

## &lt; Review &gt;

## Lessons learned from radiation protection for emergency response and remediation/decontamination work relating to the Fukushima Daiich Nuclear Power Plant accident in 2011

Shojiro Yasui

Ministry of Health, Labour and Welfare

### Abstract

This article reviewed the papers which address issues of radiation protection for emergency workers and decontamination workers relating to the Fukushima Daiichi Nuclear Power Plant accident in 2011. The papers were published from 2012 to 2017 and they extracted lessons learned from the experiences and provided guidance regarding future preparedness for a similar accident. Numerous reports have been published about the accident. However, the issues regarding the radiation protection of workers have rarely been presented. The reviewed papers provide detailed information on the problems substantiated by reliable primary sources. The article is not arranged chronologically but divided into four broad topics: (a) emergency responses for radiation protection and health care, (b) post emergency responses, (c) establishment of new regulations for decontamination/remediation, and (d) the epidemiological study on health effects of radiation exposure.

**keywords:** radiation protection, Fukushima nuclear accident, emergency response

(accepted for publication, 13th November 2017)

### I. Introduction

In response to the Fukushima Daiichi Nuclear Power Plant accident that resulted from the East Japan Earthquake on March 11, 2011, the Tokyo Electric Power Company (TEPCO) undertook emergency work to which an emergency dose limit applied [1]. The Japanese government increased the emergency dose limit from 100 mSv to 250 mSv exclusively for the emergency work performed at the affected plant from March 14 to December 16, 2011.

During the emergency work, TEPCO and the Japanese government experienced various problems in management, control and reduction of radiation exposure, and medical and healthcare management for emergency workers. For the proper implementation of radiation protection and healthcare management, the Ministry of Health, Labour and Welfare (MHLW) issued a series of compulsory directives and administrative guidance to TEPCO.

In the post-emergency situation, the MHLW conducted a fact-finding survey in response to the manipulation of personal alarm dosimeter collection efficiency. The survey provides the lessons learned about post-emergency radiation protection at the affected plant. Also, the MHLW conducted a re-evaluation of a committed effective dose of emergency workers for unifying the evaluation methodologies employed by TEPCO and the primary contractors.

Furthermore, to rehabilitate the areas contaminated by the radioactive substances released from the affected plant, the government of Japan decided to carry out decontamination work (e.g., cleanup of buildings and remediation of soil and vegetation) and to manage the waste resulting from the decontamination and unmarketable contaminated goods. To prevent radiological hazards, the government needed to provide sufficient radiation protection for the decontamination workers.

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Corresponding author: Shojiro Yasui  
1-2-2 Kasumigaseki, Chiyoda-ku, Tokyo, 100-8988, Japan.  
E-mail: syasui@st.rim.or.jp

As for examining the health effects of radiation exposure for emergency workers, the MHLW has formulated a research team and implemented a study since 2014 using the recommended study design drawn from meetings of experts.

This article reviewed the papers which address issues of radiation protection for emergency workers and decontamination workers since the Fukushima nuclear power plant accident in 2011. The papers were published from 2012 to 2017 and they extracted lessons learned from the experiences and provided guidance regarding future preparedness for a similar accident. The article is divided into four broad topics: (a) emergency responses for radiation protection and health care, (b) post emergency responses, (c) establishment of new regulations for decontamination/remediation, and (d) the MHLW-sponsored epidemiological study on health effects of radiation exposure. The article describes problems that occurred and provides discussions on the lessons learned from the responses to the issues.

## II. Methodology

Papers on radiation protection of workers involved in the accident have rarely been published in academic journals whereas numerous reports have been published about the accident itself. Most of the studies concerning workers' radiation protection were written by officers of the government and research institutions which conducted radiation dose evaluations or provided medical care for emergency workers, including the Japan Atomic Energy Agency, the National Institute of Radiological Sciences, the University of Occupational and Environmental Health, and the National Defense Medical College. This is probably because collecting data has been challenging for researchers because the information on radiation exposure and health care of emergency workers is regarded as personal information and access to the data is limited to specific authorities. Furthermore, gaining access to emergency workers has also been difficult because their workplaces were in restricted areas and their identities were not disclosed.

The official governmental reports provided limited information about workers' radiation protection and health care. The report of the Japanese government's Investigation Committee on the Accident at the Fukushima Nuclear Power Stations in 2012 rarely prescribed the issues of workers' radiation protection[2]. The report of the National Diet of Japan Fukushima Nuclear accident Independent Investigation Commission in 2012 specified the issue of workers' radiation protection in only eight pages out of 586 pages[3]. This is because both committees focused on the

issues surrounding the causes of the accident.

International organizations also published many reports concerning the accident. Unlike the reports of the Japanese national committees, they covered the issues of radiation protection and health consequences for workers in substantial volumes. The reports published by World Health Organization (WHO) in 2012 and 2013[4,5] mainly focused on the health effects of radiation exposure to the general public and the emergency workers involved. The report assessed the potential health consequences of exposure to radiation of the emergency workers assuming four scenarios that describe different exposure patterns. The reports stated that "the relative increase over background for leukemia and thyroid cancer is as high as 28% in the youngest workers" for less than 1% of workers, and "a notable risk of thyroid cancer is estimated, especially for young workers" for those few emergency workers who received very high doses to the thyroid. (p. 93 in[5]) WHO made the evaluations based on the exposure data provided by TEPCO.

The report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) published in 2013[6] indicated the health consequences of workers as "No radiation-related deaths or acute diseases had been observed among the workers and general public exposed to radiation from the accident."(p. 10 in [6]) As for "the 12 workers ... who were estimated to have received absorbed doses to the thyroid from iodine-131 intake alone in the range of 2 to 12 Gy, an increased risk of developing thyroid cancer and other thyroid disorders can be inferred." Besides, "more than 160 additional workers received effective doses currently estimated to be over 100 mSv", however, "any increased incidence of cancer in this group is expected to be indiscernible." (p. 11 in [6])

In report, the UNSCEAR conducted an independent evaluation of radiation dose data provided from TEPCO. This report criticized primary contractors because "based on the comparative assessments carried out, the Committee was unable to confirm the reliability of the internal exposure assessments reported by contractors for their workers."(p. 73 in [6] ) This criticism arose because the UNSCEAR did not use the standard diplomatic channels of the Japanese government but directly requested TEPCO to provide exposure data. These data were incomplete because TEPCO provided only the exposure data it possessed and not all the data of the primary contractors. Furthermore, TEPCO could not provide sufficient information about the methodology of internal exposure evaluation employed by the primary contractors. As background, the disclosed information about workers' exposure data from the Japanese government was limited and insufficient.

For strengthening international communication, the MHLW translated all disclosed information concerning workers' radiation protection into English and put it on the Ministry's new website established in 2012 [7]. Regarding the internal dose evaluation, the MHLW conducted two governmental re-evaluations of internal dose for unifying methodologies employed by TEPCO and primary contractors in July 2013 and March 2014; and published the results on the Ministry's website [8,9]. In response to criticism from UNSCEAR for a lack of reports published in academic journals, an officer of the MHLW – the author of this review – published 12 studies from 2013 to 2017 concerning the major topics of workers' radiation protection.

The report published by International Atomic Energy Agency (IAEA) in 2015 [10] mentioned not only health effects of radiation exposure of workers, but also provided much information concerning workers' radiation protection. The completeness of this report was due to the Japanese government dispatching several experts to the IAEA and providing sufficient relevant information from TEPCO and Japanese government.

This review mainly examined academic papers referred to in the reports of the WHO, UNSCEAR and IAEA. Because of the nature of a review, press release documents of the Japanese government, such as the MHLW, and of TEPCO were not examined. Records of the press release documents are referred to in the reviewed papers. As an exception, the booklet which summarized the actions taken by the MHLW, published in 2013, was included in this review.

### III. Emergency responses for radiation protection and health care management

#### 1. Radiation protection problems

During the emergency work, the MHLW observed the following radiation protection problems [11,12].

(a) *Inappropriate Exposure Monitoring because of a Shortage of Personal Dosimeters*: The tsunami damaged a large number of electronic personal alarm dosimeters (PADs). The surviving dosimeters could not be recharged because of the electrical blackout at the site. The number of usable dosimeters decreased to approximately 320 on March 15, 2011, whereas the number of emergency workers increased progressively. Under these circumstances, from March 15 to March 31, 2011, TEPCO could not supply PADs to all workers but only one dosimeter for each work group who engaged in outdoor works and the monitored exposure dose was regarded as the common dose of the group.

- (b) *Inappropriate Dosimeter Circulation Management and Exposure Control*: Given the breakdown of the electronic exposure management system, TEPCO implemented paper-based dosimeter circulation management at the affected plant until April 4 (until June 8 in the support facility known as J-Village). However, some workers wrote down only their family names, and others wrote in illegible characters. As a result, TEPCO faced the difficulty of conducting a name-based aggregation of doses and a calculation of accumulated individual doses.
- (c) *Workers Who Were out of Contact*: During the process of the name-based aggregation, on June 20, 2011, it was revealed that several workers whose identities could not be confirmed appeared on the circular list. The number of workers who were not on the rosters reached a maximum of 174.
- (d) *Delayed Internal Exposure Monitoring*: After the accident, TEPCO could not operate the whole body counters (WBCs) that were located in the affected plant because of the increase of the background radiation level. In response, on March 22, 2011, TEPCO started to operate two vehicle-mounted WBCs. However, the capacity of the WBCs was insufficient to cover all of the emergency workers. Furthermore, workers who required identification of short-half-life radionuclides, had to be dispatched to specialized institutions for evaluation of internal dose [13].
- (e) *Exceeding Emergency Dose Limits*: The exposure doses of six emergency workers had exceeded the emergency dose limit (250 mSv), which the Japanese government increased from 100 mSv on March 14, 2011.
- (f) *Internal Exposure That Resulted From the Inappropriate Use of Protective Masks*: Internal exposure beyond record levels were repeatedly found until September, 2011, which was six months after the accident.
- (g) *Protection against Beta-Ray Exposure From Contaminated Water*: During the emergency work, several incidents of beta-ray exposure occurred in relation to contaminated water, such that workers received beta-ray exposure on their feet after they stepped into 30 cm deep contaminated water while wearing half boots to install electrical cables in a reactor building basement [14].
- (h) *Worker Training*: From the time of the accident until May 2011, TEPCO and the primary contractors conducted training for newcomers to the affected plant for only 30 min.

#### 2. Medical and health care problems

During the emergency work, the MHLW observed the following medical and health care problems [15].

(a) *Implementation of Emergency Medical Examinations*: In

March 2011, the MHLW issued compulsory orders to TEPCO to implement special medical examinations for screening for acute radiation syndrome or local radiation injuries every month. The implementation rate from March to September rose gradually but remained low.

- (b) *Establishment of On-Site Medical Care Systems:* Although a few thousand emergency workers per day continuously engaged in emergency work in the affected plant, TEPCO could maintain the presence of physicians and medical staff only during the daytime for a few days each week during the early stages of the accident [16-18].
- (c) *Patient Transportation from the Affected Plant:* Three of the five initial medical facilities were located in the evacuation zone and a hospital was located in the indoor evacuation zone. At the other hospital, supply of water and electricity were lost or malfunctioned [19,20]. Three days after the accident, Fukushima Medical University prepared to accept patients. However, the transfer from the affected plant took 3-4 hours.
- (d) *Prevention of Heat Illness:* The MHLW was concerned that heat illness could develop if emergency workers spent long hours under the blazing sun while wearing full-face respiratory masks and HAZMAT garments [21].
- (e) *Lodging and Food:* During the emergent situation, approximately 400 workers had to sleep on the floor of the Seismic Isolation Building of the affected plant or the gymnasium of the Fukushima Daini NPP, 13 km from the affected Fukushima Daiichi NPP. For the prevention of internal exposure, TEPCO restricted the food supply to workers to boil-in-bag foods.
- (d) *Long-term Healthcare:* For the long-term health care of emergency workers, the action plan of the government stated that a database should be constructed that could track the radiation exposure of all emergency workers long-term, including after retirement, and long-term health care activities should be implemented for them [7,18].

#### IV. Post emergency responses

##### 1. Reduction of emergency dose limits

In response to the accident, on March 14, 2011, the MHLW enforced an ordinance that temporarily increased the radiation exposure dose limit allowed during the emergency to 250 mSv. Subsequently, the MHLW succeeded in reducing the emergency dose limit back to the original limit through a phased approach [22]. In the first phase, the MHLW reduced the emergency dose limit allowed for newcomers to the affected plant to 100 mSv on or after November 1, 2011. On December 16, 2011, in

the second phase, the MHLW abolished the exemption ordinance when STEP 2 in the emergency response plan, a cold shutdown condition of the affected nuclear reactors, was completed.

##### 2. Response to the manipulation of PAD collection efficiency

In December 2011, it was found a subcontractor had demanded that its contracted workers cover their PADs with 3-mm thick lead plates to lower dosimeter readings. As a response, the MHLW conducted a fact-finding survey to identify similar cases and devise measures to prevent a recurrence of this incident [23]. The results of the survey provide lessons that can also be applied to the transition from emergency radiation protection to normal operation given that the application of emergency dose limits ceased on December 2011 in the affected plant.

##### 3. Governmental re-evaluation of the committed effective dose

In April 2013, the MHLW noticed that significant discrepancies were present between the committed effective dose (CED) data provided by TEPCO and data reported by five primary contractors. Based on a re-evaluation of the data, the MHLW required TEPCO and the five primary contractors to readjust the CED data for 479 workers (2.5% of 19,346 emergency workers) [8]. Major issues addressed during re-evaluation included a) selection of the intake scenario, b) assumptions about the intake date, c) assessments of exposure to radiation from short half-life nuclides, and d) assumptions of undetected <sup>131</sup>I exposure due to monitoring delay.

Furthermore, in January 2014, TEPCO learned that the CED for nine emergency workers had been assessed using a method other than the standard assessment methods established by the MHLW in a re-evaluation conducted in July 2013 [9]. The MHLW requested that TEPCO and primary contractors review all CED data for 6,245 workers who were engaged in emergency work in March and April 2011 except those previously reviewed. New issues were addressed during the tertiary evaluation such as setting a conversion coefficient between two different measurements of internal exposure [24,25].

#### V. Establishment of new regulations for radiological protection for decontamination / remediation work

##### 1. Decontamination work and recovery and reconstruction work

Existing government regulations assumed that the

radiation sources were controlled and collected in indoor restricted areas referred to as planned exposure situations. The government had not considered the possibility of a situation where radiation sources were scattered and workers would have to deal with radioactive material outdoors (referred to as an existing exposure situation). ICRP recommendations state that exposure involving long-term rehabilitation of the contaminated areas should be treated as a part of planned exposure, although it does not provide details regarding exposure management.

Given the insufficient international recommendations, the MHLW decided to establish new regulations on occupational radiological protection in an existing exposure situation by using the protection in a planned situation as a reference. During its deliberation, the MHLW employed the following three principles [26,27] :

- (a) Ensure that the level of protection is equivalent to or greater than the level in a planned situation and adhere to existing regulations in a planned situation.
- (b) Be practical and function smoothly in the situation around the affected plant, which is limited by restricted infrastructure, supplies and resources for the decontamination work.
- (c) Be consistent with the radiological protection for the inhabitants around the work sites to avoid anxiogenic effects because decontamination projects have to be carried out in daily living areas, in full view of inhabitants, unlike in the case of work in radiation-controlled areas.

## 2. Disposal of contaminated soil and waste

Disposal of contaminated materials removed by decontamination requires workers to engage in work primarily conducted in indoor radiation-controlled areas. The MHLW therefore applied the existing general regulation for radiation protection to disposal workers. However, those regulations were difficult to apply to the disposal of decontamination-removed materials because this involves the handling of huge amounts of materials, requires large-scale facilities, involves fragmentation processes and landfill operations, and includes operations that must be conducted in high-ambient-dose-rate environments [28]. Thus, the MHLW decided to amend the general regulation and establish new prescribed radiation protections for workers engaged in disposal of materials removed as part of decontamination work.

## 3. Central dose registration system

The newly established regulations for radiation protection of decontamination workers obligated employers to monitor, record, and store workers' dose records and to

assess their past dose records at the time of employment. However, cumulative doses may not be properly maintained if a worker declares incorrect values for past doses. In response, with facilitation by the MHLW, primary contractors of decontamination work decided to establish a central dose registration system [29]. The system started its operation in December 2013 and provided dose distributions in April and July 2015.

## VI. Epidemiological study on health effects on emergency workers

Results from medical examinations of workers who were engaged in emergency work in 2012 showed that the prevalence of abnormal findings was increased compared with that prior to the accident. The MHLW concluded that the 2010 and 2012 data could not be easily compared because 70% of the enterprises that reported the 2012 results differed from those that did so in 2010. However, the MHLW decided to implement a comprehensive epidemiological study on the health effects of radiation exposure on all emergency workers [30]. The scope of the study covers physiological effects in response to the observed medical distresses and mental health problems [31,32]. The study team formulated and implemented the pilot study in 2014 and started the full-scale study in April 2015 with funding from a research grant from the MHLW.

## VII. Discussion

### 1. Lessons learned on radiation protection and health care management

The lessons learned described in [11,12] told that nuclear operators need to make sufficient preparation to avoid similar problems of radiation protection in the case of an accident. The major points of those articles are as follows.

Sufficient measures and systematic preparation for radiological management should be ensured, including the following: (a) Assistance from the power company's corporate office or off-site support facilities outside an evacuation area is indispensable; (b) Primary contractors should independently implement exposure management operations for the employees of their subcontractors; (c) NPP operators should compile an operations manual, stockpile personal protective equipment and PADs, and prepare emergency systems and whole body WBCs.

To reduce the exposure dose, the following lessons should be shared: (a) To prevent internal exposure, it is necessary to monitor the radioactivity concentration of the indoor air of the workplace during an emergency, to stockpile and use appropriate respiratory protection and

train newcomers how to use, fit and fit-test the respirators; (b) To prevent unnecessary beta-ray exposure, liquid-proof garments should be mandatory when workers handle contaminated water; (c) To reduce external exposure, it is indispensable to develop well-prepared work plans prior to doing the work and to monitor the ambient dose rate of the work area to develop proper working procedures; (d) To promote the early deployment of remote-controlled vehicles and the utilization of tungsten shielding vests for reduction of exposure.

The lessons learned described in [15] told that the proper management and implementation of medical and health care management would require the following : (a) The government needs to assist in dispatching medical staff to an affected plant; (b) Nuclear facility operators, medical facilities and fire departments should make a prior agreement that clarifies the division of the roles played in the event of an accident and they should conduct emergency drills periodically with the full attendance of related personnel to identify and resolve problems; (c) Operators need to develop a support base at a safe distance from the plant and to prepare to develop makeshift lodgings in the case of an emergency; (d) Operators need to come to an agreement to share food stocks among closely located nuclear plants and prepare cooking equipment that can be used in the case of an electrical blackout to provide warm foods and drinks to as many workers as possible; (e) Both the government and operators should conduct long-term follow-up for emergency workers, including their health care system, medical examinations and mental health consultations.

## **2. Lessons learned on temporary increase of emergency dose limits**

In the accident, the increase and subsequent reduction in the emergency dose limit was initiated at the political level. To avoid this intervention, the lessons learned described in [22] showed that the government needs a pre-defined protocol of the process and conditions to apply or amend the emergency dose limit.

Regarding standard setting of emergency dose limits, considering external exposures, the dose limit of 250 mSv was sufficient to implement the necessary emergency operations in response to this large scale nuclear accident involving four nuclear reactors.

In the process of application of the dose limits, an application of a high-level emergency dose limit to all workers without any exception was unavoidable in the early stage of the accident. However, after the chaotic situations were resolved, based on the principle of optimization, the government should have established plural emergency

dose limits and applied them to specific work based on the urgency of the work and the ambient dose rate at the work site.

## **3. Problems to be resolved in establishing new regulations in the existing exposure situation**

### **1) Decontamination work and recovery and reconstruction work**

It was problematic to determine how radiation protection systems intended for planned exposure situations should be applied to the existing exposure situation, because there was no sufficient scientific basis. Lessons learned described in [27] told that further research and development concerning the following issues is warranted:

- (a) The relationship between the radioactivity concentrations of materials handled and the risk of internal exposure: The amended regulation requires the use of appropriate personal protective garments and masks, as well as internal exposure monitoring in accordance with exposure estimation, based on the radioactivity concentration multiplied by the density of dust at work sites. However, there were no scientific experimental data available to prove the validity of this estimation.
- (b) The relationship between the radioactive concentration of the soil and the workers' surface contamination level: Experimental and empirical studies of this relationship would make it possible to establish a standard for when to require contamination screening. Further development of this subject is warranted.

### **2) Disposal of contaminated soil and waste**

For establishing new regulations, the lessons learned described in [28] showed that two issues need further considerations. The first was the balance between the competing goals of radiation protection and ensuring work efficiency, which is necessary for the smooth disposal of 30 million tons of contaminated materials. The issue became apparent in the discussion of radiation protection in landfill operations for removed soil. The other issue was the application of regulations to conventional waste disposal facilities, which were not originally designed to handle radioactive substances.

## **4. Issues to be resolved for the epidemiological study on health effects on emergency workers**

The discussion about the basic study design of the epidemiological study described in [30] identified challenges that could not be resolved and thus required further consideration by the study researchers. The major issues included: (a) study methods and target group, (b) evaluation of cumulative doses, (c) health effects (end points), (d)

control of confounding factors, and (e) study implementation framework. Identified key challenges that required further deliberation were: (a) preventing arbitrary partisan analysis, (b) ensuring a high participation rate, (c) inquiry about the medical radiation doses, and (d) the preparedness of new analytical technology.

Based on the results of an open application, the MHLW offered the grant to the Radiation Effects Research Foundation as the study's controlling research institution. Cooperating research institutions include the National Institute of Radiation Sciences, the University of Occupational and Environmental Health, Osaka University, Jichi Medical University, Kanazawa Medical University, and the Japan Atomic Energy Agency. The research team began a preliminary study in 2014, and started the full-scale study from April 2015.

### VIII. Conclusion

“It was an unforeseen disaster.” The phrase was repeatedly used when officers of TEPCO and the government talked about the accident. Emergency response plans prepared before the accident mostly did not work. As a result, TEPCO and the government needed to reconstruct the accident management system while responding to the accident through stop-gap measures.

Conversely, the accident has offered plenty of lessons learned. The author hopes this review could explain the lessons learned for nuclear operators, governmental officials and practitioners who are responsible for radiological protection of workers and it could provide guidance regarding future preparedness for a similar accident.

### Conflict of Interest

The author has no affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this article.

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Shojiro Yasui

## 福島第一原子力発電所事故に係る緊急作業及び 除染作業における放射線防護に関する教訓

安井省侍郎

厚生労働省安全衛生部

### 抄録

本総説は、2011年に発生した東京電力福島第一原子力発電所に係る緊急作業及び除染作業における放射線防護に関する学術論文をレビューしたものである。これら論文は、2012年から2017年に出版され、本事故の経験に基づく教訓を明らかにするとともに、同様の事故に対する準備に関する指針を提供したものである。本事故については多数の学術論文が報告されているが、作業員の放射線防護に関するものは数少ない。本総説でレビューされた論文は、信頼できる一次情報に基づき、放射線防護上で発生した問題点について詳細な情報を提供しているものである。本総説は、論文を時系列に整理するのではなく、以下の4つの大きなトピック－(a)緊急作業における放射線防護と健康管理、(b)緊急作業後の対応、(c)除染作業に関する新たな法令の制定、(d)放射線の健康影響に関する疫学調査－に分類してレビューを行った。

キーワード：放射線防護，福島第一原子力発電所事故，緊急作業