Proceedings of the 18th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2016
September 18-23, 2016, Kobe, Japan

Paper No. 3041

Extraction of New Lessons Learned from the Great East Japan Earthquake 2011 with Resilience Engineering Methodology

Atsufumi Yoshizawa
Former President, Nuclear Fuel Transport Co., Ltd.

Kyoko Oba
Japan Atomic Energy Agency

Masaharu Kitamura
Research Institute for Technology Management Strategy (TeMS)

Abstract

The Great East Japan Earthquake caused substantial damage to complex socio-technical systems essential for modern life. For preventing such damage resulting from a disaster or accident and alleviating such damage, it is important that protections be prepared in advance and a flexible response undertaken after such a catastrophe hits. However, as we actively deduce all sorts of problems that have been brought to light by past disasters in order to protect society from the next disaster, in other words, extract lessons based on "things that went wrong" with socio-technical systems, we have only made a partial effort to deduce lessons based on "things that went right," such as for example, the actions taken that hindered "factors directly related to failures" which arose after the disaster struck. As a result, we run the risk of overlooking lessons which are critical for protecting society from future disasters and which allow us to learn from "things that went right." This article references Resilience Engineering, which is indicative of the importance of learning from "things that went right," and analyzes things that went right in field responses to the earthquake during the Fukushima accident as well as transport operations, in an attempt to deduce new lessons about emergency responses and preparations against unforeseen contingencies, which are common to socio-technical systems.

Introduction

The Great East Japan Earthquake, which struck on March 11, 2011, had a significant impact on many socio-technical systems, including transportation and nuclear power. Even within this context, the accident at Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Station (hereinafter, "Fukushima accident") brought to light not only the extensive scale of such damage, but also revealed hidden issues pertaining to safety assurance in the modern age, which is a time when we employ such complex systems. However, although many entities have conducted analyses of the Fukushima accident and identified lessons to be learned, most of these investigations have focused on analyses that zoom in on "factors that led to the accident" and deduce lessons to be learned. The perspective of such accident analyses and lesson deductions is the idea that some sort of defect must be lurking for the accident to occur (to put it another way, there is the assumption that systems will work as intended unless some sort of mistake is made or failure arises) and is based on the approach to safety expressed in ISO/IEC Guide 51 that safety is “freedom from risk which is not tolerable” [1]. In fact, for ensuring safety in keeping with the ISO/IEC Guide 51 definition referenced in a wide range of industries, it is necessary to adopt an approach whereby the “risks” entailed in a system are identified, and these are eliminated or reduced to a acceptable level. So, as a matter of course, for earthquake or other disaster experience to be useful in preventing or mitigating damage brought about by future earthquakes, the focus is directed to accidents where the earthquake reveals things that went wrong and there is no choice but to concentrate on the so-called “find and fix” method [2], which is a method for improvement whereby causes are identified and fix them to prevent recurrences.

On the other hand while the earthquake registered the maximum of seven on the Japanese seismic scale and was accompanied by strong tremors registering a weak six across a broad area, the efforts put forth by East Japan Railway Company (hereinafter, “JR East”) to respond, which did not allow any crew or passenger casualties including on the Shinkansen which runs at a maximum speed of 270 km/h, and the actions of the maritime transport industry, which protected vessels and the lives of many crewmembers against the tsunami while at the same time sustaining damage from to the tsunami, are related to the “freedom from risk which is not tolerable,” which was appropriately implemented and came to light during the earthquake. However, because these are not failures, they have only been partially reported or broadcast in the media. Still, such efforts have not gone so far as to identify lessons to be learned that may be common to socio-technical systems. Also, as stated by Yotaro Hatamura, Chair of the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, in the Final Report: “The events that occurred within the nuclear power station after it was flooded as a result of the tsunami were a series of incidents that people involved with nuclear power generation in Japan had never encountered before, and without the actions of those involved in dealing with the accident at the facilities, who risked their lives, the accident would have worsened further and radioactive materials might well have dispersed over a clearly much wider area than at present.” [3] Nevertheless, in analyses of the Fukushima accident, efforts have principally focused on factors leading to the accident as mentioned earlier, and there are almost no reports treating and analyzing the Fukushima accident as an event that avoided a “further catastrophe.”

Based on these observations, this article takes into account the experiences of the first author in responding on-site during the Fukushima accident, and attempts, while referencing the approach of Resilience Engineering which has garnered attention in recent years, to deduce new lessons to be learned about the emergency response as well as preparations for unforeseen contingencies, which may be shared by socio-technical systems, on the basis of “things that went right” during the earthquake response in the field during the Fukushima accident and maritime transport operations.

1. Methodology

This article attempts to deduce from acts carried out in the field, using as a reference the approach of Resilience Engineering which has been advocated for the purpose of finding the answer to the question of how to make systems resilient.

The basic characteristic of organizations that are resilient, which is the purpose that Resilience Engineering seeks to attain, is that they do not lose control in seeking to achieve the purposes for which the organization operates, and they are able to continue operating or recover. In order for organizations to be imbued with this basic characteristic, the organization needs to know what has happened (Learning), what is happening (Monitoring), what to do (Responding), and what may happen (Anticipating) as its means for maintaining control. Along with the organization being endowed with the abilities to anticipate, detect and address issues, it is essential that there be a system in place for updating these abilities through Learning [4)]. Resilience Engineering defines these capabilities, such as Learning, Monitoring, Responding and Anticipating as the four cornerstones[5)].

In addition, E. Hollnagel, an advocate of Resilience Engineering, has defined the concept of safety into two terms, Safety-I and Safety-II, and stated that, in the future, we should enhance safety based on the concept of Safety-II[2)]. Explanations of Safety-I and Safety-II are provided here. Safety-I refers to safety defined traditionally as a static concept and in a negative form. That is, just as stated in ISO/IEC Guide 51, safety is the “freedom from risk which is not tolerable.” Accordingly, using the four cornerstones that comprise Resilience Engineering, Safety-I is realized by learning from instances where unacceptable risks came to light (things that went wrong) and by monitoring and anticipating by means of risk assessment methods and other such techniques. In addition, faithfully implementing what has been prescribed beforehand is central to responding.

On the other hand, Safety-II is safety for which the purpose is to be able to continue to operate and avoid a catastrophic situation by flexibly employing resilient behavior in conditions where systems are incapable of maintaining usual operations or performance[2)]. Consequently, an important component of learning includes case studies where unacceptable risks were prevented from coming to light (things that went right) and case studies of responses flexibly adapted as circumstances required in emergency situations where unacceptable risks were revealed, and the focus of monitoring and anticipating includes not just risks but also chances. In this way, in our present day when Safety-I is central, Safety-II is not a concept that contrasts with Safety-I, but it is appropriate to think of Safety-II as affording a safety goal based on a new and effective perspective that is an extension of Safety-I, where, to a certain extent, a high degree of safety is already ensured. Resilience Engineering is positioned as an engineering methodology for pursuing this goal[6)].

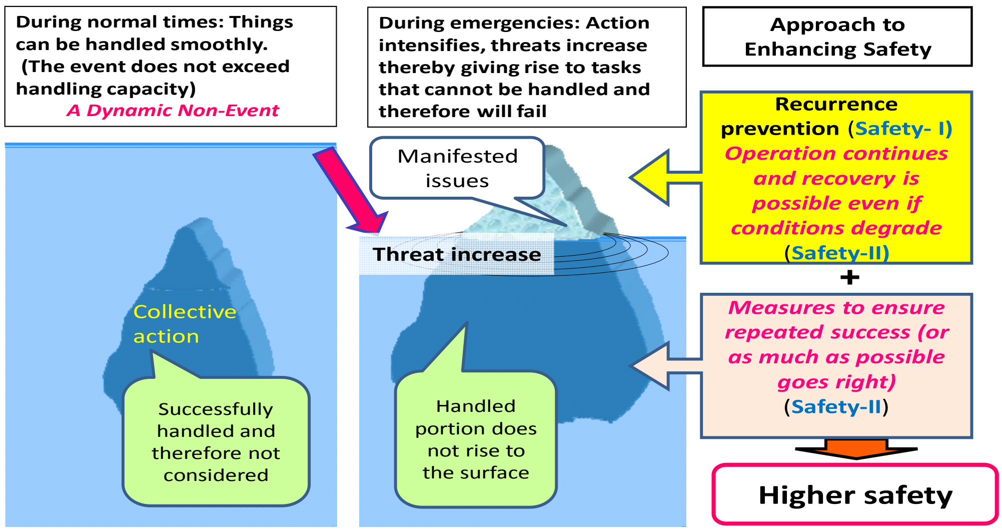


Figure 1. Model comparing the Safety-I and Safety-II approaches to enhancing safety

A conceptual model is shown in Figure 1 of the responses during normal times and emergencies[7)]. The iceberg represents the aggregate of actions. With complex systems, it is appropriate that the event be expressed as a conglomeration of many acts. Also, the surface of the water represents the competence of organizations and people.

As shown in Figure 1, a series of acts, which enable a system to function, are carried out during normal times within the scope of the competency of the people and organization, and any variations are absorbed. However, when faced with a significant crisis, systems require many acts, and organizational competency declines due to time pressure and other such factors. The result is that some acts, which exceed the current competency and are not able to be managed, fail, and, as a result, the event per se ends in failure. However, this failure does not mean that all acts comprising the event were failures. More specifically, we know that two approaches are needed for ensuring safety. The first is to work to prevent recurrences so that failures are not repeated, and the second is to make sure that successful actions are able to be reliably and effectively addressed. The former refers to countermeasures that adopt the Safety-I perspective, but the latter corresponds to the direction that Safety-II and Resilience Engineering aim.

Maintaining an awareness of the four cornerstones and referencing the approach of Resilience Engineering, the following and later sections analyze and assess case studies from JR East and the maritime transport industry as well as the Fukushima accident.

2. Cases and Investigations

Case 1: Protect the Shinkansen (JR East) [8)]

When the Great East Japan Earthquake struck, JR East effectuated the emergency shutdown of all 27 Tohoku Shinkansen lines, which were in commercial operation (max. speed of 270km/h), without any trains derailing nor any casualties among the crew or passengers. The subsequent investigation found that cases, in which JR East's long-term steady efforts that mainly focused on its scrupulous advance preparations to ensure safety, underlie this achievement. JR East's efforts are arranged in a time series and an analysis provided of the background behind this achievement of safety that focuses on the four cornerstones of Resilience Engineering.

(1) Time Sequence of the Response

① Efforts Aimed at Ensuring Railway Line Safety after the Great Hanshin-Awaji Earthquake (1995) and Sanriku-Minami Earthquake (2003)

Anticipating: The Great Hanshin-Awaji Earthquake was an earthquake whose intensity was within the design parameter (maximum seismic intensity: 7), and brought about events in which bridges collapsed. JR East personnel, who provided support for the recovery on-site, saw conditions with their own eyes and realized that the trusses collapsed, even though they were appropriately constructed based on existing seismic design.

Learning, Anticipating: This is leaning about the relationship between active faults and truss collapses or other points where the railways was damaged. (As a result of preparing a large diagram that plotted points where damage occurred along conventional lines and the Sanyo Shinkansen and the location of active faults on a topographic map of the Hanshin region after the Great Hanshin-Awaji Earthquake, it was realized that the locations where damage was sustained were within a 3km range to the left and right of active faults.)

Monitoring: The Seismic Reinforcement Project Team (Civil Engineering Section, Facility Electric Department) confirmed the presence of railway lines within a range of 3 km to the left and right of active faults and reviewed maintenance plans.

Responding: While instructions issued by the government called for construction based on economic priority areas rather than the distance between railway lines and active faults, JR East implemented maintenance that surpassed these instructions. (Additional proposals were submitted for maintenance in the Nagaoka vicinity (Joetsu Shinkansen), Shiroishi-Zao vicinity (Tohoku Shinkansen) and Kumagaya vicinity (Joetsu Shinkansen), and these plans were approved by the board of executive officers and implemented.)

② Efforts Aimed at Preventing Derailment and Overturning of Railway Cars after the Chuetsu Earthquake (2004)

Learning: It was during the Chuetsu Earthquake that a Shinkansen derailment occurred along the Joetsu Shinkansen line for the first time. However, thanks to the implementation of maintenance beyond that instructed by the government, no bridge trusses collapsed even during earthquakes registering a strong six on the Japanese seismic scale, which occurred almost directly under the Shinkansen railway line, and the Shinkansen "ended up" derailing. Furthermore, because the derailed cars did not roll over, progress was attained in reaching the next stage where the aim was to further ensure railway line safety and prevent railway cars from overturning. In particular, it was very significant also that the company was aware of the appropriateness of measures for ensuring railway safety and the importance of respecting the opinions of those possessing specialized knowledge.

Anticipating: a. Rail guards mounted on bogies fulfilled the function of preventing railway cars from overturning. (The right rail was caught between the fourth axle of the right wheel and the position where the rail guard was mounted, and the left rail was caught between the fourth axle on the left wheel and the gear case.)

b. The danger of rail friction heat from derailed railway cars was solidly realized. (Rail friction heat here is the amount of energy generated by a car maintaining a speed that far and away exceeds that along conventional lines.)

Responding: a. Deviation prevention guides were developed and fitted; b. the earthquake detection system, which is linked to bringing railway cars to an early stop, was improved.

Monitoring: a. Equipment performance was measured as it relates to preventing railway cars from overturning; b. the distance until railway cars would stop during an earthquake was measured.

Responding: a. Rail overturn protection devices and other such equipment were introduced; b. power interruption detection devices were newly installed, making it possible to ascertain earthquakes even sooner.

(2) Case Study and Lessons

This case study shows an example, which is based on to the four cornerstones, of achieving safety through meticulous measures implemented in advance as a result of consolidating JR East's Shinkansen earthquake countermeasures. In other words, the fact that there were no derailments of Shinkansen trains operating during the Great East Japan Earthquake was not mere coincidence, but it was due to JR East being a resilient organization that engaged in appropriate learning based on "what had happened" during the Great Hanshin-Awaji Earthquake, Sanriku-Minami Earthquake, Chuetsu Earthquake and other such events, and the company was able to respond with appropriate speed by employing efforts aimed at ensuring railway line safety and efforts aimed at preventing railway cars from overturning. The safety maintained here is considered to be the preventive-type Safety-I, but consideration also needs to be given to underlying factors. In this case study, a sincere and serious analysis was conducted of the accident site after the Great Hanshin-Awaji Earthquake and safety measures implemented for bridges, which went beyond the approval and authorization requirements, thereby achieving zero fatalities even while a Shinkansen derailment was experienced during the Chuetsu Earthquake. While confirming the appropriateness of efforts for ensuring railway line safety, JR East implemented proactive efforts with the aim of further raising the level of safety. Underlying factors, which have prevented accidents as a result of such efforts, have played a significant role, and these include a sense of mission and corporate culture during normal times in supporting responses suited to the circumstances, and comprise many aspects of Safety-II that are supported by positive aspects which people maintain.

Case 2: Emergency Response of Maritime Transportation

The Great East Japan Earthquake inflicted serious damage on the maritime transport industry. However, as the tsunami swept towards the coastline, there were crewmembers that devoted themselves to ensuring the safety of their vessel and other crewmembers. With respect to these vessels, there have been no reports of accidents involving the death of a crew member on board such a vessel that was caused by this massive earthquake. This study conducted questionnaires and interviews that focused on vessels and other ships anchored in port at the time of the earthquake. From the responses received, an assessment was conducted of 31 ships (excluding fishing vessels) which were 1000 tons or greater, the level equivalent to that of the vessels transporting radioactive materials in Japan (total tonnage: 5000). From these results, an analysis was conducted of the emergency response, using the four cornerstones of Resilience Engineering (survey figures show the percentage of respondents).

(1) Response at Time of Earthquake

① Status of Vessels When Earthquake Struck and Acquisition of Tsunami Information (Monitoring)

When the earthquake hit, most of the vessels moored at quays were either loading or unloading cargo (89%) or preparing to do so (11%), and most of these vessels, or 76%, had between 80% and 100% of their crew on board. Because vessels were engaged in cargo operations, there were also vessels that did not have a full crew as well as vessels where there were more personnel on board than a full crew. As for the sources for acquiring tsunami information, TV and radio ranked the highest (64%) followed by the harbormaster and Coast Guard offices (25%), but all of the vessels, which responded to the survey, acquired information about the tsunami in some form or another.

② Tsunami Predication, Judgment and Action (Anticipating, Responding)

Subsequently, the vessels took steps to perform an emergency undocking (64%), moor at a quay (14%) or other actions, but 65% of these decisions were based on the earthquake strike and tsunami information, far surpassing decision based on recommendations to evacuate or company instructions (13%). With regard to vessels that performed an emergency undocking, those that received assistance from on land were limited to 59%. Also, the time required after detection of the earthquake until the vessel undocked was for the most part within one hour (83%).

Of the 18 cases of vessels that executed an emergency undocking, 14 were successful in the end. However, although the remaining four were able to protect the crew, the vessels became stranded or experienced some other maritime accident. Of these, three vessels had arrived and docked, and they required time to undock.

(2) Case Study and Lessons

This case study presents lessons about ensuring safety through an emergency response when faced with unforeseen circumstances. As was revealed from the questionnaire and other research, vessels moored at quays were very likely in the process of loading or unloading cargo. When the earthquake struck, they were forced to perform a series of emergency responses for discontinuing the cargo operations and executing an emergency undocking. There were many instances of communication equipment on land becoming inoperable due to power source or circuit failures during the Great East Japan Earthquake, and vessels had to depend on unreliable information which they obtained on their own as they were unable to sufficiently contact people on land. Ship captains were central to implementing measures during the emergency. Nevertheless, most of the captains predicted the tsunami (anticipating) and envisioned the transition to the next measures. They monitored the status of cargo handling, crew deployment, vessel standby status and work time for undocking (monitoring), and shifted to directing and implementing the response (responding). When we consider that the emergency undocking time was less than one hour in most cases, captains were pressured to make decisions in a short amount of time and crew members had to perform much work, a high level of practical ability (skill) was required. What is extremely important for ensuring the safety of people and vessels during the earthquake disaster was estimating the time required for emergency undocking (anticipating). Of course, there was considerable uncertainty in estimating the time when a tsunami would arrive in forecasting the short amount of time after the disaster struck, but the captains had to make decisions about vessel responses while looking at both aspects. Because the vessels were either loading or unloading cargo, there have been reports of instances where the time required for disconnecting equipment on land ended up taking longer than estimated, instances where the time required for emergency undocking could be accurately ascertained based on emergency training experiences, and instances where vessels converged on the port exit and had to wait in order to exit which ended up taking longer than expected. Of these instances, there were also cases in which vessels ran aground or suffered other damage. No matter which option was selected, it is assumed that the choice would be a “sacrifice judgment.”

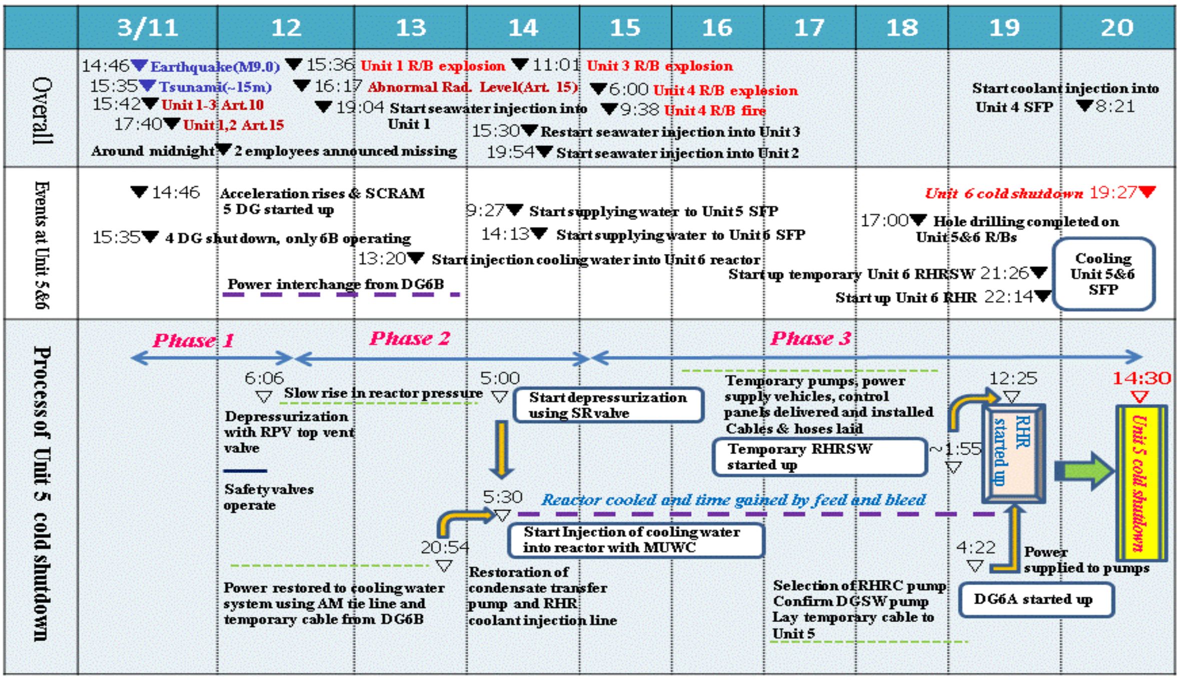
Of the cases where emergency undocking was performed, examples have been reported where information was shared and the captain exercised leadership to bring about a successful conclusion. The environmental conditions in which vessels in port found themselves were extremely complex as they did not comprise only oceanic phenomena but also cargo operations, loading operations, port and other vessel conditions as well as combinations of these factors, and the creation of detailed manuals beforehand for such responses is not realistic. To successfully undock in a short period of time, it is inevitable that a plan of action must be decided upon and work prioritized. Also, in shortening the emergency undocking time, requirements were also defined in advance that made such a response feasible, including the direction that the ship arriving in port is facing (bringing a ship into or out of port), the vessel’s undocking performance (availability of bow thrusters, propulsion system performance, etc.), whether or not the engines were warmed up, and other such factors.

Case 3: Fukushima Daiichi NPS Unit 5 Cold Shutdown[9),10),11)]

At Units 1~4 at Fukushima Daiichi Nuclear Power Station, the tsunami that formed due to the Great East Japan Earthquake caused a loss of all AC power, buildings exploded (at Units 1, 3 and

4) and core meltdowns occurred (at Units 1, 2 and 3), and this event was accompanied by large-scale resident evacuations. The resulting accident was equivalent in scale in international ratings to the accident that occurred at the Chernobyl Nuclear Power Plant. However, the response carried out in the field enabled any “further catastrophe” to be avoided, including damage to fuel and spent fuel pools as well as damage at Units 5 and 6, a fact that has subsequently become clear based on testimony from many people involved. This section analyzes the event all the way through the successful cold shutdown of Unit 5 where all AC power was lost just as at Units 1~4 and is one example of a further catastrophe having been avoided.

Table 1. Unit 5 Chronology of Key Events from Loss of All AC Power to Cold Shutdown



Prepared based on the Tokyo Electric Power Company “Fukushima Nuclear Accidents Investigation Report” (June 20, 2012) and Report of the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company (July 23, 2012)

(1) Time Sequence of the Response

On March 11 prior to the earthquake, Unit 5 was undergoing periodic inspection, so pressure tests were being conducted of the reactor pressure vessel while the reactor was shut down with all control rods inserted. Following the loss of off-site power due to the earthquake, the tsunami knocked out all AC power sources, and Unit 5, which sustained damage to seawater pumps and other equipment necessary for maintaining cooling function, was able to maintain the reactor in a shutdown state, but it lost function for removing fuel decay heat. Because the reactor was shut down, the amount of decay heat being generated was relatively low, but the reactor’s internal temperature and pressure rose, and the safety valve was activated in the early morning of March 12, and high temperature steam began to blow into the pressure suppression chamber.

① Ensuring Power Sources (Monitoring Functions) (Phase 1)

·Monitoring: (Although the main control room had lost interior lighting due to the loss of AC power,)

DC power sources made it possible to use instruments to monitor the reactor. However, the DC power sources were only able to be used for limited periods of time.

·Responding: From the emergency generator at Unit 6 which was the only one that could supply power at the power station (Unit 6 was adjacent to Unit 5 and used the same main control room), a power interchange line and temporary cables, which had been readied in advance based on the accident management measures, were laid and the response gave priority to maintaining the capability to monitor reactor parameters.

② Maintaining Function for Injecting Cooling Water into Reactor (Phase 2)

·Anticipating: In the field, compared to Units 1~3 which were operating at the time of the earthquake, Unit 5 had a greater margin of time for responding, but personnel were aware that it would take time to restore the equipment necessary to engage the ordinary cooling system, and a determination was made that a different response was needed.

·Responding: First, to serve as stopgap measures, water was injected into the reactor to maintain the water level, and a course of action developed and executed to buy time until the equipment was fully restored. Specifically, in order to shore up time while waiting for the equipment necessary for maintaining cooling function to be restored, a line was constructed for injecting cooling water into the reactor which had been readied based on the accident management measures, and steps were taken that were appropriate for the situation at hand to depressurize the reactor, which did not proceed as described in the manuals, and cooling water was injected into the reactor.

③ Restoring Reactor Cooling and Cold Shutdown (Phase 3)

・Monitoring: With regard to operations, it was confirmed that cooling was able to be maintained by injecting cooling water into the reactor while at the same time assessing reactor conditions.

・Anticipating, Responding: It was anticipated and there was a shared understanding that it was necessary to restore cooling function soon. The necessity of parallel implementation of a variety of options was acknowledged and executed. Specifically, restoration of cooling function was considered through the restoration of equipment in the field and use of temporary equipment. In the field and headquarters, human resources were augmented and roles assigned to personnel so as to achieve a recovery of the cooling function in parallel with restoration of the adjacent Unit 6. Ultimately, one emergency generator was restored in the field and a temporary pump for seawater cooling was brought in, which along with other achievements resulted in successfully achieving a cold shutdown of the reactor on March 20.

(2) Case Study and Lessons

This case study is an <u>example of safety having been ensured by maintaining a course of</u>

action and responding flexibly in a manner suited to the circumstances while effectively utilizing advance preparations. In this case study which succeeded in maintaining cooling function while at the same time ensuring power for maintaining monitoring functions, the maintenance of functions for monitoring the reactor even after the loss of all AC power sources made it possible to transition to a levelheaded response based on such results within the context of personnel anticipating that it would take time for restoration of the facilities based on the extent of the damage sustained by equipment and other factors. Heading towards the goal of achieving a cold shutdown, personnel in the field closely examined feasible options with the limited human resources as well because of the hydrogen explosions at other units and other factors, and they engaged in responding that prioritized such options. Also, underlying such responding, the sense of mission which personnel maintained in carrying out hazardous work under high temperature and high radiation conditions while aftershocks continued to occur, the load sharing which was made possible in cooperation with the Head Office (workload management) as well as the accident management measures which had been prepared in advance based on learning from past case studies, and the existence of a base-isolated building that made it possible to carry out the response to the accident even in a severe environment all fulfilled important functions. The cold shutdown of Unit 5 was the result of originality and ingenuity devised by each and every personnel in their respective duties as well as the accumulation of measures adapted to suit the circumstances at hand. In reviewing the Fukushima accident, many reports mention problems in siting multiple plants in their respective locations and accident management measures, but the successful cold shutdown of Unit 5 was brought about also by siting multiple plants in their respective locations and accident management measures.

4. Discussion

The aforementioned three events are examples of successes in ensuring the safety of different socio-technical systems, and each has its own distinguishing features in terms of the method for how the success was achieved. Based on the results of analyses referencing Resilience Engineering, the following common points have been identified.

① The foundation for success is laid through advance preparations, in terms of either equipment or procedures, as well as the abilities developed through such preparations that are based on "Learning" from past examples, such as JR East's seismic reinforcement of bridges and prevention of railway car derailment and overturning, maritime transport industry training on ships and other vessels, and the accident management measures developed from Fukushima accident case studies. The improvement of preparations is effective in mitigating damage due to an accident or disaster. This shows that a Safety-I (preventive) response is fundamental for ensuring safety even with complex systems.

② However, because time and resources are limited, it is important that the people involved in "Responding" during an emergency share an awareness that the response will not necessarily proceed as detailed in manuals or as may be implemented during ordinary times. In other words, although actions are premised on manuals regardless of whether they are executed during normal times or emergencies, with systems exposed to complex environments, safety cannot always be ensured just by faithfully executing manuals and rules.

③ While premised on manuals, in cases where a flexible response is demanded in accordance with the environmental conditions and other factors at the time, the ability of people (Responding) is essential for the execution of such a response, and it is necessary to improve the capabilities of an organization's personnel to execute a flexible response in terms of the organization's resilience. In areas exceeding Safety-I preparations, a response based on Safety-II is needed. The case studies of the maritime transport industry and Fukushima accident, in particular, are able to verify that safety can be assured through a flexible response adapted to the circumstances.

④ During the earthquake disaster, actions are required within a limited amount of time and based on a priority ranking, but it is possible that, in some cases, a response may not be able to be instituted according to the rules or manuals. Also, as the maritime transport industry and Fukushima accident case studies show, it is not uncommon for "sacrifice judgments," which are made within the context of uncertain information, to have great significance and impact. In other words, even though sufficient preparations are made in advance, the ability is also required to prevent a catastrophe in situations where such conditions are exceeded. It is necessary not only to conduct proficiency training so that actions can be performed as detailed in manuals, but also to have arrangements to improve Safety-II abilities through training and other exercises that better approximate reality.

⑤ Lastly, it has become clear that attitude, leadership, practical skills, workload management, corporate culture and other such elements are underlying factors supporting such responding during an emergency.

4. Conclusion

This article was an attempt to analyze "things that went right" in the response to the Fukushima accident and that executed by the transport industries during the Great East Japan Earthquake, while referencing the approach of Resilience Engineering, so as to deduce lessons that are common to a variety of socio-technical systems. This has shown that Safety-I, which entails risk-elimination type safety goals, and Safety-II, which are success-extension type safety goals, each function effectively in ensuring safety during the earthquake. Also, this article succeeded in presenting common factors for ensuring safety and enhancing organizational resilience, which aid in safety assurance. These make it clear that manuals and engineering measures, which are able to be executed in advance, as well as training and other preparations classified as Safety-I are imperative for ensuring safety, and, at the same time, while making such preparations to the extent feasible, the necessity is clear that measures for realizing safety under the standard of Safety-II need to be enhanced on the presumption that conditions will not be as assumed in preparations.

Acknowledgments

The results of the “Survey of Vessel Actions at the Time of the Great East Japan Earthquake Tsunami Strike and Review of Navigation Safety Measures (October 2014),” which was commissioned by the Nuclear Fuel Transport Company, Ltd., were used in analyzing the maritime transport industry case study.

We, the authors, would like to extend their heartfelt condolences to the many people still living as evacuees from the Fukushima accident and for all of the anxiety and inconvenience caused to local communities and society at large. In addition, we would like to express our sincere gratitude for the support of many people who devoted themselves to responding to the accident under severe conditions, and extend our deepest sympathies to their two co-workers who unfortunately lost their lives in the tsunami and to Station Director Masao Yoshida who commanded the response at Fukushima Daiichi Nuclear Power Station and passed away due to illness.

References

1) ISO/IEC(The International Organization for Standardization and the International Electrotechnical Commission), “Safety aspects- Guidelines for their inclusion in standards,” *Guide51 Chapter 3.14*. 2014
2) Hollnagel, E. “*Safety-I and Safety-II, The Past and Future of Safety Management*,” ASHGATE, 2014.
3) Hatamura, Y., “Chairperson’s Remarks”. In Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, *Final Report*, pp528-529. 2012.
4) Hollnagel, E. and Woods, D.D., “Epilogue: Resilience Engineering Precepts.” In Hollnagel, E., Woods, D. and Leveson, N. (eds.), *Resilience Engineering: Concepts and Precepts*, pp.346-358. ASHGATE, 2006.
5) Hollnagel, E., “Prologue: The Scope of Resilience Engineering.” In Hollnagel, E., Pariès, J., Woods, D. D. and Wreathall, J. (eds.), *Resilience Engineering in Practice: A Guidebook*, ASHGATE, 2011.
6) Kitamura, M., “Chapter 4: Resilience Engineering for Safety of Nuclear Power Plant with Accountability.” In Nemeth, C. N. and Hollnagel E. (eds.), *Resilience Engineering in Practice, Vol.2: Becoming Resilient,* pp.59-60, ASHGATE, 2014.
7) Yoshizawa, A., Oba, K. and Kitamura, M., Experiences in Fukushima Daiichi Nuclear Power Plant in Light of Resilience Engineering. *Proceedings of the 6th Resilience Engineering Symposium*, 2015.
8) East Japan Railway Company, *Safety Report 2012*. 2012. (in Japanese)
9) Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, *Final Report*,2012.

10) Tokyo Electric Power Company (TEPCO), *Fukushima Nuclear Accidents Investigation Report*, 2012 .
11) Yoshizawa, A., Kunito, S., Oba, K., and Kitamura, M., Enhancement of Organizational Resilience in Light of the Fukushima Dai-ichi Nuclear Power Plant Accident (III)–Analysis of Unit 5 operation by Time-flow Responding Structure-. *The Japan Society of Mechanical Engineers, Proceedings of the 2015 Annual Conference*, G1700105, 2015. (in Japanese)