

Fukushima-Daiichi Accident Analysis from Good Practice Viewpoint

Hiroshi UJITA

Institute for Environmental & Safety Studies

38-7 Takamatsu 2-chome, Toshima-ku, Tokyo 171-0042, JAPAN, E-mail: kanan@insess.com

Abstract. Fukushima-Daiichi Accident has been analyzed from the viewpoint of good practice, that is from resilience engineering viewpoint. The good cases of resilience response are observed in individual base and organizational base as below: The effectiveness of insight on accident cases (inundation in Madras, 9.11 terrorism and B.5.b. order for the countermeasures) and of the risk evaluation, Decision of continuation of sea water infusion (individual base), Reflection of the experience on Chuetsu-Oki Earthquake, Improvement of seismic building which is equipped emergency power source system and air conditioning system (organizational base), Deployment of fire engines (organizational base), The effectiveness of command system in ordinal time (on-site of organizational base), and Support by cooperation companies and manufacturers (designers and site workers of organizational base). It is important to 'establish the feedback system on organization learning in ordinal time', that is to establish the system admitting violation of order. The decision at on-site are given priority than other ones. The representative example is the decision of sea water infusion continuation which was given priority at on-site, even though the official residence and the main office of Tokyo Electric Power Company had ordered to stop the infusion.

Keywords: Resilience Engineering, High Reliability Organization, Risk Literacy, Fukushima Accident, Bounded Rationality, Information Limitation, Time constraint, Context

1 Introduction

Whereas the direction which discusses the safety from the accident analysis, a new trend of analytical methods such as resilience engineering, high reliability organization, or risk literacy research [1-3], which analyze the various events by focusing on the good practices, are becoming popular.

The results of Fukushima Daiichi Accident investigation with diversified characteristic have been released until now. Based upon the analyses of the investigation, the success cases (good practice) and failure cases for emergency responses were analyzed concerning to personal- response capability, organizational-response capability, and communication ability with external organizations, and then the problems of responses were extracted. The action of sea-water infusion on Fukushima Daiichi nuclear power plant No.1 was paid attention and analyzed based on the 'Accident Analysis Report of Fukushima Nuclear Accident' [4] (Accident Report) by TEPCO, Tokyo Electric Power Company, especially focus on the decision making of continuation of pouring sea water.

2 History of Accident and human error type

The history of accident and human error type trend is shown in Fig. 1 [5]. In the era when the plant system was not so complicated as in the present age, it was thought that technical defects are the source of the problem and accidents can be prevented by technical correspondence. As the system became more complex, it came to the limit of human ability to operate it, accidents caused by human error occurred. Its typical accident happened at Three Mile Island (TMI) nuclear power plant in 1979. For this reason, individuals committing errors are considered to be the source of the problem, improvement of personnel capacity by appropriate selection and training of personnel, and proper design of interface design are considered effective for error prevention.

Thereafter, accidents caused by complicated interrelationships of elements such as technology, human, society, management, organization and so on occurred, and then the problem was interaction between society and technology. Furthermore, not only within the plant and enterprises but also accidents where the relationship failure with external stakeholders and organizations is a source of the problem becomes noticeable, and a framework for comprehensive problem solving including inter-organizational relationship has become to be necessary. A recent

accident is a so-called organizational accident in which the form of an accident is caused by a complex factor and its influence reaches a social scale [5].

For this reason, the analytical methods, as well as type and social perceptions of error or accident, are changing with the times also. Human error and Domino accident model had initially appeared, are then has been changing to system error and Swiss cheese accident model, and recently move to safety culture degradation and the organizational accident.

3 Accident model and Error model.

As a result that the technology systems become huge, complex and sophisticated, safety issues are shifted to the problem of organization from human, and further from hardware, such socialization is occurring in every technical field. For this reason, the analytical methods, as well as type and social perceptions of error or accident, are changing with the times also. Table 1 shows trends of the accident model and error model [6]. Human error and Domino accident model had initially appeared, are then changing to system error and Swiss cheese accident model, and recently move to safety culture degradation and the organizational accident.

A conventional accident model is the domino model, in which the causation of trouble and the error is analyzed and measures are taken. In the model, slip, lapse, and mistake are used which are the classification of the unsafe act to occur by on-site work. These are categorized as the basic error type, while violation which is intentional act violating rule has become increased recently and considered as cause of social accident.

Design philosophy of the defense in depths has been established, and the accident to occur recently is caused by the excellence of the error of a variety of systems. The analysis of the organization blunder is necessary for the analysis by this Swiss cheese accident model in addition to conventional error analysis.

An organization accident is a problem inside the organizations, which reaches earthshaking event for the organization as a result by the accumulation of the best intentions basically. It is an act of the good will, but becomes the error. As for the organization accident, the interdependence inside of the organization or between the organizations is accumulated by fallacy in the defense in depths, and it becomes a problem of the deterioration of the safety culture in its turn. The organizational management based on the organization analyses such as behavioral sciences will be necessary for these measures.

4 Bounded Rationality in Context vs. Judge by God

In the field of cognitive science and the cognitive system engineering, the human being is considered as to think and judge something reasonably along context while there are information limitation and time constraint. Sometimes the decision may be judged as an error by the outside later. It is called "bounded rationality in the context" vs. "judge by God". The absurd action of the organization had been often explained in human illogicality conventionally, while the approach has recently come out to think that the human being rationality is the cause [7].

There are three approaches proposed from Organizational (Behavioral) Economics, business cost theory (reluctant to do), agency theory (information gap), and proprietary rights theory (selfishness) as shown in Table 2 [8]. Business cost theory analyses action of opportunity principles and sunk cost, agency theory, moral hazard and adverse selection (lemon market), and proprietary rights theory, cost externality. The common supposition is "the bounded rationality and the utility maximization".

It is necessary to find the social context that the error is easy to occur, in the engineering for human beings hereafter. In other words, a way of thinking has changed in the direction to analyzing the social context that is easy to cause an error, from analyzing direct cause of the error. Because this direction is beyond the range of conventional ergonomic treating the contents of the error, it is very difficult. However, we should recognize it now, if we do not analyze an error in the viewpoint the relationship between safety and the environmental element surrounding human being, we can not to lead to measures. The measures should be matched with human rational characteristics.

Countermeasure on Business cost theory is business cost saving system which changes organizational style from group organization, via. centralization of power type organization, and to decentralization of power type organization, agency theory, agency cost reduction system based on mutual exchange of the

information, and proprietary rights theory, internalization of the system externality based on proprietary rights distribution.

5 The methodology on Resilience Engineering, High Reliability Organization, and Risk Literacy

Whereas the direction which discusses the safety from the accident analysis, a new trend of analytical methods such as resilience engineering, high reliability organization, or risk literacy research, which analyze the various events by focusing on the good practices, are becoming popular.

The resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions. A practice of Resilience Engineering / Proactive Safety Management requires that all levels of the organization are able to:

- Monitor
- Learn from past events
- Respond
- Anticipate

Organizational process defined by the High Reliability Organization is shown below. There are 5 powers in 2 situations.

- ✓ Preparedness for Emergency Situation in Ordinal Time:
 - Carefulness (Confirmation),
 - Honesty (Report),
 - Sensitivity (Observation),
- ✓ Emergency Response in Emergency Situation:
 - Alert (Concentration),
 - Flexibility (Response),

Ability of Risk Literacy is also defined by followings, which is largely divided to 3 powers and further classified to 8 sub-powers.

- ✓ Analysis power
 - Collection power
 - Understanding power
 - Predictive power
- ✓ Communication power
 - Network power
 - Influence power
- ✓ Practical power
 - Crisis Response Power
 - Radical Measures Power

6 The analysis based on Resilience Engineering, High Reliability Organization, and Risk Literacy

6.1 Chronological analysis

The analysis for the detail of sea-water infusion to Fukushima-Daiichi No.1 unit has been performed. Chronological analysis was drawn up from “The main chronological analysis of Fukushima Daiichi nuclear power plant No.1 unit from earthquake occurrence to the next day” and “The status response relating to pouring water to No.1 unit”, which came from the ‘Accident Report’.

The chronological analysis shows that the preparation of sea-water infusion is decided and ordered concurrently with pouring freshwater, and also shows that continuation of sea-water infusion is decided as on-site judgment although an official residence and the main office of TEPCO directed to stop the infusion, in taking into consideration of the intention of official residence. The necessity of continuation of sea-water infusion was recognized consistently by on- site judgment, and these measures were taken. This means that

the main office of TEPCO and the official residence violate the fundamental principle which on-site judgment should be preceded in emergency situation.

6.2 Organizational factors analysis

The process of sea-water infusion on Fukushima Daiichi No.1 unit is analyzed from the point of resilience capability, high reliability organization capability, and risk-literacy capability [1-9]. The analysis example by risk-literacy capability is shown in Table 3 from the viewpoint of risk-management, which is described in 'Introduction of Risk Literacy- Lessons Learned from Incidents' [3]. The definition of risk literacy capability which can extract communication power that is important both for ordinary time and for emergency situation is the most appropriate for analysis. The horizontal axis shows response capabilities which are suggested in each study, and the vertical axis shows each level of individual, organization, which is further divided management and on-site, and correspondence to outside such as official residence. The gothic font in green means success case or good practice, while the italic font in red means failure case.

The analysis of emergency correspondence like this kind of huge accident cannot be analyzed enough using conventional framework. As a whole of one organization, the classifications were reviewed and revised from two points. One is that the differences in correspondence and the problems in cooperation between on-site and administration department cannot be clarified. And the other one is that communication power has two sides which are the information cooperation in ordinal time and collaboration in case of emergency situation. The analysis power and information transmission power correspond to ordinal time, and the influence power and normal time skill correspond to the case of emergency situation. In this analysis, the contact with official residence and the cooperation inside government are also included in correspond to external organizations.

7 Success and failure cases

From the viewpoint of Resilience Engineering, the cases of success and failure are listed and analyzed.

7.1 Good practice of resilience response

The good practices of resilience response are observed in individual base and organizational base as below.

- The effectiveness of insight on accident cases (inundation in Madras, 9.11 terrorism and B.5.b. order for the countermeasures) and of the risk evaluation.
 - Decision of continuation of sea water infusion (individual base)
- Reflection of the experience on Chuetsu-Oki Earthquake
 - Improvement of seismic building which is equipped emergency power source system and air conditioning system (organizational base)
 - Deployment of fire engines (organizational base)
- The effectiveness of command system in ordinal time (on-site of organizational base)
- Support by cooperation companies and manufacturers (designers and site workers of organizational base)

For Tsunami countermeasures in other plants, good practices were also observed in organizational base:

- Onagawa plant level was enough high to prevent Tsunami disaster due to clear understanding of the effect and sharp decision by top management,
- Tokai-Daini plant installed water stuck for sea-water pump to protect infusion due to good communication and corporation among prefecture officers and utility managers.

The reason why the good cases are occurred in on-site, the officers and workers always felt that their mission is to carry out with the sense of ownership and also with critical mind. They had trained the accident management in ordinal time, which works effectively in emergency situation, which is the just significant frame derived from the development of safety culture. It is important to 'establish the feedback system on organization learning in ordinal time'. But there were a little lack of information between control room and emergency response room, they will be able to solve by taking physical measures to clarify the circumstances at on-site. The TV conference system of Fukushima Daini nuclear power plant had worked effectively to

communicate among on-site, the main office of TEPCO and the outside organizations. Furthermore using the white board for information sharing, which is the good practice that the resilience works well, could prevent the confusion at on-site.

7.2 The failure of comprehensive power in organization, the fallacy of composition of risk awareness

The many failure cases are defined under national government level and nuclear industry level which are the problems of rare event awareness and of organization culture. Although everyone had same recognition for the risk of power loss and Tsunami, the accurate decision had not been made by national government level, just only made by individual level. The ordinal time training at on-site also work in emergency situation at the accident, while the level of administration department and government didn't work well.

- Risk misrecognition of Loss of offsite power and damage by Tsunami (national government level, industry level)
- Confusion of command system (organization base- between on-site and the main office of TEPCO)
- Confusion of command system (external correspondence base- national government level, and organization base- among official residence, regulation, and the main office of TEPCO)

The continuations of emergency training in ordinal time with assuming the severe accident progression is considered to be the effective way. As many lacks in emergency correspondence in management department and in national government level are observed, and then the emergency training is necessary in management level, in which responsibility assignment is regularly taken, the incident seriousness is evaluated, and the mode is switched from ordinal time to emergency situation.

7.3 Points in common and difference in Fukushima Daiichi and Daini, Tokai Daini, and Onagawa Plants

Cold Shutdown could be successfully achieved due to survive if power supply, where good practices of corporation among operators and between on-site and head office were observed based on correct information. Because Air Cooling EDG (Emergency Diesel Generator) continued to operate in Fukushima Daiichi plant 5 and 6 units, and 3 EDGs in Fukushima Daini plant. Especially, TV conference system was effectively functioned in Fukushima Daini plant, because of enough information by survival indicators energized from survived batteries.

TEPCO put the priority onto countermeasures on Chuetuoki Earthquake and only considered without making countermeasures on Tsunami affect. Important Anti-seismic Building and Portable Fire Engine had been installed for seismic countermeasures in every plant of TEPCO before huge earth quake and Tsunami, and those apparatuses were used in the accident effectively in Fukushima Daiichi and Daini plants. Good practices of Tsunami countermeasures of site height decision process of problem institution by professionals and acceptance by administration performed in both Tokai Daini and Onagawa Plants.

One point we should understand is that Tsunami estimated height has drastically changed as time passed, which means it is not reliable information. At the information limitation circumstance, four plants showed good resilience examples. The difference of the correspondence is due to difference in priority policy. Fukushima made efforts on earthquake measures, on the other hand, Onagawa and Tokai Daini, efforts on Tsunami measures. It seems that the differences in suffered effect and in its correspondence between Fukushima Daiichi 1-4 and 5-6& Daini both owned by TEPCO are due to relative relationships between actual tsunami height and site height.

7.4 Consideration on Organizational problem

The true nature of the problem in Japanese organization that doesn't change from when the 'Substance of Failures' [9], in which Japanese military operation failures in the World War II were analyzed, was written by Tobe, Nonaka, et. al. Failure cause was described as standpoint of irrationality in Japanese on this book. But the problems in organization are not able to be resolved by irrationality in Japanese. It should be explained using by bounded rationality which Kikusawa advocate in 'Absurdity of Organization' [8]. His idea is that decision making which are made under limited circumstances based on limited information will end in failure from the eye of God. He also advocates destroying the bounded rationality for failure measures. It means that it is important to 'establish the system admitting violation of order in emer-

gency situation'. The decision at on-site are given priority than other ones. The representative example is observed in the decision of sea water infusion continuation, the decision at on-site were given priority even though the official residence and the main office TEPCO had ordered to stop the infusion. Otherwise it is the failure case that occur delay of PCV vent, for time loss to get the permission of national government and local government.

It is important to 'establish the feedback system on organization learning in ordinal time'. The continuations of emergency training in ordinal time with assuming the severe accident progression is considered to be the effective way. The emergency training is necessary in management level, in which responsibility assignment is regularly taken, the incident seriousness is evaluated, and the mode is switched from ordinal time to emergency situation.

The problems as above can be explained by "Homogeneous way of thinking" and "Concentric Camaraderie", as shown in Fig. 3, which are the hindrance on safety pursuit in Japan. 'Bottom-up decision making structure' connects to 'Absence of top management', and then becomes to 'Delay of decision making and Lack of understanding on valuing safety'. Due to the Japanese are excellent as noncommissioned officer (Soldier: Russian, Junior officer: French, Chief of staff: German, General: American), they often show their ability at emergency situation. But Japanese are short of management abilities, they often make heavy intervention or omission.

'Multilayered faction structure' appeared in "Concentric Camaraderie" makes 'Organization from Gesellschaft to Gemeinschaft', and then 'Adhesion and back-scratching' are spread in the organization. For the "Concentric Camaraderie", the feedback system in organization learning leads to the failure due to be preceded to internal logic than social common sense even in national government level or nuclear industry level.

8 Discussion

Rare Event is high consequence with low frequency. Low consequence with high frequency event is easy to treat by commercial reason, while it is very difficult to handle the rare event even the risk is just the same. "Unexpected event" has been used frequently, but it is the risk-benefit issues to assume or not. Tsunami Probabilistic Risk Analysis has been carried out, and safety related personnel knew the magnitude of the effect well.

Regardless of the initiating event, lack of measures to "Station blackout" is to be asked. According to the "Defense in Depth" concept reflecting Fukushima accident, we should consider three level safety functions; usual normal system, usual safety system, and newly installed emergency system including external support functions. Anyway the diversity is significantly required for not only future reactor concept but also existing plant back-fit activities.

Swiss Cheese Model proposed by Reason, J indicates operational problem other than design problem [5]. Fallacy of the defense in depth has frequently occurred recently because plant system is safe enough as operators becomes easily not to consider system safety. And then safety culture degradation would be happened, whose incident will easily become organizational accident. Such situation requires final barrier that is Crisis Management.

Concept of "Soft Barrier" has been proposed [6]. There are two types of safety barriers, one is Hard Barrier that is simply represented by Defense in Depth. The other is Soft Barrier, which maintains the hard barrier as expected condition, makes it perform as expected function. Even when the Hard Barrier does not perform its function, human activity to prevent hazardous effect and its support functions, such as manuals, rules, laws, organization, social system, etc. Soft Barrier can be further divided to two measures; one is "Software for design", such as Common mode failure treatment, Safety logic, Usability, etc. The other is "Humanware for operation", such as operator or maintenance personnel actions, Emergency Procedure, organization, management, Safety Culture, etc.

9 Conclusion

The good practices or success cases of resilience response are observed in individual base and organizational base as below.

- The effectiveness of insight on accident cases (inundation in Madras, 9.11 terrorism and B.5.b. order for the countermeasures) and of the risk evaluation.

- Decision of continuation of sea water infusion (individual base)
- Reflection of the experience on Chuetsu-Oki Earthquake
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- Confusion of command system (organization base- between on-site and the main office of TEPCO)
- Confusion of command system (external correspondence base- national government level, and organization base- among official residence, regulation, and the main office of TEPCO)

It is important to 'establish the feedback system on organization learning in ordinal time', that is to establish the system admitting violation of order. The decision at on-site are given priority than other ones. The representative example is the decision of sea water infusion continuation which was given priority at on-site, even though the official residence and the main office TEPCO had ordered to stop the infusion.

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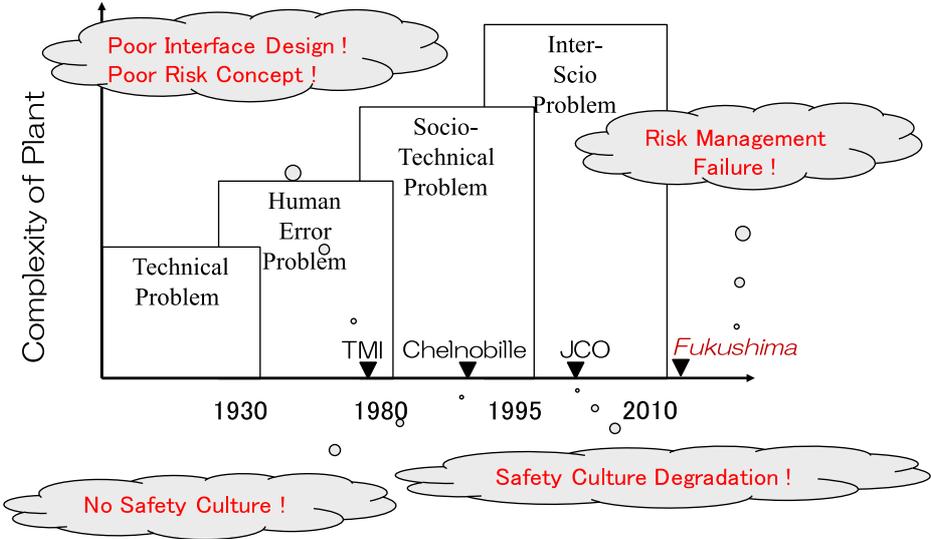


Fig. 1. Safety issue scope (Reason, 1993).

Table 1. Accident model and error model.

Accident Model	Error Model	Analysis Method	Management
Domino (failure chain)	Component Failure and human Error	Cause-Consequence Link	Encapsulation, Seek & Destroy
Swiss Cheese (Loss of Diversity)	System Error (Common mode Failure)	Risk Evaluation	Defense & Barrier
Organizational Accident (Fallacy of Defense in Depth)	Safety Culture Degradation	Behavioral Science Safety Culture Check List	Monitor & Control (Organizational Learning)

Design
Management

Table 2 Three approaches by behavioral economics (The organization fails rationally: Kenshu Kikusawa 2009).

	Transaction cost theory (Bothersome)	Agency theory (Information gaps)	Property rights theory (Selfish)
Object	Business relationship	Agency relationship (Principle and Agency)	Ownership relationship
Inefficiency	<ul style="list-style-type: none"> Opportunistic behavior Sunk cost 	<ul style="list-style-type: none"> Moral Hazard Adverse Selection (Lemon Market) 	Externalities
Institutional resolution	Transaction cost saving system (Organization style change: fellow- centralized- decentralized)	Agency cost reduction (Symmetrical information)	Internalization of externalities (Ownership allocation)
Example	<ul style="list-style-type: none"> One-man management - external monitoring 	<ul style="list-style-type: none"> Work sharing 	<ul style="list-style-type: none"> Fellow consciousness and organizational concealment

Common assumptions: bounded rationality and utility maximization

Table 3. Evaluation of response capability from the viewpoint of risk literacy: The analysis of sea water infusion process on Fukushima Daiichi No.1.

Risk literacy Analysis level	In Ordinal Time			In Emergency Situation				
	Analysis Power			Communication Power		Practical Power		
	Collection Power	Comprehensive Power	Predictive Power	Information Transmission Power	Influence power	Crisis Response Power	Radical Measures Power	
Individual	•Damage of Tsunami	•Risk recognition of Tsunami damage	•Risk recognition of Power Loss	—	—	•Continuation of Sea water infusion	• Training for emergency	
organization	on-site	•Collection of accidents: •Jyogan-Tsunami	•Earthquake •Tsunami •Evaluation of influence range by PSA	Recognition of accidents damage	•Information sharing at on-site	•Command system (on-site) •Centralized at seismic building •Contact between Control Room & Emergency Response Room	•Infusion of fresh water and sea water •Vent •Prevention of damage expansion	•Preparation of seismic building and fire engines •Command system •AM measures •Tsunami protection measures
	Management	•Collection of accident: Jyogan-Tsunami, JNES Tsunami PSA, Infusion at Le Blayais & Madras	•Risk misrecognition of Tsunami damage	•Risk misrecognition of Power Loss	•Information sharing between main office and on-site Failure event	•TV conference system (2F site) •Confusion in command system between main office and on-site		•Review the education and training system Success event
External correspondence (official residence, etc.)	•Anti- terrorism in overseas <i>Collection of example : 9.11 terrorism- B.5.b.</i>	•Classification of importance on accidents •Risk misrecognition of earthquake and Tsunami	•Importance of external events •Risk misrecognition of infrastructure damage		•Media, local government, publicity to overseas •Confusion of command system among official residence, main office, & on-site	•Delay of initial response •Governmental command system	•Support by vendor and cooperation company •Support by external organizations •Drastic measures : Structure reform (Regulation/ Electric power company)	

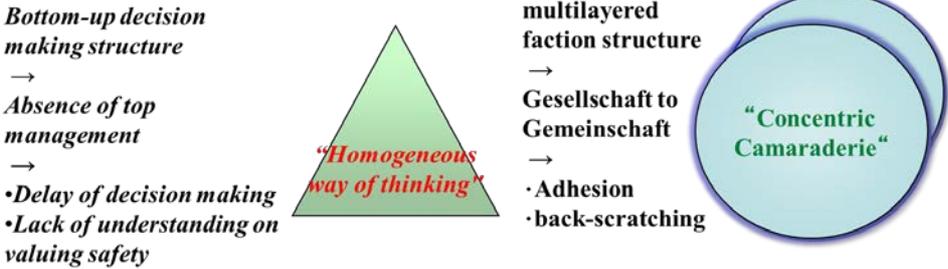


Fig. 2. “Homogeneous way of thinking” and “Concentric camaraderie”, obstruction factors on safety pursuit in Japan.