Nuclear Emergency Response in Industry 4.0: Fukushima Lessons and Gaps to Fill

Ali Ayoub[a], Haruko Wainwright[a], and Giovanni Sansavini[b]
[a] MIT, Cambridge, Massachusetts, USA, aliayoub@mit.edu, hmwainw@mit.edu
[b] ETH Zurich, Zurich, Switzerland, sansavig@ethz.ch

Abstract: Post-accident mitigation and consequence analysis have been subjects of extensive research in the nuclear industry. Strict regulatory guidelines and radiation monitoring networks are usually in place to support the prompt implementation of protective actions (evacuation, sheltering, etc.) in case of emergency. However, the Fukushima Daiichi nuclear accident has exposed the challenges in nuclear emergency responses, since the existing plans had to be adapted several times, and monitoring data as well as dispersion codes could not be used as planned, hence aggravating the situation. In this paper, we present a comprehensive retrospective analysis of the Fukushima accident, presenting the accident timeline with an explicit connection between the onsite progressions and the offsite decision-making and emergency response. Additionally, we summarize the different health consequences and radiation exposure. Furthermore, we discuss the faced managerial, organizational, procedural, as well as technological shortfalls that led to the many decision delays and response complications. Accordingly, we discuss some of the attempts made to tackle these issues. Finally, we identify the remaining gaps in the design, planning, and organization of future emergency responses to meet the ambitions of industry 4.0, with more accident-resilient societies and environments.

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1. INTRODUCTION

The accident at the Fukushima Daiichi nuclear power plant (FDNPP) on March 11, 2011 has tremendous impacts not only on the local communities who have endured more than 10 years of evacuation and relocation, but also on the choice of electricity generation sources across the world. The event started with a 9.0 earthquake followed by a 14m high tsunami, taking the lives of more than 15,000 people and triggering the evacuation of about 150,000 [1]. As a result of the extreme natural events, the coastal FDNPP faced a station blackout scenario and difficulties to maintain core cooling in its operating units, resulting in a core damage and reactor pressure vessel (RPVs) breach in Units 1, 2, and 3, in addition to several radioactive releases that continued for many days after [2]. Although the operators did a courageous job trying to save the reactors and find ways to prevent the exacerbation of the situation onsite, the severe accident management actions faced many difficulties and mistakes [3], aggravated by the harsh conditions onsite caused by the earthquake and tsunami.

Over the past ten years, there has been numerous studies in different disciplines, analyzing the course of the accident, and extracting the numerous observed mistakes and lessons in severe accident management and design improvements. One group of studies has been focused on the engineering and management side – i.e., the aspects inside the plant – which led to or exacerbated the accident. For example, the U.S. National Academy of Sciences [4] studied the managerial, design, and operational causes of the accident and identified the necessary lessons for the U.S. operating fleet covering the systems needing improvement, necessary training, human resources, safety culture, and regulatory requirements. Yang [5] examined the accident from a risk point of view, and suggested the necessary steps to enhance the safety of nuclear installations. Cai and Golay [6] interviewed the engineers of Tokyo Electric Power Company (TEPCO) to extract the multiunit risk factors that contributed to the FDNPP accident and ultimately suggest the required site improvement.

At the same time, there are studies focused on the health consequences and emergency responses flaws, which are related to the aspects outside the plants. For example, Tanaka [7] analyzed the accident and presented some lessons for the radiation protection of residents and the emergency preparedness of local municipalities. Callen and Homma [8] studied the FDNPP emergency response and highlighted lessons on multiple dimensions (public notification, protective actions, medical response, food and agriculture) and for the different time periods (early, intermediate, and long-term). As part of the SHAMISEN project, Liutsko et al. [9] and Ohba et al. [10] developed some guidelines to better cope with future nuclear accidents based on a holistic evaluation of the impact of Chernobyl and the FDNPP accidents. They suggested a series of recommendations to improve preparedness, emergency response, and long-term living conditions of affected populations.

However, there are few studies that have analyzed the accident across the disciplines and boundaries, in particular, the connection between the plant operational decisions and evacuation decisions during the accident. Although general guidelines for evacuation exist or have been modified since the FDNPP accident, they do not consider the detailed timeline of accident progressions. For example, the major release happened three days after the accident initiation [11]. In addition, the evacuation orders were announced in multiple stages as the accident progressed. Such adaptive nature of emergency responses was not considered in the emergency responses before the FDNPP accident, which resulted in confusions and government distrust during and after the event.

The objective of this study is to provide a comprehensive retrospective analysis of the FDNPP accident, with a focus on the offsite emergency response in conjunction with detailed plant conditions and onsite decision-making. To make an explicit connection between the onsite and offsite decision-making, we reconstruct the accident timeline across different domains – major systems status, core and containment status, radioactive releases as well as governmental protective measures and decisions. In parallel, we summarize the health consequences and radiation exposures in areas within and outside the evacuation zones. These are based on multiple reports documenting the presented timeline and health consequence. We then extract and summarize the most important complications faced during the offsite emergency response, and present the potential remedies.

Through this study, we aim to identify the open challenges in the design, planning, and organization of future emergency responses to meet the ambitions of industry 4.0. The nuclear industry is moving towards unprecedented levels of safety, with retrofitted operating fleets, and planned advanced reactors characterized by passive safety systems, extended grace periods, sophisticated instrumentation and control, high levels of automation, and advanced containment systems [12]. However, accidents in all industries are destined to happen. The difficulties faced during the FDNPP post-accident emergency response created a space for research to extract the lessons and needs for better coping strategies, tackling the faced managerial, organizational, procedural as well as technical and technological complications. Our particular focus here is to identify resilience – rather than prevention – measures in most serious accidents such as the FDNPP so that we can mitigate the accident impact on our societies.

The organization of the manuscript is as follows. The paper starts by presenting the timeline of the FDNPP accident and the accident’s health consequences and radiation exposure follows in Section 2. Section 3 summarizes the critical mistakes and lessons in emergency response. Section 4 presents the remaining gaps and opportunities.

2. THE FUKUSHIMA DAIICHI NUCLEAR ACCIDENT

2.1. Plant Description

The FDNPP is a six-unit boiling water reactors (BWRs) site. Unit 1 is a BWR generation-3 reactor with an isolation condenser (IC). Units 2-5 are BWR generation-4 reactors with a reactor core isolation cooling system (RCIC) and high-pressure coolant injection system (HPCI). Unit 6 is a BWR generation-5 reactor with a RCIC system and high-pressure core spray system (HPCS).

When the earthquake occurred, Units 1, 2 and 3 were in normal operation and Units 4, 5, and 6 were shut down for refueling and maintenance outage. Unit 4 had its fuel offloaded to the spent fuel pool, while Units 5 and 6 had their fuel assemblies in the core [2].

2.2. Timeline

In this section, we reconstruct the timeline of the in-plant accident progression and government protective actions and emergency response based on multiple official sources [2, 13-15].

Table 1: Timeline of key events during the Fukushima Daiichi nuclear accident.

Day	Time	In-plant Accident Progression	Governmental Actions and Emergency Response
Mar 11	14:47	Earthquake, loss of offsite AC power. Units 1-3 automatically shut down, Units 4-6 already offline at the time	
	~14:50	U1 IC and U2 & U3 RCIC operated to cool reactors	
	15:03	U1 IC stopped operation	
	~15:40	Tsunami (~14 m high), loss of remaining onsite AC power for Units 1-5 - Units 1-5 station blackout (SBO)	
	15:50	Flooding killing DC power in U1 and U2 (core cooling and safety systems status undeterminable)	
	16:45		Nuclear emergency status reported to government: SBO and presumed failure to inject core cooling water to U1 and U2
	~17:00	U1 water level below top of fuel (loss of ability to inject water to the reactor)	
	~late evening	**Start of core damage at U1.** U2 status still undeterminable	
	20:50		Local government evacuation order for residents within 2 km radius from the NPP
	21:23		National government evacuation order for residents within 3 km and sheltering within 3-10 km from the NPP
Mar 12	02:55	U2 RCIC operability confirmed by onsite inspection	
	~05:00	High PCV pressure in U1 (~0.8MPa) and preparations for PCV venting. Increase in measured site dose rates.	
	05:44		National government extends evacuation boundary to 10 km from the NPP
	~noon	U3 RCIC stopped operating, HPCI started injecting water into reactor	
	~14:30	U1 PCV venting	
	15:36	Hydrogen explosion blowing off U1 reactor building	
	18:25		National government extends evacuation boundary to 20 km

Mar13	02:42	U3 HPCI stopped (failure of all alternative core cooling systems)	
	~08:00	U3 water level below top of fuel	
	9:00	Opening of U3 RPV SRVs using car batteries	
	~09:20	High PCV pressure in U3 (~0.65MPa). Start of U3 PCV venting 1	
	11:00	Opening of U2 PCV vent valves in preparation for venting	
	~noon	**Start of core damage at U3.** U3 PCV venting 2	
Mar 14	~early morning		Start of evacuation of patients from hospitals within 20 km from NPP
	11:00	Hydrogen explosion in U3 reactor building	
	~13:00	U2 RCIC stopped operating	
	~17:00	U2 water level below top of fuel	
	18:00-mid night	Opening of several U2 RPV SRVs to reduce pressure (U2 RPV venting 1, 2, 3)	
	~late evening	**Start of core damage at U2**	
	23:20	High PCV pressure in U2 (~0.75MPa).	
Mar 15	~01:00	Further openings of U2 RPV SRVs (U2 RPV venting 4)	
	~03:00	Unsuccessful attempts to vent U2 PCV (neither DW nor WW)	
	~06:15	Hydrogen explosion in U4 reactor building from backflow of U3 hydrogen	
	07:30-late evening	U2 PCV failure and multiple recorded releases to the atmosphere	
	09:38	Fire in U4 reactor building	
	11:00		National government ordered sheltering within 20-30 km from the NPP
	~16:00	U3 PCV venting 3	
Mar 16	08:30	White smoke from the Unit 3 reactor building (U3 PCV leakage)	
	10:35		National government order to distribute potassium iodide pills to evacuees within a radius of 20 km
Mar 17			Evacuation of hospitalized patients and elderly in nursing care within 20-30 km
Mar 18	05:30	U3 PCV venting 4	
Mar 20	11:00 onwards	U3 PCV venting 5 and signs of leakage	
	Afternoon	U5 & U6 enter cold shutdown	
Mar 25			National government recommended evacuation for residents within 20-30 km
Apr 22			Sheltering order lifted, and assigning areas for deliberate evacuation and relocation

			based on the established dose criteria (20 mSv/yr)
May 15			Start of relocation of the public from relocation established areas
Dec 16		Units 1-3 reach cold shutdown conditions	

U: unit, PCV: primary containment vessel, SRV: safety relief valves, DW: dry well, WW: wet well

The accident started with an earthquake on March 11 at 14:47 JST causing the loss of offsite power for all units. The emergency core cooling systems started operation in all units, however, Unit 1 lost its cooling capabilities slightly after, with the isolation condenser stopping at 15:03. The earthquake triggered a 14m high tsunami at around 15:40, flooding the site and disabling the onsite emergency power systems. With the resulting station blackout across units and consequently, the failure to inject cooling water in Unit 1 (and potentially in Unit 2), the operators notified the government that a nuclear emergency is taking place as specified under the Japanese Nuclear Emergency Act [16, 17]. Accordingly, the local government ordered the evacuation for residents within 2 km radius from the plant at 20:50. Just half an hour after, and due to the limited coordination and the overlapping responsibilities with the local government [8], the national government issued an evacuation order for residents within 3 km and ordered sheltering within 3-10 km from the plant.

The pressure in Unit 1 PCV was increasing, and in the early morning of March 12, it reached 0.84 MPa, with the core already melting, and the generated heat escaping to the containment. As the operators started to prepare for venting of Unit 1 PCV, the national government decided to extend the evacuation boundary to 10 km at 05:44. After confirming the completion of evacuation, and after several hours of struggles to open the vent lines due to the site conditions (due to radiation levels and limited lighting), the operators successfully vented Unit 1 PCV at 14:30 [14]. Shortly after, a hydrogen explosion took place blowing off the reactor building of Unit 1, and resulted in a release of radionuclides to the environment as confirmed by the operating onsite monitoring stations [2]. The hydrogen, generated by Zirconium oxidation in the core, has leaked from the inert PCV to the reactor building due to a potential boundary failure of Unit 1 PCV [18]. Following the release, the national government extended the evacuation order to 20 km at 18:25.

The core cooling in Unit 3 stopped at 2:42 on March 13. The pressure in Unit 3 PCV was rising and exceeded the maximum design pressure on the morning of March 13. Accordingly, venting operations started at around 9:20 and continued, while the core continued to overheat and ultimately melt by noon as no core cooling systems were available [14]. At 11:00, the operators successfully opened the Unit 2 PCV vent valves so that venting can commence straight after the pressure exceeds the rupture disk's design pressure [2].

On the morning of March 14, the decision was made to evacuate the patients from the nearby hospitals. Many of the evacuated patients had to take a 200 km+ routes with limited accompanying medical staff, to find admitting facilities, as no previous arrangements were in place [8]. At 11:00, a Hydrogen explosion occurred in the Unit 3 reactor building and was accompanied by further release to the atmosphere. The explosion caused the closure of the Unit 2 vent valves, which could not be opened afterwards. With the failure of Unit 2 emergency core cooling systems, and the several openings of the SRVs to depressurize the RPV, the pressure in Unit 2 PCV started to rise significantly between 21:00 and 23:30. The operators attempted several times to vent the PCV, however unsuccessful, failing to open the air operated vent valves (neither from the wet well nor the drywell) [2].

In the morning of March 15, the pressure readings in Unit 2 PCV dropped suddenly, hence, suggesting its failure. Shortly after, the nearby radiation monitoring stations started recording extremely high dose rates (~10 mSv/h) [2] confirming the uncontrolled release of radioactive material to the environment.

With the alarming radiation conditions on site, the national government extended the protective actions further beyond, and ordered sheltering for residents within 20-30 km from the plant on March 15 at 11:00. In the morning of March 16, and after many ongoing discussions and concerns regarding the side effects of potassium iodide pills, the national government ordered the distribution of potassium iodide pills to evacuees within a radius of 20 km. At that time, however, evacuations within 20 km were already completed and some of the evacuees had already been exposed to radioactive iodine [19].

The sheltering order remained in place until April 22 when the criteria for deliberate evacuation and relocation was established [2]. During the extended sheltering period, daily necessities started to run out in the area and the basic supplies (food, fuel, medications) halted due to delivery personnel's concerns of radiation exposure. In fact, some hospitals within the sheltering area had to evacuate their patients (already on March 17) due to the shortage of medical supplies and commodities.

The public started to be relocated from the established relocation areas on May 15. By December 16, a cold shutdown state was reached at the plant, and the long-term recovery phase was entered [2].

2.3. Radiation Exposure and Health Consequences

There have been multiple investigations by the international organizations, which reported that there were no direct deaths in residents due to radiation or the explosions in the reactors [20]. In fact, several researchers and organizations calculated the exposure of the residents in evacuated areas to be very low [21, 22], with a maximum of 25 (mSv) for the very few – well below the 100-mSv benchmark associated with increased cancer risk [23]. In 2013, the Fukushima Prefecture estimated that around 99.3% of the evacuees received less than 3 mSv external dose, and 99.9% received less than 1 mSv of internal dose [22]. Similarly, no significant contamination was found in the evacuated patients despite the fact that, for around 840 people, evacuation was delayed until March 14 [20].

According to the Aerial survey data collected by the U.S. National Nuclear Security Administration (NNSA) between March 17-19, 2011 [24], the dose rates in about 40% of the land regions of the 20km evacuation zone were relatively low compared to the international standards. Specifically, the evacuated regions north, south, and southwest of FDNPP experienced dose rates below 0.022mSv/hr, equivalent to ~ 3.5mSv for a 1-week stay, which according to the IAEA intervention criteria [25], does not necessitate any protective actions in the early stage. On the other hand, with the main plume dominantly traveling northwest [11], some residents in northwestern areas outside the 20-km evacuation zone were exposed to high radiation levels (close to 50 mGy per month), and were not evacuated until May 2011 [8, 26].

When it comes to non-radiation health effects, the family separations, isolations, social distress, as well as the uncertainty and fear of the "invisible" radioactivity have been reported to have compromised the mental health of several thousands who fled from the disaster's zones [27]. After the accident, around 15% of the evacuees reported mental health problems and 70% reported sleeping difficulties [28]. Besides, Satoh et al. [29] reported that there was a 6.2% increase in hypertension, 2% increase in diabetes, and 9% increase in dyslipidaemia among the evacuees.

Furthermore, according to the National Diet of Japan [30], more than 60 patients and elderly (from nursing care) died during or after evacuation experiencing hypothermia, dehydration, and deterioration of medical conditions due to the unorganized evacuations. Additionally, around 50% of the same group were reported to have died in the first 9 months after the accident, having significantly higher mortality rate than the average [31].

3. CRITICAL MISTAKES AND LESSONS IN EMERGENCY RESPONSE

3.1. Evacuation Zone Extent

Plans for the adaptive/expanding evacuation zones and protective actions (evacuation, sheltering, iodine pills, etc.) were lacking beyond the presumed 8-10 km emergency planning zone. In fact, before the FDNPP accident, Japan used to consider evacuation unnecessary outside the 8-10 km radius EPZ [32]. Moreover, there were no predetermined deposition dose criteria to necessitate emergency actions in areas beyond the emergency planning zone (EPZ), causing delays in relocation/evacuation of some seriously contaminated areas. For example, only on 11 April, the Nuclear Emergency Headquarters established the dose criteria for Deliberate Evacuation Zones outside the 20-km established evacuation zone, and relocation in some of these areas did not actually begin until 15 May.

In addition, radioactive release and dose prediction models – which were developed as an emergency response tool– failed to provide useful information due to the unavailability of monitored reactor data and source term information in the early stage of the accident [33]. This caused initial evacuation decisions to be based on ad hoc and predefined estimates and was behind the delays in the protective actions.

There have been several governmental actions as well as research studies after the FDNPP to address these aspects. Ohba et al. [34] recommend the preparation of evacuation plans inside as well as outside the preset EPZ as the radioactive plumes may reach further distances depending on the source term and meteorological conditions. However, the PRA level 3 – off-site accident consequence assessments – is not mandated by regulators nor is part of the licensing process at the moment in most countries [35, 36]). Along the same line, there have been numerous developments in real-time radioactive release and dose prediction models [37], however, they still inherent many uncertainties and do not assimilate real-time radiation measurements into their predictions [38]. This for example prompted the Japanese government to hesitate to use any prediction models for evacuation decisions in the future as they do not trust their accuracy and predictive power [39].

3.2. Planning, Execution, Communication, and Decision Making

The unorganized and delayed evacuation of hospitals during the FDNPP have caused tens of fatalities as no previous arrangements and appropriate transport were in place prior to the accident. According to Ohba et al. [34] only one hospital had an evacuation plan in case of a nuclear emergency. Furthermore, there were significant delays in instructing and distributing potassium iodide pills, which should have been implemented in parallel with evacuation decisions. On a parallel note, the government implemented extended sheltering periods without the pre-planning of the supply of daily necessities to the affected areas. This resulted in difficulties to the public as well as to hospitals and healthcare facilities to maintain their operating stock [34].

The overall emergency response situation was exacerbated by the failure of the prompt transmission of critical information to the affected population as well as between governmental organizations due to the damage of the power lines and communication systems (earthquake, tsunami, and station blackout). Similarly, there was a lack of real-time radiation monitoring capabilities; for example, 23 out of 24 radiation monitoring stations on the FDNPP site were malfunctioned after the Tsunami [40]. Although rapid monitoring such as airborne and car-borne measurements were deployed, the information was not properly used in decision making.

To address some of these aspects, Callen et al. [8] proposed to pre-distribute the potassium iodide tablets for the near-plant population to ensure its timely intake, i.e. before, or shortly after, the inhalation of radioactive iodine. At the same time, they recommend that the responsible authority be more informed of the side effects and potassium iodide procedures to avoid the unnecessary delays and discussions.

Regarding sheltering execution, the IAEA [25] recommends not to carry out sheltering for long periods (no more than 2 days). However, the experience in the FDNPP accident suggested the need to include extended sheltering in emergency response.

To have more reliable communication, Ohba et al. [34] suggested the use of multiple satellite lines with emergency power supply and redundant communication means that can operate in harsh environments during emergencies.

3.3. Multi-hazard and Multi-dimensional Risk Considerations

The national emergency management plans at the time were inadequate to deal with an accident of such scale (nuclear accident concurrent with a natural disaster such as earthquake, tsunami). The changes in the evacuation zones and decisions during the early-stage of the accident resulted in tremendous confusions. This was partly due to the overlap in responsibilities (because of the different hazards involved in the event) and absence of coordination between local and national governments. In fact, the Prefecture Headquarters for Disaster Control plans were formulated on the presumption that a natural disaster and a nuclear emergency would not take place at the same time. Furthermore, the decisions to isotropically evacuate the residents to minimize their radiation exposure without the consideration of other risk dimensions had, unnecessarily, compromised the lives of many evacuees as illustrated in the health consequences in section 2.3.

To tackle the problem of conflicting responsibilities in multi-hazard situations, the US follows a bottom-up approach in managing the offsite responses [41]. There, the responsibility for emergency management starts at a local level and can go up to the state then federal level on need basis, regardless of the hazards involved. Furthermore, there have been some developments in characterizing and modeling multi-hazard risks [42], however, there are still a lot of uncertainties and gaps in capturing the interactions between the different hazards.

4. REMAINING GAPS AND OPPORTUNITIES

There are still several gaps that must be addressed in the design, planning, and organization of future emergency responses to lessen the accidents' impacts, and arrive to more disaster-resilient societies and environments. We here present the major areas that we consider to have a serious capacity for improvement in industry 4.0; therefore, we recommend that further research and collaborations be directed towards achieving them.

1. **Adaptive Evacuation Zones**: The evacuation zones or other protective actions (iodine pills, and sheltering) should be adaptively informed by sensor datasets. In addition, there is a need to leverage technological advancements to allow a prompt risk-informed decision making during emergencies. Concretely, when it comes to the actual execution of the emergency response, our state-of-the-art tools are still not catching-up with current trends in big data and machine learning, monitoring advancements, simulation power, data assimilation, and weather forecasting advances. Furthermore, there is a need to mandate PRA level 3 codes by regulation to push their development and utilization in pre-planning as they can help to generate factual scenarios and provide a sense of what to expect.
2. **Planning, Execution and Decision Making**: The FDNPP accident exposed the inadequacy of pre-accident planning and the execution difficulty. As can be recognized from the timeline of events at the FDNPP accident, it usually takes about 12-24 hours before major releases can happen – thanks to defense in depth and the layered confinement structures. This provides enough grace period to implement orderly evacuations, executed by threat-priority, and accordingly, organized sequentially (in blocks) to avoid congestions. Furthermore, evacuation should be optimized considering demographics, transport routes (which might be impaired as in FDNPP accident), transport means, and evacuation destinations. When it comes to protective actions logistics, there is a need to plan for an adaptive stockpiling of food, fuel, medical resources, and other necessities, and to maintain the supply chains, as the experience have shown the potential need for extended sheltering and evacuation periods. For real-time surveillance, we recommend the standby-availability of promptly deployable monitoring sensors in a nearby offsite location (a neighboring plant, district emergency center, etc.).

3. **Multi-hazard and Multi-dimensional Risk Considerations**: Further development and utilization of multi-hazard risk assessment methodologies. On top of that, emergency response guidelines should reflect the latest results of these methods across disciplines. A review of the ongoing developments in multi-hazard risk analysis have been reported by Wang et al. [42]. Furthermore, the FDNPP accident suggested that the health consequences are not just radiation-induced but can be due to evacuation, long-term relocation and the associated psychological and social factors. Therefore, there is a need for the consideration of all the risk dimensions when it comes to decision making. This requires approaching risk as a multi-dimensional problem, developing models that take into account the different risk metrics for the different stakeholders. It also requires involving the people – the real stakeholders – in the action plan, using mobile applications and modern social media and communication platforms for real-time tracking of the situation to help them understand the decisions, and even possibly make their own, during the emergency.

References

1. NAIIC, *The official report of The Fukushima Nuclear Accident Independent Investigation Commission*. 2012, The National Diet of Japan Tokyo, Japan.
2. IAEA, *The Fukushima Daiichi Accident*. 2015.
3. Song, J.H., Kim, T.W., *SEVERE ACCIDENT ISSUES RAISED BY THE FUKUSHIMA ACCIDENT AND IMPROVEMENTS SUGGESTED.* Nuclear Engineering and Technology, 2014. **46**(2): p. 207-216.
4. *National Research Council. Lessons Learned from the Fukushima Nuclear Accident for Improving Safety of U.S. Nuclear Plants*. 2014, Washington, DC: The National Academies Press. 394.
5. Yang, J.-E., *FUKUSHIMA DAI-ICHI ACCIDENT: LESSONS LEARNED AND FUTURE ACTIONS FROM THE RISK PERSPECTIVES.* Nuclear Engineering and Technology, 2014. **46**(1): p. 27-38.
6. Cai, Y., Golay, M.W., *Multiunit nuclear power plant accident scenarios and improvements including those based upon interviews with TEPCO engineers concerning the 2011 Fukushima accidents.* Nuclear Engineering and Design, 2020. **365**: p. 110707.
7. Tanaka, S.-i., *Accident at the Fukushima Dai-ichi nuclear power stations of TEPCO—outline & lessons learned—.* Proceedings of the Japan Academy, Series B, 2012. **88**(9): p. 471-484.
8. Callen, J., Homma, T., *Lessons learned in protection of the public for the accident at the Fukushima Daiichi nuclear power plant.* Health physics, 2017. **112**(6): p. 550-559.
9. Liutsko, L., Oughton, D., Sarukhan, A., Cardis, E., *The SHAMISEN Recommendations on preparedness and health surveillance of populations affected by a radiation accident.* Environment international, 2021. **146**: p. 106278.
10. Ohba, T., Liutsko, L., Schneider, T., Barquinero, Joan F., Crouaïl, P., Fattibene, P., Kesminiene, A., Laurier, D., Sarukhan, A., Skuterud, L., *The SHAMISEN Project: Challenging historical recommendations for preparedness, response and surveillance of health and well-being in case of nuclear accidents: Lessons learnt from Chernobyl and Fukushima.* Environment International, 2021. **146**: p. 106200.
11. Chino, M., Terada, H., Nagai, H., Katata, G., Mikami, S., Torii, T., Saito, K., Nishizawa, Y., *Utilization of 134Cs/137Cs in the environment to identify the reactor units that caused atmospheric releases during the Fukushima Daiichi accident.* Scientific reports, 2016. **6**(1): p. 1-14.
12. Kröger, W., Sornette, D., Ayoub, A., *Towards Safer and More Sustainable Ways for Exploiting Nuclear Power.* World Journal of Nuclear Science and Technology, 2020. **10**(3): p. 91-115.
13. TEPCO, *Fukushima nuclear accident analysis report*. 2012, Tokyo: Tokyo Electric Power Company, Incorporated.
14. GE, *General Electric Advanced Technology Manual, Fukushima Dai-ichi Earthquake and Tsunami Event. Chapter 7.1. Available from:* https://www.nrc.gov/docs/ML1414/ML14140A185.pdf.

15. Miller, C., Cubbage, A., Dorman, D., Grobe, J., Holahan, G., Sanfilippo, N., *RECOMMENDATIONS FOR ENHANCING REACTOR SAFETY IN THE 21ST CENTURY: THE NEAR-TERM TASK FORCE REVIEW OF INSIGHTS FROM THE FUKUSHIMA DAI-ICHI ACCIDENT*. 2011, U.S. Nuclear Regulatory Commission.
16. *GOVERNMENT OF JAPAN, National Report to the 5th Review Meeting on the Convention on Nuclear Safety*. 2010.
17. *Act on Special Measures Concerning Nuclear Emergency Preparedness, as last amended by Act No. 156, 17 December 1999*. Japan.
18. Mizokami, S., Rempe, J.L., *The Events at Fukushima Daiichi*, in *Encyclopedia of Nuclear Energy*, E. Greenspan, Editor. 2021, Elsevier: Oxford. p. 53-66.
19. Hatamura, Y., Oike, K., *Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company.* Final Report, 2012.
20. Tanigawa, K., Hosoi, Y., Hirohashi, N., Iwasaki, Y., Kamiya, K., *Loss of life after evacuation: lessons learned from the Fukushima accident.* The Lancet, 2012. **379**(9819): p. 889-891.
21. UNSCEAR, *United Nations Scientific Committee on the Effects of Atomic Radiation, Developments since the 2013 UNSCEAR Report on the levels and effects of radiation exposure due to the nuclear accident following the great east-Japan earthquake and tsunami: A 2015 White Paper to guide the Scientific Committee's future programme of work*. 2015: UN.
22. Nagataki, S., Takamura, N., Kamiya, K., Akashi, M., *Measurements of individual radiation doses in residents living around the Fukushima Nuclear Power Plant.* Radiation research, 2013. **180**(5): p. 439-447.
23. Brumfiel, G., *Fallout of fear.* Nature, 2013. **493**(7432): p. 290.
24. NNSA, *US DOE/NNSA Response to 2011 Fukushima Incident- Data and Documentation*. 2011, National Nuclear Security Administration, Department of Energy: USA.
25. IAEA, *Intervention Criteria in a Nuclear or Radiation Emergency. IAEA Safety Series No. 109*. 1994, Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY.
26. Imanaka, T., Endo, S., Sugai, M., Ozawa, S., Shizuma, K., Yamamoto, M., *Early radiation survey of Iitate village, which was heavily contaminated by the Fukushima Daiichi accident, conducted on 28 and 29 March 2011.* Health Physics, 2012. **102**(6): p. 680-686.
27. Bromet, E.J., *Emotional consequences of nuclear power plant disasters.* Health physics, 2014. **106**(2): p. 206.
28. Yabe, H., Suzuki, Y., Mashiko, H., Nakayama, Y., Hisata, M., Niwa, S.I., Yasumura, S., Yamashita, S., Kamiya, K., Abe, M., *Psychological distress after the Great East Japan Earthquake and Fukushima Daiichi Nuclear Power Plant accident: results of a mental health and lifestyle survey through the Fukushima Health Management Survey in FY2011 and FY2012.* Fukushima journal of medical science, 2014.
29. Satoh, H., Ohira, T., Hosoya, M., Sakai, A., Watanabe, T., Ohtsuru, A., Kawasaki, Y., Suzuki, H., Takahashi, A., Kobashi, G., *Evacuation after the Fukushima Daiichi nuclear power plant accident is a cause of diabetes: results from the Fukushima Health Management Survey.* Journal of diabetes research, 2015. **2015**.
30. *National Diet of Japan, The Official Report of THE FUKUSHIMA NUCLEAR ACCIDENT INDEPENDENT INVESTIGATION COMMISSION*. 2012, The National Diet of Japan Tokyo, Japan: Tokyo.
31. Igarashi, Y., Tagami, T., Hagiwara, J., Kanaya, T., Kido, N., Omura, M., Tosa, R., Yokota, H., *Long-term outcomes of patients evacuated from hospitals near the Fukushima Daiichi nuclear power plant after the Great East Japan Earthquake.* PloS one, 2018. **13**(4): p. e0195684.
32. NSC, *Emergency Preparedness for Nuclear Facilities (May 2007)*. 2013, Government of Japan: Tokyo.
33. Sugawara, S., Juraku, K., *Post-Fukushima controversy on SPEEDI system: contested imaginary of real-time simulation technology for emergency radiation protection*, in *The Sociotechnical Constitution of Resilience*. 2018, Springer. p. 197-224.

34. Ohba, T., Tanigawa, K., Liutsko, L., *Evacuation after a nuclear accident: Critical reviews of past nuclear accidents and proposal for future planning.* Environment international, 2021. **148**: p. 106379.
35. Sornette, D., Kröger, W., Wheatley, S., *New ways and needs for exploiting nuclear energy*. 2018: Springer.
36. *Nuclear Energy Subcommittee, Advisory Committee for Natural Resources and Energy, The Use of PRA in Foreign Countries*. in *the 3rd Meeting of the Working Group on Voluntary Efforts and Continuous Improvement of Nuclear Safety*. 2013. Tokyo.
37. Terada, H., Nagai, H., Tanaka, A., Tsuduki, K., Kadowaki, M., *Atmospheric-dispersion database system that can immediately provide calculation results for various source term and meteorological conditions.* Journal of Nuclear Science and Technology, 2020. **57**(6): p. 745-754.
38. Zhang, X., Su, G.F., Yuan, H.Y., Chen, J.G., Huang, Q.Y., *Modified ensemble Kalman filter for nuclear accident atmospheric dispersion: Prediction improved and source estimated.* Journal of hazardous materials, 2014. **280**: p. 143-155.
39. Yamada, R., Tamakuma, Y., Iwaoka, K., Hosoda, M., Shiroma, Y., Akata, N., Mizuno, H., Yamada, K., Kuroki, T., Tokonami, S., *Measurement system for alpha and beta emitters with continuous air sampling under different exposure situations.* Applied Radiation and Isotopes, 2017. **126**: p. 79-82.
40. WNA. *Fukushima Accident. London, UK: World Nuclear Association*. 2014; Available from: https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-daiichi-accident.aspx.
41. *U.S. Department of Homeland Security, National Response Framework: Second Edition May 2013*. 2015: CreateSpace Independent Publishing Platform.
42. Wang, J., He, Z., Weng, W., *A review of the research into the relations between hazards in multi-hazard risk analysis.* Natural Hazards, 2020. **104**(3): p. 2003-2026.