An Overview of Progress in Environmental Research on Radioactive Materials Derived from the Fukushima Nuclear Accident

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Abstract

The Fukushima Daiichi Nuclear Power Station accident caused radioactive pollution of various environmental media. In the face of a perceived unprecedented environmental issue, many organizations in the public and private sectors and academia have carried out multifaceted research to help restore the environment of affected areas starting from immediately after the accident. The national and local governments have conducted off-site cleanup, treatment of contaminated waste and other endeavors. These challenging efforts need to be further augmented for the environmental regeneration of Fukushima Prefecture and other affected areas.

Key words: environmental research, Fukushima accident, radioactive release, radiological contamination

1. Introduction

Enormous amounts of radioactive materials were released into the environment during the Fukushima Daiichi Nuclear Power Station accident (below, the Fukushima accident). Radioactivity released into the atmosphere and ocean was transported and deposited widely not only in Fukushima Prefecture but also in neighboring prefectures. This resulted in the radioactive pollution of inland and sea water; soil; ecosystems; agricultural, forestry and fisheries products; sewage and water treatment sludge; waste incinerator ash; and various other environmental media (Fig.1). In the face of perceived unprecedented environmental consequences, many organizations in the public and private sectors and academia have carried out multifaceted research to help restore the environment of the affected areas, starting from immediately after the accident. On the public administration side, the national and local governments have conducted off-site cleanup, treatment of contaminated waste and other endeavors. The present paper gives an overview of progress in environmental research on the radiological contamination derived from the accident, mainly by introducing research activities carried out by the Japan Atomic Energy Agency (JAEA) and National Institute for Environmental Studies (NIES).

2. The Fukushima Accident and its Environmental Impacts

2.1 The Fukushima Accident

More than five years have passed since the Great East Japan earthquake and subsequent tsunami of the 11th March 2011 devastated the entire northeastern coastal region of Japan. Despite major losses of life and destruction of infrastructure, the focus of environmental concerns following this event was the series of accidents at TEPCO's Fukushima Daiichi Nuclear Power Station which led to meltdowns of the reactor cores in Units 1 to 3 and the extensive release of radioactive materials.

Units 1 to 3 were boiling water reactors (BWR) and were successfully scrammed prior to loss of power. A delay thus occurred before the meltdowns, allowing some of the most active, short-lived radionuclides to greatly diminish through significant decay. The related Unit 4 contained no fuel then, and two newer units at the site were under cold shutdown for planned maintenance at the time. The earthquake did, however, disrupt off-site power, and the on-site generators switched on to provide the required cooling for Units 1 to 3 and the fuel storage ponds associated with Units 1 to 4. The subsequent tsunami, however, was far larger than had been planned for and over-topped the defences, flooding all the

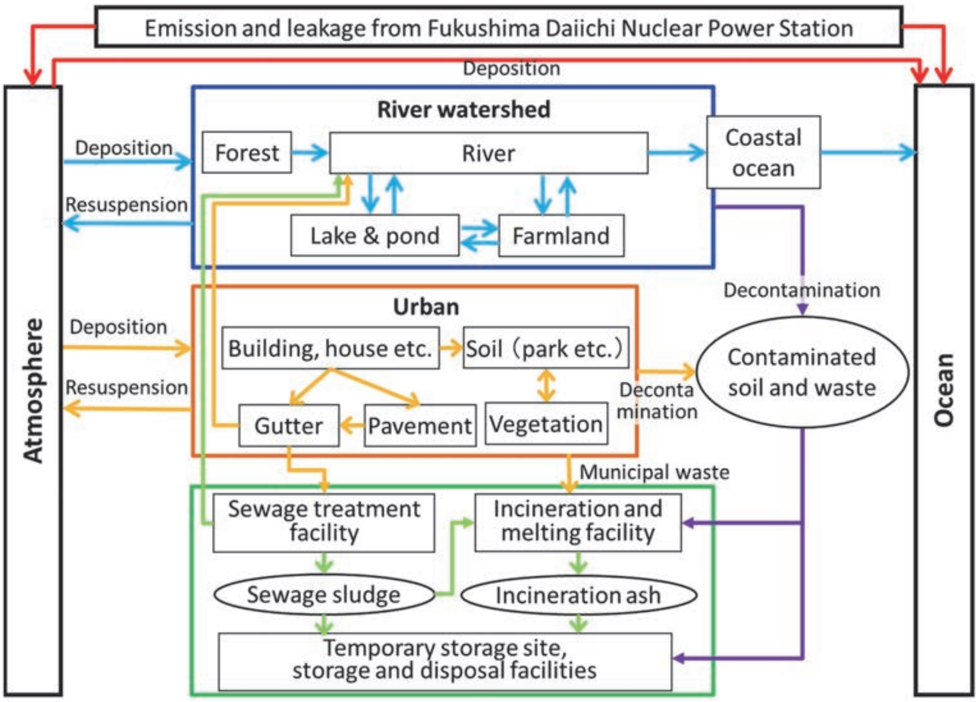

Fig. 1 Schematic diagram of flow of radioactive materials in multimedia environment and target area of environmental restoration research.

emergency generators for Units 1 to 4. The resulting total blackout extended beyond the lifetime of the emergency batteries, leading to reactor core damage.

Core damage resulted in hydrogen formation, which in turn led to explosions in Units 1 and 3 and also the defueled Unit 4 as a result of hydrogen leakage from Unit 3 flowing in through shared ductwork with Unit 4. The background to the accident and its causes and progression are described in detail elsewhere (e.g., NAIIC, 2012). It should be emphasised, nevertheless, that due to loss of power and damage to instrumentation, there are still considerable uncertainties associated with interpretations of how the accident proceeded, which are reported on in updates provided by the Tokyo Electric Power Company (TEPCO) (e.g., TEPCO, undated).

2.2 Radioactive Releases from the Fukushima Accident and Regional Fallout of Volatile Radionuclides

The reactor pressure vessels and primary containment had to be vented on several occasions due to excessive pressure build-up within, releasing radioactive gases from stacks on site. These gases also leaked into the secondary containment, resulting in the major explosions that damaged the reactor buildings of Units 1, 3 and 4. Core damage also caused the Unit 2 containment vessel to be breached. These events released a significant quantity of radioactive materials into the environment. The radionuclides involved were predominantly noble gases and more volatile radionuclides, of which iodine (I) and cesium (Cs) isotopes were the most radiologically significant. Although the values are uncertain probably by a factor of about 2, there is a reasonable consensus that effectively the entire inventory of noble gases was released—equivalent to about 10 exabecqerels (10^{19} Bq) of short-lived (5-day half-life) xenon (Xe)-133 (Ministry of Economy, Trade and Industry (METI), 2011). Releases of volatile I were lower, with the key safety-relevant isotope, I-131 (8-day half-life), about two orders of magnitude less, ~ 200 petabecqerels (2×10^{17} Bq).

Radioactive releases from Fukushima Daiichi were due to specific events (venting, explosions) and the fallout patterns of the radionuclides were complex and depended on the wind strength and direction and whether it was raining or snowing at the time. The quantity and characteristics of the fallout differed considerably depending on whether "dry" or "wet" deposition occurred and its subsequent behavior depended on the local topography and land use. Although initial concerns focused on radioiodine with an eight-day half-life, cesium isotopes now dominate contamination outside the Fukushima Daiichi site, especially Cs-137 (30-year half-life), with rapidly decreasing activities of Cs-134 (2.1-year half-life).

Less volatile radionuclides would also have been released to some extent, possibly predominantly as aerosols and maybe associated with the hydrogen explosions. The radiological activities of such releases have greater uncertainties, but have been estimated to be about 1 percent of the Cs-137 activity for fission products like strontium(Sr)-90 and a further four orders of magnitude lower for actinides like plutonium(Pu)-238 (METI, 2011). Even if estimated releases are accurate, aerosols would be expected to be less stable in air and more likely to fall out locally. This is consistent with a limited number of off-site measurements indicating Sr-90 activities of up to four orders of magnitude lower than those of Cs-137 (Steinhauser *et al.*, 2013) and extremely low levels of Pu isotopes, which are at a similar level to residual fallout from atmospheric bomb testing and are maybe indicative of transport by dust (e.g., Shinonaga *et al*., 2014).

Ideally, in a major accident releasing volatiles, stack measurements of the source term are combined with meteorological data to predict potential contamination, which is then refined by regional radiation monitoring networks. The Fukushima Daiichi releases, however, were poorly defined and much of the monitoring network was knocked out by the earthquake/ tsunami. Aerial surveys of gamma doses thus played a critical role in mapping contamination, calibrated by point analysis on the ground where access was possible. The data were initially used to run the fallout model “SPEEDI” in inverse mode in order to quantify releases.

The resulting fallout maps clearly show the highest activities in a zone to the northwest of Fukushima Daiichi. This information was initially used to guide evacuation, which was difficult due to damaged transport infrastructure. Logistics were further complicated by the scale of evacuation due to tsunami damage, which affected a larger area than radioactive contamination.

Later, contamination maps were used to plan decontamination. Local dose rates in air were manually measured at several thousand locations and soil profiles were sampled to build up a detailed 3D understanding of both the initial fallout and its subsequent redistribution. Most soil profiles of Cs concentration show a marked decrease with depth: almost the entire inventory is still contained within the upper five centimeters (Nuclear Regulation Authority (NRA), 2016).

In Fukushima Prefecture, vegetation is an important factor, as about 70 percent of the land area is forested. The extent of fallout capture depends on the size and type of tree (deciduous or evergreen) and the subsequent distribution of fallout between foliage, leaf litter and soil varies significantly with time for different kinds of forests in different topographic settings.

2.3 Comparison with the Chernobyl Accident for Contamination Context

It should be clear that the releases from Fukushima Daiichi differed highly in nature from those from the Chernobyl accident. Despite both accidents being assigned to the highest category (7, “severe accident”) of the IAEA International Nuclear and Radiological Event Scale (INES), the quantity and nature of the resultant contamination differed greatly. Chernobyl Unit 4 experienced a power surge during a test shutdown, the core exploded and exposed the graphite moderator, which caught fire and burned for about two weeks. A large proportion of the total inventory of radioactive materials in the core was dispersed outside the reactor site in the form of fine particulates, aerosols and volatiles in an atmospheric plume, which spread throughout Europe. Extremely high radiation fields and local contamination caused extensive (occasionally lethal) radiation sickness amongst the firefighters and other emergency workers who stabilized the remaining core and collected the most highly contaminated debris that was scattered about the vicinity (the remaining three reactors at this site continued to operate after the accident). There was also evidence of acute contamination of local populations, especially in the nearby town of Pripyat — which was not evacuated until more than 24 hours after the accident.

The fact that the units were scrammed prior to loss of power and that further time delays occurred before the meltdowns in the Fukushima Daiichi case allowed significant decay of the shortest-lived radionuclides, which contribute most to early radiation fields. Even more importantly, the primary containment at Fukushima Daiichi was effective in greatly limiting releases of even volatile radionuclides and ensured negligible loss of the most toxic, alpha-emitting actinides. Thus, although radiation levels were very high within the damaged reactors, exposure to workers was limited and thus helped avoid any cases of acute radiation sickness. Releases of noble gases such as Xe-133 would have exceeded those at Chernobyl simply due to the larger power of the three Fukushima Daiichi units (Stohl *et al*., 2012). Xenon-133, however, has little radiological significance as it is effectively dispersed in the atmosphere and does not fall out or concentrate in the biosphere. Despite the larger reactor power, the total release of non-noble gas isotopes was about 10 percent of that from Chernobyl (Steinhauser *et al*., 2014) and the impact of releases was further reduced by the fact that most of the releases (~80%) were dispersed over sea rather than land (e.g., TEPCO, 2012). After the decay of radioiodine, the remaining radionuclides in the off-site environment are dominated by radiocesium, with total activity decreasing significantly over time due to the decay of the shorter-lived, higher dose contributor Cs-134.

This contrasts with the exclusion zone around Chernobyl, which is completely different from Fukushima in that it contains the entire spectrum of radionuclides explosively released from the reactor core and subsequent fires.

With regard to contamination, therefore, the immediate zone around Chernobyl is a poor analogue to Fukushima Prefecture. If anything, the distant fallout of volatile radionuclides in Fenno-Scandinavia and the uplands of northern England and southern Scotland would have much more similarity to Fukushima (with a few exceptions of higher Cs deposition), with the latter also having a more analogous climate (e.g., temperate coastal with significant seasonal storm events). In terms of fallout in the vicinity of a nuclear accident, the Windscale fire of 1957 is more similar to Fukushima than Chernobyl. Indeed, even though rated only as INES 5, the radiotoxicity of the Windscale releases may well have been higher than those of Fukushima Daiichi due to the highly toxic polonium(Po)-210 also released (Garland & Wakeford, 2007).

In absolute terms, the levels of radiocesium contamination in much of the evacuated zone are low and comparable to those resulting from the 1957 Windscale fire or the distant fallout from Chernobyl in Fenno-Scandinavia, the UK and the southern European Alps.

In these other examples, there were some restrictions on use of local foodstuffs but generally no attempt at decontamination. As in Fukushima, air dose rates dropped at a rate greater than that expected by radioactive decay alone, due to wash-off of soil-bound radionuclides and redistribution deeper into the soil column. The aim of regional decontamination is to enable the rapid return of evacuees and provide assurance that they can resume their previous lifestyles without health concerns for themselves or their future generations.

2.4 Governmental Efforts after the Accident

After the Fukushima accident, the government of Japan as well as local governments carried out measures for handling environmental contamination by radioactive materials emitted from the Fukushima Daiichi Nuclear Power Station. The "Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District - Off the Pacific Ocean Earthquake that Occurred on March 11, 2011" (hereinafter referred to as the "Act") was approved and enacted in August 2011. This Act was established to address the urgent issue of promptly reducing the impact of environmental contamination on human health and the living environment from radioactive materials released by the Fukushima accident associated with the Great East Japan earthquake. It stipulates that the basic principles regarding the handling of environment pollution caused by radioactive materials be determined in a cabinet meeting, and that monitoring and measurement be carried out to determine the status of environmental contamination by accident-derived radioactive materials. It also establishes procedures and other matters relating to the disposal of wastes and the decontamination of soil, etc., contaminated by radioactive materials.

Under the Act, the Minister of the Environment (MOE), giving due consideration to the degree of contamination, designated areas (Special Decontamination Area; including eleven municipalities in Fukushima Prefecture; within 20 km of Fukushima Daiichi or having over 20mSv/ y of additional annual dose) where it was necessary for the national government to develop plans for decontamination measures and then carry out these measures in these areas. In addition, the Ministry of the Environment (MOE) has designated areas (Intensive Contamination Survey Area) other than the Special Decontamination Area, where states of contamination are expected not to conform to requirements (air dose rates of 0.23μSv/h or less). As for zones recognized as not conforming to the requirements through investigation into the state of contamination in the Intensive Contamination Survey Area, the local governor develops plans designating matters regarding measures for decontamination. Based on these plans, the national government, prefectural governor, mayor of the municipality, etc. carry out decontamination measures. As of the end of September 2016, decontamination had been completed in the area based on the initial plans in the seven municipalities of the Special Decontamination Area and was progressing in other municipalities.

In Fukushima Prefecture, large quantities of contaminated soil and waste have been generated from decontamination activities. Currently, it is unclear what methods will be adopted for the final disposal of such soil and waste. Hence, it has been necessary to establish Interim Storage Facilities (ISF) to manage and store the soil and waste safely until final disposal becomes available. The MOE in October 2011 presented its basic philosophy under the Act, titled "Basic Philosophy on Interim Storage and Other Facilities Required for the Handling of the Environmental Pollution from Radioactive Materials Associated with the Accident at the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company." This Basic Philosophy on Interim Storage includes the flow schematics for treatment of wastes and a roadmap towards the installation of interim storage facilities in Fukushima Prefecture, where significant amounts of removed soil and other wastes are anticipated to be produced. According to the present plan, two kinds of materials were generated in Fukushima Prefecture: (1) soil and waste (such as fallen leaves and branches) generated from decontamination activities, which have been stored at temporary storage sites, and (2) incineration ash with radioactive concentrations exceeding 100,000 Bq/ kg, which will be stored at the ISF. During 2015–2016, pilot transportation of soil and waste around of 1,000 m^3 each from 43 municipalities in Fukushima Prefecture to the ISF was completed.

For disposal of wastes contaminated by radioactive materials, the MOE developed a plan regarding disposal of "waste within the management area" (former Restricted Areas and Deliberate Evacuation Areas) of Fukushima Prefecture. In addition, the MOE designated wastes (specified wastes) which are located outside the management area and whose state of contamination by radioactive materials exceeds 8,000 Bq/kg. Disposal of the specified waste and the waste in the management area is carried out by the national government on the basis of these standards. For the management area, the MOE is conducting contaminated waste disposal based on its "Treatment plan for waste within the management area." On the other hand, the specified waste generated in the areas outside Fukushima Prefecture will be treated in each prefecture based on the MOE Basic Philosophy.

The specified waste generated in Fukushima Prefecture and the wastes in the countermeasures area are planned to be transported to the ISF for wastes with over 100,000 Bq/kg and to the existing controlled landfill site in Fukushima Prefecture for wastes with less than or equal to 100,000 Bq/ kg. Combustible portions (such as sewage sludge, rice straw, compost, etc.) of the specified waste generated in Fukushima Prefecture is incinerated for stabilization and waste volume reduction.

In addition to measures related to decontamination of soil and disposal of contaminated wastes, which are the most extensive efforts against radiological contamination by the government, environmental radiation monitoring based on the comprehensive radiation monitoring plan (Monitoring Coordination Meeting, 2016), collection and analysis of information on the effects of environmental radiation on natural ecosystems, and public communication on decontamination and radiation have been conducted by the government. Furthermore, the government supports health management in Fukushima Prefecture, including through grants to the Fukushima Residents Health Management Fund. One of the ways Fukushima Prefecture has been utilizing those grants is to conduct the Fukushima Health Management Survey (Fukushima Medical University, 2017).

3. Progress in Environmental Restoration Research

3.1 Overview of Environmental Restoration Research in Japan

Many different research institutions, government agencies and researchers are studying the radioactive materials released into the environment as a result of the Fukushima accident. This research covers methods for measuring radioactive materials and monitoring the environment (e.g., Saito *et al*., 2016); dynamics and impacts of these substances in the environment (e.g., Hayashi, 2016; Iijima, 2016; Imaizumi *et al*., 2016; Morino & Ohara, 2016, Saito, 2016; Tamaoki, 2016, Yaita *et al*., 2016); decontamination, treatment and disposal of waste (e.g., Endo, 2016; Kawase, 2016; Kuramochi *et al*., 2016); and many other fields. The researchers carrying out this work are specialists in many different academic fields.

Japanese scientists and scientific organizations need to tackle the serious environmental problems posed by Fukushima Daiichi-derived radioactive contamination head on. From immediately after the accident, many scientists dedicated themselves to ascertaining the status of radioactive contamination in soil, forests, the ocean, organisms and ecosystems. Research has been carried out on the volume and spread of radioactive materials released into the atmosphere and ocean. The researchers involved have shown tremendous mettle in the face of such a serious environmental crisis, and their actions have demonstrated the true value of researchers in environmental and nuclear research fields. These initial activities began spontaneously as small-scale grassroots initiatives launched by individual researchers and laboratories that gradually became more organized. Conducted at a time when Japanese society was enveloped in gloom, these forward-looking endeavors have performed a significant role in the reconstruction of the affected areas. However, given the extent and seriousness of the environmental contamination involved, overall research efforts still lack intensity, and much remains to be done. One of the key shortcomings is the paucity of interdisciplinary research efforts.

Developing an accurate overall understanding of all this research is not easy, but the recommendation published by the Science Council of Japan (Science Council of Japan, 2014) serves as a useful panoramic overview. It includes a chart titled “Movements of radioactive materials between media, and main research bodies” that lists the MOE; Ministry of Education, Culture, Sports, Science and Technology (MEXT); Nuclear Regulatory Agency; Fukushima Prefecture; research organizations (JAEA, NIES, Meteorological Research Institute, Central Research Institute of Electric Power Industry, National Institute of Radiological Sciences, Japan Agency for Marine-Earth Science and Technology, National Agriculture and Food Research Organization, National Institute for Agro-Environmental Sciences, Forestry and Forest Products Research Institute, Fisheries Research Agency, National Institute of Public Health, and National Institute of Health Sciences); universities (University of Tsukuba, University of Tokyo, Tokyo University of Marine Science and Technology, Ibaraki University, Tokyo Institute of Technology, and others); and TEPCO. Large-scale interdisciplinary research projects are also underway, such as the MEXT Grant-in-Aid for Scientific Research on Innovative Areas’ “Interdisciplinary Study on Environmental Transfer of Radionuclides from the Fukushima Daiichi Nuclear Power Plant Accident” (ISET-R) project (Available at http://www.ied.tsukuba.ac.jp/hydrogeo/isetr/ISETRen/indexEN.html; Fig. 2).

In the spring of 2016, the Centre for Environmental Creation opened in Fukushima Prefecture and an inter-institutional research system for environmental restoration and creation was established in collaboration with the Fukushima prefectural government, JAEA and NIES. In the future, the Centre is expected to become a research network hub for many domestic and international organizations involved in addressing the Fukushima accident.

3.2 JAEA Mission to Enhance Fukushima Environmental Resilience

As Japan’s sole comprehensive research and development institute in the field of nuclear energy, JAEA makes it a mission to contribute to the welfare and prosperity of society through nuclear science and technology. One of the top priority fields for achieving JAEA’s mission is enhancing off-site environmental resilience in Fukushima by fully applying JAEA’s scientific and technical expertise, based on the Basic Policy for Recovery and Reconstruction of Fukushima (Reconstruction Agency, 2012).

To enhance Fukushima environmental resilience, the

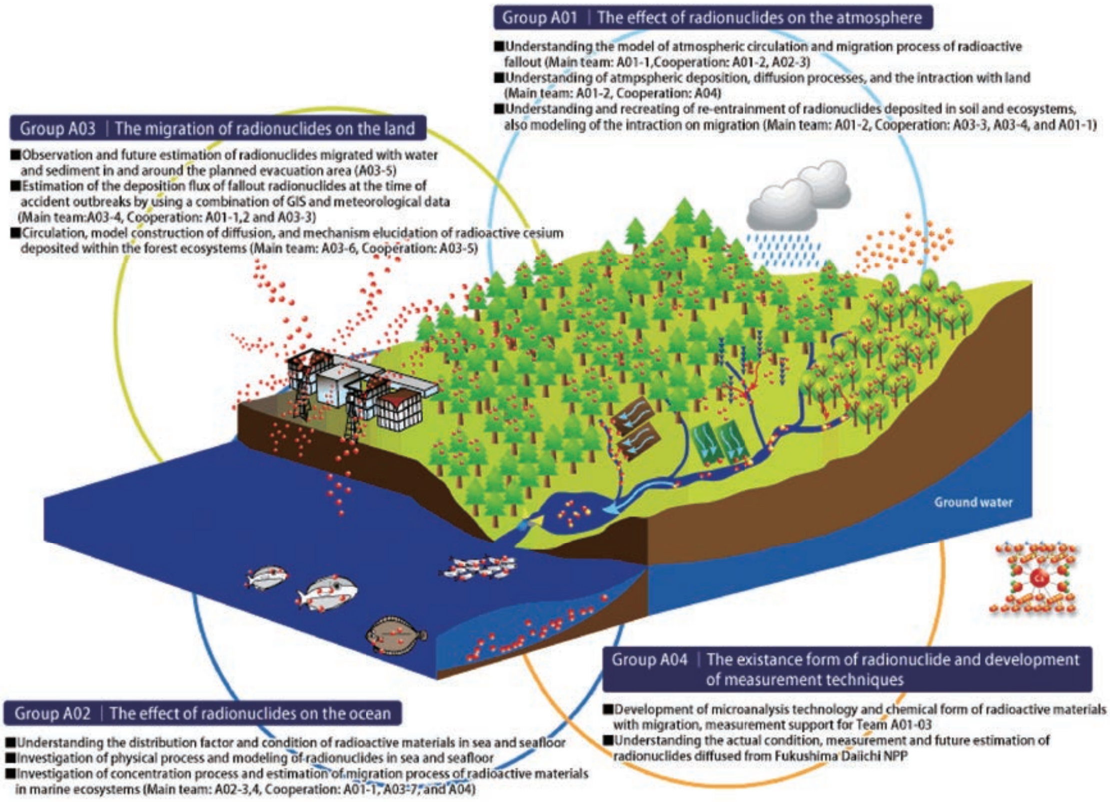

Fig. 2 Research outline of "Interdisciplinary Study on Environmental Transfer of Radionuclides from the Fukushima Daiichi Nuclear Power Plant Accident" (ISET-R) project (http://www.ied.tsukuba.ac.jp/hydrogeo/isetr/ISETRen/indexEN.html).

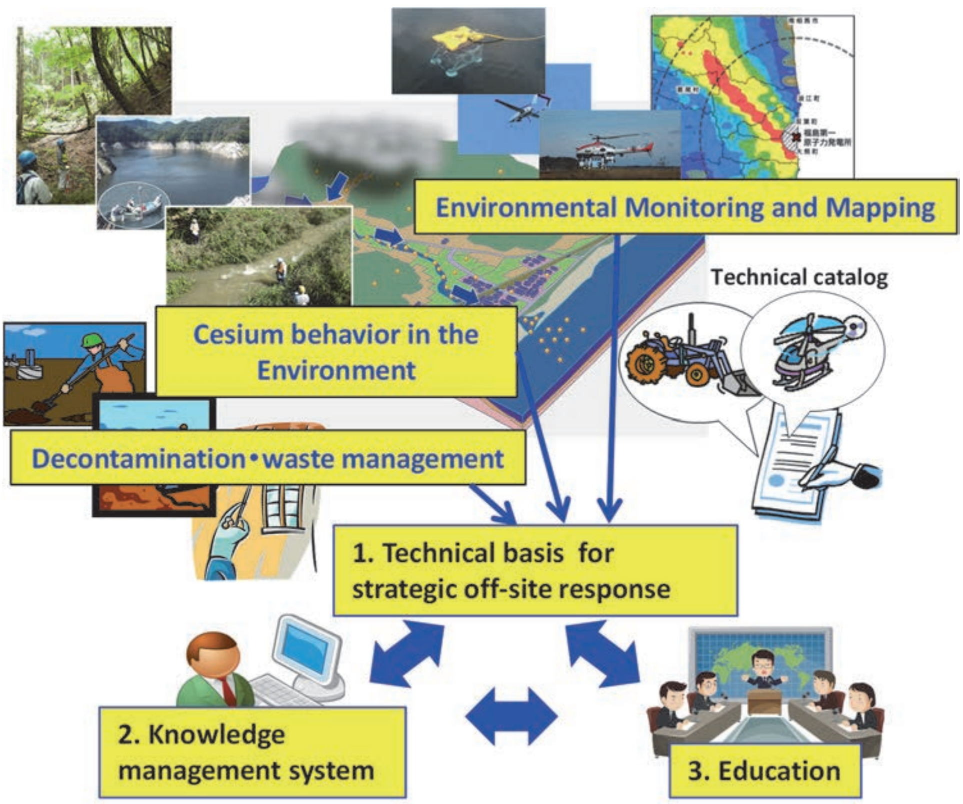

Fig. 3 JAEA's Research and development for Enhancing Fukushima Environmental Resilience.

needs for better scientific and technological capabilities to assess, predict, and minimize the impact of radiological contamination must be addressed and the understanding of radiation and associated risks to the public must be enhanced. It reflects the role of JAEA in research associated with both decontamination of contaminated areas and natural contamination migration processes in non-remediated areas (Fig. 3).

JAEA is working with a number of Japanese and international organisations and research institutes in research on decontamination. This has proceeded in a stepwise fashion. First, JAEA tested technology required at two locations outside the evacuated zones where contamination was low. This allowed alternative approaches for measuring contamination, removing it and handling the resulting wastes to be developed and tested in a representative range of agricultural and rural settings. This work formed the basis of a larger-scale test of the technology when JAEA contracted engineering company consortia to carry out decontamination in a wider range of settings, including urban and industrial areas and locations with higher contamination levels (Decontamination Pilot Project). Novel decontamination approaches and the potential for optimisation of these decontamination approaches were also investigated (e.g., Kawase, 2016).

Currently, contractors working for the MOE and local municipalities are carrying out regional decontamination. JAEA supports such work predominantly through development of monitoring technologies and improved understanding of the long-term behaviour of radiocesium in this setting.

Environmental monitoring and mapping to define boundary conditions in terms of the distribution of radioactive materials and resultant doses, guides the subsequent response. Radiation protection considerations set constraints, with approaches developed to estimate doses to different critical groups and set appropriate dose reduction targets.

Since the Fukushima accident, large-scale environmental monitoring activities have been successfully implemented and enormous amounts of environmental monitoring data have been accumulated, which makes it possible to analyze precisely the regional and temporal characteristics of the state of contamination around the Fukushima Daiichi Nuclear Power Station site (e.g., Saito *et al*., 2016).

The radionuclide deposition densities obtained in the Fukushima mapping project were utilized in the International Commission on Radiation Units and Measurement (ICRU) 2013 Report as the basic data for evaluating exposure doses to the public in Japan. The IAEA extensively discussed the features of radionuclide distributions in the terrestrial environment based on the data obtained in the mapping project together with aerial monitoring data (IAEA, 2015a). Further, decreasing of air dose rate trends under various conditions were discussed on the basis of air dose rates repeatedly measured by different methods in the mapping project (IAEA, 2015b).

Air dose rates in environments related to various human activities were found to decrease much faster than would result from physical decay; while, in pure forest, the air dose rate reduction was close to that from physical decay. On the basis of a statistical analysis of large amounts of data obtained, an empirical model for predicting air dose rates was developed.

JAEA developed a new database aggregating various monitoring data obtained by national projects, local governments and research institutes (JAEA, 2016). The aggregated data are presented in several different ways such as numerical data, maps and graphs indicating time-trends together with some simple analysis softs.

Decontamination activities have been generating huge volumes of contaminated soil and vegetation waste, which must be managed safely and cost-effectively. In particular, future reuse of the soil in construction is an important option, if constraints in terms of allowable organic and clay content can be managed. As Cs is very strongly bound to clay minerals, use as ballast or infill might provide options for both reducing the total costs and also minimizing the environmental impact based on undestanding Cs sorption-desorption behaviours in clay minerals for waste reduction.

Sorption behavior of Cs in clay minerals has been studied by microscopic analysis supported by molecular orbital calculation to provide the newest information about identification of sorption sites, incorporation mechanisms and stabilization mechanisms, which facilitate understanding of how limited clay minerals such as weathered biotite and ferruginous smectite concentrate radioactive Cs. These results are informative for developing volume-reduction processing methods such as classification of soil particles, chemical and thermal treatments (Yaita *et al*., 2016).

Assessment of the natural behavior of contaminating radionuclides and their mobility in the environment is now focused almost entirely on radiocesium (project termed F-TRACE), evaluating the extent of required management of forested areas that cannot be simply decontaminated, developing quantitative models of the natural self-cleaning processes that eventually transport radioactive materials through river systems into coastal marine environments and assessing the ability of control measures to minimize environmental impacts (Iijima, 2016). Here, the impact of natural mobility in terms of self-cleaning/ re-concentration in cleaned areas is evaluated, along with possible actions to modify such transport or manage potential areas of radiocesium accumulation.

A large fraction of the radiocesium inventory captured by forest canopies has gradually migrated to the ground through rain wash-off and leaf fall and transited within the litter layer, eventually being captured (in most cases) by the forest soil layer underneath. Catchment-scale movement of Cs-loaded suspended sediments in the aquatic environment has been observed through streams, rivers and estuaries into the coastal marine environment, accounting for trapping of Cs in ponds, lakes and dams, including its transfer back to the terrestrial environment (mainly flood plains during periods of high river flow).

Overall, the F-TRACE project and related studies are developing a comprehensive knowledge base on Cs transport mechanisms in specific Fukushima environments. This can form the basis of rigorous future dose forecasts and plans for countermeasures required to reduce such doses

Many trials for evaluating exposure doses to the public have been performed since the Fukushima accident. It has been shown that doses to the public from external exposures have been more significant than those from internal exposures. This is thought to be due to restrictions on consumption of contaminated foods and drinks being introduced rather promptly after the accident. Annual additional external doses to Fukushima residents in recent years are all estimated to be within several mSv. It is expected that residents will not receive large additional external doses after they return to the areas from which the evacuation orders will be lifted (Saito, 2016).

Extensive efforts have been made to communicate such work to the public, although it is clear that even more could be done here. Although evacuees are already returning to some of the remediated areas, decontamination of the most highly contaminated areas near Fukushima Daiichi will take a long time and may require effective technical communication to be maintained over that period, with the tacit knowledge of the multidisciplinary teams involved. Thus modern knowledge management tools will be needed. A version of the communication platform (Cleanup Navi; JAEA, undated) is available in English and information has been summarized in JAEA technical reports (JAEA, 2015a, 2015b; Miyahara *et al*., 2015) and communicated during two international workshops (JAEA, 2013, 2014).

3.3 NIES Research for Contributing to Environmental Recovery and Rebuilding

NIES is Japan's only research institute that undertakes a broad range of environmental research in an interdisciplinary and comprehensive manner. Since its inception, NIES has played a vital role in solving a variety of environmental problems. NIES has undertaken disaster-related environmental research as an extremely important field since the Great East Japan earthquake. It has thereby contributed to the recovery and rebuilding of the environment in the devastated areas, based on the Basic Policy for Recovery and Reconstruction of Fukushima (Reconstruction Agency, 2012).

Since immediately after the Great East Japan earthquake struck on March 11, 2011, NIES has leveraged its rich experience in environmental research to investigate environmental issues resulting from the earthquake, tsunami and Fukushima accident, positioning this research as the discipline of "Environmental Emergency Research." NIES shifted these research activities into high gear in the second half of fiscal 2011, focusing in particular on developing technologies and systems for the proper treatment and disposal of disaster waste and waste contaminated with radioactive materials (contaminated waste research); on elucidating and predicting the behavior of radioactive materials in the environment through measurement and simulation; and on assessing human radiation doses and impacts on organisms and ecosystems (multimedia environmental research; Fig. 4).

In its contaminated waste research (on waste materials and soil contaminated with radioactive materials), NIES is conducting field surveys, basic experiments, field verification tests, systems analysis and other research on the development, refinement and evaluation of disposal process control technologies and systems (temporary storage, volume reduction through incineration, reuse, interim storage, final disposal, etc.) (e.g., Kuramochi *et al*., 2016; Endo, 2016), and on methodologies for the long-term management and eventual dismantling and removal of related treatment facilities based on the fundamental physical properties and behavior of the radioactive materials. NIES is also studying measurement, analysis and monitoring technologies; radioactive material management strategies; stocks and flows in waste disposal/resource recycling systems; and risk communication methods. NIES is contributing to the appropriate treatment and disposal of contaminated waste by collating and providing its research findings to the MOE and other bodies.

For multimedia environment research, NIES is conducting research that combines multimedia environmental monitoring, environmental dynamics measurement and environmental data analysis to ascertain and predict future trends in the status of contamination and environmental dynamics for soil, forests, rivers, lakes and coasts of watersheds suffering various degrees of contamination with radioactive materials (e.g., Hayashi, 2016; Imaizumi *et al*., 2016; Morino & Ohara, 2016). NIES's research findings in this area are providing scientific support for the environmental recovery measures being implemented by national and local governments. NIES has developed a method for wide-area estimation of human radiation doses and is using it to ascertain exposure levels. NIES is also researching the impacts of radioactive materials on organisms and ecosystems (e.g., Tamaoki, 2016), and has embarked on research into changes in ecosystems resulting from human evacuation and decontamination.

In addition to this Environmental Recovery Research Program, NIES is implementing two other research programs— the Environmental Renovation Research Program for supporting disaster area reconstruction and sustainable community development, and the Environmental Emergency Management Research Program for leveraging the experience and lessons of the Great East Japan earthquake to prepare for future disasters from an environmental perspective.

NIES is committed to supporting the reconstruction

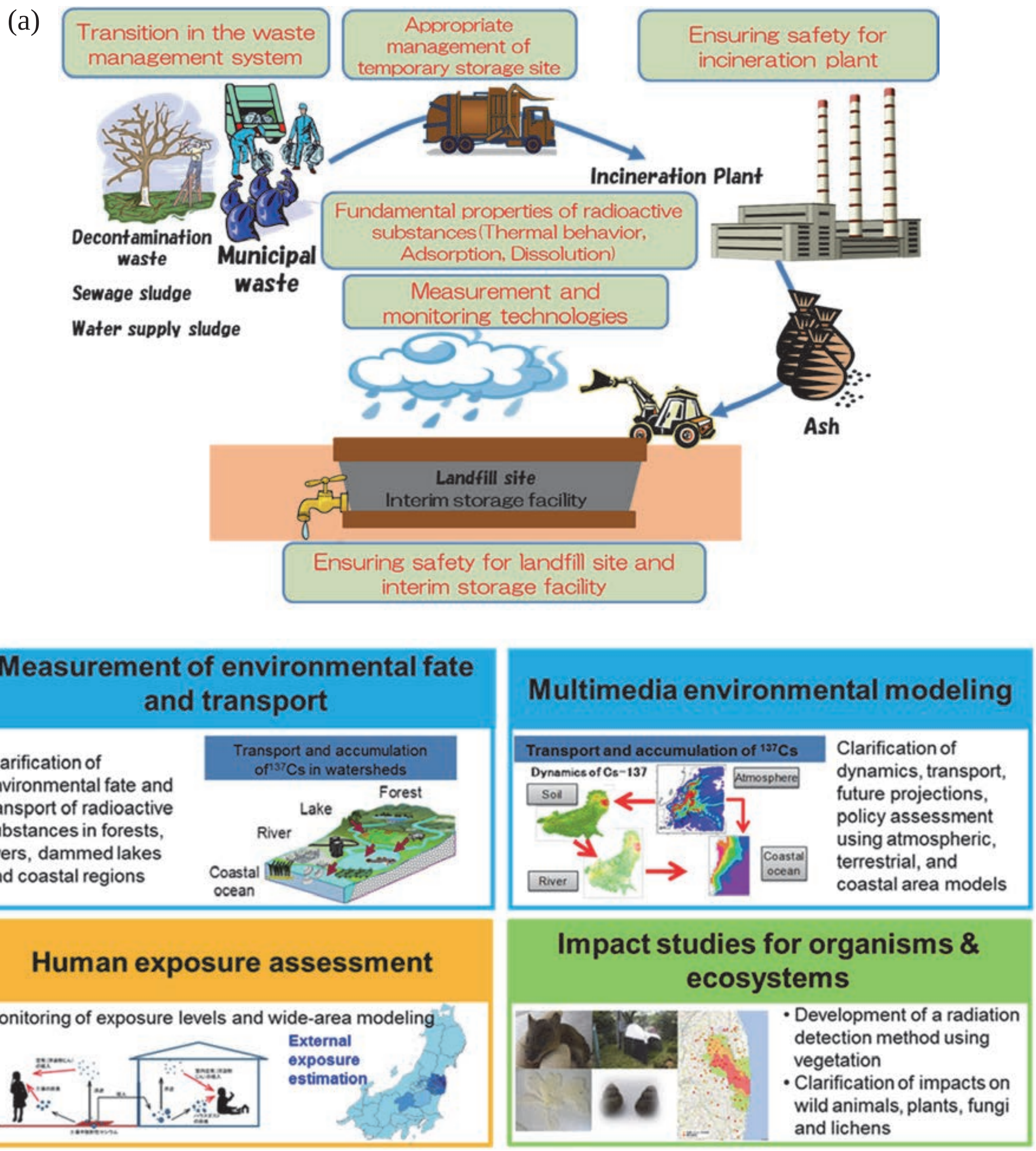

Fig. 4 NIES's research activities for contributing environmental recovery and renovation: Research on the treatment and disposal of radioactively contaminated wastes (a) and the movements and impacts of radioactive substances in the environment (b).

and environmental recovery of areas affected by the Great East Japan earthquake disaster through research and technology within the framework of these three Environmental Emergency Research programs, and to contributing to the creation of sustainable technological and social systems equipped to withstand future disasters. These research activities have been summarized in English-language booklets (NIES, 2015, 2016a, 2016b).

4. Summary

Six years have now passed since the Fukushima Daiichi Nuclear Power Station accident. Many research organizations such as JAEA, NIES, universities and private sector organizations have carried out environmental research for contributing to environmental restoration in Fukushima Prefecture and other areas. We are still looking, though, for ways of resolving the issue of environmental contamination by radioactive materials released as a result of the accident. Radiological contamination is a new kind of pollution that constitutes an extremely serious environmental problem from various perspectives, including its spatio-temporal spread, the scale of its impact on human health as well as on that of other organisms and ecosystems, and the fact that diverse environments have been contaminated. This issue can only be resolved by marshaling the many different scientific capabilities available in Japan while also enlisting the cooperation of other nations. Further research and governmental efforts will be needed.

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