Chapter 7

Damages to Energy Infrastructures

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Abstract
Working Group 5 (WG5) was organized with support from the JSME Power and Energy System Division to investigate energy policies and to research and analyze various issues related to energy infrastructures, such as nuclear power stations, thermal power stations, hydroelectric power stations, power transmission and distribution systems, gas stations, and oil factories. In order to cover a broad range of topics, the four sub-working groups (A: Nuclear Power, B: Thermal Power, C: General Equipment of Energy Infrastructures, and D: Energy Policy) were established within WG5 from the standpoints of production, supply, and use of energy. The significant results obtained by each sub-working group are reported herein.

Key words : Nuclear power plant, Thermal power plant, Field survey, Energy system, Energy policy, Questionnaire survey

1. Damage survey of power plants

The Kanto and Tohoku regions along the Pacific coast were severely hit by the Great East Japan Earthquake on March 11 in 2011. Damage surveys of nuclear and thermal power plants were narrowed down to the affected area of the earthquake and tsunami. The surveyed power plants are listed in Fig. 1. Those are the five nuclear power plants, Higashidori, Onagawa, Fukushima Diichi, Fukushima Daini, and Tokai Daini, and the nine thermal power plants including the one pilot plant of integrated gasification combined cycle(IGCC), Sendai, Shin-sendai, Shinchi, Hara-machi, Hirono, Nakoso, Hitachi-naka, and Kashima. The field surveys were conducted at the underlined plants in Fig.1.

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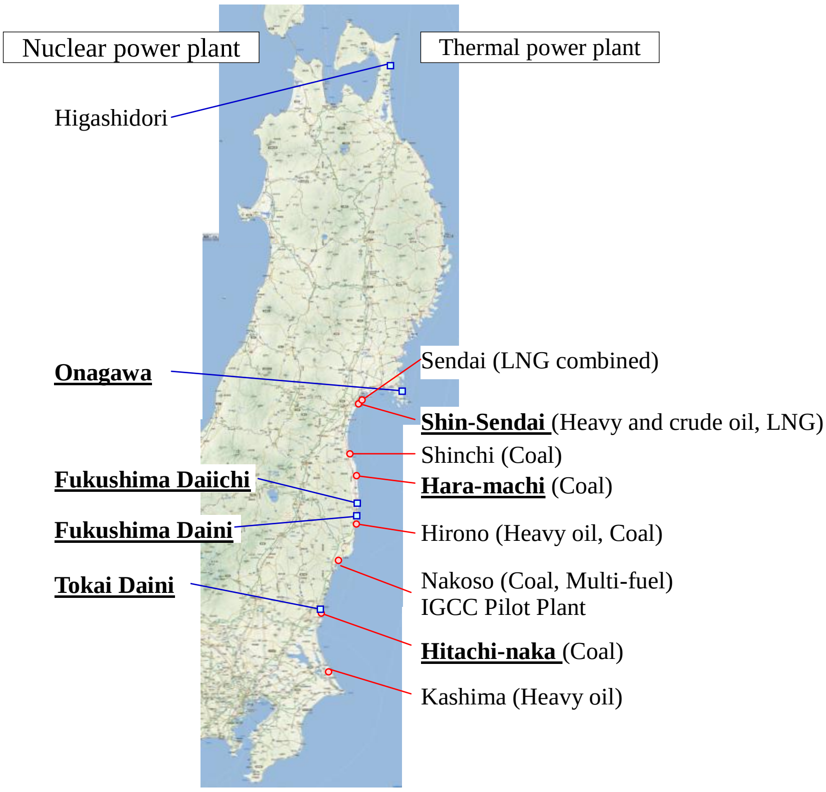

Fig. 1 Nuclear and thermal power plants in the Kanto and Tohoku regions along the Pacific coast.

1.1 Nuclear power plant

Figures 2 and 3 show the tsunami hitting the Fukushima Daiichi nuclear power plant and the reactor buildings damaged by the hydrogen explosion that was caused by the subsequent station blackout and core meltdown, respectively. Based on the results of the investigation and analysis of the accident at the Fukushima Daiichi nuclear power stations, the following important technical issues were recognized: (a) important equipment such as emergency batteries and emergency generators should be stored or located in water-resistant areas, and (b) power-supply cars and switchboards should be placed on higher ground. An investigation was also conducted on the accident management. First, it was estimated that the nuclear reactor core of unit #1 was under complete exposure before 18:00 JST on 11 March 2011 (Aritomi, 2012). This implies that there was only a very limited amount of time during the accident management to avoid serious outcomes, such as the release of radioactive materials into the environment. Furthermore, it was considered that the persons in charge at the site, the central office of the Tokyo Electric Power Company and the headquarters of the Japanese government, did not adequately recognize the aforementioned serious situation. Understanding the spatial and temporal development of the events expected after the occurrence of an accident and the information of the plant status are the basis used to take appropriate accident management procedures. Therefore, instrumentation systems to determine the plant status should be available under any circumstances. During the past 40 years, since unit #1 of the Fukushima Daiichi nuclear power plant began full operation, various experiences and effective safety measures pertaining to a possible nuclear power plant accident, including TMI-2, have accumulated (U.S. NRC, 2002). Additionally, the outcomes of the researches on severe accidents carried out by the Japan Atomic Energy Agency (JAEA) and Japan Nuclear Energy Safety Organization (JNES) were reported (Nariai, 2011), but the knowledge obtained from these was unfortunately not used sufficiently for “kaizen” or for the improvement of the existing nuclear power plants in Japan. In the investigation report of the TMI-2 accident that was published over 30 years ago, it was already pointed out that when new knowledge is obtained, it should be applied immediately to existing plants to extract new important issues, maintain the effort for kaizen, and to re-examine the institutional design (President’s commission on the accident at Three Mile Island, 1979). In addition, unit #1 was developed by the General Electric Company as a turnkey project; in other words, unit #1 was not developed by JSME. In view of this, it may be obvious that it was of particular importance to thoroughly investigate the previous accidents at nuclear power plants and the outcome of severe accident research to improve the safety features of nuclear power plants in Japan. As a

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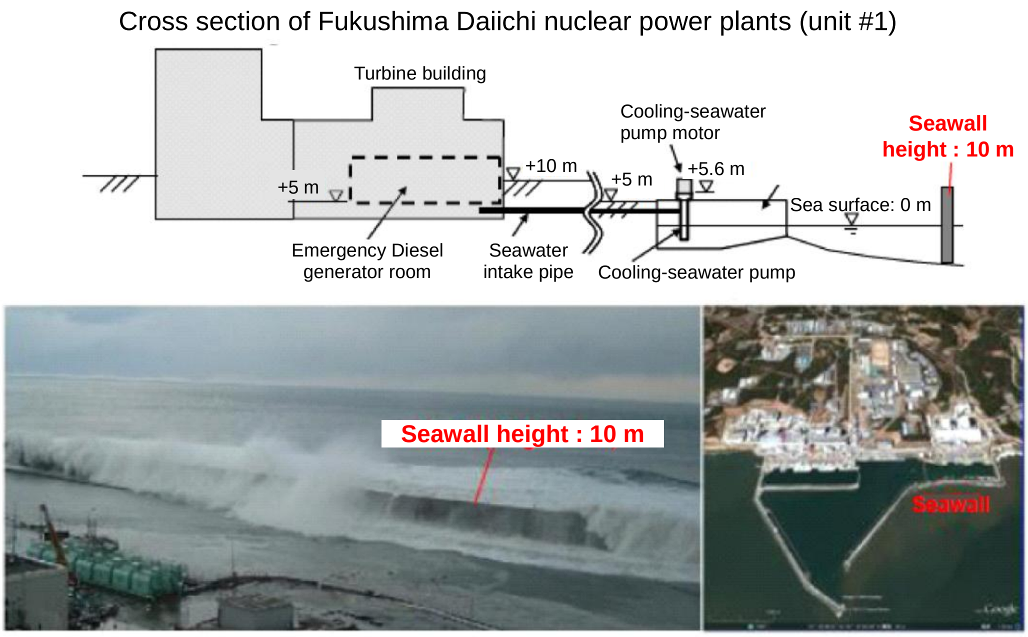
response to the September 11 attacks, the United States Nuclear Regulatory Commission (US NRC) pointed out the possibility of a nuclear power station blackout caused by terrorism and requested a countermeasure be taken to ensure that the cores can be cooled under any circumstance (US NRC, 2012). It is of our deepest regret that we did not follow such a measure, but this will certainly be in place for future operations.

Many important lessons were also learned from the events that occurred at the nuclear power plants (NPPs) other than the Fukushima Daiichi nuclear power plant. At the Tokai Daini nuclear power plant, the Japan Atomic Power Company increased the height of the wall surrounding the seawater pump and improved the water-tightness of the penetration sections; these measures were taken before 11 March 2011 in response to a map that showed where flooding caused by a tsunami was expected, as provided by Ibaraki Prefecture in October 2007. As a result of implementing these countermeasures, two out of the three seawater pumps for the emergency diesel generators were able to avoid the flooding caused by the tsunami (Fig. 4). The Fukushima Daini nuclear power plant was struck by a tsunami that was higher than expected, but a cool shutdown was achieved by prompt operations, which included the implementation of temporal electric cables and the transportation and placement of alternative pump motors (Fig. 5). This confirmed the importance of preparing backup systems, creating manuals for accident management, and ensuring the use of alternative equipment. In the Onagawa nuclear power plant, an electrical short circuit occurred in a high-voltage power panel and caused a fire, which threatened the seismic class-S equipment. As for the Fukushima Daiichi nuclear power plant disaster, the seismic class-S equipment of the nuclear power plant units that were investigated was not damaged due any of the earthquake motions. Thus, it can be considered that the precautionary measures taken for earthquake motions were appropriate. However, a re-examination is required for the possibility that the functionality of the class-S equipment was influenced by the damage of the class-B and/or C equipment caused by the subsequent fires. Another notable event occurred at the Onagawa nuclear power plant. During this event, although the tsunami height was less than the ground height, several pumps were flooded due to the tsunami, which caused the emergency diesel generators to fail. The top of the box containing the tide indicator was blown off due to the increase in sea level caused by the tsunami. As a result, the reactor building was connected to sea to cause the flooding of the reactor building by the sea water (Fig. 6). The box top was very weak because the tide indicator was added after the nuclear power plant began operating without taking the risk of flooding into careful consideration. This is an important example that shows that meticulous attention is needed when implementing countermeasures to ensure water-tightness.



Reference: The Tokyo Electric Power Co., Inc. Release
[Online] http://www.tepco.co.jp/tepconews/pressroom/110311/index-j.html

Fig. 2 Layout of the seawall and an image showing the tsunami hitting the Fukushima Daiichi nuclear power plants.

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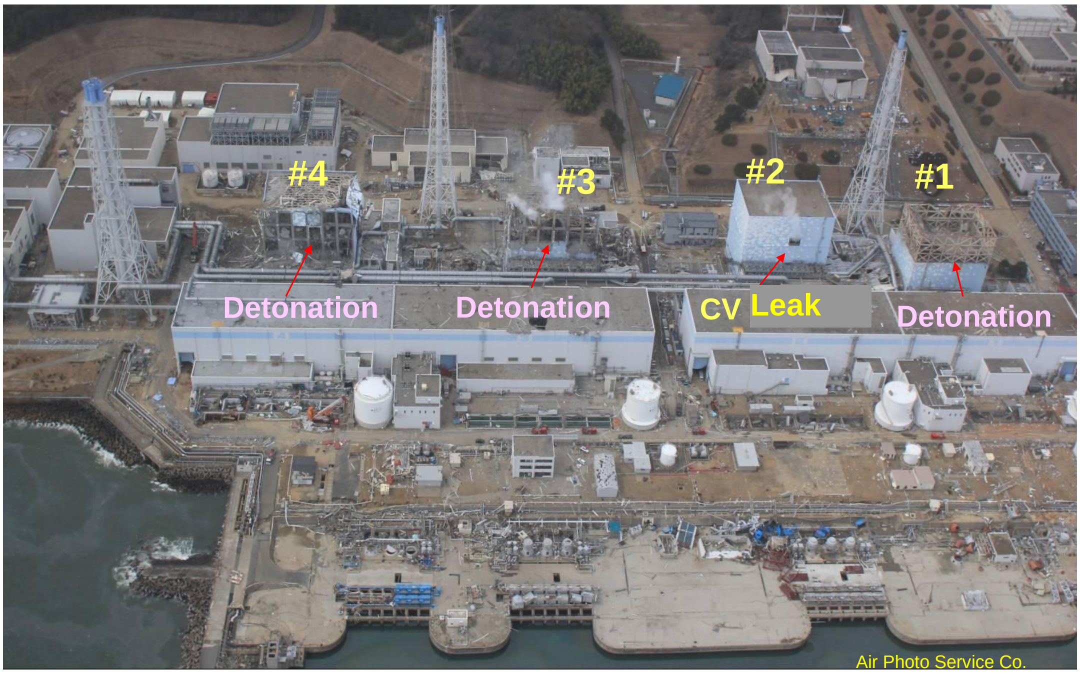

Fig. 3 Reactor buildings of the Fukushima Daiichi nuclear power plants after the occurrence of the hydrogen explosions (Courtesy of Air Photo Service Co.).

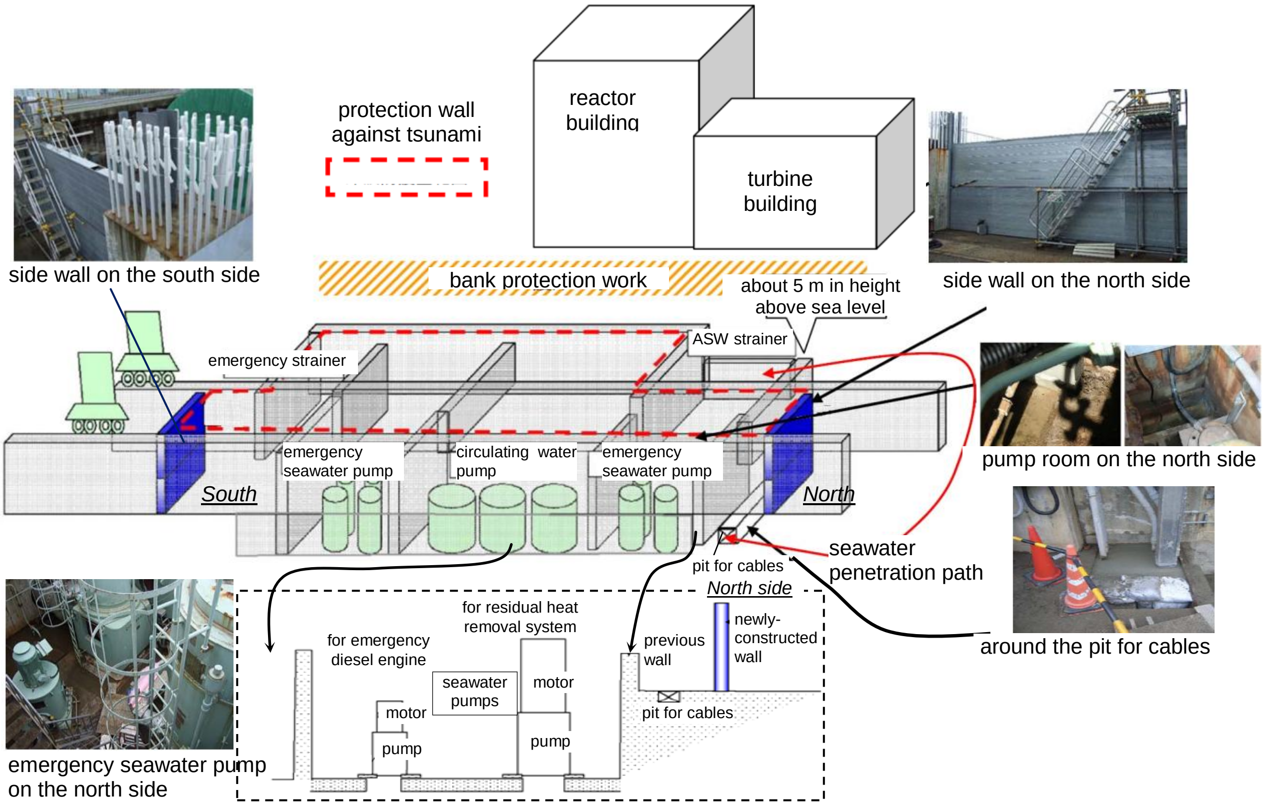

Fig. 4 Layout of the seawater pumps for the emergency diesel generators at the Tokai Daini nuclear power plant (The Japan Atomic Power Company, 2011).

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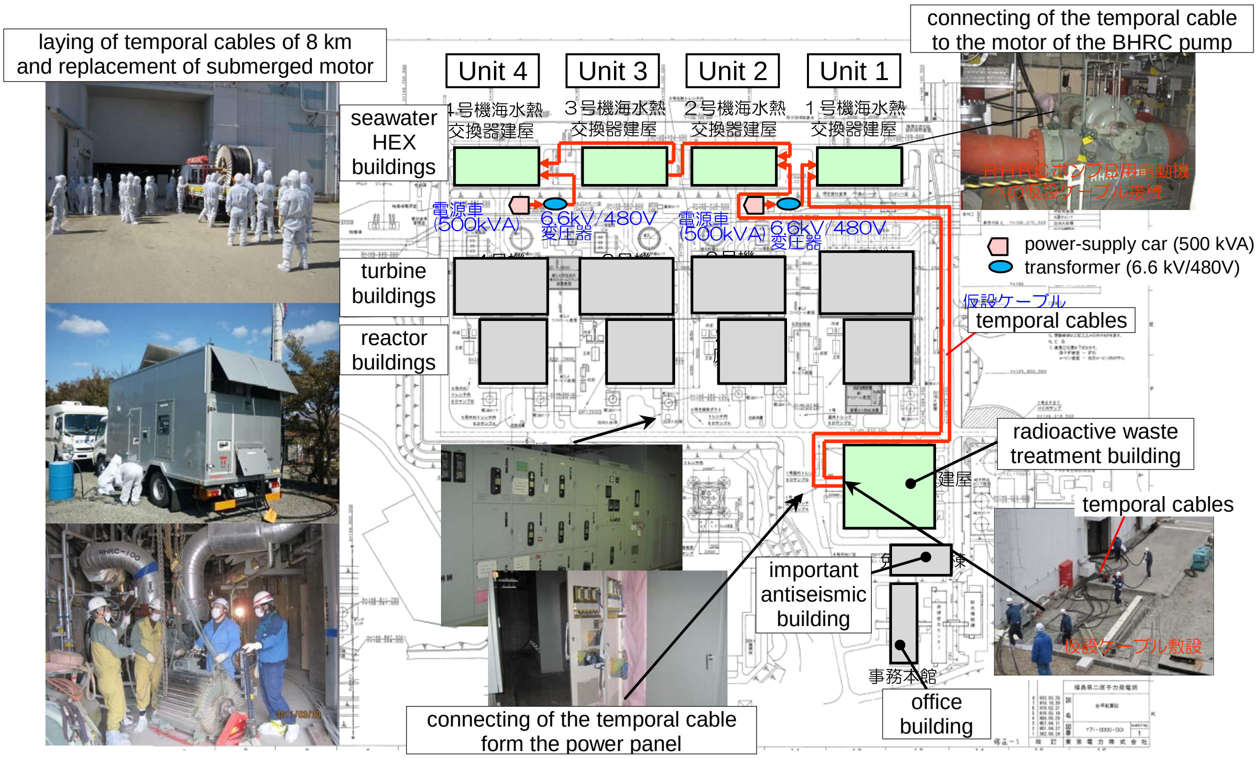

Fig. 5 Layout of the temporal electric cables and the transportation and placement of the alternative pump motors at the Fukushima Daini nuclear power plant (Tokyo Electric Power Company, 2012).

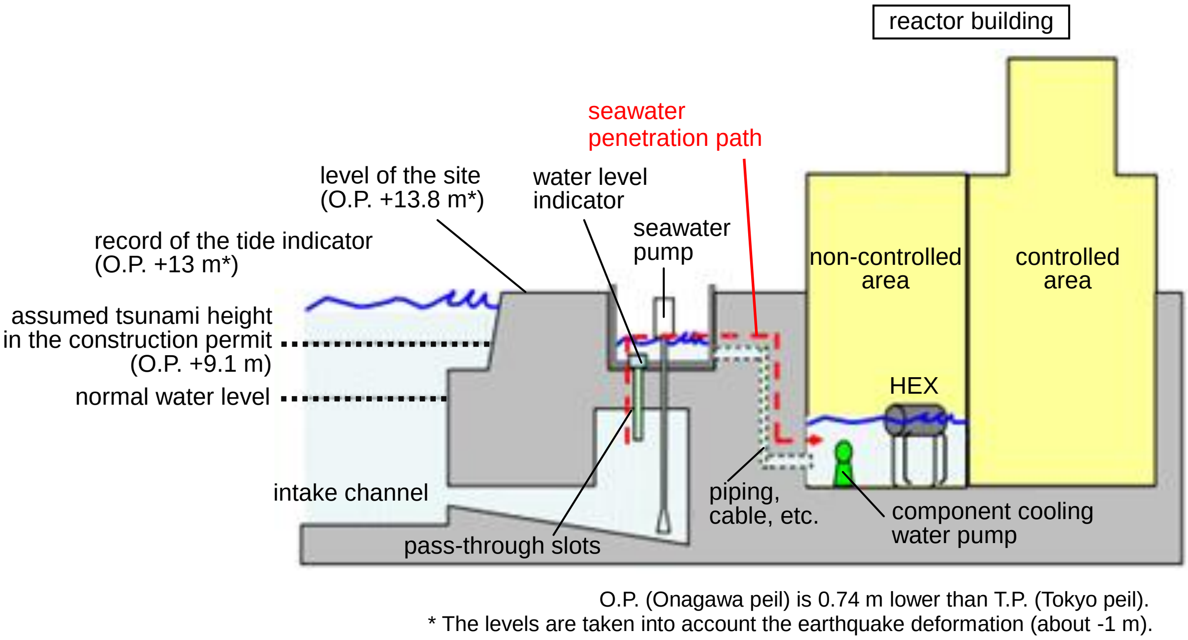

Fig. 6 Image showing how the building next to the nuclear reactor building of unit #2 flooded at the Onagawa nuclear power plant (Tohoku Electric Power Company, 2011).

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1.2 Thermal power plant

On-site surveys and hearing surveys using questionnaires were conducted by Group B on eight thermal power plants and one pilot plant of the integrated gasification combined cycle (IGCC) in the Kanto and Tohoku regions along the Pacific coast that were damaged by the earthquake and tsunami. The causes and degree of damage were investigated.

The summarized results of the questionnaires that were provided during the investigation are shown in Tables 1 (a) to (c) for each cause of damage. The level of damage is classified into four levels. Level "A" indicates no damage, "B" indicates minor damages that can be repaired by only replacing a few parts, "C" indicates severe damages that require many replacement parts, and "D" indicates that the facility is no longer usable. Table 1 (a) shows that the main facilities of the thermal power plants were robust enough to withstand the shock of the earthquake. Although the boilers were damaged by the shock of the earthquake, which included damages to the hydraulic anti-vibration equipment and the deformation and formation of cracks in the super heater, evaporator, and economizer, the damages were only minor. The tsunami devastated the thermal power plants along the coast. In particular, the Hara-machi coal-fired thermal power plant was devastated by an enormous tsunami that had a height of about 18 m. An office building was flooded to the ceilings of the third floor. The electrostatic precipitator was also flooded, and the buoyancy force acting on destroyed the basement and the connecting induced draft fan to demolish. Despite such devastating damages, the Hara-machi power plant started to commission its second plant on 3 November 2012 and its first plant on 28 January 2013. A station blackout due to the tsunami caused the other plants to experience extreme difficulties. A steam turbine was not operable after it came to an emergency stop. Another steam turbine was damaged because its lubrication oil system was not functioning. However, these damages on the steam turbines are considered to be only minor. On the other hand, a thermal power plant on an artificial island experienced liquefaction and subsidence. Although the soil liquefaction affected conveyor belts and pipelines, the damage was repairable by rearranging the support legs. Main buildings and facilities were not damaged due to their foundation pile. All investigated thermal power plants except the Hara-machi thermal power plant began operating within a year after the disaster due to dedicated efforts.

The following list states what can be taken from the experiences of the disaster.

a. Emergency evacuations

Emergency evacuations during the earthquake and from the tsunami were effective. However, there was an unfortunate case of human loss during a secondary disaster response. Guidelines and drills of an emergency evacuation for a secondary disaster are required.

b. Ensure emergency communications are provided

A portable satellite telephone is the most effective tool during disaster conditions. However, its battery needs to be charged for it to be used continuously.

c. Emergency power systems

There was one in which an emergency power supply did not function, since the room with the control rack was flooded; however, the power generator and batteries were safe from the flooding caused by the tsunami. Thus, it is strongly recommended to place the emergency power source on the turbine floor with its control rack. A power source for startup must also be kept at this location. An emergency power supply is required not only for facility conservation, but also to protect the staff.

d. Fires in electric systems

There was one case in which the electrical room in a service building was on fire. The ignition source may have been a spark in the terminal or frictional heating caused by the shock of the earthquake. Consideration on the use of flame retardant materials will be required to prevent the ignition and dispersal of fires.

f. Floating objects due to the tsunami

There was a case in which a windbreak net prevented floating objects, such as automobiles and containers, to flow into a yard. Since automobiles often become causes of fire, parking lots for automobiles must be on higher ground or surrounded by a windbreak net.

g. Improvement in quake resistance for fixed components

There were cases in which ceiling panels collapsed in a central control room and an accident occurred due to the

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collapse of a grating floor. The structures of these fixed components need to be improved.

h. Improvement in the water-tightness of buildings

Roll-up doors were easily damaged due to the increase in water pressure caused by the tsunami. Instead of roll-up doors, watertight doors should be used for electrical rooms.

Table 1 Damage conditions classified by their cause.

(a) Shock of the earthquake

Components	1	2	3	4	5	6	7	8	9
Facilities for fuel supply	A	A	A	A	B	A	B	A	B
Gas turbine and its accessories	B	-	-	-	-	-	A	-	-
Boiler and steam lines	B	B	B	C	B	B	A	B	B
Steam turbine and its accessories	B	A	B	A	B	A	B	A	B
Facilities for cooling water	A	A	A	A	B	B	A	B	A
Facilities for air supply and flue gas exhaustion	A	B	A	A	B	B	A	B	A
Facilities for the receiving and transmission of power, and emergency power system	A	A	A	A	B	A	A	A	A
Other components									
Buildings and facilities	B	B	B	B	B	B	B	A	A
Communication facilities	A	B	A	A	A	A	B	A	A
Dock and road	A	B	A	B	C	A	A	A	A

(b) Tsunami

Components	1	2	3	4	5	6	7	8	9
Facilities for fuel supply	B	B	D	D	D	C	B	C	A
Gas turbine and its accessories	B	-	-	-	-	-	A	-	-
Boiler and steam lines	B	B	B	C	A	A	B	A	A
Steam turbine and its accessories	A	C	B	C	C	A	A	A	A
Facilities for cooling water	B	C	C	C	D	C	B	A	A
Facilities for air supply and flue gas exhaustion	A	B	B	D	B	A	B	A	A
Facilities for the receiving and transmission of power, and emergency power system	B	B	C	D	D	C	A	A	A
Other components									
Buildings and facilities	B	B	C	D	B	A	B	A	A
Communication facilities	B	B	C	C	A	A	B	A	A
Dock and road	B	B	C	C	C	B	B	B	A

Table 1 Damage conditions classified by their cause.

(c) Liquefaction and subsidence

Components	1	2	3	4	5	6	7	8	9
Facilities for fuel supply	A	A	B	A	A	A	A	C	A
Gas turbine and its accessories	A	-	-	-	-	-	A	-	-
Boiler and steam lines	A	A	A	A	A	A	A	A	A
Steam turbine and its accessories	A	A	A	A	A	A	A	A	A
Facilities for cooling water	A	A	A	C	A	A	A	A	B
Facilities for air supply and flue gas exhaustion	A	A	A	A	A	A	A	A	A
Facilities for the receiving and transmission of power, and emergency power system	A	A	A	A	A	A	B	A	B
Other components									
Buildings and facilities	A	A	A	A	A	A	A	A	A
Communication facilities	A	A	A	A	A	A	A	A	A
Dock and road	A	B	A	A	C	A	A	C	B

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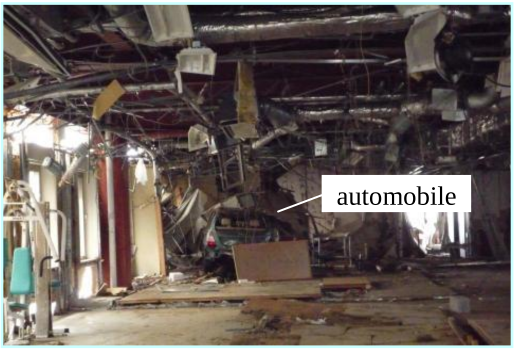
(a) Damaged coal unloader and sea water pump.

(b) Damaged light and heavy oil tanks.

(c) Damaged concrete wall.

(d) Damages to unit #1.

(i) Wall facing the sea.



(ii) The 2nd floor.

(e) Damaged service building.

Fig. 7 Damaged facilities of the Hara-machi thermal power plant.

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2. General Equipment of Energy Infrastructures

Group C covers topics of the general equipment of the energy infrastructures, and an investigation summary of this group is listed below.

(1) The lessons learned from the 1995 Great Hanshin-Awaji Earthquake

The damage ratio of the electric power transmission facilities to the transformation facilities arising from the 2011 Great East Japan Earthquake (M9.0) has been reduced after reviewing the technical standards, which were based on the Great Hanshin-Awaji Earthquake, for electrical equipment. However, the 2011 Great East Japan Earthquake was different from the disasters with an earthquake that had an epicenter near large cities. From this point of view, the damages and consequences of previous disasters have been taken into consideration and the design policy on the technical standards does not require many significant changes. However, a further study on the design basis by accumulating actual data of the damages will be expected.

Table 2 Summary of the damage ratio of the power station and facilities of TEPCO.

Electric power transmission and transformation facilities (N of damages / N of total facilities)			
Earthquake intensity	Overhead transmission lines	Underground transmission lines	Transformation facilities
7	0 / 21	0 / 0	0 / 0
6	33 / 6271	4 / 202	74 / 1490
5	8 / 24263	26 / 3512	30 / 6898
Maximum damage ratio of the distribution facilities			
Overhead power lines		Underground power lines	
Supports 0.2%		Maintenance holes 21%	

(2) Importance of preparation in terms of “disaster mitigation”

Earthquake countermeasures put in place previously have been effective to a certain extent, especially against seismic motion. However, severe damages have been caused by remarkable intensities of liquefaction or the unexpected severity of tsunamis. Infallible countermeasures for a great tsunami caused by a great earthquake with a magnitude of nine are almost impossible. In fact, in terms of the design policy on electrical equipment against great tsunamis with heights of 15 m or more, it is important to prepare redundant or distributed backup systems for severe damages that need to be quickly repaired, because technical matters go beyond the realistic mechanical designs of equipment, such as a high anchorage strength or high waterproof performance. With regard to the energy infrastructures that cannot be moved to higher grounds, such as oil refineries or LNG bases, there is no countermeasure against great tsunamis within an affordable cost. Thus, energy service providers have no other alternative but to take business continuity plans (BCPs) based on “disaster mitigation” preventing human loss and minimizing disaster damages. From the viewpoint of disaster mitigation for energy infrastructures, the following issues are important:

- To control incidents before severe accidents occur
- To prevent local damages from expanding to other areas
- To minimize nationwide aftermaths by stopping operations of energy services
- To restore facilities as soon as possible by taking precautions against severe damages

(3) Securing diverse energy sources

It is necessary to secure both usual and emergency energy sources, because Japan frequently experiences natural disasters. In particular, electric power supplies rank as the first priority for lifelines. Therefore, in addition to securing energy stations equipped with onshore self-sustainable power sources, it is important to develop mobile power stations from ships to onshore facilities and emergency guidance and communication frameworks, as shown by the previous great tsunamis. Furthermore, it is necessary to secure storage stations and supply chains of emergency fuel and to deregulate or revise any relevant laws. For example, relaxation of regulations under the Fire Defense Law that will allow an increase in fuel storage capacity and consequently extend the operation time of emergency power generation facilities, especially in emergency evacuation centers, should be considered when developing effective countermeasures.

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3. Energy Policy

After the 2011 Great East Japan Earthquake Disaster, the energy policy of Japan was discussed. Sub-working group D attempted to confirm the important issues of the energy policy based on a broad investigation of the basic stances and opinions of mechanical engineers and researchers in order to consider the directionality in rearranging the scientific data and knowledge regarding the energy infrastructures and future scenarios. From 1 August 2011 to 30 October 2011, a questionnaire survey was provided on the JSME website to JSME members that were registering to the power energy systems division as first to third priorities, and 320 answers were returned. As for their age, 15% of the respondents were in their 30s, 21% were in their 40s, 30% were in their 50s, 21% were in their 60s, and the remaining 13% were in another age group. Engineers and researchers comprised 50% of the respondents and 16% were university teaching staff, which reflects the characteristics of the personnel composition of the division. The questionnaire was composed of the following ten main categories: (1) the progress of science and the status of comfort and convenience, (2) energy supply structures and commitment to nuclear power in the future, (3) alternative energy of nuclear power and commitment to renewable energy, (4) concentration and dispersion of urban functions, (5) expectations for the smart grid, (6) preparation for large-scale power outages or rolling blackouts, (7) cooperation with the neighboring countries in terms of energy infrastructures, (8) how to deal with large natural hazards, (9) direction of energy policies and future technological developments, and (10) robust energy infrastructures that are significantly at risk.

The results of the questionnaire revealed the thinking process of the engineers and researchers and their ideas regarding the energy issues. The perspectives that are important when discussing and determining the future energy policies of Japan were considered based on the following viewpoints:

- Involvement of energy and civilization after the Industrial Revolution
- Changes in the structure of energy consumption in Japan
- The state of energy in Japan after the 2011 Great East Japan Earthquake Disaster
- Possibility of replacing nuclear power with renewable energy
- The difference between Japan and foreign countries regarding power conditions (comparison with the power conditions of Germany)
- Impact of the conversion of energy structures on society

The above results of the questionnaire were taken into consideration and are summarized as follows:

(1) Important viewpoints when considering an energy policy

Japan relies on imports for most of its resources, and it is difficult to output as much energy as the neighboring countries do, unlike those of Europe, and nuclear power is responsible for the base load of power that supports the industry. The current situation of Japan needs to be understood to clarify the difference between Japan and other countries, and to recognize them correctly.

(2) Impact of the conversion of energy structures on society and the roles of engineers

A rapid full conversion to renewable energy or the conversion to thermal from nuclear power can cause an extremely serious future impact on society, such as an increase in fuel procurement costs, an increase in power generation costs, and a reduction in the production capacity of the industry due to power shortages, which can lead to companies being traded to overseas owners and the oppression of people's lives due to a decrease in income and employment. The conversion can also make it difficult to achieve the objectives regarding global warming, to contribute newly developed technology to the emerging countries that use nuclear energy (see Fig. 8), and to contribute nuclear non-proliferation, which can lead to the loss of trust among the international community. Providing scientific explanations to people is one of the most important missions of the academic society. Those who are responsible for conducting risk communication to the public, such as mass communication, should understand their position in society, and they need to recognize a way to disclose correct information and how to form a bridge between engineers and society.

(3) Towards the future construction of energy in society

Future power constitutions can have a significant impact on the fate of nations that have few resources, including

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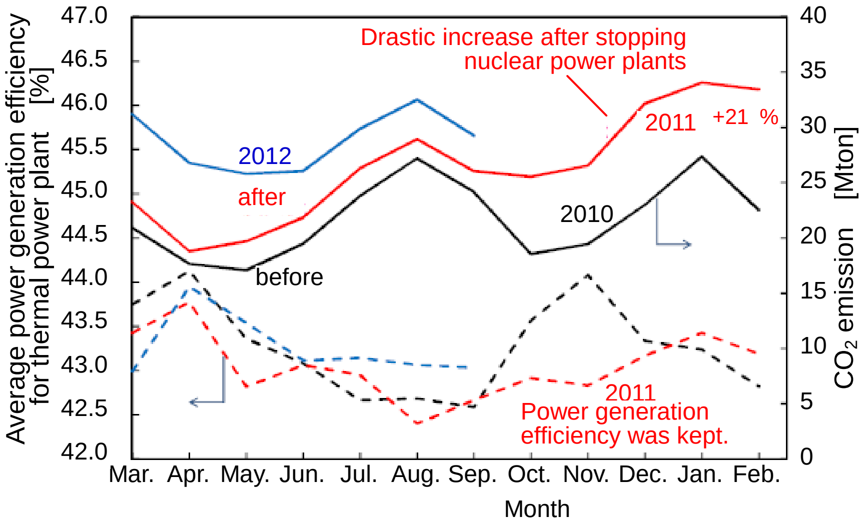
the lives of people and society, and they should be determined after a careful discussion that takes into careful consideration the scientific knowledge and evidence without being influenced by simple cost estimations and emotional discussions. We should study various complex issues, such as ensuring long-term energy security, the impact of the industry, economy, and employment on social life, and the impact of global warming, from a variety of viewpoints. Both industrial growth and the improvement of human life should be achieved, and it is necessary to ensure that the safety measures of nuclear power are sufficient. Furthermore, it is important to build an optimum energy supply system that includes the appropriate development of renewable energy that takes the characteristics of the power generation systems of the existing nuclear and thermal power plants into consideration.



These data were obtained from "Electricity Statistics Information" published by the Federation of Electric Power Companies in Japan.

(Average power generation efficiency) = (total power generation amount) ／ Σ[(comsumption × heating value) for each fuel]

(CO_2 emission) = Σ[(comsumption × CO_2 emission coefficient) for each fuel]

Fig. 8 CO_2 emission and power generation efficiency before and after the earthquake.

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