6. Situation at Other Nuclear Power Stations

(1) Higashidori Nuclear Power Station

Unit 1 was under periodic inspection at the time of earthquake occurrence on March 11, and all the fuel in the reactor core had been taken out and placed into the spent fuel pool.

Since all of the three lines of off-site power supply had stopped due to the earthquake, off-site power supply was lost and the emergency DG (A) (the emergency DG (B) was under inspection) fed power to the emergency generating line.

After the off-site power supply was lost due to the Miyagi Earthquake occurred on April 7, emergency DGs started, and the power was securely restored. Following this, although off-site power supply was restored, the emergency DGs stopped operation in an incident, and all the emergency DGs became inoperable.

(2)Onagawa Nuclear Power Station

Units 1 and 3 were under constant rated thermal power operation at the time the earthquake occurred on March 11 and Unit 2 was under reactor start-up operation. Four out of the five lines of off-site power supply stopped as a result of the earthquake, but off-site power supply was maintained through the continued operation of one power line.

The reactor at Unit 1 tripped at 14:46 due to seismic acceleration high, and the emergency DGs (A) and (B) started automatically. Since the start-up transformer stopped due to an earth fault/ short-circuit in the high-voltage metal-clad switchgear caused by the earthquake at 14:55, this led to a loss of power supply in the station. The emergency DGs (A) and (B) fed power to the emergency generating line.

Since all feed water/condensate system pumps stopped due to loss of normal power sources, the RCIC fed water to the reactor and the Control Rod Hydraulic System fed water after reactor depressurization. Since the condenser was unavailable due to the stoppage of the circulating water pump, the MSIV was totally closed, the cooling and depressurization operations of the nuclear reactor were performed by the RHR and the SRV, and the reactor reached a state of cold shutdown with a reactor coolant temperature of less than 100°C at 0:57 on March 12. Since the reactor was in start-up operation, Unit 2 shifted promptly to cold shutdown because the reactor had stopped automatically at 14:46 as a result of the great seismic acceleration. The emergency DGs (A), (B) and (H) automatically started due to issuance of a field failure signal from the generator at 14:47. But the three emergency DGs remained in a stand-by state since off-site power source was secured.

Subsequently, because the reactor auxiliary component cooling water system B pump, reactor cooling seawater system (RSW) B pump, and the high-pressure core spray auxiliary component cooling system pumps were inundated as a result of the tsunami and lost functions, the emergency DGs (B) and (H) tripped. However, because the component cooling water system A pump was intact, there was no influence on the reactor's cooling function.

The reactor at Unit 3 tripped at 14:46 due to seismic acceleration high. The off-site power source was maintained but the turbine component cooling seawater pump was stopped due to inundation by tsunami. All the feeding water/condenser pumps were then manually stopped and the RCIC fed water to the reactor. In addition, the control rod hydraulic system and condensate water makeup system fed water to the reactor after the reactor depressurization.

Since the condenser was unavailable due to the stoppage of all circulating water pumps resulted from undertow of the tsunami, the MSIV was totally closed and cooling and depressurization operations of the reactor were performed by the RHR and the SRV, leading the reactor to a state of cold shutdown with a reactor coolant temperature of less than 100°C at 1:17 on March 12.

(3) The Tokai Daini Power Station

The Tokai-Daini Power Station was under constant rated thermal power operation at the time of earthquake occurrence on March 11. At 14:48 on the same day, the reactor tripped due to turbine trip caused by turbine shaft bearing vibration large signal due to the earthquake. Immediately after the occurrence of the earthquake, all three off-site power source systems were lost. However, the power supply to the equipment for emergency use was secured by the activation of three emergency DGs.

The HPCS and the RCIC started automatically in response to the fluctuation of the water level immediately after the trip of the reactor, and the water level of the reactor was kept at a normal level. The water level of the reactor was then maintained by the RCIC, and the pressure of the reactor was controlled by the SRV. Moreover, RHRs A and B were manually started in order to cool the S/C for decay heat removal after the nuclear reactor tripped.

Subsequently, the DG2C seawater pump for emergency use tripped as a consequence of tsunami and the DG2C pump became inoperable. But the remaining two DGs secured power supply to the emergency equipment, and the cooling of the S/C was maintained by residual heat removal system RHR (B).

One off-site power supply system was restored at 19:37 on March 13, and the nuclear reactor reached a state of cold shutdown with a coolant temperature of less than 100°C at 0:40 on March 15.

Figure IV-6-1 Map showing the Location of Nuclear Power Stations

7. Evaluation of accident consequences

In the wake of the occurrence of loss of functions in many facilities due to an extensive earthquake and a tsunami, items to be improved in the future will be identified by evaluating a variety of aspects.

(1) Causes of the accident at the Fukushima-Daiichi Nuclear Power Station

Units 1, 2 and 3 of the Fukushima-Daiichi Nuclear Power Station lost all off-site power sources immediately after the earthquake. But the emergency DGs started operation and secured on-site power supply, maintaining the normal operation of cooling systems of the RCIC and the IC.

Then, due to an attack of tsunami, the emergency DGs and the metal-clad switchgear were inundated and covered with water, resulting in loss of all AC power. The seawater cooling system was also covered with water and the function to transport heat to the sea, which is the ultimate heat sink, was lost.

Since all AC power was lost (dc power was also lost for unit 1), the IC of Unit 1 became inoperable. In addition, reactor core cooling of Units 2 and 3 also stopped following the depletion of dc power (in the form of a storage battery) and the halt of cooling water supply. Damage to the reactor began due to the lowering of the water level in the reactor core, resulting in eventual core melt.

Despite the fact that the emergency DGs and the seawater cooling system of the Fukushima-Dai-ni Nuclear Power Station were hit by the earthquake and the tsunami, continued power supply from the off-site power source maintained the water level of the reactor. Additionally, since monitoring of plant conditions was also possible, plant management was possible to control the reactor, and high temperature shutdown could be maintained in a stable way. Meanwhile, recovery efforts, such as the exchange of the electric motors of the seawater cooling system that was covered with water due to tsunami, were conducted, and the system reached a state of cold shutdown within a number of days. Similarly, the Onagawa Nuclear Power Station and the

Tokai-Daini Power Station, also hit by the earthquake and the tsunami, reached cold shutdown states since off-site or on-site power supplies were secured.

From these facts, the direct cause of the accident in Units 1, 2 and 3 of the Fukushima-Daiichi Nuclear Power Station is thought to have been the loss of all power sources, which led to the failure of cooling the reactor core, then damage to the reactor core, resulting in a core melt.

In the light of these facts, it appears that, in cases of complete loss of ac power and losses of seawater and water cooling functions, a power supply necessary for operating the cooling systems, such as the RCIC and a water supply necessary for reactor core cooling, are indispensable. Extensive measures such as prior securing of essential machines and materials and the preparation of response plans such as manuals to be used in case of emergency, were necessary for emergency measures.

(2) Evaluation from the standpoint of preventing accidents: Countermeasures for earthquakes and tsunamis

The accident was caused by the attack of an earthquake and a tsunami.
At present, damage caused by the earthquake was concerned with off-site power supply systems. Damage to safety-important systems and components was not confirmed, and the plant was in a manageable condition until the arrival of the tsunami. However, detailed nature of the destruction has not been clear and remains to be seen. In addition, it has been verified that the acceleration response spectrum of the seismic ground motion observed on the basement of the reactor building of the Fukushima-Daiichi Nuclear Power Station exceeds the acceleration response spectrum at the same location relative to standard design ground motion Ss settled on based on the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities in a part of the oscillation band. Evaluation of seismic safety by seismic response analysis for the reactor buildings and major safety-important systems is necessary in the future (units 2 and 4 will be evaluated by the middle of June and units 1 and 3 by the end of July).

As for off-site power supply systems, each unit was connected to the power system by more than one power line in accordance with Guideline 48(G48) of Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities (Electrical Systems), and the redundancy requirement was satisfied. However, the point of the Guideline is to secure a reliable off-site power supply, although this is not clearly required in the Guideline.

For instance, the following events occurred in the accident:

- Actuation of protective devices due to collapse and short-circuits of transformers at the major substations connected to the Fukushima-Daiichi Nuclear Power Station.
- The switching stations (Units 3 and 4 and Units 5 and 6) where the off-site power supply is received were damaged by the tsunami. The power receiving circuit breaker was destroyed in Units 1 and 2 due to the earthquake.

Considering these facts, the facilities were not sufficiently prepared in the context of securing resistance to earthquakes, independence, and reducing the likelihood of common cause failure.

As for tsunami, the design tsunami height at Fukushima-Daiichi NPS was O.P. + 5.7 m. But experts estimated that tsunami of 10 m or higher attacked, though no record of tide gauge readings was available as described in III 2(1). Consequently, water tightness of buildings and other facilities in some plants was insufficient for tsunami of such height, and this resulted in total loss of power, including DC power supply, which was outside the scope of design. The design tsunami height at Fukushima-Daini NPS was estimated to be O.P. + 5.2 m. As described in III 2(2), neither record of tide gauge readings nor the height estimated by experts is available, and it is not sure how high the tsunami was. Nevertheless, it is considered that the actual tsunami height exceeded the design tsunami height.

Documented procedures did not assume ingress of tsunami, but specified only operation of stopping circulating water pumps used for cooling condensers as measures against undertow. The PSA referred to in accident management survey of these units did not take into account long time loss of functions of emergency DGs and loss of ultimate heat sink, which could be caused by tsunami.

Just like other equipment, emergency DGs in most units became inoperable due to loss of the emergency DG main units, sea water pumps for cooling, and the metal-clad switchgear. On the other hand, Units 5 and 6 of Fukushima-Daiichi NPS kept operating after tsunami, and kept supplying AC power required for removing residual heat at both Units 5 and 6 through a tie line. This is because the metal-clad switchgear, and the air-cooled emergency DG(B) for Unit 6, which is installed in the emergency DG building and requires no sea water pump for cooling, escaped inundation. This indicates the importance of assuring not only redundancy but also diversity of equipment of especially high importance for safety, from the aspects of arrangements and operation methods.

It is known that Units 2 and 4 of Fukushima-Daiichi NPS are equipped with air-cooled emergency DGs in the common pool building but these units became inoperable as the metal-clad switchgear connecting the DG to an emergency bus line was inundated. This indicates that it is very important to pay close attention to securing of system diversity to eliminate common cause failures.

(3) Main factors that developed the events of accident

This accident resulted in serious core damage in Units 1 through 3 of Fukushima-Daiichi NPS. But Units 5 and 6 of Fukushima-Daiichi NPS and Units 1 through 4 of Fukushima-Daini NPS succeeded in cold shutdown without causing core damage. If any disturbance occurs in a plant during power operation, such as an event of loss of off-site power supply, the following three functions are required to shift the plant into the cold shutdown state; reactor sub-criticality maintenance, core cooling, and removal of decay heat from PCV. Figures IV-7-1 through IV-7-3 show function event trees indicating event sequences these plants followed. These function event trees develop event sequences headed by main functions, such as reactor sub-criticality maintenance, core cooling, removal of decay heat from PCV, AC power, water injection to PCV, and hydrogen control, which were caused by the earthquake and accompanying tsunami and are considered to have seriously affected the progress of events before and after core damage. Estimated event sequences of this accident are shown by thick lines. Based on the above-mentioned event sequences, whether or not a unit suffered from core damage in this accident was mainly estimated by the following events:

a) AC power was not recovered early because:

- it was impossible to interchange electricity because of simultaneous loss of AC power for neighboring units,
- metal-clad switchgear and other accessory equipment were inundated due to tsunami, and
- off-site power supply and emergency DG was not recovered early.

b) Due to accident management carried out at the time of total AC power loss, core cooling was maintained for some time but was not sustained up until recovery of power supply.

c) The tsunami caused loss of functions of the system of transporting heat to the sea, which is the ultimate heat sink.

d) There was no sufficient means to substitute for the function of removing decay heat from PCV.

Next we evaluate whether or not regulatory guides established by the NSC Japan specify safety assurance measures against events that occurred or are estimated to occur in Fukushima-Daiichi NPS and Fukushima-Daini NPS as design requirements for nuclear power stations. If regulatory guides specify such design requirements, we further evaluate whether or not each nuclear power station was designed to satisfy the requirements. We also evaluate whether PSA took these events into consideration and whether or not the accident management, which had been developed by TEPCO under the accident management guidelines, functioned effectively.

1) Tohoku District - Off the Pacific Ocean Earthquake.

It has been confirmed that acceleration response spectra of seismic ground motions caused by this earthquake and observed in the basement of reactor buildings of Fukushima-Daiichi NPS exceeded the acceleration response spectrum of the design basis earthquake ground Motion (DBEGM) Ss in the basement determined under the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities. However, damage caused by the earthquake was found in the off-site power supply system and no serious damage was found in safety-important systems and components in nuclear facilities. They were kept under control until the tsunami arrived, but detailed damage states are still unknown, requiring further investigations.

Back-check of seismic safety is being carried out for existing nuclear power reactors. Tsunami assessment was not covered in the interim reports submitted by TEPCO regarding Units 3 and 5 of Fukushima-Daiichi NPS and Unit 4 of Fukushima-Daini NPS. Reviews of tsunami were to be carried out later, though government agencies finished reviews of the earthquake. Assessment of residual risks was being carried out by licensees.

2) Loss of off-site power supply

Guideline 48 (Electrical Systems) of the Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities specifies that the external power system shall be connected to the electric power system with two or more power transmission lines. However, it did not give sufficient consideration on measures to reduce possibilities of common cause failures, for example, by using the same pylon for both lines.

On the contrary, events of loss of off-site power supply are taken as design basis events in the Regulatory Guide for Reviewing Safety Assessment of Light Water Nuclear Power Reactor Facilities. TEPCO installed at least two emergency DG for each unit, having a sufficient capacity to activate required auxiliary systems.

In the internal event PSA and the earthquake PSA, loss of off-site power supply is assessed as one of initiating events and induced events. The earthquake PSA did not sufficiently examine measures to prevent loss of off-site power supply in order to reduce occurrence of total AC power loss, with the knowledge that total AC power loss is a critical event leading to core damage.

For example, no sufficient consideration was given to the following actions required for improving reliability of off-site power supply and auxiliary power system.

- Assessment to assure reliability of supplying power to nuclear power stations if a main substation stops supply
- Measures to improve reliability by connecting external power transmission lines to units at the site
- Seismic measures for external power lines (power transmission lines)
- Tsunami countermeasures for power receiving equipment in switching stations

Considerations should also have been given to measures to prevent metal-clad switchgear, storage batteries, and other power supply equipment from being inundated.

An assessment technique for tsunami accompanying earthquake (tsunami PSA) is under development now.

3) Tsunami

TEPCO voluntarily assessed the design tsunami height based on the largest tsunami wave source in the past by using the Tsunami Assessment Method established in 2002 by the Japan Society of Civil Engineers, and took such measures as raising the installation level of pumps and making buildings and other facilities water-tight, based on the assessment results. Nevertheless, the tsunami accompanying the earthquake was higher than the design tsunami height estimated by TEPCO. The design tsunami height at Fukushima-Daiichi NPS was estimated to be O.P. + 5.7 m based on the above-mentioned tsunami assessment method. But experts estimated that tsunami of 10 m or higher arrived, though no record of tide gauge readings was available as described in III 2(1). The design tsunami height at Fukushima-Daini NPS was estimated to be O.P. + 5.2 m. As described in III 2(2), neither record of tide gauge readings nor value estimated by experts was available, and it is not sure how high the tsunami was. Nevertheless, it is considered that the actual tsunami height exceeded the design tsunami height. Documented procedures did not anticipate the ingress of tsunami, but specified only operation of stopping circulating water pumps used for cooling condensers as measures against undertow.

4) Loss of Total AC Power Supply

In the PSA referenced in deriving the level of the accident management system that has been established to date, no consideration has been given to the long-term functional loss of the emergency DGs and loss of the power supply interchange capability between adjacent nuclear reactors.

For the PSA concerning tsunami, assessment methods are under development at present, and trial assessments have been carried out as part of the method development. Such assessments recognized the importance of the above-mentioned functional losses including consideration of simultaneous functional losses of the emergency DG, metal-clad switchgear, etc. that are caused by tsunami, but never leading to reflection in the accident management system. In other words, the analysis of the threat that could cause such a situation was insufficient in considering measures against the total loss of the AC power supply.

In addition, as part of accident management, facilities are provided that ensure interchange of the power supply for the working-use AC power supply (6.9 kV) and low-voltage AC power supply (480 V) between adjacent nuclear reactor facilities, and the documented procedures for the facilities were specified. For Unit 1 through Unit 4 at Fukushima-Daiichi NPS, however, this accident management system did not function effectively since the adjacent units were also subject to the total loss of the AC power supply.

5) Securement of Alternative AC Power Supply (Power Supply Vehicle, etc.)

In the PSA referenced in deriving the accident management system that has been established to date, it was regarded that the probability leading to a serious accident would be sufficiently reduced by giving consideration to the power supply interchange, recovery of the off-site power supply and the emergency DG. For this reason, the securement of a power supply vehicle, etc. was not considered as part of accident management.

This time, as an ad hoc applicable operation, a power supply vehicle was arranged to be carried in the site. But, this could not be utilized smoothly due to the difficult access caused by defects, etc., of the heavy machinery for removing rubble and debris generated by the influence of the tsunami, and water damage of a metal-clad switchgear that was also caused by the tsunami.

6) Securement of Alternative DC Power Supply (Temporary Storage Battery, etc.)

In the PSA referenced in deriving the accident management system that has been established to date, a mechanical failure of a storage battery has been considered, and a period of time during which the DC power supply must function has been defined as 8 hours in the event tree of the off-site power supply loss event. In consideration of the presence or absence of power supply recovery within 8 hours, if the off-site power supply fails to recover during this period, it is assessed that the RCIC system could not continue running. As a result, it was assessed that the off-site power supply might be more likely to recover, and loss of the DC power supply facilities would not be an event having a significant influence on the risk. Therefore, the preparation of temporary storage batteries was not a matter to be dealt with.

In this accident, arrangements were made for carrying the storage batteries in the site. But, since carry-in works were difficult and such work was performed in the dark due to the impact of the earthquake and tsunami disasters, difficulties arose in the recovery of the operation of the equipment following the accident, and the operation of the instrumentation system for recording plant parameters. Furthermore, the plant parameters that serve as important data in developing preventive measures after termination of the accident could not be sufficiently saved.

7) Measures Against Functional Loss of Seawater Pump (Loss of Ultimate Heat Sink)

In the PSA referenced in deriving the accident management system that has been established to date, the functional loss of a seawater pump has been considered in a fault tree related to loss of the residual heat removal capability, but no consideration has been given to the simultaneous functional losses of all the seawater pumps due to tsunami.

For the PSA concerning tsunami, assessment methods are under development at present, and trial assessments have been carried out as part of the method development. Such assessments indicated that the risk sensitivity of an event in which simultaneous functional losses of all the seawater pumps are generated due to tsunami was high. However, being a result of trial assessment, this was not shared widely among those involved, which never brought the importance of this accident management to their attention.

In this accident, as an ad hoc applicable operation, the measures were taken for replacing the seawater pumps suffering from functional losses with temporary seawater pumps, but this was not intended to be provided as part of the accident management.

8) PCV Vent

The PCV venting facilities were put in place as part of accident management before and after damage of the core. In the case of this accident, venting was performed after damage of the core due to depressurization of the reactors and the delay of water injection. Because of the total loss of the AC power supply, motor driven valves had to be opened manually for the PCV venting operations. For operation of pneumatically-actuated valves, the pressurized air required for operating such valves could not be assured, and thus a temporary air compressor had to be mounted to assure the pressurized air. For such reasons, the facilities could not be operated in accordance with the documented operation procedures for severe accidents, which caused the PCV venting operation to be delayed.

9) Alternative Water Injection (Depressurization of Reactor Vessel, Alternative Water Injection Line)

The systems for alternative water injection, including depressurization operations of the reactors and the subsequent utilization of fire pumps, were put in place as part of the accident management. In this accident, depressurization and the subsequent cooling operations of the reactors were carried out using those systems. Due to the total loss of AC power supply, however, difficulties arose in assuring the air pressure for driving the SRV necessary for depressurization and maintaining the excitation of the electromagnetic valves in the air supply line, resulting in time-consuming depressurization operations. Alternative water injection into the reactors, using heavy machinery such as fire engines, was not considered as part of the accident management, but in this accident, as an ad hoc applicable operation, water injection into the reactor using a chemical fire engine that was present at the site was attempted. Nevertheless, since the reactor pressure was higher than the pump discharge pressure of the chemical fire engine, injection of freshwater into the reactor was not available in a few cases.

10) Alternative Water Injection (Water Sources)

As water sources used for alternative water injection, a condensate storage tank and a filtrate tank were considered as part of the accident management, and those tanks were practically utilized. As water sources utilized by a fire engine, a fire-prevention storage tank and seawater were used, but work was required to line up the water injection line.

11) Measures against Hydrogen Explosion at Reactor Building

The Guideline 33 (System for Controlling Containment Facility Atmosphere) of the Regulatory Guide for Reviewing Safety Design of

Light Water Nuclear Power Reactor Facilities requires the provision of functions capable of controlling the atmosphere of the containment facilities so as to ensure safety against assumed events. To meet this requirement, the FCS was installed at BWR plants along with inactivation inside the PCV. No requirements are specified for measures against hydrogen explosion at the reactor building. Also, the Common Confabulation Interim Report which deals with "beyond design basis events" does not describe such requirements.

The PSA includes a scenario in which hydrogen arising from meta-water reaction following core damage, and from the radiolysis of water, leaks from the PCV into the reactor building filled with the normal air resulting in burning inside the reactor building in a severe accident, but this is an assessment from a viewpoint of the integrity of the PCV, and no discussions were made for damage to the reactor building.
It was expected that the FCS installed to cope with the design basis events would be available under the severe accident environment as well. But, since power supplies were not available this time, this capability was not utilized.

For measures against a hydrogen explosion at the reactor building, no consideration was given to the facilities or the documented procedures.

12) Alternative Water Injection into Spent Fuel Pool and Cooling

The Guideline 49 (Fuel Storage Facilities and Fuel Handling Facilities) of the Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities requires a system capable of removing the decay heat and transfer it to the sea, the ultimate heat sink, in the spent fuel pool. However, there are no requirements for the capability to perform alternative water injection in preparation for the case of loss of ultimate heat sink. As it is considered that the risk presented by the spent fuel pool is sufficiently smaller compared to the reactor, there are fewer PSA implementation examples for the spent fuel pool. In the PSR at Unit 1 of Fukushima-Daiichi NPS that was published in March 2010, the PSA was implemented for the spent fuel pool when all of the fuel rods in the reactor were taken out into the spent fuel pool. But, since the risk was thought to be small, no consideration was given to the facilities or documented procedures related to the injection of seawater into the spent fuel pool.

13) Water Injection into D/W for Cooling Reactor or PCV

Further, in addition to installing alternative capabilities, as part of the accident management for water injection into the space of a foundation (pedestal) supporting the RPV in the D/W, TEPCO put the capability to perform water injection using the same piping as the alternative spray capability in place.

The PCV pressure increased in Unit 3 during this time. For depressurization, spray to the S/C was used, and it was confirmed that the accident management system functioned properly. In units 1 and 2, the PCV vent was superseded, and thus the PCV spray (D/W and S/C) was not performed.

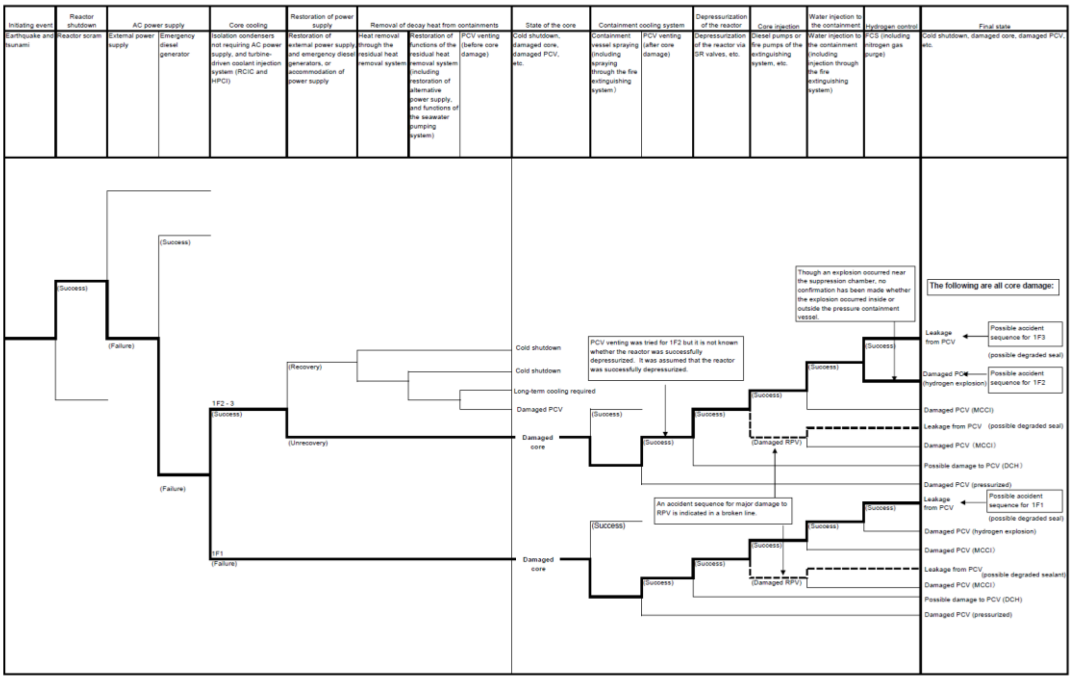

Figure IV. 7-1: Function event tree for units 1, 2 and 3 of Fukushima-Daiichi Nuclear Power Station

Figure IV-7-1 Function Event Tree of Unit 1 to Unit 3 at Fukushima-Dai-ichi NPS

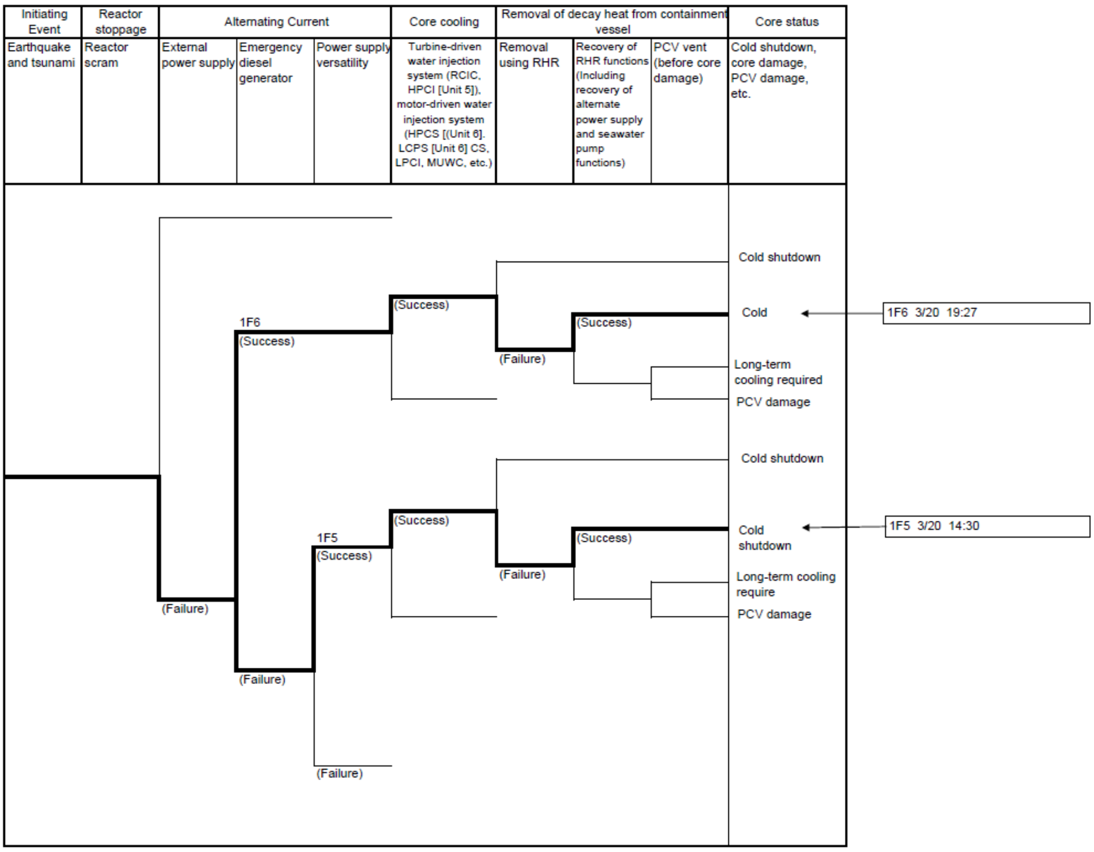

Figure IV-7-2 Function Event Tree of Unit 5 and Unit 6 at Fukushima-Dai-ichi NPS

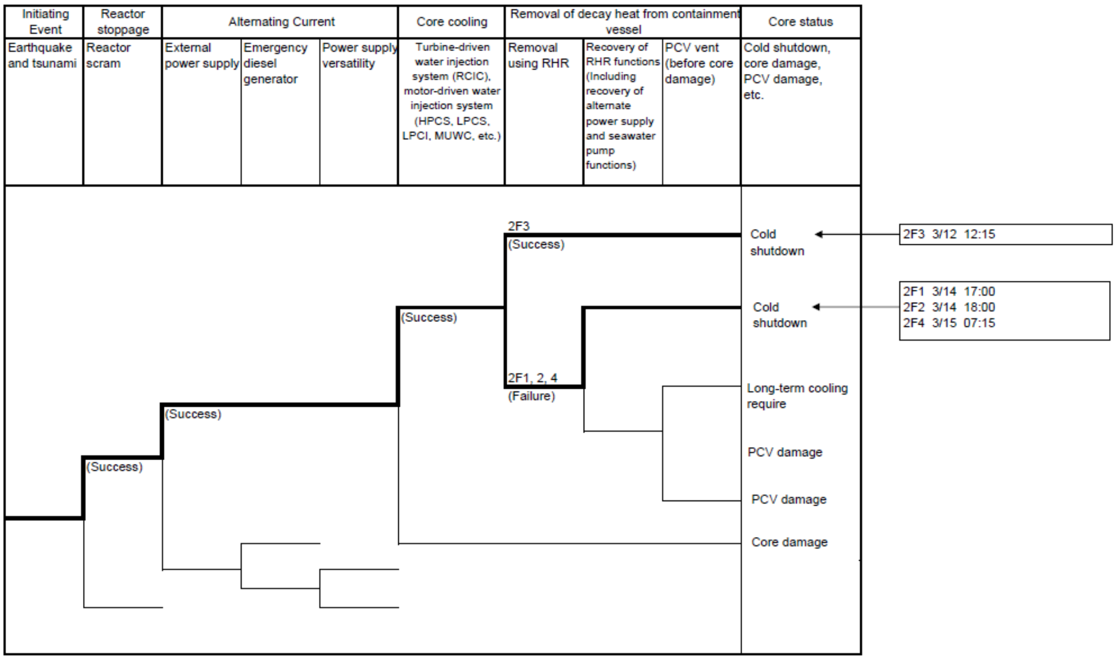

Figure IV-7-3 Function Event Tree of Unit 1 to Unit 4 at Fukushima-Dai-ni NPS

(4) Comprehensive Assessment

1) Conception for tsunami in design stage.

Tsunami Evaluation Group, Nuclear Engineering Committee, Japan Society of Civil Engineers announced in 2002 the "Tsunami Assessment Method for Nuclear Power Plants in Japan"[IV7-1] which established a deterministic tsunami water level evaluation method, triggered by the Hokkaido south-west offshore earthquake which took place in 1993. This characterizes, in setting up design basis tsunami, a consideration of tsunami of which the occurrence in the past was accurately confirmed, as well as a requirement of a method to address uncertainty (variation), accompanied during the course of setting a proper method. Based on this, each licensee voluntarily reviewed the design basis, and the Nuclear Power governmental agency was not involved in this review.

Incidentally, the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities finalized in 2006 specifies in "8. Consideration for the event accompanied by an earthquake" that "During the service period of the facilities, safety features in the facilities might not be significantly affected even by such a tsunami that could likely to occur on very rare occasions," and the guideline asks for proper design for such a assumed tsunami.

The massive tsunami of last March made it clear that an earthquake or tsunami could cause multiple common cause failures of equipment of safety significance in a nuclear power plant.

For that reason, considering the risk that may be caused by an attack on facilities by tsunami beyond assumed design basis tsunami, from now on, it is required to make efforts to reduce the risk to a level as low as reasonably attainable.

On the other hand, Tsunami Evaluation Group, Nuclear Engineering Committee, Japan Society of Civil Engineers has initiated compiling a detailed work for "a method to analyze tsunami hazard using probability theory (Draft), while recognizing that a sufficient safety level in a nuclear power plant facility cannot always be attained against an earthquake or tsunami which could cause multiple common cause failures, even after providing design measures against a presumed earthquake or tsunami."

Meantime, the Nuclear and Industrial Safety Agency (NISA) conducted back checks based on the most recent findings for all of the existing nuclear power plants under the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities revised based on the information given by the Nuclear Safety Commission. In Fukushima-Daiichi Nuclear power plants No.3 and No.5, an interim report was prepared which has been reviewed by NISA. However, any evaluation relating to tsunami and any remaining risk were left to be made later. From this it is pointed out that the persons in charge had little understanding of designs against tsunami, and that a deterministic approach will never guarantee that a tsunami exceeding the predicted strength will not occur. But, for the responsibility of attaining the targeted safety level (safety goal), they are required to prepare proper design measures and accident management taking the (target) safety level into consideration after analyzing the characteristics of the plant against the attack of an unexpected tsunami exceeding the predicted safety level, .

Background shows that the nuclear regulatory agency supposedly did not have an attitude to translate the standard of "constitute no hindrance to disaster prevention" which was expected in society as a standard of judgment into "Target Safety Level" which was commonly owed to society, nor an attitude to establish a dialogue with society over whether it is adequate or not.

2) Guidelines for accident management

Since the guidelines for accident management were established by the Nuclear Safety Commission in 1992, accident management was prepared at each nuclear power plant over ten years.

Such accident management based on PSA and an analysis of scenarios involving internal events caused by equipment failure and human error conducted in 80's. This guideline was highlighted to emphasize the effectiveness of introducing accident management, and failed to focus on the environmental conditions so as to make accident management effectiveness.

So, the nuclear regulatory agency should have mandated the licensees that the results of PSA in relation to new findings of common cause failures and external events be referenced and training under realistic conditions be periodically implemented at the stage on which equipment and materials provided for accident management are arranged for training. Further, this guideline also should have been revised taking the experience of such efforts and the results of earthquake PSA and tsunami PSA into consideration.

However, accident management was considered to be conducted independently by each licensee and did not require a PDCA system for introducing new findings or improvements. Also, the Nuclear Safety Commission has never reviewed the accident management system.

Taking into account the importance of the role that accident management has for achieving the safety goal, the nuclear regulatory agency should have constantly reviewed the accident management guidelines by introducing new findings for effective operation.

The Fukushima-Daiichi Nuclear Power Station attacked by a large tsunami has six reactor facilities at one site and all the reactors have suffered accidents. Despite the multi-plant attributes, the accident management guidelines did not address these attributes and the licensees did not train for these attributes.

3) Diversity to important systems in safety: Preparation for commonly caused faults

The accident this time was characterized by having a lot of electrical machinery and appliances in the significant safety systems, including a metal-clad switchgear for connecting to an emergency DG and an emergency bus bar, inundated and becoming useless after the arrival of the tsunami, which resulted in the loss of final heat sink Further, some plants lost their direct-current power source, leading to severe accidents. Namely, water supply to the nuclear reactor by using a fire fighting system maintained to use in good condition for accident management, or PVC vents, did not function immediately due to malfunctions of a pump, a solenoid valve, an air operated valve (AO valve), etc.

On the other hand, a part of the steam-driven system, such as the RCIC continued to cool the reactor core beyond eight hours and only until the battery was exhausted. An emergency DG installed at a higher level worked satisfactorily since the body of the emergency DG and its power source were free from submersion.

Beyond Design Basis Accidents (BDBE) are likely to be due to multiple failures of important facilities caused by earthquake, tsunami, fire, etc. Therefore, in order to limit the occurrence of Beyond Design Basis Accidents (BDBE) and the influences exerted by it, some good ideas are essential to convert or modify a plant to comply with such severe conditions caused by such external events. Also for the preparation of such accident management to work effectively under such severe conditions, some method to avoid simultaneously occurring malfunctions of the facilities is needed.

Therefore, the Nuclear Power governmental agency should have emphasized the necessity of insuring a diversity of facility installation sites, power sources and support systems, from the view point of minimizing the possibility of common cause failures together with water, vibration and sufficient protection against fire. Also, for the accident management of licensees to install a nuclear power plant, training should have been required to ensure that accident management should work effectively under the severe conditions in mind, and reviewing its effectiveness should also have been required.

4) Design pressure of PCV and vent system.

As the loss of PCV functions due to an accident will provide a direct adverse effect on the surrounding environment, the soundness of the PVC should be maintained even when multiple malfunctions, such as those in the Fukushima-Daiichi power plant, occurs. For this purpose designed temperatures and pressures should be determined in consideration of the occurrence of core damage. At the same time a vent system to be free from damage by emergent excess pressure should be kept in good condition as part of accident management. Judging from the accident this time, the radiation level adjacent to the PCV increased after the core was damaged.

From this the vent system should have been remotely controllable even when AC power source was lost. The PCV vent system should have been equipped with a filter with sufficient radiation decontamination capability. Since temperature and pressure are possibly routed, in the occurrence of core damage, through a system connecting to the PCV vent line, the common use of the system should be minimized as much as possible so as to avoid the leakage of hydrogen or radioactive substances from the building. Further, special attention to design allowances in pressurized equipment for continuous parts, or apparatus sealed by packing, should have been taken so that no leakage would occur in the liquid layers even when the designed pressure is exceeded.

5) Hydrogen explosion in nuclear reactor building.

In the accident this time, a hydrogen explosion in the nuclear reactor building had greatly impeded actions to resolve the situation. In the BWR plant as a countermeasure to the hydrogen explosion, all eyes were focused on activation and installation of the FCS in the PCV. This was considered effective even after the core was damaged. This time the generation of hydrogen was contained to some extent, but while paying attention to the loss of the power source and fixing it, hydrogen leaked from a pressurized PVC exploded in Fukushima-Daiichi Nuclear power plants No.1 and No.3. In Fukushima-Daiichi Nuclear power plant No.4, an explosion is supposed to have occurred due to an inflow of hydrogen from the PCV vent in Fukushima-Daiichi Nuclear power plant No.3.

From this, for accident management after the occurrence of core damage, ventilation facilities to prevent an explosion in the nuclear reactor building due to hydrogen leakage from the PCV, and some measures of equipment to prevent the collection of hydrogen should have been provided, including an independently-driven power source.

6) Risks relating to the spent fuel pool

In this accident, the cooling function for the spent fuel pool was lost due to a loss of power supply. Notably, because of reactor core internal shroud replacement work at Fukushima Daiichi Nuclear Power Station, Unit 4, there was one reactor core's worth of fuel with relatively high levels of decay heat being stored. As well as dealing with the accident in terms of the reactor core, it also became necessary to quickly carry out measures to introduce an alternative cooling function for the spent fuel pool.

However, as the embedded radioactive inventory is low compared to the reactor core, even though the radioactivity containment function is inferior to that of the reactor core, a definitive decision was made that there was only a small possibility of risks originating from the spent fuel pool, and as such, no particular accident management was considered.

7) PSRs and PSAs

Since 1992, PSRs, that evaluate the overall safety of existing nuclear plants based on the latest technological knowledge, have been carried out as a voluntary security measure by the licensees approximately every 10 years. One of the items in the PSR is to carry out a PSA, and to come up with measures to deal with the results of the assessment. Reviews on the appropriateness of these actions have been carried out by the nuclear regulatory authorities.

However, during the review of the PSR carried out in 2003, other requirements were made operational safety program requirements based on the Reactor Regulation Act, while the PSA remained at the discretion of the licensees, and reviews by nuclear regulatory agency ceased to be carried out. PSAs make known the risk structure that is subject to regulations for risk management for the people, and the nuclear regulatory authorities were somewhat lax in managing quality, in having the licensees carry out PSAs, and in using those results to make regulatory decisions. As a result, there was ambiguity in distinguishing what is significant and what is not significant in achieving the required safety standards. This may have led to deterioration in nuclear safety culture.

The nuclear regulatory agency should have considered it their mission to act on the people's behalf to investigate whether the risks at nuclear reactors were being kept to a minimum and to provide explanations. They should have had the licensees evaluate internal and external risks of each plant and enforce appropriate accident management based on that. This should have then been reviewed and enhanced based on the latest knowledge.

8) Effects of ageing

Data acquired from surveys on equipment operation following the earthquake and the intensity of the shaking showed no there had been no effect on important safety related equipment and devices in the reactor. As such, it is thought that the accident was not caused directly by deterioration due to ageing (embrittlement of the reactor, cyclic fatigue, pipe damage, heat ageing, cable deterioration, etc.), but instead was caused largely by insufficient cooling of the reactor, or a halt in cooling of the reactor, resulting in damage to one of the reactor cores and core melt.

In addition, it is necessary to examine in detail from now on whether the reactor systems were vulnerable to such an earthquake and tsunami because of their age. Through PSRs, mentioned above, or by other means, such factors should be investigated thoroughly and, where necessary, safety systems and equipment renewed or upgraded.

9) Environments for dealing with accidents

It is clear that at the time of the accident poor habitability of the main control room and inadequacies in accident clocking devices led to delays in making operational decisions. This stems from the fact that a prolonged loss of AC power supply was not considered as a design standard, and was also not considered as part of accident management.

In the future, for accident management to be effective against prolonged losses of AC power supply, stipulations should have been made on maintaining the habitability of the main control room and surrounding routes following damage to the reactor core. Stipulations should also have been made on ensuring the reliability of instrumentation and a stable direct current power supply to run such instruments if an accident occurs.

In addition, for twin plants with a common main control room, or where plants are adjacent to each other, accidents at the adjacent plant should have been considered as external factors affecting the plant. In the same way, it should also have been a requirement to ensure the necessary habitability for continued operation at the adjacent plant.

Such requirements also are also applicable for on site emergency stations.

When the accident occurred and operators from the main control room took shelter, the on site emergency station became the plant's main means for assessing the situation at the plant. But, poor habitability hampered work to swiftly implement accident management. In consideration of such events, in order to enable accident management to be carried out effectively even in difficult accident environments, detailed investigation should have been carried out into creating emergency stations with all the necessary requirements, including dedicated ventilation and air conditioning systems.

Following damage to the emergency station at the Kashiwazaki Kariwa Nuclear Power Station during the Niigataken Chuetsu-oki Earthquake in July 2007, an independent decision was made at the Fukushima Daiichi Nuclear Power Station to make its emergency station earthquake-proof. It can be said that this measure was of benefit during the earthquake. Investigation should be carried out to determine whether it is necessary to make such functions a regulatory requirement at other nuclear power stations' on site emergency stations as well.

10) Reactor building requirements

One of the difficulties hindering restoration efforts following this accident is the fact that the damaged section of the PCV is positioned low down. Water injected into the nuclear reactor is leaking out into the turbine building, as much electrical conduit and piping runs through the lower levels of the reactor building, and these sections are not water-proofed. As flooding can be considered as a factor of accident management, it would have been advisable to ensure that the lower sections of the nuclear reactor building were water-proof as a measure against flooding and to ensure external cooling of the PCV could be carried out.

In addition, in light of the fact that the presence of ground water is hindering the management of contaminated water, accident management activities should have included investigations into the detrimental effects caused by ground water, and measures such as positioning important sections of the reactor above ground water level or siting the building on premises with water shielding should have been taken.

11) Independence from adjacent plants

One of the difficulties hindering restoration efforts following this accident is the fact that there are underground connections to adjacent plants through which contaminated water runs. Although it is more economically efficient to construct plants adjacent to each other so that facilities and control can be shared, it is important to ensure that the detrimental effects of an accident at one plant can be kept isolated from the adjacent plant. As such, investigation should have been carried out to plan the physical separation of adjacent plants or to make it possible to plan the physical separation of adjacent plants.