causes of the Accident

Final Report of the AESJ Investigation Committee

1. **Lack of awareness on the roles & responsibilities by experts**
2. **Shortfalls in establishing safety measures & fostering safety awareness by utilities**
3. **Lack of safety awareness by the regulatory body**
4. **Inadequacies in attitude of learning from efforts and collaborative works in the international community**
5. **Shortage of qualified personnel dedicated to ensuring safety and inadequacies in organization & management framework**

Recommendations made by Final Report of the AESJ Investigation Committee

50 Items in 5 Categories

1. **Items Related to Direct Causes (5)**
2. **Items Related to Organizational Factors of the Underlying Causes (14)**
3. **Items Related to Nuclear Safety Fundamentals (14)**
4. **Common Items (12)**
5. **Items Related to Post-Accident Management (5)**

Recommendation I
- *Nuclear Safety Fundamentals* -

1. **Clarification of nuclear safety objectives**
   ① Establishing consensus on nuclear safety goal
   ② Systematic requirements by regulatory standards
   ③ Enhancement of nuclear security

2. **Deepening understanding and reinforcement of defense-in-depth**
   ① Clarification of Fundamental Safety Principles
   ② Stipulation/documentation of defense-in-depth

Recommendation II
- Items Related to Direct Cause -

1. Enhancing Measures for External Events

① Individual plant examination for external events
② Measures for cliff edge effects
③ Measures for intentional attacks

2. Reinforcing Severe Accident Management Measures

3. Enhancing Framework for Emergency Preparedness and Response

① Establishment of collaboration between utilities and local governments
② Clarification of the roles of related parties
③ Conducting drills and exercises
④ Radioactive material dispersion analysis
⑤ Establishing integrated management framework with other natural disaster
⑥ Enhancing competence in managing radiation protection

4. Enhancing Nuclear Safety Assessment Technique

① Utilization of Probabilistic Risk Assessment
② Utilization of simulation based on leading edge computing technologies
③ Better understanding on issues & limitations on safety assessment technique
④ Promotion of international collaboration

Recommendation III
- Organizational Factors of Underlying Causes -

1. Efforts by Professional Societies and the Academia

① Re-acknowledging responsibilities of academic societies
② Fostering open and inclusive atmosphere for discussions at academic societies
③ Enhancing safety research
④ Promoting inter-disciplinary collaboration
⑤ Contributing to continuous improvements of safety regulations

2. Efforts by Nuclear Industries

① Sharing lessons learned on the accident by nuclear industrial community
② Implementation of continuous improvements for nuclear safety
③ Top management commitment to nuclear safety

3. Efforts by Nuclear Safety Regulatory Body

① Restoring public confidence
② Continuous improvements
③ Introduction of risk-informed regulations
④ Transition from regulations emphasizing tangible aspects to regulations focusing on intangible aspects
⑤ Guiding utilities to establish voluntary safety enhancement efforts
⑥ Well-balanced approach in utilizing professional expertise in broad areas

Recommendation Ⅳ *- Common Items -*

1. Enhancing nuclear safety research platform

① Keep the driving force in safety enhancement
② Importance of maintaining & developing qualified personnel resources
③ Responsibility of government organizations, industries, and the academia for safety research
④ Extensive application of PRA technique
⑤ Development of roadmap for wide range of safety research

2. Enhancing international collaboration

① Developing system to reflecting the outcomes of international activities on domestic system
② Contributing to activities of countries newly introducing nuclear power
③ Participation by the industrial community in international activities

3. Development of nuclear personnel resources

① Values on the overriding priority of nuclear safety
② Enhancement of personnel qualification system
③ Importance of university level education & research on nuclear energy
④ Education on nuclear energy & radiation in junior/senior high school

Recommendation V
- Items Related to Post-Accident Management -

Environment Remediation and Decommissioning Activities

① Environment monitoring

② Regulations and guidelines

③ Designation of areas to be decontaminated

④ Decontamination and decontamination technique

⑤ Management & storage of decontaminated wastes

Summary of the Recommendations

Final Report of the AESJ Investigation Committee

- **Recommendations have been made over broad areas based on the results of root cause analysis.**
- **A broad range of issues need to be addressed for ensuring nuclear safety:**
  - fundamental concept on nuclear safety must be clearly shown
  - PRA appropriately applied
  - safety goal defined clearly
  - defense-in-depth accurately understood and applied to plant design, accident management, disaster management, etc.
- **The importance on the role of nuclear safety research for resolving these issues and its continuous development is emphasized.** Research activities will lead to expand knowledge-base; to get deeper insight on the broader issues and to generate better and optimized solutions out of possible options.

Epilogue

- **The recommendations have been made to prompt government organizations, the industries, the academia and research institutions to take concrete actions for promoting nuclear safety.**
- Some of the recommendations involve goals to be pursued by the AESJ. Concurrently with making efforts on necessary improvements, the AESJ aims to interact with related organizations for the realization of the recommendations.
- These recommendations have been proposed, in view of the significance of transparency of nuclear-related information, to be shared by all parties with interest in nuclear power. It is critically important for all organizations and experts to take to heart the items recommended and to endeavor earnestly for the achievement of nuclear safety.
- **Unless these goals are realized, organizations and experts in nuclear power field are not qualified to be involved in nuclear activities. (Prof. Satoru Tanaka, Chairman of the Committee)**

English version of Final Report of the AESJ Investigation Committee, available from Springer

Springer

springer.com

ISBN 978-4-431-55159-1

Editor :
Atomic Energy Society of Japan

The Fukushima Daiichi Nuclear Accident

Final Report of AESJ Investigation Committee

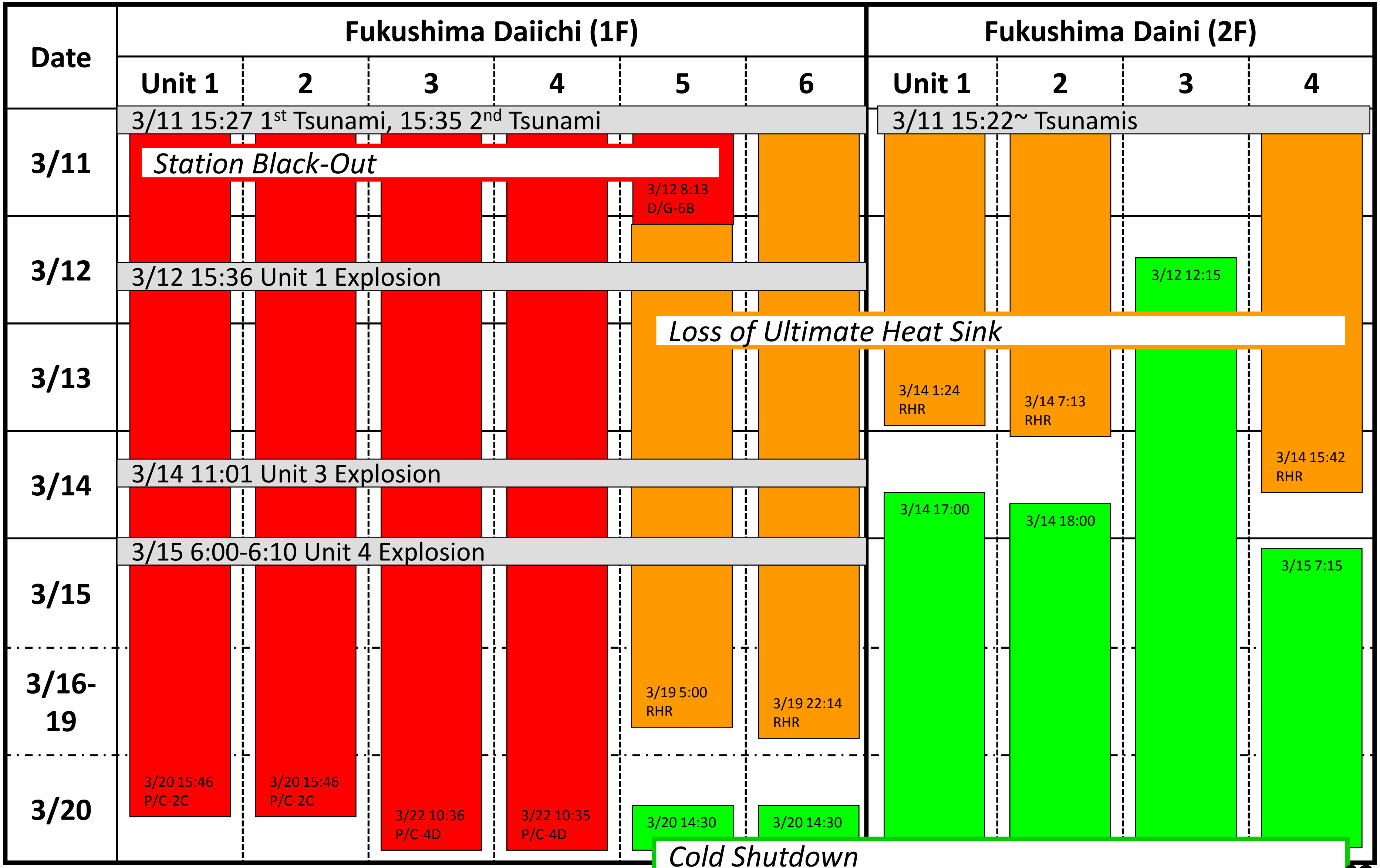
560 pages

This report was completed by the AESJ, Japanese academia in nuclear science/engineering, with concerted effort by specialists.
It covers all aspects of technical issues of the Accident.

New Book

Thank you very much for your attention

Summary of the Accidents in Fukushima Daiichi and Fukushima Daini



Maximum Acceleration Observed in Fukushima Daiichi

Location of Seismometer (bottom floors of the reactor buildings)		Records: Max. Acceleration (Gal)			Max. Response Acceleration to the Design Basis Ground Motion, Ss (Gal)		
		NS	EW	UD	NS	EW	UD
Fukushima Daiichi	Unit 1	460※1	447※1	258※1	487	489	412
	Unit 2	348※1	550※1	302※1	441	438	420
	Unit 3	322※1	507※1	231※1	449	441	429
	Unit 4	281※1	319※1	200※1	447	445	422
	Unit 5	311※1	548※1	256※1	452	452	427
	Unit 6	298※1	444※1	244	445	448	415

※1： Each recording was interrupted at around 130-150(s) from recording start time

※2： 1 Gal=0.01m/s^2 , 981 Gal=1G

Source: Added to "The impact of the 2011 off the Pacific coast of Tohoku Earthquake to Nuclear Reactor Facilities at Fukushima Dai-ichi Nuclear Power Station" (Sep. 9, 2011, revised Sept. 28, 2011, TEPCO)

Tsunami in Fukushima Daiichi on March 11, 2011

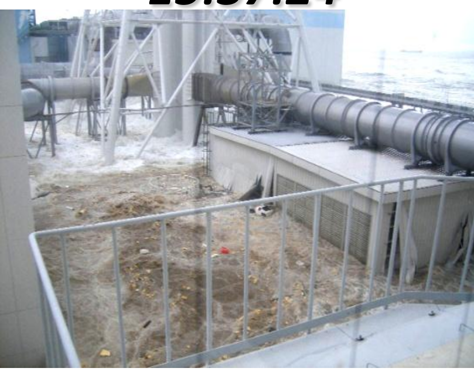
15:36:10

15:36:16

15:36:56

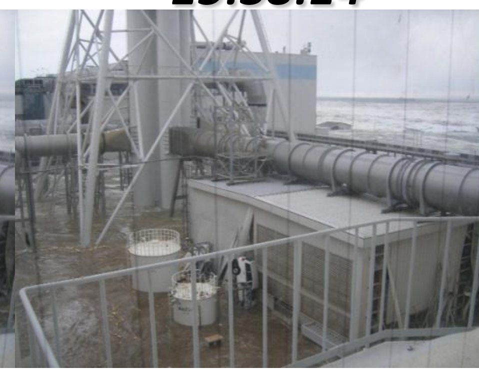
15:37:06

15:37:24



15:37:48

15:38:14



15:38:28

15:39:40

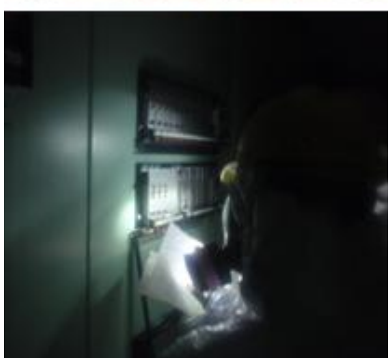
15.5 m above the sea level

Source: TEPCO

Inundation height of the Tsunami in Fukushima Daiichi was about 15.5 m above the sea level.

(Correction of Time based on TEPCO)

Data from Instrumentations Systems on March 11 in Units 1 & 2



Source: TEPCO

- Since DC power was lost, plant parameters in Unit 1 and Unit 2 could not be observed
- Operators in Unit 1 & 2 could not confirm whether water injection was active or not

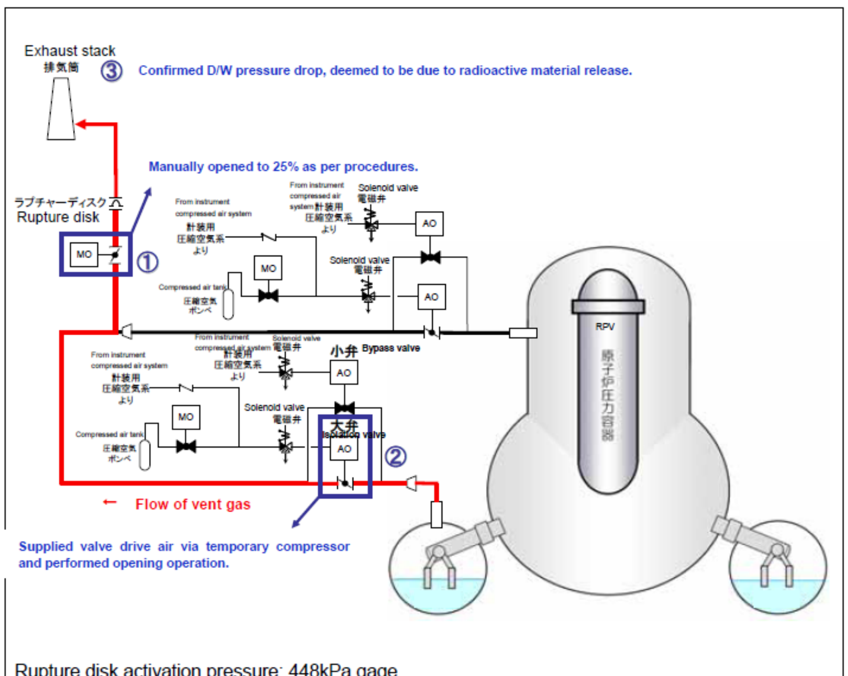
- At 20:07, Unit 1 reactor pressure was confirmed to be 6.9 kPa, by checking pressure gage in the R/B.
- At 20:47, The ERC Recovery Team brought small generator and restored lighting in Unit 1&2 MCR.
- At 21:19, Unit 1 reactor water level indicator was restored, showing +200 mm, but the value was found to be incorrect later (explained afterwards)
- At 21:51, Radiation dose rose in Unit 1 R/B
- At 21:50, Unit 2 reactor water level was determined as TAF +3,400 mm
- At 23:25, Unit 2 D/W pressure was confirmed to be 141 kPa
- At 23:50, Unit 1 D/W pressure was confirmed to be 600 kPa

- Plant parameters showed
  - Unit 1 was under severe condition
  - Unit 2 was stable

Protecting Containment Vessel in Unit 1

- In the morning of March 12, Unit 1 PCV pressure stabilized round 750 kPa.
- At 9:04, operators headed to the field for venting operation
- At 9:15, first team opened PCV vent valve (MO valve)
- Second team could not reach to the S/C vent bypass valve due to high dose rate
- From 10:17, remote operation of the valve was performed
- At 14:30, release of radioactive material by venting was determined

⇒ Rapture of PCV was prevented, but leakage occurred due to the overheating

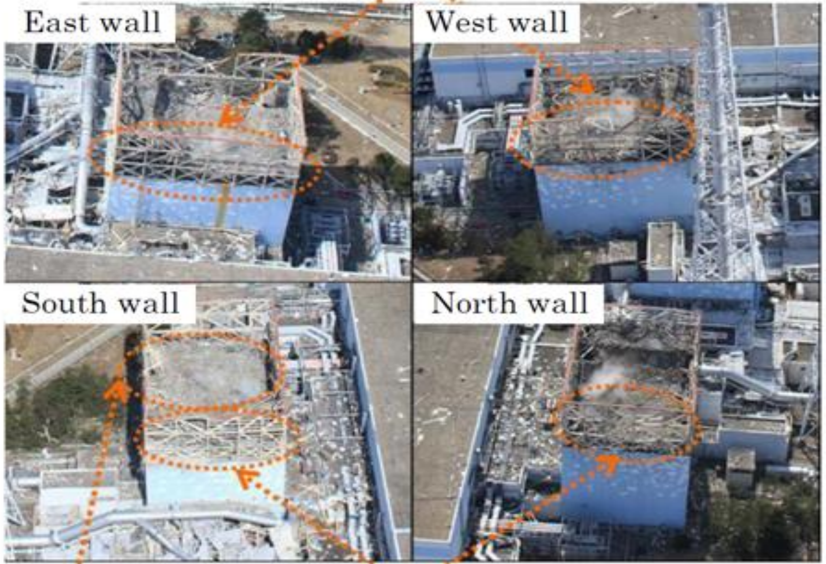


TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 8-6,

Hydrogen Explosion in Unit 1

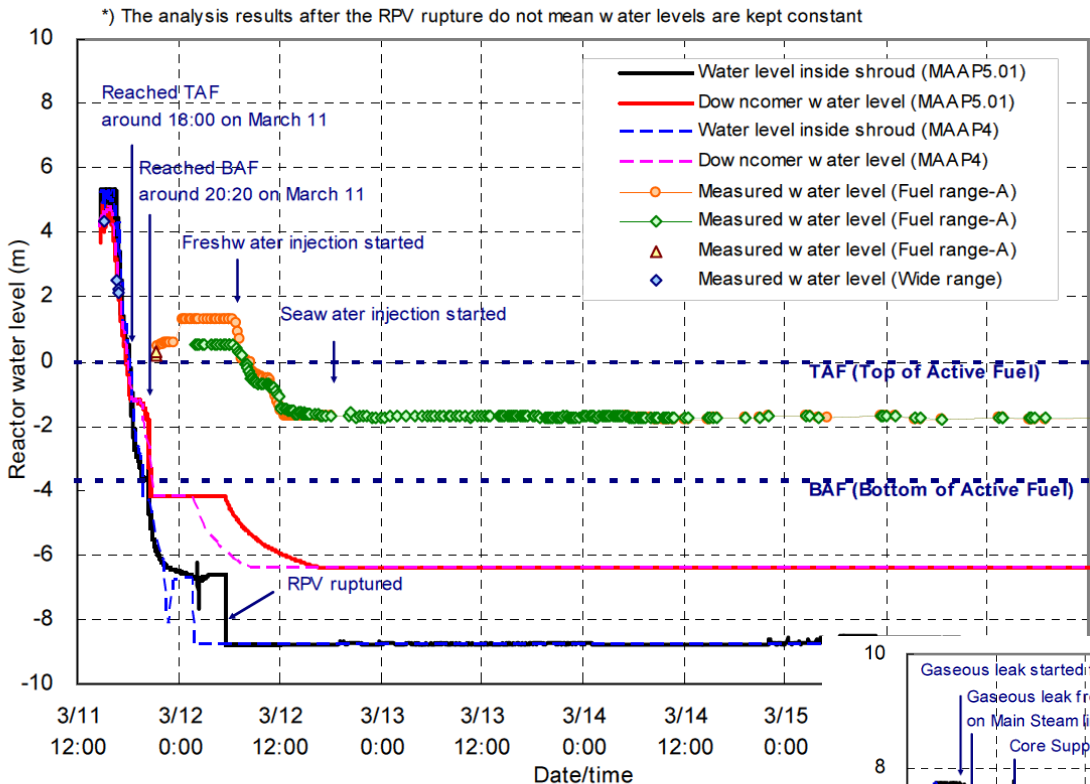
- At 21:51 on March 11, radiation dose rose in Unit 1 R/B.
- In the morning of March 12, Unit 1 PCV pressure stabilized round 750 kPa.
- At 15:36 on March 12, explosion occurred at 4th & 5th floor in Unit 1 R/B
- Hydrogen was generated due to core damage and leaked from PCV to R/B
- The hydrogen explosion injured 5 people, destroyed an high voltage power generating truck that had just been connected with the survived power distribution board in Unit 2, and sprayed debris that is highly radioactive.

Source: TEPCO

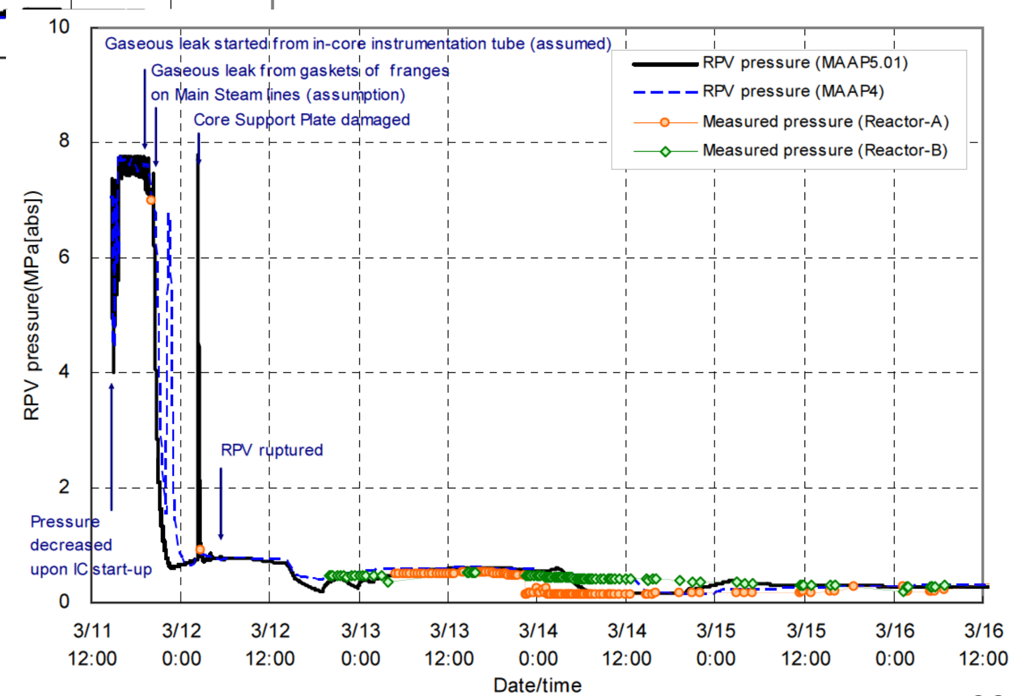


AESJ-NSD, Report of the Seminar to investigate the Accident at the Fukushima-Daiichi Nuclear Power Station, p. 31

Unit 1

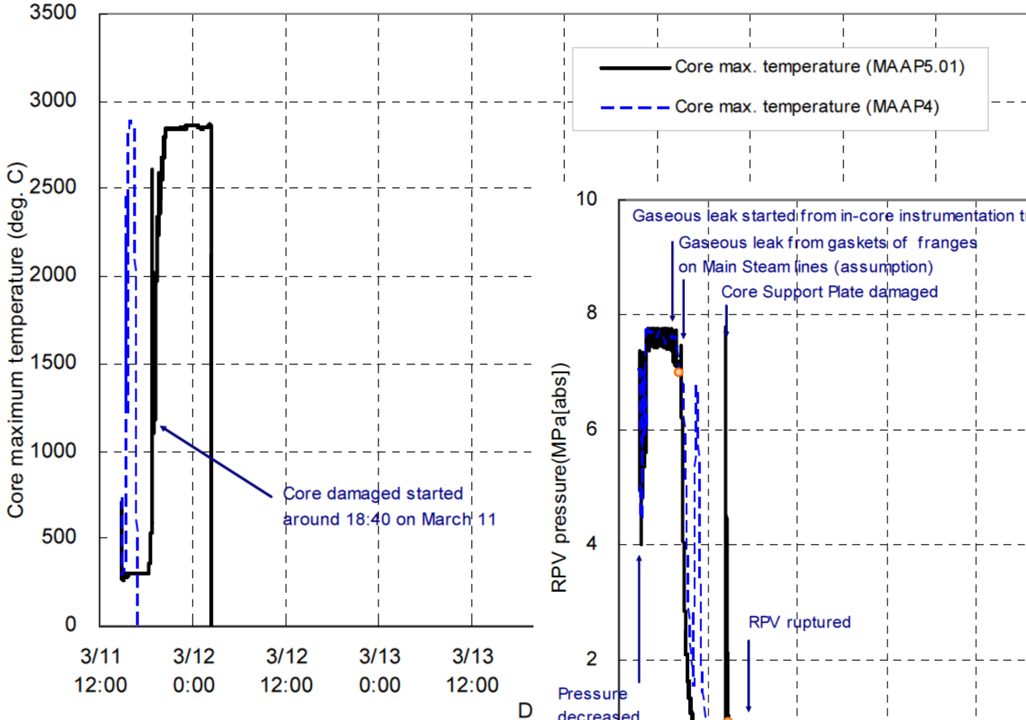


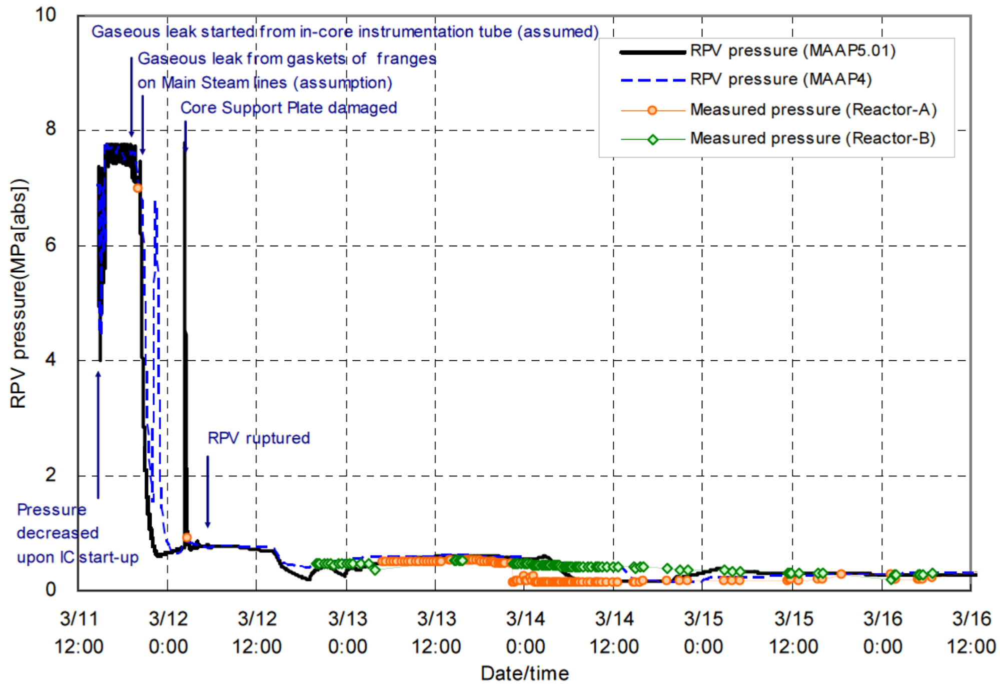
*) The analysis results after the RPV rupture do not mean w ater levels are kept constant
Reached TAF
around 18:00 on March 11
Reached BAF
around 20:20 on March 11
Freshw ater injection started
Seaw ater injection started
TAF (Top of Active Fuel)
BAF (Bottom of Active Fuel)
RPV ruptured
Water level inside shroud (MAAP5.01)
Dow ncomer w ater level (MAAP5.01)
Water level inside shroud (MAAP4)
Dow ncomer w ater level (MAAP4)
Measured w ater level (Fuel range-A)
Measured w ater level (Fuel range-A)
Measured w ater level (Fuel range-A)
Measured w ater level (Wide range)
Reactor water level (m)
10
8
6
4
2
0
-2
-4
-6
-8
-10
3/11 12:00
3/12 0:00
3/12 12:00
3/13 0:00
3/13 12:00
3/14 0:00
3/14 12:00
3/15 0:00
Date/time

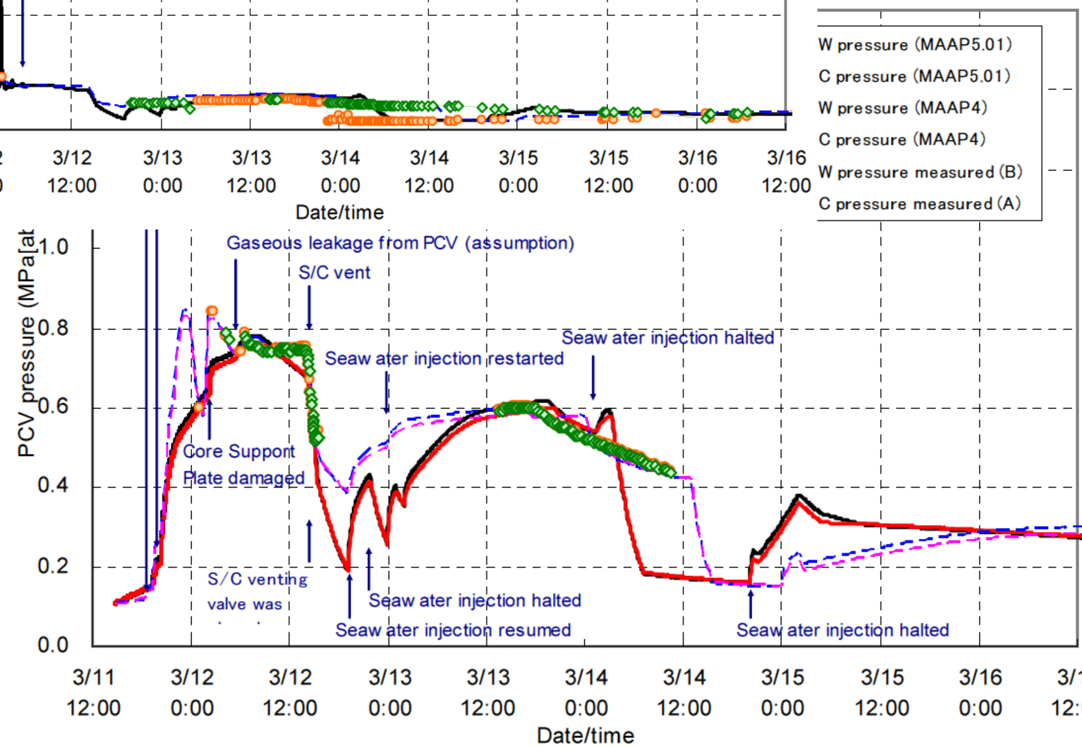


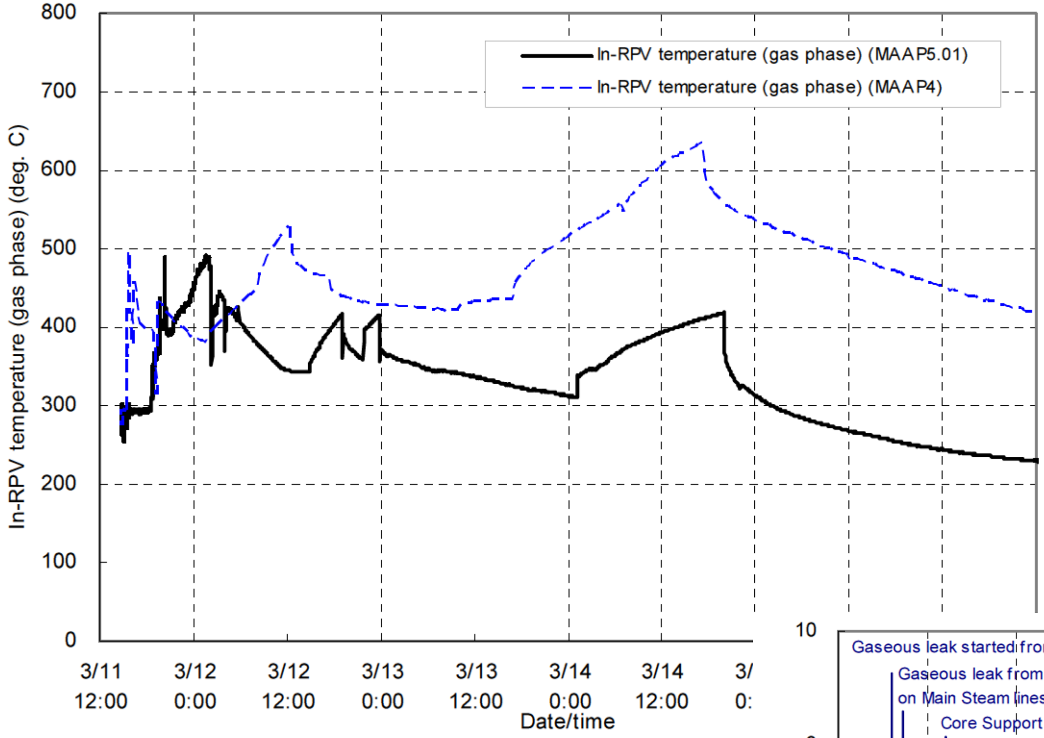
Gaseous leak started from in-core instrumentation tube (assumed)
Gaseous leak from gaskets of flanges
on Main Steam lines (assumption)
Core Support Plate damaged
RPV ruptured
Pressure
decreased
upon IC start-up
RPV pressure (MAAP5.01)
RPV pressure (MAAP4)
Measured pressure (Reactor-A)
Measured pressure (Reactor-B)
RPV pressure(MPa[abs])
10
8
6
4
2
0
3/11 12:00
3/12 0:00
3/12 12:00
3/13 0:00
3/13 12:00
3/14 0:00
3/14 12:00
3/15 0:00
3/15 12:00
3/16 0:00
3/16 12:00
Date/time

Unit 1


Core max. temperature (MAAP5.01)
Core max. temperature (MAAP4)
Core maximum temperature (deg. C)
Core damaged started
around 18:40 on March 11
3/11 12:00
3/12 0:00
3/12 12:00
3/13 0:00
3/13 12:00

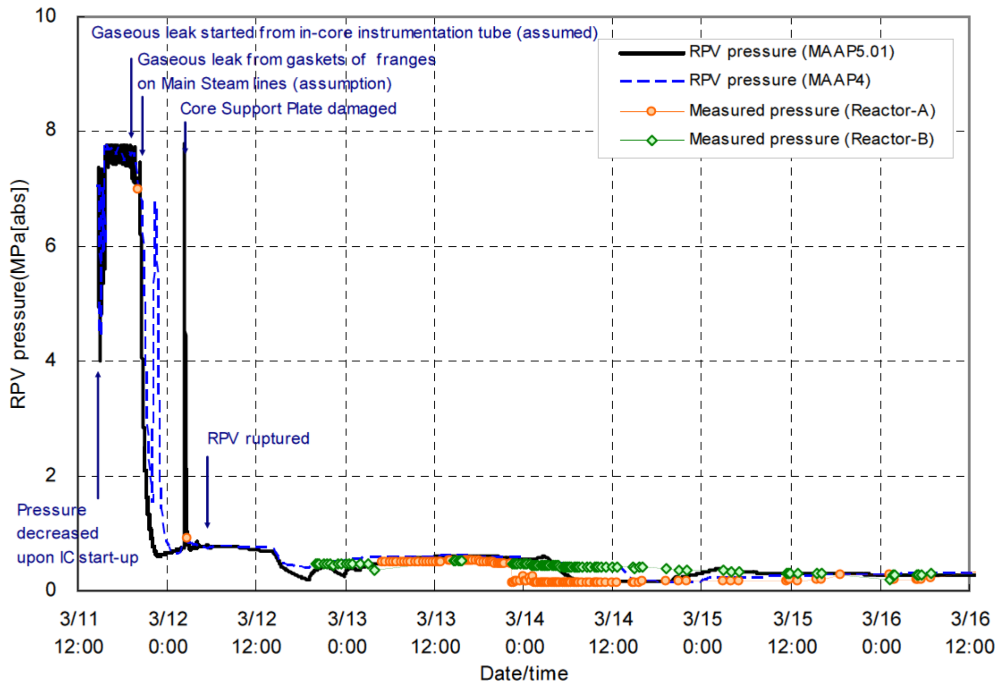

Gaseous leak started from in-core instrumentation tube (assumed)
Gaseous leak from gaskets of flanges
on Main Steam lines (assumption)
Core Support Plate damaged
RPV ruptured
Pressure
decreased
upon IC start-up
RPV pressure (MAAP5.01)
RPV pressure (MAAP4)
Measured pressure (Reactor-A)
Measured pressure (Reactor-B)
RPV pressure(MPa[abs])
Date/time


W pressure (MAAP5.01)
C pressure (MAAP5.01)
W pressure (MAAP4)
C pressure (MAAP4)
W pressure measured (B)
C pressure measured (A)
PCV pressure (MPa[at
Gaseous leakage from PCV (assumption)
S/C vent
Seaw ater injection halted
Seaw ater injection restarted
Core Support
Plate damaged
S/C venting
valve was
Seaw ater injection halted
Seaw ater injection resumed
Seaw ater injection halted
Date/time



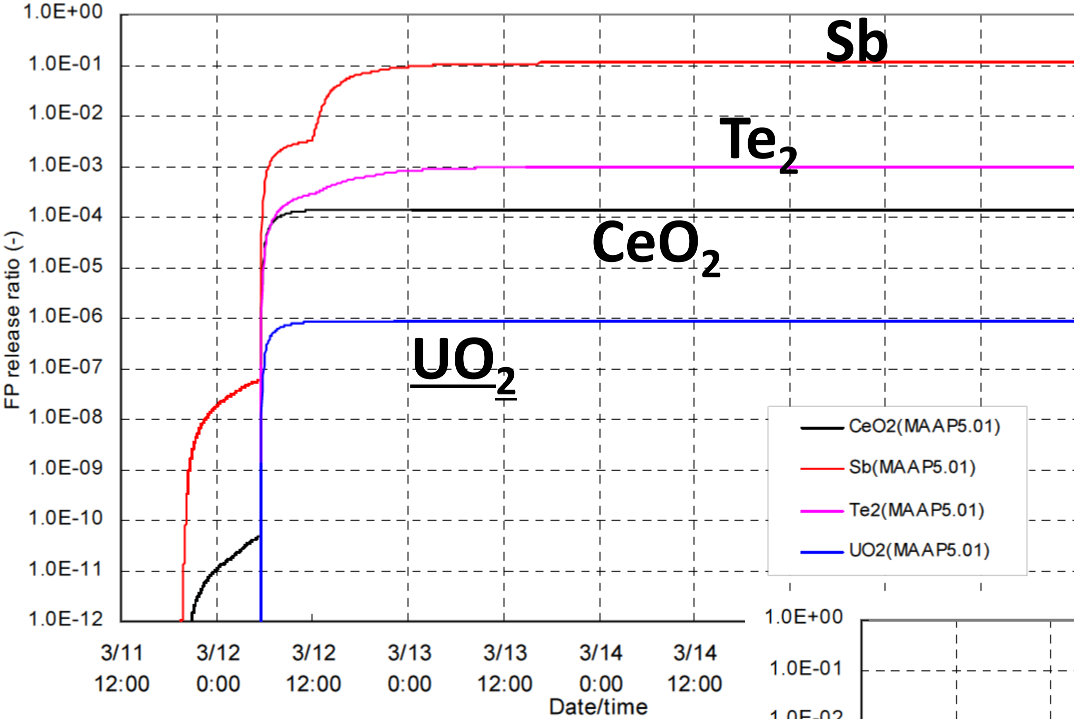
In-RPV temperature (gas phase) (MAAP5.01)
In-RPV temperature (gas phase) (MAAP4)
In-RPV temperature (gas phase) (deg. C)
Date/time

Unit 1

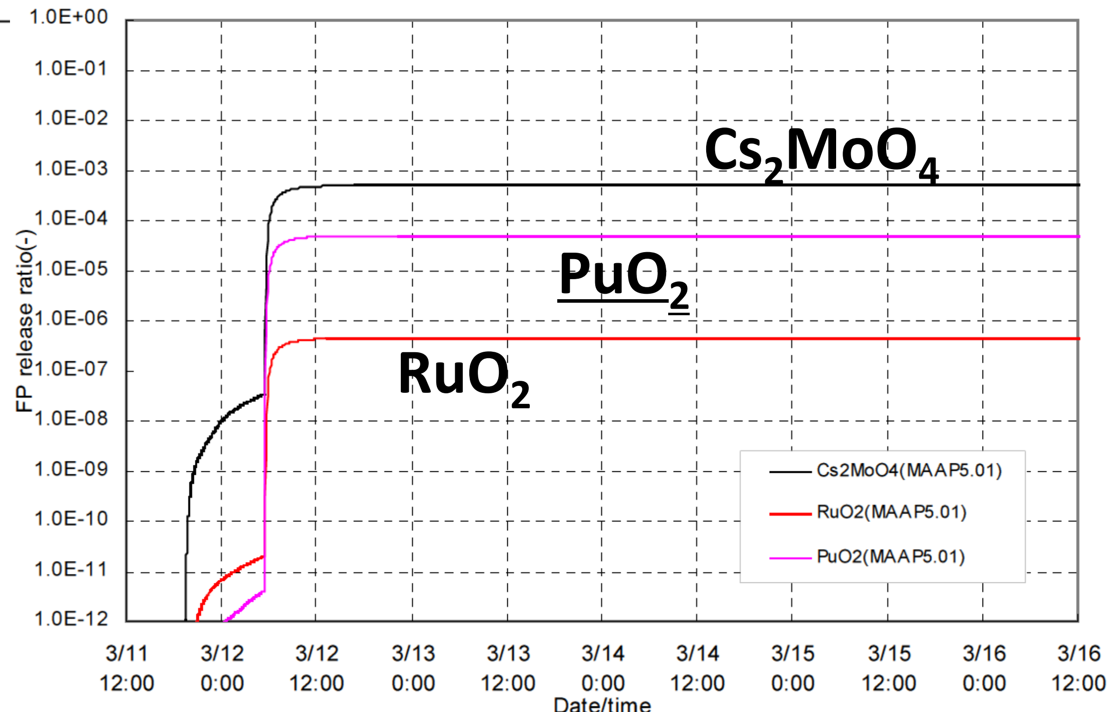


Gaseous leak started from in-core instrumentation tube (assumed)
Gaseous leak from gaskets of franges on Main Steam lines (assumption)
Core Support Plate damaged
RPV ruptured
Pressure decreased upon IC start-up
RPV pressure (MAAP5.01)
RPV pressure (MAAP4)
Measured pressure (Reactor-A)
Measured pressure (Reactor-B)
RPV pressure(MPa[abs])
Date/time

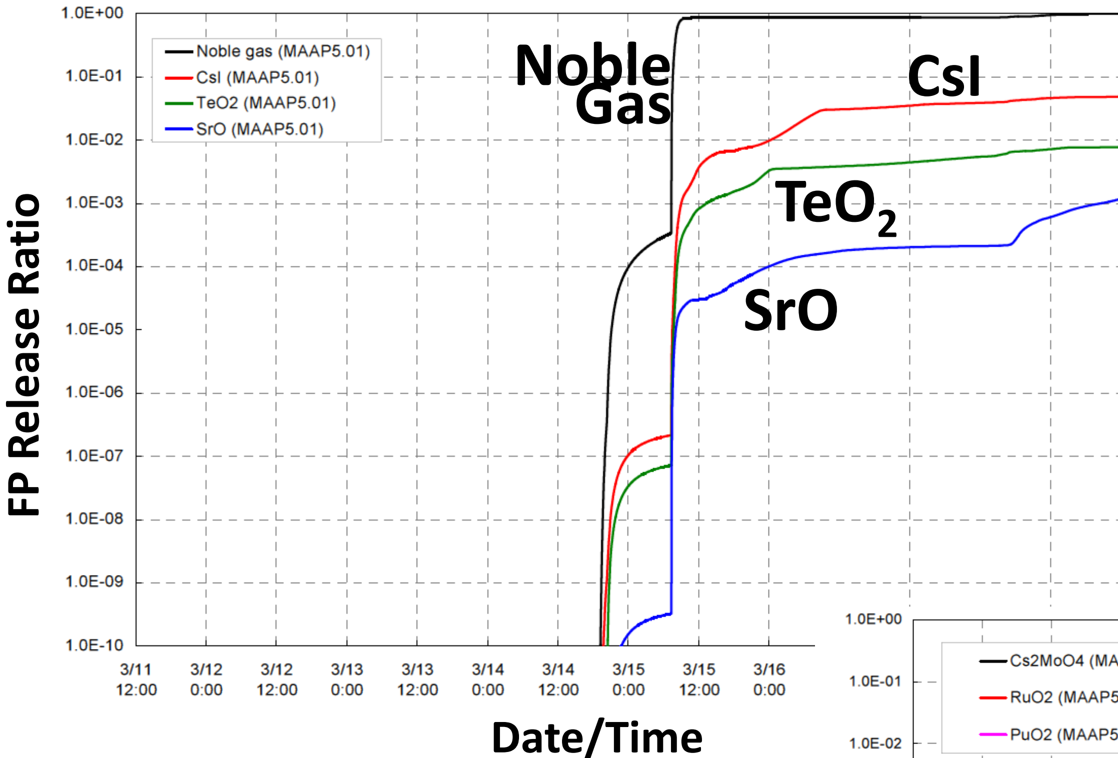
Release Rates of Fission Products in Various Chemical Forms in Unit 1



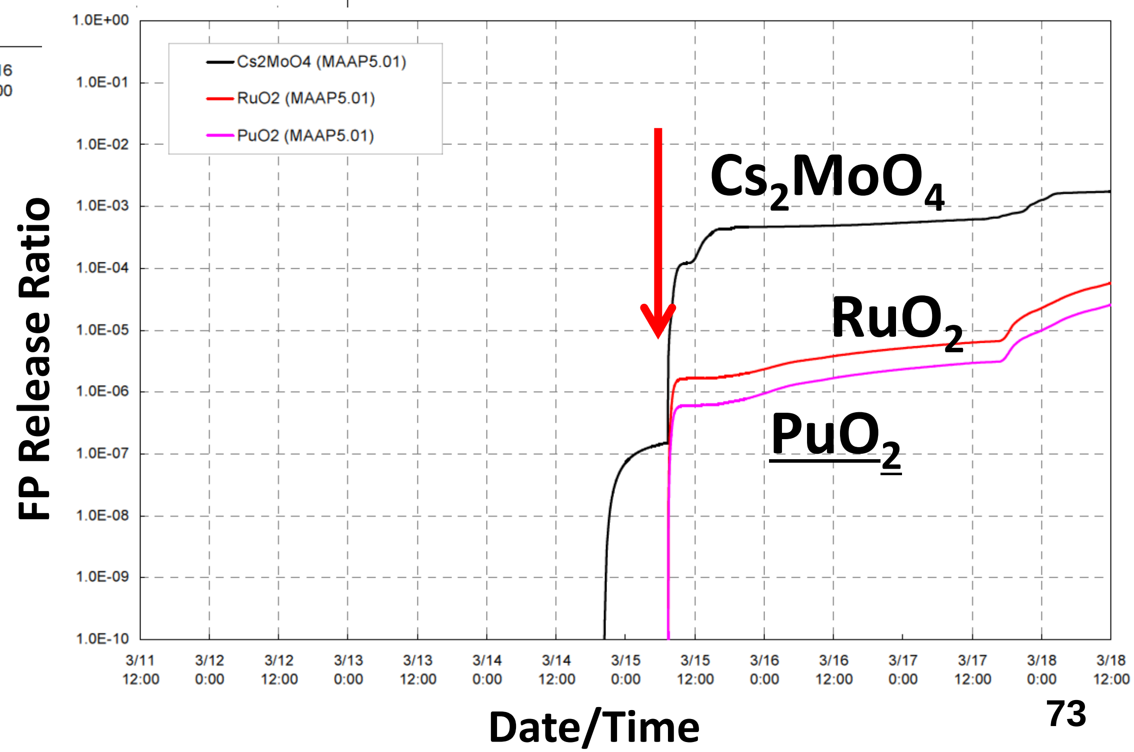
Unit 1



Release Rates of Fission Products in Various Chemical Forms in Unit 2 (MAAP code)



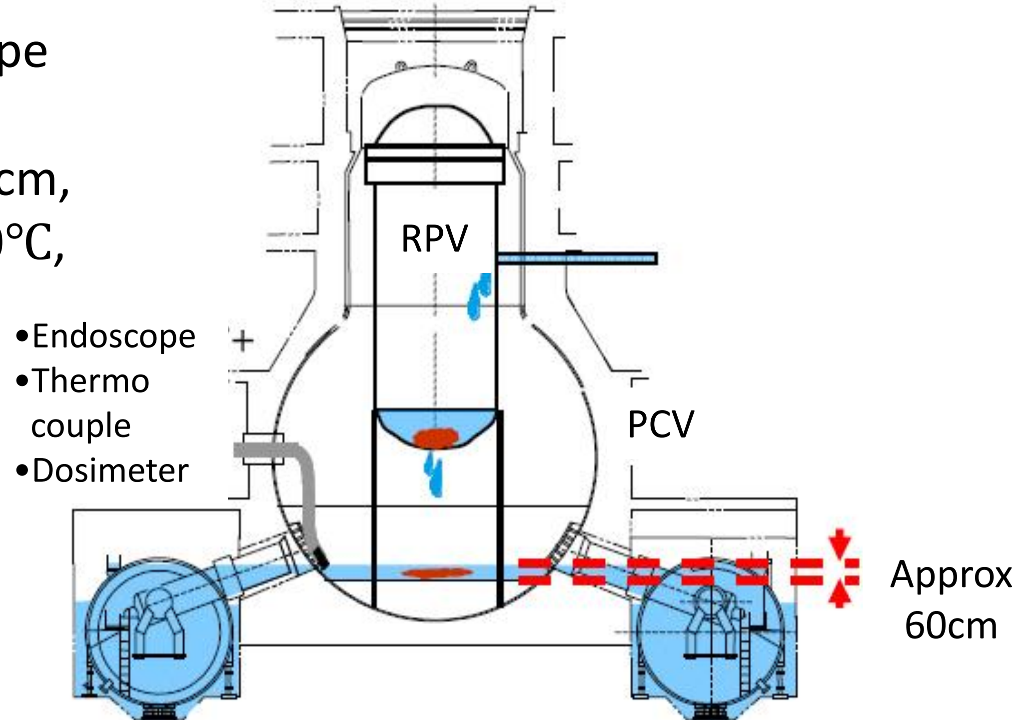
Unit 2



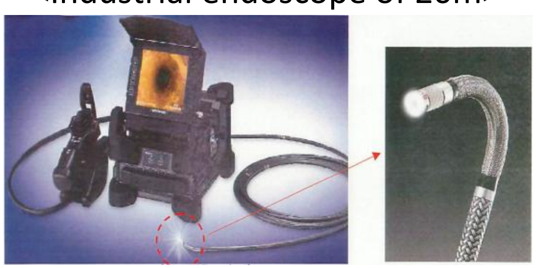
Investigation Result of the Inside of PCV of Unit 2

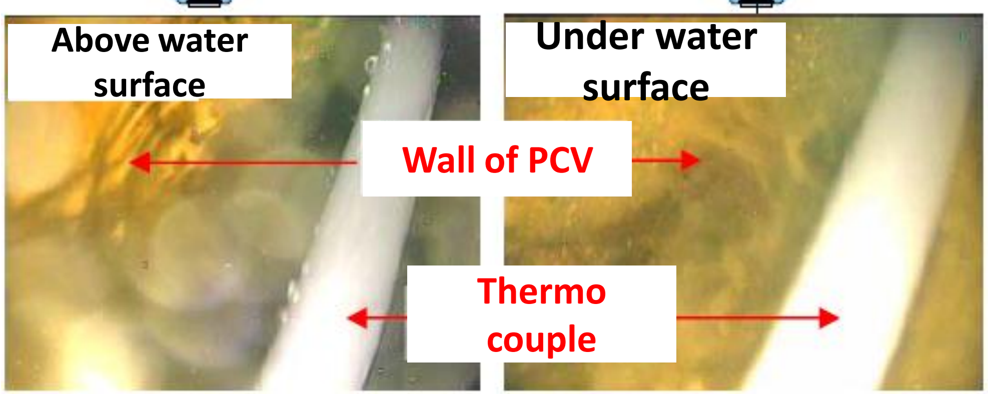
By investigations using an endoscope system, it was confirmed that:

- Water level in PCV is approx. 60 cm,
- Water temperature is approx. 50°C, and
- Dose rate of gas phase is 73 Sv/h.



<Industrial endoscope of 20m>





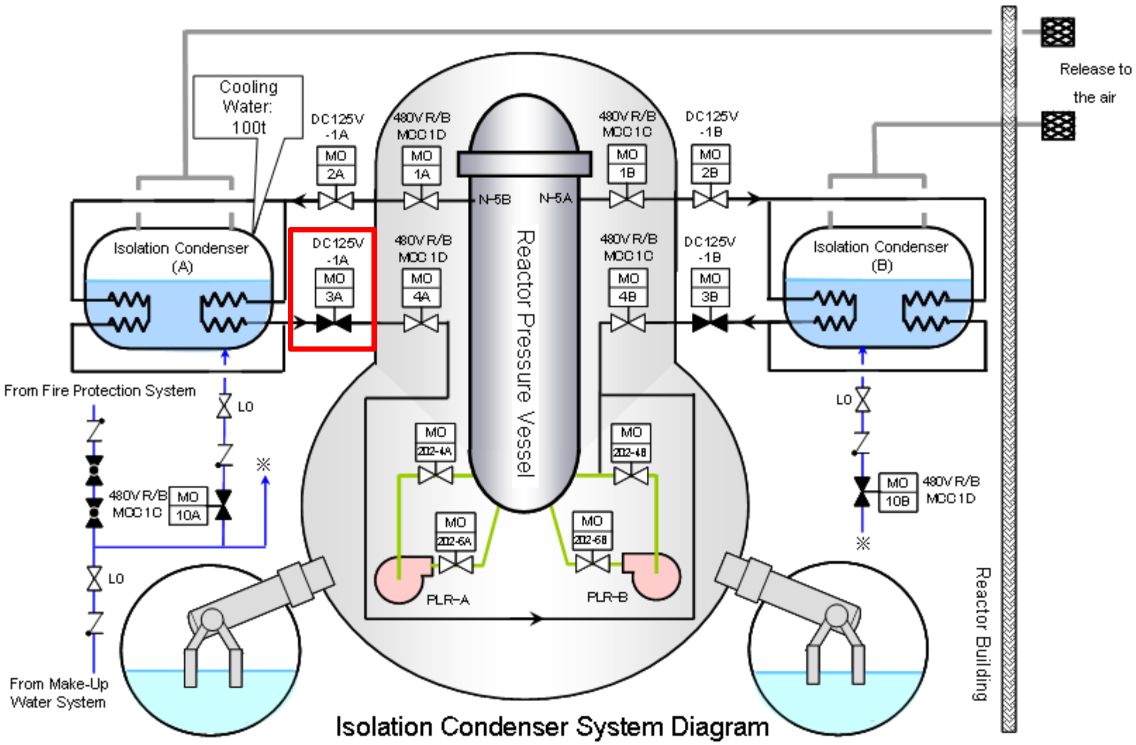
(Source: TEPCO)

Damage of Field on Site caused by the Earthquake and Tsunami

TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 6-9,

Failure of Water Injection Using Isolation Condenser System in Unit 1

Though Unit 1 IC was a passive injection system, it lost the function due to the loss of both AC and DC power supply.



Isolation Condenser System Diagram

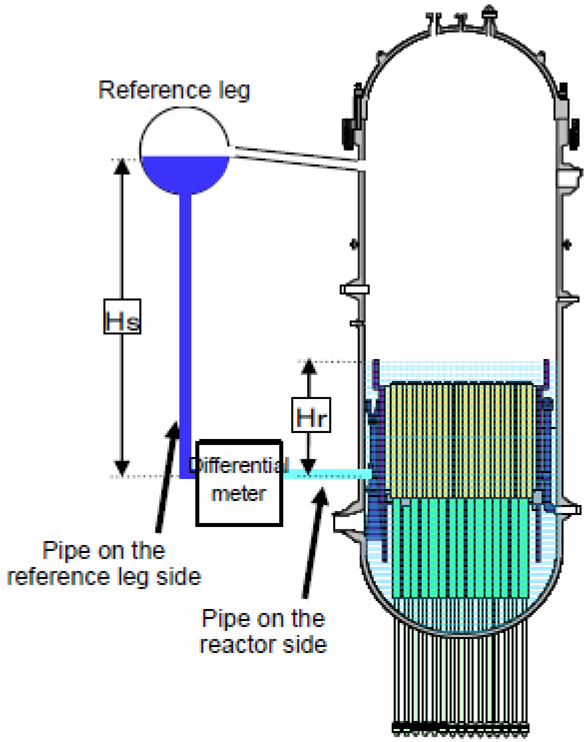
When tsunami attacked,

- Operator was using IC-A to control reactor pressure
- DC power for system A was lost
- Rapture detection circuit for IC-A was lost
- Valve 1A and 4A inside PCV were closed using AC power due to fail safe mechanism. IC-A lost its function
- AC power was lost. Restoration got difficult.

TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 8-6,

Water Level Measurement in Unit 1

At 21:19 on March 1, Unit 1 reactor water level gage was powered.
It showed TAF +200 mm, but･･･



In fact, fuel had been exposed at that time.

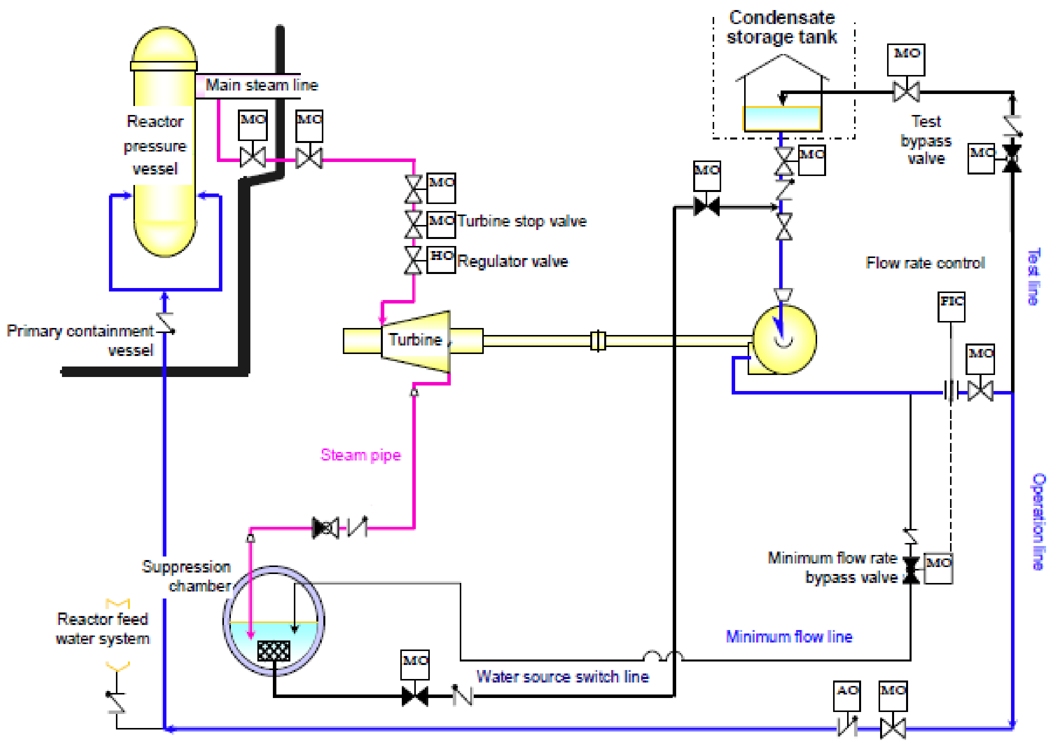
Water gauges measures the difference of pressure between the Reference leg and the water phase of the reactor

Water gauges was required calibration when the reference leg was dried-off or water level decreased significantly

TEPCO, Fukushima Nuclear Accidents Investigation Report, p. 223

RCIC in Unit 2 Sustained the Function after Loss of DC Power

Though Unit 2 RCIC was not a passive injection system, it had partly sustained the function after the loss of power supply until March 14

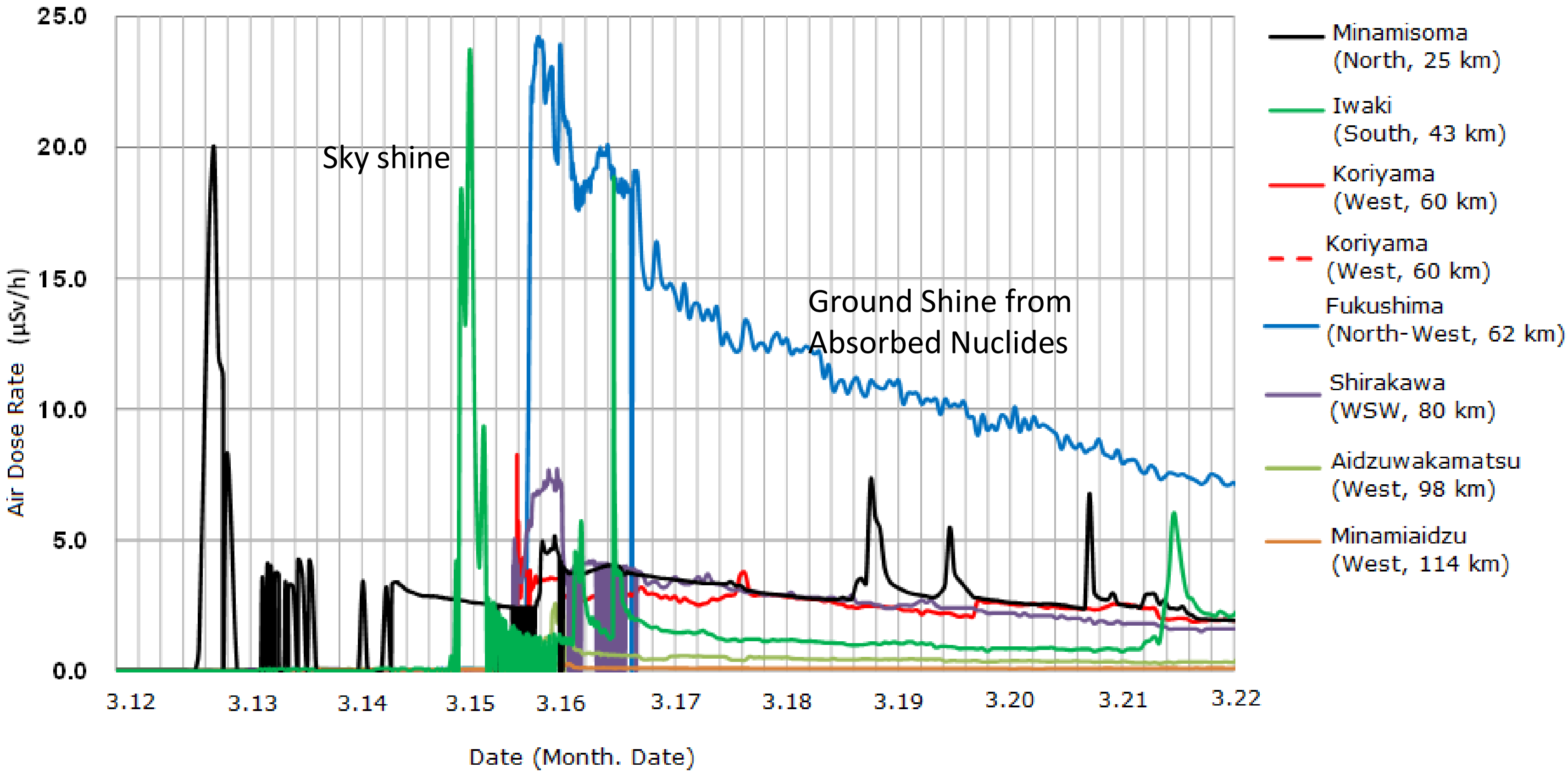


- When power for RCIC was lost, the valves for RCIC operation was open
- RCIC did not stop the operation due to the loss of the automatic control
- RCIC turbine was driven by two-phase flow when water level was higher than the limit

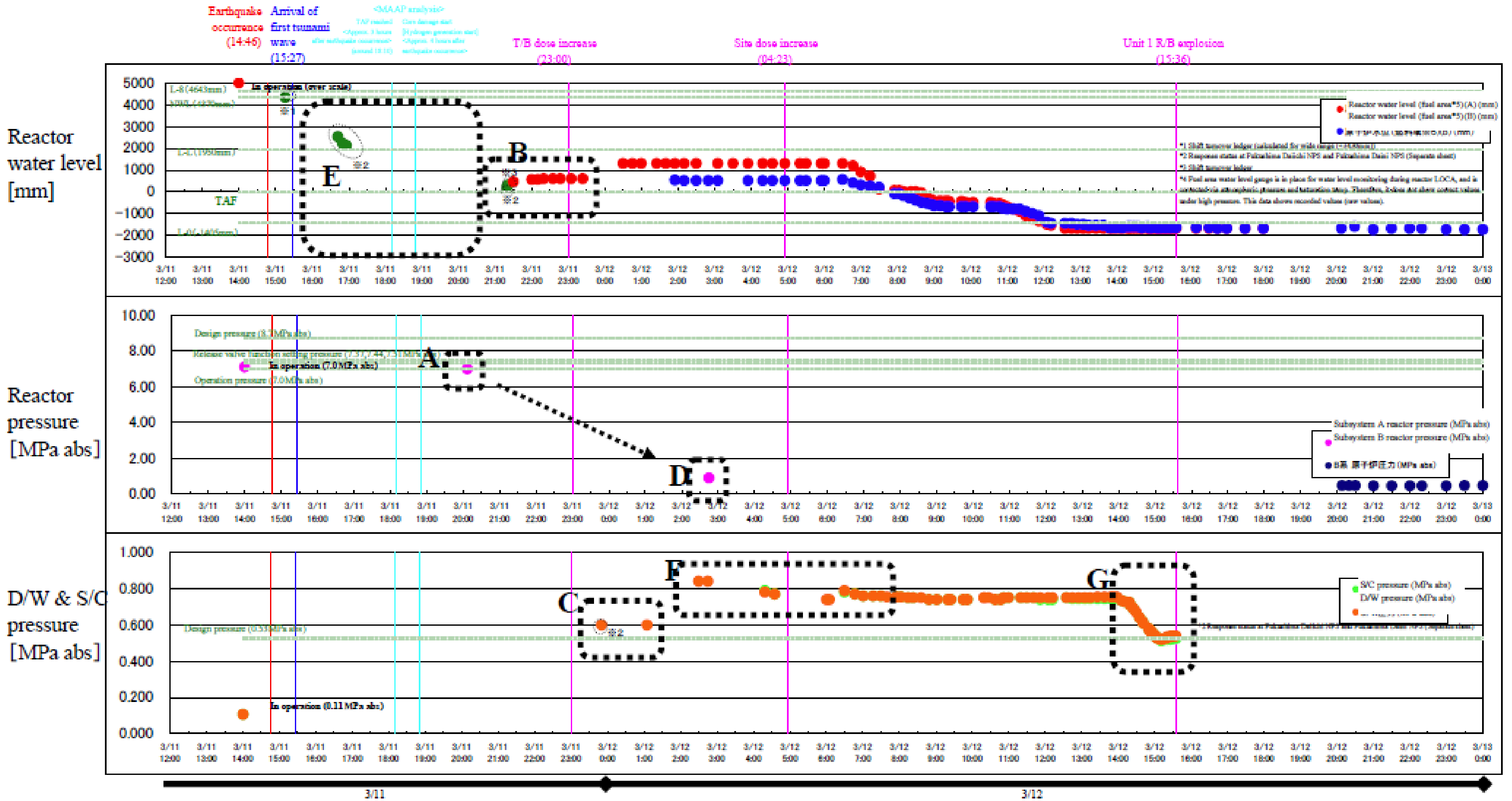
TEPCO, Fukushima Nuclear Accidents Investigation Report, P. 224.

Air Dose Rate in Fukushima Daiichi NPS

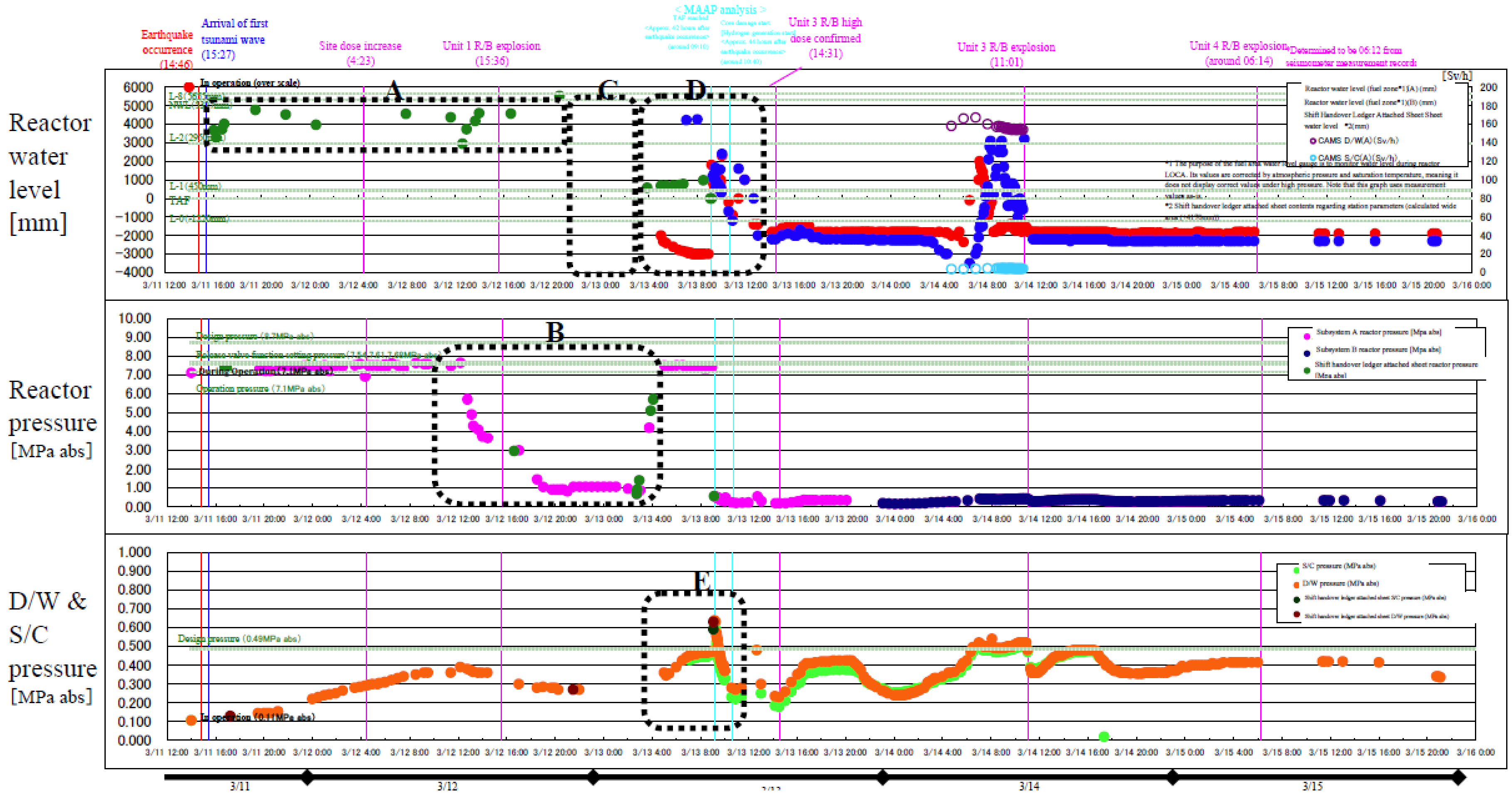
- The closest monitoring posts were not available due to the earthquake, tsunami, and blackout.
- Migration of radioactive plume was strongly affected by daily circulation of the wind.
  - Towards South (early morning) → Towards West (morning) → Towards North-West (afternoon) → Towards East (night)
- Radionuclides were contaminated on North-West region of the NPS after the rain in the midnight of March 15.



Plant Parameters in Unit 1



Plant Parameters in Unit 3



TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 8-15,

Cooling Unit 2 Reactor Core

- While Unit 2 RCIC was functioned,
  - SRV control panel was powered by potable batteries on March 13 to depressurize after RCIC stop
  - Seawater injection line was prepared using fire engine
  - PCV vent line was completed except the break of rapture disk
- But these measures were damaged by hydrogen explosion in Unit 3.

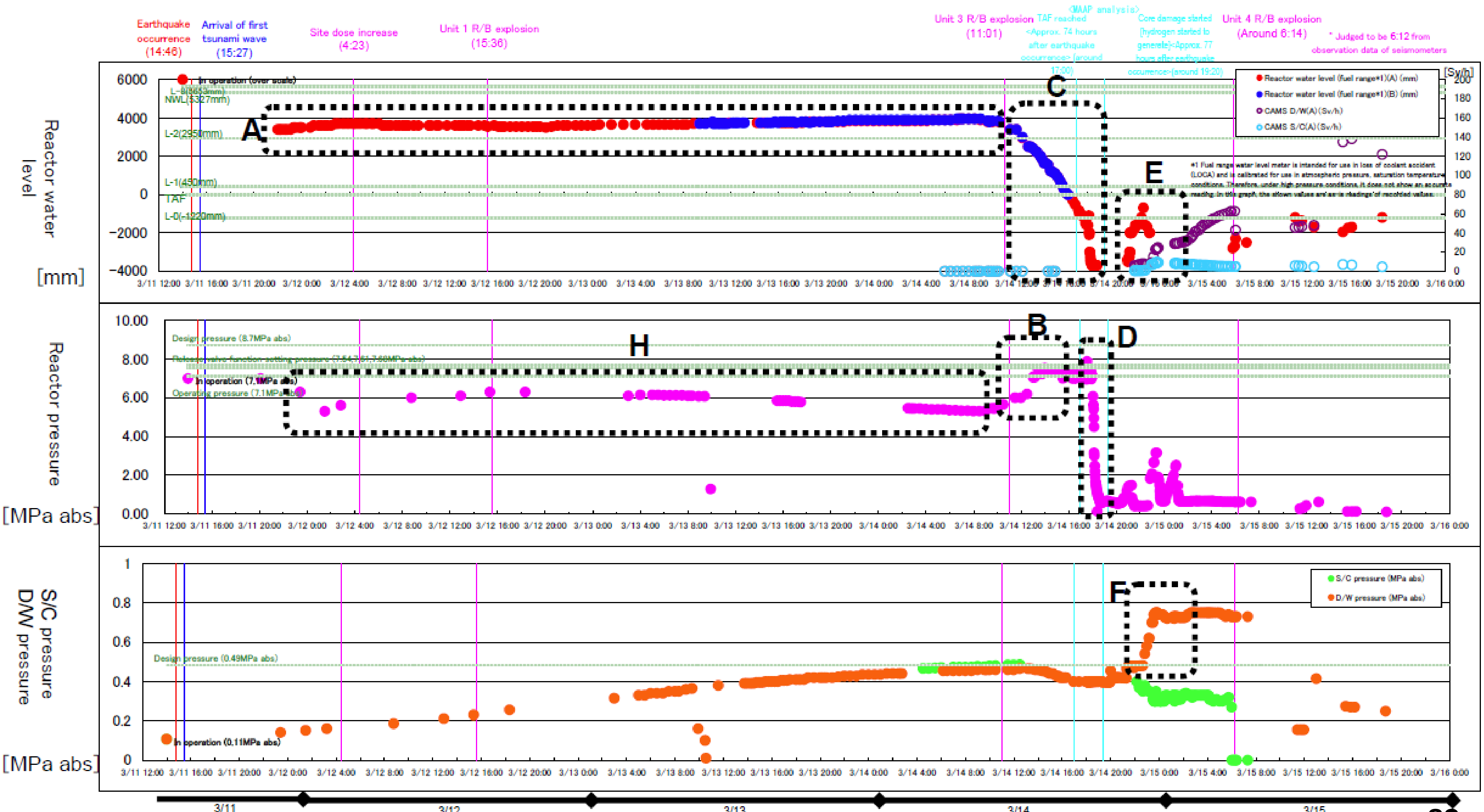
- At 13:25 on March 14, loss of RCIC was confirmed.
- Since S/C temperature exceeded 100 ^{o}C and the steam would not condense easily, decision was made to depressurized after venting was lined up.

Source: TEPCO

- At 14:43, connection of fire engine was restored, but restoration of venting took time.
- At 16:21, the president of TEPCO ordered to depressurize at first, but SRV did not worked well until 18:02.
- At 19:20, shutdown of fire engine due to the lack of fuel was confirmed.
- At 19:57, two fire engines started up, and sea water injection was commenced.

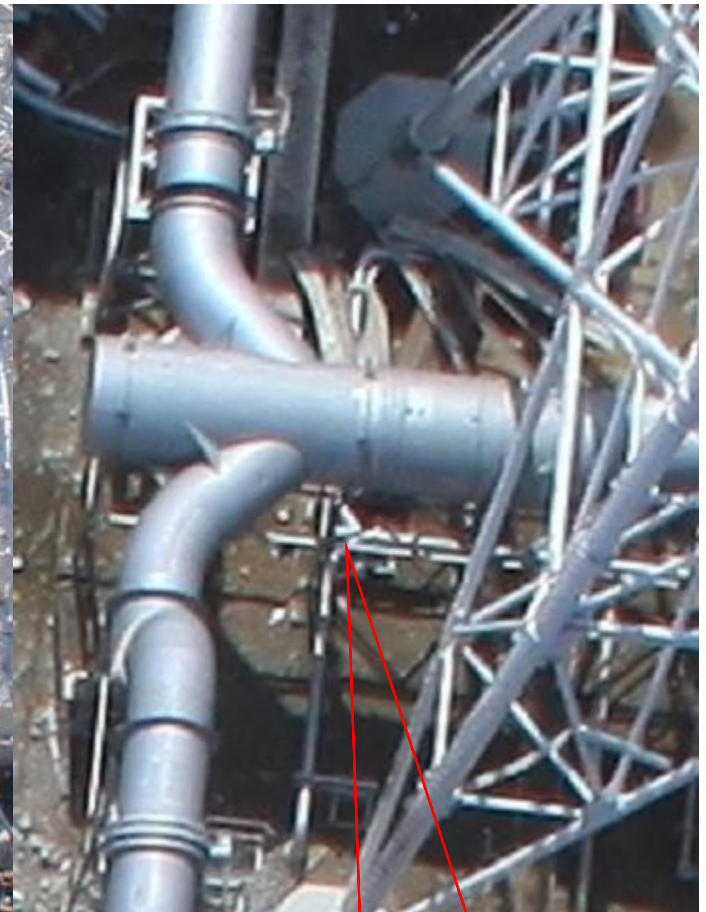
Plant Parameters in Unit 2

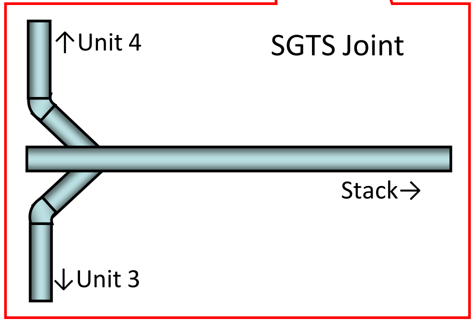
- According to the severe accident simulation, fuel started exposing around 9:10, and core damage stared 10:40 on March 13.



TEPCO, Fukushima Nuclear Accidents Investigation Report, Attachment 8-12,

Stand-by Gas Treatment Systems for Units 3 and 4

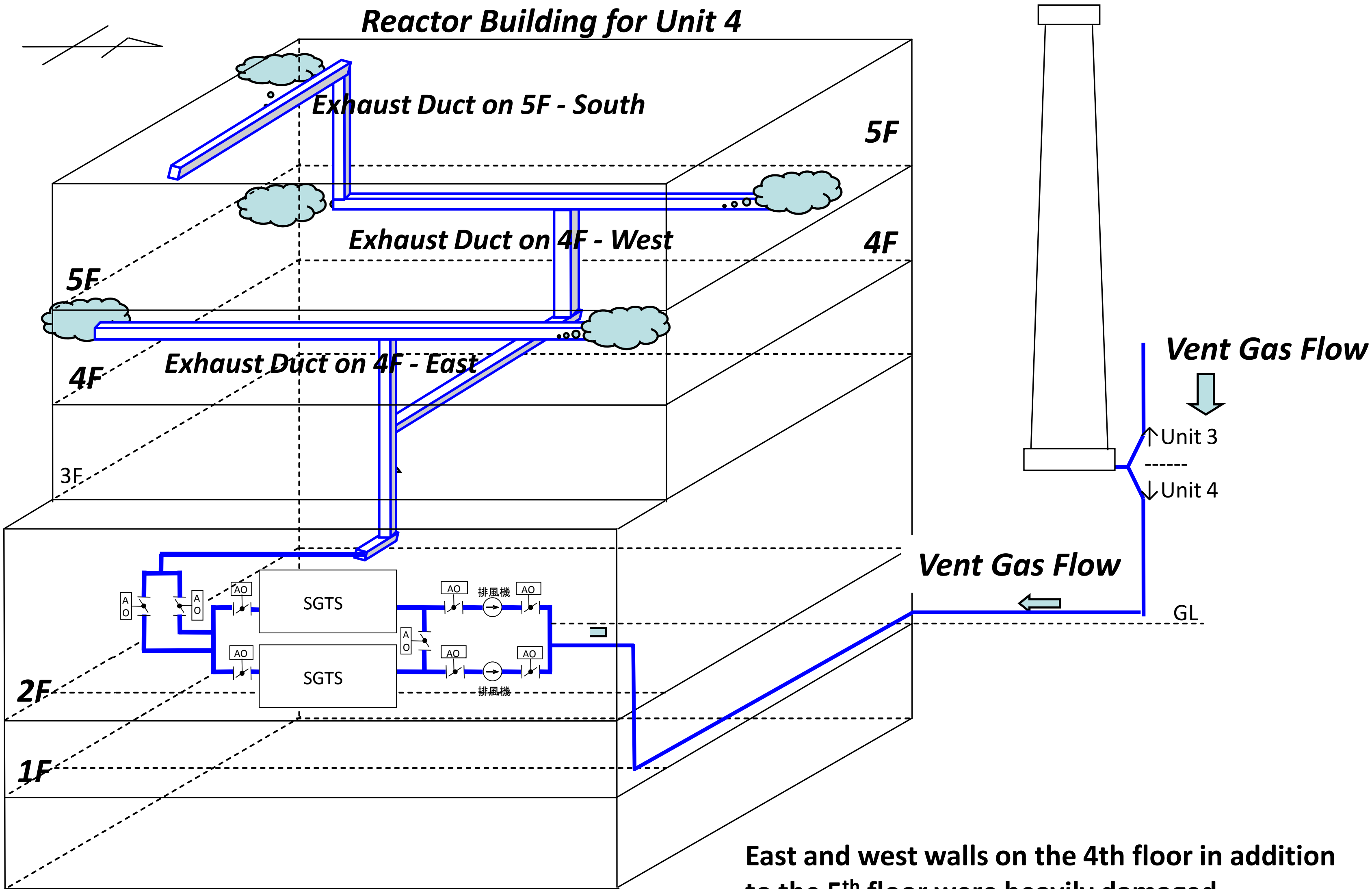




Pipes of stand-by gas treatment systems for Units 3 and 4 are connected.

Source: TEPCO

Possible Mechanism of Hydrogen Explosion in Unit 4



East and west walls on the 4th floor in addition to the 5th floor were heavily damaged.

Source: TEPCO

Amount of Released Radioactive Material to determine INES Rating (April 11, 2011)

	Estimated release from Fukushima Daiichi		Release from **Chernobyl**
	by NISA	by Nuclear Safety Commission	
I-131 (a)	$1.3X10^{17}$Bq	$1.5X10^{17}$Bq	$1.8X10^{18}$Bq
Cs-137	$6.0X10^{15}$Bq	$1.2X10^{16}$Bq	$8.5X10^{16}$Bq
Iodine value conversion (b)	$2.4X10^{17}$Bq	$4.8X10^{17}$Bq	$3.4X10^{18}$Bq
(a) + (b)	**$3.7X10^{17}$Bq**	**$6.3X10^{17}$Bq**	$5.2X10^{18}$Bq

INES level 7 > 10^{16}Bq Iodine equivalent

INES : International Nuclear Event Scale

INES Manual (2008) co-sponsored by IAEA and OECD/NEA

International Nuclear Event Scale (INES)

Level	*Off-site Impact*	*On-site Impact*	*Defense-in-Depth Degradation*
7	Major release		
6	Significant release		
5	Limited release	Severe damage	
4	Minor release	Significant damage / Fatal exposure of worker	
3	Very small release	Severe spread of contamination / health effects to worker	Near accident
2		Significant spread of contamination / overexposure of worker	Significant failure
1			Beyond Operation limit
0			

Out of scale

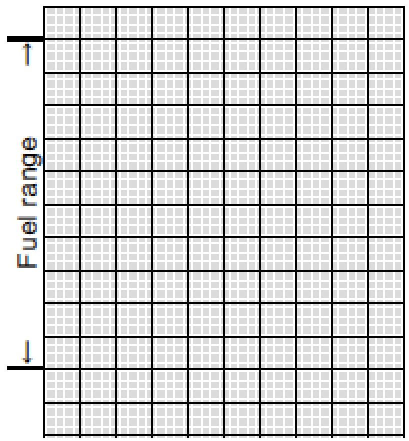
INES Manual (2008) co-sponsored by IAEA and OECD/NEA

Overview of Events in Unit 1

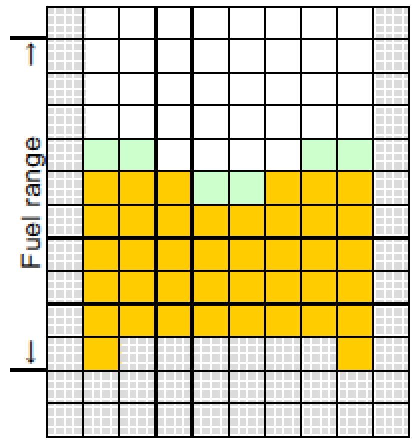
- 14:46 on March 11, 2011 : Earthquake
  Reactor scram
  Loss of offsite power, AC power with DG
  Hot standby wit Isolation condenser (IC)
- 15:30 on March 11 : Tsunami arrival
  Loss of all AC & DC power
  => Loss of ECCS & IC
  => Loss of reactor cooling
- Shortly before 7:00 pm Mar. 11th
  Core damage
- Approx. 4:00 am Mar. 12th
  Reactor core coolant injection via
  fire engine begins
- 3:36 pm Mar. 12th
  Hydrogen explosion in reactor
  building

Estimated Core Damage in Unit 1

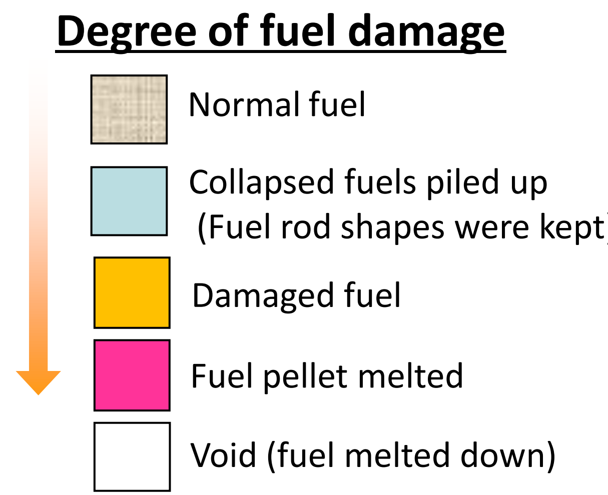
- Simulation Results of Fuel Damage by the MAAP code -

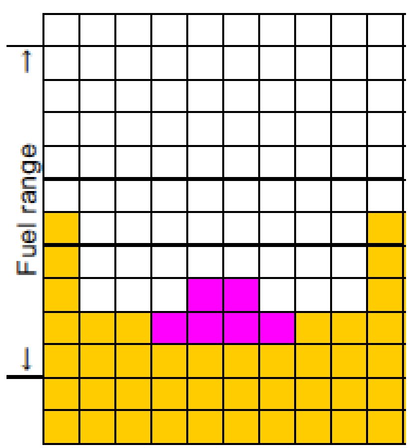


About 3.9 hours after SCRAM

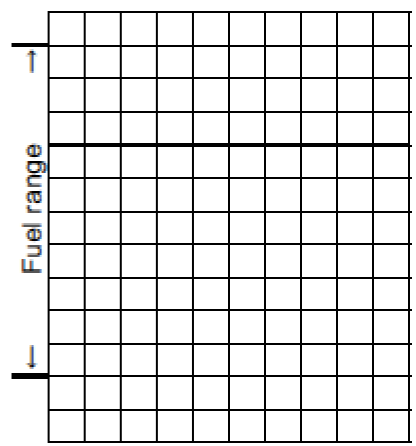


About 5.0 hours after SCRAM





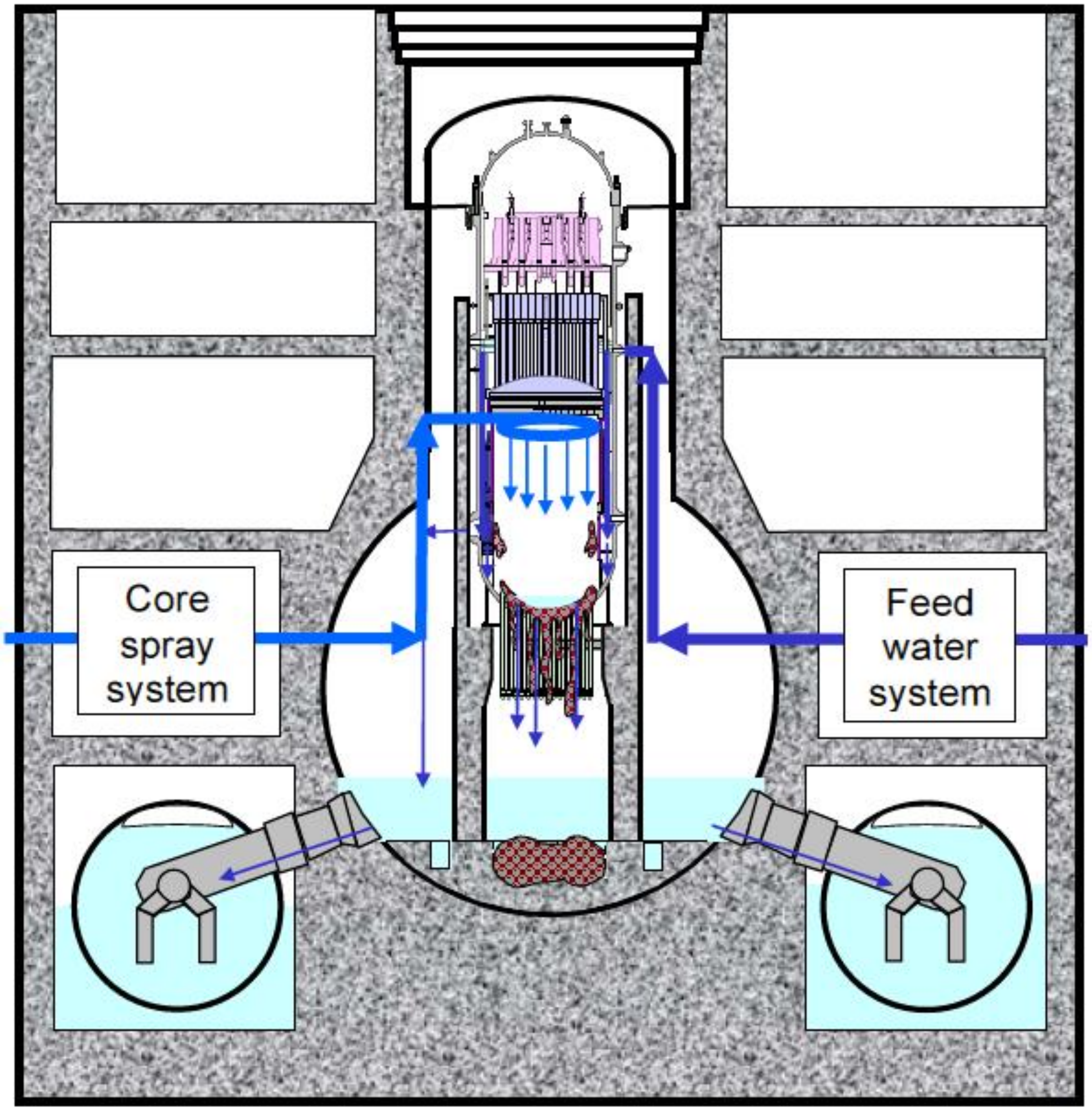
About 11.5 hours after SCRAM



About 12.0 hours after SCRAM

- Melting starts from the central part of the core.
- In 12 hours after scram, most part of the core fell down to the RPV bottom.

Summary of Core Damage in <u>Unit 1</u>



- Severe Accident code analysis indicates;

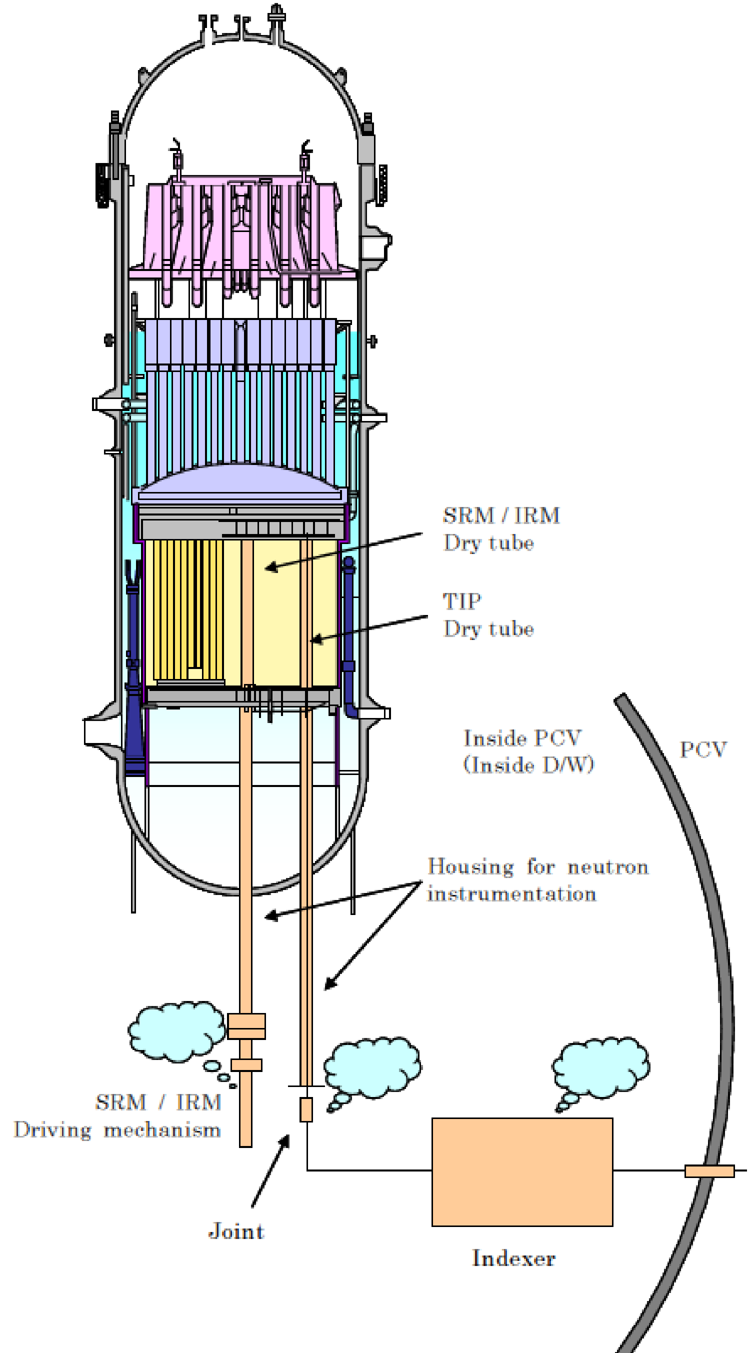
<u>**All fuel rods were melted and relocated to the RPV bottom. Considerable amount of fuel dropped to the PCV bottom.**</u>

- **Almost all fuel dropped to the PCV bottom, is in contact with water, and is cooled.**
- Currently water is injected to the RPV via the feed water piping and core spray piping. Temperature of the RPV bottom and the PCV is stable well below 100 C.

Source: TEPCO

Location of Gas Leak from RPV to PCV in Unit 1

- Possible paths of gaseous leakage from the reactor vessel to the D/W are the in-core instrumentation dry tube or the main steam line flange gasket.
- The in-core instrumentation dry tube can be damaged when fuel temperatures are elevated.
- The main steam line flange gasket may lose its airtightness at temperature of about 450 C.



SRM : Source Range Monitor
IRM : Intermediate Range Monitor
TIP : Travelling In-core Probe

Overview of the Events in Unit 2

- **2:46pm Mar. 11th Earthquake occurrence: Offsite power failure**
  Plant scrammed to shutdown
  RCIC and SR valves => transit to hot standby
- **3:30pm Mar. 11th tsunami arrival:**
  Loss of all AC and DC power sources => loss of ECCS
  RCIC was manually activated before power failure, and it ran uncontrolled
- **Noon Mar. 14th: loss of RCIC**
- **7:20pm Mar. 14th: reactor core damage**
- **7:57pm Mar. 14th: reactor core injection begins via fire engine**
- **No hydrogen explosion in reacto building (because reactor blowo panel was released open by the explosion in Unit 1)**

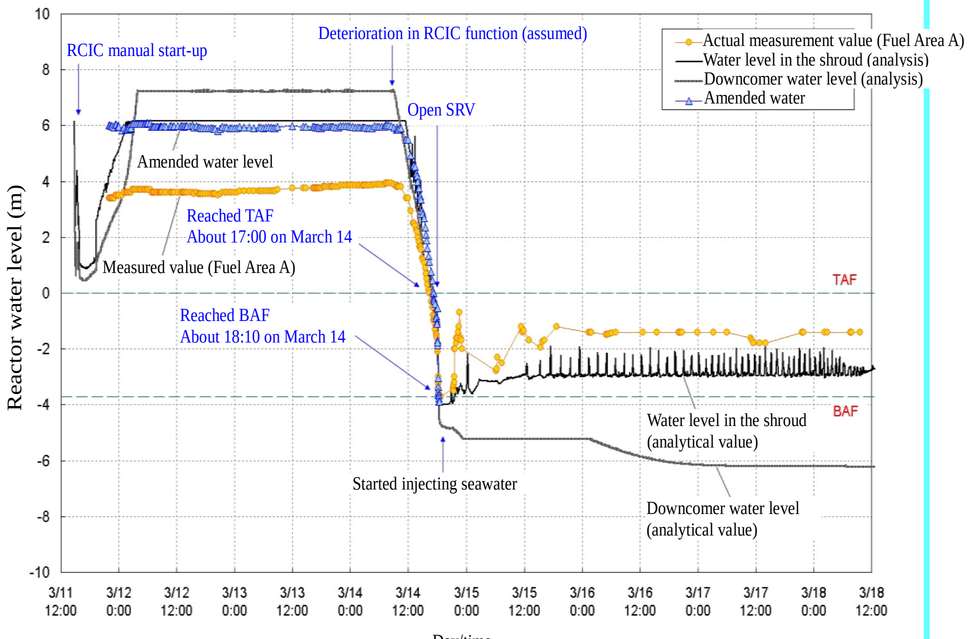


Fig. 3.7 Reactor water level (Unit 2)

Overview of the Events in Unit 3

- **2:46pm Mar. 11th Earthquake occurrence: Offsite power failure**
  Plant scrammed to shutdown
  RCIC and SR valves => transit to hot standby
- **3:30 pm Mar. 11th Tsunami arrival**
  Loss of all AC power source => Low-pressure ECCS failure
  DC power maintained => Reactor cooling via RCIC, HPCI
- **2:42 pm Mar. 13th**
  HPCI suspended (DC power loss) => Failure in switching to D/DFP
- **9:25am Mar. 13th**
  After de-pressurization via SR valve,
  coolant injection into reactor core vi
  fire engine begins
- **10:40am Mar. 13th**
  Core damage
- **11:01am Mar. 14th**
  Hydrogen explosion of reactor build

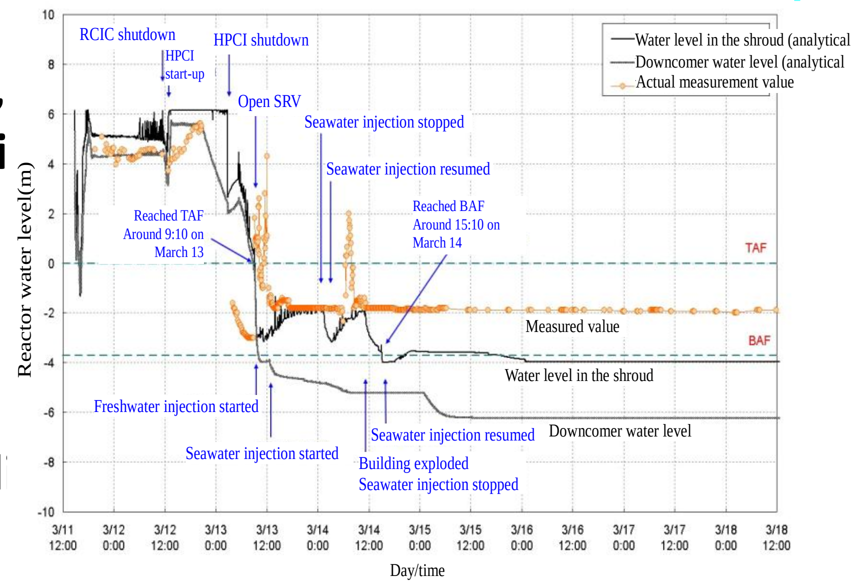


Fig. 3.11 Reactor water level (Unit 3)

Fundamental Safety Functions for Light Water Reactors

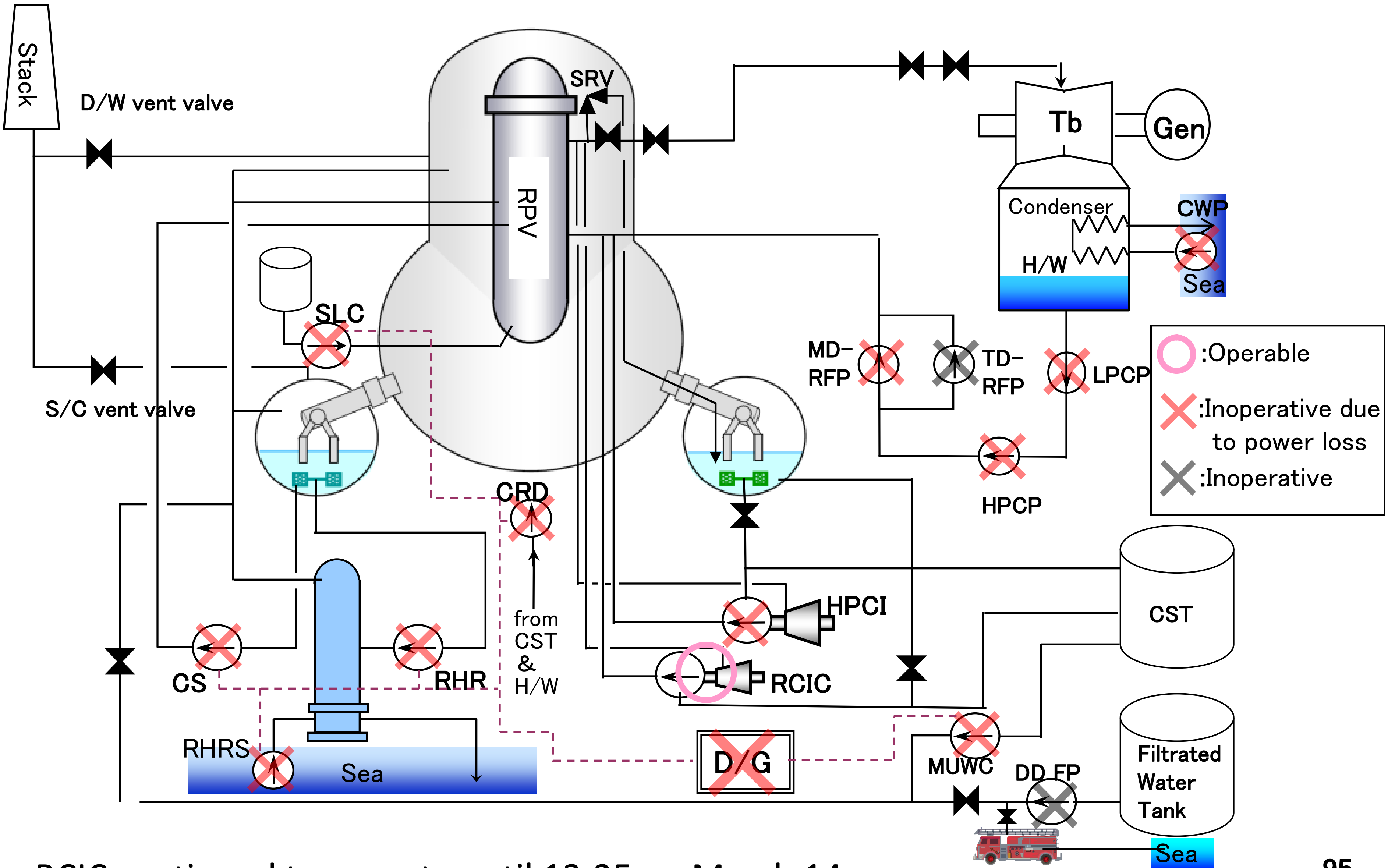
<u>Shutting Down</u> by interrupting fission chain reaction through insertion of control rods

<u>Cooling Down</u> the fuels through continuous water injection and circulation

<u>Confining</u> radio-active materials inside the boundary (RPV and PCV)

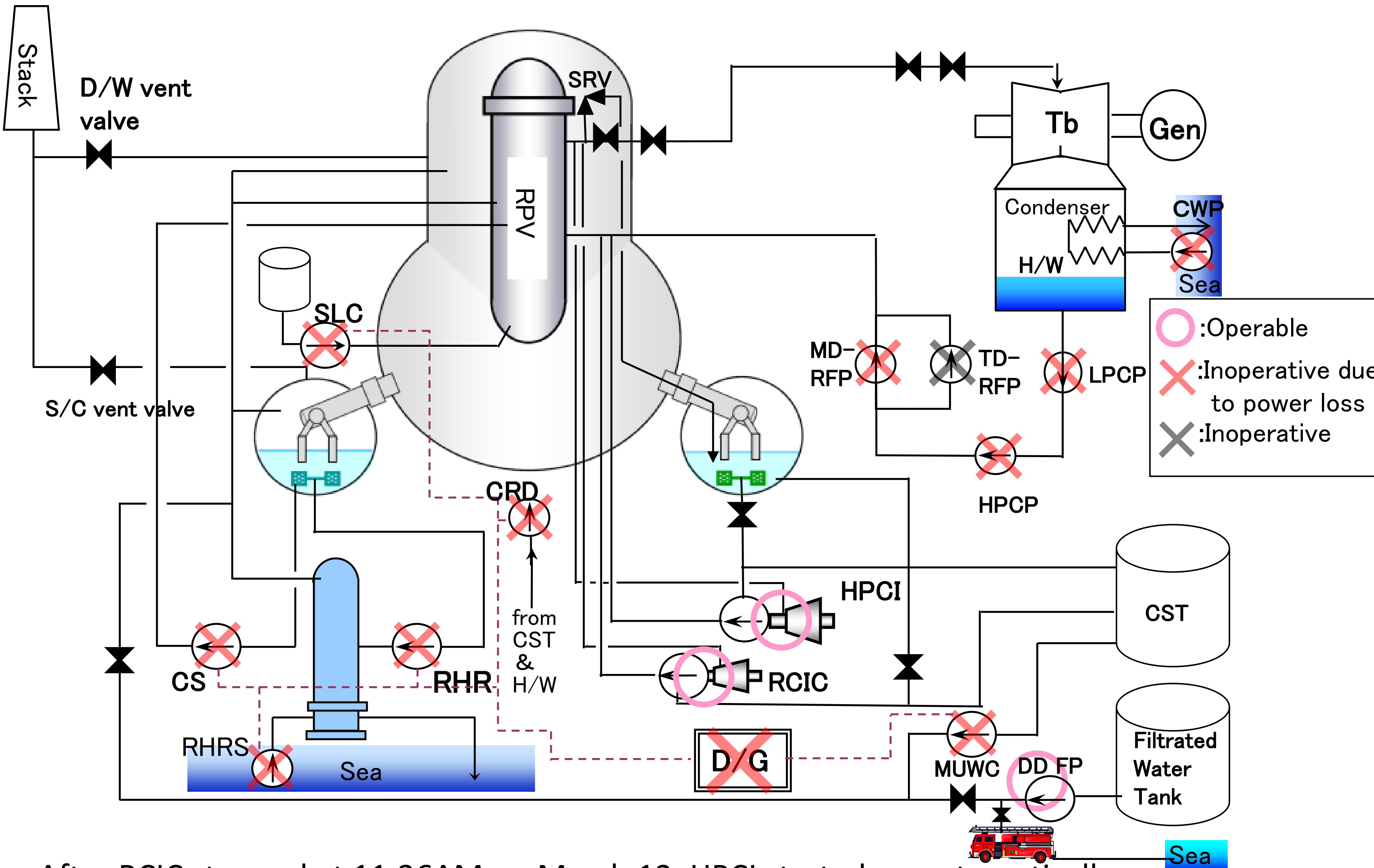
1. **High-pressure Coolant Injection**
2. **Depressurization**
3. **Low-pressure Coolant Injection**
4. **Heat Removal to Ultimate Heat Sink (Ocean)**

Schematic System Diagram in Unit 2 after the Tsunami



RCIC continued to operate until 13:25 on March 14.

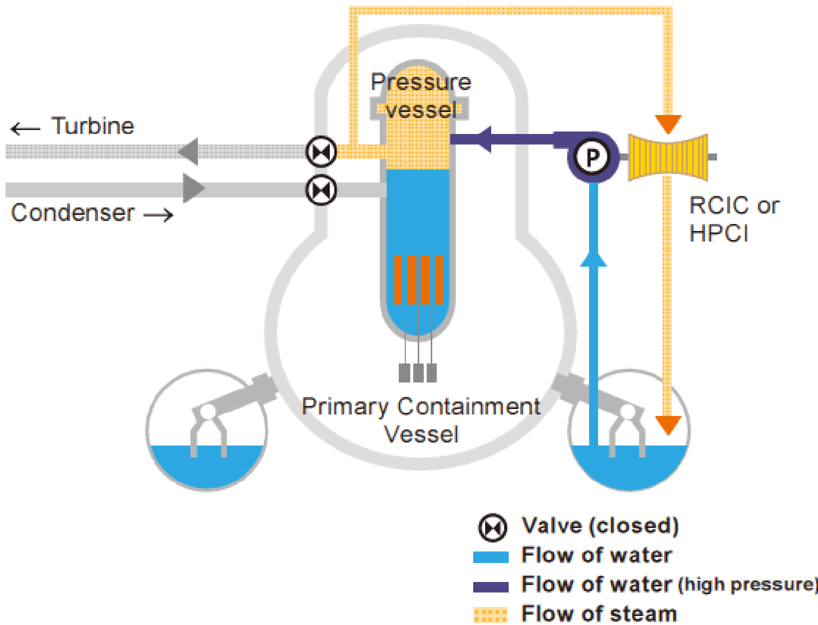
Schematic System Diagram in Unit 3 after the Tsunami



After RCIC stopped at 11:36AM on March 12, HPCI started up automatically.
Batteries ran out, and HPCI stopped by 2:42AM on March 13.

High-pressure Coolant Injection

Water is put into the high-pressure reactor pressure vessel to cool the reactor core and maintain water levels.



High-pressure coolant injection system (HPCI)

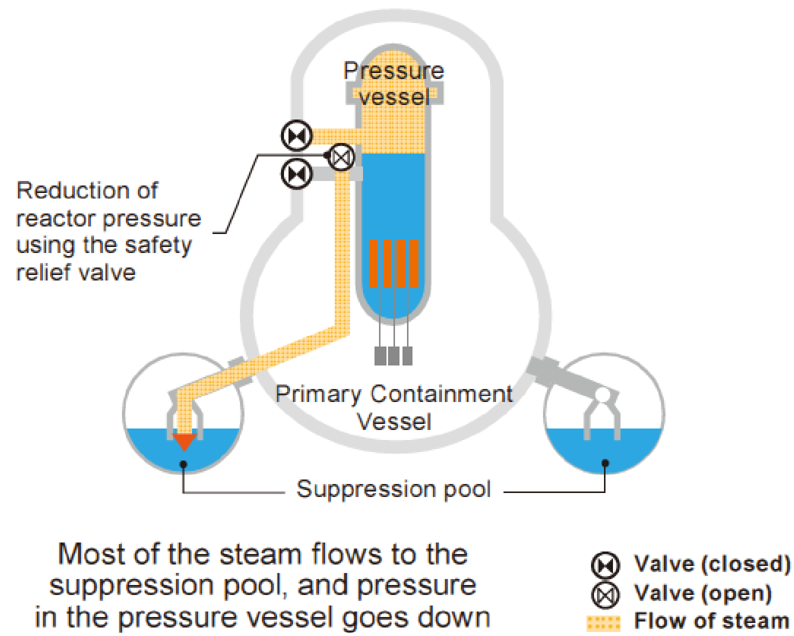
Reactor core isolation cooling system (RCIC)

Reactor steam

DC power (for control use)

Depressurization

Lower the pressure of the pressure vessel to enable low-pressure coolant injection and heat removal.



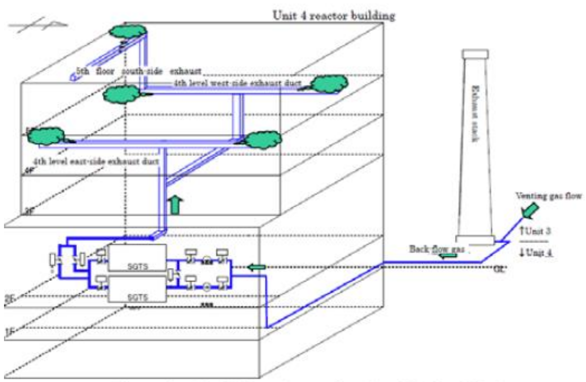
Safety relief valve

Nitrogen gas under high pressure

DC power (for control use)

Hydrogen Explosion in Unit 4

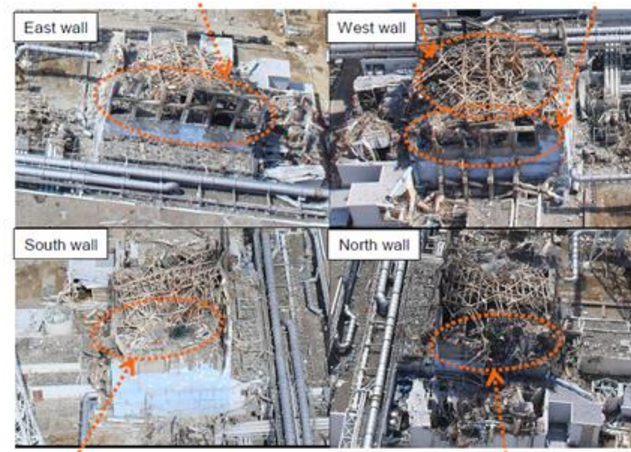
- At 6:12 on March 15, with loud noise and vibration, Unit 4 R/B was damaged.
- Later investigation showed that hydrogen generated in Unit 3 flew into Unit 4
  - There is a possible path from PCV vent line shared by Unit 3&4 through Unit 4 SGTS line into Unit 4 R/B
  - Fuels in spent fuel pool (SFP) are not damaged.



Flow path of the PCV venting gas flow from Unit 3 to Unit 4

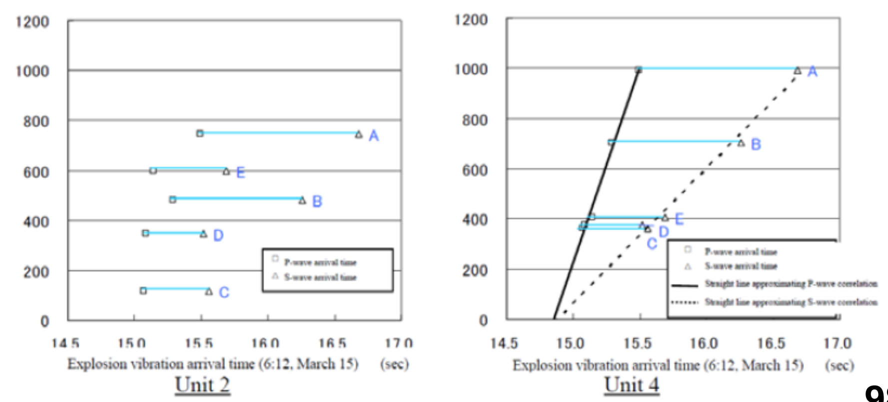
TEPCO, Fukushima Nuclear Accidents Investigation Report, p. 345

Source: TEPCO



AESJ-NSD, Report of the Seminar to investigate the Accident at the Fukushima-Daiichi Nuclear Power Station, p. 41

- At the same time of the explosion, S/C pressure in Unit 2 dropped to be zero.
- People thought that the explosion occurred in Unit 2.
- But the assumption was denied by the seismic records.

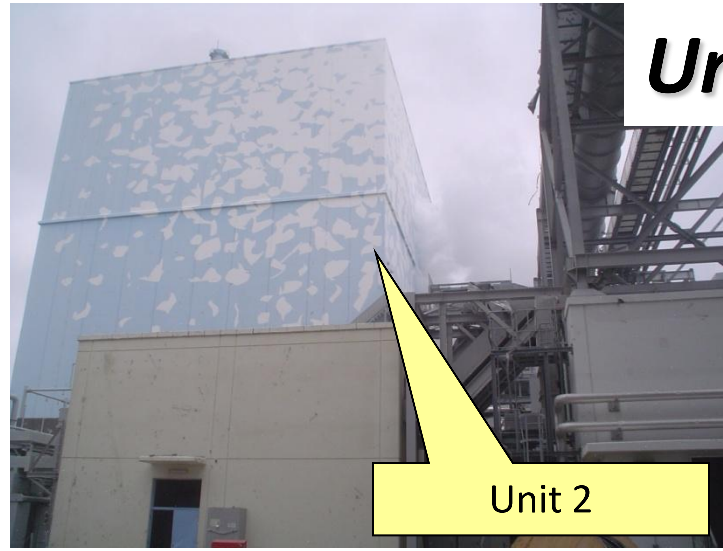


TEPCO, Fukushima Nuclear Accidents Investigation Report, p. 339

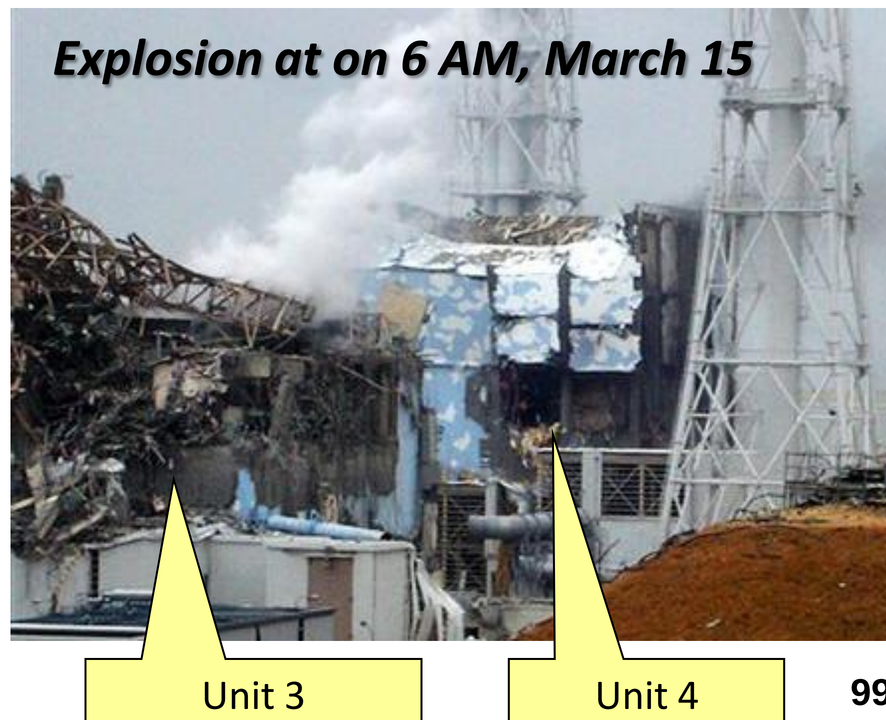
Unit 3

Hydrogen Explosion on 11 AM, March 14

Unit 2

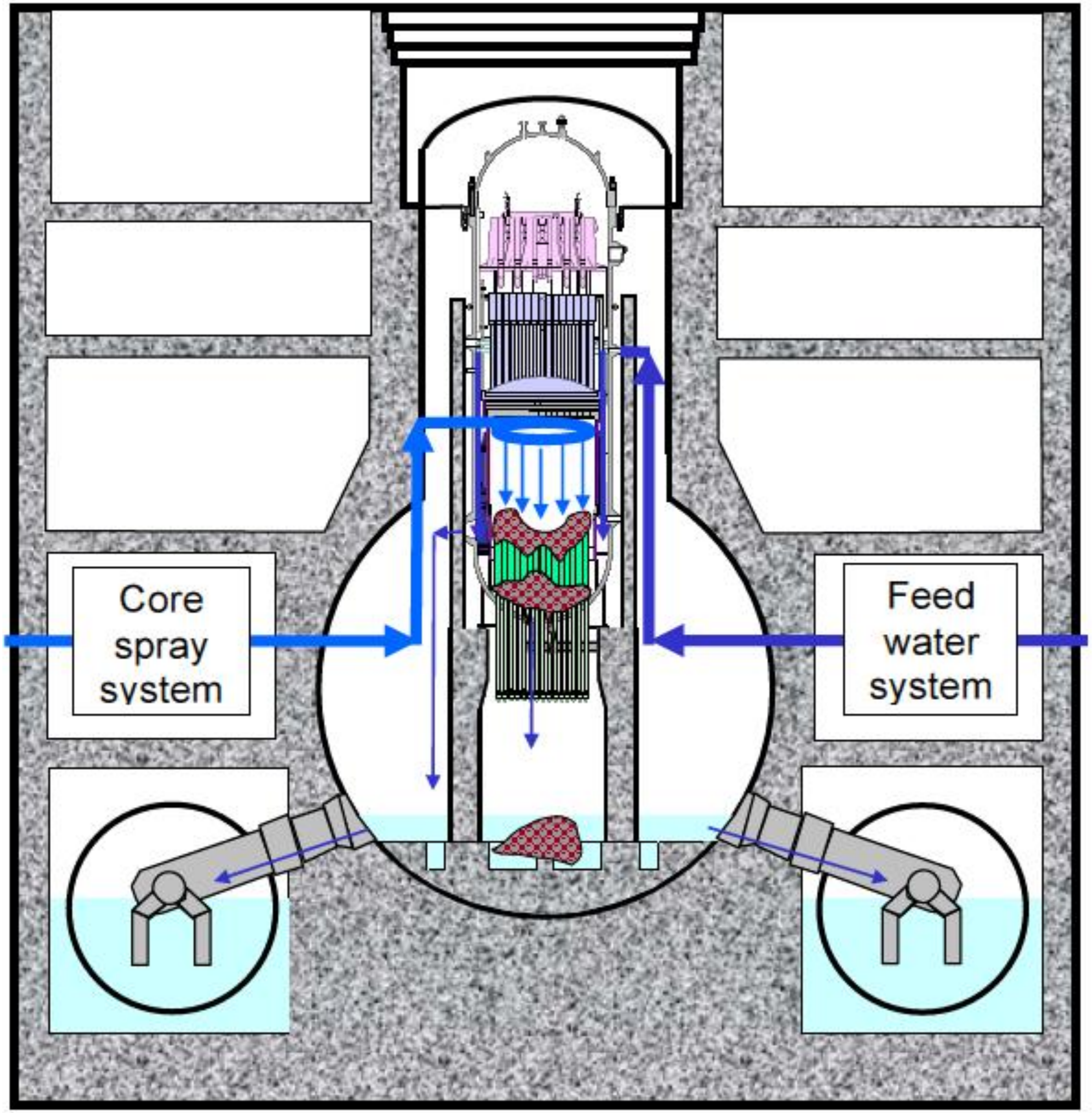


Unit 4



Source: TEPCO

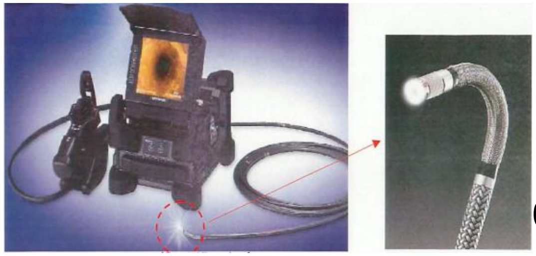
Summary of Core Damage in Unit 2



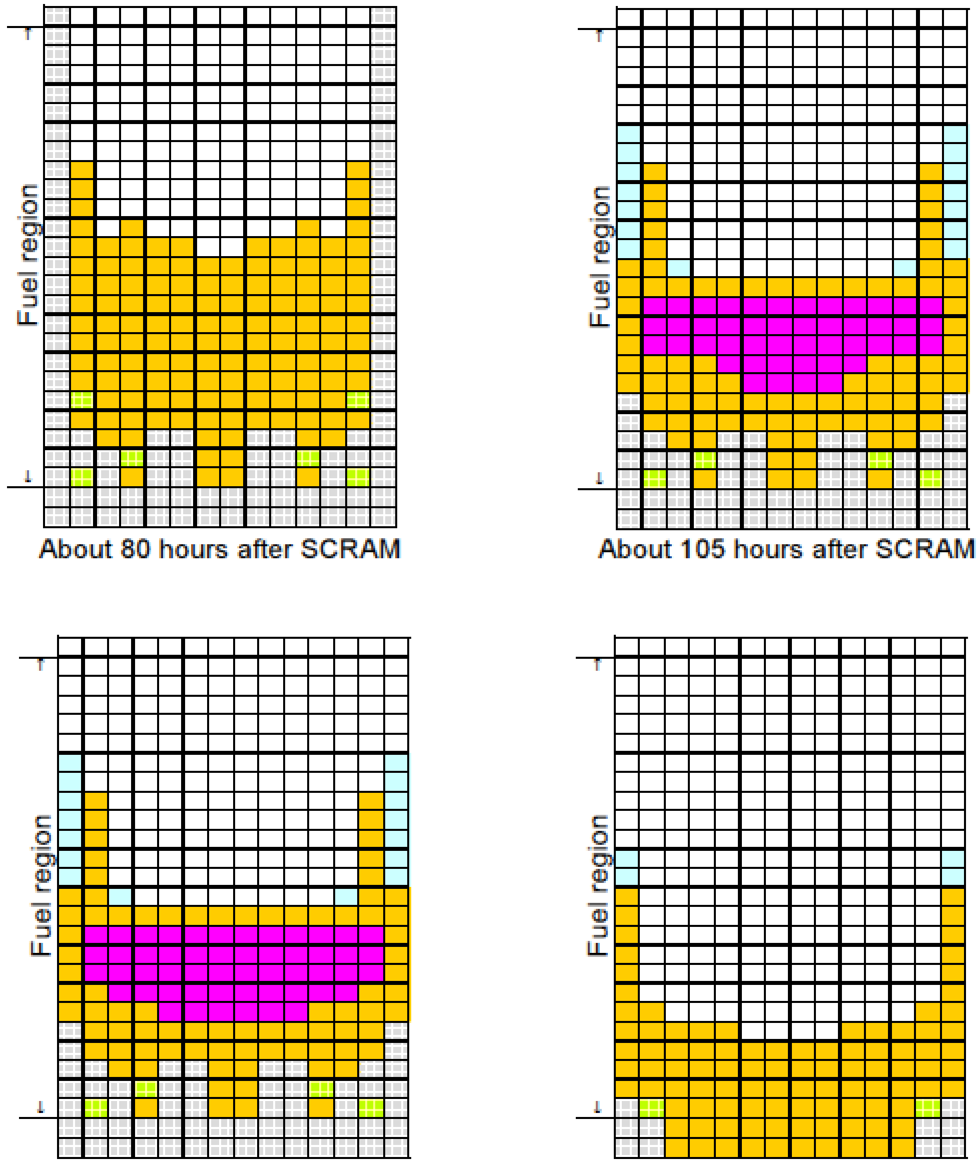
By investigations using an endoscope system, it was confirmed that:

- Water level in PCV is approx. 60 cm,
- Water temperature is approx. 50℃, and
- Dose rate of gas phase is 73 Sv/h.

<Industrial endoscope of 20m>



Estimated Core Damage in Unit 2
- Simulation Results by the MAAP code -



About 80 hours after SCRAM

About 105 hours after SCRAM

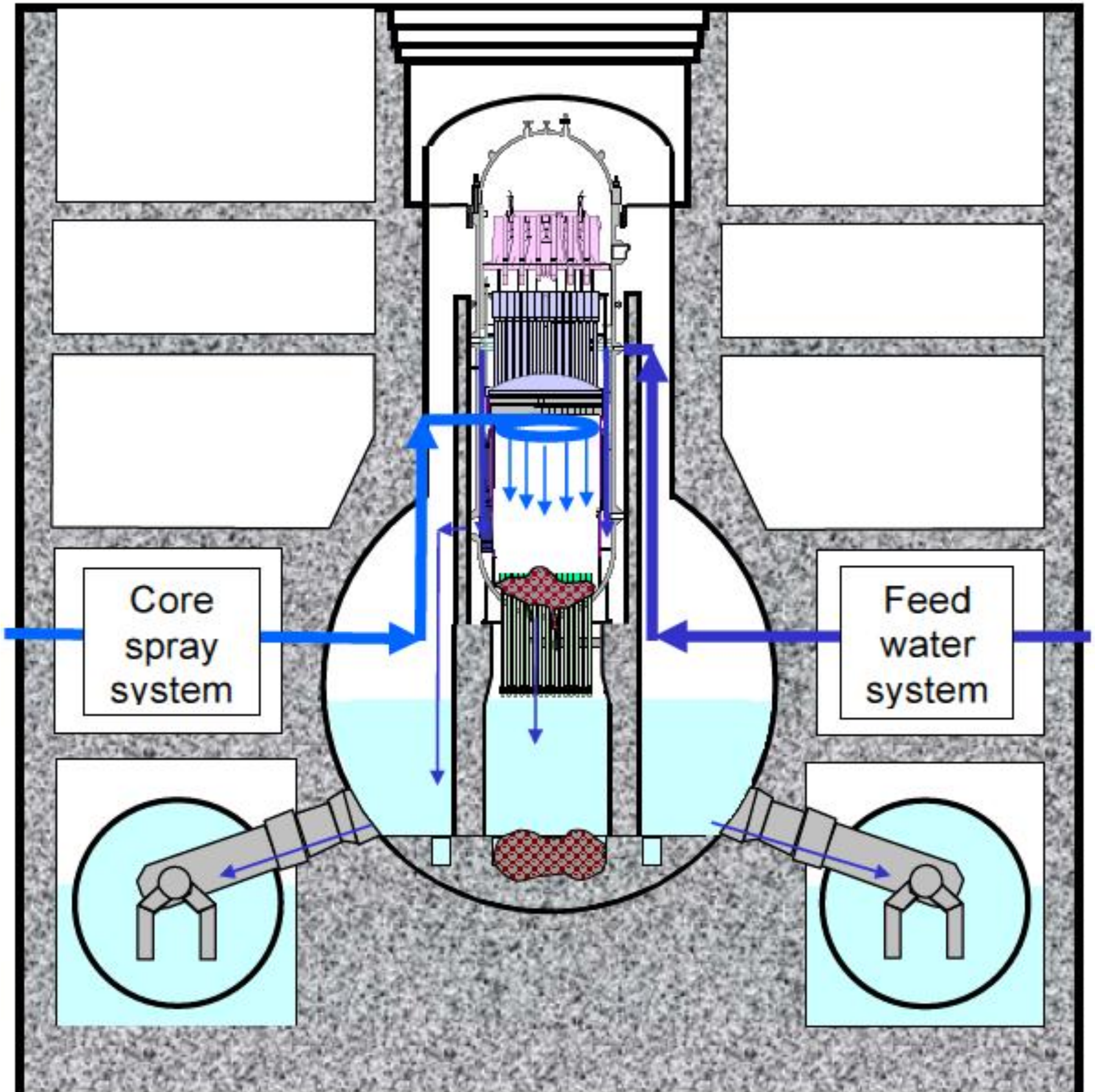
About 130 hours after SCRAM

About 155 hours after SCRAM

Degree of Fuel Damage

- Normal fuel
- Collapsed fuels piled up (Fuel rod shapes were kept)
- Fuel rod diameters increased due to molten fuel flowing down on their surfaces and solidifying there
- Fuel rod diameters further increased and blocked the downward flowing path
- Molten core pool formed
- Void (fuel melted down)

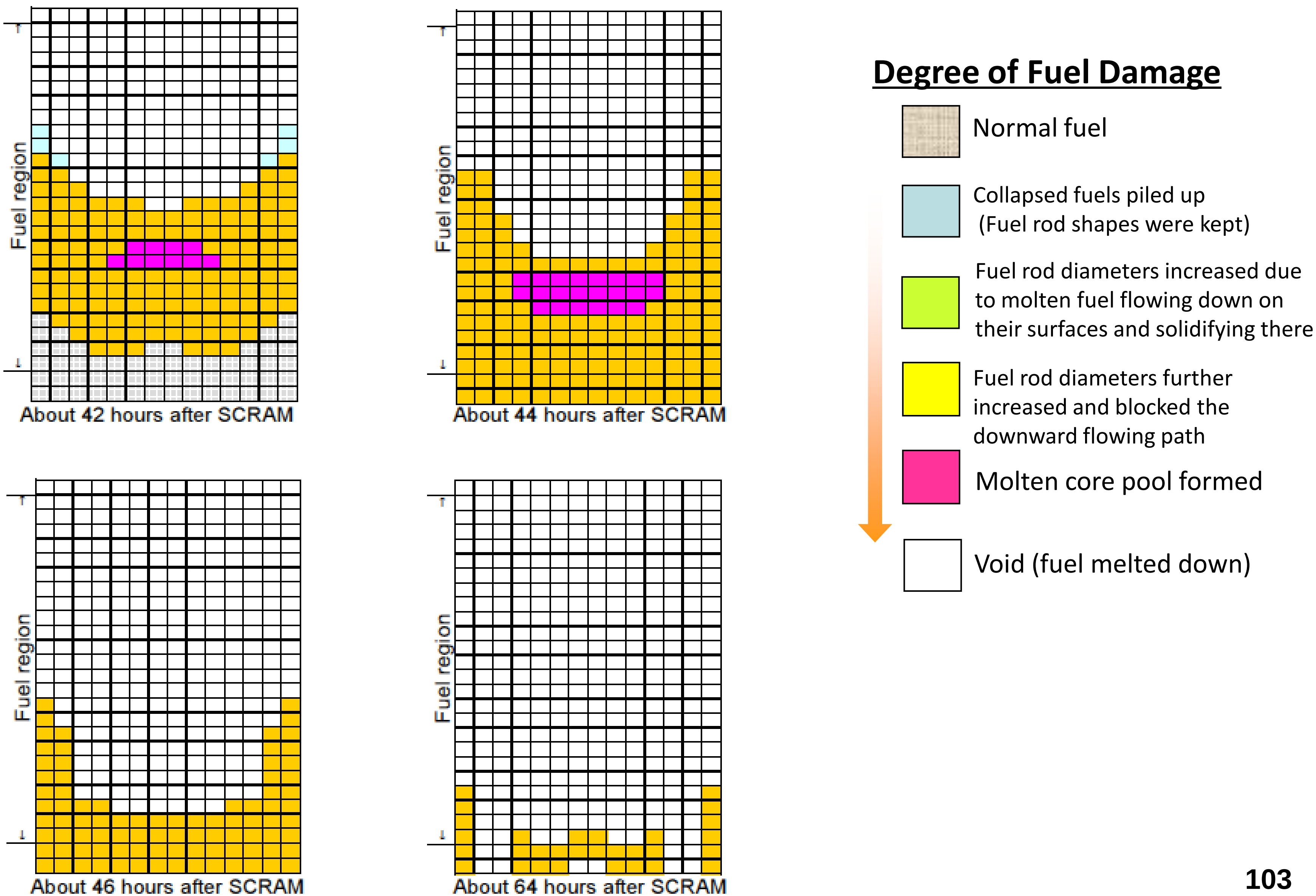
Summary of Core Damage in Unit 3



- It was possible to control the RCIC and HPCI and continue cooling, as batteries can be used.
- After RCIC stopped at 11:36 on March 12, HPCI started up automatically.
- At 20:00 on March 12, reactor pressure fell below HPCI design condition 1MPag to about 0.8 MPag.
  (No cooling water was injected into the reactor after that time.)
- Batteries ran out, and HPCI stopped by 2:42 on March 13.
- A hydrogen explosion occurred in the reactor building at 11:01 on March 14.

Estimated Core Damage in <u>Unit 3</u>

- Simulation Results by the MAAP code -



Radionuclides considered Important in the Reactor Safety Study Consequence Analysis (1)

3,200 MWth PWR case

Radionuclides	Half-life [days]	Shutdown inventory [MCi]
1) Noble gases		
^{85}Kr*	3950	0.56
^{85m}Kr*	0.183	24
^{87}Kr*	0.0528	47
^{88}Kr*	0.117	68
^{133}Xe	5.28	170
^{135}Xe	0.384	34
2) Halogens		
^{131}I	8.05	85
^{132}I	0.0958	120
^{133}I	0.875	170
^{134}I	0.0366	190
^{135}I	0.28	150
3) Alkali metals		
^{134}Cs	750	7.5
^{136}Cs	13	3
^{137}Cs	11000	4.7
^{86}Rb*	18.7	0.026
4) Tellurium group		
^{127}Te*	0.391	5.9
^{127m}Te	109	1.1
^{129}Te*	0.048	31
^{129m}Te	0.34	5.3
^{131m}Te	1.25	13
^{132}Te	3.25	120
^{127}Sb	3.88	6.1
^{129}Sb	0.179	33
5) Barium and strontium group		
^{89}Sr	52.1	94
^{90}Sr	11030	3.7
^{91}Sr	0.403	110
^{140}Ba	12.8	160

*** Indicates negligible contribution to health effects**

Radionuclides considered Important in the Reactor Safety Study Consequence Analysis (2)

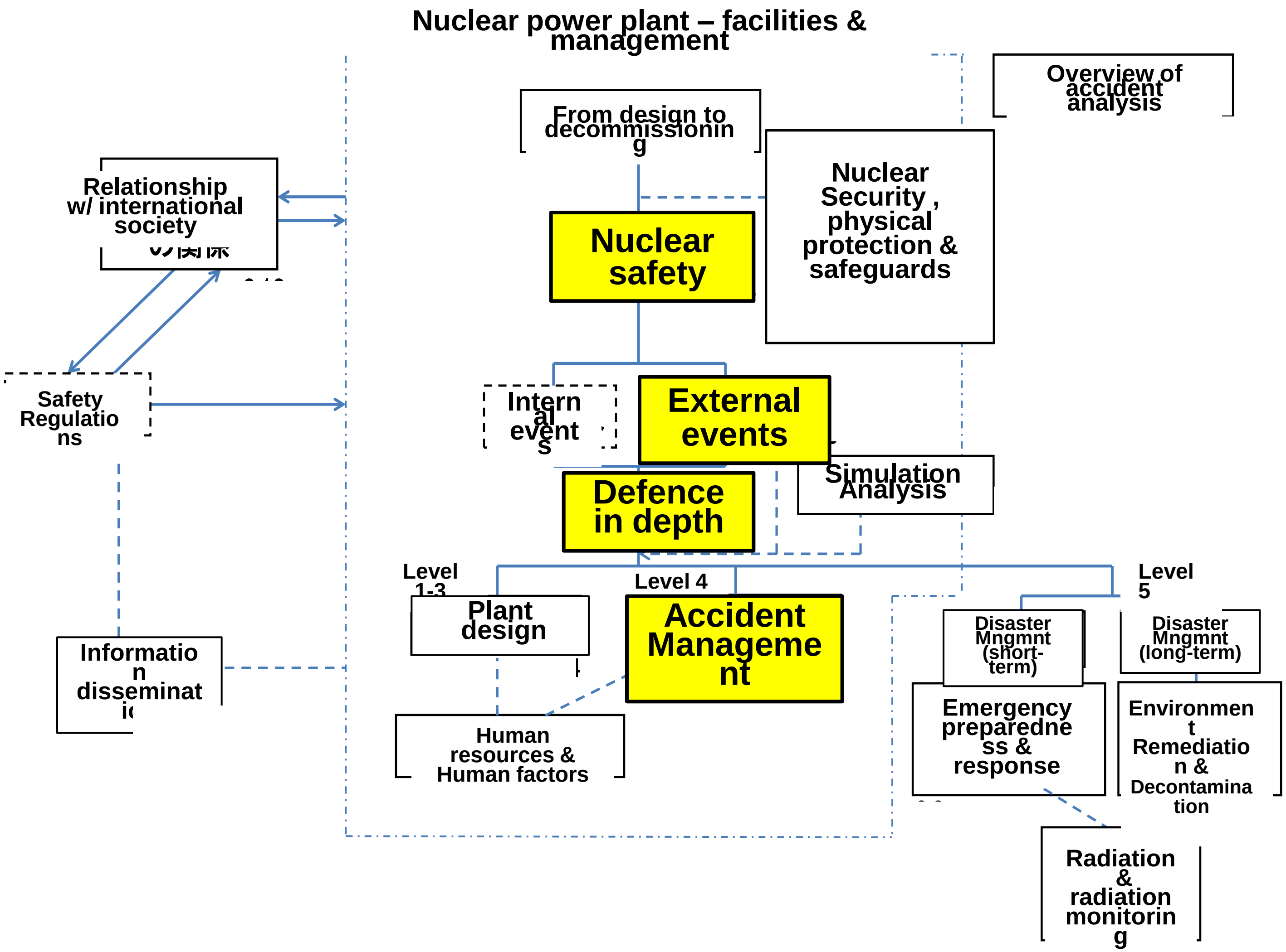
Radionuclides	Half-life [days]	Shutdown inventory [MCi]
6) Noble metals		
^{58}Co*	71	0.78
^{60}Co*	1920	0.29
^{99}Mo	2.8	160
^{99m}Tc*	0.25	140
^{103}Ru	39.5	110
^{105}Ru*	0.185	72
^{106}Ru	366	25
^{105}Rh*	1.5	49
7+8) Lanthanides and cerium group		
^{90}Y*	2.67	3.9
^{91}Y	59	120
^{95}Zr	65.2	150
^{97}Zr	0.71	150
^{95}Nb	35	150
^{140}La	1.67	160
^{141}Ce	32.3	150
^{143}Ce*	1.38	130
^{144}Ce	284	85
^{143}Pr	13.7	130
^{147}Nd*	11.1	60
^{239}Np	2.35	1640
^{238}Pu	32500	0.057
^{239}Pu	8.90E+06	0.021
^{240}Pu	2.40E+06	0.021
^{241}Pu	5350	3.4
^{241}Am*	1.50E+05	0.0017
^{242}Cm	163	0.5
^{244}Cm	6630	0.023

3,200 MWth PWR case

*** Indicates negligible contribution to health effects**

Overview of Chapter 6 in the AESJ Final Report

Chapter 6 focuses on analysis on the accident from various perspectives.



Additional Slides

New Safety Standards in Japan

< Previous Safety Standards>

Design Basis Standard
to prevent Severe Core Damage
(Only assuming single failure etc.)

- Consideration for Natural Events
- Consideration for Fire
- Consideration for Reliability
- Reliability of power source
- Performance of cooling equipment
- Performance of other equipment
- Tolerability for Earthquake & Tsunami

< New Safety Standards>

New (Countermeasures against Severe Accident):

- Preventing Large Scale Release
- Intentional Airplane Crash
- Preventing CV Failure
- Preventing Severe Core Damage (Assuming multiple malfunction)

Enhancement:

- Consideration for Natural Events
- Consideration for Fire
- Consideration for Reliability
- Reliability of power source
- Performance of cooling equipment
- Performance of other equipment

Enhancement:

- Tolerability for Earthquake & Tsunami

Enhancement of Design Basis Standard

Review Design Basis Standard completely,

"Design Basis Standard with No Severe Core Damage assumed"

① **Tornadoes and Bushfires included as Natural Events to be considered**

② **Enhancement of Fire Protection**

③ **Enhance Reliability of Components particularly important to the safety**
(Redundancy of Components with Long Time Demand)

④ **Enhancing external electricity supplies**
(Multiple Power Line Systems from Separate Substations)

⑤ **Physical Protection of Heat Removal System**
(Protection of Seawater Pumps)

Countermeasures against SA (Severe Core Damage)

Requirements for Countermeasures against Severe Core Damage assuming beyond the Design Basis Accidents.

① Countermeasures for Failure of Reactor Shutdown

② Countermeasures for Loss of Cooling Reactor (at high pressure)

③ Countermeasures for Loss of Depressurization

④ Countermeasures for Loss of Cooling Reactor (at low pressure)

⑤ Countermeasures for Loss of Ultimate Heat Sink (LUHS)

⑥ Securing Support Function (Make-up Water, Electricity Sources)

Countermeasures against SA (Containment Vessel Failure)

Requirements for Countermeasures against Containment Vessel Failure assuming Severe Core Damage.

① Countermeasures for Cooling, Depressurization and Radioactive Material Mitigation (CV Spray)

② Countermeasures for Cooing and Depressurization of CV (Filtered Venting system)

③ Countermeasures for Cooling Melted Core fallen to the Bottom of CV

④ Countermeasures against Hydrogen Explosions inside CV

⑤ Countermeasures against Hydrogen Explosions at the Reactor Building, etc.

⑥ Countermeasures for Cooling of Spent Fuel Storage Pools

Countermeasures against Extreme External Hazards

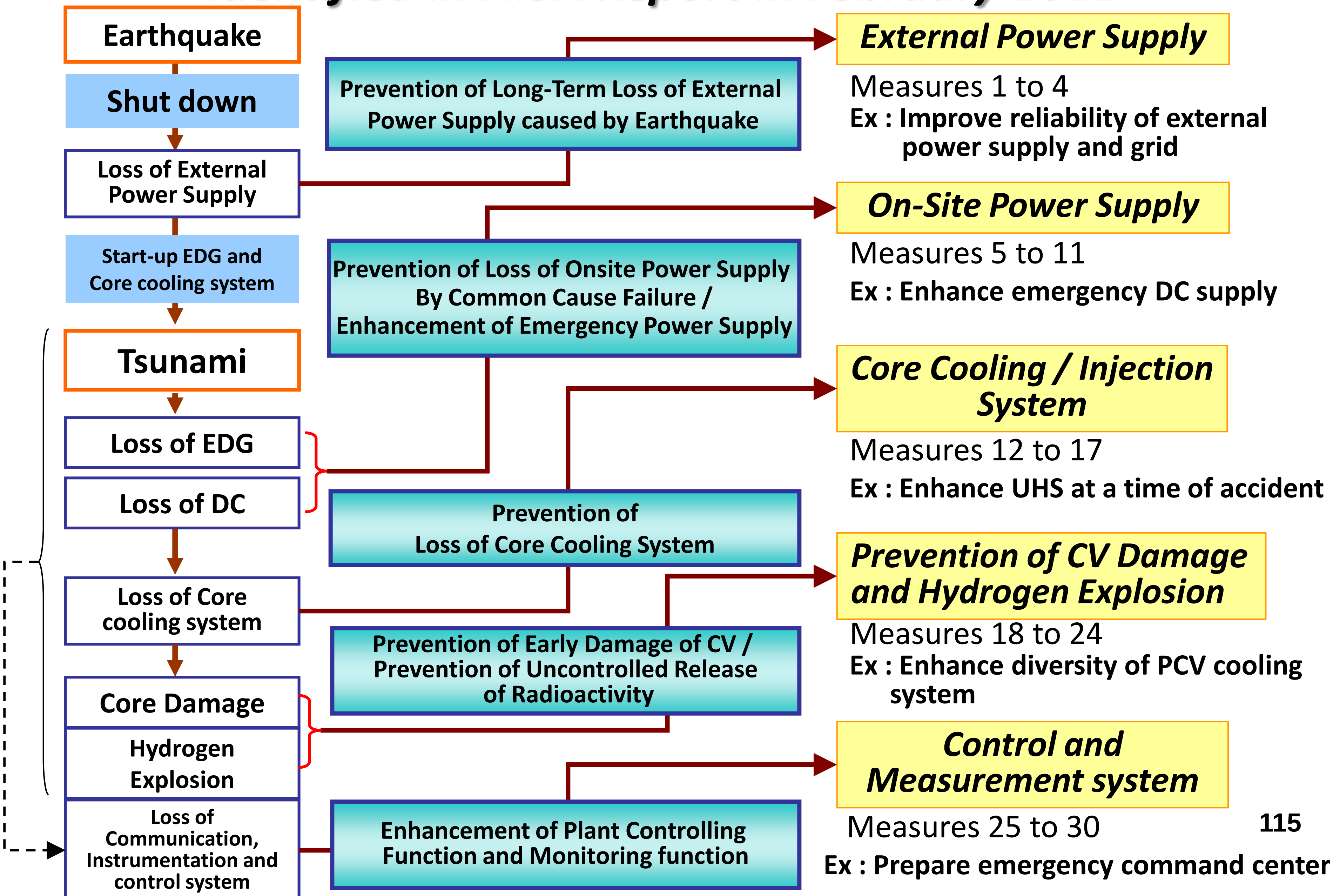
- **Flexible measures mainly by mobile facilities**
  - Against loss of large area of plant by various accidents, hazards, and attacks
  - To maintain/restore cooling function in PCV, CV, and SFP
  - Facilities stored safely against extreme external hazards
  - Electricity and water inlets available under loss of large area of plant

- **Hardened fixed facilities**
  - Against postulated external events beyond design basis with relatively high frequency
  - To improve reliability of countermeasures
  - To prevent large release of radioactive substances
  - Hardened facilities, e.g. water injection to CV spray and pedestal, filtered vent

Regulatory Requirements for Power Supply

- Fuel for emergency diesel generators should be stored in the for 7 days of continuous operation (to prepare possible loss of external power supply)
- Independent power supply as severe accident measure (in case of possible station black out)
- No core damage before the connection to independent power supply (as plant design criteria)
- DC power supply capability for 24 hours (as severe accident management criteria)
- Additional sets of DC power supply before 2020

30 Measures that Should Be Addressed to Regulation Identified in NISA Report in February 2012



Basic Policies for the New Regulatory Requirements

➢ **Establish requirements to prevent loss of safety functions due to common causes and progression of severe accidents**

Prevent simultaneous loss of all safety functions due to common causes (prevention of severe accidents)

(Insufficient measures before the Fukushima accident)

- **Strengthen measures against large-scale natural disasters**
  - Revise evaluation method for earthquakes and tsunamis
  - Introduce measures against tsunami inundation
  - Include volcanic eruptions, tornadoes, and forest fires into design consideration
- **Enhance durability against fires, internal flooding, and power failure, etc.**
  - Strict and thorough measures against fires
  - Introduce measures against internal flooding
  - Enhance the reliability of off-site power sources
  - Prepare redundant on-site power sources and switchboards and place them in diverse locations
  - Strengthen systems for monitoring and communication, etc.

Prepare equipment and procedures to deal with a severe accident

(Not required before the Fukushima accident)

- **Prevent core damage**
  - Strengthen measures to shut down reactors
  - Strengthen measures to reduce reactor pressure
  - Strengthen measures to inject water into reactors and remove heat
  - Strengthen measures to inject water into spent fuel pools
- **Maintain confinement integrity**
  - Strengthen measures to prevent containment vessels failure
  - Introduce measures to prevent hydrogen explosions at reactor buildings, etc.
- **Suppress radioactive materials dispersion**
  - Introduce measures to suppress radioactive materials dispersion
- **Ensure ~~the~~ support function for emergency response**
  - Prepare an emergency response center

(There are commonalities in measures to be taken.)

Prepare measures for terrorism and intentional aircraft crashes

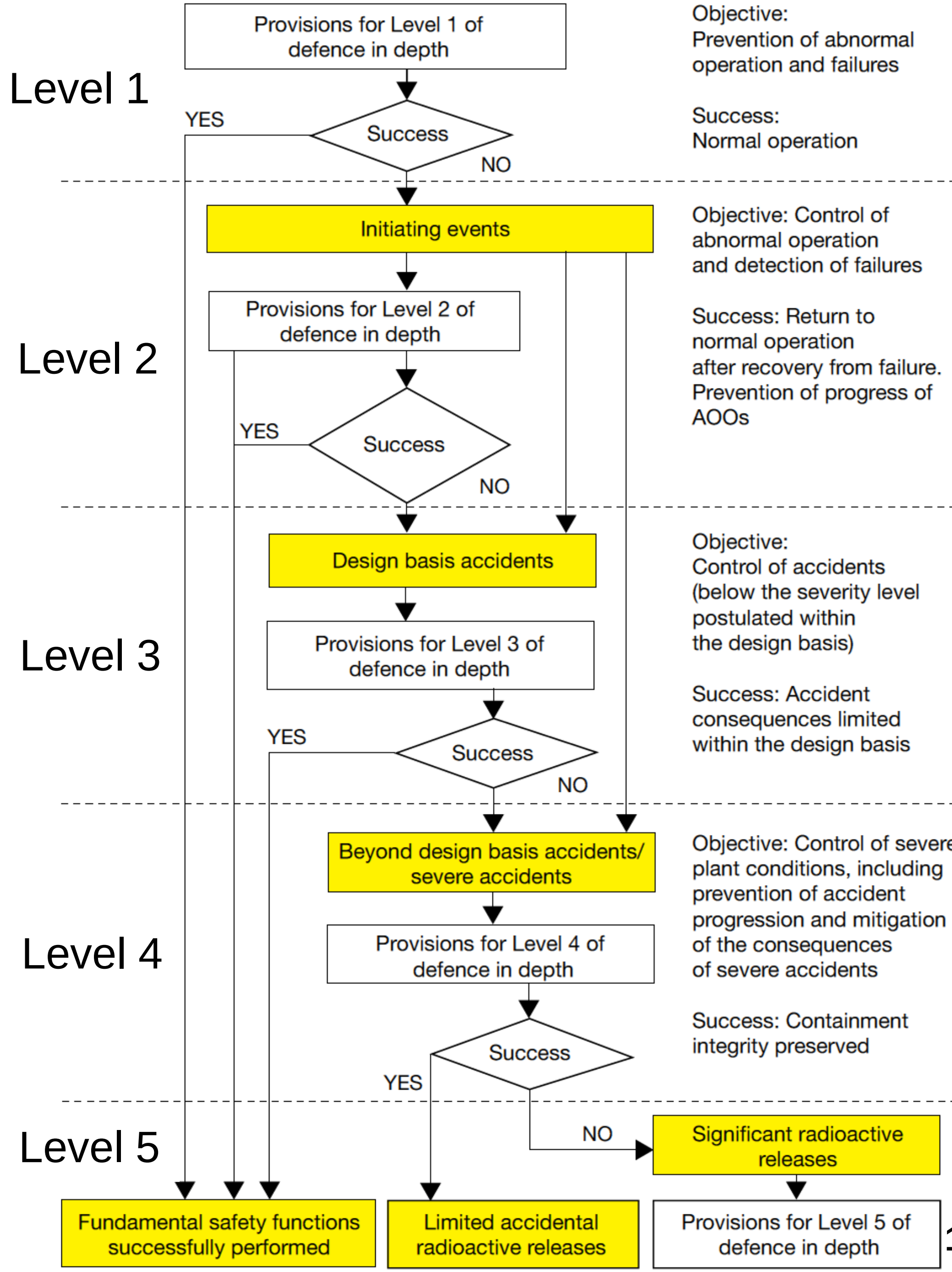
(Not required before the Fukushima accident .)

- **Prepare measures in the event of damage to equipment outside of reactor buildings**
  - Keep power units, etc. at a place 100m away from reactor facilities, and establish a permanent facility (a specialized safety facility) as a means to further enhance reliability

Flow chart for Defense-in-Depth

(IAEA INSAG definition)

- Success is defined for each level of defense -in-depth.
- If the provisions of a given level of defense fail to control the evolution of a sequence, the subsequent level will come into play.



Summary of Insights from Beyond Design Basis Considerations

Inadequate Consideration of Beyond Design Basis Accidents (BDBA)

Inadequate Assurance of Core Cooling Capability for BDBA Scenarios in the Design

- Failure to ensure core cooling in BDBA conditions
- Failure of plant indication in MCRs and ERCs

Inadequate Consideration of BDBA in Accident Management

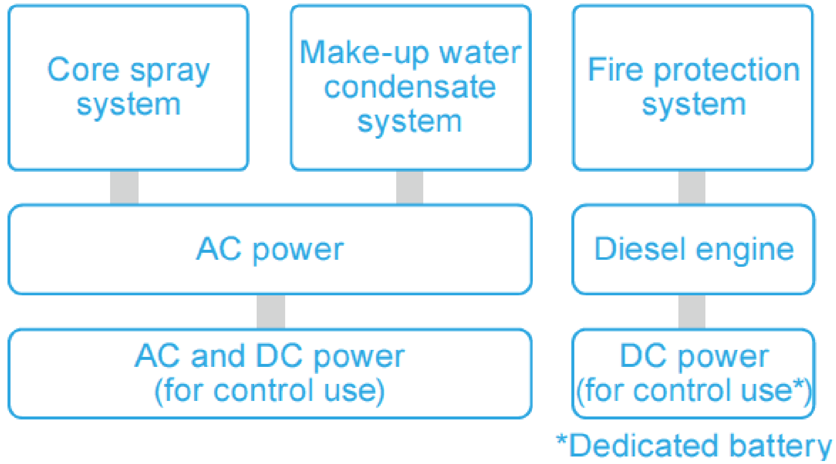
- BDBA documented guidance inadequate
- Insufficient classroom training, drills and exercises

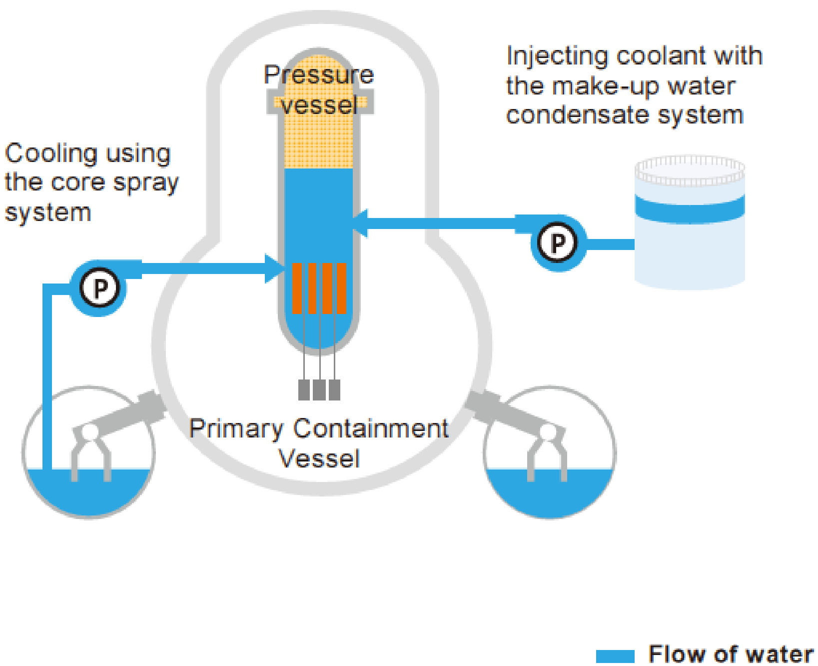
MCR : Main Control Room
ERC : Emergency Response Center

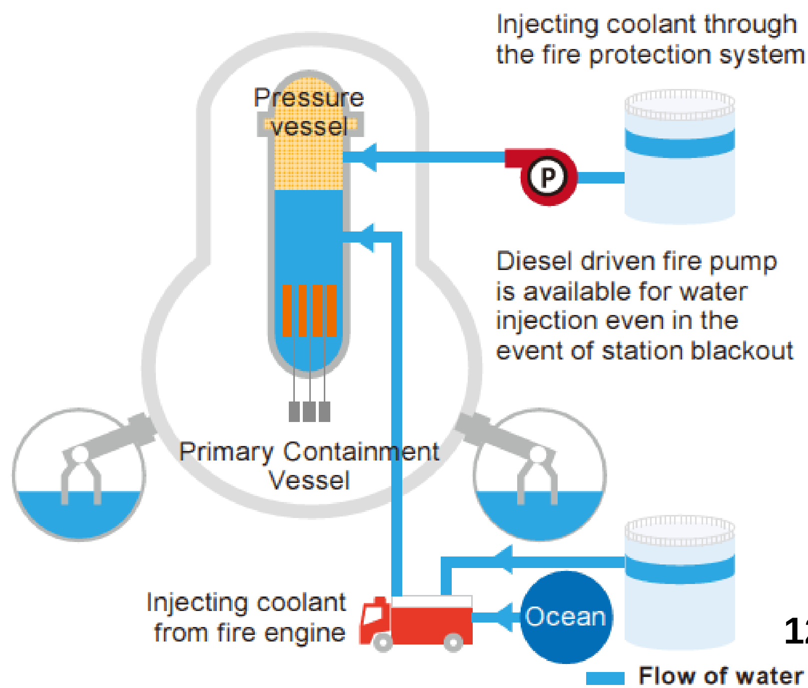

Visit to Fukushima Daiichi Site on April 9, 2012
Unit 4

Low Pressure Coolant Injection

- Introduce water to cool the reactor core and maintain water levels

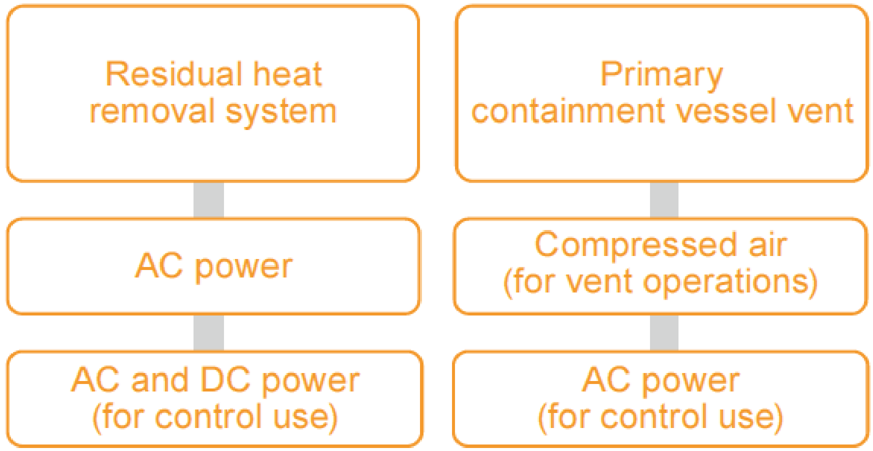


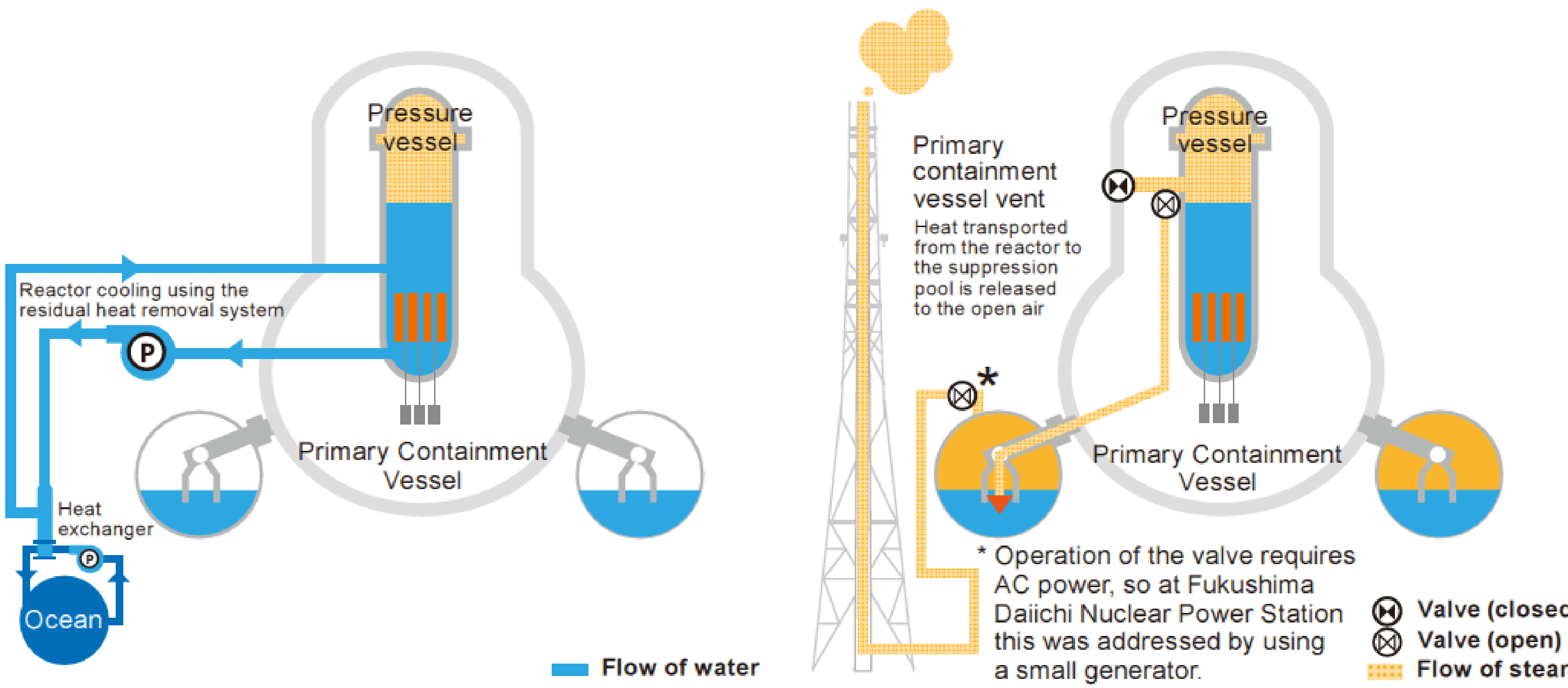




Heat Removal

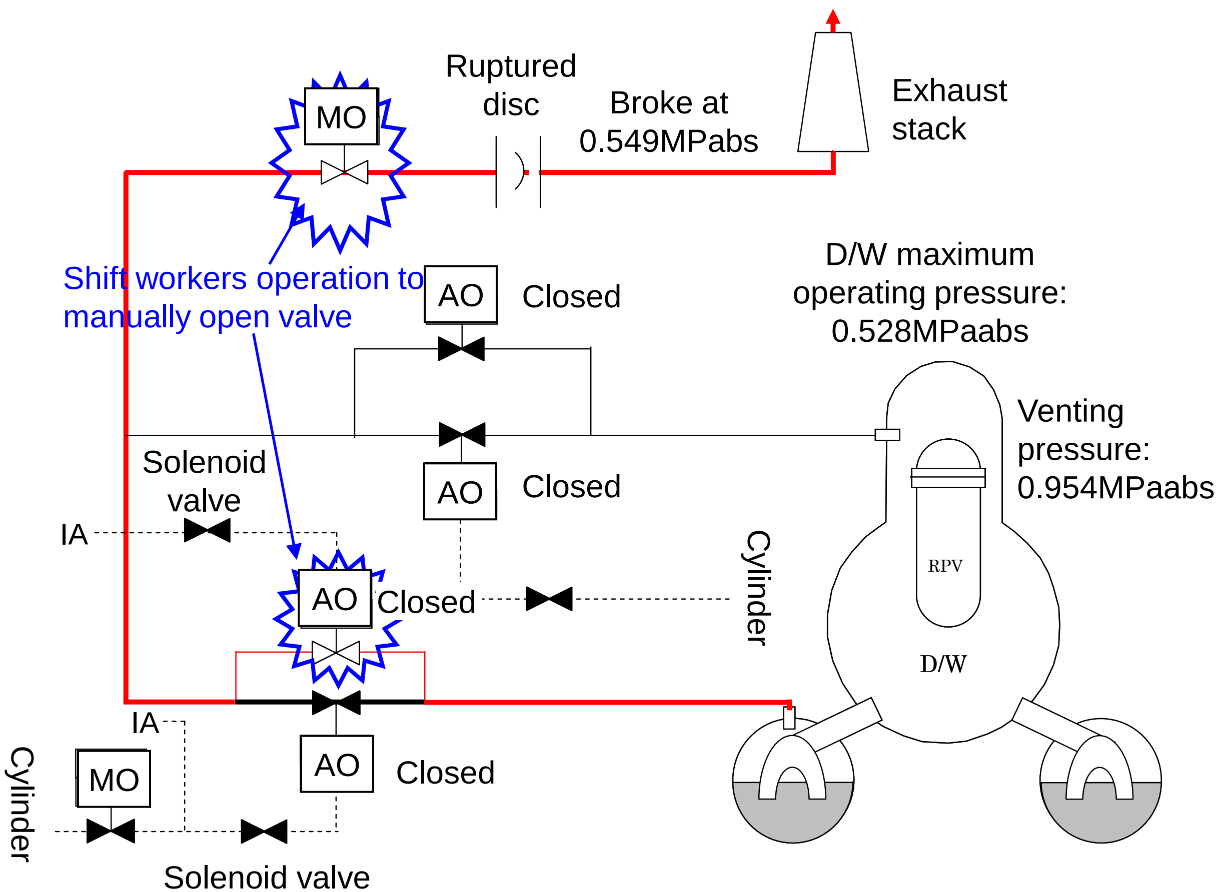
- Transfer the heat coming from the reactor core to water to release it outside





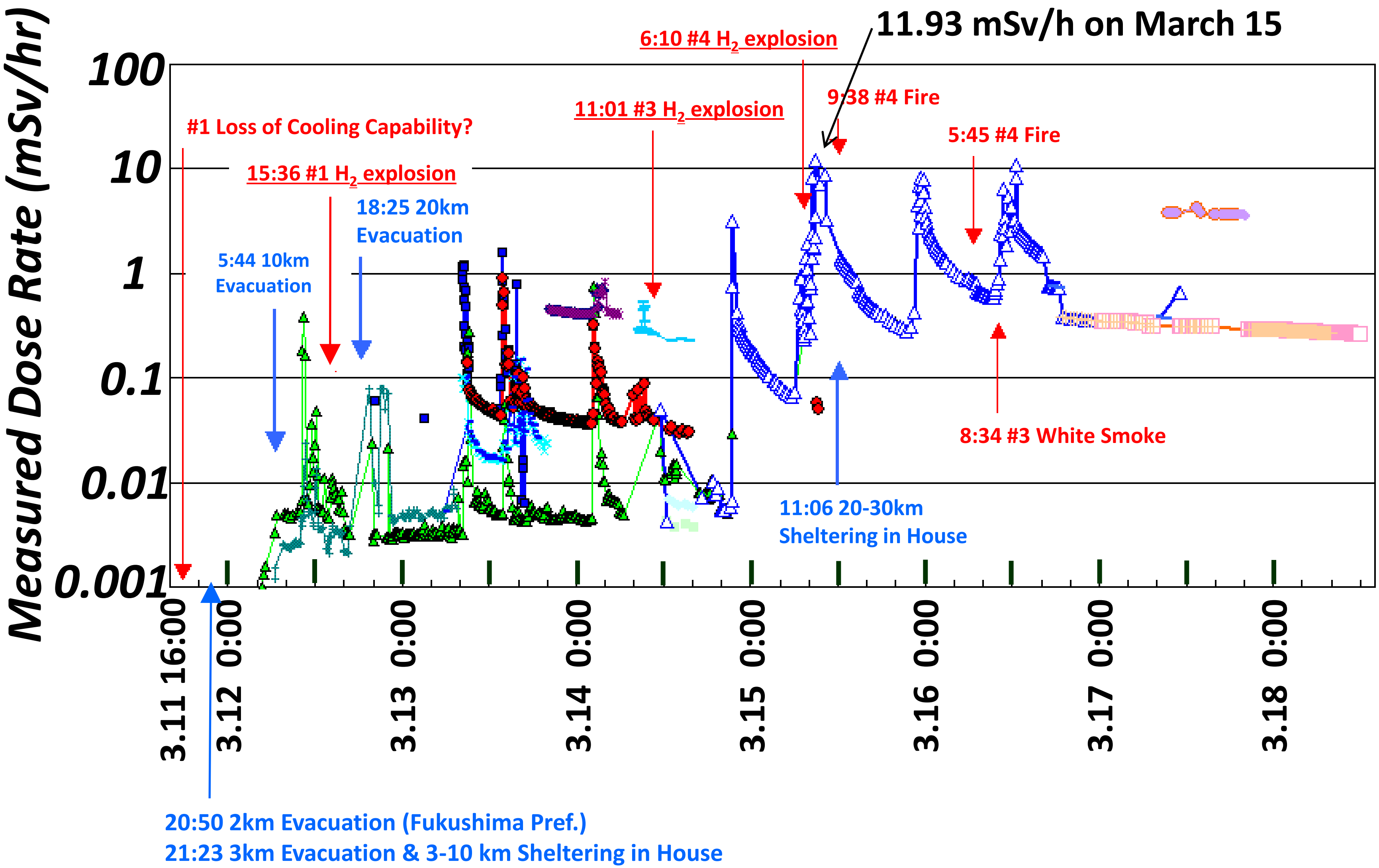
Primary Containment Vessel Venting Operation

No power source for the MO-valve	➡	Manual operation
No power source to the solenoid valve	➡	Engine driven generator
Low pressure to actuate the AO-valve	➡	Engine driven air compressor
High radiation level in R/B		



Self-contained breathing apparatus

On-site Radiation Monitoring in Fukushima Daiichi Site From March 11 to 18, 2011



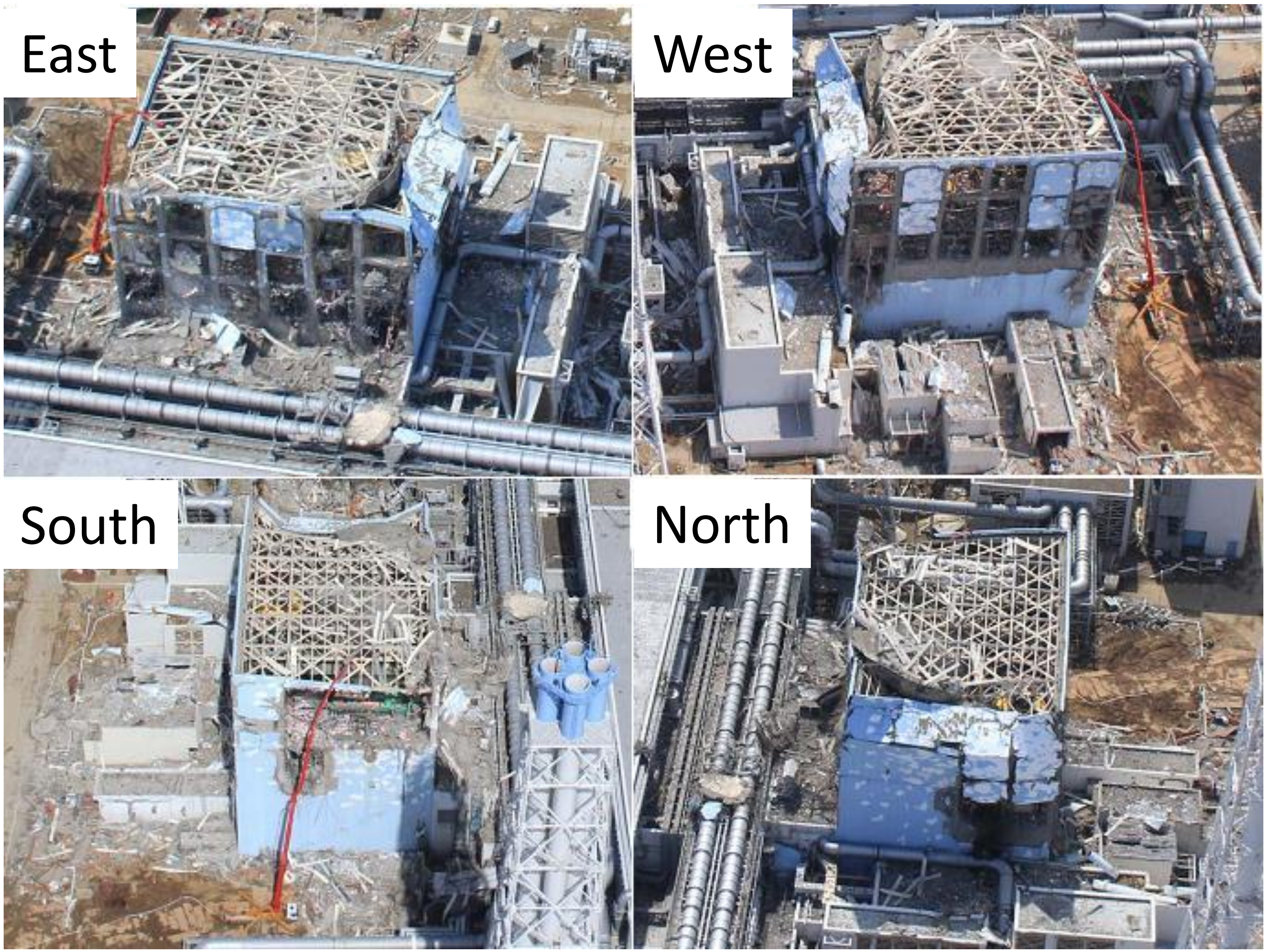
Fuel Assemblies in Reactor Core and Spent Fuel Pool

Unit	*1*	*2*	*3*	*4*	*5*	*6*
Number of Fuel Assembly in the Core	400	548	548*	-	548	764
Number of Spent Fuel Assembly in the SFP	292	587	514	1,331	946	876
Number of New Fuel Assembly in the SFP	100	28	52	204	48	64
Water Volume (m^3)	1,020	1,425	1,425	1,425	1,425	1,497
Heat Generation in Spent Fuel Pool (MW)	0.18	0.62	0.54	2.26	0.08	0.07

** including 32 MOX Fuel Assembly*

Hydrogen Explosion in Unit 4 on March 15

Possible mechanisms ; (1) Zr-H_2O reaction in the SFP, (2) H_2 from Unit 3,
(3) Decomposition of H_2O into H_2 and O_2 under radiation



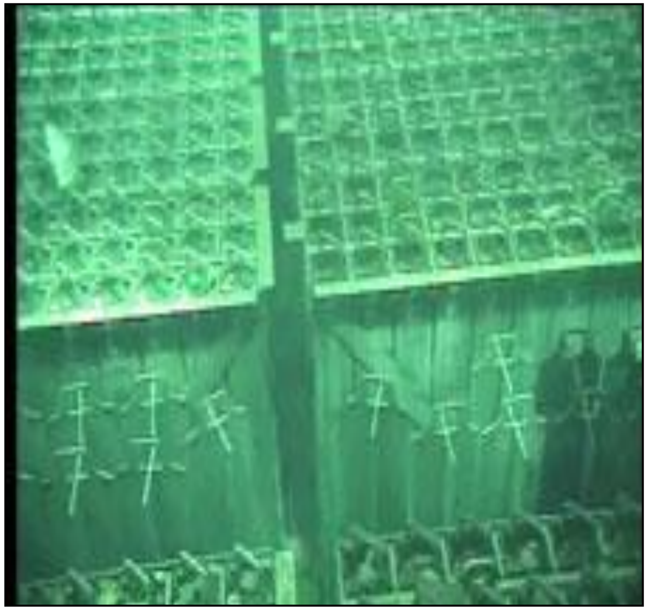
Unit 4 : Spent Fuel Pool

- ***No significant damage was identified by underwater camera inspection***
- ***Water sampling also shows relatively low radioactivity in SFP water***

Analysis result of water in the SFP of Unit 4 (Date of Collection April 12 and 28)

Detected Nuclides	Density (Bq/cm^3) on April 12	Density (Bq/cm^3) on April 28
Cesium 134	88	-
Cesium 137	93	55
Iodine 131	220	27

Source: TEPCO



Source: TEPCO

✗ (1) Zr-H_2O reaction in the SFP at high temperature

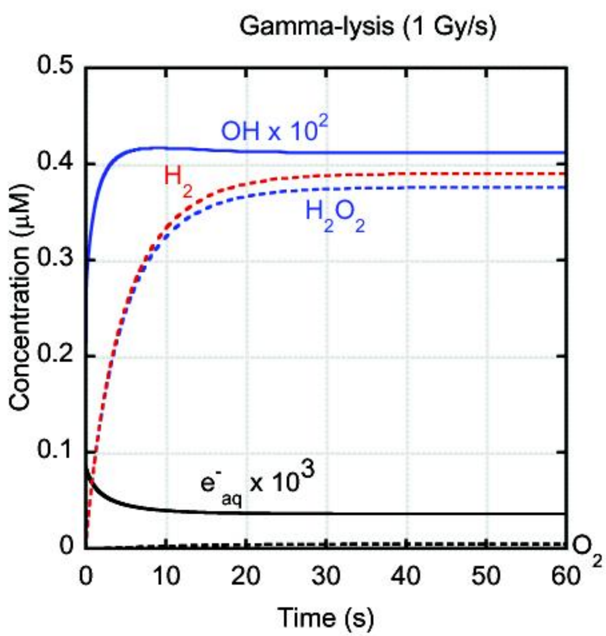
Experiments on High Concentration of Hydrogen Gas under Radiation at Boiling Temperature

G-values	$-H_2O$	e^-_{aq}	OH	H	H_2O_2	H_2	HO_2
Gamma-ray	4.1	2.7	2.8	0.56	0.68	0.45	~0.01
Alpha-ray	2.65	0.06	0.24	0.21	0.985	1.3	0.22

May 16, 2011

Prof. Katsumura Group

The University of Tokyo and JAEA

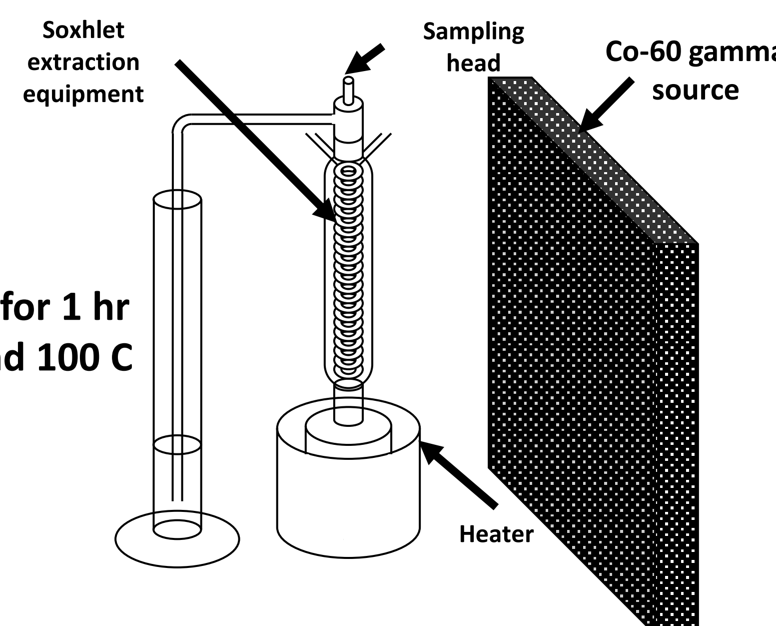


Typical BWR condition simulation of radiation chemistry reactions considering the reaction between H_2 and OH, resulting in steady state concentration of H_2.

New Finding by H_2 production under irradiation;

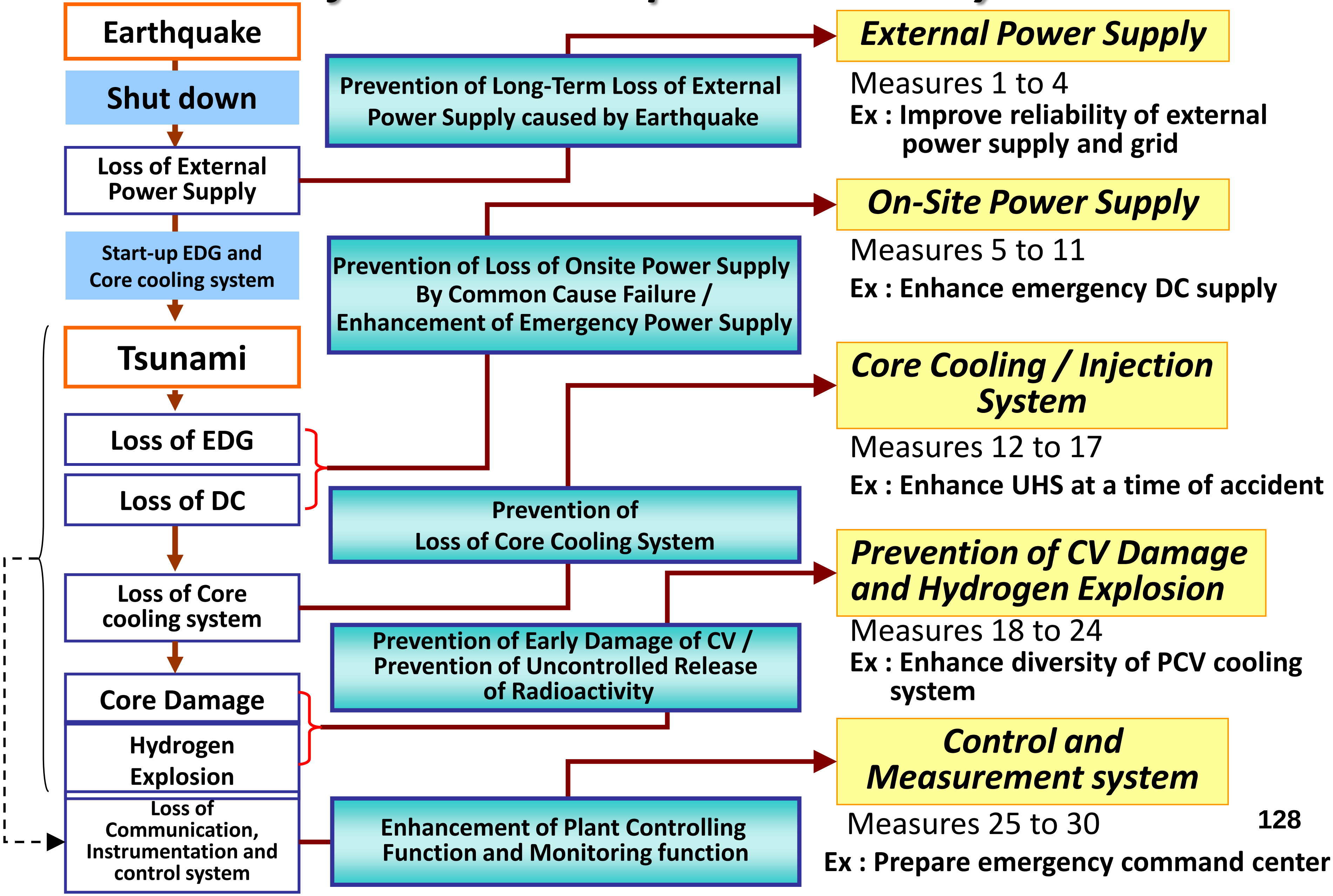
- ***Effective transfer of H_2 into gas phase at 100 C***
- ***High concentration of H_2 through condensation of H_2O at lower temperature region***

6.8 kGy/ h for 1 hr at 80, 97 and 100 C



Experimental Set-up at JAEA Takasaki

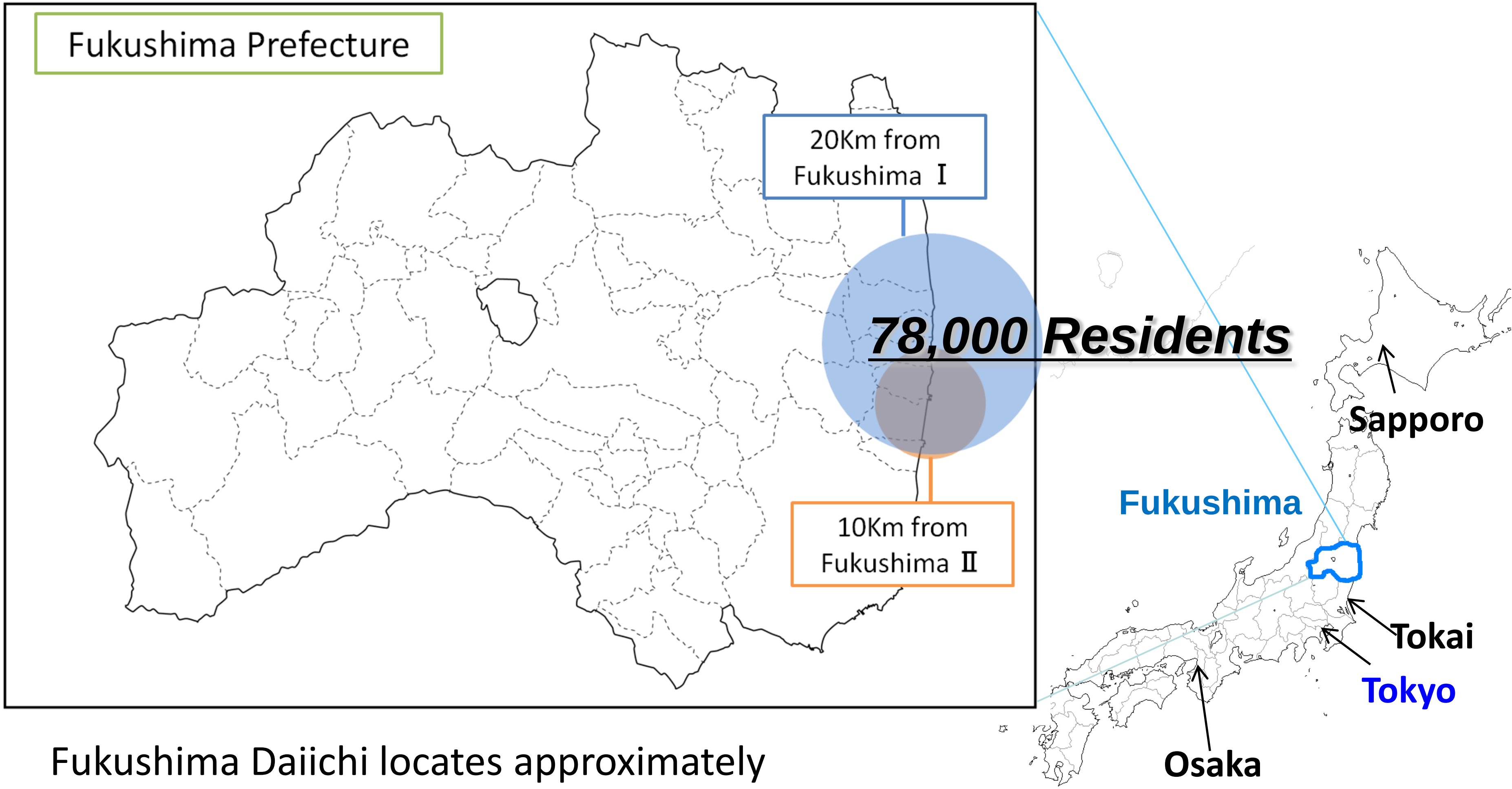
30 Measures that Should Be Addressed to Regulation Identified in NISA Report in February 2012



Lessons Learned Identified in Report to IAEA Ministerial Conference in June 2011

Enhancement of Preventive Measures against Severe Accidents	(1) Strengthening of measures against earthquake and tsunami (2) Ensuring power supplies (3) Ensuring robust cooling functions of reactors and PCVs (4) Ensuring robust cooling functions of spent fuel pools (5) Thorough accident management (AM) measures (6) Resolution of issues concerning multi unit site (7) Consideration of NPS layout in basic designs (8) Ensuring water tightness of essential equipment / facilities Source: Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html
Enhancement of Mitigation Measures of Severe Accidents	(9) Enhancement of measures to prevent hydrogen explosion (10) Enhancement of containment venting system (11) Improvement of environment / habitability for emergency response (12) Enhancement of radiation protection management system in case of accident (13) Enhancement of training responding to severe accidents (14) Enhancement of instrumentation for reactors, PCVs, ctc. (15) Implementation of centralized control of equipment for emergency and rescue team
Enhancement of Nuclear Emergency Responses	(16) Response to combined emergencies of natural disasters and prolonged nuclear accident (17) Enhancement of environmental monitoring (18) Clarification of roles and responsibilities of central and local organizations (19) Enhancement of communication in case of accident (20) Enhancement of response to assistance from overseas and information supply to international community (21) Adequate understanding and prediction of consequences of radioactive releases (22) Clarification of standards for evacuation in wide areas and radiation protection in case of emergency
Reinforcement of Safety Infrastructure	(23) Enhancement of framework for safety regulation (24) Enhancement / implementation of legal framework and regulatory guides and standards (25) Human resources for nuclear safety and nuclear emergency preparedness and response (26) Ensuring independence and diversity of safety systems (27) Effective use of probabilistic safety assessment (PSA) in risk management
Safety Culture	(28) Strong initiative to foster safety culture

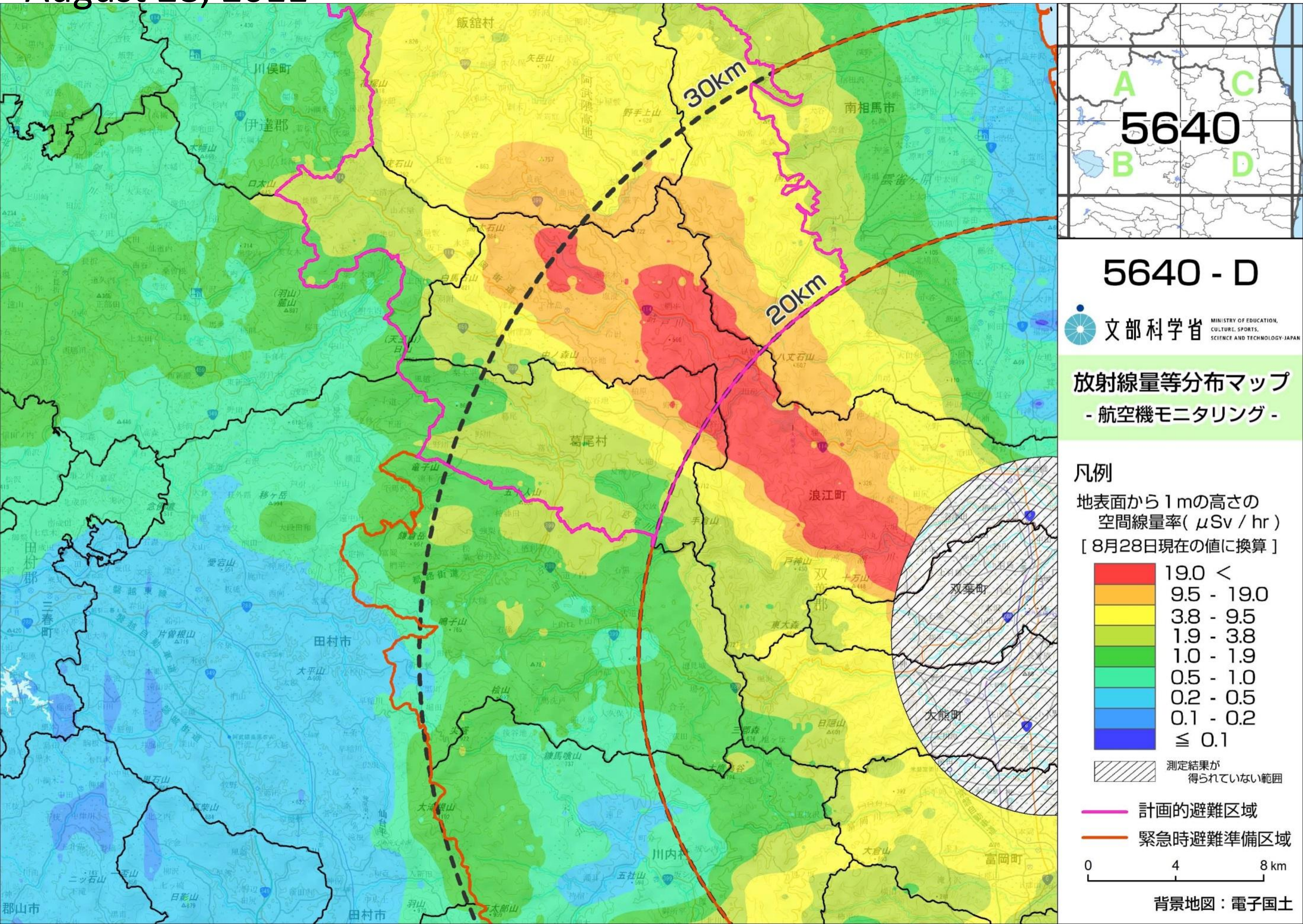
Evacuation of Residents



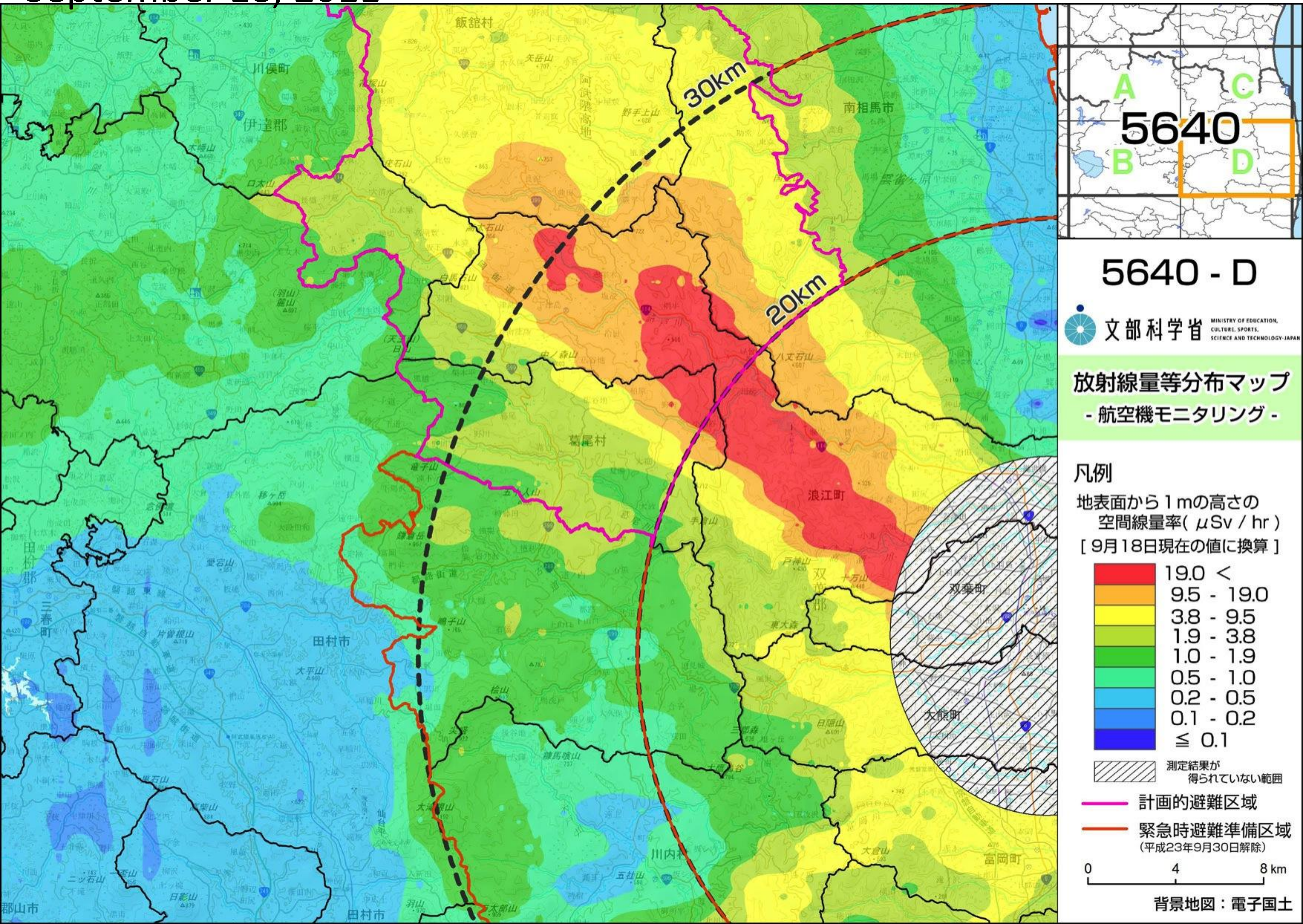
Fukushima Daiichi locates approximately

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

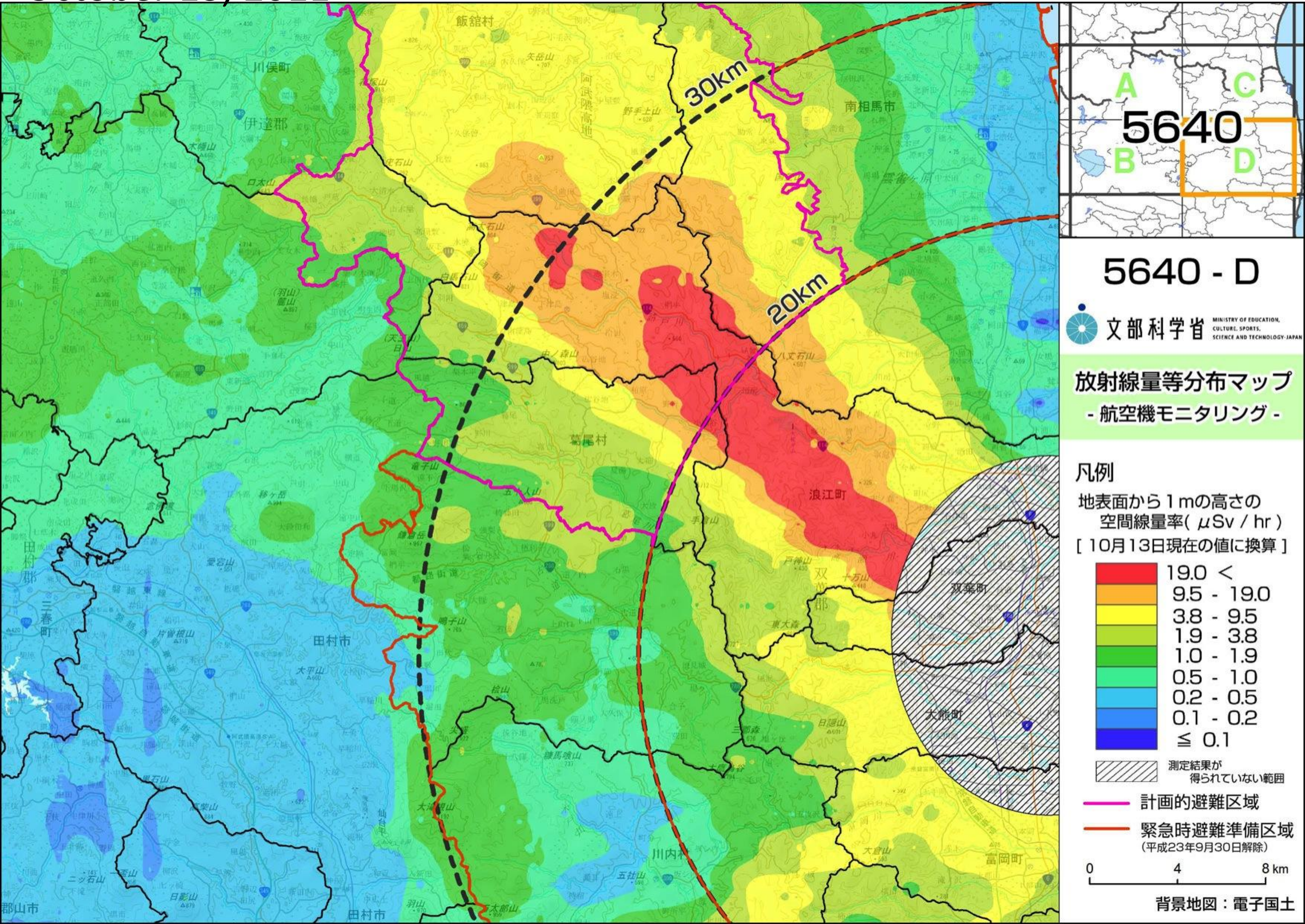
August 28, 2011



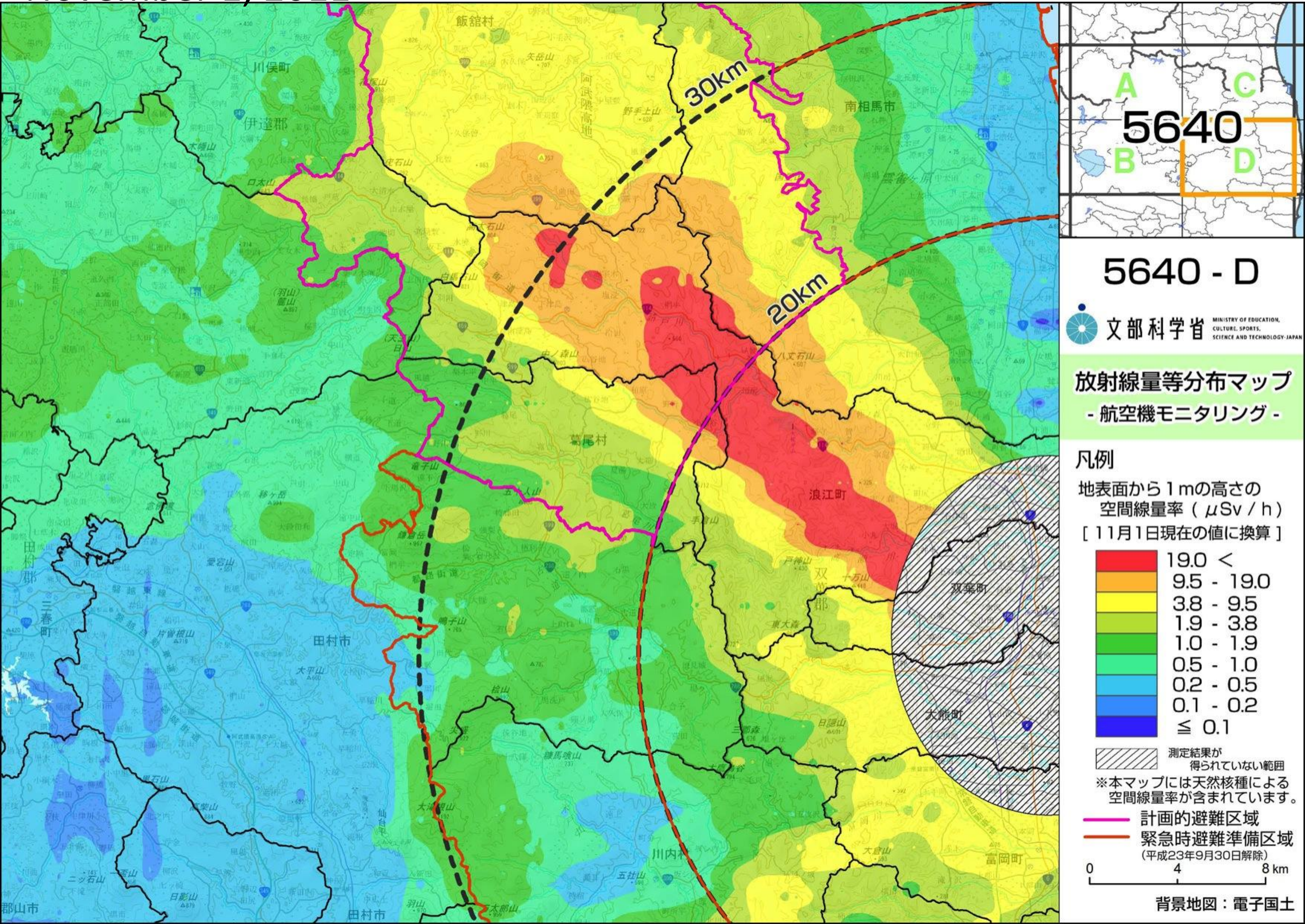
September 18, 2011



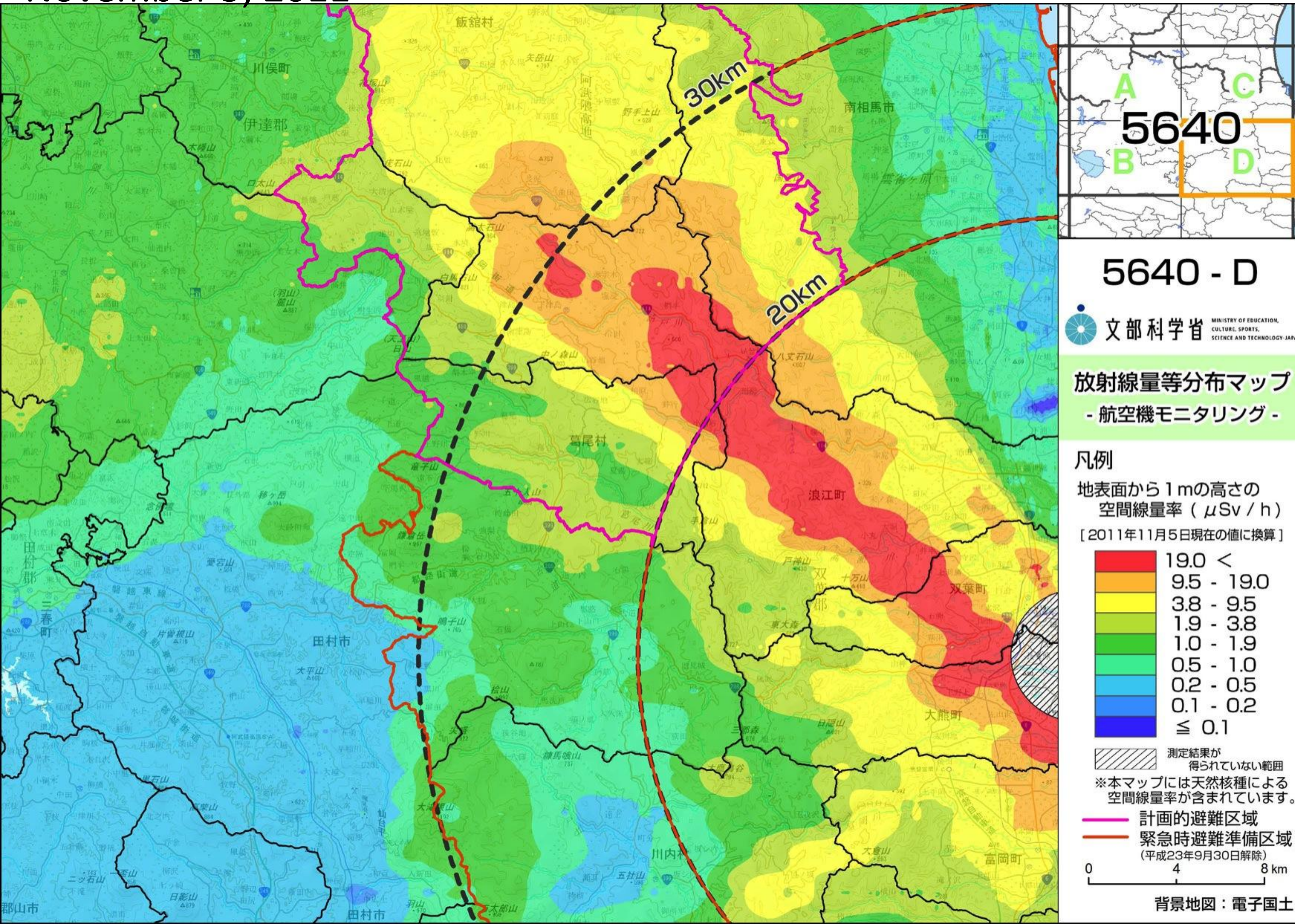
October 13, 2011



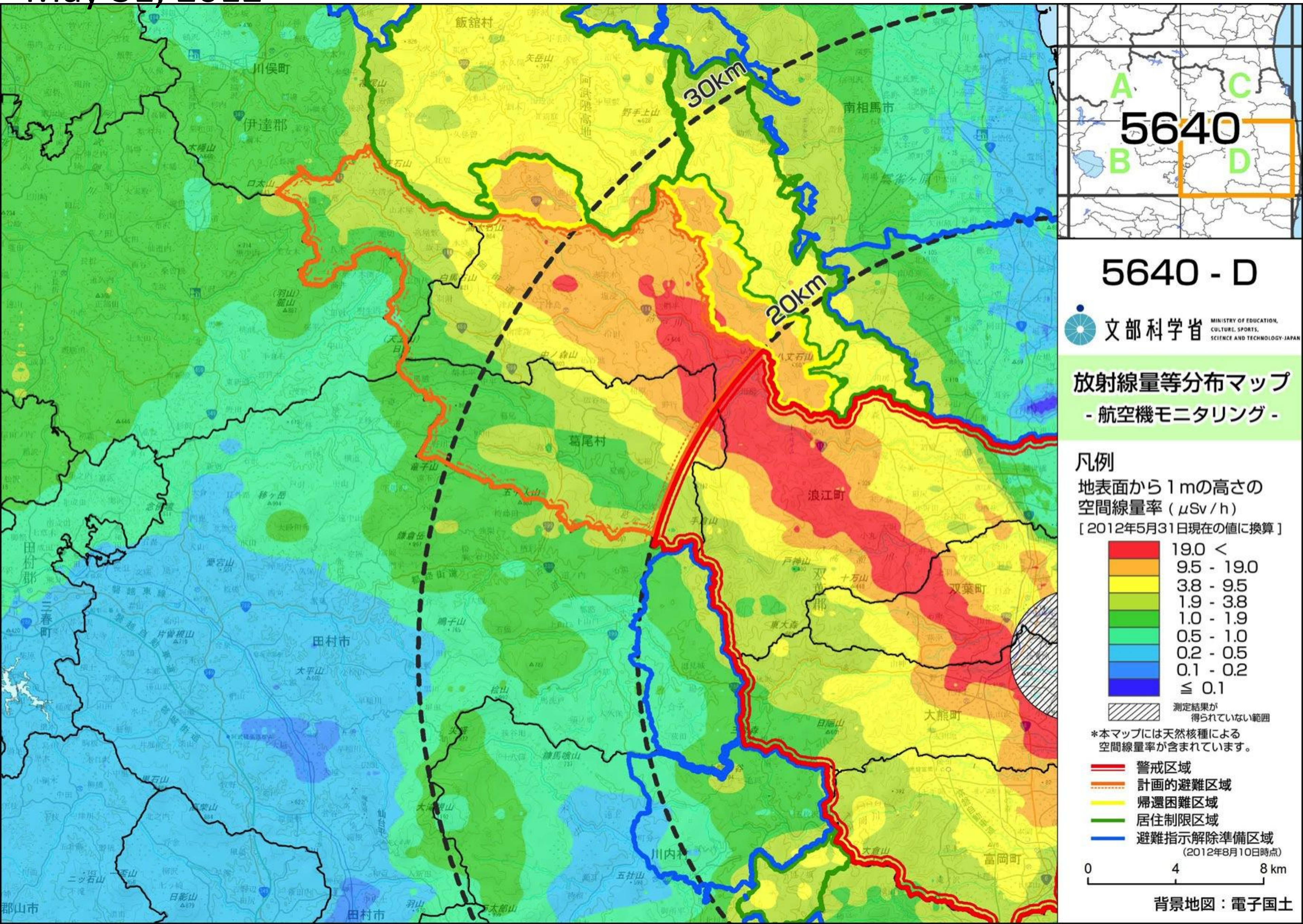
November 1, 2011



November 5, 2011

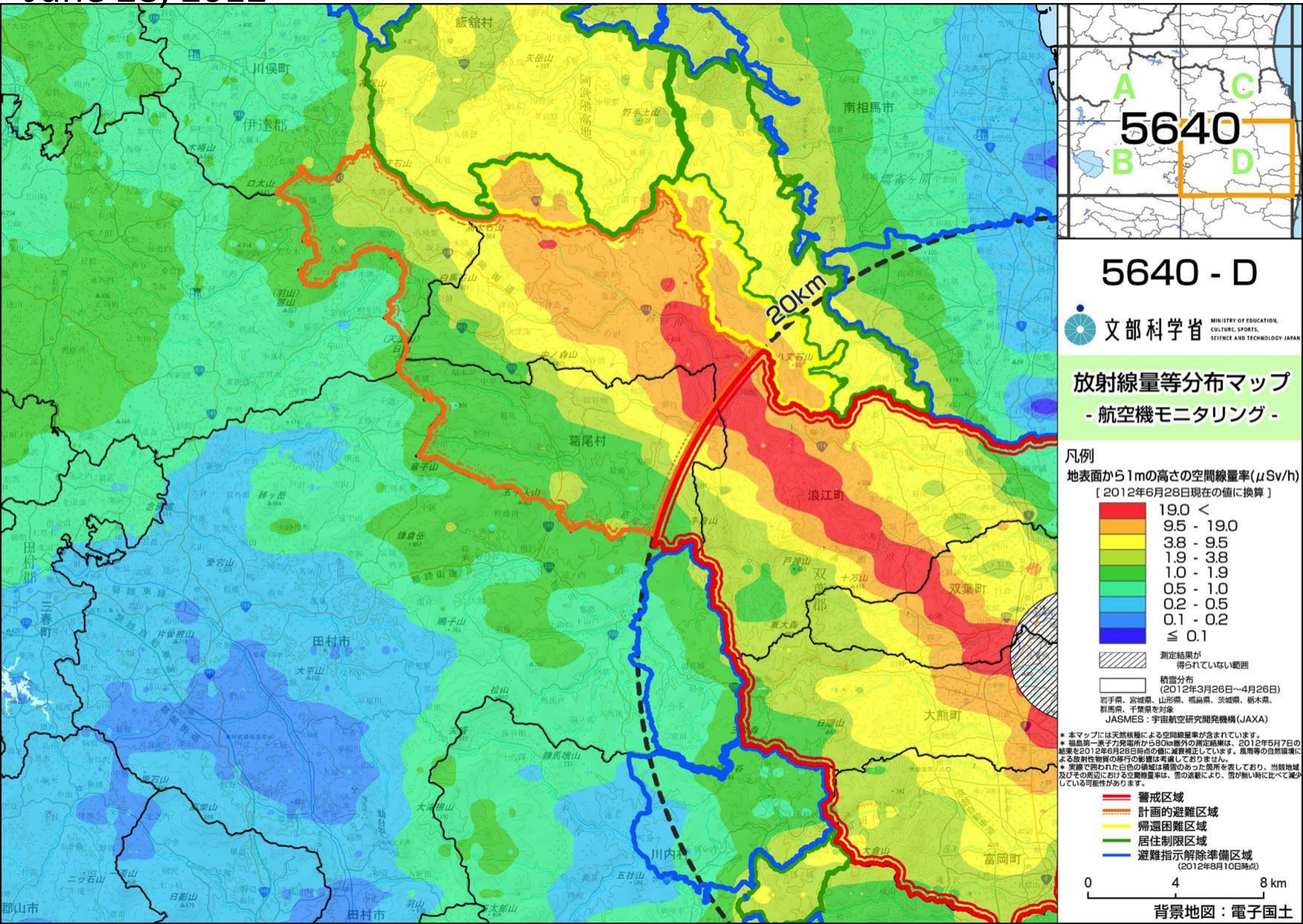


May 31, 2012



5640
A
B
C
D
5640 - D
文部科学省
MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN
放射線量等分布マップ
- 航空機モニタリング -
凡例
地表面から１ｍの高さの
空間線量率（μSv/h）
［2012年5月31日現在の値に換算］
19.0 <
9.5 - 19.0
3.8 - 9.5
1.9 - 3.8
1.0 - 1.9
0.5 - 1.0
0.2 - 0.5
0.1 - 0.2
≦ 0.1
測定結果が
得られていない範囲
*本マップには天然核種による
空間線量率が含まれています。
警戒区域
計画的避難区域
帰還困難区域
居住制限区域
避難指示解除準備区域
(2012年8月10日時点)
0
4
8 km
背景地図：電子国土
30km
20km
飯舘村
南相馬市
川俣町
伊達郡
葛尾村
浪江町
双葉町
大熊町
富岡町
田村市
川内村
郡山市

June 28, 2012



5640
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B
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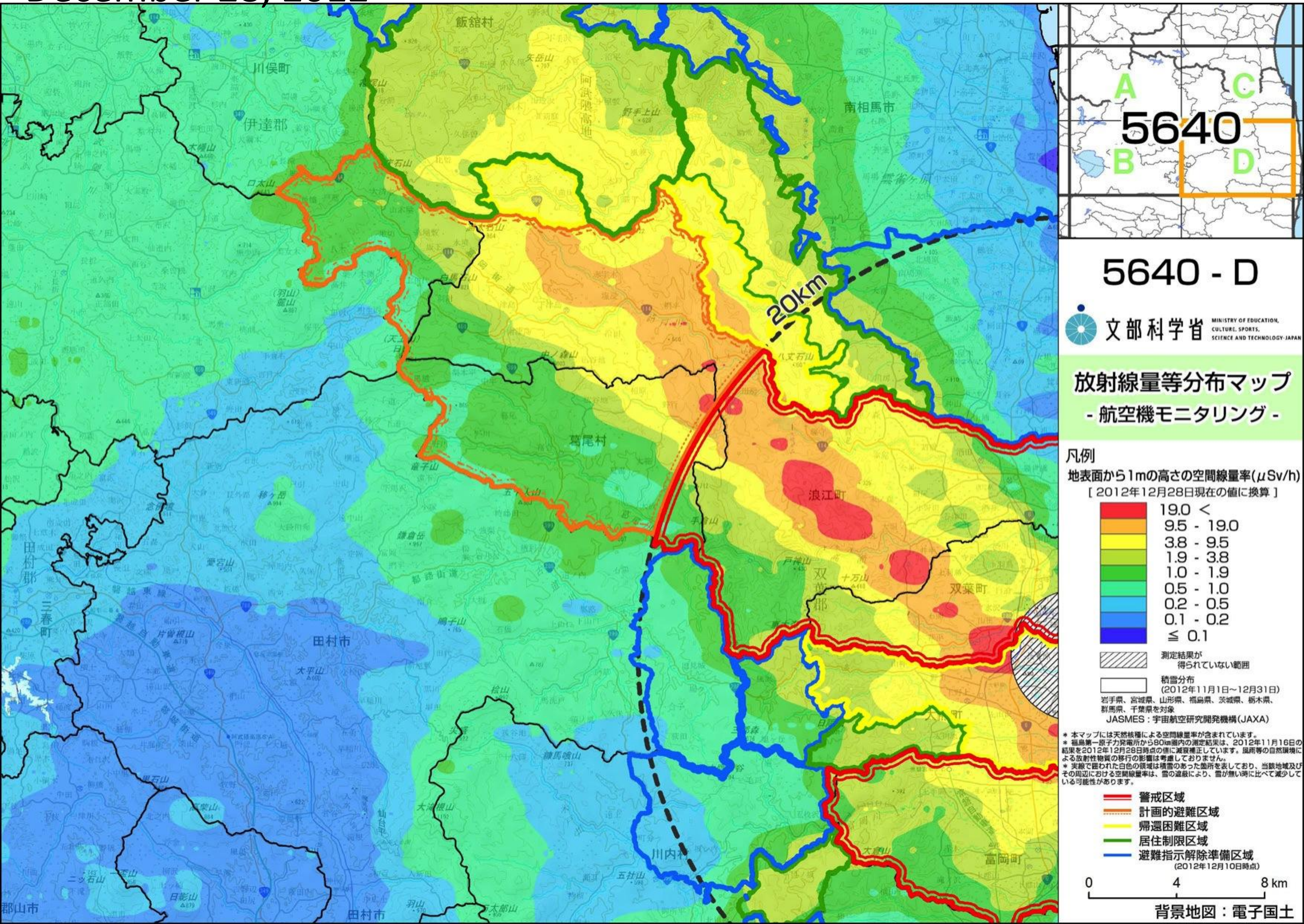
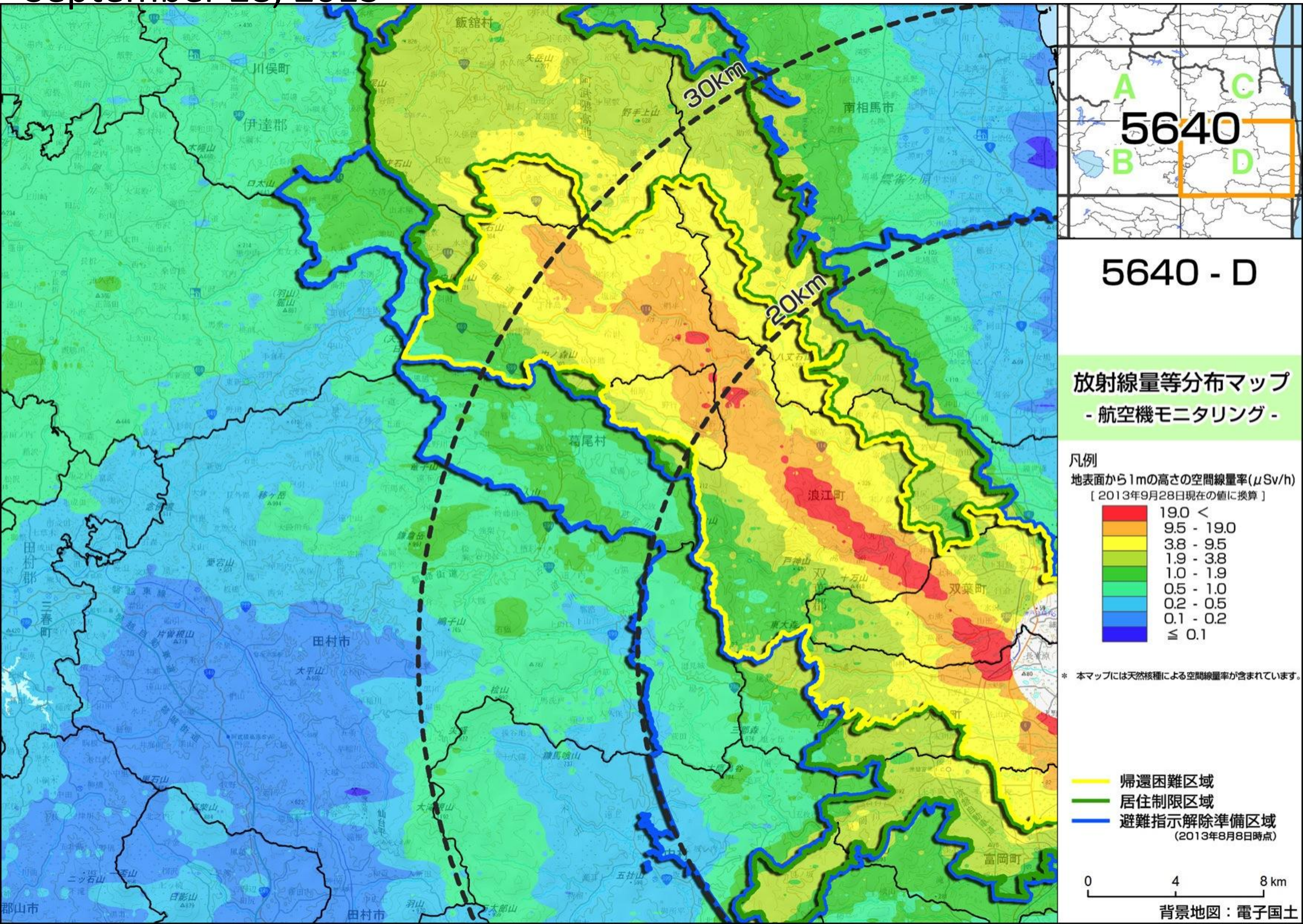
D
5640 - D
文部科学省
MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN
放射線量等分布マップ
- 航空機モニタリング -
凡例
地表面から1mの高さの空間線量率(μSv/h)
[2012年6月28日現在の値に換算]
19.0 <
9.5 - 19.0
3.8 - 9.5
1.9 - 3.8
1.0 - 1.9
0.5 - 1.0
0.2 - 0.5
0.1 - 0.2
≦ 0.1
測定結果が得られていない範囲
積雪分布
(2012年3月26日~4月26日)
岩手県、宮城県、山形県、福島県、茨城県、栃木県、群馬県、千葉県を対象
JASMES：宇宙航空研究開発機構(JAXA)
＊ 本マップには天然核種による空間線量率が含まれています。
＊ 福島第一原子力発電所から80km圏外の測定結果は、2012年5月7日の結果を2012年6月28日時点の値に減衰補正しています。風雨等の自然環境による放射性物質の移行の影響は考慮しておりません。
＊ 実線で囲われた白色の領域は積雪のあった箇所を表しており、当該地域及びその周辺における空間線量率は、雪の遮蔽により、雪が無い時に比べて減少している可能性があります。
警戒区域
計画的避難区域
帰還困難区域
居住制限区域
避難指示解除準備区域
(2012年8月10日時点)
0
4
8 km
背景地図：電子国土
20km
飯舘村
川俣町
伊達郡
南相馬市
葛尾村
浪江町
双葉町
双葉郡
大熊町
富岡町
田村市
川内村
郡山市

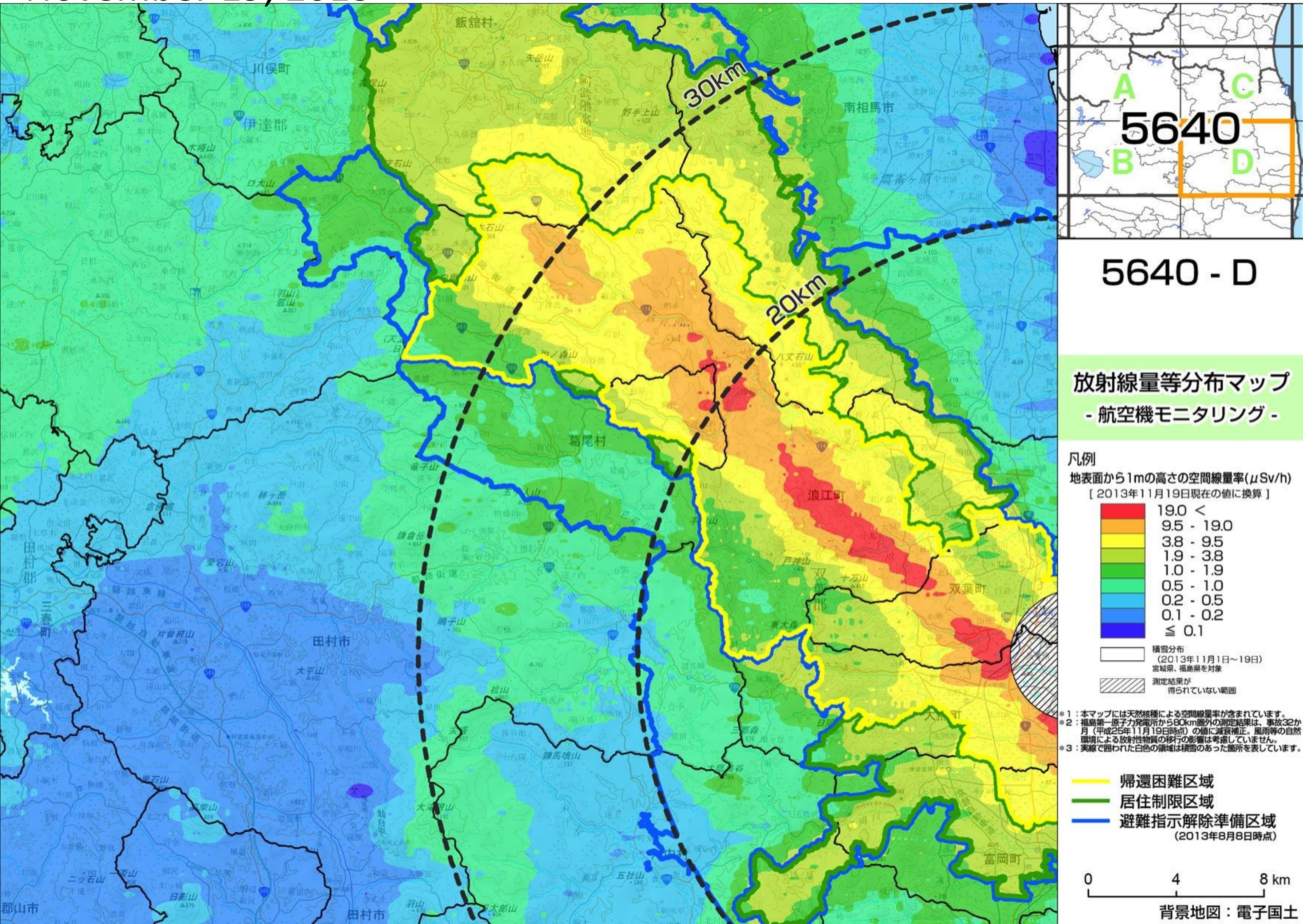
December 28, 2012



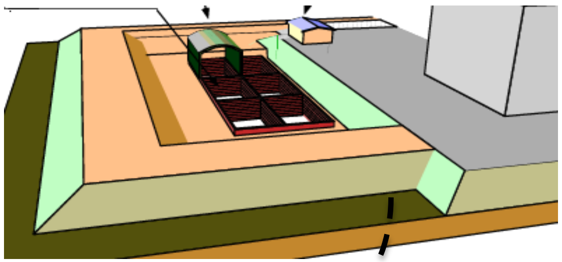
September 28, 2013



November 19, 2013



Model for Decontamination and Waste Management



Disposal

Radioactive decay

$A\tau\ \tau = 0,\ \beta\ (kBq/m^2)$

Contaminated area

Cs-137 (fraction r_{137})

$A\ (m^2)$ Cs-134 (fraction r_{134})

$d\ (m)$

(1) Radioactive decay

λ_{137}=0.023 yr^{-1}

(half life = 30 yr)

λ_{134}=0.347 yr^{-1}

(half life = 2 yr)

(2) Reduction by natural dispersion

λ_S=0.05 yr^{-1} or

(IAEA Safety series #19)

λ_S=0.534 yr^{-1}

(from Fig. 5.6)

(3) Decontamination by human action until 1 mSv/yr is achieved.

λ_R=0.223 yr^{-1}

20 % reduction per year

(IAEA STI/PUB/1239 -- Chernobyl)

Interim storage

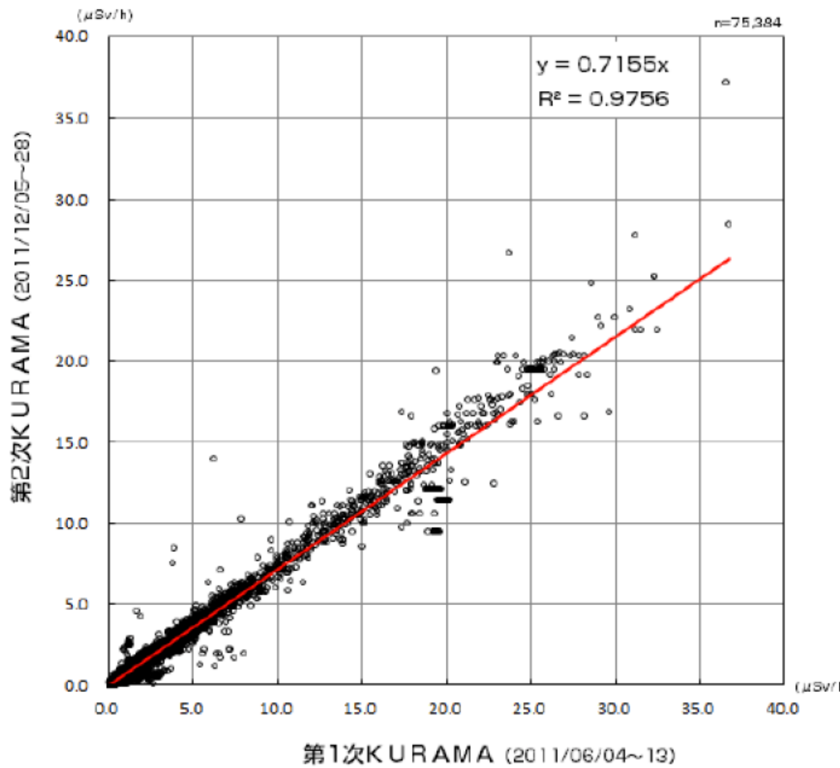
Radioactive decay

Recent Observations

Correlation between 2011/06 data and 2011/12 data

✓Approximately 30% reduction in 6 months

- Observations
  - Decrease by Radioactive Decay
    - 17% decrease in 6 months
      - Cs-134: Half life of 2 years
      - Cs-137: Half life of 30 years
  - Natural Dispersion
    - 13%
    - $\lambda = 0.534\ yr^{-1}$
    - Compare:
      - $\lambda_S = 0.05\ yr^{-1}$ (IAEA Safety series



Effects of Decontamination and Natural Dispersion

Initial contamination (kBq/m²)	*Years to reach 20 mSv/yr*				*Years to reach 1 mSv/yr*			
	No decontamination		*With decontamination*		*No decontamination*		*With decontamination*	
	Fast	*Slow*	*Fast*	*Slow*	*Fast*	*Slow*	*Fast*	*Slow*
> 3000	*>1.43*	*>4.32*	*>1.10*	*>2.19*	*>5.67*	*>38.4*	*>4.25*	*> 9.83*
1000 – 3000	*0.90*	*2.52*	*0.70*	*1.36*	*5.06*	*32.8*	*3.81*	*8.62*
600 – 1000	*--*	*--*	*--*	*--*	*3.72*	*20.3*	*2.83*	*6.08*
300 – 600	*--*	*--*	*--*	*--*	*2.91*	*13.0*	*2.23*	*4.64*
100 – 300	*--*	*--*	*--*	*--*	*1.81*	*5.90*	*1.40*	*2.80*
60 – 100	*--*	*--*	*--*	*--*	*0.61*	*1.66*	*0.48*	*0.92*

The goals set by the law:

- the annual dose is to be made less than 20 mSv/year within 2 years, and
- 1 mSv/year or lower at any location in the long term.

Fast: natural dispersion rate = 0.534 yr^{-1}

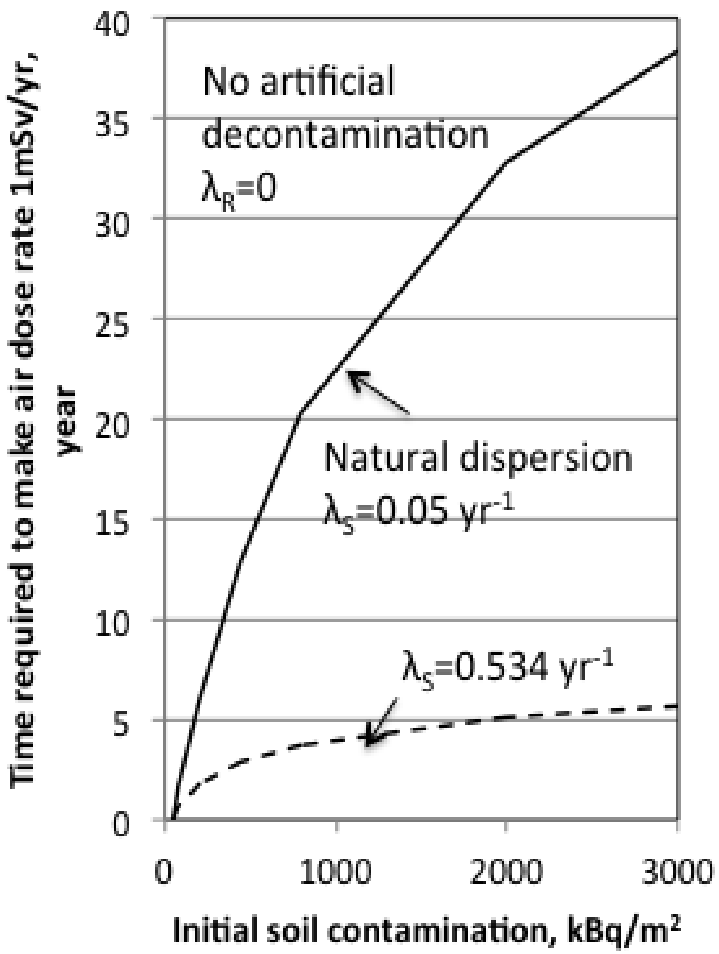
Slow: natural dispersion rate = 0.05 yr^{-1}

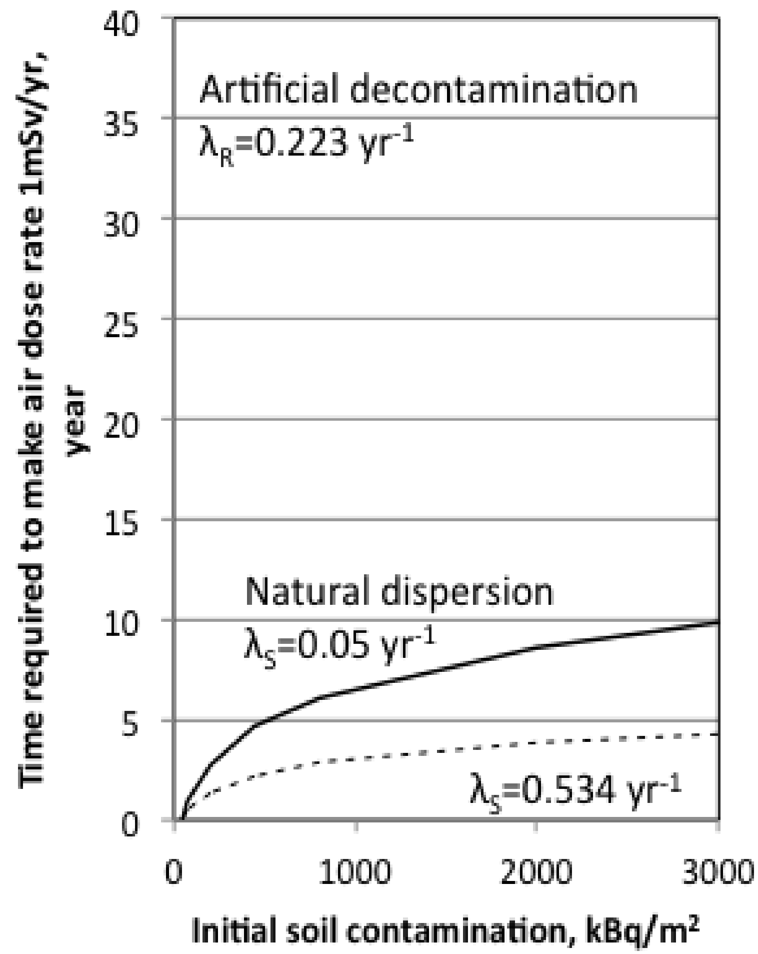
-- : air dose rates always below 20mSv/yr

Estimated Volume and Cost of Disposal for Radioactive Waste Arising from Decontamination

Initial soil contamination (kBq/m^2)	Area included (km^2)	Waste volume (million m^3)		Estimated cost (trillion yen)	
		Fast dispersion	*Slow dispersion*	*Fast dispersion*	*Slow dispersion*
> 3,000	*183*	*5.6*	*8.1*	*3.6*	*5.3*
1,000 – 3,000	*368*	*10.5*	*15.7*	*6.8*	*10.2*
Subtotal	*551*	*16.1*	*23.8*	*10.5*	*15.5*
600 – 1,000	*282*	*6.6*	*10.5*	*4.3*	*6.8*
300 – 600	*721*	*14.1*	*23.2*	*9.2*	*15.1*
Subtotal	*1,003*	*20.7*	*33.7*	*13.5*	*21.9*
Total	*1,554*	*36.8*	*57.5*	*23.9*	*37.4*

Time required for the air dose rate to become < 1 mSv/year





Summary of Fukushima Daiichi Nuclear Power Plant

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
PCV Model	Mark-I	Mark-I	Mark-I	Mark-I	Mark-I	Mark-II
Electric Output	460MWe	784MWe	784MWe	784MWe	784MWe	1100MWe
RPV Operation Pressure	6.89MPa	6.93MPa	6.93MPa	6.93MPa	6.93MPa	6.93MPa
RPV Max. Design Pressure	8.24MPa	8.24MPa	8.24MPa	8.24MPa	8. 62MPa	8.62MPa
RPV Max. Operation Temp.	300℃	300℃	300℃	300℃	302℃	302℃
PCV Max. Design Pressure	384kPa	384kPa	384kPa	384kPa	384kPa	279kPa
PCV Max. Pressure *	427kPa	427kPa	427kPa	427kPa	427kPa	310kPa
PCV Max. Temp	140℃	140℃	140℃	140℃	138℃	171℃:D/W 105℃:S/C
Commercial Operation	1971.3.26	1974.7.18	1976.3.27	1978.10.12	1978.4.18	1979.10.24
Emergency DG	2	2 **	2	2 **	2	3 **
Electric Grid	275kV×4				500kV×2	
Plant Status on March 11, 2011	In Operation	In Operation	In Operation	Long Outage for Shroud Replacement	Refueling Outage	Refueling Outage

* Typical operating pressure of PCV is about 5 kPa.

** One Emergency DG is Air-Cooled

Important Lessons Learned from Regulatory Points of View

- **Points to be addressed relevant to regulatory framework**
  - Enhancement of **Defense-in-Depth**
  - **Diversity, Flexibility and Operability** of Measures against Severe Accidents
  - Enhancement of **Consistency with International Standards and Practices**

- **Lessons learned as a regulatory organization**
  - **Lack of System Perusing Safety Enhancement**
  - **Needs for Feedback of Latest Knowledge and Findings, etc.**

Source: Technical Findings on Accident at TEPCO Fukushima-Daiichi NPP (ad interim report), NISA, Feb. 2012.
http://www.meti.go.jp/press/2011/02/20120216004/20120216004.html

Important Lessons Learned (1/2)

- **Design Basis Tsunami:**
  - DB-Ts was re-evaluated in 2002, but was seriously underestimated.
  - New information such as Jyogan Tsunami (869) was not thoroughly considered.

    ➡ Continuous efforts to **reduce uncertainty of external hazard** were needed.

- **Beyond Design Basis Tsunami :**
  - We should have been prepared for **Design Basis Tsunami being exceeded.** Such a risk exists even if the best efforts are made to determine DB-Ts. (preparation for "**Low likelihood, high consequence**" events)

    ➡ Protection against **dynamic force** of tsunami, **water tightness** of doors, **diversity in layout** of equipment, etc., were needed to **prevent common cause failures (CCFs)**.

- **Protection against Severe Accidents (SAs)**:
  - **Accident management (AM) measures** implemented against SAs were not effective. No AM measures had been taken for **spent fuel pools** (SFPs)

Source: Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety
http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html

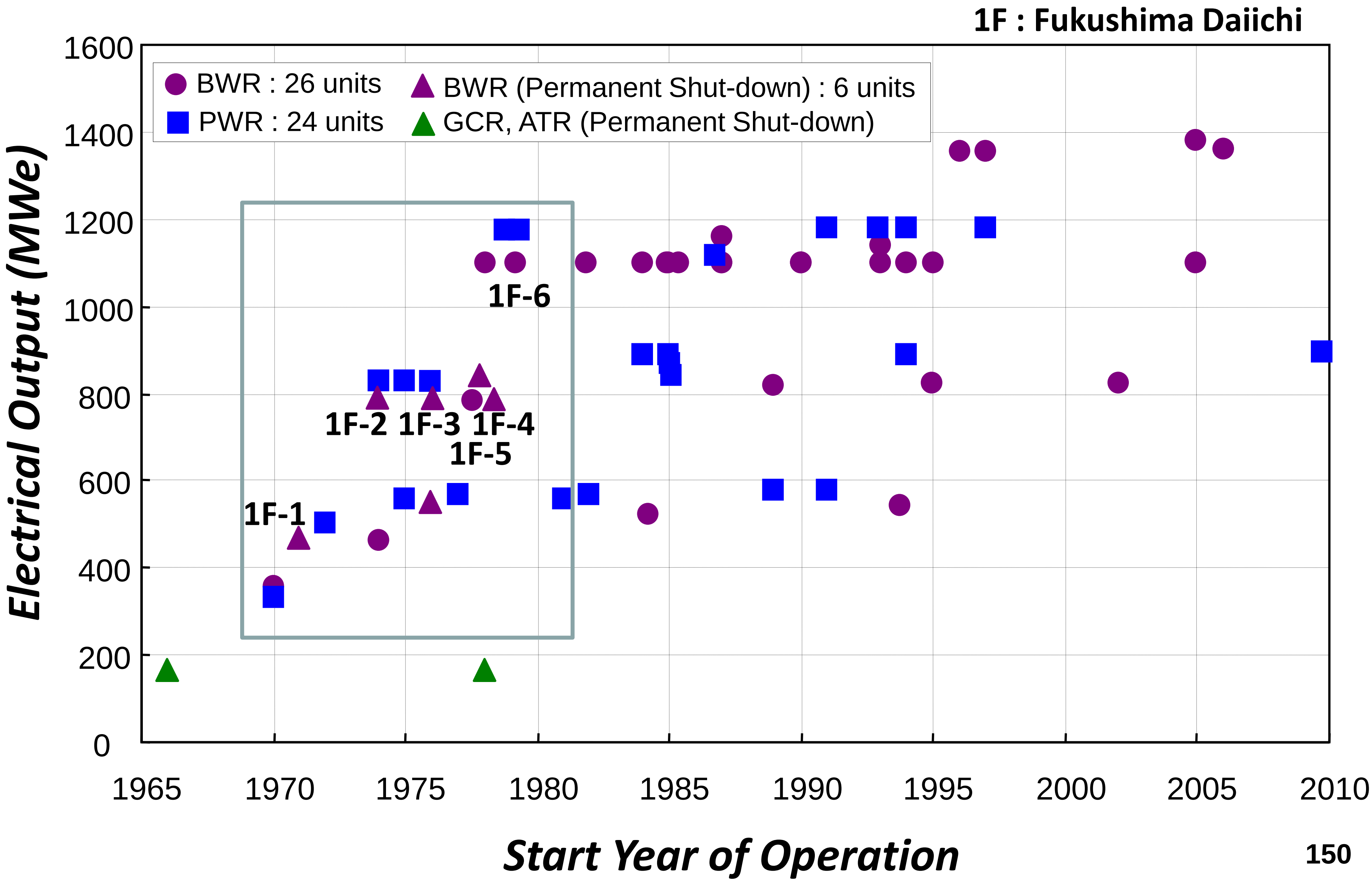
Important Lessons Learned (2/2)

- **Emergency Preparedness and Responses:**
  - Improvement of preparedness (communication, resources, etc.) assuming **combination of large-scale natural disasters and prolonged nuclear accident**.
  - Enhancement of **environmental monitoring** for emergency
  - Clarification of roles / responsibilities **between central and local organizations**
  - many others

- **Strengthening of Safety Culture:**
  - We need to ask ourselves:
    - ✓ Were we vigilant enough to the plant vulnerabilities?
    - ✓ Were we careful enough for new technical findings?
  - **There's no "continuous improvement of safety" without "safety culture".**

Source: Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety
http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html

Nuclear Power Plants in Japan



Effects of Ageing in the Fukushima Accident ?

- **As the results of the evaluation based on the knowledge obtained so far, it is quite unlikely that there was an effect of ageing degradation on loss of functions in SSCs important to safety due to the ground motion by the earthquake.**
- **It is also unlikely that ageing degradation phenomena have caused the occurrence and enlargement of the Fukushima Daiichi accident.**

- **However, as it is difficult to confirm the status of equipment at this moment, additional investigation will be needed, when new knowledge is obtained in the future.**

Report of the Expert Meeting on Ageing Management in NISA (February 7, 2012)

Evaluation of Additional Effect of the Earthquake on Low Cycle Fatigue of Main Steam Line Piping of Unit 1

Cumulative Fatigue Coefficient for 60 years	Fatigue Coefficient considering Earthquake		
	Due to Seismic Load		Total
0.064	S_2	0.252	0.316
	S_S	0.269	0.333
	Earthquake on March 11, 2011	0.264	0.328

Equivalent number of cycle due to seismic load is conservatively assumed to be 100.
S_2, S_s : Design basis seismic ground motion

Evaluation of Effect of the Earthquake on March 11, 2011 on Structural Integrity of Important Pumps considering General Corrosion of Anchor Bolts

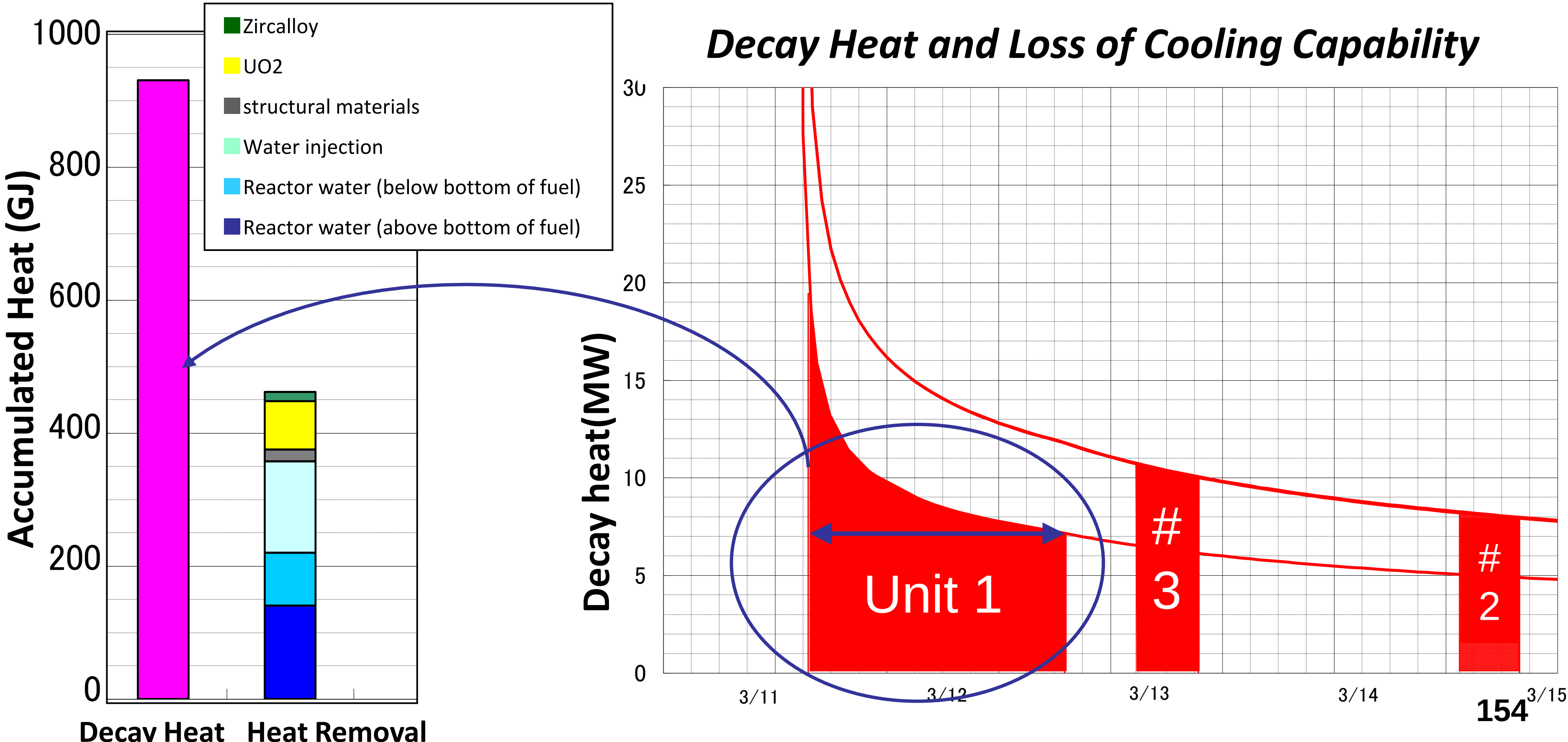
	Pumps Evaluated	Shear Stress [MPa]		Allowable Stress [MPa]
		Without Corrosion	With Corrosion for 60 years	
Unit 1	Reactor Shut Down Cooling System Cooling Pumps	8	9	127
Unit 2	Residual Heat Removal System Pumps	34	36	202
Unit 3	Residual Heat Removal System Pumps	23	24	202

- The corrosion of the anchor bolts was evaluated by multiplication of cross-section decrease rate (6.0%/y) in consideration of the corrosion amount for 60 years of 0.3 mm.
- The shear stress with consideration of the amount of corrosions for 60 years was confirmed that there was sufficient margin to the allowable stress.

Macroscopic Balance between Decay Heat and Heat Removal in Unit 1

Decay Heat > Heat Removal

- **Total decay heat before sea water injection greatly exceeds the amount of heat which reactor water and structural materials could absorb.**
- **All molten core moved to RPV bottom and they damaged RPV and run down to PCV.**

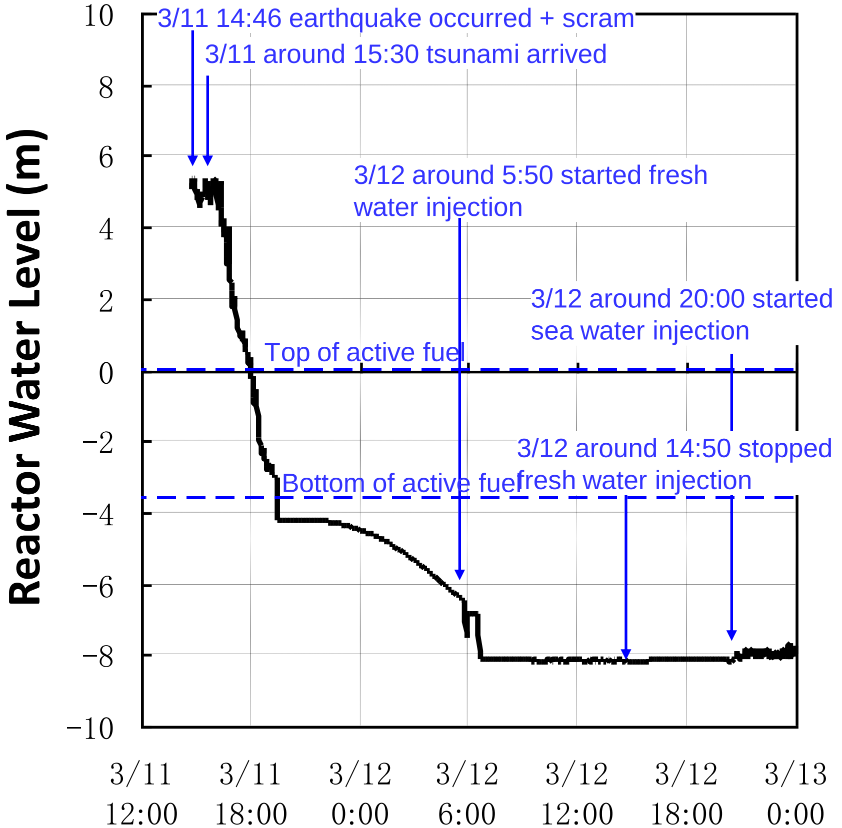


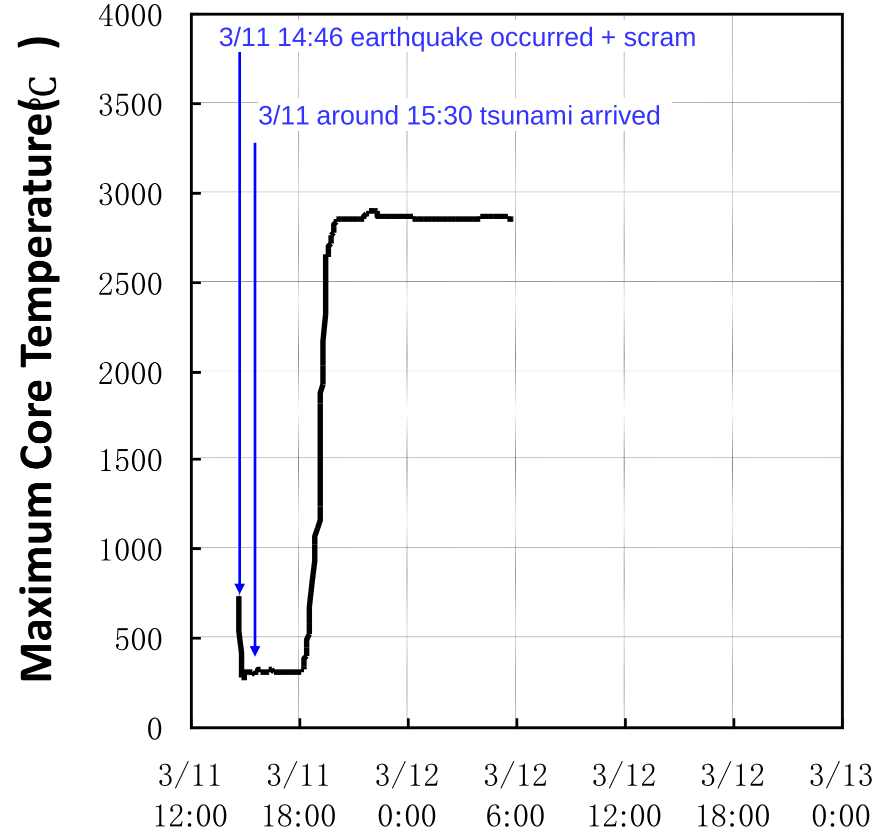
Source: TEPCO

Reactor Water Level and Core Temperature in Unit 1

- Simulation Trial by the MAAP code -

Assuming that IC lost its function by the Tsunami





- reached top of active fuel in 3 hours (around 18:00) after the scram
- reached bottom of active fuel in 4 and a half hours (around 19:30) after the scram

The core temperature started increasing when the reactor water level became lower than top of active fuel, then reached the core melting temperature.

Source: TEPCO

Failure of Power Supply and Cooling Systems

The reactors shut down automatically due to the Earthquake, loss of external power supply.

↓

Power supply equipment such as D/Gs was not unavailable due to the Tsunami, loss of all AC power supply

Units 1 & 2

Loss of function of DC power supply due to the Tsunami

Unit 1

IC was unavailable to check status and operate. HPCI was unavailable to start up.

Led to accident at early time

Unit 2

RCIC continued cooling.

RCIC continued to operate until 13:25 on March 14.

Unit 3

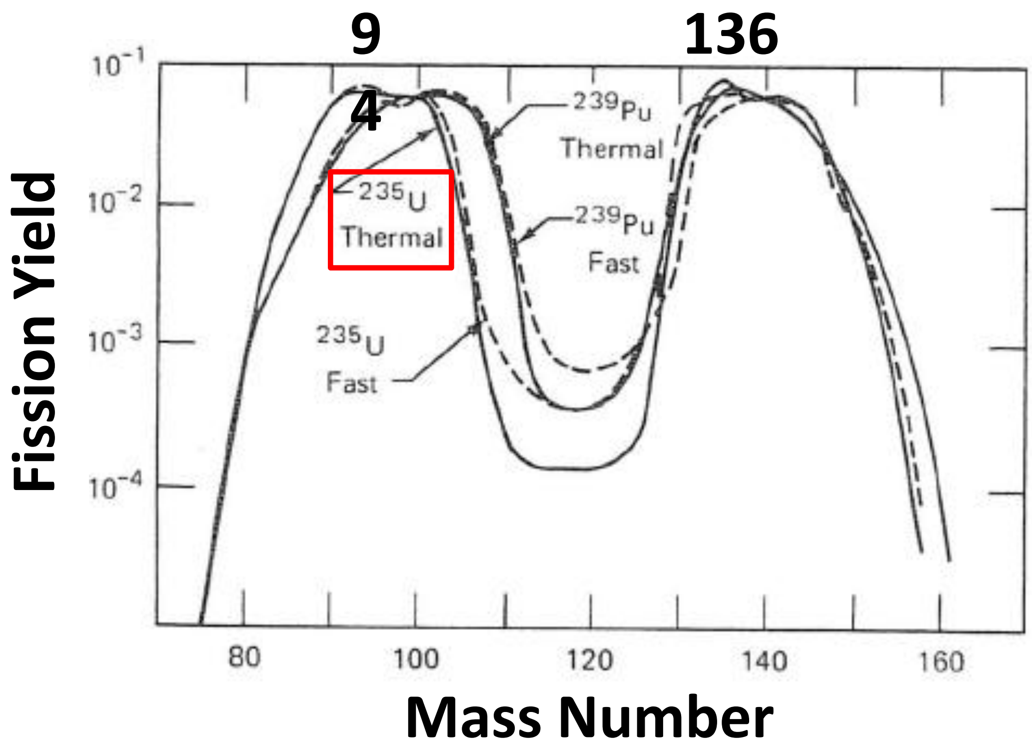
Function of DC power supply maintained

Unit 3

RCIC or HPCI continued cooling until battery ran out.

After RCIC stopped at 11:36 on March 12, HPCI started up automatically due to low level of water in reactor.

Fission Products



- **More than 30 chemical elements are produced by fission reaction**
- **Chemical state of fuel can evolve substantially during burn-up**
- **20-25% of fission products are gas atoms (Kr, Xe)**

Groups of Radionuclides from Nuclear Fuel

Group #	*Designation*	*Elements*
1	**Noble Gases**	Xe, Kr
2	**Halogens**	I, Br
3	**Alkali Metals**	Cs, Rb
4	**Tellurium Group**	Te, Sb, Se
5	**Barium, Strontium**	Ba, Sr
6	**Noble Metals**	Ru, Rh, Pd, Mo, Tc, Co
7	**Lanthanides**	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am
8	**Cerium Group**	Ce, Pu, Np

NUREG-1465

Radionuclides considered Important in the Reactor Safety Study Consequence Analysis (1)

3,200 MWth PWR case

Radionuclides	Half-life [days]	Shutdown inventory [MCi]
1) Noble gases		
^{85}Kr*	3950	0.56
^{85m}Kr*	0.183	24
^{87}Kr*	0.0528	47
^{88}Kr*	0.117	68
^{133}Xe	5.28	170
^{135}Xe	0.384	34
2) Halogens		
^{131}I	8.05	85
^{132}I	0.0958	120
^{133}I	0.875	170
^{134}I	0.0366	190
^{135}I	0.28	150
3) Alkali metals		
^{134}Cs	750	7.5
^{136}Cs	13	3
^{137}Cs	11000	4.7
^{86}Rb*	18.7	0.026
4) Tellurium group		
^{127}Te*	0.391	5.9
^{127m}Te	109	1.1
^{129}Te*	0.048	31
^{129m}Te	0.34	5.3
^{131m}Te	1.25	13
^{132}Te	3.25	120
^{127}Sb	3.88	6.1
^{129}Sb	0.179	33
5) Barium and strontium group		
^{89}Sr	52.1	94
^{90}Sr	11030	3.7
^{91}Sr	0.403	110
^{140}Ba	12.8	160

*** Indicates negligible contribution to health effects**

Radionuclides considered Important in the Reactor Safety Study Consequence Analysis (2)

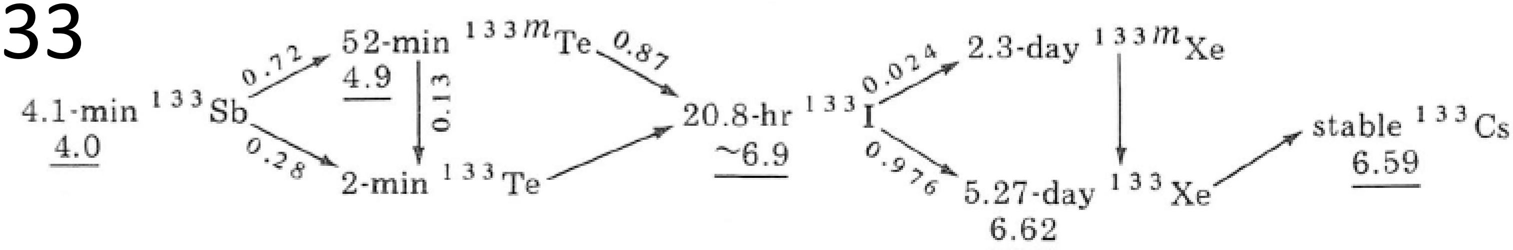
Radionuclides	Half-life [days]	Shutdown inventory [MCi]
6) Noble metals		
^{58}Co*	71	0.78
^{60}Co*	1920	0.29
^{99}Mo	2.8	160
^{99m}Tc*	0.25	140
^{103}Ru	39.5	110
^{105}Ru*	0.185	72
^{106}Ru	366	25
^{105}Rh*	1.5	49
7+8) Lanthanides and cerium group		
^{90}Y*	2.67	3.9
^{91}Y	59	120
^{95}Zr	65.2	150
^{97}Zr	0.71	150
^{95}Nb	35	150
^{140}La	1.67	160
^{141}Ce	32.3	150
^{143}Ce*	1.38	130
^{144}Ce	284	85
^{143}Pr	13.7	130
^{147}Nd*	11.1	60
^{239}Np	2.35	1640
^{238}Pu	32500	0.057
^{239}Pu	8.90E+06	0.021
^{240}Pu	2.40E+06	0.021
^{241}Pu	5350	3.4
^{241}Am*	1.50E+05	0.0017
^{242}Cm	163	0.5
^{244}Cm	6630	0.023

3,200 MWth PWR case

*** Indicates negligible contribution**

Examples of Decay Chains containing Cs from Fission Reaction of ^{235}U by Thermal Neutrons

133



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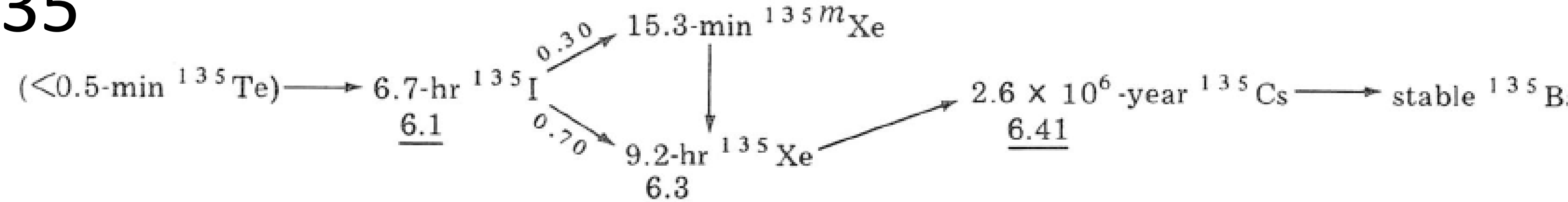

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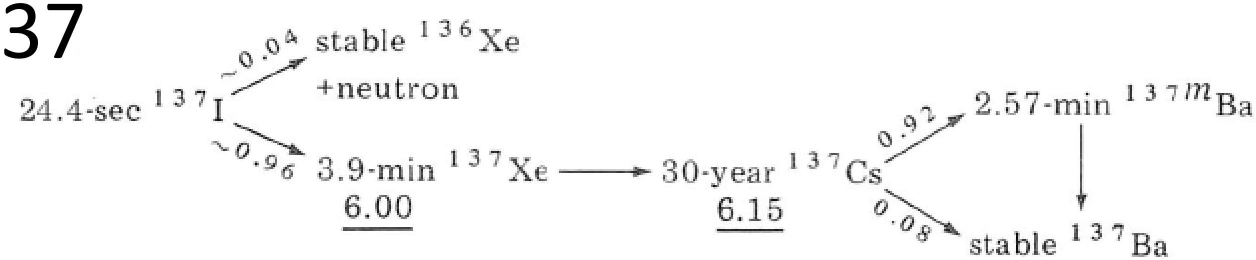


Fission Gas Yield

Isotopes	^{235}U	^{239}Pu
^{83}Kr	0.40	0.30
^{84}Kr	0.85	0.50
^{85}Kr	0.15	0.13
^{86}Kr	1.40	0.80
Total Kr	**2.8**	**1.7**
^{131}Xe	3.2	3.8
^{132}Xe	4.7	5.3
^{134}Xe	6.6	7.5
^{136}Xe	5.9	6.6
Total Xe	**20.4**	**23.2**

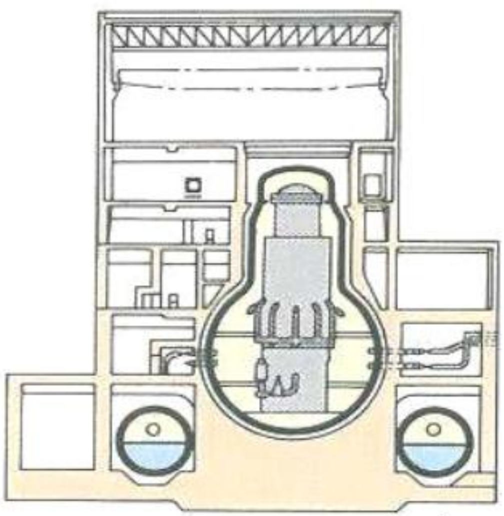
- **Minor actinides (Am, Cm) also produce significant quantities of He during further irradiation by (n,α) reaction**

Tsunami on March 11, 2011

Source: TEPCO

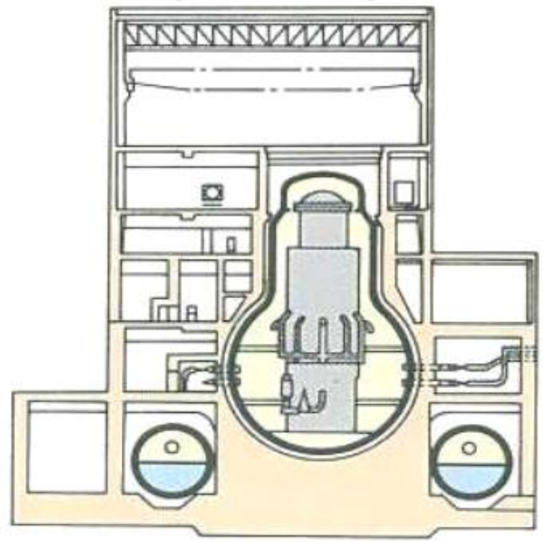
Mark-I and Mark-II Primary Containment Vessel (6 BWR Units in Fukushima Daiichi)

Unit 1 (Mark-I)



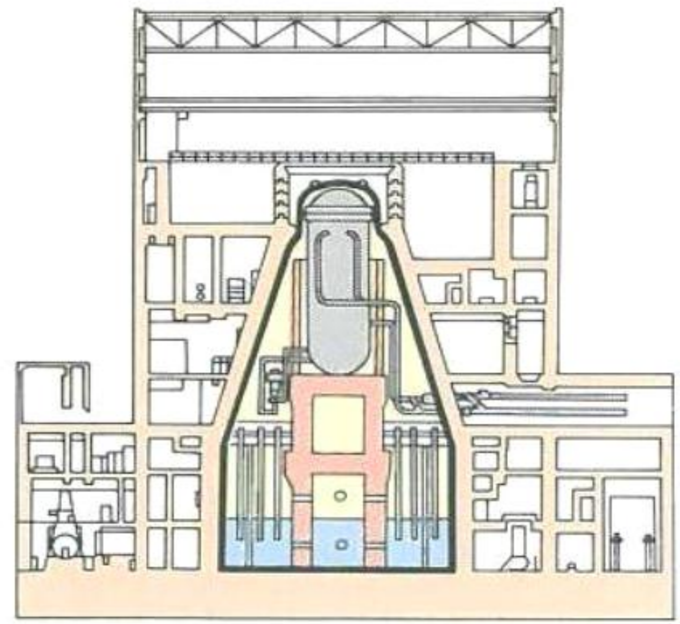
460 MWe

Units 2,3,4 and 5 (Mark-I)



784 MWe

Unit 6 (Mark-II)

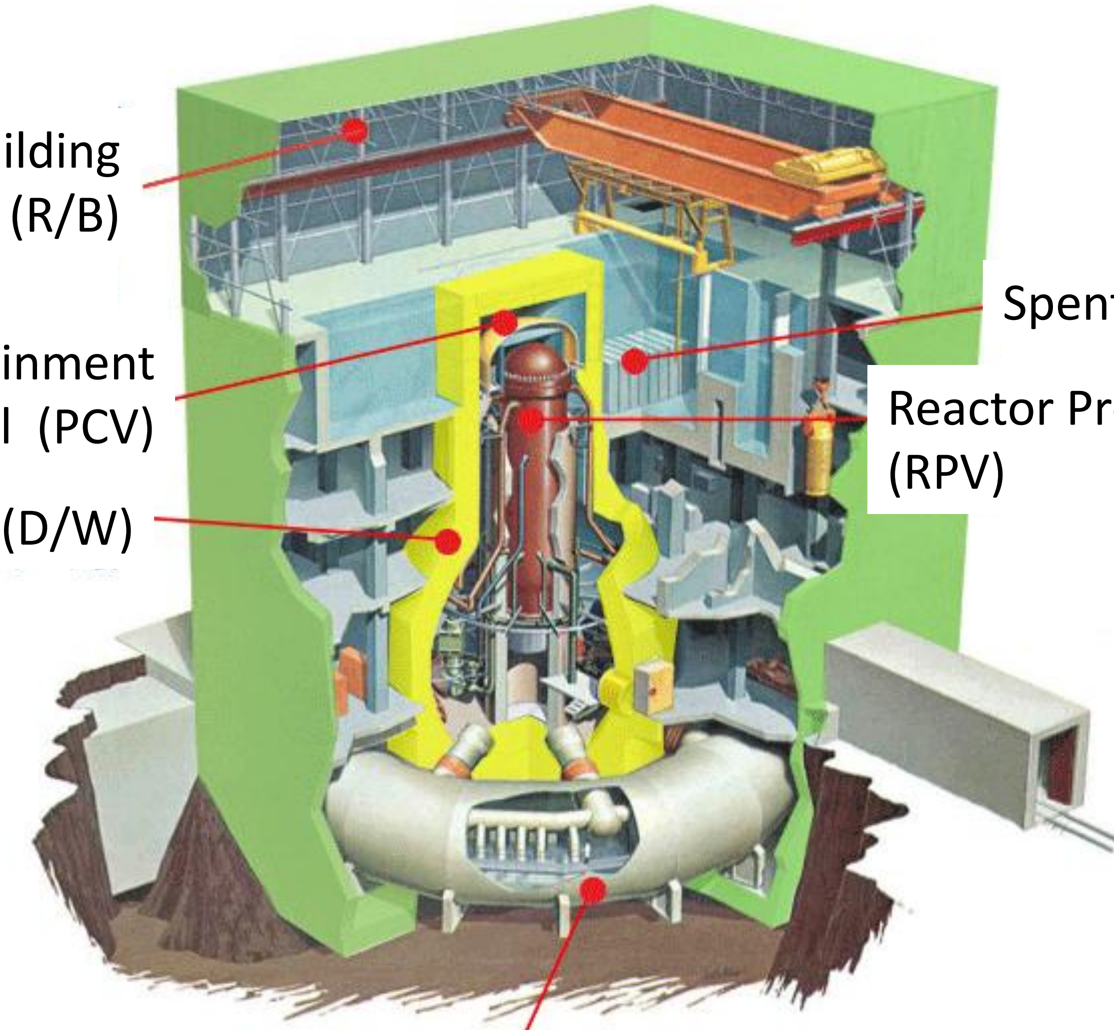


1,100 MWe

- Volume of Mark-II containment vessel is larger than that of Mark-I.

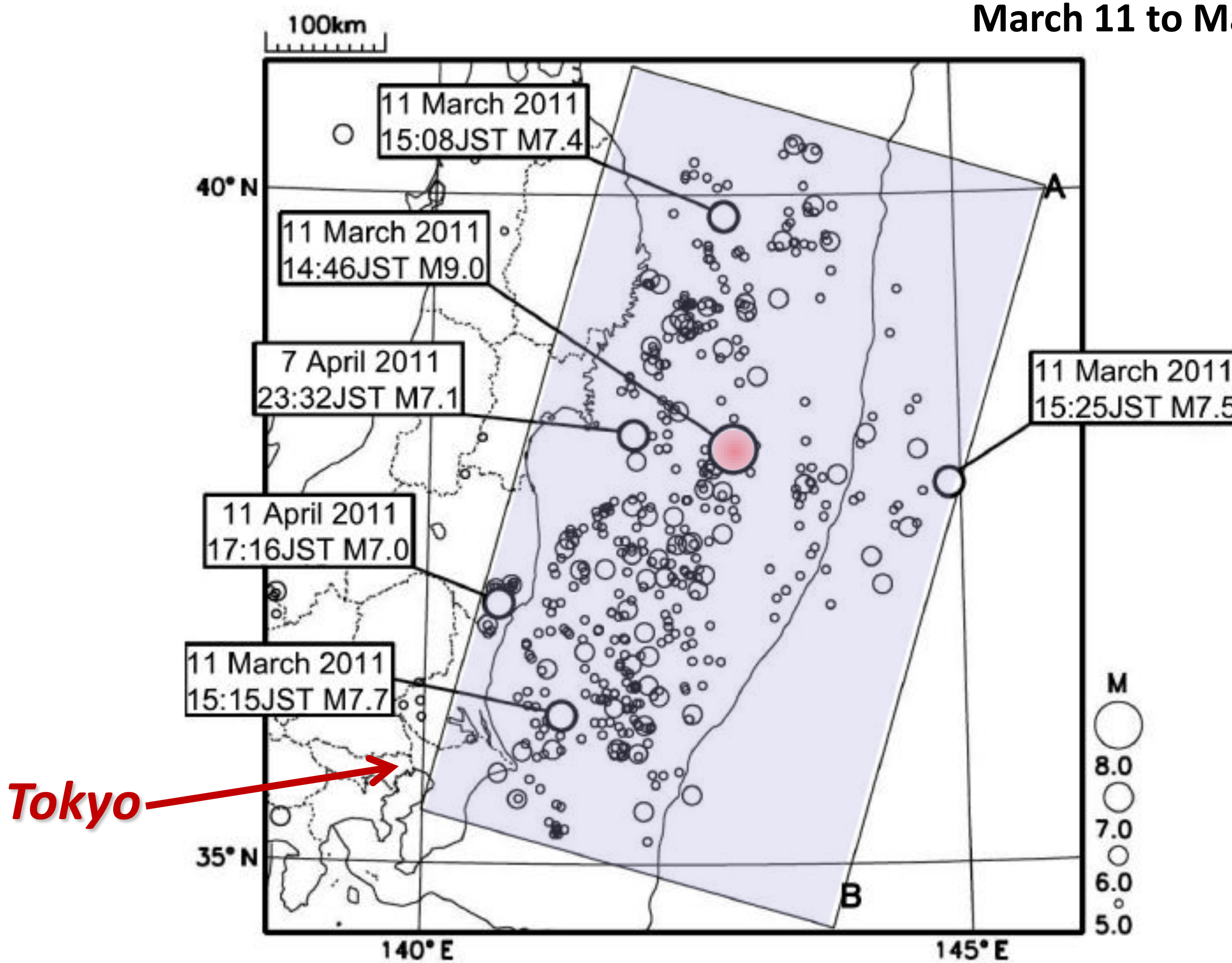
- Units 1-3 were operating at the time of the Earthquake.
- Unit 4-6 were in refueling outage

BWR with Mark-I Type Containment Vessel
(Fukushima Daiichi, Units 1,2,3,4 and 5)



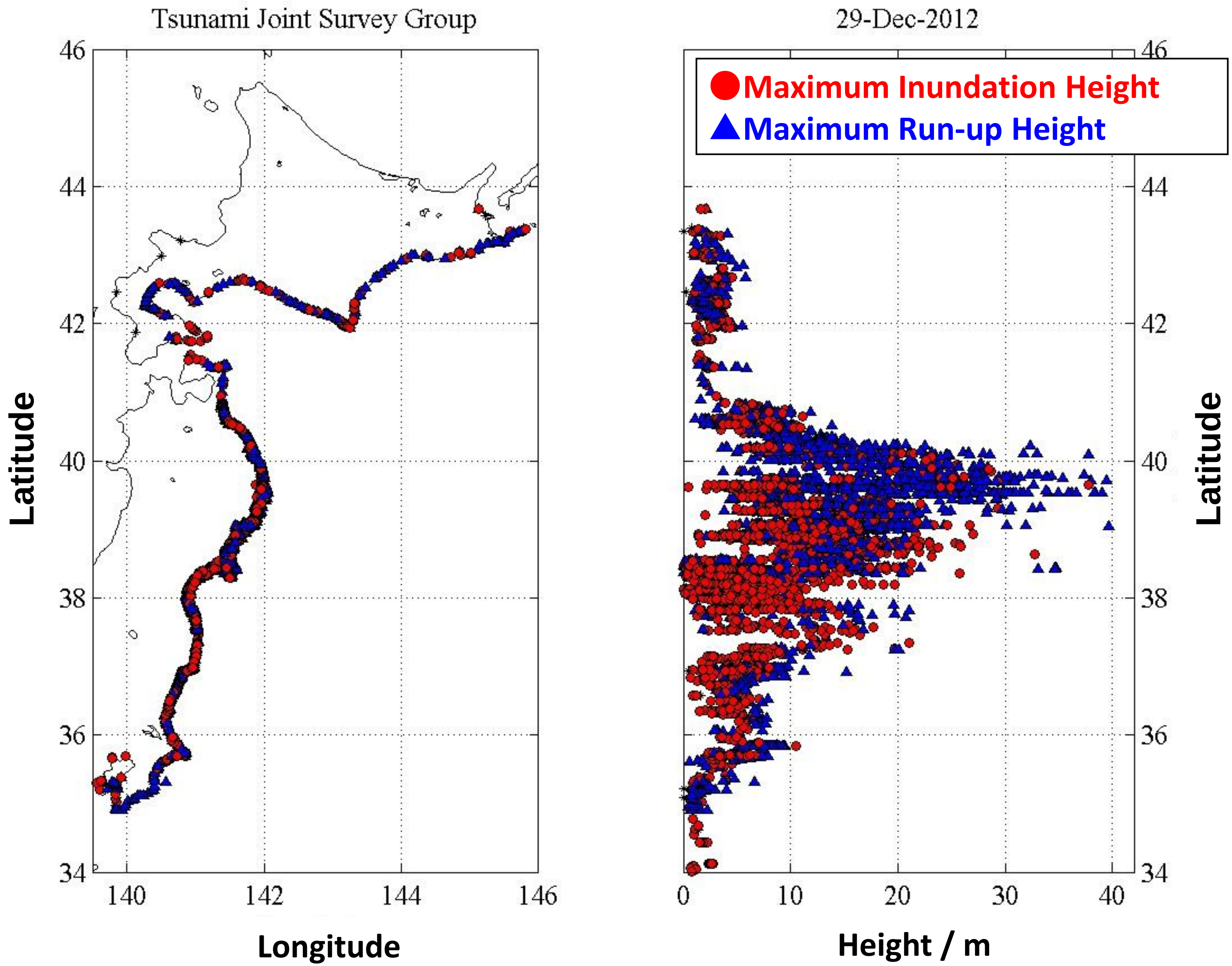
The Main Shock (and Aftershocks) of the Earthquake on March 11, 2011

March 11 to May 13, 2011



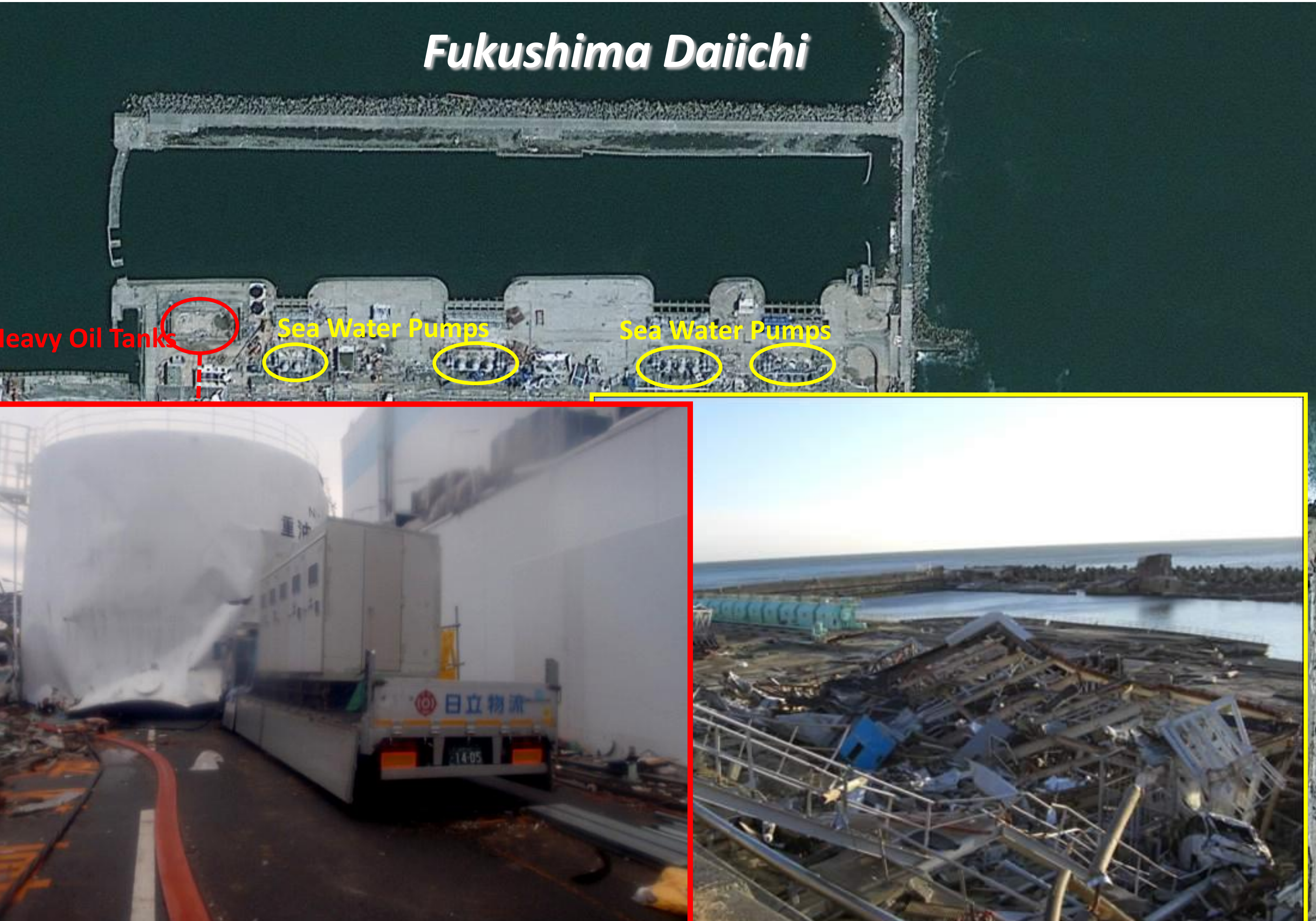
Earthquake Research Institute, The University of Tokyo

Tsunami after the Earthquake on March 11, 2011

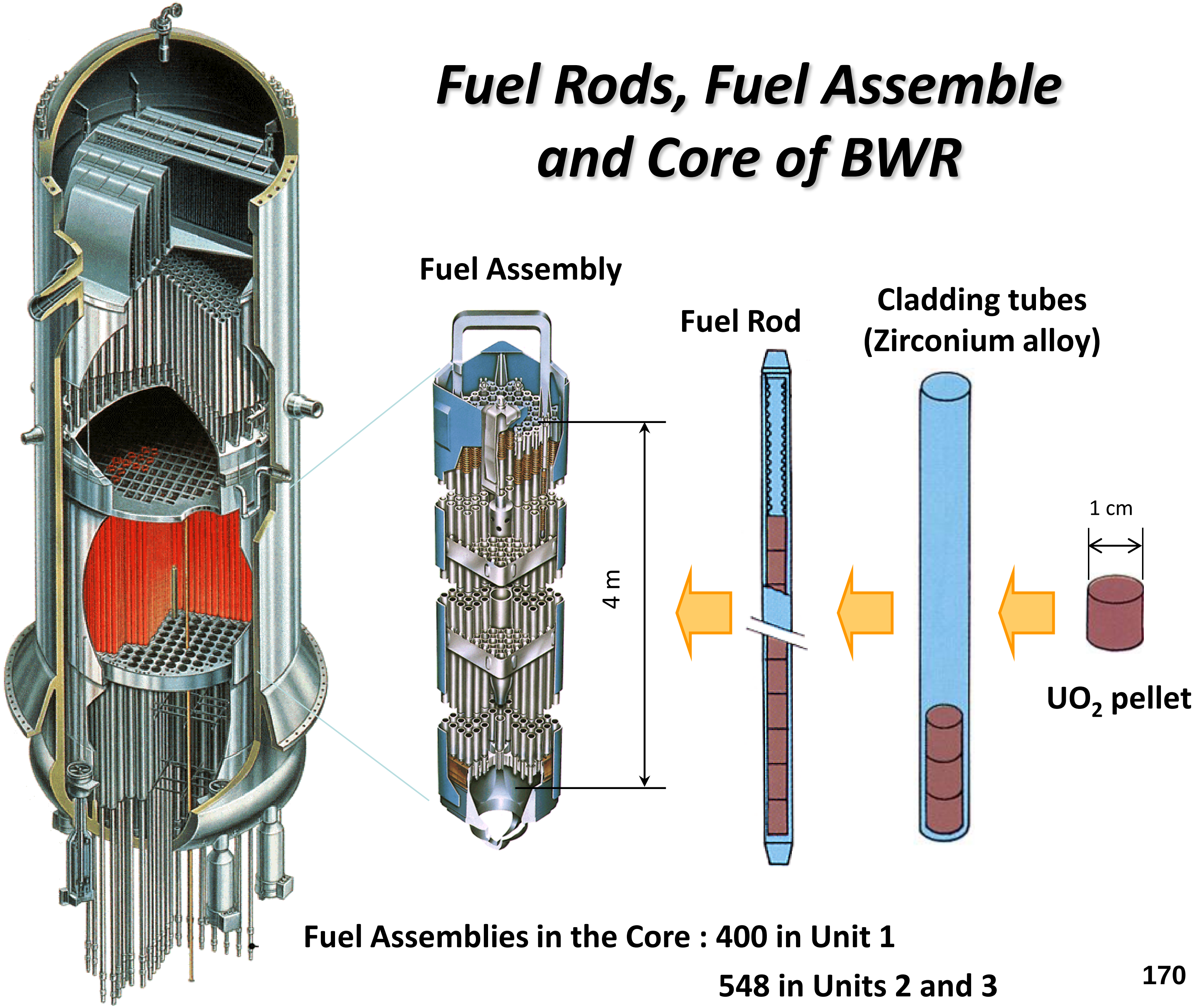


http://www.coastal.jp/ttjt/

Tsunami on March 11, 2011



Fuel Rods, Fuel Assemble and Core of BWR

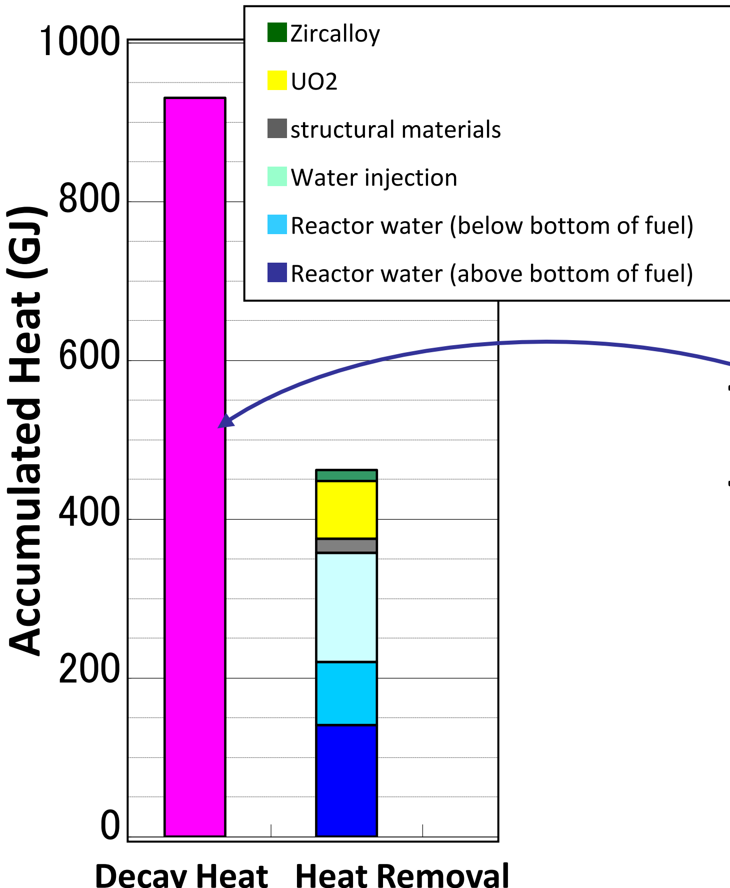


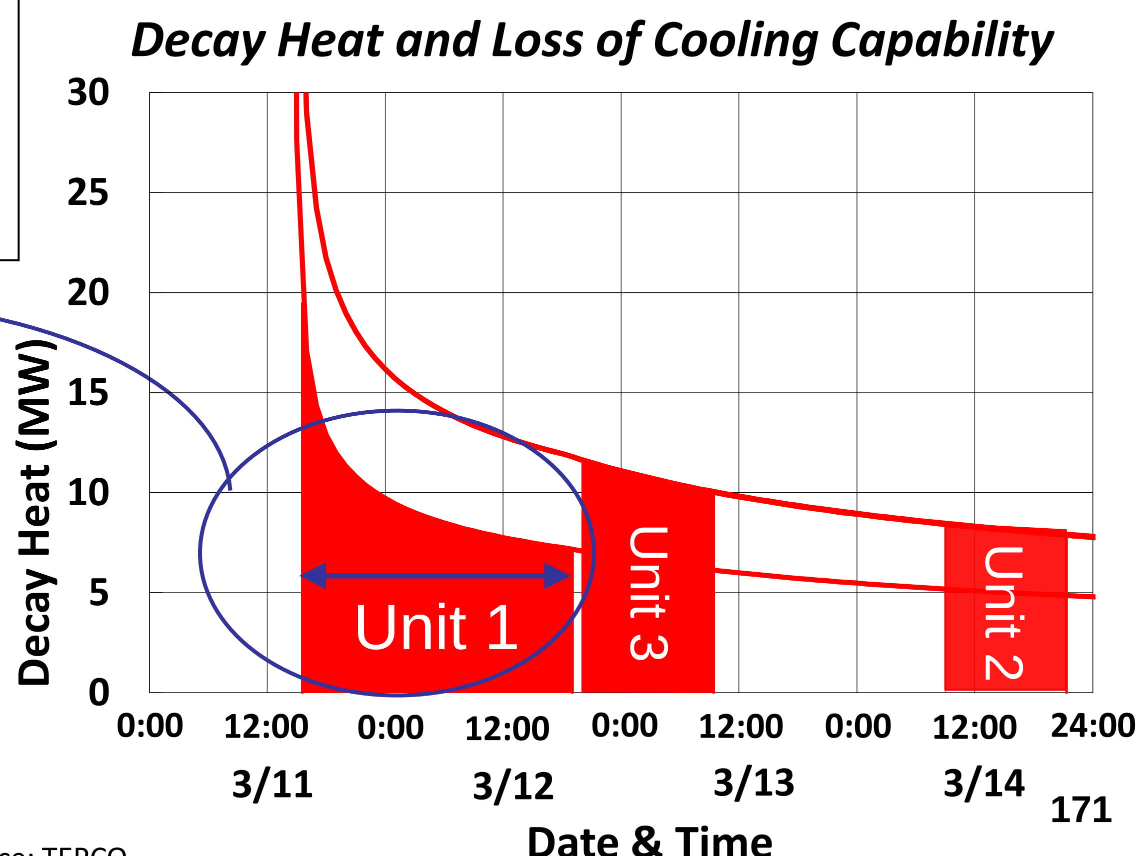
Fuel Assemblies in the Core : 400 in Unit 1

548 in Units 2 and 3

Macroscopic Balance between Decay Heat and Heat Removal in Unit 1

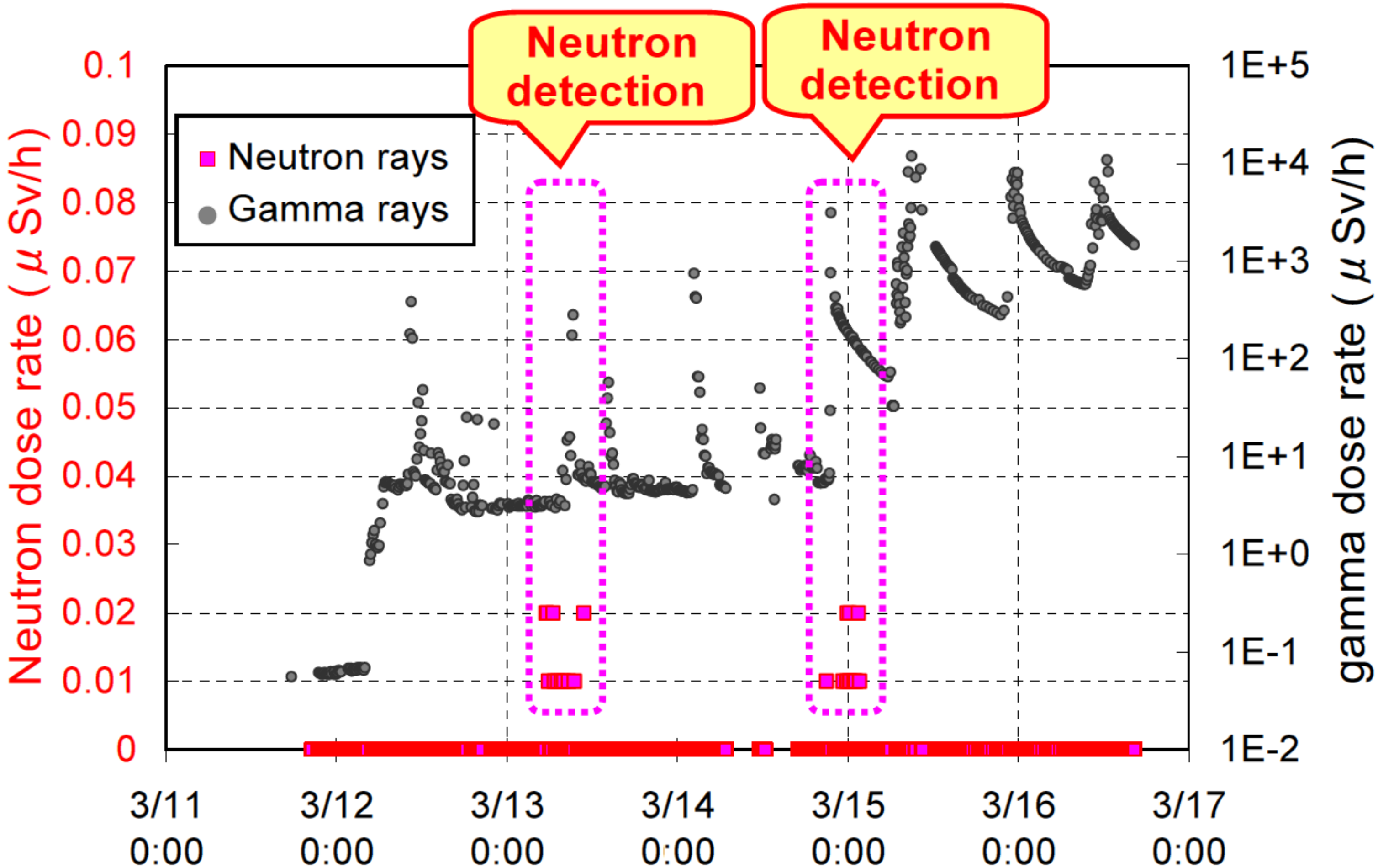
- **Total decay heat before sea water injection greatly exceeds the amount of heat which reactor water and structural materials could absorb.**
- **Oxidation reaction of Zr provides additional heat to promote the core damage.**
- **All molten core moved to RPV bottom and they damaged RPV and run down to PCV.**





Source: TEPCO

Detection of Neutrons



- Neutrons detected in the morning of March 13 and in the night of March 14 were released in the course of fuel melting at Units 3 and 2, respectively.
- Neutrons may have been generated by the spontaneous fission of released actinides.

Radiation Control for Site Workers

Radiation Dose from External and Internal Exposure for Workers in Fukushima Daiichi Nuclear Power Station

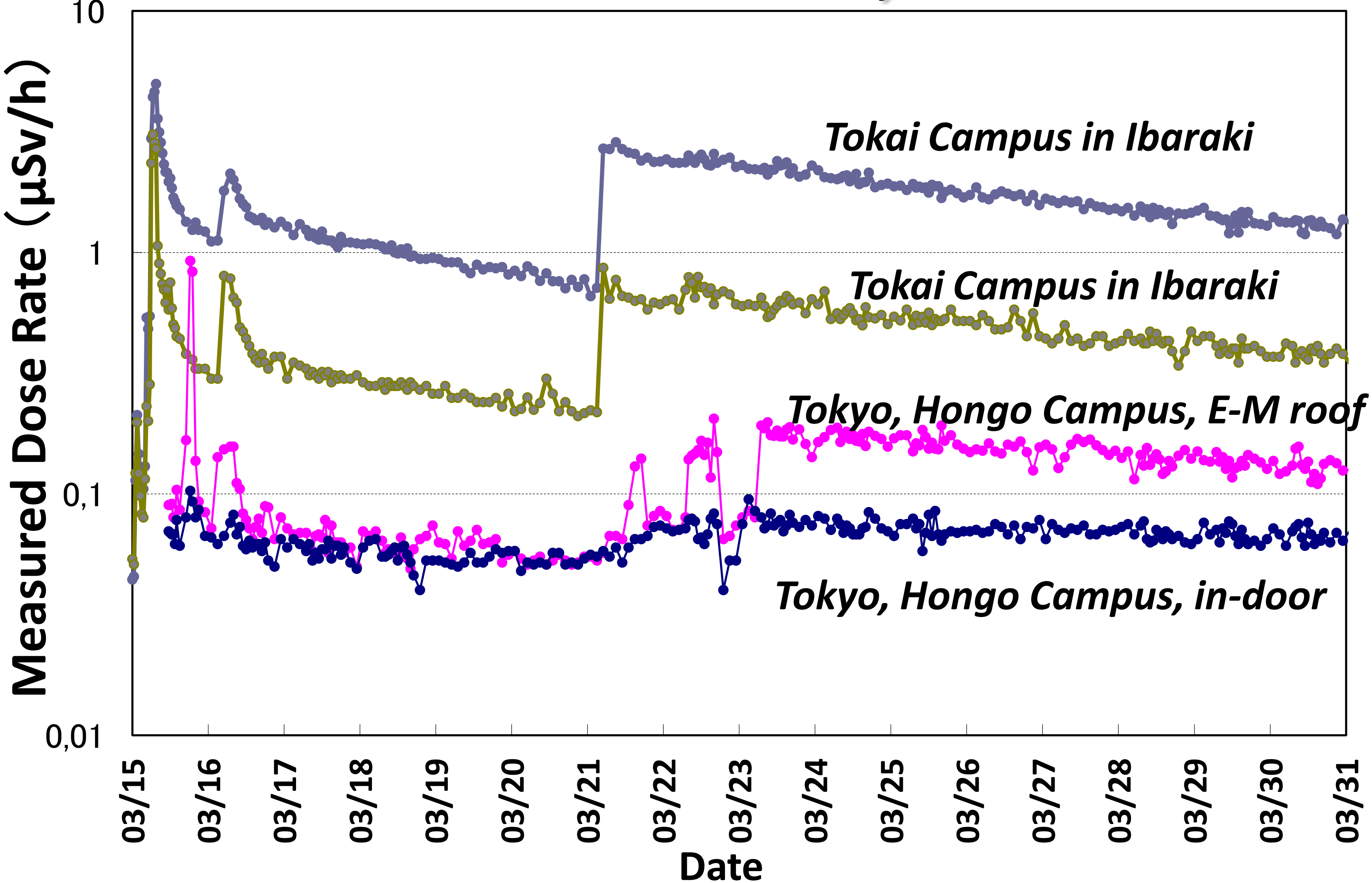
3,695 Workers (working from March) and 3,388 Workers (from April) *
have been inspected by July 29, 2011

Radiation Dose (External + Internal): Number of Workers

100mSv～150mSv	: 86
150mSv～200mSv	: 14
200mSv～250mSv	: 2
250mSv～	: 6
	(309mSv～ 678mSv)

* out of total workers 3,747(from March) + 3,776 (from April)

Radiation Monitoring at The University of Tokyo From March 15 to 31, 2011



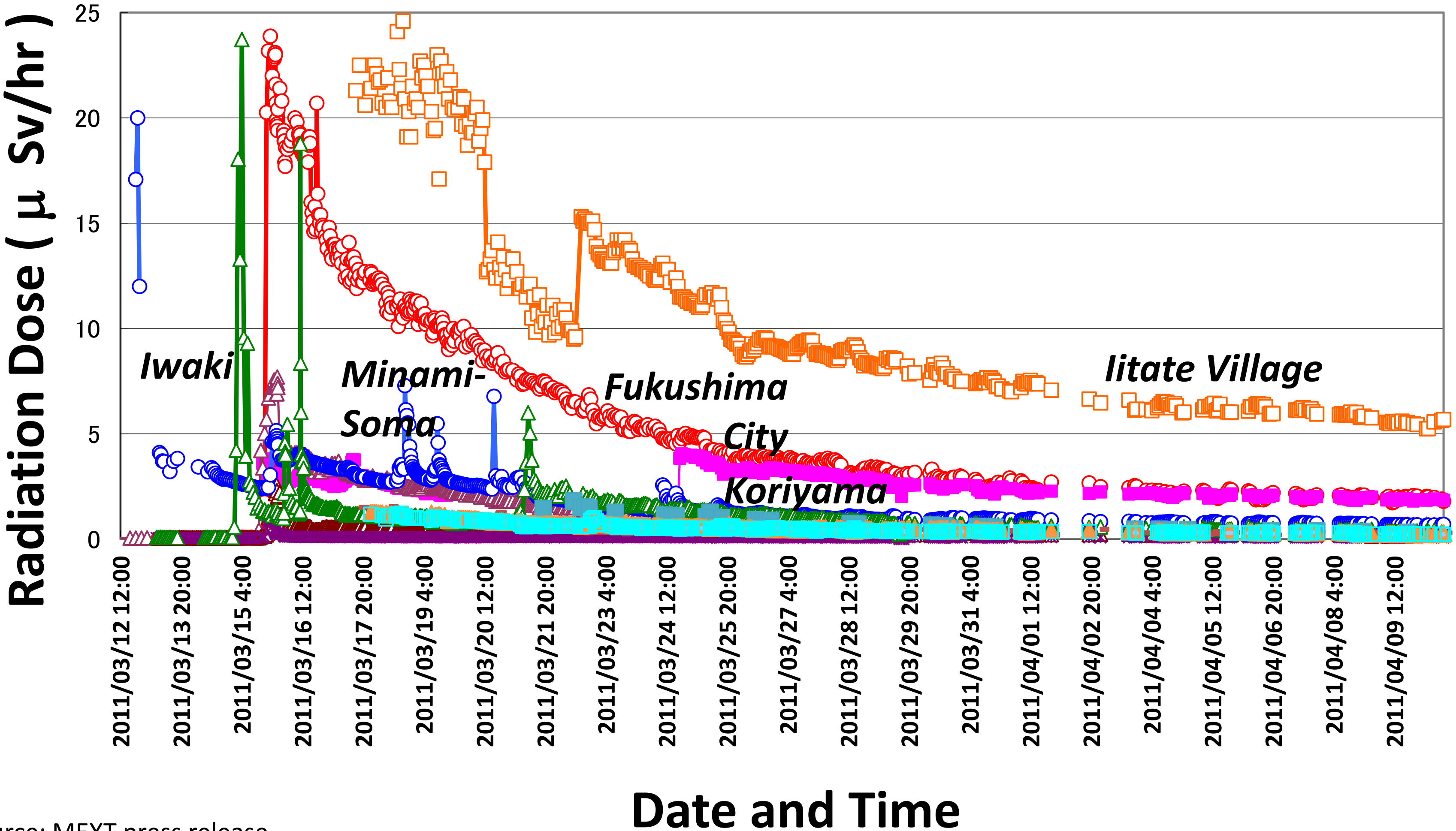
Distance from Fukushima Daiichi NPPs

Ibaraki, Tokai Campus : 110 km

Tokyo, Hongo Campus : 230 km

Radiation Monitoring at The University of Tokyo
From March 15 to May 24, 2011

Monitoring Radiation Dose in Fukushima Prefecture



Source: MEXT press release

Defense in Depth (1)
Approach and Lessons Learned

- Key issues to be addressed in Fukushima Daiichi NPS accident
  (Lack of flexible response to unanticipated events)
  - Level 1 (Prevention of abnormal operation): Simultaneous functional loss of many safety components by tsunami/external event
    => Protection against external event
  - Level 2 (Control of abnormal operation): Scramming, activation of EDGs
  - Level 3 (Mitigation of effects): Failure of engineered safety SSCs due to total power loss.
  - Level 4 (Accident Management): Failed due to severe conditions such as loss of total power
    and high radiation dose
    => Effectiveness and reliability of AM

5.4 (2) Accident Management
Basic Approach on the Development of Accident Management

- Strategy on organization of accident management (AM)
  Since accident management concerns effectively controlling event progression and managing accident recovery, safety must be ensured by combining measures on both tangible/hardware (SSCs) aspects and intangible/human aspects (education & training, procedure manuals, organization).
- AM on hardware/tangible aspects

  Effective use of not only safety margin and engineered safety features in the design, but possible use of other functions beyond their originally intended function, and provisions as new installation of SSCs to respond to accident conditions, etc.
- AM on tangible/human aspects
  Because accident management depends largely on the actions and manipulations by the operating staff, it should include both tangible/hardware aspects (e.g., improvement of SSCs) and intangible/human aspects such as development of education & training, organization, procedures & guidelines manuals.

Failure of Containment Functions of PCV

(1) Leakage path for Gaseous radioactive material

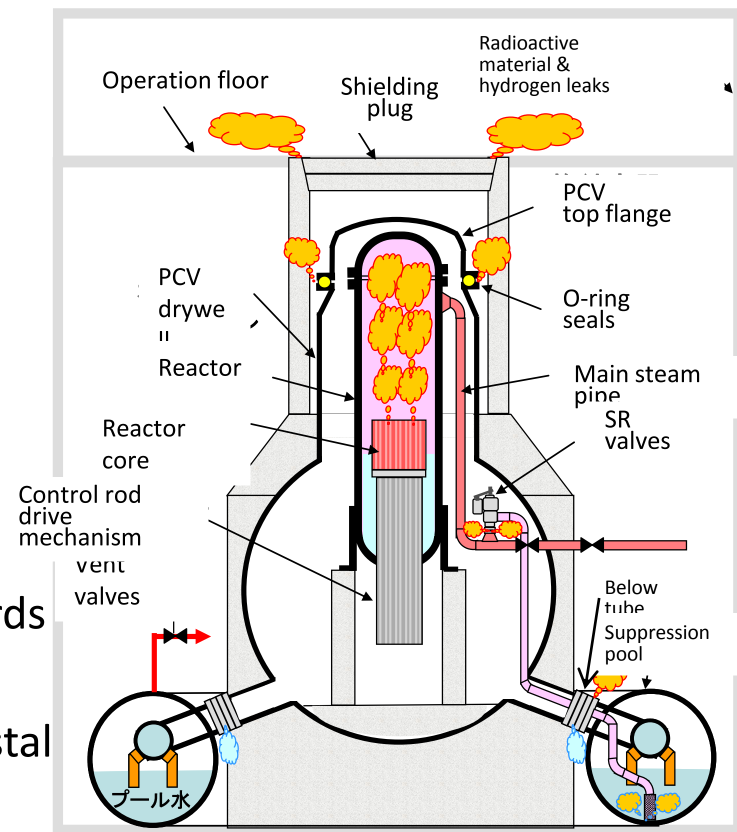
- Likelihood of leaks from PCV penetrations, hatch, and silicon rubber seals of PCV upper flange (200 centigrade heat resistant)
- Need to confirm leak points by conducting onsite surveys

(2) Contaminated water leaks

- Damages in the lower part of PCV, from where contaminated water is assumed to have leaked via the turbine building.
- Verified leaks from part of vent pipe in Unit 1. (Nov. 2012, report by TEPCO)
- Need to reduce leak events

(3) Requires provisions for PCV rupture caused by over-pressure and over-heat

- PCV cooling via containment spray and safeguards against over-pressure via filtered vents;
- safeguards against damages on the lower pedestal of PCV (e.g., coolant injection to PCV pedestal, etc.).



Loss of Power Supply in Units 1-4

Loss of the External Power Supply

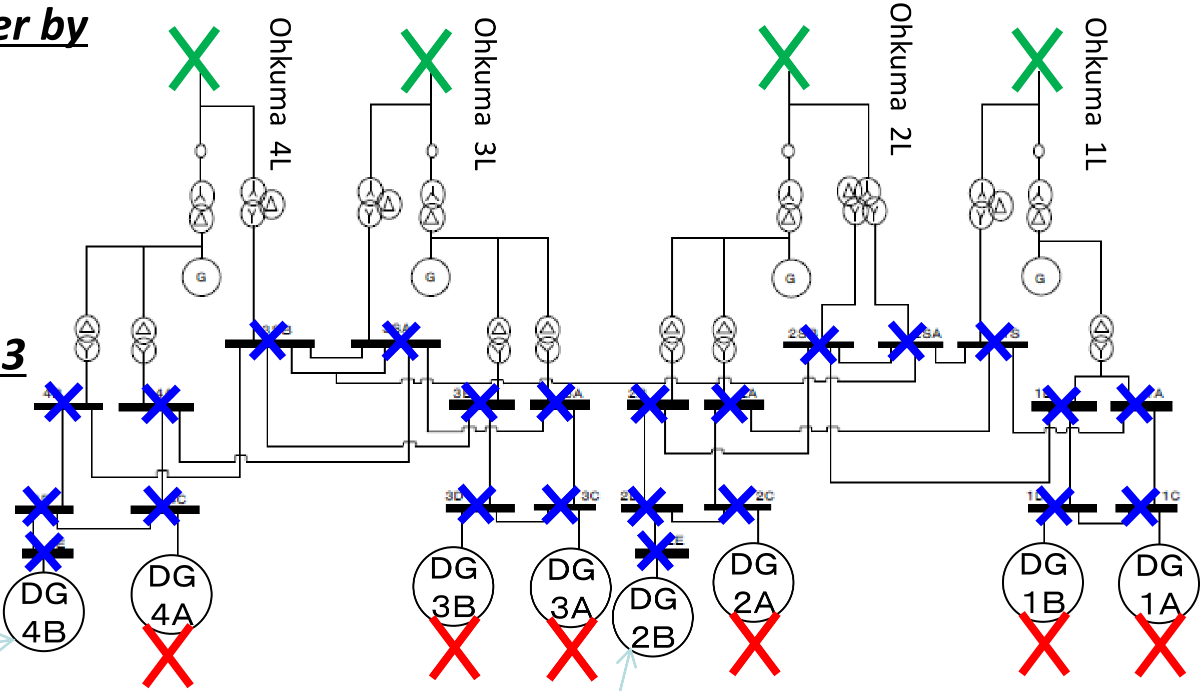
Breakers were broken due to the earthquake

Okuma 3L : Under modification

Loss of all the EDG Functions either by

1)Damage in Generator
2)Loss of Sea-Water Cooling System
3)Damage at Power Panels
by the Tsunami flood

Loss of DC Battery except for Unit 3



Air-Cooled

Air-Cooled

(EDG : Emergency Diesel Generator)

**** Recovery of Off-site Power Supply***
Unit 2 on March 20, Units 1,3 and 4 on March 22

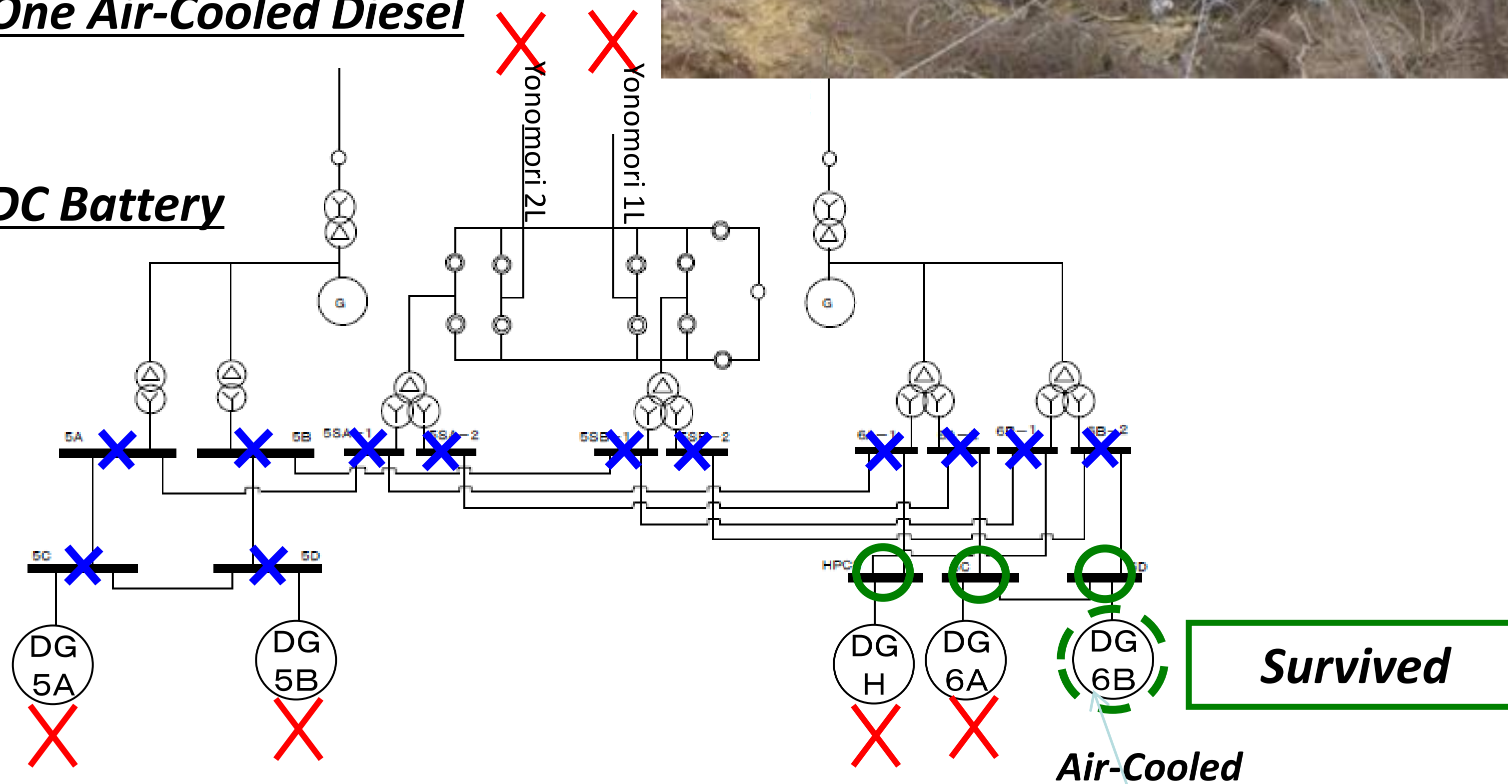
One Air-Cooled DG (DG6B) survived in Units 5 & 6

Loss of Off-site Power Supply

- *Collapse of Pylons by the Earthquake*

Survival of One Air-Cooled Diesel Generator

Survival of DC Battery



Damage in sea-water cooled EDGs by the Tsunami

** Recovery of Off-site Power Supply on March 20-21*

Photographs from One of the Fukushima 50

Source: TEPCO

- **After the Tsunami,**
  - **No lighting available**
  - **What they can get are flashlights, batteries (some are removed from automobiles), fire trucks and some compressors**
  - **Very difficult to measure the major safety parameters like water level, reactor pressure, CV pressure**
  - **No communication tools between the Emergency Response Room and workers at the field**