A Perspective on Long-Term Recovery Following the Fukushima Nuclear Accident - 12075

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ABSTRACT

The tragic events at the Fukushima Daiichi Nuclear Power Station began occurring on March 11, 2011, following Japan's unprecedented earthquake and tsunami. The subsequent loss of external power and on-site cooling capacity severely compromised the plant's safety systems, and subsequently, led to core melt in the affected reactors and damage to spent nuclear fuel in the storage pools. Together with hydrogen explosions, this resulted in a substantial release of radioactive material to the environment (mostly Iodine-131 and Cesium-137), prompting an extensive evacuation effort. The latest release estimate places the event at the highest severity level (Level 7) on the International Nuclear Event Scale, the same as the Chernobyl accident of 1986. As the utility owner endeavored to stabilize the damaged facility, environmental contamination continued to propagate and affect every aspect of daily life in the affected region of Japan. Elevated levels of radioactivity (mostly dominated by Cs-137 with the passage of time) were found in soil, drinking water, vegetation, produce, seafood, and other foodstuffs. An estimated 80,000 to 90,000 people were evacuated; more evacuations are being contemplated months after the accident, and a vast amount of land has become contaminated. Early actions were taken to ban the shipment and sale of contaminated food and drinking water, followed by later actions to ban the shipment and sale of contaminated beef, mushrooms, and seafood. As the event continues to evolve toward stabilization, the long-term recovery effort needs to commence — a process that doubtless will involve rather complex decision-making interactions between various stakeholders. Key issues that may be encountered and considered in such a process include (1) sociopolitical factors, (2) local economic considerations, (3) land use options, (4) remediation approaches, (5) decontamination methods, (6) radioactive waste management, (7) cleanup levels and options, and (8) government policies, among others. This paper offers a perspective on this likely long and arduous journey toward establishing a "new normal" that will ultimately take shape. Toward this end, it is important to evaluate the "optimization" process advocated by the international community in achieving long-term recovery from this particularly fateful event in Fukushima. In the process, experience and lessons learned from past events will be fully evaluated and considered.

INTRODUCTION

On March 11, 2011, a severe earthquake registering 9.0 on the Richter Scale struck Japan's northeast coastal region, causing significant loss of life and property. The quake subsequently induced an unprecedented tsunami that struck the Tohoku District, inundating an area of 561 km^2 and leading to the death or disappearance of approximately 25,000 people [1]. The tsunami also caused a cascading effect, triggering a chain of events involving the Fukushima Daiichi Nuclear Power Plant located in the Fukushima Prefecture. The subsequent series of fires and equipment failures lead to a core meltdown that incapacitated the nuclear reactors at the plant. The event affected all reactors (Units 1 through Unit 6; all boiling water reactors) at the Fukushima Daiichi Nuclear Facility; although some were more seriously affected than others. This was the largest nuclear accident in Japan's history and only the second-largest nuclear accident in the history of mankind; the first being the 1986 Chernobyl nuclear accident in Ukraine [2], in the former Soviet Union. The combined disaster caused by the earthquake, tsunami, and the resulting nuclear accident created an unprecedented situation that has challenged the modern society of Japan.

Based on the loss of alternating current (AC) power at Units 1 and 2, the Japanese government initially issued a provisional accident designation of Level 2 on March 11.[a] As the event protracted and escalated over the following weeks, the provisional level was raised to Level 7, which is on par with the Chernobyl accident [1]. The contamination is thus deemed to be extensive, although much of it has been confined to within Japan, unlike in the Chernobyl accident, which caused widespread contamination across much of Europe and other regions of the world.

While much of the initial response effort focused on containing the accident at the affected Fukushima reactors, release of large quantities of radioactive materials (mainly Iodine-131, Cesium-134, and Cesium-137) prompted evacuation of nearby populations. Accordingly, the initial evacuation zone was set to a 3-km radius and the in-place sheltering zone was set to a 3-to-10-km radius, respectively, from the plants. The escalation of the event subsequently extended the evacuation zone to a 20-km radius and the in-place sheltering zone to a 30-km radius. The total number of evacuees had peaked to over 450,000 in March and decreased to around 80,000 by June, 2011. In addition, the widespread contamination had led to the ban of food production and consumption of food and water, and control of land uses in the most-affected areas.

In an attempt to stabilize the situation at Fukushima Daiichi Nuclear Power Station following the accident, Tokyo Electric Power Company (TEPCO) announced the "Roadmap towards Restoration from the Accident in Fukushima Daiichi Nuclear Power Station" on April 17 [3]. The plan designated two steps as targets: (1) Step 1 — radiation dose in steady decline, and (2) Step 2 — release of radioactive materials brought under control and radiation dose being held

[a] The level is based on the International Nuclear and Radiological Event Scale (INES) developed by the International Atomic Energy Agency (IAEA), together with the Organization for Cooperation and Economic Development's Nuclear Energy Agency (OECD/NEA), to communicate the severity of the nuclear or radiological event [4]. There are seven levels designated; Level 0 is the lowest and Level 7 is the highest.

down significantly. The timeline for Step 1 was set to around three months, and for Step 2, was set to be between three to six months following completion of Step 1. Although no timetable for long-term recovery has been specifically mentioned, it is anticipated that certain planning activities will occur during the Step 1 and 2 processes.

ISSUES CONCERNING LONG-TERM RECOVERY

Widespread Contamination

By April 12, more data had been accumulated from monitoring efforts. While the Nuclear and Industrial Safety Association (NISA) issued its initial estimate of 370,000 TBq total radioactivity released based on analyses of the reactor status and other data, the release estimate was later upped to 770,000 TBq ,based on dust monitoring data (see http://ecocentric.blogs.time.com/2011/04/11/what-does-fukushima%E2%80%99s-new-%E2%80%9Clevel-7%E2%80%9D-status-mean/). The estimated amount of Iodine-131 was 150,000 TBq, and the amount of Cesium-137 was 12,000 TBq [1]. Based on these estimates, NISA raised the provisional level to Level 7. Compared to the total radioactivity released from the Chernobyl accident, the estimated release from the Fukushima accident represents about 15 percent of the Chernobyl release [1].

Shortly after the accident, some of the prevailing winds had blown toward populated areas, particularly to the northwest. During that time, weather conditions, including rain, snow, and hail, enhanced the deposition of radioactive materials in certain parts of the region, including some areas beyond the 20-km evacuation zone (see http://ajw.asahi.com/article/0311disaster/fukushima/AJ2011101114071). The subsequent weather conditions further spread the contamination beyond the 20-km evacuation zone, resulting in a wide area of contamination with varying levels of radioactive concentrations on the ground. The contaminated areas were estimated initially to be 1,800 km^2 for dose levels greater than 5 mSv/y, and about 13,000 km^2 for dose levels greater than 1 mSv/y; the latter dose level being the annual regulatory limit for members of the general public that is endorsed by Japanese Environmental Ministry.

Short- and Long-Term Priorities

In a society highly disrupted by the major earthquake, tsunami, and subsequent nuclear accident at the Fukushima nuclear power station, the compound effects are truly unprecedented. As in any case following a major event caused either by natural disaster or human activity, there is an overriding urgency to return to normalcy (or close to normalcy) in an expedient manner.

The natural disaster (earthquake and tsunami) had already inflicted destruction upon the land near the coastal areas (three prefectures) of the region. The Fukushima nuclear accident that followed further exacerbated the conditions already caused by the natural disaster. With so many concerns to address, the primary task is to establish the major objectives and priorities for recovery. Given that a large population (about 80,000) had been evacuated[b] following the Fukushima accident, the primary objectives would appear to be those of restoring the community and repatriating the displaced population.

In the short term, it is important to attend to the evacuees, stabilize the environment, and clean up the debris. It is also important to restore critical infrastructure such as electric power, water supply, transportation, etc. For the long term, however, one must consider a few principal "drivers" that would lead to successful long-term recovery:

- Repatriation of the displaced population. The impacts on the evacuees have been physically, economically, and psychologically substantial. How to repatriate such a population in the most expedient manner is a considerable challenge, as the issues involve housing, education (reopening of schools), health, employment, business, and public assistance.
- Economic issues. Lost businesses (e.g., commercial industry, fishery, or tourism) and livelihoods (e.g., houses, farms, etc.) cannot be restored or replaced easily. It would take careful long-term planning and extensive coordination by the government, business sectors, private organizations, and citizens to achieve economic recovery for the affected areas.
- Social & cultural issues. Displacement of people from their communities may disrupt their social and cultural activities and interactions, contributing to the already harsh conditions they have faced due to the disaster.
- Cleanup of contaminated areas. All recovery activities are predicated on an assurance that short-term and long-term health protection will be provided for the people involved. This means that the contaminated areas need to be cleaned up properly.
- How clean is clean? This is a very important question surrounding the cleanup of properties and the environment. The criteria applied will not only ensure that health is protected, but will also play a pivotal role in determining the amount of effort, cost, and time required to achieve the objective. Thus, the decision-making process involved is necessarily a multifaceted one that requires an optimization approach (see discussion below) to reach an agreement with stakeholders. To this end, the International Atomic Energy Agency (IAEA) has urged Japan to take a "more focused and realistic approach" to dealing with contamination (see http://online.wsj.com/article/SB10001424052970203914304576631002932214520.html).
- Future land use options. Given that some areas are heavily contaminated and will require extensive and time-consuming cleanup efforts, it is important to identify and evaluate potential land use options that could deviate from the original land use. For example, could the cleaned-up land be used for light industry instead of the traditional farming industry, since agricultural products grown on contaminated land (such as rice or other farm products) may not be deemed safe (due to contamination or stigma)? All

[b] This is on top of the catastrophe already caused by the earthquake and tsunami combined in the region; the Japanese National Police Agency has confirmed 15,824 people dead, 5,942 injured, and 3,847 missing, across eighteen prefectures, as well as over 125,000 buildings damaged or destroyed [5].

potentially viable options ought to be carefully evaluated during the decision-making process.

Waste Management and Disposal

Generation of radioactive wastes or secondary wastes from decontamination or cleanup activities has occurred in past events [2, 6]. This will also be the case for the pending cleanup actions following the vast contamination issues arising from the Fukushima nuclear event. Based on the surveillance data, the contaminated area is estimated to be 1,800 km^2 (more than twice the size of New York City) with an annual dose level above 5 mSv; and about 13,000 km^2 (or approximately the size of the state of Connecticut) with a dose level between 1-5 mSvm (see http://ajw.asahi.com/article/0311disaster/fukushima/AJ2011101114071). Based on the full decontamination of the areas above 5 mSv and partial decontamination of the areas between 1–5 mSv, the estimated amount of radioactive waste (i.e., decontaminated soil and debris) would be approximately 29 million cubic meters (see http://ajw.asahi.com/article/0311disaster/fukushima/AJ2011101114071). This includes 1.02 million cubic meters from residential areas, 17.43 million cubic meters from farmlands, and 8.76 million cubic meters from forests. Storage of such waste would require one single facility of 1 km^2 with a 30-meter depth; or it would require an equivalent of 23 Tokyo domes (see http://www.japantimes.co.jp/text/nn20110929a3.html)! Thus, the IAEA has recommended using flexible approaches to managing such large quantities of waste, such as utilizing existing municipal and industrial waste infrastructure [7].

Stakeholder Involvement

Practical involvement of stakeholders is a necessary step toward long-term recovery. Learning from the earlier miscues and confusion during the initial event and the evacuation process, Japanese authorities have made vast improvements. For example, The Japan Ministry of Environment has established the Fukushima Decontamination Promotion Team to communicate and coordinate activities with local communities, and to provide assistance. The Japan Atomic Energy Agency (JAEA) established a Fukushima Office to interact with relevant prefecture organizations and citizens [7]. In addition, the authorities have provided telephone hotlines and expert help and have conducted frequent public outreach efforts. There are also large numbers of volunteers participating in the cleanup effort, which represent an important self-help mechanism.

Financial Burdens to Society

The potential costs to society for long-term recovery are likely to be enormous. So far, no specific official figure has been made available. Of course, for a very complex and far-reaching effort such as this, it would be considerably difficult to project such an estimate without understanding the actual scope of the entire effort. However, the sheer magnitude of the costs can be previewed from a glimpse of some isolated, individual activities. For example, the decontamination measure discussed for remediating the 13,000 km^2 area with a dose level between 1-5 mSv would alone cost the Japanese government an estimated amount of $15.6 billion (see http://ajw.asahi.com/article/0311disaster/fukushima/AJ2011101114071). This does not include consideration of the feasibility of disposing the very large quantities of waste involved (about 27 million cubic meters of radioactive waste, or roughly three times the capacity of the U.S. commercial low-level radioactive disposal site at Clive, Utah, owned and operated by the EnergySolutions, Inc.). Any costs expended for recovery would be in addition to the economic losses already inflicted by the natural disaster and the nuclear accident. In addition, the task of battling the potentially persistent stigma issues may linger long after the recovery is "completed."

Long-term Monitoring of Public Health and the Environment

It is important to continue monitoring public health and the environment, even after the community has gone through cleanup. In fact, a long-term registry should be established for the affected population to support continued follow-up. And monitoring of the environment will likewise be necessary for a considerable length of time. At a minimum, authorities will need to provide further assurance that residual contamination no longer poses health or environmental threats to the region. In fact, the Japanese government began health screening efforts in October 2011, with a plan to screen approximately 360,000 children who were under 18 at the time of the accident and track their health throughout their lifetimes (see http://www.nytimes.com/2011/10/11/world/asia/japan-studies-radiation-effects-on-children.html?_r=1).

OPTIMIZATION FOR DECISION MAKING

Optimization as a Radiation Protection Principle

The principle of optimization has been a tenet of and has played an increasingly important role in radiation protection. The principal of optimization of protection is the second principle of radiation protection (the first principle being the principle of justification, and the third being the principle of application of dose limits). The International Commission on Radiological Protection (ICRP) states in its latest recommendation [8] on the principle of optimization:

> "… *the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors*."

Thus, the level of protection offered should be the best possible under the prevailing circumstances, maximizing the margin of potential benefit over harm. It is also the only principle that recognizes the importance of non-radiation-related issues in protection considerations. In fact, one must realize that there are other important factors besides human health that should be considered in the decision-making process. This is particularly important for long-term recovery, where there are a multitude of socioeconomic issues, as discussed above, which need to be addressed with varying priorities.

Elements of Optimization

According to ICRP, long-term exposure to residual radiation following a nuclear or radiological event is considered as an *existing exposure situation* (as opposed to the *planned exposure situation* for a licensed facility) [8]. Toward this end, the ICRP recommends a reference level band in the range of 1 mSv to 20 mSv per year, plus the effort to maintain the dose at a level as low as reasonably achievable (ALARA) [9]. The ICRP also aims to achieve the lower end of the reference level of 1 mSv. A key area of focus is protection above the reference level. That is, a greater weight is placed on protecting the most exposed groups of people rather than the general population. Of course, further dose reductions should continue in accordance with the optimization principle, even when the reference level is achieved.

In response to concerns about late-phase recovery issues, certain latitude has been recommended to offer flexibility. Consistent with the ICRP recommendations, the Department of Homeland Security, in its published guidance on the protective actions guides [10], said:

> "*Because of the extremely broad range of potential impacts that may occur from RDDs and INDs (e.g., light contamination of one building to widespread destruction of a major metropolitan area), a pre-established numeric cleanup guideline is not recommended as best serving the needs of decision makers in the late phase. Rather, a process should be used to determine the societal objectives for expected land uses and the options and approaches available, in order to select the most acceptable criteria*."

The ALARA Principle has thus been a requirement in all existing regulations for control of radiation exposures, including the statutes on cleanup of nuclear facilities.

Stakeholder Involvement and Acceptability

Faced with the daunting task of recovering from the Fukushima nuclear accident, the Japanese people are beginning to contemplate possible courses of action. Government agencies are working with community leaders and volunteers to formulate plans and initiate actions. This has been manifested in local activities such as cleaning up schoolyards, roads, and other public spaces, as well as private quarters. However, the longer-term concerns such as future land use, commerce, and survival of private businesses, will require careful long-term planning and feasibility studies. For example, decisions must be made regarding the feasibility of continuing the traditional farming in the heavily contaminated areas in the Fukushima Prefecture, or whether it is feasible to return some 80,000-plus evacuees to their homeland in a timely manner.

These are difficult decisions that require direct input from stakeholders. The multitude of issues leading to long-term recovery cannot be resolved by a "top-down" government-driven approach. Rather, a heavy stakeholder involvement must be maintained throughout the decision-making process (a "bottom-up" approach). Unlike the life-saving rescue efforts in the immediate phase following an accident, where authorities play a major role, the major initiatives in the recovery phase ought to be led by the stakeholders, with the government playing a supporting role to facilitate the actions.

The U.S. Presidential/Congressional Commission on Risk Assessment and Risk Management has recommended an approach to the decision-making process for environmental health risk management [11]. In this approach, implementation of the cleanup decisions requires input from all relevant stakeholders, taking into account a broad set of long-term objectives.

LESSONS LEARNED

Considerable experiences and lessons have been learned from past nuclear and radiological events. These include the *Chernobyl nuclear accident at Pripyat, Ukraine (Former Soviet Union) in April 1986* [5]. The Chernobyl event is likely the worst nuclear power plant accident in history worldwide, which resulted in a widespread release of radioactive materials following a massive nuclear explosion. The accident released an estimated total of 5,200,000 TBq of radioactive material into the environment [5]. An estimated 336,000 people were evacuated within an extended "exclusion zone" of 4,300 km^2. An estimated 2.6 million km^2 of agricultural land were affected, with extensive contamination of the environment and the ecosystem. The release affected parts of the western Former Soviet Union, Eastern Europe, Western Europe, Northern Europe, and other parts of the world. Potential costs of the cleanup effort cannot be measured readily, although the initial estimate for Belarus alone in a 30-year program to rehabilitate the affected areas was about US$235 billion (32 times the nation's annual budget at the time of the accident) [12]. As such, the accident has been characterized as INES Level 7 (i.e., a major accident), because it resulted in "a major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures."[3]

Another event involved the *cesium source accident at Goiania, Brazil, September 1987* [6]. It was perhaps the worst accident involving radioactive sources, which resulted from an inadvertent scavenging of a radioactive medical teletherapy source (containing Cs-137) in an abandoned hospital. Since the accident was not recognized for several days, it propagated further, resulting in four deaths and injuries to several other people caused by radiation exposure. In addition, part of the city was contaminated and required an extensive decontamination and remediation effort lasting several months, largely due to the lack of preparedness and specific guidance for responding to such an unprecedented event. A total of 44 TBq of Cs-137 was accounted for in the contamination (out of a total of 51 TBq in the original cesium chloride source), with an estimated contamination area reaching 1 km^2 [6]. In all, 3,500 m^3 of waste was generated through the cleanup effort, which was stored at a temporary waste storage site located about 20 km away from Goiania.

Although the total final cost for the cleanup effort is not known, it is believed to be substantial. The accident has been designated as an INES Level 5 accident (accident with wider consequences).

The Fukushima event has been assessed at an INES Level 7 accident, the same level as Chernobyl nuclear accident, although its total environmental release is only about 15 percent of that from the Chernobyl accident. In October 2011, following initial visits to Japan, the IAEA issued a summary report of the preliminary findings on the remediation of the large contaminated areas outside of the 20-km exclusion zone of the Fukushima Nuclear Power

Station [3]. The report includes the initial lessons learned, together with nine acknowledgements and twelve points of advice to improve strategy. The objective of the IAEA effort was threefold, to (a) provide assistance to Japan in managing the remediation of large areas contaminated by the Fukushima nuclear accident, (b) review remediation-related strategies currently undertaken by Japan, and (c) share the findings with the international community as lessons learned.

While acknowledging Japan's initial effort in responding to the accident, IAEA also offers its advice in several areas. At the top of the list is a caution against over-conservatism in establishing the remediation strategy. Instead, the principle of optimization was suggested for balancing the net benefit of remediation measures to ensure dose reduction (also see discussion above). Other advice includes strengthening the coordination effort; designating the evacuation area; characterizing and managing radioactive waste; clarifying the risk and its interpretation; developing a data management plan; basing agricultural decisions on realistic data; properly exempting radioactive waste based on risk levels; making safety assessments prior to remediating forest areas; continuing monitoring freshwater and marine systems; and working closely with stakeholders in decision making.

SUMMARY AND CONCLUSIONS

The tragic events caused by the cascading effects of the earthquake near Japan in March 2011 evolved into an unprecedented nuclear accident at the Fukushima Nuclear Power Station. While no known fatalities have been recorded due to excess radiation levels near the power plant, a substantially large area in eastern Japan has suffered extensive contamination.

As illustrated in the past events of similar nature, such as the 1986 Chernobyl nuclear accident in Ukraine and the 1986 Goiania radiological source accident in Brazil, Japanese society likely will face a daunting prospect of rather complex recovery challenges. Such challenges are multifaceted in nature; ones that must take into account sociopolitical factors, economic considerations, government policies, technologies, land use considerations, etc.

Planning for long-term recovery from the likes of the Fukushima event has been lacking across the world. Responding to such events requires tremendous effort. The Government Accounting Office has raised questions about U.S. preparedness [13], which were echoed further recently [14, 15]. Although the concerns were most focused on nuclear or radiological terrorism issues (i.e., prior to the Fukushima event), the long-term recovery issues would be similar in most cases. Efforts are currently underway to address the general issues associated with long-term recovery from nuclear or radiological events, such as those undertaken by the National Council on Radiation Protection and Measurements (NCRP).[c] As unfortunate as the Fukushima event has been, it likely will serve as a benchmark to fortify world preparedness efforts for future such events.

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