Review of Accident at Tokyo Electric Power Company Incorporated's Fukushima Daiichi Nuclear Power Station and Proposed Countermeasures
(Summary)

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Japan Nuclear Technology Institute
Fukushima Daiichi Nuclear Power Station Accident Investigation and Review Committee

Introduction

This report is a compilation of the aggregate efforts of the nuclear power industry comprising electric power operators and manufacturers in Japan as concerns the accident at Tokyo Electric Power Company Incorporated's Fukushima Daiichi Nuclear Power Station ("Fukushima Daiichi") which resulted from the Great East Japan Earthquake that occurred on March 11, 2011. This report analyzes the accident based on published facts, knowledge grounded in operational experience accumulated to date, and knowledge developed through plant design, and formulates measures and proposals to be addressed in the future.

We believe that implementing these measures and proposals will ensure that nuclear power stations are even safer.

1. Overview of Fukushima Daiichi Nuclear Power Station and the Accident

1.1 Overview of Fukushima Daiichi Nuclear Power Station

Fukushima Daiichi is located in northeastern Japan (latitude 37 degrees north and longitude 141 degrees east), and looks out over the Pacific Ocean at a distance approximately 225km north of Tokyo.

The first unit commenced operation in 1971, and has a total electrical output of 4,696MW. The principal specifications for each unit are given in the table below.

Unit	Output (MW)	Start of operation	Reactor type	Containment model	General contractor
1	460	March 26, 1971	BWR-3	Mark I	GE
2	784	July 18, 1974	BWR-4	Mark I	GE & Toshiba
3	784	March 27, 1976	BWR-4	Mark I	Toshiba
4	784	October 12, 1978	BWR-4	Mark I	Hitachi
5	784	April 18, 1978	BWR-4	Mark I	Toshiba
6	1100	October 24, 1979	BWR-5	Mark II	GE & Toshiba

1.2 Overview of Accident Following Earthquake off Pacific Coast in the Tohoku Region

At Fukushima Daiichi, as Units 1 thru 3 were operating and Units 4 thru 6 were in the refueling outage, an earthquake occurred off the Pacific coast in the Tohoku [Northeastern] region of Japan at 14:46 on March 11, 2011, and Units 1 thru 3 automatically shut down in accordance with the signal indicating "increasing seismic acceleration."

Following the reactor shutdown, generators shut down and, moreover, functionality of any external power source system equipment was also lost. However, AC power for each unit was supplied by emergency diesel generators ("emergency DG").

Subsequently, due to the tsunami which struck the station, all emergency DG except for one air-cooled unit at Unit 6 shut down, and all AC power sources at Units 1 thru 5 were lost.

Furthermore, DC power sources were also lost due to inundation at Units 1, 2 and 4, and such function was also lost at Unit 3 as a result of batteries being depleted, resulting in a situation where all power being supplied to Units 1 thru 4 was lost.

As a result of the loss of AC power sources, existing cooling function for reactors and spent fuel pools was lost, and cooling was attempted using temporary power sources and alternative coolant injection, but the situation escalated into one where fuel in the core was damaged and radioactive material released into the environment.

1.2.1 Earthquake Impact

In observation record of the earthquake, although the response spectrum based on standard ground motion Ss was surpassed in some periodic bands, values were equivalent overall. In addition, prior to the tsunami arrival, equipment on safety systems was functioning. The earthquake response analysis which Tokyo Electric Power Company conducted of the reactor building as well as equipment and pipe systems critical for earthquake safety on the basis of observation records, showed that all equipment important for safety maintained its functionality.

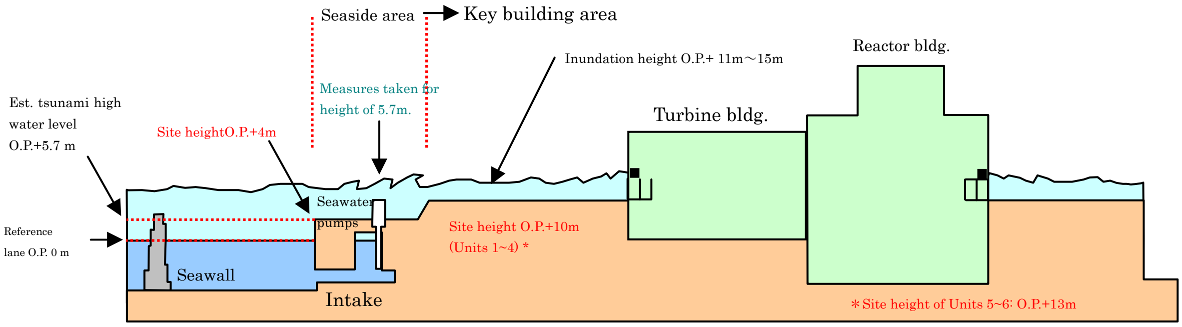
1.2.2 Tsunami Impact

The height of the tsunami exceeded the water level designed for tsunami as shown in the diagram below, and almost the entire area around important buildings was inundated. Although there was no significant damage to the structural framework of key buildings, seawater flowed into the buildings through openings and other penetrations, and a broad expanse of the underground levels was also inundated through passageways, stairwells and other such routes.

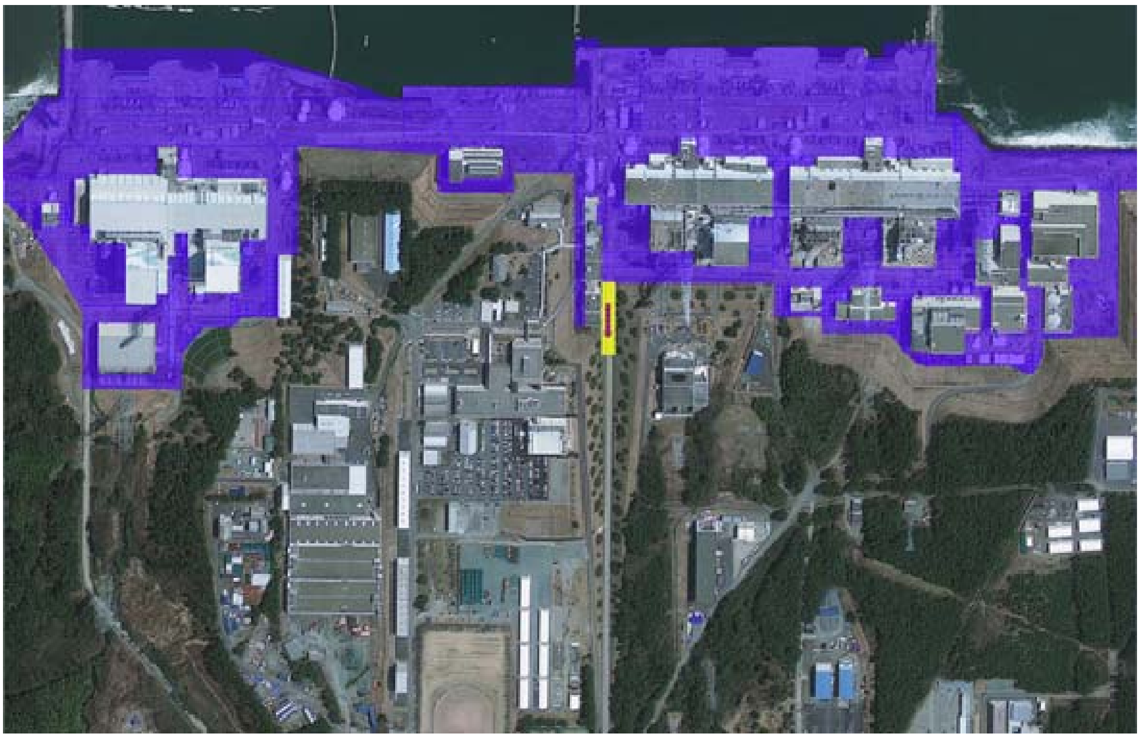
In addition, many of the emergency DGs and electric power panels which were installed on the lower levels of the reactor and turbine buildings were damaged by tsunami. With the exception of Unit 6, functionality of emergency power sources was lost.

Moreover, all seawater pumps for cooling were damaged by tsunami, and any means of releasing heat from the core or other areas into the sea were lost.

Important safety equipment also was damaged by seawater flooding into the buildings.



Tsunami Conditions



Scope of Inundation within Power Station (Purple area indicates seawater inundation and yellow area inidcates a run-up point)

2. Analysis of Accident Event Causes and Issues Derived

2.1 Course of Progression of Accident Events

The course along which events progressed is shown in Diagram 2.1-1, using the example of Unit 1.

The reactor at Unit 1 was cooled by the isolation condenser ("IC") in accordance with the shutdown procedures and guided into a cold shutdown, but the tsunami caused a loss of emergency AC and DC power source functionality, and it is possible that most of the valves were in a closed state.

Consequently, it is inferred that the core was not cooled, became damaged and hydrogen was generated which leaked from the containment vessel to the reactor building, leading to the hydrogen explosion.

The reactors in Units 2 and 3 were being cooled using the reactor core isolation cooling system ("RCIC") and other functions in accordance with shutdown procedures.

After the tsunami struck, Unit 2 maintained core cooling using the RCIC even after the loss of emergency AC and DC power sources. However, after the RCIC shut down, time was required until alternative coolant could be injected and the amount of coolant injected was small, so it is inferred that such conditions led to core damage. Also, a rapid decrease in pressure in the pressure suppression chamber and containment vessel was confirmed. Subsequently, it is inferred that hydrogen leaked from the reactor pressure vessel and containment vessel.

At Unit 3, core cooling was secured through operation of the RCIC and high pressure coolant injection system ("HPCI") even after the loss of emergency AC power sources, but depletion of the batteries led to a loss of the DC power source, and the RCIC and HPCI lost functionality. Time was required until alternative coolant could later be injected and the amount of coolant injected was small, so it is inferred that the core was damaged and hydrogen generated, and that the hydrogen leaked into the containment vessel and reactor building, which led to the hydrogen explosion.

Unit 4 was in the refueling outage and all of the fuel was stored in the spent fuel pool. From the results of fuel observations with a camera and the results of analysis of nuclides in the pool water, it is inferred that there was no significant damage to the fuel. It is possible that hydrogen which exploded in Unit 4 was hydrogen which generated in Unit 3 and seeped into Unit 4 through the standby gas treatment system exhaust to then build up inside the reactor building.

In order to clarify the factors in the progression of events above, the particulars divaricating convergence and expansion of events have been arranged and consolidated into the event tree shown in Diagram 2.1-2.

The subsequent progression of events differs depending on (1) the circumstances entailed in loss of power source functions due to the earthquake and tsunami, (2) condition of core cooling function, and (3) success or failure of measures to mitigate events after core damage, as well as other factors.

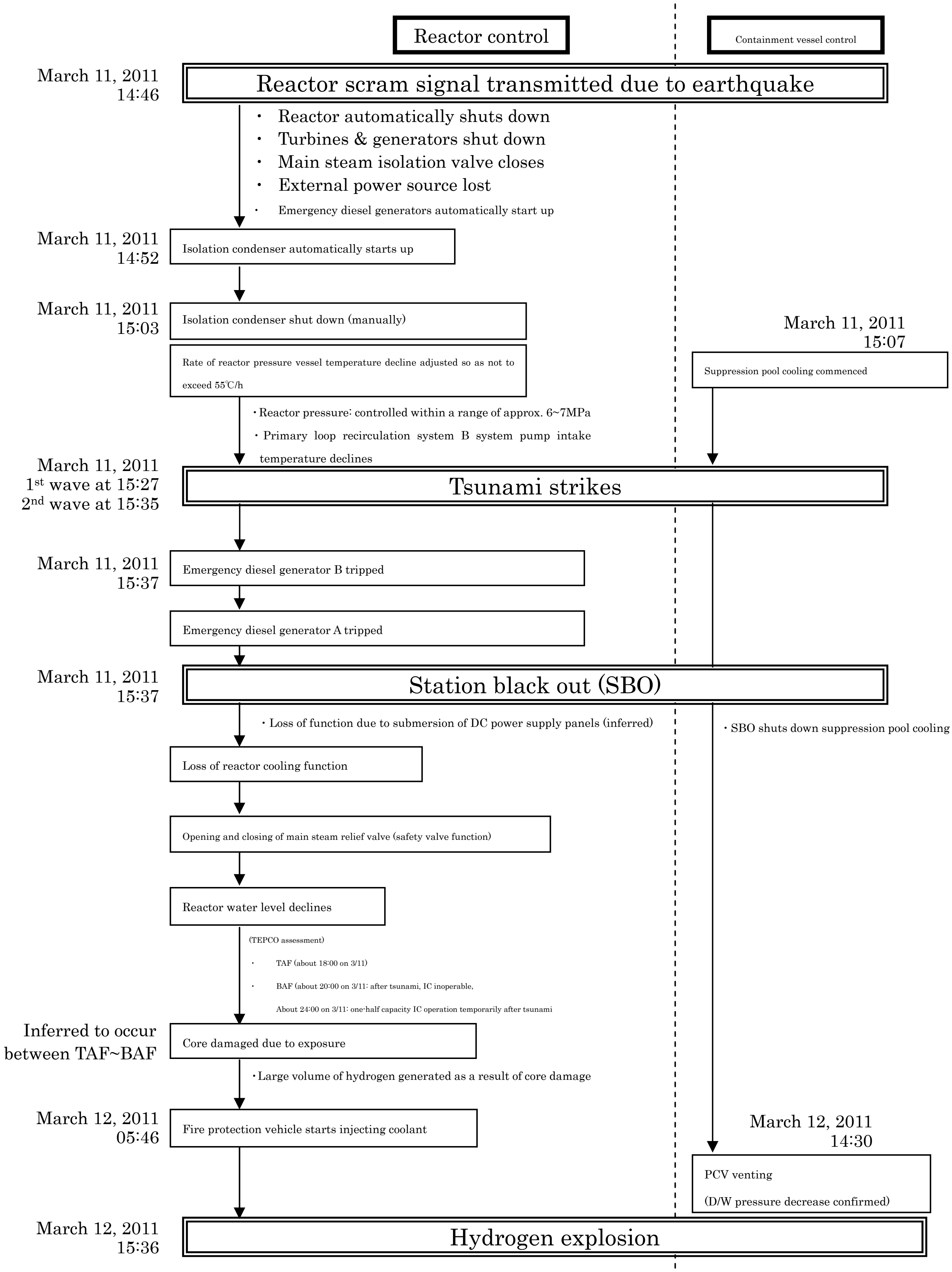


Diagram 2.1-1 Course of Accident Event Progression at Fukushima Daiichi Unit 1 Nuclear Power Station after Earthquake

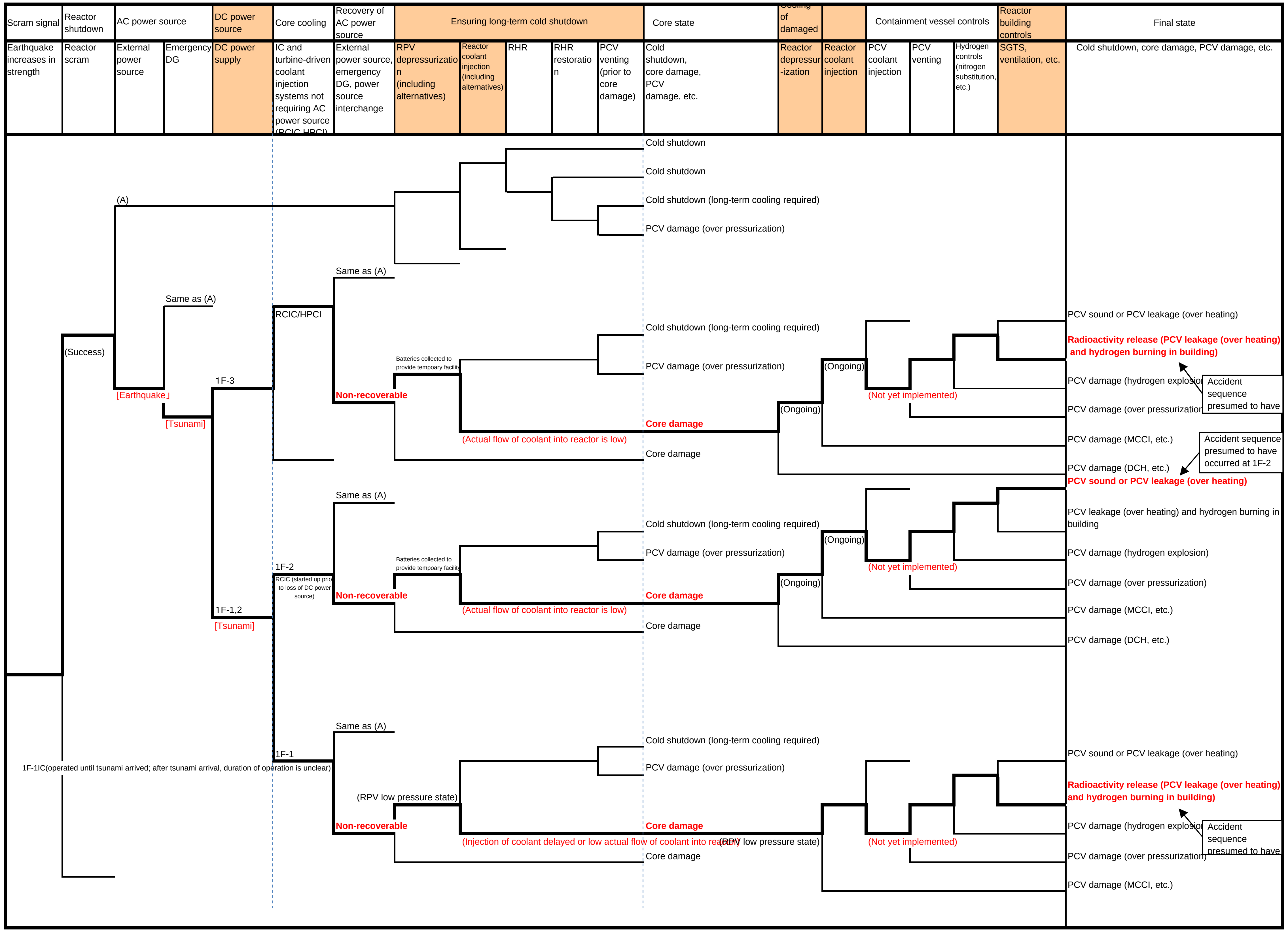


Diagram 2.1-1 Event Tree Showing Progression of Accident at Fukushima Nuclear Power Station Units 1~3

2.2 Analysis of Accident Event Causes and Issues Derived

2.2.1 Analysis of Causes from the Progression of Accident Events

From an analysis of the accident using the course of accident event progression (event tree) 2.1, three major factors, which formed significant turning points in the progression of the accident and escalated the accident, have been deduced ((1) inability to supply AC power to the station, (2) inability to remove heat from the reactor, and (3) leakage of hydrogen into the building and the hydrogen explosion), and issues pertaining to these factors have been derived.

The results of a factor analysis regarding the "inability to supply any AC power source" are shown in Diagram 2.2.1.

(1) Inability to Supply AC Power to the Station

The inability to supply power attributable to the external power source, the inability to supply power using emergency diesel generators, the inability to interchange power sources, and the inability to restore power at an early stage have been cited as factors from an equipment and operational aspect as to the inability to supply AC power to the station.

(2) Inability to Remove Heat from Reactor

The inability to depressurize using the main steam safety relief valve, the inability to remove heat using the core spray and residual heat removal system, the inability to remove heat using accident management equipment (alternative coolant injection equipment), and the inability to vent the containment vessel have been cited as factors from an equipment and operational aspect that failed to remove heat from the reactor.

(3) Leakage of Hydrogen into Building and Hydrogen Explosion

The factor which led to hydrogen leaking into the building has been given to be hydrogen leaking from the containment vessel and circulating into and around the common exhaust equipment, and one of the causes of the hydrogen explosion has been cited as the inability to detect hydrogen leaking into the reactor building.

2.2.2 Consolidation of Issues Confirmed as Functional Aspects

The basic safety functions of a nuclear power station are "stopping," "cooling," and "confining," and the factors which caused these respective functions to malfunction were analyzed. In addition, the basic requirements necessary for implementing "stopping," "cooling," and "confining" operations (main control room heating, ventilating and air conditioning system, communication equipment and other equipment environments) were also analyzed.

Moreover, the common factors which impeded the achievement of each function were the "inability to supply electric power" and "inoperability of auxiliary cooling," and these factors were analyzed and issues derived.

The results of an analysis of accident factors according to function for Unit 1 and the issues consolidated are shown in Table 2.2.2.

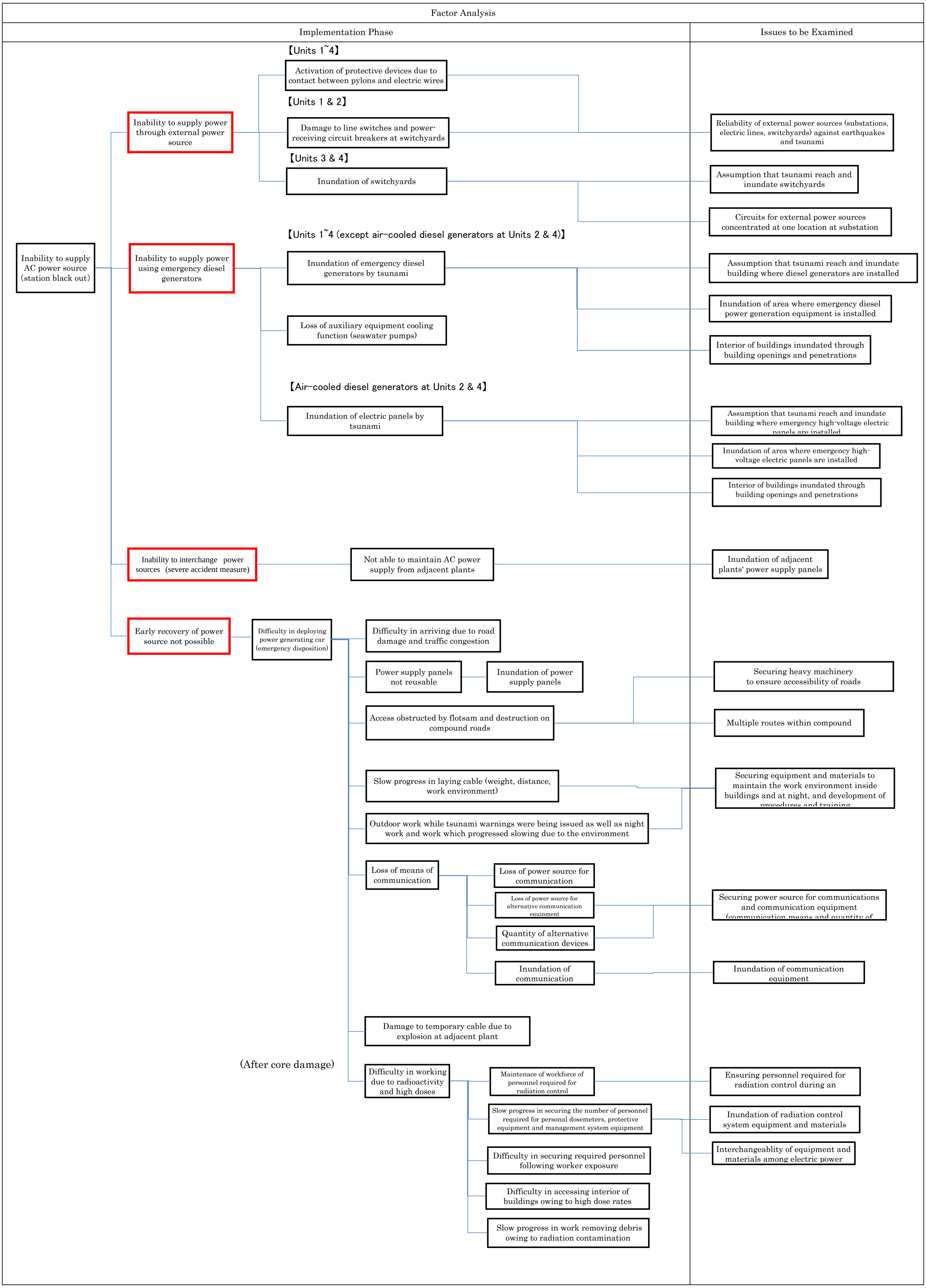


Diagram 2.2.1 Analysis of Factors Leading to Inability to Supply AC Power

Table 2.2.2. Analysis of the 1F U1 accident factors and the issues consolidated

Safety Functions		Related Equipment, etc.	Loss of Function or State of Deteriorated Function		Factor Analysis	Issues to be addressed
Stopping	Emergency shutdown function for reactor	Safety protection systems, control rods and control rod drive systems	○	(Operated normally during earthquake)	–	–
	Alternative reactivity control	Recirculation pump trip (AM)	–	(Not necessary due to scram success)	–	–
		Alternative rod insertion	–	(Not necessary due to scram success)	–	–
	Subcriticality maintenance function	Standby liquid control system	–	(Not necessary due to scram success)	–	–
Support systems	Power supply function	External power source	×	Loss of external power source due to earthquake	Earthquake damaged Okuma line 1L receiving-line circuit breaker at switchyard for Units 1 & 2	① Reliability of switchyard circuit breakers
		Emergency diesel generator	×	Loss of function due to inundation	Inundation of emergency diesel generator by tsunami	② Inundation of emergency diesel generators
		6.9kV high-voltage power supply	×	Loss of function due to inundation	Inundation of 6.9kV high-voltage power supply panels by tsunami	③ Inundation of 6.9kV high-voltage power supply panels
		480V low-voltage power supply	×	Loss of function due to loss of 6.9kV high-voltage power supply	Inundation of 6.9kV high-voltage power supply panels by tsunami	Same as ③
				Loss of function due to inundation	Inundation of 480V low-voltage power supply panels by tsunami	④ Inundation of 480V low-voltage power supply panels
		125V DC power supply	×	Loss of function due to inundation	Inundation of 125V DC power supply panels by tsunami	⑤ Inundation of 125V DC power supply panels
	Alternative power supply function	Power supply interchange	×	Power supply from adjacent plant not able to be	Tsunami caused loss of station power supply at adjacent plant	⑥ Inundation of power supply panels at adjacent
		Power generating car (emergency deployment)	×	Difficulty in arriving at site	Difficulty in arriving due to road damage and traffic	⑦ Furnishing alternative electricity from outside
				Tie-in work progressed slowly	Connection not possible due to inundation of Unit 1 AC power supply panels	Same as ③ and ④
					Difficulty with work laying cable (weight, distance and work environment)	⑧ Laying of cable for alternative power supply
					Intermittant aftershocks and continuously issued tsunami warnings	–
					Loss of communication means due to loss of AC power supply	⑨ Communication means during loss of AC power supply
				No capacity to supply electric power	Automatic shutdown of power generating car and damage to cable due to explosion at Unit 1 reactor building	–
	Auxiliary cooling function	Containment cooling service water system	×	Loss of function due to inundation	Inundation of containment cooling service water system pumps by tsunami	⑩ Inundation of containment cooling service water system pumps by tsunami
				Loss of function due to loss of AC power source	Inundation of 6.9kV high-voltage power supply panels by	Same as ③
		Auxiliary cooling seawater system	×	Loss of function due to inundation	Inundation of auxiliary cooling seawater pumps by tsunami	⑪ Inundation of auxiliary cooling seawater pumps
				Loss of function due to loss of AC power source	Inundation of 6.9kV high-voltage power supply panels by	Same as ③
				Loss of function due to loss of DC power source	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
		Reactor building cooling water system	×	Loss of function due to loss of auxiliary cooling seawater system	Inundation of auxiliary cooling seawater pumps by tsunami	Same as ⑪
				Loss of function due to loss of AC power source	Inundation of 6.9kV high-voltage power supply panels by	Same as ③
				Loss of function due to loss of DC power source	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
	Pressure relief function for reactor coolant pressure boundary	Main steam safety relief valve (safety valve function)	–	(Controlled by isolation condenser)	–	–
	High-pressure core cooling function	High pressure coolant	×	Loss of function due to loss of DC power source	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
		Isolation condenser (main unit)	△ (Operated temporarily)	Functionality deteriorated due to loss of DC power source (remote operation not possible)	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
				Isolated due to transmission of isolation signal (inner isolation valve halfway open due to loss of AC power supply)	Operation of pipe rupture detection circuit due to loss of DC power supply	⑫ Suitablity of design of isolation signal to handle loss of DC power supply
		Isolation condenser (support system): Make up water purified system	×	Loss of function due to loss of AC power source	Inundation of 480V low voltage power supply panels by tsunami	Same as ④
		Isolation condenser (support system): Fire protection system	△ (Operated temporarily)	Electric motor pumps unusable due to loss of external power source	Earthquake damaged Okuma line 1L receiving-line circuit breaker	Same as ①
				Shutdown of diesel driven fire protection pump	Mechanical failure (presumed)	–
	Alternative coolant injection function (high pressure)	Standby liquid control system (AM)	×	Loss of function due to loss of AC power source	Inundation of 480V low voltage power supply panels by	Same as ④
				Slow progress made in operation to restore power supply	【Non-recoverable】Automatic shutdown of power generating car and damage to cable due to explosion at Unit 1 reactor	–
		Conrol rod drive hydraulic system (AM)	×	Loss of function due to loss of AC power source	Inundation of 480V low voltage power supply panels by	Same as ④
				Loss of function due to loss of DC power source	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
				Loss of function due to loss of auxiliary cooling seawater system	Inundation of auxiliary cooling seawater pumps by tsunami	Same as ⑪
	Reactor depressurization function	Main steam safety relief valve (relief valve function/automatic	×	Loss of function due to loss of DC power source	Inundation of 125V DC power supply panels by tsunami	Same as ⑤

Safety Functions		Related Equipment, etc.	Loss of Function or State of Deteriorated Function		Factor Analysis	Issues to be addressed
Cooling	Low-pressure core cooling function	Core spray system	×	No capacity to inject coolant due to inablity to depressurize reactor	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
				Loss of function due to loss of AC power source	Inundation of 6.9kV high-voltage power supply panels by	Same as ③
				Loss of function due to loss of DC power source	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
				Loss of function due to loss of containment cooling service water system	Inundation of containment vessel cooling seawater pumps by tsunami	Same as ⑩
	Alternative coolant injection function (low pressure)	Make up water condensate system (AM)	×	No capacity to inject coolant due to inablity to	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
				Loss of function due to loss of AC power source	Inundation of 480V low voltage power supply panels by	Same as ④
		Containment vessel cooling system (AM)	×	No capacity to inject coolant due to inablity to depressurize reactor	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
				Loss of function due to loss of AC power source	Inundation of 6.9kV high-voltage power supply panels by	Same as ③
				Loss of function due to loss of DC power source	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
				Loss of function due to loss of containment cooling service water system	Inundation of containment vessel cooling seawater pumps by tsunami	Same as ⑩
		Fire protection system (AM)	×	No capacity to inject coolant due to inablity to depressurize reactor	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
				Shutdown of diesel driven fire protection pump	Mechanical failure (presumed)	−
		Fire protection vehicle (support during Chuestsu-oki earthquake)	△ (Insufficient flow, and work progressed slowly)	No capacity to inject coolant due to inablity to depressurize reactor	Inundation of 125V DC power supply panels by tsunami	Same as ⑤
				Difficulty in securing coolant flow required	Difficulty in ensuring capacity of fire control cisterns used as water sources	⑬ Depletion of fresh water supply
				Work progressed slowly	Obstructions resulting from earthquake and tsunami	⑭ Obstructions resulting from earthquake and tsunami
					High dose debris and evacuation of site due to explosion at Unit 1 reactor building	⑮ Worsened working environment due to rise in dosage and hydrogen explosion
					Seawater injection hose damaged and relaid due to explosion at Unit 1 reactor building	Same as ⑮
					Intermittant aftershocks and continuously issued tsunami warnings	−
					Loss of communication means due to loss of AC power supply	Same as ⑨

2.3 Summary of Analysis of Causes

The number one cause as to why the accident at Fukushima Daiichi escalated was that the loss of power sources for driving safety system equipment brought about a secondary loss of a number of safety system equipment functions.

With regard to power sources, if electric power generation shuts down, power is first supplied from an external power source. The system is designed so that, if the external power source loses functionality, an emergency DG supplies power to safety system equipment. This time, functionality of the external power source was lost due to the earthquake, and then tsunami submerged emergency DGs and inundated electric power panels. Because access to power source connections was lost due to inundation of the panels, rapid restoration was not possible, which led to the accident escalating.

The essence of the problem is that preparations assuming a contingency brought about by tsunami strike were ineffectual. What was necessary to prevent an accident from escalating was that provisions be made to implement profound measures for ensuring safety where the preparations undertaken assuming an escalating accident scenario would be expressed as: “If a tsunami floods the site, electric power panels and various important safety equipments will be submerged. In response, necessary countermeasures will be identified and the required equipment provided for in advance. Furthermore, all needed preparations will be made beforehand on the chance that such equipment does not function.”

The fact that external power sources, emergency DGs, electric power supply panels and other equipment related to power supply lost functionality, and that preparations were ineffectual for a situation in which function of such facilities was lost due to a tsunami are considered to have been significant factors leading to escalation of the accident.

The issues deduced in 2.2 have been arranged and consolidated into the following five categories.

- Preparations for earthquakes and tsunami (natural hazards)
- Preparation of power sources
- Measures to counter heat sink loss
- Hydrogen countermeasures
- Preparations for emergency situations

Category	Deduced issues

Category	Deduced issues
Preparations for earthquakes and tsunami	・Loss of function of external power sources due to earthquake or tsunami ・Loss of function of switching stations due to tsunami ・Loss of function of seawater facilities due to tsunami ・Inundation of seawater pump rooms ・Loss of function of emergency DG due to tsunami ・Infiltration of seawater through building openings
Preparation of power sources	・Incoming lines for external power sources at one location ・Submersion of power supply equipment due to tsunami ・Depletion of DC power supplies ・Securing storage battery capacity ・Furnishing of power source externally (power generating cars, etc.) ・Responding to secure supply of AC power ・Laying of cable for alternative power sources
Measures to counter heat sink loss	・Inundation of seawater pumps ・Not all equipment is damaged at once in the face of a tsunami ・In preparation for damage by tsunami, means are provided that are not impacted by tsunami ・Transmitting a signal to isolate the isolation condenser in response to a loss of DC power source ・Securing materials and equipment to respond to a loss of driving source for valves ・Development of procedures and training ・Depletion of fresh water supplies ・Maintaining function of fire protection pipes against the occurrence of earthquake or tsunami ・Furnishing fuel for fire protection vehicles ・Enhancing driving source for pressure vent line valves ・Inoperability of ruptured disks at low pressure

Category	Deduced issues
	・Securing compressed air for maintaining containment vessel vent valves in an open state
Hydrogen countermeasures	・Enhancing seals on penetrations and containment vessel gaskets ・Circulation of hydrogen gas into and around buildings from pressure vent lines ・Circulation of hydrogen gas into and between units having a common exhaust stack ・Retention of hydrogen inside reactor building ・Hydrogen detection
Preparations for emergency situations	・Securing personnel for radiation control ・Tsunami protection measures for radiation control equipment ・Obstructions resulting from earthquakes and/or tsunami ・Communication means when AC power sources are lost ・Materials and equipment for supporting night and outdoor work ・Materials and equipment for securing accessibility of roads ・Securing multiple routes within the station grounds ・Interchange system between electric power operators ・Worsening environment due to hydrogen explosions and rising doses

For some of the aforementioned issues, such as enhancing seals on penetrations and containment vessel gaskets, securing storage battery capacity, and transmitting a signal to isolate the isolation condenser in response to a loss of DC power source, it has been determined, having taken into account the feasibility and effectiveness of measures, that these issues be covered by measures to address other issues and not measures directly responding to such issues.

3. Proposed Measures

After examining the extracted issues intently, the facts were arranged once again in line with the course along which the same accident progressed and countermeasures based on the issues were deduced.

All measures deduced have been arranged in a diagram and are shown in Diagram 2.4-1.

Also, as shown in Table 2.4-1, safety functions, that is measures directly related to power supplies, heat sinks (coolant injection and cooling), measures to prevent a hydrogen explosion, maintaining the water level in the spent fuel pool (SFP) as well as ensuring other functions have been arranged in accordance with the deep protection approach, and high priority measures have been selected from among all the countermeasures. From the standpoint of preventing a recurrence of the accident (giving depth to preparations assuming a scenario in which an accident escalates), even more measures have been put in place in the fourth tier.

The measures have been selected in combination, giving consideration to the safety of the whole plant, and various combinations of these measures are conceivable depending on the conditions at respective power stations and strategies for ensuring safety.

It is necessary to have effective measures sufficient to prevent and mitigate severe accidents by putting in place measures in a multitiered manner so that safety is able to be ensured, even if the measures readied, which are a combination of the various steps detailed here plus those taken into account since the design and construction stages, lose functionality in succession.

Keeping the aforementioned point in mind, the following measures are those which are particularly recommend for adoption by all companies.

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－Power sources

- Installation of seawalls or tide embankments for important safety equipment
- Preventing against inundation of sections where important safety equipment is installed
- Preventing against inundation including improving seals around penetrations and air inlets and other openings in proportion to the height of inundation
- Development of watertight locations for deployment of power receiving transformers and switchyards or measures to prevent against inundation of equipment
- Development of watertight locations for deployment of DC power supply equipment or measures to prevent against inundation of equipment

- Deployment of power generating cars or large capacity power supplies (gas turbines and diesel generators), and development of procedures for emergencies
- Development of routes for recharging DC power supplies by means of backup power sources
- Improving reliability through measures to prevent against inundation of equipment for interchanging power sources between units (severe accident measure)

—Heat sinks (coolant injection and cooling)

- Bulkheads around seawater pumps and other inundation protection measures
- Deployment of spare parts for seawater pump motors
- Deployment of mobile seawater pumps
- Preventing against inundation of sections where the emergency core cooling systems and other safety system equipment are installed
- Measures to prevent against inundation of equipment for severe accident measures
- Backup power supplies, standby air cylinders and other preparations for SRV drives (BWR)
- Ensuring core cooling via SG by means of the main steam relief valve (PWR)
- Deployment of backup power sources and driving sources for venting operations (BWR)
- Improving reliability of existing coolant injection systems through deployment of backup power generating cars or large capacity power supplies
- Movable pumps, hoses, etc. not dependant on existing equipment
- Securing water supplies
- Releasing heat into the atmosphere through containment vessel venting (BWR)

—Measures to protect against hydrogen explosion

- Releasing and reducing retained hydrogen
- Measures to prevent against inflow from pressure strengthened venting lines
- Preventing hydrogen from circulating around between units having a common exhaust stack

Since the accident at the Fukushima Daiichi Nuclear Power Station, all sorts of measures have been adopted by companies, and these which are shown in

Table 2.4-1 along with the approach at a typical plant. At the present stage, it is able to be confirmed that necessary measures have been adopted at each stage from the standpoint of deep protection, and a substantial improvement in safety has already been achieved.

1
【Protection against building inundation】
①Measures to prevent inundation including seal performance at penetrations and openings such as air supply openings and exterior doors to buildings in proportion to the height of any inundation
②Measures to prevent inundation of sections where important safety equipment is installed
③Deployment of portable discharge pumps
④Taking into account the wave force on building exterior doors directly impacted by tsunami

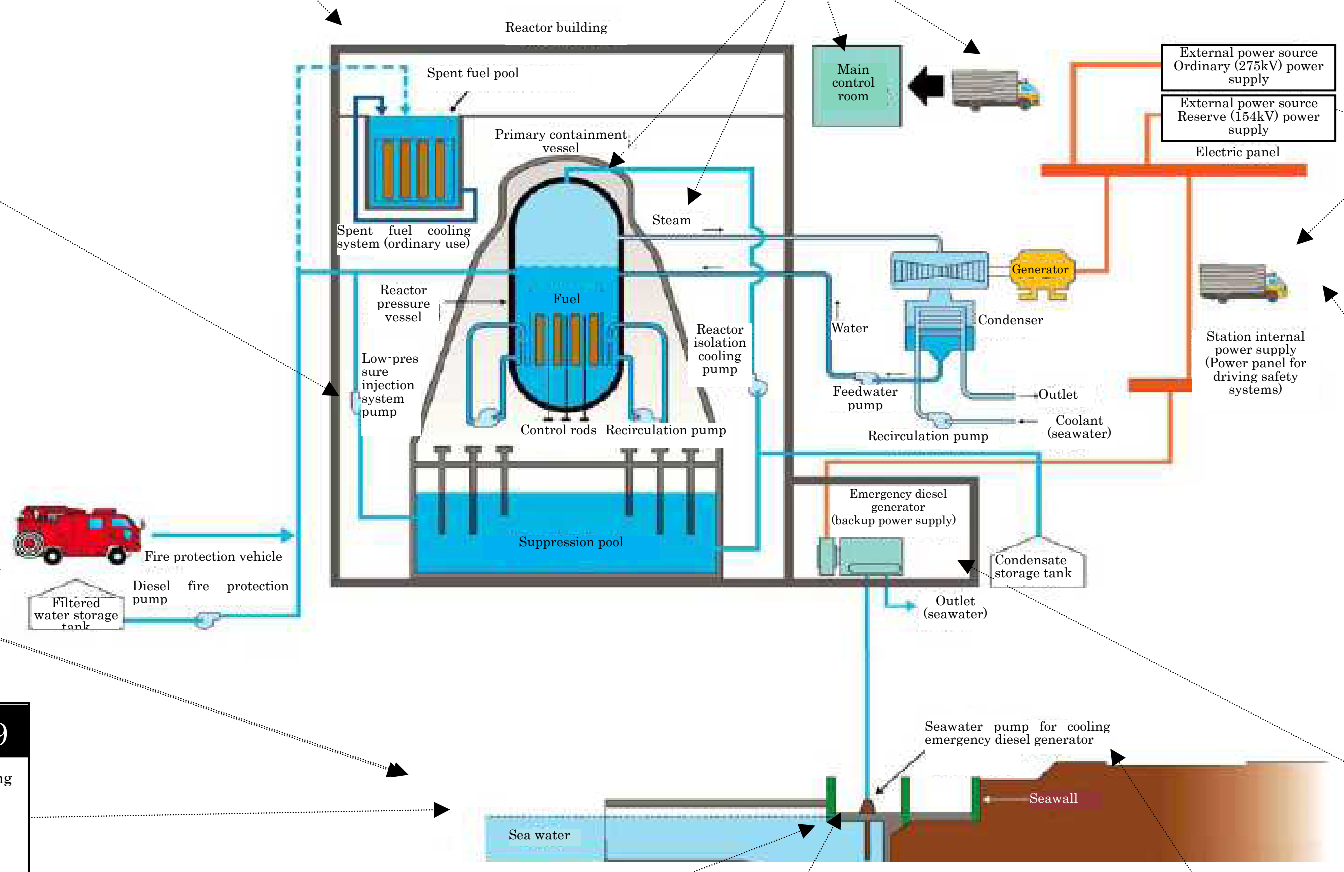
2
【Injection of coolant into reactor】
①Preparation of backup air cylinders, etc. and backup power supplies for driving SRV
【Loss of seawater cooling】
②Release of heat into the atmosphere by venting containment vessel
【Containment vessel venting】
③Deployment of temporary power supplies for monitoring instrumentation for venting operations, and deployment of venting operation backup power supplies and driving sources
④Optimization of conditions for venting operation and timing of commencement
⑤Enhancement of alternative containment vessel spraying

3
【Station black out and loss of DC power supply】
①Deployment of power generating cars or large capacity power supplies (gas turbine or diesel generators), and development of procedures for emergencies
②Development of watertight sections for deployment of power receiving transformers and switchyards as well as measures to guard against inundation of equipment
③Watertight sections for deployment of DC power supply equipment and measures to prevent against inundation of equipment
④Development of routes for recharging DC power supplies by means of backup power sources
⑤Improvement of reliability by means of measures to address inundation of power supply interchange equipment between units

11
【Injection of coolant into reactor】
⑫Measures to prevent inundation of sections where equipment for countering severe accidents or emergency core cooling systems are installed

10
【Injection of coolant into reactor】
⑩Coolant injection using portable motorized pumps and hoses not dependent on existing power sources
⑪Securing sources of water (including seawater as a last resort)

4
【Injection of coolant into reactor】
⑥Improvement of reliability of currently installed coolant injection systems through deployment of backup power generating cars or large capacity power supplies
【Loss of seawater cooling】
⑦Power supplies for providing backup for minimum required function of seawater pumps



9
【Assumption that earthquake/tsunami will occur】
⑩Formulation of standard seismic ground motion Ss takes into account interlocking of multiple seismic centers
⑪Revision of conditions configured for cases when tsunami height is assessed

5
【Station black out and loss of DC power supply】
⑥Watertight sections for deployment of emergency D/G, power supply equipment and emergency D/G cooling equipment and measures to guard against inundation of such equipment

8
【Loss of seawater cooling】
⑧Deployment of seawater pump motor backup and development of interchange procedures to be employed after loss of function
⑨Deployment of materials for washing and drying seawater pump motors

7
【Measures to protect against inundation of seawater systems】
⑦Floodwalls and other steps to prevent inundation around seawater pumps
⑧Deployment of spare parts for motors
⑨Deployment of mobile seawater pumps and installation of pumps with waterproof specifications

6
【Preventing tsunami from flooding the site】
⑤Installation of seawalls or tide embankments at locations necessary for protection of important safety equipment
⑥Protection against tsunami turning tanks and other objects into flotsam and hindering any emergency response. Deployment of heavy machinery for removing flotsam.

Diagram 2.4-1 Typical Measures 1/3

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【Radiation control/work management】

①Diversification of power supplies for radioactivity measuring instruments (battery-type), securing long-term power supplies, provisions placed on high ground, and company- external interchanging

②Securing mobile WBC at other facilities

③Securing protective equipment and gear

④Radiation protection of aseismic important buildings, etc., sharing of site dose rate information, promotion of understanding about emergency exposure treatment

⑤Development of system supporting personnel required for radiation control

13

【Ensuring soundness of spent fuel】

①Enhancing status monitoring and supply of electricity from emergency power sources to water temperature meters and water level meters for spent fuel pool

②Securing alternative cooling function

14

【Hydrogen countermeasures】

①Measures for releasing and reducing retained hydrogen

②Installation of hydrogen gas detectors

③Measures for preventing hydrogen from circulating into branch pipes from containment vessel venting exhaust pipes

④Preventing hydrogen from circulating around between units sharing a stack

⑤Training that anticipates a hydrogen explosion

15

【MCR air conditioning and shielding】

⑥ Securing power supply and developing procedures for operating MCR ventilation systems during emergencies

⑦MCR radiation protection measures

【Measuring during accidents】

⑧Securing connection cables and temporary storage battery cells for instrumentation

⑨Review of instrument power supplies

⑩Selection of parameters required for new instrumentation and review of instrumentation systems

21

【Communication】

㉚ Backup power supplies for independent communication equipment not impacted by earthquake or tsunami

㉛ Communication equipment able to withstand natural disasters

㉜ Deployment of multiple communication devices and clarification of operating methods

㉝ Deployment of equipment for communication with site workers

【Environmental monitoring】

㉞ Review the equipment required for interchanging during emergencies and the number of such equipment required

㉟Review required support personnel and develop routes for deployment

㊱ Securing alternative power supplies for permanent monitoring posts, etc. and reinforcing transmission lines

㊲ Enhancing durability of permanent monitoring posts, etc.

㊳ Clarification of alternative methods for permanent monitoring posts, etc.

㊴ System for cooperation and support for environmental monitoring implemented by local communities

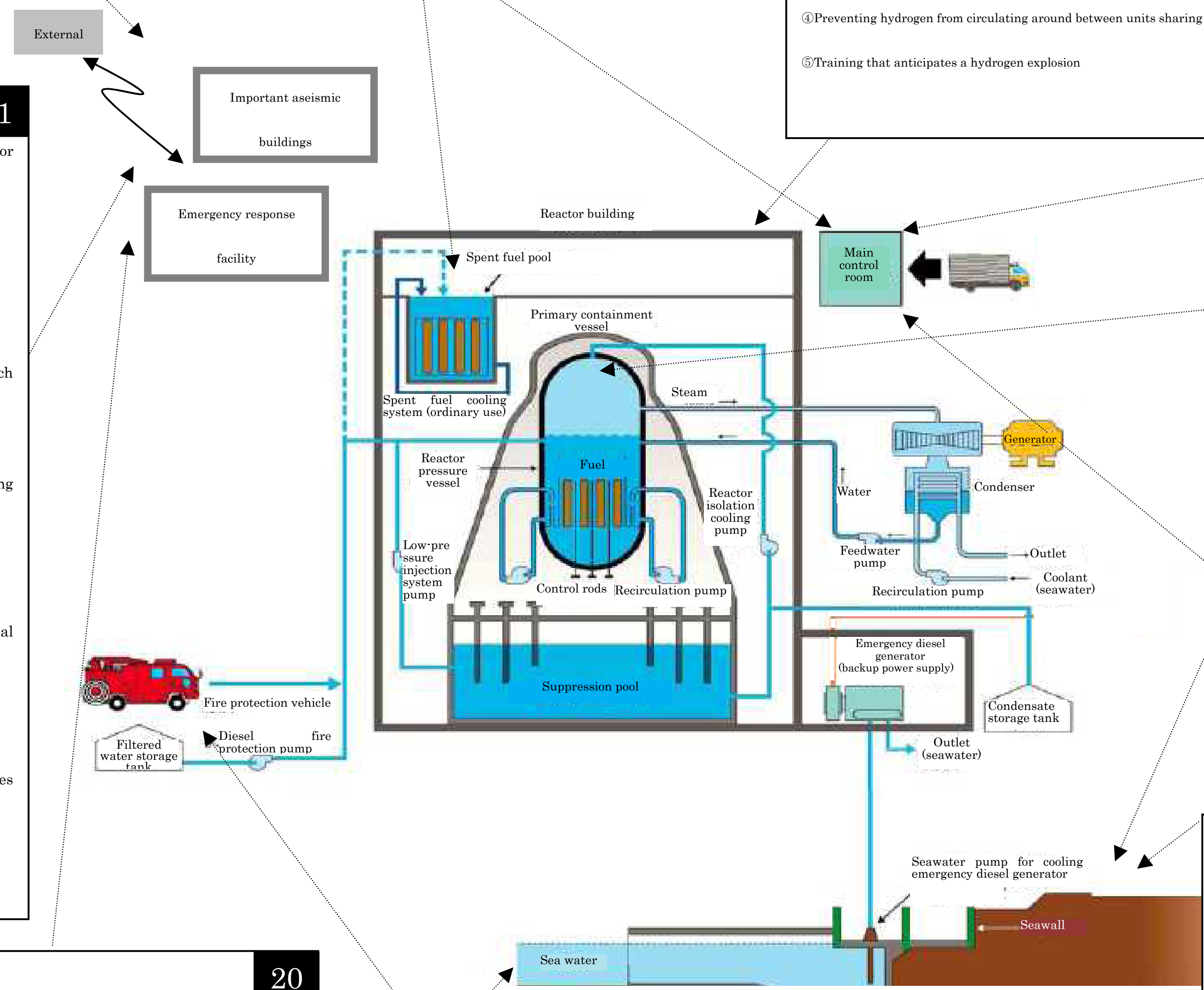
㊵ Clarification of content of information to be disclosed to general public, etc. and methods

【Preparations for dealing with disasters, and cooperative framework during emergencies】

㊶ Diversification of means for transporting materials, equipment and personnel when access routes are blocked

㊷ Securing necessary materials and equipment

㊸ Redevelopment of inter-operator (power company) interchange system



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【Measuring during accidents】

⑪Measures for facilities and instrument measuring range taking account of severe accidents

⑫Development of instruments for severe accidents (environmental resistance, diversity of measuring methods)

17

【Communication】

⑬Deployment of equipment for communications between workers and main control room, etc. and proficiency in such operation

18

【Training】

⑭Consolidation of required knowledge and skills as well as implementation of training

⑮On-site activity training for severe accident measures

⑯Implementation of training simulating night work, having no means of communication, presence of heavy riggings, and obstacles hindering access to site

⑰ Highly effective training including uninformed training, real-time and other such components

⑱Understanding of impact that activities, which are implemented for responding during an accident, have on how events progress

⑲Utilization of simulators

【Preparations for dealing with disasters, and cooperative framework during emergencies】

⑳Deployment of heavy machinery to remove debris

㉑ Cooperation in developing and introducing remotely operable equipment for nuclear disaster prevention, and development of cooperative frameworks

20

【Emergency response facility】

㉒ Structures and siting conditions able to withstand earthquakes, tsunami

㉓ Securing emergency power supply independent of plant

㉔ Securing means of contacting the site, main control room and means of monitoring plant parameters

㉕ Radiation protection measures

㉖ Ensuring habitability

㉗ Securing emergency materials and equipment

㉘ Scrutinizing and securing documentation necessary for emergency countermeasures

【Organization/command and control】

㉙ Clarification of timing of decisions and preparations for rapid operations through early external coordination

19

【Ensuring soundness of spent fuel】

③Securing water supplies, injection routes and injection of coolant by fire protection vehicles, etc.

Diagram 2.4-1 Typical Measures 2/3

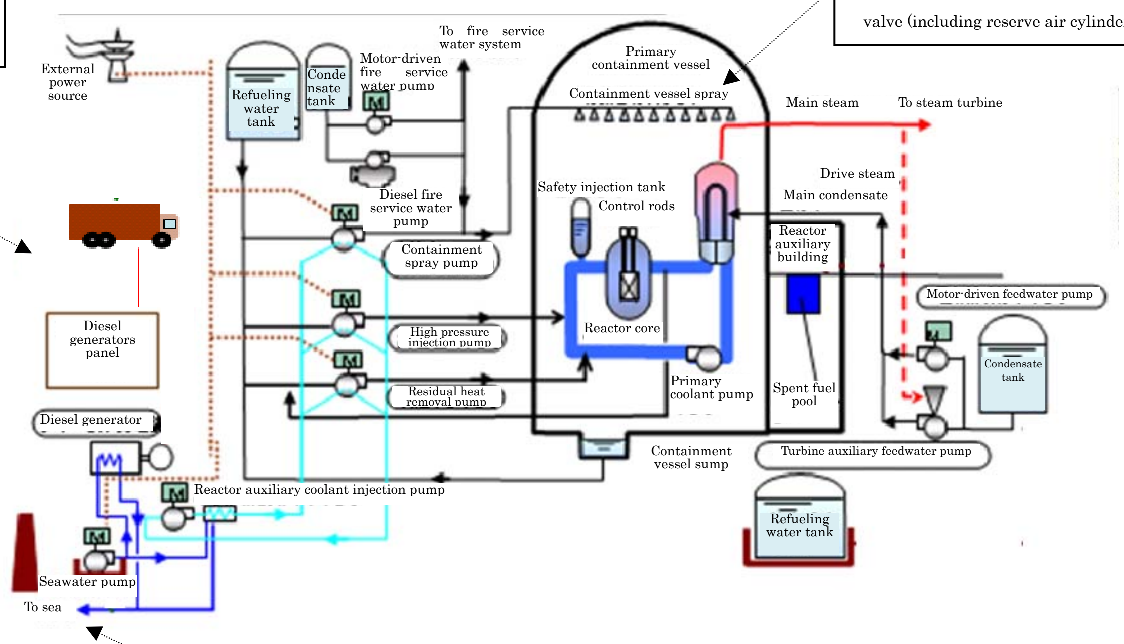
【Injection of coolant into reactor】 1

①Securing coolant injection means through deployment of backup power generating cars or large capacity power supplies

【Injection of coolant into reactor】 2

②Securing alternative means of injecting coolant into steam generator by using portable electric-power pumps, hoses, etc.

③Reactor cooling through steam generator by using the main steam relief valve (including reserve air cylinders, etc.)



【Injection of coolant into reactor】 3

④Securing sources of water (including seawater as a last resort)

Diagram 2.4-1 Typical Measures 3/3

Table 2.4-1 Checklist Arranged from the Standpoint of Deep Protection (Status of Commitment at Typical Plant)

			Preventing accidents from occurring / Mitigating the effects of accidents				
Multiple Protection Levels			First Tier (Preventing abnormalities from occurring)	Second Tier (Preventing abnormalities from spreading and developing into an accident)	Third Tier (Preventing the extraordinary release of radioactive material)	Fourth Tier (Preventing severe accidents from occurring)	Fourth Tier (Mitigating the impact of a severe accident)
Objective			Preventing abnormal operation and accidents	Controlling abnormal operation and detecting failures	Controlling accidents to within design standards	Preventing an accident from progressing	Mitigating the impact of SA
Essential means			Conservative design and construction High quality in operation	Control, confining and protection systems	ECCS and accident procedures	Supplementary means and severe accident measures	Supplementary means and severe accident measures including protecting the PCV
Core	Power sources	Prior to the disaster	・Based on past records, the aseismatic class is configured using a sufficiently conservative design premise and the site height is designed by estimating twice the margin necessary ・Inundation through building air supply, exhaust and other openings due to tsunami not taken into account ・When a plant's power generation shuts down, electric power is supplied by an external power source ・Redundant emergency DGs are set up, and if the external power source fails, backup is provided by the emergency DG ・Restoration is assumed in a short period even if the power shuts down ・The diversity and multiplicity of power sources is ensured by deploying a variety of power sources across multiple systems using external power systems, emergency DG, and DC batteries	・Emergency DG automatic startup from detection of low voltage signal on high-voltage power source bus ・Along with the automatic startup of emergency DG, related equipment starts up sequentially	・On receipt of the automatic startup signal for the ECCS pump, the emergency DG automatically starts up despite supply from an external power source ・Power supply is secured by DC batteries and emergency DG which have redundancy	・The restoration of AC power source is anticipated at an early stage (8 hours) and long-term power outage is not assumed ・After the failure of AC power sources, core cooling is done using DC-driven euipment and the recovery of AC power source is expected ・Development of recovery procedures	・Power source interchange developed between units as a severe accident measures. However, loss of power sources simultaneously at multiple units not assumed.
		Proposed measures	○Seawalls and bulwarks are installed for equipment important for safety ●Preventing against inundation of sections where important safety equipment is installed ○Preventing against inundation including improving seals around penetrations and air inlets and other openings in proportion to the height of inundation ●Development of watertight locations for deployment of power receiving transformers and switchyards and measures to prevent against inundation of equipment ●Development of watertight locations for installation of DC power supply equipment and measures to prevent against inundation of equipment			●Deployment of power generating cars or large capacity power supplies (gas turbines and diesel generators), and development of procedures for emergencies ●Development of routes for recharging DC power supplies by means of backup power sources ●Deployment of portable drainage pumps, etc.	○ Improving reliability through measures to prevent against inundation of equipment for interchanging power sources between units (severe accident measure)
	Heat sinks (Coolant injection and cooling)	Prior to the disaster	・Based on past records, the aseismatic class and site height are designed using a sufficiently conservative design premise ・Heat removal systems are installed which have redundancy ・Multiplicity or diversity and independence are ensured for heat removal systems	・In response to transient events, capability to respond through operations even if ECCS and other safety system equipment cannot be hoped for ・Due to inundation of seawater pumps and power supply panels, the simultaneous loss of function of all units is not assumed ・When the seawater pump is tripped, the backup automatically starts up ・Detectors having to do with the safety of the reactor are designed so that they can be tested even during operation of the reactor and maintenance of soundness and multiplicity can be confirmed	・ECCS and other safety systems are installed along multiple systems ・Even when external power sources cannot be used, power is supplied by the emergency DG ・Systems (IC,HPCI,RCIC) are installed which function on power supplied from DC batteries even when the AC power source fails for a short time ・Ensuring diversity for driving sources through the installation of steam-driven equipment ・Although there are the HPCI and RCIC for which seawater cooling systems for cooling oil and bearings are not needed, their functions fail if DC power is lost	・Severe accident measures (accident management) were developed. Existing equipment used as alternative cooling equipment as necessary ・Inundation or loss of power source for a long period not assumed ・No different alternative types of drive sources for valve types	・Development of connections to fire protection vehicles or other fire fighteing system pipes
		Proposed measures	○Bulkheads around seawater pumps or other measures to prevent inundation ●Preventing against inundation of sections where the emergency core cooling systems and other safety system equipment are installed		● Improving reliability of existing coolant injection systems through deployment of backup power generating cars or large capacity power supplies ○ Deployment of backup power sources and driving sources for venting operations (BWR) ● Backup power supplies, standby air cylinders and other preparations for SRV drives (BWR)	○Deployment of spare parts for seawater pump motors ●Deployment of washing and drying materials for seawater pump motors ●Deployment of mobile seawater pumps ○Preventing against inundation of equipment for severe accident measures ●Movable pumps, hoses, etc. not dependant on existing equipment ●Securing water supplies (including seawater as a final means) ・Releasing heat into the atmosphere through containment vessel venting (BWR) ● Ensuring core cooling via SG by means of the main steam relief valve (PWR)	●Releasing heat into the atmosphere through containment vessel venting (guaranteeing soundness of containment vessel) (BWR) ○Deployment of backup power sources and driving sources for venting operations (BWR)
	Hydrogen	Prior to the disaster			・Installation of combustible gas concentration control systems to control the concentration of hydrogen and oxygen which is generated when there is a cooling failure accident ・Preventing hydrogen from being generated by cooling the core using the ECCS, etc. ・By filling the PCV with nitrogen, an inert environment is created which controls the concentrations of hydrogen and oxygen inside the containment vessel when there is an accident environment to keep it below the flammability threshold	・ Gas circulating between units not taken into account	・If core is damaged, hydrogen may leak from containment vessel.
		Proposed measures				● Releasing and reducing retained hydrogen ● Preventing hydrogen from circulting from pressure strengthened venting lines ●Preventing hydrogen from circulating around between units sharing an exhaust stack	● Releasing and reducing retained hydrogen

≪Description of measures at typical plant≫

Guide to column for typlical measures : ●⇒Items for which implementation is completed or which have been taken into account initially due to factors characteristic of the site
○⇒Items being implemented or such capability is being planned

In Closing

In this report, the nuclear power industry, which is comprised of Japan's electric power companies and manufacturers conducted an examination focused mainly on analyzing factors as to why a core meltdown was not able to be prevented after tsunami struck the Fukushima Daiichi Nuclear Power Station and on formulating measures to counter such a situation.

The causes of the accident were that tsunami strikes inundated station electric installations, particularly the emergency AC and DC power supply panels, which caused cooling, control and monitoring functions to be lost, that time was required to establish means for cooling the core which were not dependent on permanent electric power sources, and that the core was not able to be maintained in a submerged state.

In this review, in keeping with the progression of the accident, we focused on whether the functions expected at each stage worked or not, analyzed causes and factors, and deduced issues and countermeasures. We looked at all measures in combination with existing equipment and countermeasures, arranged the measures from the standpoint of deep protection having the capability to ensure safety, and deduced those with high priority to be multitiered measures.

In addition, we have confirmed that safety has been substantially improved by the emergency safety measures already implemented by each company.

As new information about the accident is obtained, we plan to conduct further studies and review this report.