Critical review on what factors affected the evolution of the Fukushima accident

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Abstract: This paper focuses on why the Fukushima disaster caused such different outcomes at the Fukushima Daiichi nuclear power station (NPS) and the Fukushima Daini NPS, although both NPSs were hit by the largest tsunami in Japanese historical records and are located only 10 km apart. First, the authors' study classifies the progression of the Fukushima accident into four phases: Phase I (between earthquake occurrence and tsunami inundation), Phase II (after tsunami inundation), Phase III (efforts at restoration) and Phase IV (recovery from harsh conditions), in order to clarify the difference in the accident progression in each unit of both NPSs.

The course of the accident's evolution at each unit is compared to derive the differences of mechanical and human factors which affected the accident's progression. Second, the differences of both factors are reviewed from resilience engineering perspectives to know what factors are important to improve the safety of nuclear power plants. As the conclusions of this critical review, it can be said that: (i) the system, structures and components of NPS are systematically designed, manufactured and maintained to perform the intended functions for expected events, however they have limitations to cope with unexpected events, and (ii) the plant personnel can respond to such situations successfully by changing their approach flexibly in a number of ways.

Keyword: Fukushima accident; resilience engineering; nuclear power plant safety; human factors

1 Introduction

The Great East Japan Earthquake and the ensuing tsunami that occurred on March 11, 2011 caused a severe accident at the Fukushima Daiichi nuclear power station (NPS) and severe damage at the Fukushima Daini NPS. The Tokyo Electric Power Company, Inc. (TEPCO), both the Japanese Government and National Diets, the International Atomic Energy Agency (IAEA) and other organizations have subsequently published reports [1-10], in which individual institutions made their own investigations from their own viewpoint regarding the accidents.

The authors of this paper noticed the difference of accident courses between the Fukushima Daiichi NPS and the Fukushima Daini NPS, although the plants are located only 10 km apart. First, the authors undertook a critical review on the differences in accident evolution in each Fukushima NPS based on the Fukushima Nuclear Accident Analysis Report by TEPCO (hereafter "TEPCO report"), conducting surveys on the whole course of the accident progression in each unit. The accident progression was thus classified into four phases from the beginning of the accident, to the branching point whether or not it would progress to a severe accident, in order to make the differences more easily understandable. Following the description of this, the paper next reviews the accident evolution in each phase in detail. Thirdly, a review of the results from both factors of machine and human intervention is discussed in relation to how they may be able to control accident evolution. Finally, the authors evaluate the Fukushima accident from resilience engineering perspectives in order to clarify what factors are important to improve the safety of nuclear power plants.

2 Overview of accident

At the Fukushima Daiichi NPS, units No.1 to 3 (hereafter abbreviated as 1F-1, 1F-2 and 1F-3 respectively) were in operation, and units No.4 to 6 (similarly as 1F-4, 1F-5 and 1F-6, respectively) were undergoing outage when the earthquake occurred. 1F-1, 1F-2 and 1F-3 went into automatic shutdown

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due to the earthquake. Simultaneously they lost off-site power supply due to the collapse of transmission lines and the failure of transformer station, but power supplies for safe shutdown were secured by successful start-up of the emergency diesel generators (EDGs). Operating crews on duty confirmed the safe shutdown of these units and carried out the operating procedures to bring these units state toward cold shutdown (CSD) as they had mastered in training. At the Fukushima Daini NPS, units No.1 to 4 (2F-1, 2F-2, 2F-3 and 2F-4 respectively) were also shutdown automatically with off-site power supply maintained. Operating crews found no abnormal indications. *The Shift Supervisor felt that "things could come to a close (cold shutdown)"*. (TEPCO report)

The situation of the Fukushima Daiichi and Daini NPSs was drastically changed by tsunamis which hit the both NPSs about 40 minutes after the earthquake. At the Fukushima Daiichi NPS, all EDGs of 1F-1, 1F-2, 1F-3, 1F-4 and 1F-5 stopped operation, and almost all power supply facilities failed due to tsunami inundation on the Fukushima Daiichi site. Thereafter, the residual heat of the reactor cores could not be removed using the seawater system. As for 1F-1, DC power was also lost so that lighting, monitoring instruments and display lamps in the main control room (MCR) went out. *As the sound of alarms faded out, the MCR was left enveloped in silence.* (TEPCO report)

At the Fukushima Daini NPS, the residual heat removal functions of the seawater system were lost in the same way as at the Fukushima Daiichi NPS, but the alternate low pressure injection systems were available because off-site power remained for all units. In addition, MCR monitoring instruments and display lamps were functioning.

Approximately eight hours after tsunami inundation, a big difference occurred in the two plants. At the Fukushima Daiichi NPS, operating crews, maintenance and engineering personnel, subsidiary company employees, fire brigade members and others continued their restoration work with available systems, structures and components (SSCs) under harsh conditions with the fear of aftershocks, tsunamis,

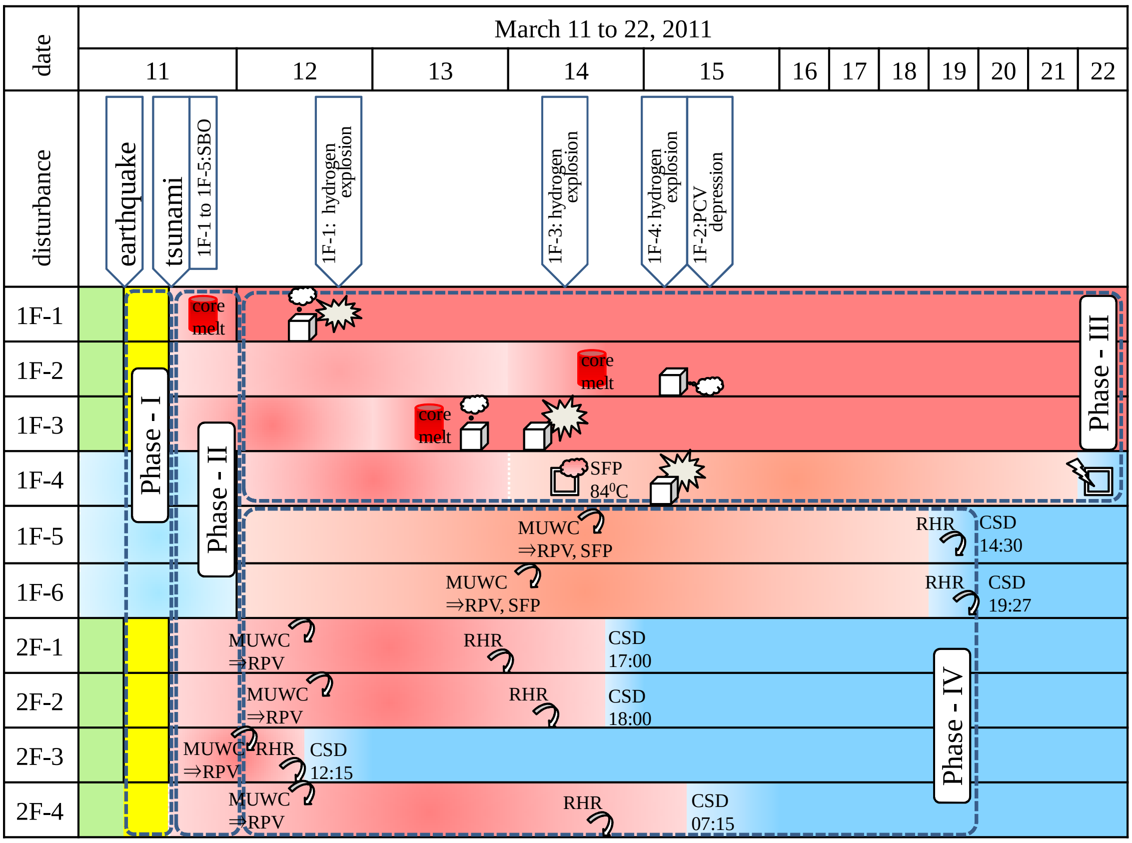

Fig.1 Overview of the Fukushima accident.

hydrogen explosions and high radiation levels. In spite of their efforts, reactor cores of 1F-1, 1F-2 and 1F-3 could not be cooled sufficiently by any means, resulting in core meltdown. Furthermore, the restoration of cooling function at the 1F-4 spent fuel pool (SFP), that stored a lot of fuel, was made more difficult by an unexpected hydrogen explosion in the reactor building (R/B).

As for 1F-5 and 1F-6, plant personnel carried out the countermeasures successfully, because residual heat of their reactor cores was low, and the plant parameters could be monitored. They made great efforts to reconfigure power supply systems - such as connecting available electric panels of 1F-5 and an air-cooling EDG of 1F-6 with temporary cables. They successfully accomplished a CSD state in both units.

At the Fukushima Daini NPS, plant personnel restored the function of the residual heat removal system with the remaining emergency cooling pumps and off-site power supply. The four units accomplished CSD relatively easily.

The evolution of the accident in all the units of the Fukushima Daiichi NPS and the Fukushima Daini NPS are illustrated in Fig.1, where the accident progression is classified into four phases below, in order to better understand the differences;

- Phase I: between earthquake occurrence and tsunami inundation (for all units)
- Phase II: after tsunami inundation (for all units)
- Phase III: efforts at restoration (1F-1, 1F-2, 1F-3 and 1F-4)
- Phase IV: recovery from harsh conditions (1F-5, 1F-6, 2F-1, 2F-2, 2F-3 and 2F-4)

3 Evolution of the accident

In this chapter, the safety of nuclear power plants, earthquakes and tsunamis, SSCs and personnel are highlighted as follows to deal with the accident evolution at Fukushima:

(1) Safety of nuclear power plants including SFP is <object> that should be managed or controlled.

(2) Earthquake and tsunamis including subsequent hydrogen explosions and high radiation levels are <disturbances> that affect <object>, <mechanical factors> and <human factors>.

(3) Systems, structures and components including their temporary features are <mechanical factors> important for safe or safety shutdown of <object>.

(4) Personnel including off-site human resources are <human factors> needed to secure <object> and restore <mechanical factors>.

Then in the subsequent sections of this chapter, the Fukushima accident will be summarized along with the four phases mentioned in Chapter 2, by considering the relationships between <object>, <disturbances>, <mechanical factors> and <human factors>.

3.1 Phase I: between earthquake occurrence and tsunami inundation

As for 1F-1, 1F-2 and 1F-3 <object>, protection and control systems <mechanical factors> were functioning normally and the electric power vital to safe shutdown was supplied from EDGs <mechanical factors>, immediately after the earthquake occurrence <disturbances>. Operating crews on duty <human factors> initiated response operations toward CSD in accordance with established operating procedures and their experience.

As for SFP of 1F-4 <object>, cooling systems <mechanical factors> and countermeasures by operators <human factors> were not required immediately, because the level and temperature of SFP water was properly maintained when the earthquake <disturbances> occurred.

The condition of 1F-5 and 1F-6 <object> was not affected greatly by the earthquake <disturbances>. Operators <human factors> confirmed that plant parameters <mechanical factors> were stable.

As for 2F-1, 2F-2, 2F-3 and 2F-4 <object>, the earthquake <disturbances> triggered an automatic reactor scram by the protection system <mechanical factors>. All SSCs <mechanical factors> important to safe shutdown functioned and off-site power <mechanical factors> was available. Though multiple plants <object> were stopped at the same time, operating crews on duty <human factors> could carry out their operation in accordance with emergency operating procedures.

This phase is the limited time from the earthquake occurrence to the first tsunami inundation (for the Fukushima Daiichi NPS 41 minutes after the earthquake, for the Fukushima Daini 36 minutes). Both SSCs <mechanical factors> and operating crews <human factors> functioned smoothly.

Though it was not written in the TEPCO report, operators must have prepared for some kind of worrisome influence on seawater system (*i.e.* drops in seawater pump performance due to tide level change due to tsunamis) from their past experience (*e.g.* the Kashiwazaki-Kariwa NPS operated by TEPCO was struck by a huge earthquake in 2007). However, they might not have thought that they would be unable to use EDGs and power supply panels installed in the buildings. In addition, they may have obtained almost no information on the incoming tsunamis after the earthquake, because they were busy operating after plant stop.

3.2 Phase II: after tsunami inundation

As for 1F-1, 1F-2 and 1F-3 <object>, the tsunami <disturbances> disabled the function of the EDGs <mechanical factors> and resulted in station black out (SBO). Furthermore, 1F-1 and 1F-2 lost DC power supply <mechanical factors> approximately one hour later. In this situation, plant personnel <human factors> started recovery work such as preparing lights and instruments in MCRs, gathering necessary diagrams and collecting small generators, batteries, and cables. TEPCO headquarters <human factors> ordered all of their power stations to transport power supply cars <mechanical factors> to the Fukushima Daiichi NPS and requested other utilities, too.

As for 1F-1, operators <human factors> tried to use the isolation condenser (IC) <mechanical factors> for maintaining the water level of the reactor pressure vessel (RPV) <object> in accordance with operating procedures, but they could not monitor the water level and pressure of the RPV from the MCR because DC power was lost. Therefore, they tried to confirm steam discharge from the IC vent pipe by sight (steam seen over the R/B), but harsh conditions (*e.g.* aftershocks, tsunami alerts) prevented them from going there. (TEPCO report "*presumed that an isolation signal due to DC power loss caused the close of the IC system valves.*")

Subsequently, under the orders of the Site Superintendent, operators <human factors> started up the diesel driven fire pump (DDFP) <mechanical factors> so that cooling water injection after the depressurization of the reactors would occur, since the configuration of the alternate water injection lines to the reactors was complete. However, reactor pressure was too high to inject with the DDFP.

Furthermore, the Site Superintendent <human factors> ordered deliberation and preparation for venting the pressure containment vessel (PCV) because of high pressure in the dry well (D/W). Plant personnel <human factors> investigated relevant diagrams and asked contractors to confirm valve types/structures and whether or not the valves necessary for the venting operation could be opened manually.

Operators who entered the R/B to check reactor water level reported to the shift supervisor that the alarm pocket dosimeter value rose in a very short time. Upon receiving this report, the health physics team went to the field to measure radiation levels and confirmed the high dose <disturbances>. The Site Superintendent then forbade entry into the R/B.

As for 1F-2, the reactor core isolation cooling (RCIC) system <mechanical factors> was in operation, but operators <human factors> could not monitor and control the RCIC due to the loss of DC power supply. However, "*the RCIC continued its operation without any operator control for about three days and maintained the water level of the RPV* <object>." (TEPCO report)

The shift supervisor <human factors> decided to assemble an alternate injection line for the reactor using the fire pump (FP) line <mechanical factors>, upon considering 1F-1 radiation levels and the need for action before radiation levels increased.

As for 1F-3, DC power was available after tsunami inundation until the battery <mechanical factors> was exhausted. (The battery is designed to be charged by AC power.) Operators <human factors> maintained the water level of the RPV <object> using the RCIC and the high pressure coolant injection system (HPCI) <mechanical factors>. Then, in order to save even more battery power, operators and maintenance personnel <human factors> carried out load separation for the minimum equipment required for monitoring and operation control.

In this phase, it was recognized that the state of 1F-1, 1F-2 and 1F-3 <object> had advanced toward the worst situation. Plant personnel <human factors> continued to reconstruct <mechanical factors> with the remaining SSCs and alternative equipment under harsh conditions.

As for the SFP of 1F-4 <object>, the cooling and feedwater functions <mechanical factors> were lost, but plant personnel <human factors> postponed the countermeasures due to misjudgment that there was some margin at the time. As for 1F-5 and 1F-6 <object>, their residual heat removal function <mechanical factors> was lost, but plant personnel <human factors> had thought that countermeasures could be held off.

As for the Fukushima Daini NPS, all emergency core cooling system (ECCS) pumps <mechanical factors> except some pumps of 2F-3 lost function. However, most of the power supply facilities, the reactor injection systems, and the monitoring instrumentation of MCRs <mechanical factors> were intact. In other words, the Fukushima Daini NPS only lost part of <mechanical factors>. Therefore, <human factors> could start the reconstruction of <mechanical factors> relatively easily.

3.3 Phase III: efforts toward restoration

As for 1F-1, according to analysis in the TEPCO report, "*the RPV* <object> *was damaged before early morning of March 12 and almost the entire molten core had fallen onto the pedestal beneath the RPV*". Consequently, the high radiation dose level <disturbances> made it difficult to access to the R/B and open valves located on the PCV vent path, but maintenance personnel <human factors> installed a temporary air compressor <mechanical factors> at the MCR to open them. After the completion of local resident evacuation was confirmed, the PCV vent was carried out three times on the morning of March 12. However, it was believed that the venting might not have had sufficient effect due to the radiation level drop in an hour.

At the same time, water injection to the RPV by fire engines <mechanical factors> was continued and preparation work for changing the source water from fresh water to seawater <human factors> was progressed. At that time, a hydrogen explosion <disturbances> occurred at the topside of the R/B and damaged the seawater injection hose and power cable for the standby liquid control system <mechanical factors>. (TEPCO report "*presumed that majority of hydrogen leaked directly from the PCV to the R/B via the seal of the PCV head flange.*") Restoration and preparation works were halted until field conditions could be confirmed. Thereafter, the seawater injection to the RPV was initiated with the fire engine <mechanical factors>. Regarding the seawater injection, the governmental nuclear regulator was concerned about the possibility of reactor re-criticality caused by seawater injection and required its cessation <disturbances>, but the Site Superintendent <human factors> judged that continuing water injection to the RPV was vital to prevent the accident from progressing further. As a result, the seawater injection to the RPV was actually continued.

As for 1F-2, operators <human factors> recognized that the water level of the condensate storage tank (CST), which was the water source for the RCIC, was low, therefore they switched the water source from the CST to the suppression chamber (S/C) to ensure water injection into the reactor.

The power supply restoration of the RPV injection system <mechanical factors> progressed, but temporary cables were damaged by the 1F-1 hydrogen explosion <disturbances> and works <human factors> were in vain. In addition, the circuit for activation of the air-operated valve that was needed to open the PCV vent <mechanical factors> came off due to the 1F-3 hydrogen explosion <disturbances>. The fire engine on the seawater injection line <mechanical factors> that was completed by plant personnel <human factors> also became unusable due to the 1F-3 explosion <disturbances>.

"*The Site Superintendent believed the RCIC function may have been lost due to reactor water level drop.*

Estimations based on the current situation predict that the top of active fuel (TAF) was reached around 16:30 of the same day." (TEPCO report)
The RPV was depressurized by the safety relief valve (SRV) using electricity from batteries <mechanical factors> that were collected from many cars of plant personnel and fire engines began water injection to the RPV, but core cooling was insufficient and the reactor core <object> was damaged. An impact sound and vibrations occurred in the morning on March 15, and the radiation measurements at the monitoring car near the main gate increased sharply.

As for 1F-3, the RCIC shut down and the HPCI automatically started at noon on March 12. However, operators <human factors> manually stopped the HPCI <mechanical factors> in the early morning of the next day because they were concerned that reactor steam leakage would occur due to equipment damage caused by the decrease in the HPCI system turbine revolution speed. As a consequence, the water level of the RPV dropped gradually. Operators tried to restart the RCIC and the HPCI, but they could not carry it out due to the depleting of batteries.
"*Since the switch to low pressure injection after the HPCI system shutdown did not immediately succeed, this resulted in worsening the fuel cooling. This is believed to have started core damage. It is believed that the sudden drop in retained water amount due to the S/C steam release with accompanying reactor depressurization had also worsened the fuel cooling. The pressure rise in the D/W around the same time suggests that hydrogen generation caused by core damage had begun.*" (TEPCO report)
They secured a battery necessary for the operation and started injection to the RPV with a fire engine that had been moved from the Fukushima Daini NPS. However, seawater injection stopped because a hydrogen explosion <disturbances> occurred in the R/B and the fire engine and hoses were damaged.

As for 1F-4, the cooling and feedwater systems <mechanical factors> of the SFP <object> were stopped; therefore the water temperature of the SFP increased gradually and reached 84^{o}C in the morning of March 14. The hydrogen explosions of 1F-1 and 1F-3 and at the R/B of 1F-4 <disturbances> made the cooling of the SFP <object> remarkably difficult. TEPCO judged afterwards that "*the hydrogen that resulted in explosion at 1F-4 was the PCV vent gas flowed from 1F-3*". On March 16, it was confirmed that the water level of the SFP was being maintained as expected. On March 22, the water injection to the SFP was started using concrete pump vehicles as temporary substitute for proper water pumping system.

In this phase, almost all <mechanical factors> did not function. <Human factors> carried out a lot of restoration work, but they were often interfered with by <disturbances> such as hydrogen explosions. <Object> resulted in a severe accident.

3.4 Phase IV: recovery from harsh conditions

As for 1F-5, power supply restoration using power supply from the EDG of 1F-6 with a temporary cable and other actions were progressed <human factors > from March 12 to 13. The residual heat removal system <mechanical factors> functioned due to the installation of temporary water pumps and power supply cars. 1F-5 <object> achieved CSD. As for 1F-6, the water level of the RPV was controlled by the condensation supply water system <mechanical factors>. Two EDGs were then started, residual heat removal system pumps <mechanical factors> were operated and 1F-6 <object> achieved CSD.

As for 2F-1, 2F-2 and 2F-4, the water temperature of the S/C increased at one time, but the S/C spray gave a time margin until restoration of residual heat removal system <mechanical factors>. Plant personnel <human factors> carried out restoration work such as connecting electric panels with temporary cables, replacing the motors and checking the state of pumps. These units <object> achieved CSD in a few days. As for 2F-3, it <object> was pushed forward to CSD easily by operators <human factors> because the residual heat removal pump <mechanical factors> was partly available.

In this phase, the reconstruction of <mechanical factors> that had collapsed was completed by <human factors>. <Object> affected by <disturbances> was secured safely.

4 Relationship between mechanical factors and human factors

4.1 Expected disturbance

The functions of mechanical and human factors cooperate with each other, and can lead the object to a stable state.

- The nuclear power plants in operation <object> were automatically shutdown due to the earthquake <disturbances> and maintained in a subcritical state by plant protection and control systems <mechanical factors>, and were moved to CSD by operating crews on duty <human factors>. Although plants had lost off-site power supplies, the EDGs started automatically and supplied necessary electric power. (All units)

4.2 Unexpected disturbance

Whether or not the object ends in a stable condition depends on the damage to the mechanical factors or the initial condition of the object.

- If some of the SSCs are still functioning, the stable state of plant <object> is achieved relatively easily. Operating crews <human factors> could cool down the reactor using the available residual heat removal system <mechanical factors>. (2F-3)
- Although most of the SSCs important to safe shutdown do not function temporarily, if they are restored (*i.e.* reconstruction of the mechanical factor is possible), the stable state of the plant <object> is achieved with a time delay. Plant personnel <human factors> carried out restoration work such as connecting electric panels with temporary cables, replacing the motors and checking the state of pumps <mechanical factors>. (2F-1, 2F-2 and 2F-4)
- If the initial condition is stable, the stable state of plants <object> is achieved relatively easily. Plant personnel <human factors> have enough time to restore the residual heat removal system <mechanical factors>. (1F-5 and 1F-6)
- If most of the SSCs important to safe shutdown do not function, it is very difficult to identify and achieve progress to a stable state. Almost all water injection systems to the RPV such as the IC, the RCIC and the HPCI <mechanical factors> lost their functions. Plant personnel <human factors> tried alternative injection systems such as low pressure injection system using fire engines <mechanical factors>, but they could not complete it and core damage occurred. (1F-1, 1F-2 and 1F-3)
- Although the initial condition is stable, if the disturbance spreads from other plants, it is difficult to carry out restoration work in a timely manner. Plant personnel <human factors> lost time restoring the SFP cooling system <mechanical factors> through repeated trials and errors. (1F-4)

4.3 Mechanical factors

The mechanical factors are systematically designed, manufactured and maintained to perform their function for expected events. However, they are often vulnerable to unexpected events.

- The mechanical factors do not have the ability of self-reconstruction. Once they fail, human factors must restore them or replace them with alternatives.
- The mechanical factors are required to maintain their original function as individual parts even if they are interfered with or damaged by the disturbances.
- It is rational to have temporary mechanical factors that can be useful for reconstruction.

4.4 Human factors

The human factors can support the situation to change flexibly in various ways. However, this has both positive and negative aspects.

- The human factors such as operators who are well trained through routine work and training can demonstrate their ability even during an unexpected event.
- The human factors such as maintenance and engineering personnel who are experienced and have enough knowledge about the object can restore the existing mechanical factors or plan new or alternative ones.
- The human factors such as plant personnel including the subsidiary company’s employees, fire brigade and support personnel can perform their tasks under the direction of the organization. Conspicuous disagreement is not seen in the communication between them.

- However, as the range of human factors such as regulatory person increases, the knowledge, experience and recognition of the human factors concerned are greatly different from the plant personnel, and this becomes a barrier to smooth progress.

5 Resilience engineering perspective

Erik Hollnagel [11-12] *et al*. proposed "resilience engineering" as a new paradigm for safety management, advocating proactive safety management (hereafter called "safety-2") as distinct from traditional reactive "safety-1". Safety-1 intends a reduction in the number of adverse events, while safety-2 lays down the importance of human ability to success even under changing situations. According to Hollnagel, a resilient organization is required to have the following four main abilities:

(1) Ability to monitor; knowing what to look for, or being able to monitor what in the near term changes, or could change.
(2) Ability to anticipate; knowing what to expect, or being able to anticipate developments, threats, and opportunities further into future.
(3) Ability to respond; knowing what to do, or being able to respond to regular and irregular variability, disturbances, and opportunities.
(4) Ability to learn; knowing what has happened, or being able to learn from experience.

In this section, by borrowing the above-mentioned concept of resilience engineering, the Fukushima accident is evaluated from view of its soundness in relation to mechanical and human factors. The ability to monitor corresponds with the battery of the mechanical factor which is a driving source of the plant monitoring instruments. The abilities to anticipate and to respond correspond with the human factors. The ability to learn also corresponds with the design concepts of having off-site AC power supply, EDG and batteries, in the sense that the design of these facilities reflects learning from past incidents. EDG is considered to include switchboard. Even if the EDG itself is sound, it does not function in the case of switchboard damage. Figure 2 summarizes the evaluation of the Fukushima accident in the above-mentioned way from resilience engineering perspectives. The individual observations for the four phases of the Fukushima accident are summarized below.

Phase I: Although most off-site AC power supplies were lost due to the earthquake, this phase was within a design basis event, and the EDGs were started successfully. The ability to monitor the system was maintained by the fact that the batteries were functioning. The abilities to anticipate and to respond were sufficiently addressed by traditional operator training in this phase. Regarding the ability to learn, a weakness of the design is reflected in that the restoration of the accident was difficult at any phase.

Phase II: The inundation of the tsunami after the big earthquake was beyond the design basis of the Fukushima NPSs, and so the functions of the mechanical factors were largely destroyed. The degree of the damage was dependent on the machine factors implemented in each unit and was greatly influenced by the development of subsequent events. Having batteries (enabling the ability to monitor) particularly significantly impacted the operators' abilities to anticipate and respond.

Phase III: Because of the higher level of radiation dose in the site due to core meltdown, the ability for operators to respond to the accident properly was significantly aggravated. The hydrogen explosions of 1F-1, 1F-3 and 1F-4 made it even more difficult to respond for operators.

Phase IV: Because the battery function was operational and the function of off-site AC power supply or partial supply from EDGs were also maintained, it was possible for operators to demonstrate the abilities to anticipate and to respond properly.

In short, Fukushima Daiichi NPS Units 1F-1, 1F2 and 1F-3 led to severe accidents, while the Fukushima Daiichi NPS Unit 1F-4 to 1F-6 and all units of the Fukushima Daini NPS were restored from accidents, based on differentiation in the four main abilities in resilience engineering. Wherein, Phase II is the branching point that divides the occurrence of a severe accident and the avoidance of the severe accident.

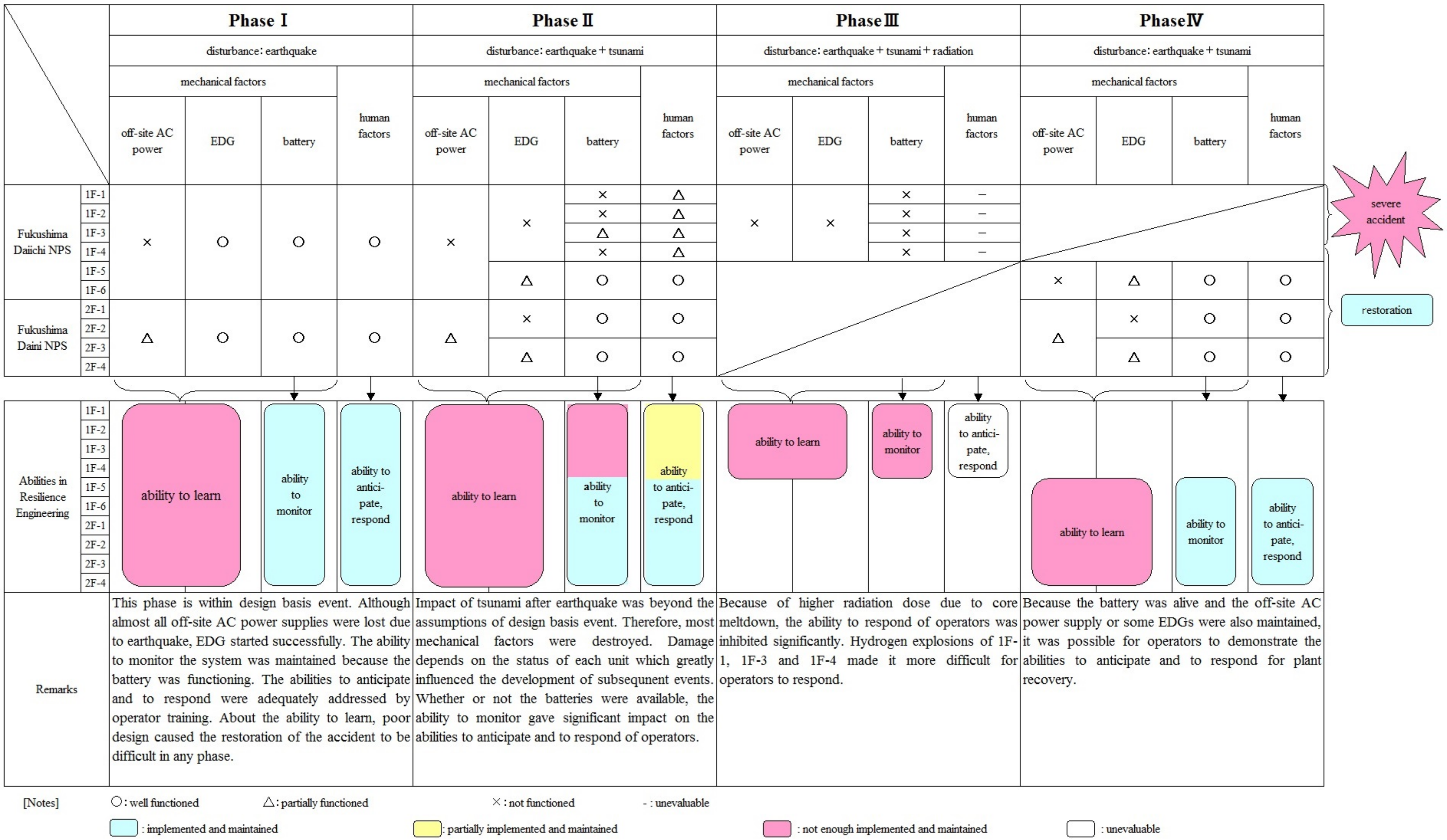

Fig.2 The relation between the Fukushima NPS accident and abilities in resilience engineering.

Due to the loss of function of the battery, the ability to monitor the plant was inhibited and manipulating functions such as valves were lost. The ability to anticipate was therefore significantly inhibited. It is considered that this is the one factor that makes it difficult to respond properly to the progress of the event. Countermeasures to the severe accident have already been studied and carried out by utilities after the Fukushima accident. The authors of this paper emphasize that extensive training on severe accident response and ensuring the batteries are functioning are particularly important from the viewpoint of the fostering the abilities to monitor, anticipate and respond.

6 Branching point of the Fukushima accident – what went wrong or not

In this chapter, the authors of this paper would like to clarify what the differences are between the Fukushima Daiichi NPS and the Fukushima Daini NPS regarding whether a severe accident would occur, using a simple illustrative picture - Fig. 3.

Prior to the earthquake, all nuclear units are stable as shown in Fig. 3(a).

Furthermore as shown in Fig. 3(b), after the earthquake occurrence, all units were kept in a stable state by EDGs substituting for off-site power between earthquake occurrence and tsunami inundation. Operating crews on duty carried out response operations toward CSD.

However, after tsunami inundation, the situations of all units are drastically changed. At the Fukushima Daiichi NPS, 1F-1 to 1F-5 resulted in SBO due to coverage of AC power supplies by water. Operating crews could not utilize almost any SSCs important to safety shutdown. These units became unstable as shown in Fig. 3(c). At the Fukushima Daini NPS, 2F-1 to 2F-4 just barely kept in a stable state, although they temporarily lost function of the ECCS equipment (*i.e.* residual heat removal system) as shown in Fig. 3(d).

A big difference occurred from approximately eight

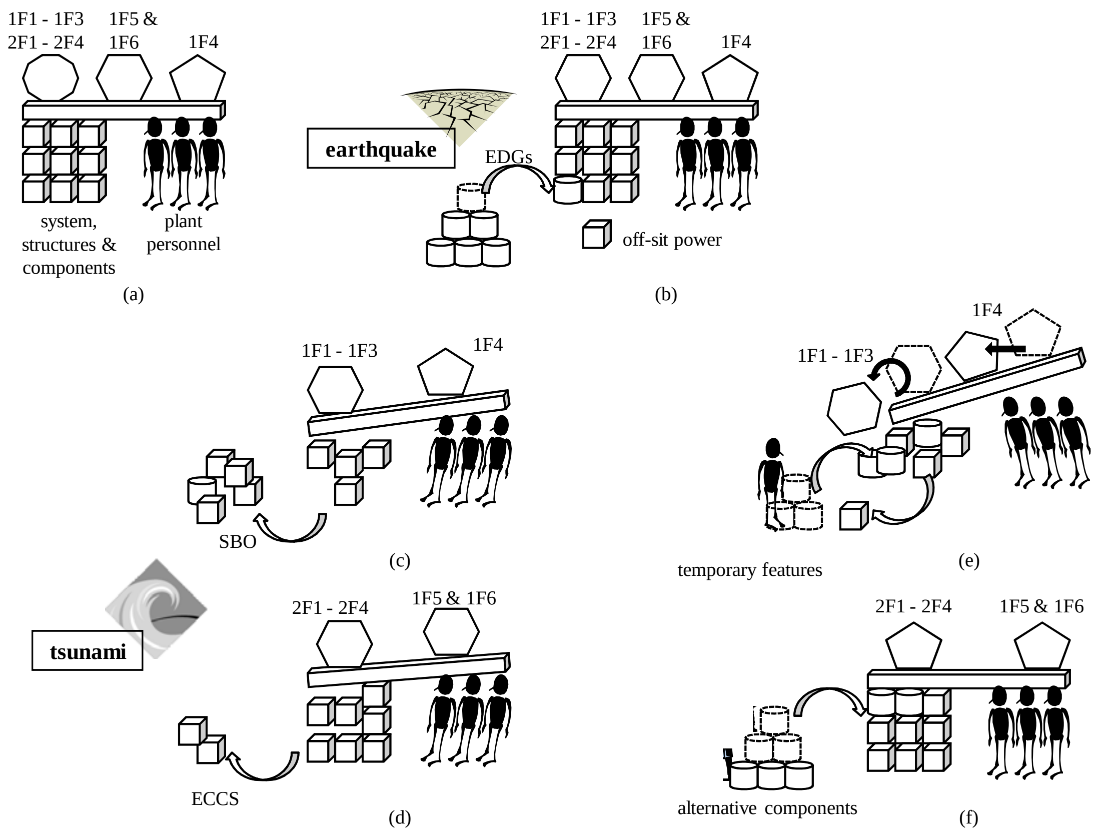

Fig.3 Difference in result between the Fukushima Daiichi NPS and the Fukushima Daini NPS.

hours after the earthquake. At the Fukushima Daiichi NPS, plant personnel continued their restoration work with available SSCs and temporary features under harsh conditions. In spite of their efforts, reactor cores of 1F-1, 1F-2 and 1F-3 could not be cooled sufficiently by any means and resulted in core meltdown as shown in Fig. 3(e). It also became difficult to restore the cooling function of the SFP of 1F-4.

At the Fukushima Daini NPS, plant personnel completed the restoration work using available SSCs, alternative components and human resources. As a result, 2F-1 to 2F-4 regained cooling function and pushed toward CSD within a few days as shown in Fig. 3(f).

The both functions of mechanical factors and human factors which are already defined in this paper are expected to cooperate with each other to lead the object NPS to recover in a stable state, when any disturbance happens to occur. However, the evolution of the plant system toward the stable state or not depends on the damage of the mechanical factors or the initial condition of the object, prior to the disturbance.

Resilience engineering points out the importance of keeping in mind that the situation always changes. For the further safety improvement of nuclear power plants, it is necessary not only to increase the robustness of individual SSCs but to prepare alternative SSCs or temporary features such as EDGs, DC power and batteries.

In addition, it is absolutely necessary to secure the ultimate heat sink for maintaining safe shutdown at long term SBO. In the case of BWR plants, the high pressure injection system such as RCIC or the HPCI pumps feeds water to the RPV just after scram. These pumps are driven by steam turbines that exhaust the steam to the S/C. The low pressure injection system such as the make up water condensate (MUWC) pumps feed water to the RPV after it is depressurized by the SRV. The steam goes through the SRV from the RPV to the S/C. Therefore, the PCV venting or the S/C cooling must be performed in a short time until the water temperature of the S/C reaches the saturated temperature. On the other hand, in the case of PWR plants, the residual heat is removed through the steam generator (SG) secondary side by feed and bleed operations that are configured off the turbine driven auxiliary feedwater pump and the main steam relief valve. The non-radioactive steam generated in the SG is discharged via the steam relief valve to the atmosphere directly. This (*i.e.* (i) the time allowance for turnover to ultimate heat sink and (ii) radioactive release to the environment) may be better in a severe accident management than that in BWR.

7 Concluding remarks

This paper classifies the Fukushima accident into four phases to clarify the difference of accident results at the Fukushima Daiichi NPS and the Fukushima Daini NPS easily. It reviews the accident evolution at each phase and discusses the mechanical and human factors which controlled it. In addition, it evaluates the accident in light of resilience engineering.
It clarifies what factors are important to improve the safety of nuclear power plants. The system, structures and components of NPS are systematically designed, manufactured and maintained to perform its function for expected events, but they often have vulnerability to unexpected events. The plant personnel can respond to the situation to change flexibly. They can also get effective support from outside organizations, although they spend a lot of time for coordinating the various complicated issues. In other words, it is most vital to prepare human resources who have sense of mission, knowledge about and skill in operating their plant and are well trained or experienced for unexpected events.

Nomenclature

CSD	Cold Shutdown
CST	Condensate Storage Tank
DDFP	Diesel Driven Fire Pump
D/W	Dry Well
ECCS	Emergency Core Cooling System
EDG	Emergency Diesel Generator
FP	Fire Pump
HPCI	High Pressure Coolant Injection
IAEA	International Atomic Energy Agency
IC	Isolation Condenser
MCR	Main Control Room

MUWC	Make Up Water Condensate
NPS	Nuclear Power Station
PCV	Pressure Containment Vessel
R/B	Reactor Building
RCIC	Reactor Core Isolation Cooling
RHR	Residual Heat Removal
RPV	Reactor Pressure Vessel
SBO	Station Black Out
S/C	Suppression Chamber
SFP	Spent Fuel Pool
SG	Steam Generator
SLC	Standby Liquid Control
SRV	Safety Relief Valve
SSCs	Systems, Structures and Components
TAF	Top of Active Fuel
TEPCO	Tokyo Electric Power Company Inc.

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