Report

Progress and Challenges in Research and Studies on Environmental Contamination Caused by the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station

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Subcommittee on Nuclear Safety

Committee on Comprehensive Synthetic Engineering

Science Council of Japan

This Report is issued in accordance with the outcome of the deliberations of the Subcommittee on Nuclear Safety of the Committee on Comprehensive Synthetic Engineering, Science Council of Japan. The Report is based on the results of deliberations by the Working Group on Environmental Contamination Investigation of the Subcommittee on Nuclear Safety of the 24th term, which succeeded the Working Group on Environmental Contamination Investigation of the Subcommittee on Nuclear Accident Response of the 23rd term.

Disclaimer: This English version does not reflect updates such as the UNSCEAR 2020/2021 report since the publication of Japanese version, in order to keep strict identity with the original contents.

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Secretary	Haruo	Tsuruta		Visiting Researcher, Remote Sensing Technology Center of Japan
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Executive Summary

1 Background

In April 2011, the Subcommittee on Nuclear Accident was established in the Comprehensive Synthetic Engineering Committee of the Science Council of Japan. The activities of both the accident investigation and environmental contamination investigation Working Groups established in the Subcommittee were continued in the 22nd and 23rd terms, and were succeeded by the Subcommittee on nuclear safety in the 24th term. As for the environmental contamination investigation, a report on the comparison of model calculation results on the transportation and deposition process of radioactive materials was compiled in the 22nd term. Subsequently, the Working Group inherited the activities of the informal working group on data archives established in the 22nd term and established a new informal working group on exchange of accident and environmental information in the 23rd term. This report summarizes these activities and others related to the investigation of environmental contamination from accidents that the Working Group has taken the lead in.

2 Current status and problems

About nine years have passed since the accident at the TEPCO's Fukushima Daiichi Nuclear Power Station caused a massive release of radioactive materials into the environment, spreading contamination to various media. During this time, research and studies have been conducted on the dynamics of radioactive materials in the environment, impact assessment, decontamination, waste treatment, and other countermeasures, and the results have been accumulated. It is not easy to grasp the whole picture of the research on environmental contamination, as it is carried out by many organizations and involves a wide range of related academic fields and associations. In contrast to reports by international organizations, there have been no systematic reports by domestic organizations, making it difficult to get a bird's eye view of the research on environmental contamination.

3 Contents of the report

This report provides an overview of the scope of research and studies on environmental contamination, and the actors engaged and funding sources provided for them. Then, we summarized the progress and challenges of research in each of the major fields, and identified common issues and lessons learned. We also summarized these findings and made specific proposals in the following six items.

(1) Cooperation between the fields of accident progression analysis and environmental impact analysis

Temporal variations in the amounts of radioactive materials released into the environment have been estimated mainly by inverse analyses from the measurements of the environment. However, for short-lived radionuclides, the measured data during the early post-accident period are extremely limited, and the temporal variations depend greatly on the propagation of the reactor events. Although it is difficult at present to obtain information on the amounts of releases of each radionuclide and the change of the chemical forms over time, which is required for the assessment of environmental impacts, from the accident progression analysis code alone, the exchange of information between the two academic fields is of great significance for inferring the causes of the observed changes in the composition and forms of radionuclides in the environment. For the time-series elucidation of the environmental releases during the accident, the clarification of the release pathways from the containments and buildings as well as the in-core events is an important issue.

(2) Necessity of environmental dynamics model and environmental monitoring according to the time elapsed since the accident

For the early post-accident period, international comparisons of atmospheric transportation, dispersion and deposition models have made further progress, and new measurements have been obtained to reproduce the events of that time. Within a few years after the accident, interdisciplinary research and studies by various organizations have made progress in measuring and modeling the medium- and long-term environmental fates of radioactive materials within and among various components of the environment, and models for predicting future air dose rates have been developed including a sophisticated model based on statistical analyses and empirical equations from a large amount of environmental monitoring. While, monitoring, which was started as a response to emergency situations, has been shrinking, the succession of monitoring to obtain information essential for the scientific analyses of the events is an urgent issue.

(3) Long-term organizational measures to prevent dissipation of information and samples

In contrast to the monitoring data under the jurisdiction of public institutions, which are being consolidated centrally, data from researchers, individuals, and the private sector do not have a mechanism for centralized collection and preservation, and there is concern that they may be lost. A permanent system for systematic collection and preservation is needed for these data. As a starting point, the construction of a metadatabase is underway to enable searches of the location of all measurement data from the public, private, and academic sectors using meta-information. In addition, it is urgent to establish a storage system for environmental samples and a law and system for disposal of samples with reduced needs in order to ensure the availability of useful samples and to prevent their dissipation.

(4) Cooperation and role sharing between academia and government agencies

In an emergency situation at a nuclear facility, members of academia may participate in the counter measures of the government as experts in response to requests from governmental agencies. On the other hand, it is important to ensure independence, neutrality, and autonomous information dissemination as academia, and to guarantee freedom of speech and ideas, in order to respond quickly and appropriately in the emergency and to ensure the reliability of the information disseminated. At the same time, it is also the mission of academia to view the issue as an academic subject from a long-term and humanistic perspective. It is necessary for academia and government to work together to establish a system that allows information and requests to be shared quickly and smoothly, a system that allows researchers to make long-term commitments, and a system that allows research funds to be used in emergencies.

(5) Importance of education on radiation

What this accident has revealed is the lack of knowledge related to radiation in our society. It is an important role of the government to disseminate knowledge on radiation, and it is necessary to establish systematic education on radiation in school, and to provide lectures on environmental radiation that can be taken by all students regardless of faculty or department as part of comprehensive education at universities. In order to realize such measures, the relevant academic associations are expected to propose concrete plans to the Ministry of Education, Culture, Sports, Science and Technology.

(6) Need for a full picture of research progress, interdisciplinary analysis and reporting of environmental contamination research as the party concerned

One of the recommendations of the 22nd term [5] pointed out the need for interdisciplinary and cross-ministry efforts. Research and studies have progressed in various fields and many results have been obtained, but it is not easy to grasp the full picture of the diverse research results, and interdisciplinary analysis, such as the linkage between environmental contamination surveys and health surveys, is still insufficient. As the tenth anniversary of the accident approaches, it is a challenge for the party concerned to compile a comprehensive and detailed report so that the full picture of the environmental impact of the accident can be grasped. In addition, it is proposed that no environmental modification be carried out in some areas to allow for long-term environmental contamination surveys and training in fields where radioactive contamination is actually present.

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I. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake that occurred at 14:46 on March 11, 2011, and the resulting massive tsunami caused the station black out at the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Station (hereinafter referred to as TEPCO's 1F or simply 1F), leading to the core meltdowns of the three operating reactors and the release of large amounts of radioactive materials into the environment. At the time of the disaster, the Science Council of Japan was in its 21st term, and one week after the disaster, the Executive Board issued a statement [1], followed by a series of six emergency recommendations to April 15. The second recommendation [2] focused on environmental contamination by radioactive materials, recommending the need for large-scale surveys of surface contamination, airborne radioactivity concentrations, radiation dose rates on the ground surface, and radiation doses to local residents, and that these surveys should be conducted as soon as possible with the cooperation of universities and other institutions. The seventh recommendation [3] in August recommended long-term and continuous scientific investigation of the behavior of radioactive materials over a wide area, and the collection of the results of the investigation into a database with a uniform format and making it available to researchers around the world.

In the 22nd term, Committee on Supporting Reconstruction after the Great East Japan Earthquake was established, and the Subcommittee on Countermeasures for Radiation was established along with the Subcommittee on Building Disaster-Resilient Communities and the Subcommittee on the Promotion of Industry and Employment. The Subcommittee mainly discusses environmental contamination caused by radioactivity, and issued its first recommendation [4] in April 2012 and the second recommendation [5] in September 2014. In addition to these, there are many other recommendations and reports from the Science Council of Japan related to the Great East Japan Earthquake and the nuclear accident. The main ones are listed in Table 1 for reference.

In the Comprehensive Synthetic Engineering Committee, the Subcommittee on Nuclear Accident was established in April 2011, soon after the accident. The activities of the Working Group on Investigation of the Accident at the Fukushima Daiichi Nuclear Power Station (hereinafter referred to as the "Accident Investigation Working Group") and the Working Group to review the Investigation on Environmental Contamination Caused by the Nuclear Accident (hereinafter referred to as the "Environmental Contamination Investigation Working Group"), which were established in the Subcommittee, continued in the 22nd and 23rd terms, and were succeeded by the Subcommittee on Nuclear Safety in the 24th term. The Environmental Contamination Investigation Working Group was proposed to be established in May 2011, and the results of various surveys on radioactive materials released into the environment as a result of the nuclear power station accident were reviewed by experts in various fields, in order to select survey items necessary for countermeasures, to identify issues related to models of radioactive material behavior, and to examine the impact on society when public data is made public and the procedures for public disclosure. In the 22nd term, the Working Group compiled a report on the comparison of model calculation results for the transportation and deposition process of radioactive materials [6]. Subsequently, the Working Group inherited the activities of the Informal Working Group (IWG) on Archives of Radiation and Radioactivity Measurement Data Related to the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station, which was established in the 22nd term, and newly established the IWG on Exchange of Accident and Environmental Information in the 23rd term. This report presents the results of the activities of the Working Group including these two IWG activities.

In the early stages after the accident, it was difficult to fully grasp the actual situation regarding environmental contamination caused by the 1F accident, but as about nine years have passed since the accident, surveys and research on the elucidation of the dynamics of radioactive materials in the environment, impact assessment, and countermeasures such as decontamination and waste treatment have been vigorously conducted, and results have been accumulated. These surveys and researches have been carried out by experts from many organizations, in a wide range of related academic fields, and in many related academic associations. While there are reports by international organizations such as United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [7-10] and International Atomic Energy Agency (IAEA) [11], no systematic reports have been made by domestic organizations, and therefore it is not easy to grasp the whole picture of radioactive materials originating from the accident. This report was compiled based on the awareness that it is necessary to look over the progress of research on environmental contamination caused by the 1F accident and to organize issues and proposals for the future.

II. Scope of environmental contamination investigation and the main target of this report

A. Pathways and stages from leak/release to the destination of impact

In the 1F accident, damage to the reactor pressure vessels (RPV), primary containment vessels (PCV), and other components resulted in the releases of radioactive materials from the reactors into the environment. The largest amount was released to the atmosphere, followed by to the sea. Radioactive materials released to the atmosphere are carried by the wind and combined with precipitation (rain and snow) and fog, some of them are deposited on the ground surface, and some of them fall on the sea surface. Some of the radioactive materials that fall on the land also reach the sea through rivers and lakes, and diffuse into the ocean, along with those through the direct discharges. The earth's surface is used for a variety of purposes, such as forests, farmlands, and urban areas, and radioactive materials move between environmental media or stays in the same place for a long time, influenced by the functioning of the ecosystems in these places and by the nature of the soil and artificial surface cover that form the earth's surface.

The distribution and behavior of radioactive materials in the environment are the main targets of environmental contamination surveys in this report, but in considering the effects on human health, daily life, and livelihood, strong attention should be paid to human contact points such as the intake route of radioactive materials through inhalation and ingestion of drinking water, and agricultural, forestry, and marine products, as well as the human activities for decontamination of deposited radioactive materials and subsequent transportation, storage, treatment, and disposal of removed soil and waste.

In this report, the series of processes from the leakages and releases from the nuclear reactors to the destination of the impact will be taken into consideration. However, while closely related to the "environment", topics other than environmental contamination events themselves such as the events in the reactor causing the leaks/releases, inspection and survey on distribution of agricultural products after harvesting, treatment and disposal technologies for contaminated waste and soil after removal from the environment, and fate and effects of released radionuclides in the human body after inhalation and ingestion, are only briefly reviewed or described in relation to environmental contamination.

B. Time scale

This report mainly focuses on the events early after the accident and the progress from the accident to the present. However, considering the material cycle in forest ecosystems and the physical half-life of ^{137}Cs (about 30.2 years), it is necessary to consider the longer-term trends over at least several decades. Monitoring and research to be continued over the medium and long term will also be discussed.

C. Spatial scale

The environmental contamination caused by the accident covers a wide range of areas in East Japan, including the premises of nuclear power plants (inside the sites, so-called onsite), areas near the sites such as interim storage facilities, highly contaminated areas such as difficult-to-return areas, areas inside and outside of Fukushima Prefecture that have reached the level of decontamination, and areas that have not been decontaminated but have generated waste contaminated with radioactive materials above a certain level. Furthermore, research on radioactive materials originating from the accident on a global scale through atmospheric transport and transport over a wide area in the Pacific Ocean has been conducted since the early post-accident period, and is being utilized for inverse analysis of the amount of radioactive materials released into the environment. On the other hand, while the status of environmental contamination in and near the site is also considered to be important for academic research, the site has already been significantly altered for decommissioning, storage of contaminated surface soil and waste, etc., and is limited as a research target due to restrictions on access. It is hoped that further research efforts will be considered.

D. Institutions and academic fields engaged in the research, related research funding, and where the results are published

1. Organization engaged in research and study of environmental contamination from the accident

Academic research in the field of low-profit and high public interest, such as research on environmental pollution, is mainly carried out by public institutions and universities. The Japan Atomic Energy Agency (JAEA) and the National Institute of Radiological Sciences [1](NIRS) are two of the national research institutes that have been dealing with human and environmental effects related to the use of nuclear energy and radiation since before the accident. Under the direction by the former Science and Technology Agency, the Ministry of Agriculture, Forestry and Fisheries (including the Fisheries Agency), the Ministry of Land, Infrastructure, Transport and Tourism (including the Japan Meteorological Agency), the Ministry of Health, Labor and Welfare, and the Ministry of Defense have conducted radiation surveys since the days of atmospheric nuclear tests, and local governments have also conducted radiation surveys. However, prior to the 1F accident, radioactive materials were excluded from the scope of research on environmental pollution, pollution and environmental administration, and waste administration in a broad sense under the Japanese legal system. In order to deal with the various problems that arose after the 1F accident, the National Institute for Environmental Studies (NIES), which has mainly focused on environmental pollution in general, as well as research institutes under the umbrella of many government agencies such as the Ministry of Economy, Trade and Industry, the aforementioned Ministry of Agriculture, Forestry and Fisheries, the Ministry of Land, Infrastructure, Transport and Tourism, and the Ministry of Health, Labor and Welfare, began research on environmental contamination from the 1F accident. In JAEA, the research and study immediately after the accident was carried out by various departments mainly in the Tokai campus, but later the departments related to the accident were reorganized into the Sector of Fukushima R&D. The Fukushima Environmental Safety Center is now mainly in charge of environmental contamination research. The center, the Fukushima Branch of NIES, and Fukushima Prefecture have been conducting research and studies in cooperation at the newly established Fukushima Environmental Creation Center[2] in Miharu Town, which entered the second phase of its 10-year medium- to long-term action plan starting in FY 2015. Fukushima Prefecture, where all whole rice bags have been inspected, and other research institutes related to the environment, agriculture, forestry, and fisheries in local governments are also important players.

2. Relevant academic fields and where results have been published

It goes without saying that universities, regardless of field, are the leaders in academic research[3]. According to Kanda [12], the number of universities that have been selected for external competitive funding for research and radiation education related to the 1F accident was 27 public and 12 privates. In addition, the university academia which engaged in the investigation of environmental contamination caused by the 1F accident belongs to a wide range of research fields. Examples include nuclear engineering, radiation medicine, and other academic fields related to nuclear power and radiation use, radiation education, radiochemistry, which deals with both natural and artificial radionuclides, and environmental science, which deals with pollutants in general. In the current review categories of Grants-in-Aid for Scientific Research (hereafter referred to as KAKENHI) by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the Japan Society for the Promotion of Science (JSPS), the categories that include the word "radiation" in the category name or keywords are extracted and shown in Table 2 for reference.

The domestic academic societies where the results are presented include the traditional fields of nuclear power and radiation, such as the Atomic Energy Society of Japan, the Health Physics Society of Japan, and the Annual meeting on Radioisotope and Radiation Researches, as well as fields related to environmental studies and measurement and analysis of materials.[4] In international journals, many papers related to the 1F accident have been published in specialized journals, including several special issues in the Journal of Environmental Radioactivity, and open access journals such as Scientific Reports have been major destinations for publication. Among the many books related to the accident, only a limited number of scientific books on environmental contamination have been published [13-16], but it is noteworthy that several members of the Environmental Contamination Investigation Working Group were involved as editors and published a book [17] covering a wide range of topics, and its English version [18] disseminated knowledge and lessons learned worldwide

3. Competitive funds for research

KAKENHI is a typical source of funding for research at universities. Among these, the most large-scale project directly related to the 1F accident was the Scientific Research on Innovative Area (research area proposal type) "Interdisciplinary Study on Environmental Transfer of Radionuclides from the Fukushima Daiichi NPP Accident" (Iset-R; FY 2012-2016, PI: Professor Yuichi Onda, Tsukuba University). The project consisted of eight planned multi-disciplinary research teams (two teams for each of the four research areas: atmospheric physics, land-atmosphere processes, oceans, marine ecosystems, migration processes on land, terrestrial ecology, chemical forms, and development of measurement technology), and 22 publicly solicited research proposals and 11 of those in the first (FY 2013-14) and second (FY 2015-16) phases, respectively. In the latter research period, collaborative research projects were conducted in which the planned teams collaborated across disciplines, incorporating measures to foster young researchers. As a successor to this large-scale research, the Joint Usage/Research Center Project, "Environmental Radioactivity Research Network Center (hereinafter referred to as the "ERAN"[5]), was approved by the MEXT and started its activities in FY 2019. In addition to these two projects, the aforementioned tabulation [12] covers a total of eight projects, including five projects by the MEXT, two projects by the Nuclear Regulation Authority (NRA), and a project by the Ministry of the Environment to investigate the effects of the nuclear disaster, etc.

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1. In 2016, it was reorganized into the National Institute for Quantum Science and Technology, and is now part of the Institute's Quantum Life and Medical Science Directorate
2. Established in 2016 as a comprehensive center for monitoring, research, information collection and dissemination, and education, training, and exchange.
3. Several organizations have been established at universities. The University of Tsukuba's Center for Research in Isotopes and Environmental Dynamics was established in December 2012, and has three divisions: the Radioisotope Research Section, the Radionuclide Environmental Transfer Section, and the Environmental Dynamics & Prediction Section. At Fukushima University, the Institute of Environmental Radioactivity was established in July 2013 to conduct basic and applied research on the dynamics of radionuclides in the environment, including forests, rivers, lakes, and oceans.
4. Examples of academic societies entitled both the terms "environment" and "radioactivity" include Environmental Radiology Conference, which was established in the wake of the JCO accident in 1999, and The Society for Remediation of Radioactive Contamination in the Environment which was established after the 1F Accident.
5. Center for Research in Isotopes and Environmental Dynamics, University of Tsukuba; Fukushima University Institute for Environmental Radioactivity; Hirosaki University Institute of Radiation Emergency Medicine; Fukushima Environmental Safety Center, Fukushima R&D Department, Japan Atomic Energy Agency; Fukushima Revitalization Support Research Department, Advanced Radiation Medical Center, Quantum Life and Medical Science Directorate, National Institute for Quantum Science and Technology and Fukushima branch of the National Institute for Environmental Studies.

Besides, competitive funds other than these are also used to fund research on environmental issues originating from the 1F accident, such as the radiation measurement area of the Development of Advanced Measurement and Analysis Systems Program of the Japan Science and Technology Agency (JST) and the Environmental Research and Technology Development Fund allocated by the Environmental Restoration and Conservation Agency (under the jurisdiction of the Ministry of the Environment). There are also examples of environmental research grants from foundations [19] that specifically stated that "research related to the Great East Japan Earthquake and nuclear power station accidents such as radioactive contamination is also welcome."

E. Relationship between the target stage of environmental contamination research, the primary research entity, and the main subject of this report

The main subject of this report presented above is shown in Reference Figure 1, based on the figure published in the second recommendation of the Subcommittee on Countermeasures for Radiation of the Committee on Supporting Reconstruction after the Great East Japan Earthquake in 2014.

III. Progress and Challenges in Environmental Contamination Research in Each Major Field

A. Relevance of environmental releases to in-core events

In the 1F accident, the reactors were shut down immediately after the earthquake and the emergency diesel generators were activated to continue removing residual heat. However, all power sources were lost due to the massive tsunami, and eventually all three reactors suffered core meltdown due to loss of cooling. As a result, a large amount of radioactive fission products (FPs) such as ^{131}I, ^{134}Cs, and ^{137}Cs, which had been stored in the fuel rods, were released into the reactors and some quantities of them were released into the environment [20]. The outline of FP releases from the reactors to the environment could be understood based on the accident progression scenario. However, to determine the FP amounts released from each reactor to the environment, the detailed FP behaviors should be analyzed based on severe accident (SA) analysis codes, which were developed for determining the source term during the accident at many organizations in the world. Since the 1F accident, the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD/NEA) has been conducting benchmark evaluations of SA analysis codes, and the validity of major SA analysis codes has been evaluated. The analysis results of the series of processes from accident occurrence to core meltdown have been evaluated in detail, and the comparison with the measurement records of temperature, pressure, water level, etc. left in the process monitors showed that the analysis results by the major SA analysis codes agreed within a relatively reasonable range [21].

The process by which FP is released from the fuel to the environment by leaking through the reactor pressure vessel (RPV), primary containment vessel (PCV), and reactor building - the so-called multiple barriers - is determined by the migration behavior of gas, steam, and water, which are calculated based on the distribution of temperature and pressure in each compartment calculated by the SA analysis code. Therefore, the accuracy of the evaluation of the amount of FP released to the environment depends on the accuracy of the SA analysis code. As an example, the analysis of FP releases to the environment using the SAMPSON code [22], which is characterized by mechanistically based analysis of temperature, pressure, and steam flow in the reactor as much as possible, is described as follows. In the SAMPSON code, the RPV, PCV, and reactor building are divided into more than 40 regions to obtain the thermal-hydraulic characteristics and core deformation. In addition, the temperature, pressure, and steam transfer between regions are obtained by the FP migration calculation module, and the FP concentration in each reactor region and the FP transfer between the regions are calculated (Reference Figure 2).

The chemical form of the target FP is important in the evaluation of the FP migration amount. The same FP species behaves differently depending on its chemical forms; for instance, some chemical forms exhibit gaseous while the others exhibit aerosol suspending in the air, some are easy to dissolve in water while the others are hard to dissolve, and some easily deposit on the surface of structural materials while the others do not. Previously, stable and equilibrium chemical forms such as CsI and CsOH were assumed in the evaluation of the behavior of iodine and cesium during accidents. However, mock-up experiments using actual fuel in the Phèbus FP project in Europe confirmed that the effects of non-equilibrium states such as Cs_2MoO_4, I_2, HOI, and HI cannot be ignored. These non-equilibrium states of Cs_2MoO_4, I_2, HOI, and HI were added to the mock-up and the FP migration and release to the environment were analyzed. Unfortunately, at present, there are no measured values to evaluate the validity of the results of the analysis of FP behavior in the reactor and PCV, and it is difficult to confirm the validity of the results. On the other hand, as for the amount of major FPs, mainly iodine and cesium, released to the environment, there is a report in which the amount was determined by inverse inference from environmental data using an ATDM, World version of System for Prediction of Environmental Emergency Dose Information (WSPEEDI).

The release processes of FPs to the environment can be assumed to take various routes, such as i) releases from the pressure suppression pool (S/C) through the stack at the time of venting, ii) releases from the PCV through the sealing part of the flange and the reactor building, or iii) releases through the damaged part of the PCV and the reactor building. However, there is a lack of reliable data that can quantitatively evaluate the location and extent of equipment damage, and the evaluation will have to wait for future surveys of the actual situation in each plant. The Cs release behavior for Unit 1 with rather simple FP release routes was calculated by the SAMPSON code, which resulted in almost an order of magnitude smaller than the WSPEEDI values (Reference Figure 3). Therefore, it is important to add more detailed processes, such as the processes of releasing CsOH and other components dissolved in the suppression pool water as mist during venting, and the model is currently being improved. As for radioiodine, which has of great importance in terms of thyroid exposure, a high evaluation accuracy is required. At present, the iodine emission values are within the acceptable range of reasonable error. The overestimation is caused by the releases of iodine as a single substance, but efforts to improve the accuracy of the analysis are necessary, along with more detailed evaluation of the chemical forms of non-equilibrium.

Furthermore, regarding the amounts of emissions into the environment from Units 2 and 3, detailed evaluation of the damage to major components is essential, and a quantitative evaluation of the amount of emissions will be a future task. In addition, it is essential to improve the accuracy of the SA analysis code itself, in cooperation with the Accident Investigation Working Group.

B. Early post-accident events, especially transport through the atmosphere and initial exposure

1. Progress in intercomparison of atmospheric transport, dispersion, and deposition models (ATDMs)

The ATDM, which describes the process from release to the atmosphere to deposition on the earth's surface, plays an important role in elucidating the dynamics of radioactive materials in the environment, which is the main target of this report, especially in the early stage after the accident. In the 22nd term’s Working Group report [6], ATDMs were compared for nine regional models and six global models. The comparison of models was continued with the participation of domestic and international organizations, and developed into a comparison using common meteorological fields and changes in emissions over time (source term) [23]. In the inter-model comparisons in the 22nd term report, comparisons were made with measured concentrations in the atmosphere as well as with total global atmospheric loading, surface deposition, and their mass balance, but at that time the number of comparable sites was limited. Later, the research results of continuous measurements of ^{134}Cs and ^{137}Cs concentrations at about 100 sites in eastern Japan using the measurement of used filter paper from the station for continuous monitoring of suspended particulate matter (SPM) in the air [24-25] were published, and in combination with the results from ATDMs, the behavior of many radioactive plumes has been clarified as shown in Reference Figure 4 [26].

This made it possible to verify the reproducibility of ATDMs for atmospheric concentrations of radioactive materials, which had been difficult in the past, and inter-model comparison was conducted with the participation of seven organizations [27].

2. Progress in reproducing by measured concentrations of radionuclides in the atmosphere in the early post-accident period

Subsequently, the results of measurements at two sites within 20 km of 1F [28] were published, which clarified the behavior of radioactive plumes at short distances in more detail. This is useful for improving the accuracy of the source term, such as inverse estimation of the release time. Furthermore, in addition to the measurement of radiocesium, it was reported [29] that a long physical half-life radionuclide, ^{129}I, in collected samples of atmospheric particulate matter could be quantified by mass spectrometry. Iodine-131, which is of interest from the viewpoint of thyroid exposure, has a short physical half-life of approximately 8 days, and the actual measurement points after the accident were limited, making it difficult to know the spatio-temporal distribution, but a new possibility was provided for reproducing the regional distribution of ^{131}I in the air immediately after the accident. It was also made clear from the comprehensive analysis of the measured values of ^{131}I in the air immediately after the accident [30] that the initial post-accident radioactivity ratio of ^{131}I:^{137}Cs was about 10:1 (physical half-life corrected on March 11, 2011), which was close to the in-core inventory ratio at many points and dates. It was also revealed that there was a plume containing more ^{131}I than this.

The main findings newly obtained from the series of measurements are as follows;

-The analysis of the filter tape at the air pollution measurement station near the 1F reconfirmed that a large number of plumes passed through intermittently in both the north and south directions of the 1F,

-The maximum concentration of ^{137}Cs in the air was 13,600 Bq/m^3 observed between 14:00 and 15:00 on March 12, 2011 at a point about 3 km northwest of the station, and this was before the hydrogen explosion in Unit 1, and

-It is highly likely that this high concentration plume passed through the area where evacuation had not been completed in the northwest to north direction of the 1F, and this should be taken into account in the estimation of internal doses from inhalation.

3. Linkage between environmental dynamics analysis and dose assessment in the elucidation of initial exposure

In the 2013 report by UNSCEAR [7], exposure dose estimation using ATDM was also conducted, but it was pointed out that there was a large uncertainty due to the lack of initial observation data. In the subsequent 2015-2017 White Paper [8-10], expectations were stated that progress in research and studies in the areas indicated above in 1) and 2) would contribute to decreasing the uncertainty. In terms of radiation dose assessment, the “Comprehensive Study on Dose Assessment for Residents in the Accident at TEPCO’s Fukushima Daiichi Nuclear Power Station” (FY 2014-2016) and the “Comprehensive Study on the Elaboration of Internal Exposure Dose Assessment in the Early Phase of the Accident” (FY 2017-2018) were conducted by JAEA, the National Institute of Radiological Sciences (NIRS), etc., under the Ministry of the Environment’s Nuclear Emergency Response Project aforementioned in II.D.3. Estimation of thyroid doses by typical evacuation scenarios based on ATDM has also been conducted. The latest publication [32] showed the results of internal exposure dose estimates for each of the seven municipalities based on the evacuation behavior records immediately after the accident. On the other hand, estimation results by another research group using the actual measurement results of suspended particulate matter in the air and ATDM calculation results shown in III.B.1 and III.B.2 above [33] were also published, and progress was made in the research leading to the deepening of epidemiological analysis of health effects as discussed later in III.F.

4. Discovery of insoluble cesium particles and progress in their characterization

As described in III.A, CsI or CsOH was assumed to be the main chemical form of cesium emission in the conventional accident analysis. Although these chemical forms are water-soluble, insoluble fine particles (typical particle size of around 2 μm) with high Cs specific activity were found in filter paper collected from air samples in Tsukuba City, Ibaraki Prefecture, in the early post-accident period, through observation using imaging plates and an electron microscope [34]. These particles were named cesium balls because of their spherical shape, and then, investigation and research on the particles in various media such as river water and soil as well as atmospheric samples were conducted. On the other hand, insoluble particles of indeterminate shape with a particle size of tens to hundreds of μm and a maximum radioactivity of over 10,000 Bq per particle were also discovered, although their specific activity was several orders of magnitude lower than that of fine particles. For the sake of convenience, these are called Type B, while the initially discovered ones are called Type A. Type A non-spherical particles and Type B spherical particles were also found later, and are now referred to as Cs-bearing micro particle (CsMP). From the radioactivity ratio of ^{134}Cs:^{137}Cs, Type A is thought to have originated from Unit 2 or 3, while Type B is thought to have originated from Unit 1. From the early stage after its discovery, it was reported that Type A had a glassy structure and contained many metallic elements other than cesium, but its properties were subsequently further elucidated [35], and since the ratio of CsMP to the amount of surface deposition differed according to the orientation from 1F [36], it was considered to have been contained only in a specific radioactive plume between March 14 and 15, 2011.

These SiO_2-based glassy particles containing Cs with high specific activity were not expected before the 1F accident, and are outside the scope of the knowledge of the Chornobyl accident. Since they are silica glasses, they can exist stably in the environment and human body for a relatively long period of time, and they are not only important for the impact assessment because they cause non-uniform β-irradiation, but also they are very important evidence for the clarification of in-core events because it is currently impossible to obtain appropriate samples from inside the reactor. In other words, it has a great potential to provide important knowledge on decommissioning methods and the establishment of decommissioning safety (fuel debris recovery, in-core decontamination, safety assurance for workers and the surrounding area, etc.). However, there is little information on the content of alpha emitters such as Pu, and it is necessary to contribute to the risk assessment for decommissioning by accumulating knowledge. Although the clarification of radioactive particles has gradually progressed in the nine years since the 1F accident, there is still much room for clarification of the timing of release and its relationship with the source (reactor), the generation mechanism, accurate evaluation of the release amount, and the ratio of water-soluble to water-insoluble Cs deposited. At present, there is only an analytical method to separate individual particle, and a bulk separation method has not been established. The development of a bulk separation method is eagerly awaited, even if it requires a large amount of labor and budget, and if it is achieved, it will contribute to radioactive waste volume reduction and efficient decontamination, so continuous research is required. In addition, based on recent experimental findings, it is assumed that Cs will gradually dissolve out or the body of radioactive particles will gradually dissolve and disappear by weathering in the environment. However, the disappearance process in nature itself has not been confirmed or observed, and there are currently no efforts to address this issue. From the viewpoint of public safety and security, the development of empirical studies to monitor such a transition is strongly required.

C. Geographical distribution of surface contamination and radiation air dose rate and dose rate trends

The radioactive plume emitted into the atmosphere from the 1F caused deposition of radioactive materials over a wide area in eastern Japan. In general, the area within 80 km of 1F was heavily contaminated, in particular, the surface contamination in the area northwest of the 1F station was extremely high. In addition, there is an elongated area with relatively high surface contamination from Nakadori in Fukushima Prefecture through Tochigi Prefecture to Gunma Prefecture. Furthermore, there are enclaves of high surface contamination in the areas from the southern part of Ibaraki Prefecture to the northern part of Chiba Prefecture, and from the northern part of Miyagi Prefecture to the southern part of Iwate Prefecture.

Although several environmental measurements were conducted by different organizations immediately after the accident, the first large-scale and systematic survey of deposition was conducted in June 2011 [37] (the first Fukushima mapping project). There were several radionuclides observed over a wide area in this survey: that is ^{89}Sr, ^{90}Sr, ^{110m}Ag, ^{129m}Te, ^{131}I, ^{134}Cs, ^{137}Cs, ^{238}Pu, and $^{239+240}$Pu [37-41]. Meanwhile, at this point, 99% of the air dose rate was already due to radiocesium, and from the viewpoint of long-term exposure, radioactive cesium was confirmed to be far more important than other radionuclides. Efforts were also made to estimate the amount of ^{132}Te deposited immediately after the accident from the amount of ^{129m}Te deposition [42], and to refine the map of ^{131}I deposition by measuring ^{129}I [43]. Furthermore, a trial was made to identify the reactor unit which mainly contributed to the radionuclide deposition for arbitrary areas according to the deposition ratio of different radionuclides [44, 45]. The total amount of ^{137}Cs deposition on Japanese land was estimated to be around 2-2.5 PBq. The amount of radiocesium deposited on each land use within 80 km of 1F was estimated to be roughly proportional to the land use area, with 70% deposited in forest areas, 20% in agricultural land, and 5% in land used for buildings [46].

Fukushima mapping projects were conducted continuously thereafter, providing basic data for analyzing changes in air dose rates and deposition over time [47]. In parallel, aerial monitoring using helicopters was conducted [48]. The air dose rate maps for the period from 2011 to 2016 are shown in Reference Figure 5, and the decreasing trend of the average air dose rate is shown in Reference Figure 6. In Reference Figure 6, the contribution to air dose rates from natural gamma rays is subtracted, and the decreasing trend of air dose rates caused by radioactive cesium is shown. It is estimated that the physical half-life reduced the air dose rate to about 37% of the original level between June 2011 and August 2016. The average air dose rate on roads measured by the car-borne survey [50] decreased to about 1/3 of the dose rate expected based on physical decay alone, and the air dose rate in undisturbed flat fields [51] decreased to about half. Since the walk survey [52] started in 2013, it is not possible to directly calculate the dose rate reduction ratio from 2011, but it is assumed that the data are plotted between the car-borne survey and the undisturbed flatfield measurement based on the relative relationship with these measurements. Summarizing these results, it can be judged that by 2016, air dose rates in the living environment decayed on average by a factor of 2 to 3 faster than physical decay [49]. The causes of the decrease in air dose rates can be broadly classified into physical decay, horizontal and vertical transfer of cesium, and decontamination. Physical decay was initially the most important cause due to the relatively short physical half-life of ^{134}Cs, which is about 2 years. However, the existence ratio of ^{134}Cs is now small, and a large decrease in air dose rate due to radioactive decay is not expected in the future.

Radiocesium permeates into the ground over time. The relaxation mass depth β_{eff}, which is an index of ground penetration, has so far increased almost in proportion to the time elapsed after the accident [53] and the underground penetration of radioactive cesium has increased the gamma-ray shielding effect of soil, causing a decrease in air dose rates. Comparing the decreasing trend of air dose rates due to ground penetration with that of the Chornobyl accident, the decreasing trend in Fukushima is slower [49]. Since radiocesium is strongly adsorbed on fine particles of soil, horizontal transfer of radiocesium is also considered to be generally small; however, the horizontal transfer is considered to be a factor accelerating the decrease in air dose rates because radiocesium attached to man-made structures such as asphalt and that deposited in plowed agricultural fields is relatively mobile than in other areas. As of 2016, horizontal radioactive cesium transfer was considered to have reduced the air dose rate by up to 30% [49]. Since the effect of horizontal transfer tended to be particularly pronounced immediately after the accident, it can be predicted that the decrease in air dose rates will not occur at the same rate in the future. It is necessary to cross-validate the results with radioactive material migration studies.

As a result of comparing the data on air dose rates measured in flat fields, including and excluding points where decontamination was conducted, it was estimated that the average air dose rate in flat fields within the 80-km zone was reduced by about 20% due to decontamination. A more detailed evaluation of the impact of decontamination is needed. The decrease rate of air dose rates and the contribution of causes indicated above are only average values, and may vary greatly depending on the circumstances. Since air dose rates are related to the radiation doses of residents living there, it is necessary to conduct analysis for each specific region in order to accurately grasp the decreasing trends. Land use and human activities are factors that change the decreasing trend in air dose rates. In terms of land use, the decrease in air dose rates is relatively slow in forests, relatively fast in urban areas, and in between for agricultural land [54]. These trends are explained by the mobility of radiocesium in the environment. In addition, several phenomena suggesting that human activities accelerate the decrease in air dose rates have been observed [50, 55], and quantitative analysis of the effects of human activities is an important task for the future.

D. Environmental dynamics in terrestrial environments

Radioactive materials deposited on the earth's surface are known to migrate through the environment with mass transport. After the 1F accident, measurements of the amount of radioactive materials in forests and in various land use areas were started in conjunction with the distribution surveys immediately after the accident, as shown in Reference Figure 7. From these investigations, results were obtained regarding the transfer of radioactive materials from soil plots in forests and various land uses to rivers, the transfer of radioactive materials from paddy fields to suspended sediment, stream water, and river water, and the transport of radioactive materials in river water. Furthermore, with the addition of group research such as the Innovative Area research described in II.D.3 and systematic research [56] by research institutes such as JAEA, and NIES, the clarification of the behavior of radioactive materials on land is progressing.

As for the transfer of radioactive materials from forests, a survey in a model area in Kawamata Town has produced long-term monitoring results over a period of six years [57], and the actual conditions of the transfer process associated with rainwater in particular have been clarified [58]. As for the transfer of radioactive materials into trees, a detailed survey by the IRSN team, France [59] and a survey at a long-term monitoring site by the Forestry and Forest Products Research Institute [60] have revealed that the transfer of radioactive materials into some tree species has progressed.

The downward movement of radionuclides in soil varied greatly depending on land use, being particularly fast in paddy field areas [61] while slow in forest areas [62]. Some of the radioactive materials from the paddy fields were discharged into rivers, mainly at the time of padding, and their concentration was high in the early stage of the process [63]. The loss of radiocesium due to erosion also depended on land use, especially in the order of grassland and forest < planted farmland < land without vegetation [64], and in grassland the erosion rate was generally found to be well below 0.01%/year. The downward and subsequent erosion and transport of radioactive materials and soil are closely related to the decrease in air dose rates described above, and these related studies are needed. Migrated radioactive materials flow into rivers. The transfer of radioactive materials from forest watersheds is mainly brought about by suspended sediment [65]. On the other hand, it has been found that the dissolved state of radioactive cesium in forests is dominated by the decomposition of litter [66]. In long-term changes, suspended cesium concentrations in forests have been found to be initially low, but their reduction has been slow [67]. Radiocesium concentrations in rivers in urban areas tend to be higher than in rivers in other land use basins [68].

At the long-term monitoring site of the Abukuma River system, the concentration of suspended radioactive cesium in river water decreased at a faster rate than that after the Chornobyl nuclear power station accident during the period up to about one year after the accident. By the fifth year after the accident, it had become 1/3 to 1/21 of that of the Pripyat River [69]. The total amount of radiocesium transported to the Pacific Ocean was about 12 TBq, which was about 3% of the total amount deposited in the watershed, and almost all of the transported radioactive cesium (96.5%) was in particulate form. Analysis of long-term monitoring data from 30 sites on land showed that the main sources of radiocesium in the early stage were rice paddy fields, other agricultural fields, and urban areas, from which 85% of the total amount of radiocesium flowed out [69]. While these findings were obtained, there are still many unanswered questions regarding the transfer of radioactive materials during the first three months after the accident and for future predictions.

As for crops on land, at the early stage of the accident, contamination of vegetables was caused by direct deposition of radioactive materials [70], after that, crop contamination occurred due to translocation and root uptake [71]. After the 1F accident, research and studies on the transfer of these environmental contaminants to crops were vigorously conducted by research institutes of the Ministry of Agriculture, Forestry and Fisheries and universities. It was found that radioactive cesium transfer to brown rice could be suppressed if the amount of exchangeable potassium in the soil was sufficient [72], and under normal fertilizer management, the transfer to brown rice was slightly higher in 2011 than that before the accident [72]. It should be noted that the transfer returned to pre-accident levels in the third year [73]. In the case of forest products, the transfer of radioactive materials into the inner parts of trees has been confirmed [59], and it is necessary to continue investigating the contamination conditions in forests.

In addition to these bottom-up efforts, it will be necessary to work cross-ministry and cross-disciplinary to elucidate the transfer process of radioactive materials and assess their effects, to archive the results obtained, to disseminate them to the domestic and international community, and to contribute to the resolution of various issues related to the recovery of the environment in Fukushima. This will contribute to solving the various problems related to environmental recovery in Fukushima.

E. Environmental dynamics in the ocean

Radioactive materials in the ocean derived from the 1F accident originated from three pathways: i) direct discharges into the ocean, ii) deposition to the ocean after releases into the atmosphere, and iii) deposition on the land surface after releases into the atmosphere and migrate through rivers, with i) and ii) accounting for the major pathways and amounts. Although radionuclides other than ^{137}Cs have been observed, their radioactivities were small, and their environmental impact has been confirmed to be smaller than that of ^{137}Cs.

Total amount of direct discharges of ^{137}Cs to the ocean is estimated by the combination of ocean models and observation data near 1F [74], and is in the range of 3-6 PBq [75]. The direct discharge rate has decreased from 10^{14} Bq/day immediately after the accident to the order of 10^{9} Bq/day, but has continued in 2018 [76,77]. Total amount of atmospheric deposition of ^{137}Cs to the ocean was estimated to be 15-19 PBq by combination of atmospheric models and observations in the ocean [75]. As dissolved ^{137}Cs was supplied to the coastal ocean, its distribution is strongly influenced by coastal currents, mesoscale eddies, and the Kuroshio Current [78]. In the 22nd report, a comparison of regional ocean models was also made [6]. On the North Pacific scale, the ^{137}Cs advected eastward along the Kuroshio Extension and subducted into the intermediate layer [79]. The ^{137}Cs concentration is decreasing due to advection, diffusion, and radioactive decay, but the radioactivity level will be observable in the future. A part of ^{137}Cs in the ocean migrate to sediments, and particulate ^{137}Cs supplied from the land also deposited on the seafloor. The amount of ^{137}Cs in the sediment is estimated to be 130 ± 60 TBq based on the integration of observed results [80]. The decrease in the ^{137}Cs concentration in the sediment is slower than that in seawater, and it is necessary to elucidate the decrease mechanism through continuous observations [81]. In addition, cesium-bearing micro particles with high ^{137}Cs activity have been confirmed to exist in the sediments, and it is important to understand the role of Cesium-bearing micro particles when understanding the migration of ^{137}Cs from sediments to seawater and marine organisms [82]. The transfer of ^{137}Cs from seawater with high activity to marine organisms in the early stage of the accident caused effects such as voluntary restraint of fishing and shipping restrictions. Although the ^{137}Cs activity in marine organisms has continued to decrease, there are still issues to be solved in elucidating the intake and excretion mechanisms of ^{137}Cs for each species [83].

In order to prepare the management of future radioactive contamination of the oceans due to severe accidents, it is necessary to generalize the model of marine contamination due to the 1F accident. Since the ocean is the destination zone of radioactive materials originating from the 1F accident, it is necessary to consider the supply pathways from the atmosphere and rivers, etc. [84].

F. Environmental contamination and health effects

1. Fukushima Health Management Survey

Fukushima Prefecture has conducted the Fukushima Health Management Survey (FHMS) since the 1F accident. It consists of five surveys and examinations, including (i) a basic survey estimating external doses, (ii) thyroid examination, and (iii) health checkup [85]. In the basic survey (i), evacuation routes and timing and relocation histories of residence after the accident are surveyed with a form of writing in questionnaires. The external doses were estimated by using the dose values in those areas. In the examination of the thyroid gland (ii), the results of the examination using an ultrasonic device were reported [86, 87]. The target population was generally children under 18 years old at the time of the disaster. In the health checkup (iii), the results of general health examinations were reported.

2. Environmental contamination survey and exposure dose assessment

The role of this Working Group is to exchange information on environmental contamination surveys among various fields and to promote the progress in the research in each field. With regard to the relationship between environmental contamination surveys and health effects studies, it is important to assess the radiation doses given by the environmental contamination surveys. In other words, by examining the correlation between the radiation doses and the health effects, it can be determined whether there are any effects by radiation. The external doses were assessed in the basic survey of the FHMS in Fukushima Prefecture. For example, Saito et al. [37] classified the areas in Fukushima Prefecture into 2 km meshes and measured the air doses in each area. Such data can be used for the assessment of the external doses. As for the internal doses, for which exposure to ^{131}I need to be assessed, internal doses to the thyroid gland can be assessed using data from the IAEA report [88, 89] and Shikarev et al. [90, 91]. In addition, as shown in III.B.1 and III.B.2, significant progress has been made in research on both actual measurements and models in the atmospheric field, and as shown in III.B.3, the results are being utilized for estimating internal exposure via inhalation.

3. Investigation of the causes of cancer in other exposure accidents, etc.

The main studies that have been conducted so far on radiation dose and cancer incidence are those of the survivors of Hiroshima and Nagasaki, Chornobyl (e.g. [92]), and Semipalatinsk [93]. These studies found a correlation between radiation dose and cancer incidence, and concluded that the exposure to radiation caused cancer. Furthermore, the risk of radiation exposure is analyzed from the correlation. In particular, the risks determined in the Hiroshima and Nagasaki studies are used as the main data for radiation protection.

4. What is needed for the Fukushima survey

However, no investigation has yet been conducted in Fukushima to determine whether the accidental radiation has caused any diseases. For example, the UNSCEAR report [7] only stated that "since the radiation dose from the Fukushima Daiichi accident is much lower than the radiation dose from the Chornobyl accident, an increase in the incidence of public health effects attributable to radiation exposure from the Fukushima Daiichi accident is unlikely to be discernible", being supported by the IAEA report [88]. Such analysis can be done at least to some extent using existing data on radiation dose and health effects (e.g., the FHMS). Even if an increase in the incidence rate cannot be identified, it would be important to report that it could not be identified. For thyroid cancer, there is a study (Tsuda et al. [94]) with a statistical analysis showing that the incidence rate was significantly higher. However, the thyroid dose used in this study was later found to be based on old data and overestimated. The categorized dose range intervals were large, and the observation period was short. Ohira et al. [95] also conducted an analysis on the relationship between incidence and dose, but their analysis was based on the regional classification of external doses rather than internal doses. It is still necessary to examine the correlation with radiation dose (especially internal dose due to ^{131}I in the thyroid gland) more carefully.

As indicated in 2) above, significant progress has been made in the assessment of internal doses utilizing research results in the field of environmental contamination surveys. By linking these results to the results of thyroid examinations for the individuals in the FHMS with information on behaviors in evacuation as described in 1) above, epidemiological analysis will be deepened at this stage. Such analyses may help to answer many of the questions that have been raised, such as whether or not the increase is due to screening effects. Although we have discussed pediatric thyroid cancer as above, it is further necessary to analyze all diseases, including those of adults, as was done at the Radiation Effects Research Foundation for atomic bomb survivors. For example, an analysis for the relationship between radiation dose and disease is underway for residents of Semipalatinsk [96]. As for Fukushima, if the data is properly disclosed in a privacy-conscious manner, it may be possible for such an international team to analyze the data. It would be important to conduct the study by multiple teams including foreign experts in order to obtain the trust of the public.

G. Environmental recovery and reconstruction of contaminated areas

Although the main subject of this report is the investigation and research of environmental contamination, environmental recovery and reconstruction of the contaminated areas are also important themes in terms of the contribution of academia to society.

The second recommendation of the 22nd term’s Subcommittee on Countermeasures for Radiation of the Committee on Supporting Reconstruction after the Great East Japan Earthquake [5] also listed "strengthening academic activities related to regional reconstruction assistance" as one of the five recommendations. It should also be noted that other recommendations on the reconstruction of the areas affected by the Great East Japan Earthquake, including those other than nuclear disaster, have been issued in this field, including the recommendation of a Subcommittee under the Committee on Sociology [97].

In areas contaminated above a certain level, the national and local governments have been conducting surface decontamination under the Act on Special Measures concerning Radioactive Materials Contamination. The surface decontamination was completed in March 2018, and decontamination is now being carried out at specific reconstruction sites in areas that were not subject to decontamination under the law but are difficult to return to. In relation to the environmental contamination survey, the extent to which the effects of decontamination were manifested in the temporal changes in air dose rates and the decrease in radiation doses as described in III.C.

The Society for Remediation of Radioactive Contamination in the Environment, mentioned in II.D.2, was established as a forum for exchanging information and presenting the results of decontamination research and technological development. This was in response to the shifting and expanding needs of the local community for the storage of removed soil and waste from decontamination and the rehabilitation of the area after decontamination. In addition, of the four divisions that make up the research and study of the Fukushima Prefectural Center for Environmental Creation, two divisions, the decontamination and waste division and the environmental creation division, fall under this item. In the second phase starting in 2019, the policy is to focus on environmental dynamics and environmental creation, and it can be said that the future issue is how to link the research and study of environmental dynamics, which is the main subject of this report, to reconstruction through environmental recovery and creation.

Of the governmental research funds mentioned in II.D.3, the "Fukushima Innovation Coast Initiative

Promotion Project Utilizing the Reconstruction Knowledge of Universities, etc." is a project of the Ministry of Education, Culture, Sports, Science and Technology and the Reconstruction Agency, and 28 projects at 18 universities have been adopted for FY 2019. How research on environmental contamination can be linked with academic support for reconstruction will be an important issue in the future.

IV. Challenges and lessons learned in areas related to environmental contamination investigation

A. Collect and accumulate information on environmental contamination

1. Status of measurement data and accumulation of them since the beginning of the accident

Since the beginning of the 1F accident, a wide variety of radioactivity and radiation measurements have been carried out by various people, such as the national and local governments, private companies, researchers, and citizens. In order to conduct detailed monitoring related to the 1F accident, the government established the Monitoring Coordination Council under the Nuclear Emergency Response Headquarters to formulate a comprehensive monitoring plan, and based on this plan, relevant government ministries, local governments, and nuclear operators have been conducting extensive monitoring in cooperation with each other (Reference Table 3 and Reference Table 4) [98]. The Fukushima prefectural government has published a record of the initial response after the accident and the establishment of the current monitoring system [99]. Many of the measurement data were available on the web and could be accessed by the general public, and there had been attempts to consolidate the data by volunteers since the beginning [100]. Later, the Nuclear Regulation Authority (NRA) and the Japan Atomic Energy Agency (JAEA) created a database of measurement data under the jurisdiction of government ministries and local governments [98, 101]. However, many of the measurement data initially published on the websites of local governments are no longer linked due to site updates. On the other hand, measurement data by researchers are basically published as results through papers and oral presentations in each specialized field, but there are still few data itself being released. The bibliographic information about published papers is cataloged and searchable in the Fukushima Nuclear Accident-Related Information Archive (FNAA) [102] by the JAEA. FNAA also includes a catalog of measurement data, and is linked to the National Diet Library's digital archive project "WARP" [103], so that some sites with broken links can be viewed. On the other hand, the private sector and individuals have been actively conducting measurements since immediately after the accident, and the data have been published on blogs of individuals and volunteer groups.

These private sector data, although the measuring instruments and methods might be inadequate and the accuracy of the measurements cannot always be guaranteed, would contain valuable information such as discovery of "hot spots" in places that are difficult for the government, local governments, and researchers to discover [104], food measurements by local residents themselves [105], and long-term fixed-point observations [106]. There is no official framework for collecting private or personal measurement data, and it is up to individuals to maintain his or her own site. In general, the lifespan of information on the Internet is said to be two years, and there is a risk of losing information if it is not collected and preserved continuously. The internet archiving project, WARP, by the Library of Congress collects web contents only from government sites, while private and personal sites are outside the scope of collection.

In response to these situations, in 2013, a statement was issued jointly by the presidents of the Physical Society of Japan and the Japan Society for Archival Science, "Collect and archive all data, including private measurement data".

2. Data archiving activities in the Science Council of Japan

The Science Council of Japan (SCJ), in its first [2] and seventh [3] recommendations, has proposed the establishment of a centralized and continuous system for environmental monitoring and the creation of a database to be made public. Since 2015, the IWG [108], established under this Working Group, has been collecting metadata and constructing a metadatabase [109] that can search the location of data from meta-information, aiming to enable cross-search of all measurement data including researchers, private companies, and individuals. The metadata information to be registered includes information about the data itself, such as the date, time, location, and observables, as well as information about the data owner and data disclosure (site, methods, and availability), the purpose of measurement, and archival information (original data collection status, links to other databases, etc.).

As of November 2019, the number of registered datasets is 593, with 34,310 measurement points ranging from the Tokyo metropolitan area to Hokkaido and western Japan. On the other hand, the activities of researchers in the Iset-R selected as "Grant-in-Aid for Scientific Research on Innovative Areas" have produced a vast amount of measurement data and research results in the atmosphere, terrestrial, and ocean, which have been transferred to the Research Center for Isotope Environmental Dynamics at the University of Tsukuba, which will be established as a joint-use and joint-research center in FY 2019, then work is going on to make data publicly available by adding doi [110].

3. Problem of archiving measurement samples

In addition to data archiving, another issue is the treatment of environmental samples. Immediately after the accident, various environmental samples were collected by public institutions and individual researchers for measurement. Among these environmental samples, for example, soil samples collected in the vicinity of Fukushima [37] are stored at the Fukushima University Institute of Environmental Radioactivity, and are available for loan and distribution for research. However, many other environmental samples are kept by the institutions or individual researchers who collected them. If, more than eight years after the accident, the samples are lost or dispersed due to the retirement of the researchers who hold them, it will not only result in the loss of useful information by new measurement methods that may be possible in the future, but may also lead to the unforeseen spread of contamination. In addition, the cost of long-term storage must be taken into consideration, as water samples are large in volume and biological samples need to be kept frozen, so a sample archiving institution will be necessary.

In order to prevent the dissipation of samples currently stored at various institutions, it is urgent to establish a system for storing samples that may be useful in the future, as well as indicators for judging such storage, and to establish laws and systems for collecting and disposing of unnecessary samples. In addition, as an international responsibility to future generations, consideration should be given to the future conservation of the natural environment of some of the government-owned land, which has a high need for conservation based on the results of post-accident monitoring, while ensuring that the lives of residents are not affected.

4. Future prospects and problems

In order to consolidate and freely use the measurement data of individuals and the private sector, as well as to create a permanent archive, it is necessary to sort out legal issues such as the transfer of data copyrights and the protection of personal information of those involved, and to deal with problems such as reputational damage related to the release of data. It is necessary to make consideration to protect the people concerned by coarse-graining the measurement points and setting a non-disclosure period. The quality of registered data must be guaranteed in order to create a database. However, since the priority is to find and preserve all data, and the required quality varies depending on the application, all data should be collected and registered regardless of quality, except for malicious and fabricated data. Even though the quality of private and individual measurement data may vary, it can be used for humanistic and sociological research if we consider that the situation in which individual residents used their own measuring instruments to measure radiation has historical significance.

These activities should be continued for the next 100 years and require a permanent archival institution, but at present we are relying on the activities of university institutions, which do not necessarily guarantee such a long-term foundation. It is necessary to establish a long-term system in cooperation with public archives such as the Library of Congress and the National Archives of Japan. Regarding the storage of collected environmental samples, official measures should be taken to address the sample-specific issues of storage location and storage costs, and a system should be established to allow free access to the samples while taking into consideration the protection of all parties involved.

B. Importance of collaboration between academia and government agencies

In the event of an emergency at a nuclear facility, national government, local governments, and operating office are responsible for emergencies, in addition, relevant designated public organizations are also expected to cooperate. On the other hand, expected contributions of academic institutions such as universities are not defined. Their role and cooperation with government agencies, therefore, needs to be examined. In this section, we would like to summarize the process and issues involved, taking as examples the Soil Survey project (the first distribution survey) in 2011 [37] and the starting of a new academic field research on radiation environmental dynamics that was launched through interdisciplinary cooperation [56]. The Soil Survey, conducted under the MEXT, was started by the action of a group of nuclear physicists then spread to collaborations between universities and related academic societies. History of those two projects is presented in the following and then a desirable cooperation between academia and government agencies is discussed.

1. Academia's efforts to observe the situation of environmental contamination right after the accident

The efforts on emergency by the enthusiastic researchers and their relationship with the government right after the accident are described, for example, in Chapter 10 of Reference [14]. The initial response to the accident in academia to ascertain the status of environmental contamination was originated by the Osaka University members of the Nuclear Physics and the experimental community of nuclear physics (KAKUDAN). The first joint meeting including scientists from nuclear physics, geochemistry and radiochemistry was held at Osaka University on March 16, 2011 and resulted in unprecedented collaboration between related academic groups. Ministry of Education, Culture, Sports, Science and Technology (MEXT) started a soil survey project, as mentioned above, in response to these bottom-up activities. A large-scale atmospheric measurement system was established also through the cooperation of the Geochemical Society of Japan, the Japan Geoscience Union, and the Japan Society of Nuclear and Radiochemical Sciences, but it was started with the research funds of individual researchers because emergency research funds were not available at the time. Such a situation was similar in the fields of oceans, forests, rivers, etc. These collaborations became a major wave of cross-disciplinary research only after budgetary support was established as an Innovative Area research in 2012 of JSPS fund (Iset-R; 2012-2016) mentioned earlier.

The former is an example of a bottom-up effort by academia that turn out to be a national project, and is a success in terms of clarifying where the responsibility for large-scale surveys and the obtained data. The latter was a cross-disciplinary study within the budgetary framework of academic research. In addition to its academic significance and global dissemination, it made a significant contribution to the prediction of the future of contamination, environmental recovery, and the provision of information to residents from a neutral standpoint.

2. Cooperation between academia and government agencies

The activities described above are examples of the effective activities of academia in the early stages after the accident, but on the other hand, major issues remain in the details of the scientific data. For example, if academia and government agencies had collaborated immediately after the accident and responded promptly, more valuable data would have been obtained and useful information for the government's initial measures could have been given. In particular, the lack of ^{131}I data due to the delay in the response is most regrettable. In addition, due to the luck of management system, use of the soil samples was limited to the participant of the project. It is clear that those soil samples are valuable for understanding the initial situation of the accident for any researches. After long time, fortunately, they will be managed by the Fukushima University Institute of Environmental Radioactivity from FY 2019, and finally open to free research use. In an emergency such as the 1F accident, researchers belonging to academia, of course, would/should be sensitive to their sense of mission, social contribution, and requests from society and government. Therefore, each researcher may participate in emergency response as an expert or at the request of a government agency. On the other hand, it is essential to ensure the independence, neutrality, and autonomous dissemination of information as academia and to guarantee the free speech and ideas of researchers. It then secure quick and appropriate response and ensure the reliability of the information disseminated. At the same time, it is also a role of academia to consider the issue as a long-term academic subject and a subject of humanistic perspective. In addition, a system is required that allows academia and government agencies to collaborate to share their respective information and requests quickly and smoothly. It is also important that the system allows researchers to make long-term commitments. In order to achieve this, a system for research funding necessary in emergency situations must also be developed and guaranteed.

With the establishment of the Nuclear Regulation Authority (NRA), the division of radiation control was consolidated into the NRA, while academic research on radiation is under the jurisdiction of the MEXT. Under such an organization, jurisdiction over environmental contamination in the event of an accident is not necessarily clear. The division of roles between the two organizations is also an issue on an event of emergency, and needs to be discussed as soon as possible. In addition, care should be taken to ensure that the change in jurisdiction does not result in omissions of the archived data, information, and in ongoing monitoring on the 1F accident, as mentioned in Section IV.A.

C. Importance of education on radiation

The environmental contamination caused by the nuclear accident is a matter of concern not only to the affected parties but also to the public at large, and this concern extends internationally. With the spread of social networking services (SNS), various information about the effects of the environmental contamination caused by the accident was also sent out from sources other than public institutions and mass media. In such a situation, various information became complicated, and there were situations where the public's accurate understanding was hindered.

Considering the historical experience with radiation, our country should have the most comprehensive education and human resource development in the world. However, the 1F accident has revealed the lack of public knowledge about radiation and its data handling. Radiation has always existed in our living space and has been used in various ways, including in medicine and agriculture. However, systematic education has not always been sufficient. In the event of a major accident in the future, there are concerns about the lack of knowledge how to avoid dangerous situations and about the possibility of high-risk behavior due to excessive anxiety. Such problems would be eased if more people shared the knowledge of radiation that is currently agreed upon by the scientific community. Since the accident, school education has been enhanced through the revision of teaching guidelines and textbooks and the efforts of teachers. In addition, we recommend the related academic associations to propose the following measures to MEXT hoping for a quick implementation of them.

1. In school education, basic knowledge on radiation and its data handling needs to be systematically introduced in elementary, middle, and high schools. Science teachers need to be given opportunities to improve their skills as necessary. Measures should be taken to incorporate educational programs for teachers that include cutting-edge topics on radiation.
2. Lectures on environmental radioactivity and radiation should be given as part of general education at universities. The lectures should be open to all students, regardless of faculty or department, and in some cases open to the general public.
3. In cases where there are no faculty members in the relevant field at the university, or when there are no faculty members available for teacher training, the relevant academic associations will take the lead in delegating university faculty (including retired faculty) in the appropriate field.

In addition, it will be very effective as a place for practical education on radiation if some of the area is preserved without decontamination or modification for the future research mentioned above. Following the example of Chornobyl, if this area is managed as an international joint education and research center by researchers and local governments from around the world, it can become a symbolic place that contributes to the world in both terms of education and research.

V. Summary of the report

A. Cooperation between the research fields of accident progression analysis and environmental impact analysis

In the informal working group for exchange of accident and environmental information, 10 meetings were held during the 23rd and 24th terms, and experts in both accident progression analysis and environmental information and environmental impact analysis provided each other with the latest analysis results. They exchanged information on the chemical form of the release of radioactive radioiodine, radiocesium, and other radionuclides, the timing of the release, and the events in the reactor that caused the release.

However, for short-lived radionuclides, the measured data in the early post-accident period are extremely limited, and the temporal variation depends greatly on the propagation of the reactor accident events. Although it is difficult at present to obtain information on the amount of release of each radionuclide and the change in its chemical form over time, which is required for the analysis of environmental effects, from the accident progression analysis code alone, the information exchange between the two research fields is of great significance for inferring the causes of the observed changes in the composition and form of radionuclides in the environment. For the time-series elucidation of the environmental release during the accident, the elucidation of the release pathways from the containment and building as well as the in-core events is an important issue.

B. Necessity of environmental dynamics model and environmental monitoring according to the time elapsed since the accident

The atmospheric transportation, dispersion and deposition models (ATDMs) plays an important role from the perspective of dry and wet deposition on the ground surface, which is the main cause of the clarification of initial internal exposure and subsequent formation of contamination over the medium- and long term. Since the 22nd term's report [6], an international comparison of the ATDMs has been further developed, and new measured values that reproduce the events of that time have been obtained. Within a few years after the accident, interdisciplinary research, and modeling of the mid- to long-term environmental fate of radioactive materials within and among various components of the environment, such as rivers, dams and reservoirs, estuaries, coastal areas, marine areas, and other aquatic systems, forests, farmland, urban areas, and other land and soil, and their ecosystems, was conducted by many organizations. In addition, a large amount of statistical data on environmental monitoring has been collected. In addition, models for future prediction of air dose rates were developed including a sophisticated model based on statistical analysis and empirical equations from a large amount of environmental monitoring. These results were also provided to international organizations such as UNSCEAR and IAEA. Although actual measurements are indispensable for the validation of the model, it is possible to obtain the data from the samples collected immediately after the accident to make up for the initial lack of actual measurements.

While monitoring by government agencies, which was initiated as an immediate response to an emergency, is on a downward trend, it is important to continue monitoring in order to assess the medium- and long-term trends of contamination and to obtain information that is essential for scientific clarification of events.

C. Long term organizational response to prevent information dissipation

Measurement data on the environmental impact of the accident, such as air dose rates and concentrations of radionuclides in environmental media, have been improved step by step to facilitate centralized access to information involving public organizations such as national and local administrative agencies and research institutes. On the other hand, measurement data obtained by academic research institutions such as universities are rarely made public in their entirety, making it difficult to grasp them in an integrated manner. In addition, it is extremely difficult to preserve the information obtained by other entities, including individuals. Since it was urgent to create an archive of this series of information, the main body of data collection and methods of collection and publication were discussed, and a metadatabase was constructed to collect metadata and search for the site of data from meta-information. However, in order to prevent the information from being lost over the long term, a permanent archiving organization is needed to systematically handle the storage of information related to the environmental impact of the accident. It is also necessary to establish a long-term system in cooperation with public archival institutions such as the National Diet Library and the National Archives of Japan. With regard to environmental samples, in order to prevent the dissipation of useful samples and the dispersion of contamination, it is an urgent issue to establish a system for the storage management of samples that could be useful in the future (including the establishment of decision indicators for sample storage) and for the collection and disposal of needless samples.

D. Cooperation and role sharing between academia and government agencies

In the event of an emergency at a nuclear facility, members of academia may participate as experts in response to a request from a government agency. On the other hand, it is important to ensure the independence, neutrality, and autonomous dissemination of information as academia, as well as to guarantee the freedom of speech and ideas of researchers, in order to ensure a prompt and appropriate response in an emergency and the reliability of the information disseminated. At the same time, it is also the mission of academia to view the issue as an academic subject from a long-term and humanistic perspective. A system to ensure cooperation between academia and government agencies and to share information and requests quickly and smoothly is required, as well as a system that allows researchers to make long-term commitments and to maintain research funds for emergencies.

E. Importance of education on radiation

This accident has revealed the lack of knowledge related to radiation in our society. It is an important role of the government to popularize knowledge on radiation. It is necessary to establish systematic education on radiation in schools. At universities lectures should be arranged on environmental radiation and related matter that can be taken by all students regardless of faculty or department as part of comprehensive education at universities. In order to realize such measures, the relevant academic associations are expected to propose concrete plans to the MEXT.

F. Need for a full picture of research progress, interdisciplinary analysis and reporting of environmental contamination research as the party concerned

Although several accident investigation reports were made at a relatively early stage after the accident, there was no centralized action on the part of the government regarding environmental contamination caused by the accident even after the reorganization of the nuclear regulatory administration. For this reason, the recommendation of the Subcommittee on Countermeasures for Radiation of the 22nd term's Committee on Supporting Reconstruction after the Great East Japan Earthquake [5] pointed out the need for interdisciplinary and cross-ministry efforts regarding the environmental impact of the accident, and mentioned a new academic framework to support the nuclear regulatory administration. Surveys and researches by related ministries, agencies, and fields, including those funded by competitive research grants, have progressed, and interdisciplinary researches have been developed, and many results have been obtained in these series of surveys and researches. However, because of the wide variety of fields, it is not easy to grasp the whole picture. Therefore, interdisciplinary analysis has not progressed sufficiently. As we approach the 10-year anniversary of the accident, this report itself is intended to play a role in helping to achieve this goal. As for some of the issues, reports by international organizations are being prepared for the 10-year anniversary of the accident, but the challenge is to compile a more comprehensive and detailed report as the party concerned to the accident so that the full picture of the environmental impact of the 1F accident can be understood. In addition, it is proposed that environmental modifications should not be carried out in some areas to allow long-term environmental contamination surveys and training in fields where higher radioactive contamination is present.

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<Reference Material 1>

Progress of the 24th term's Working Group and deliberations on this report in the Subcommittee

2018

May 7: Environmental Contamination Investigation Working Group (1st meeting)

Election of officers, report on activities in the previous term, activity plan for the current term, establishment of IWGs

September 4: Subcommittee on Nuclear Safety (5th meeting)

Report on the activities of the Environmental Contamination Investigation Working Group and confirmation of the composition of its members, including IWGs

2019

February 12: Environmental Contamination Investigation Working Group (2nd meeting)

Deliberated policy aiming manifestation of intention such as the SCJ's "Report" in the 24th term.

April 11: Subcommittee on Nuclear Safety (8th meeting)

Endorsed the policy of compiling the results of the activities of the Environmental Contamination Investigation Subcommittee into a SCJ's "Report".

2019

July 11: Environmental Contamination Investigation Working Group (3rd meeting)

Decision to adopt "Report" as the manifestation of intention, and discussion of policy for preparing an outline of the Report

July 24: Subcommittee on Nuclear Safety (9th meeting)

Presentation of the policy for preparing the outline and approval of the preparation of the Report on the Environmental Contamination Investigation

November 26: Environmental Contamination Investigation Subcommittee (4th meeting)

Discussion on the contents of the draft Report

December 2: Subcommittee on Nuclear Safety (11th meeting)

Discussion and approval of the draft report of the Subcommittee

2020

May 14: Executive Board Meeting of the Science Council of Japan (290th meeting)

Approval of the report "Progress and Challenges in Research and Studies on Environmental Contamination Caused by the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station"

<Reference Material 2>

Main abbreviations and technical terms used in the text

- ATDM: Abbreviation for Atmospheric Transportation, Dispersion and Deposition Model
- doi: Acronym for Digital Object Identifier, an international identifier assigned to electronic data of content.
- FP: Abbreviation for Fission Product A general term for nuclides produced by fission and a series of radioactive decays, most of which are radionuclides, such as ^{131}I and ^{137}Cs, and which stabilize after several cycles of radioactive decay.
- IAEA: Abbreviation for International Atomic Energy Agency, one of the United Nations agencies. Headquartered in Vienna, Austria.
- PCV: Abbreviation for Primary Containment Vessel, which is an airtight vessel that contains the reactor, primary cooling system, and related equipment, which acts as a pressure barrier in the event of a loss of primary coolant accident and forms a barrier to prevent the release and diffusion of radioactive materials. It can be made of steel or pre-stressed concrete.
- Phébus FP project: A large-scale FP release and transfer experiment established in 1988 and conducted from 1993 to 2004 using the Phébus experimental reactor at the Cadarache Nuclear Research Center in France.
- RPV: Abbreviation for Reactor Pressure Vessel, which is a high-pressure vessel that contains the reactor core, in-core structures, primary coolant, etc. In a BWR (boiling water reactor), it is required to withstand a pressure of 6.7 MPa in the primary system. It is made of high tensile steel with a thickness of about 14 cm, and the wetted parts on the inner surface are treated with stainless steel surface.
- SAMPSON code: A severe accident analysis code owned by the Institute of Applied Energy, Japan. It analyzes various phenomena, from reactor scram to containment failure, mechanistically without adjustment factors by user input. It is characterized by the explanatory nature of physical phenomena for the results.
- UNSCEAR: Abbreviation for United Nations Scientific Committee on the Effects of Atomic Radiation
- WSPEEDI: Abbreviation for Worldwide version of System for Prediction of Environmental Emergency Dose Information, which was developed by the Japan Atomic Energy Research Institute (JAERI) with the cooperation of the Meteorological Research Institute and other organizations, as a disaster countermeasure in the event that a large amount of radioactive materials are released into the environment by a severe nuclear accident. It is a calculation system for rapid prediction of the transport, dispersion, and deposition in the atmosphere and subsequent impacts on the environment and the general public, including radiation dose and exposure dose. The radiation dose rate calculation module is connected to ATDM (described above). Based on numerical meteorological data, a three-dimensional meteorological field is obtained, taking into account the topography, and the predicted values of atmospheric concentration and air dose rate of radioactive materials released into the atmosphere are calculated.
- Imaging plate: Also called IP. A special phosphor, called a bright illuminant, painted to a plastic film, which detects radiation such as X-rays, electrons, and neutrons with high sensitivity and produces a two-dimensional digital image.

- Inventory: The original term has a wide range of meanings, such as property inventory, asset register, product inventory, list, etc., and is used with a specific meaning depending on the field. In this report, it refers to the type and amount of radionuclides left in the core of the accident reactor.
- Weathering: The original word means changes over a period by weather conditions. In the environment, the weathering process occurs due to exposure to fluctuating conditions such as wind, rain, solar radiation, high and low temperatures, etc.
- Inverse analysis: The problem of finding an output (result or observation) from an input (cause) is called a forward problem, while the problem of estimating an input from an output or estimating the relationship between input and output is called an inverse problem, and the calculation method for inverse problems is called inverse analysis.
- Exchangeable potassium: Potassium is one of the three elements of plant fertilizer, and it takes three forms in the soil: exchangeable potassium, fixed potassium, and potassium in primary minerals. Exchangeable potassium is the potassium ion (K^+) adsorbed on the cation exchange site of clay, and is the form that can be absorbed by plants.
- Effective relaxation mass depth: A variable that describes the depth distribution of the concentration of radionuclides after a certain time has elapsed since they were migrated in the soil column. It is the mass depth at which the radioactivity concentration is 1/e (≈1/2.7) of the ground surface.
- Severe accident (SA): An event (accident) corresponding to the fourth layer of barriers in depth., in which the core is severely damaged due to an event significantly exceeding the design basis event and beyond the control of the existing engineering safety equipment. Also referred to as a reactor core-damaged accident.
- Screening effect: Screening refers to tests to detect diseases during their incubation period. It refers to the fact that when a wide range of tests are performed, asymptomatic and unrecognized diseases and findings are found with high frequency.
- Semipalatinsk: Name of a place in the northeastern province of Kazakhstan (renamed Semey in the late 1990s). Four hundred and sixty-seven (467) nuclear tests were conducted at the test site from the first Soviet atomic bomb test on August 29, 1949 to October 19, 1990, which is about 65% of the 714 nuclear tests conducted by the former USSR.
- Source term: The time evolution of the type, amount, physical and chemical form, and especially the emission rate of pollutants that may be released outside the facility in the event of an accident or malfunction at a facility that handles substances that may pollute the environment.
- Car-borne survey: Continuous measurement of the air dose rate by a moving monitoring vehicle.
- Multiple barriers: In nuclear power plants, in addition to engineering safety equipment in case of an accident, radioactive materials are confined by five layers of physical barriers (multiple protective barriers) such as the reactor vessel and containment vessel. On the other hand, defense in depth means that irregular events are ranked into five layers, and the events within the design criteria are dealt with in layers 1-3. For events outside the design basis, the fourth barrier layer (against severe accident) is to minimize the release of radioactivity, and the fifth layer is to minimize the impact of radioactive materials on the surrounding residents as an emergency plan.
- Digital archive: An English word coined in Japan that refers to the digitization and preservation of tangible and intangible cultural resources (cultural materials and cultural goods), including the collections of museums, art galleries, archives, and libraries. Digitization facilitates the disclosure of cultural resources and their use through networks and other means.

- Bulk separation method: The original word "bulk" means "lumping together" or "aggregate" and in this case it means a method for separating insoluble cesium particles, mainly silica glass, which have similar properties.
- Vent: An emergency measure to reduce the pressure of a reactor containment vessel by venting a portion of the gas containing radioactive materials to the outside in order to prevent the pressure inside the vessel from rising to the point where cooling water injection is no longer possible or the containment vessel is damaged.
- Radioactive plume: The original meaning of the word "plume" is "feather". A phenomenon in which material emitted into the atmosphere flows like smoke or clouds.
- Walk survey: A method of collecting data by measuring the air dose rate on foot in a living environment or forest environment where monitoring vehicles cannot enter.
- Metadata: Data about data, not about the data itself, but about the attributes and related information that describe the data.

(Source: Nuclear Energy Dictionary, Atomic Energy Society of Japan Accident Investigation Report, Atomic Energy Encyclopedia ATOMICA, Weblio Dictionary, and Kotobank)

<Reference Material 3>

Materials and figures related to environmental contamination research and studies

1. Competitive external funding for research and radiation education related to the Fukushima Daiichi Nuclear Power Plant accident

(1) Competitive external funding for research related to the Fukushima Daiichi Nuclear Power Plant accident

Ministry of Education, Culture, Sports, Science and Technology

1) Academic research activity support project: Fukushima Innovation Coast Initiative promotion project using "reconstruction knowledge" of universities, etc. (from 2018) (related to radiation effects)

2) Grant-in-Aid for Scientific Research on Innovative Areas (Research Area Proposal Type): Interdisciplinary study on environmental transfer of radionuclides from the Fukushima Daiichi NPP accident (2012-2016)

3) Joint Usage/Research Center Project: Environmental Radioactivity Research Network Center (2019-2021)

Ministry of the Environment

4) Research and Survey on the Effects of Nuclear Emergency (Research and Survey on Radiation Health Effects) (2012-2017)

Radiation Health Management and Health Anxiety Countermeasures Project (Research and Survey Project on Health Effects of Radiation) (2018-)

(2) Competitive external funding for the promotion of radiation education after the accident at the Fukushima Daiichi Nuclear Power Plant of TEPCO (for university education and above)

Ministry of Education, Culture, Sports, Science and Technology

5) International Nuclear Human Resource Development Initiative Project (Issues adopted since 2011)

6) Program for developing human resources for advanced medical care with problem-solving approach (area related to radiation health risk including radiation disaster) (2016-2020)

Nuclear Regulatory Authority

7) Subsidy for promotion of nuclear human resource development (2016-2017)

8) Funding for strategic promotion of research on radiation safety regulations (radiation education and safety management network based on the Isotope Research Center for the realization of sound radiation protection) (2017-2022)

Source: Kanda, R.: "International Education and Research Hub: Current Status and Issues from the Viewpoint of Radiation Research Field", Document 2-5, Expert Meeting on International Education and Research Hub in Fukushima Hamadori Area (3rd Meeting), held on September 19, 2019.

2. Major domestic conferences/academic societies where research related to environmental pollution caused by the Fukushima accident has been presented

Atomic Energy Society of Japan, Japan Society of Health Physics, Annual meeting on Radioisotope and Radiation Researches, The Japanese Radiation Research Society, Japan Society for Radiation Safety Management, Environmental Radiology Conference, The Society for Remediation of Radioactive Contamination in the Environment, The Japan Society of Nuclear and Radiochemical Sciences, Japan Geoscience Union (JpGU)

3. Main features in academic journals and papers

Special Issue on MEXT's Large-Scale Research Project on Soil Survey in Accordance with TEPCO's Fukushima Daiichi Nuclear Power Plant Accident, *Radioisotopes*, 2013, 62（10).
https://www.jstage.jst.go.jp/browse/radioisotopes/62/10/_contents/-char/ja

A special issue of the Journal of Environmental Radioactivity related to distribution surveys

・Saito, K., Onda, Y., Hisamatsu, S. (Edits.): Special Section on Japanese National Projects on Large-scale Environmental Monitoring and Mapping in Fukushima Volume 1. *Journal of Environmental Radioactivity*, 139, 240-434, 2015.

・Saito, K., Onda, Y., Hisamatsu, S. (Edits.): Special Issue on Japanese National Projects on Large-scale Environmental Monitoring and Mapping in Fukushima Volume 2. *Journal of Environmental Radioactivity*, 166, 417-474, 2017.

・Saito, K., Onda, Y., Hisamatsu, S. (Edits.): Special Issue on Five years of Fukushima. *Journal of Environmental Radioactivity*, 210, 2019.

Reference Table 1: Major Recommendations related to the Great East Japan Earthquake and the nuclear power station accident by the Science Council of Japan (21st-22nd term)

Source: Compiled from "Recommendations and Reports" on the Science Council of Japan website.

Term	Issue date	Name of the Committee or Subcommittee in charge	Title* of the Recommendation
21	March 25, 2011	Great East Japan Earthquake Task Force	The first emergency recommendation regarding the response to the Great East Japan Earthquake
21	Apr. 4, 2011	Great East Japan Earthquake Task Force	The 2nd emergency recommendation regarding the response to the Great East Japan Earthquake: "Regarding the necessity of the investigation of radiation levels after the accident of the Fukushima Daiichi Nuclear Power Plant
21	Apr. 5, 2011	Great East Japan Earthquake Task Force	The 3rd emergency recommendation regarding the response to the Great East Japan Earthquake "For the relief of victims of the Great East Japan Earthquake and recovery of the disaster-stricken areas
21	Apr. 5, 2011	Great East Japan Earthquake Task Force	The 4th emergency recommendation regarding the response to the Great East Japan Earthquake: "Urgent proposal related to measures for earthquake disaster waste and prevention of environmental impact
21	Apr. 13, 2011	Great East Japan Earthquake Task Force	The 5th emergency recommendation regarding the response to the Great East Japan Earthquake: "Utilization of robot technology for the accident of the Fukushima Daiichi Nuclear Power Plant
21	Apr. 5, 2011	Great East Japan Earthquake Task Force	The 6th emergency recommendation regarding the response to the Great East Japan Earthquake: "Perspective of gender equality with regard to relief, support and restoration
21	June 8, 2011	Subcommittee on Grand Design for Reconstruction of Disaster-stricken Areas, Great East Japan Earthquake Task Force	Toward the Recovery of Areas Stricken by the Great East Japan Earthquake: Goals and Seven Principles for Recovery
21	June 24, 2011	Subcommittee on Energy Policy Options, Great East Japan Earthquake Task Force	Toward the Selection of Japan's Future Energy Policy: Six Scenarios for Electricity Supply Sources
21	Aug. 3, 2011	Great East Japan Earthquake Task Force	The 7th emergency recommendation regarding the response to the Great East Japan Earthquake "Scientific Survey and Analysis of Movement of Radioactive Substances over a Wide Area
21	Sep. 21, 2011	Great East Japan Earthquake Task Force & Subcommittee on New Japanese Society after 3.11 of Section 1	Employment Support and Industrial Revitalization Support in the Recovery from the Great East Japan Earthquake
21	Sep. 27, 2011	Great East Japan Earthquake Task Force & Birth and Development Subcommittee, Clinical Medicine Committee	Protecting children from the effects of the Great East Japan Earthquake and subsequent nuclear accident
21	Sep. 30, 2011	Subcommittee on Grand Design for Reconstruction of Disaster Area, Great East Japan Earthquake Task Force	Toward the Recovery of Areas Affected by the Great East Japan Earthquake - Goals and Seven Principles for Recovery (Second Proposal)
21	Sep. 30, 2011	Fisheries Science Subcommittee, Great East Japan Earthquake Task Force, Committee on Food Science	From the Great East Japan Earthquake to the Recovery of the Fisheries Industry in a New Era
22	Apr 9, 2012	Committee on Supporting Reconstruction after the Great East Japan Earthquake	Recommendations from Science Council of Japan with Confident Steps towards Reconstruction -
22	Apr 9, 2012	Committee on Supporting Reconstruction after the Great East Japan Earthquake	On Cross-regional Processing of Disaster Wastes?
22	Apr 9, 2012	Subcommittee on Building Disaster-Resilient Communities, Committee on Supporting Reconstruction after the Great East Japan Earthquake	Building Tsunami-proof Communities -Show How Tohoku Reconstruction Makes Use of Nature
22	Apr 9, 2012	Subcommittee on the Promotion of Industry and Employment, Committee on Supporting Reconstruction after the Great East Japan Earthquake	Supporting Job-Seekers e and the Establishing Reconstruction Non-profits in Disaster-Stricken Areas– Towards the Promotion of Industry and Employment to Support Victims in Disaster-Stricken Areas -
22	Apr 9, 2012	Subcommittee on Counter-measures for Radiation, Committee on Supporting Reconstruction after the Great East Japan Earthquake	A New Step towards Counter-measures for Radiation Towards Science-based Policy Action
22	Dec. 5, 2012	Subcommittee on Environmental Policy and Planning, Committee on Environmental Studies	An Urgent Proposal for the Formation of a Platform for Reconstruction and Urban Development Utilizing the Power of People and Community
22	Dec. 5, 2012	Subcommittee on Environmental Policy and Planning, Committee on Environmental Studies	An Urgent Proposal for the Integration of Disaster Waste Policy, Multiple Protection Policy, and Biodiversity Policy for the Early Realization of Safe Coastal Zone Formation that Nurtures Life
22	Jan. 31, 2013	Committee on Earth and Planetary Science	Towards the sharing of geological information - Legislation on geological information for the construction of a safe and secure society

22	March 28, 2013	Committee for the Review of Academic Research on the Great East Japan Earthquake	Academic Research on the Great East Japan Earthquake: Issues and Future Prospects
22	May 2, 2013	Subcommittee on Welfare, Committee on Sociology	The Role of Social Welfare in Disasters: Including Responses to the Great East Japan Earthquake
22	June 27, 2013	Subcommittee on the Structure of Damage Caused by the Great East Japan Earthquake and the Path to Rebuilding Japanese Society, Committee on Sociology	Recommendations on issues and approaches necessary for recovery and reconstruction from the nuclear power plant disaster
22	Sep. 6, 2013	Subcommittee on Fukushima Reconstruction Support, Committee on Supporting Reconstruction after the Great East Japan Earthquake	Urgent Proposal for Systematization of Inspection System to Counter the "Rumor" Problem of Food and Agriculture Following the Nuclear Disaster
22	March 31, 2014	Subcommittee on Radiology and Laboratory Medicine, Committee on Clinical Medicine	Establishment of a base for internal isotope therapy for urgent radiation treatment
22	Apr. 23, 2014	Subcommittee on Building Disaster-Resilient Community, Committee on Supporting Reconstruction after the Great East Japan Earthquake & Subcommittee on Environmental Policy and Planning, Committee on Environmental Studies	Proposals for the Restoration of Coastal Forests for the Formation of Safe Coastal Areas that Nurture Life
22	June 10, 2014	Subcommittee on Fisheries Science, Committee on Food Science	From the Great East Japan Earthquake to the Recovery of the Fisheries Industry in a New Era (Second Proposal)
22	June 13, 2014	Subcommittee on Nuclear Accident Response, Committee on Comprehensive Synthetic Engineering	Lessons Learned from the Accident at TEPCO's Fukushima Daiichi Nuclear Power Plant
22	Aug. 20, 2014	Subcommittee on Environmental Policy and Planning, Committee on Environmental Studies	New Developments in Environmental Policy and Planning Based on the Principles of Earthquake Reconstruction
22	Aug. 25, 2014	Subcommittee on Soil Science, Committee on Agricultural Science	Promotion of Decontamination in Radioactively Contaminated Areas - Scientific Decontamination that Confronts the Reality
22	Sep. 4, 2014	Subcommittee on Environmental Risk, Committee on Health and Life Science and Committee on Environmental Studies	Preparing for the Occurrence of a Large-Scale Disaster Involving a Nuclear Power Plant Accident from the Perspective of Environmental Risk
22	Sep. 4, 2014	Subcommittee on Radiation Protection and Risk Management, Committee on Clinical Medicine	Enhancement of radiation health risk science education, including making it compulsory in medical education
22	Sep. 11, 2014	Subcommittee on Science and Society after the Fukushima Nuclear Disaster of Section 1	Toward a Better Relationship between Science and Society: Considering the Loss of Trust after the Fukushima Nuclear Disaster
22	Sep. 16, 2014	Subcommittee on Promotion of Industry and Employment, Committee on Supporting Reconstruction after the Great East Japan Earthquake	Continue to provide employment support and industrial promotion to the victims
22	Sep. 19, 2014	Subcommittee on Counter-measures for Radiation, Committee on Supporting Reconstruction after the Great East Japan Earthquake	For long-term radiation countermeasures for reconstruction - Necessity of cross-ministry radiation countermeasures with academic experts
22	Sep. 22, 2014	Subcommittee on Building Resilience to Disasters, Committee on Supporting Reconstruction after the Great East Japan Earthquake	Toward greater resilience to disasters
22	Sep. 25, 2014	Subcommittee on the Structure of Damage Caused by the Great East Japan Earthquake and the Path to Rebuilding Japanese Society, Committee on Sociology	Recommendations on Improving Reconstruction Policies after the Great East Japan Earthquake
22	Sep. 30, 2014	Subcommittee on Fukushima Reconstruction Support, Committee on Supporting Reconstruction after the Great East Japan Earthquake	Proposals for the Reconstruction of the Lives and Homes of Long-term Evacuees from the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station
22	Sep. 30, 2014	Subcommittee on Earth and Anthroposphere, Committee on Earth and Planetary Science	Toward the formation of a safe, secure, and sustainable society based on lessons learned from the Great East Japan Earthquake
22	Sep. 30, 2014	Committee on Earth and Planetary Science	The Future Relationship between Earth and Planetary Science and Society -Lessons Learned from the Tohoku-Pacific Ocean Earthquake, Tsunami, and Radioactive Material Diffusion Problems

*) Many of the Recommendations are available only in Japanese and no official English title, for which tentative translation was applied.

Reference Table 2 Areas related to radiation and radioactivity in the review categories of scientific research funding

Source: Created by extracting sections that include the word "radiation" or “radio-“ in the section name or keywords, based on the review section table of the Japan Society for the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research FY 2018.

Basic Section		Medium-sized Section	Broad Section
31010	Nuclear engineering-related (Radiation safety, Radiation beam engineering)	31 Nuclear engineering, earth resources engineering, energy engineering, and related fields	D Engineering
34020	Analytical chemistry-related (Radiochemical analysis)	34 Inorganic/coordination chemistry, analytical chemistry, and related fields	E Chemistry
34030	Green sustainable chemistry and environmental chemistry-related （Environmental radioactivity）		
47020	Pharmaceutical analytical chemistry and physicochemistry-related (Radiochemistry)	47 Pharmaceutical sciences and related fields	H Pharmacology and Pathology
50020	Tumor diagnostics and therapeutics-related (Radiation therapy)	50 Oncology and related fields	I Medicine and Dentistry
52040	Radiological sciences-related （Diagnostic radiology, Therapeutic radiology, Radiation biology, Radiological technology）	52 General internal medicine and related fields	
57060	Surgical dentistry-related （Dental radiology）	57 Oral science and related fields	
63020	Radiation influence-related（Radiation, Measurement, Control, Repair, Biological effects, Risk, etc.）	63 Environmental analyses and evaluation and related fields	K Environmental Studies
64020	Environmental load reduction and remediation-related（Radioactive decontamination）	64 Environmental conservation measure and related fields	
80040	Quantum beam science-related （Radiation detector）	14 Plasma science and related fields 15 Particle-, nuclear-, astrophysics, and related fields	B Science

Reference Table 3: List of major monitoring in line with the Comprehensive Monitoring Plan

Monitoring targets	Contents	Target area	Organizations in charge
General environments throughout Fukushima Prefecture	・Measurement of air dose rates and integrated doses by various methods (monitoring posts, survey meters, helicopter surveys, car-borne surveys, etc.) ・Measurement of airborne dust, monthly fallout, and water supply ・Measurement of deposition and concentrations in soil ・Measurement of concentrations in indicator plants ・Data mapping and publishing	・Fukushima Prefecture and neighboring prefectures ・Within 80 km zone ・Living environments ・Evacuation zone	・Nuclear Regulation Authority ・Nuclear Emergency Response Headquarters ・Fukushima Prefectural Government, and governments of neighboring prefecture ・Nuclear operators ・Others
Aquatic environments	・Measurements of concentrations in water, bottom sediment, and environmental samples collected at rivers, lakes and marshes, etc. ・Measurement of concentrations in sea water and air dose rates at swimming beaches ・Measurement of concentrations in ground water and potable well water	・Fukushima Prefecture and neighboring prefectures	・Ministry of the Environment ・Fukushima Prefectural Government
Sea area	・Measurement of concentrations in seawater and bottom sediment ・Measurement of concentration in marine biota	・Nearshore sea area ・Coastal sea area ・Offshore sea area ・Open sea ・Tokyo bay	・Nuclear Regulation Authority ・Fisheries Agency ・Ministry of Land, Infrastructure, Transport and Tourism ・Japan Coast Guard, ・Ministry of the Environment ・Fukushima Prefectural Government ・Nuclear operators ・Others
Schools and other locations	・Measurement and disclosure of air dose rates in school yards and other locations ・Measurement of concentrations in outdoor pool water ・Measurement of concentrations in food ingredients used to prepare school-provided lunches	・Kindergartens, primary schools, junior high schools, high schools, daycare centers, parks, and other public facilities in Fukushima Prefecture ・Child welfare facilities in Fukushima Prefecture ・Others	・Nuclear Regulation Authority ・Ministry of Education, Culture, Sports, Science and Technology ・Fukushima Prefectural Government ・Local governments ・Others
Ports, airports, parks, sewage systems, and more	・Measurement of air dose rates at ports, airports, city parks, etc. ・Measurement of concentrations in sewage sludge	・Ports in the Tohoku and Kanto regions ・Dominant airports ・City parks and tourist sites in Fukushima Prefecture ・Sewage sludge treated by concerned local governments	・Ministry of Land, Infrastructure, Transport and Tourism ・Fukushima Prefectural Government ・Local governments ・Others
Wild fauna and flora, waste, removed soil, and more	・Sampling and analysis of wild fauna and flora ・Measurement of concentrations in exhaust gas and wastewater discharged by waste incineration facilities etc. ・Measurement of air dose rates at site boundaries	・Fukushima Prefecture and neighboring prefectures	・Ministry of the Environment ・Fukushima Prefecture Government ・Local governments ・Relevant business operators ・Others

Agricultural soil, forests and fields, pastures, and elsewhere	・Investigation of concentrations and transfer characteristics of radionuclides in agricultural soil ・Measurement of concentrations in forest soil, branches, leaves, bark, and timber ・Measurement of concentrations in pastures ・Measurements of concentrations in reservoirs and other	・Fukushima Prefecture and relevant prefectures	・Ministry of Agriculture, Forestry and Fisheries ・Forestry Agency ・Fukushima Prefectural Government ・Local governments ・Others
Water supply	・Inspection of purified water and raw water ・Measurement of concentrations in tap water collected at each water source point	・Prefectures concerned ・Fukushima Prefecture	・Ministry of Health, Labour and Welfare ・ Nuclear Emergency Response Headquarters ・Local governments ・Others
Foodstuff (agricultural, forestry, livestock, fishery products, and more)	・Survey of radionuclide concentrations in food stuff ・Estimation of exposure dose levels attributed to the intake of foodstuff	・Various locations including Fukushima Prefecture	・Ministry of Health, Labour and Welfare ・Nuclear Emergency Response Headquarters ・Ministry of Agriculture, Forestry and Fisheries ・Fukushima Prefectural Government ・Local governments ・Others
Nationwide general environments	・Measurement of air dose rates at monitoring posts and real-time disclosure via the Internet ・Measurement of monthly fallout per month and supplied water per year ・Airborne monitoring	・Each prefecture ・Areas with relatively high air dose rates in neighboring prefectures	・Nuclear Regulation Authority ・Local governments ・Others

Reference Table 4: Summary of the Fukushima mapping project and airborne monitoring

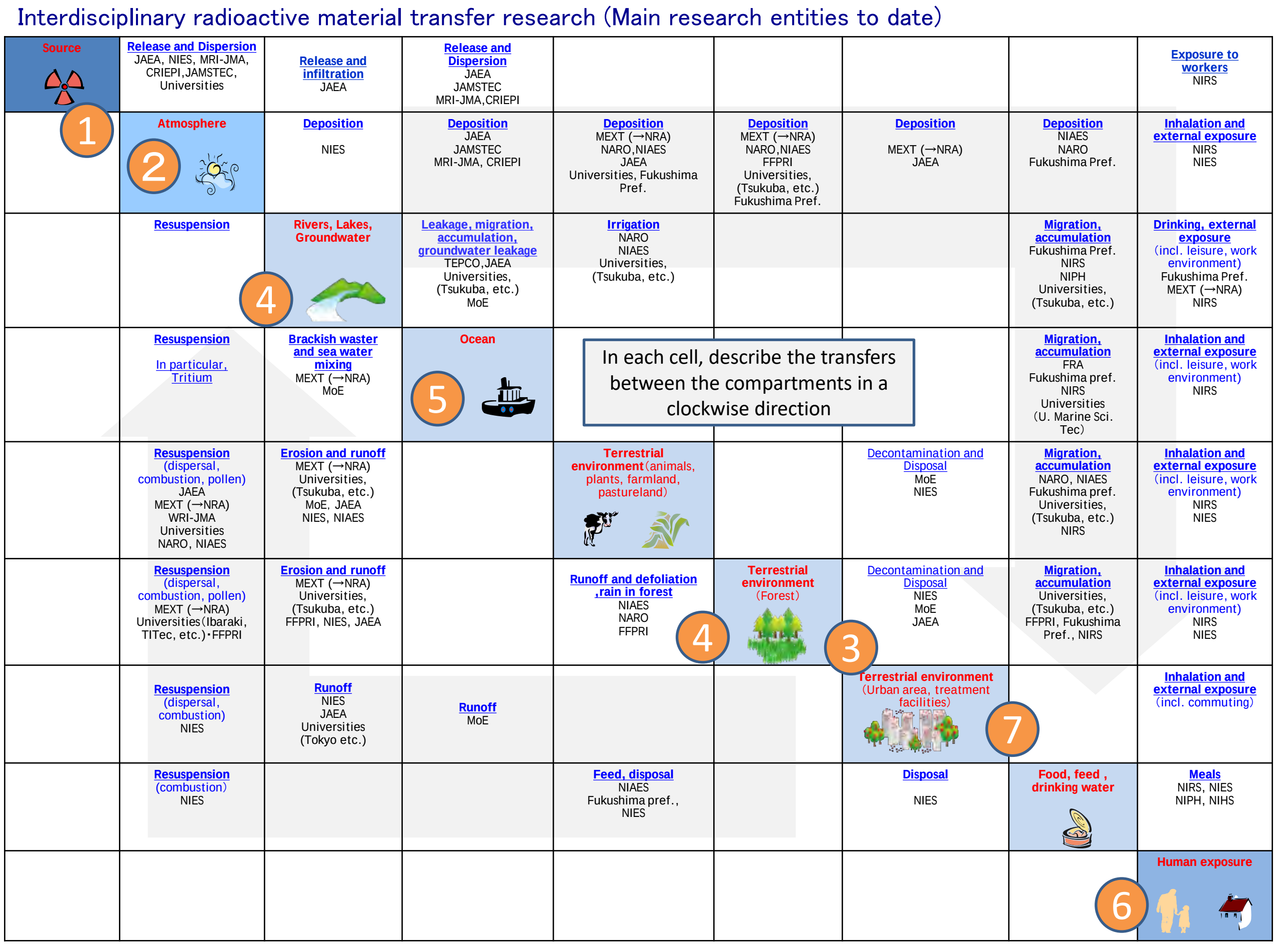
Fukushima mapping project

Period	Contents	Main target areas	Implementing organizations	Responsible authority
2011/6-2011/11	・Measurement of deposition densities (soil sampling and analysis) ・Measurement of air dose rate at fixed locations ・Car-borne survey ・Investigation on environmental migration ・Investigation on agricultural soil ・Map creation and publication	・Within 100 km ・Throughout Fukushima Prefecture	JAEA, Osaka Univ., Kyoto Univ., Univ. of Tsukuba, Univ. of Tokyo, NIRS, JCAC, FEPC, JMC, etc. (more than 700 participants from more than 120 organizations)	MEXT
2011/12-2015/3	・Measurement of deposition densities (in situ measurement, soil sampling and analysis) ・Measurement of depth profiles in ground ・Measurement of air dose rates at fixed locations ・Car-borne survey ・Investigation and modeling on environmental migration ・Map creation and publication ・Development of prediction model	・Within 80 km ・Wide area in eastern Japan (2nd campaign, car-borne survey) ・Within 3-5 km (unmanned helicopter survey)	JAEA, NIRS, Kyoto Univ., about 200 local governments, JCAC, NUSTEC, IRM, RIKEN, IRSN, Univ. of Tsukuba, TEPCO, IES, Osaka Univ., Univ. of Tokyo, Gakushuin Univ., Hiroshima Univ., Kanazawa Univ., Nagoya Univ., TIT, Chiba Univ., Ibaraki Univ., Fukushima Univ., NIAES, JMC, etc.	MEXT NRA (FY 2013, FY 2014)
2015/4-2020/3	・Measurement of deposition densities (in situ measurement, soil sampling and analysis) ・Measurement of depth profiles in ground ・Measurement of air dose rates at fixed locations ・Car-borne survey ・Unmanned helicopter survey ・Walk survey ・Map creation and publication ・Development of prediction model	・Within 80km ・Wide area in eastern Japan (car-borne survey) ・Within 5 km (unmanned helicopter survey)	JAEA, about 70 local governments, JCAC, NUSTEC, IRM, IES, JMC, etc.	NRA

Airborne monitoring

Period	Contents	Targeted areas	Implementing organizations	Responsible authority
2011/4	・Monitoring by helicopter and by aircraft ・Conversion to air dose rate at 1 m height and deposition densities of radiocesium ・Map creation and publication	・Within 80 km	DOE NUSTEC, DOE	MEXT
2011/5-2013/3	・Monitoring by helicopter ・Conversion to air dose rate at 1 m height and deposition densities of radiocesium ・Map creation and publication	・Roughly within 100 km ・Within 80 km ・Eastern Japan, Western Japan, Hokkaido ・Warning zone, Planned evacuation zone (Changed according to period)	JAEA, NUSTEC, JCAC	MEXT
2013/4-2020/3	・Monitoring by helicopter ・Conversion to air dose rate at 1 m height and deposition densities of radiocesium ・Map creation and publication	・Within 80 km ・Eastern Japan	JAEA	NRA

DOE: Department of Energy, USA, FATC: Fukushima Agricultural Technology Center, FEPC: Federation of Electric Power Companies, IES: Institute for Environmental Science, IRM: Institute of Radiation Measurements, IRSN: Institut de radioprotection et de sûreté nucléaire, France, JAEA: Japan Atomic Energy Agency, JCAC: Japan Chemical Analysis Center, JMC: Japan Map Center, MEXT: Ministry of Education, Culture, Sports, Science and Technology, NARO: National Agriculture and Food Research Organization, NIAES: National Institute for Agro-Environmental Sciences, NIRS: National Institute of Radiological Sciences, NRA: Nuclear Regulatory Authority, NUSTC: Nuclear Safety Technology Center, RIKEN: Institute of Physical and Chemical Research, TEPCO: Tokyo Electric Power Company, TIT: Tokyo Institute of Technology

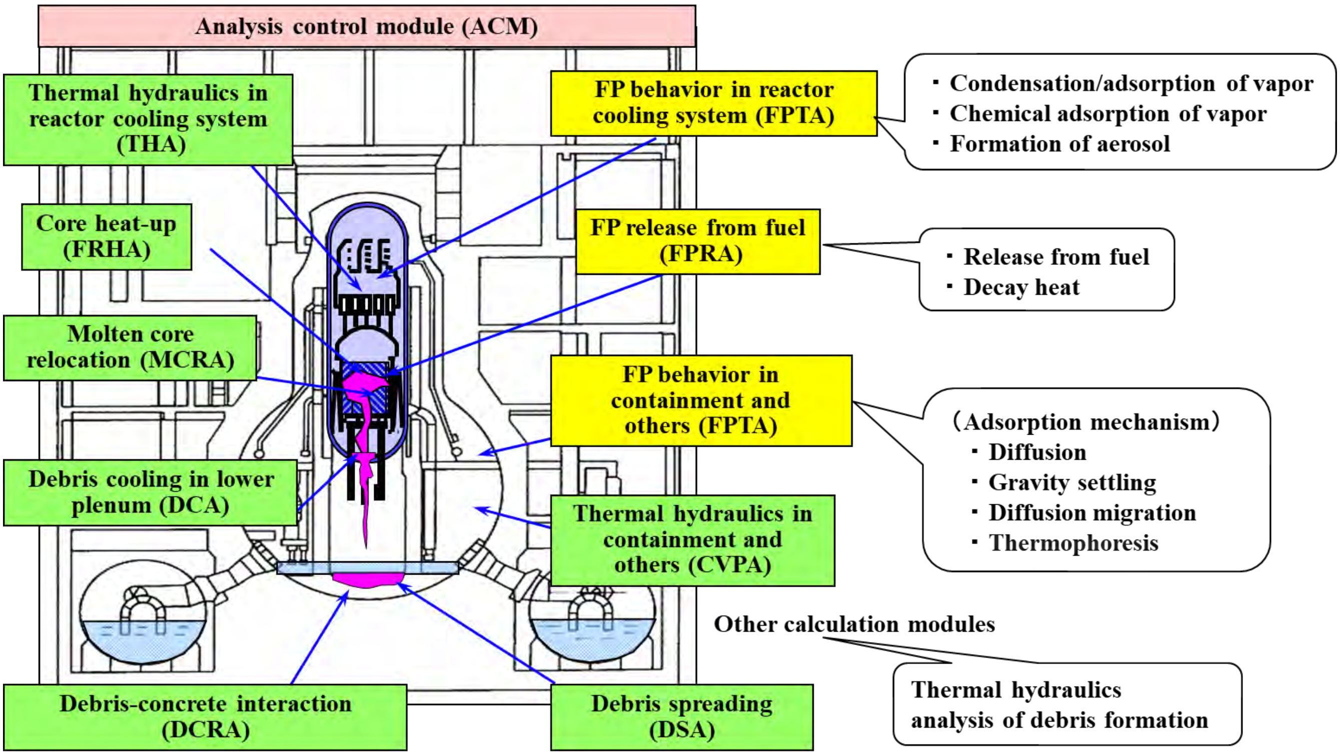


Reference Figure 1 Relationship between the targets of environmental contamination research, the main actors, and the main targets of this report

Source: Reprinted from the September 2014 proposal [5] of the Great East Japan Earthquake Reconstruction Support Committee of the Science Council of Japan, indicating the main topics covered by the sections (circled numbers) in Chapter III of this report.

Based on the matrix diagram of radioactive material transfer by IRSN*) in France, the causal relationship of radioactive material transfer is described in a clockwise direction for the status of environmental dynamics studies of radioactive material transfer in Japan. For example, in the upper right side of the diagonal cells, first row-second column represents emission from sources to the atmosphere, second row and fifth column represents deposition from the atmosphere to land, fifth row eighth column represents transfer from farmland to food, and eighth row ninth column represents internal exposure due to food intake. On the lower left side of the diagonal cells, fourth row seventh column represents runoff from land to the ocean, and second row fourth column represents evaporation from the ocean to the atmosphere.

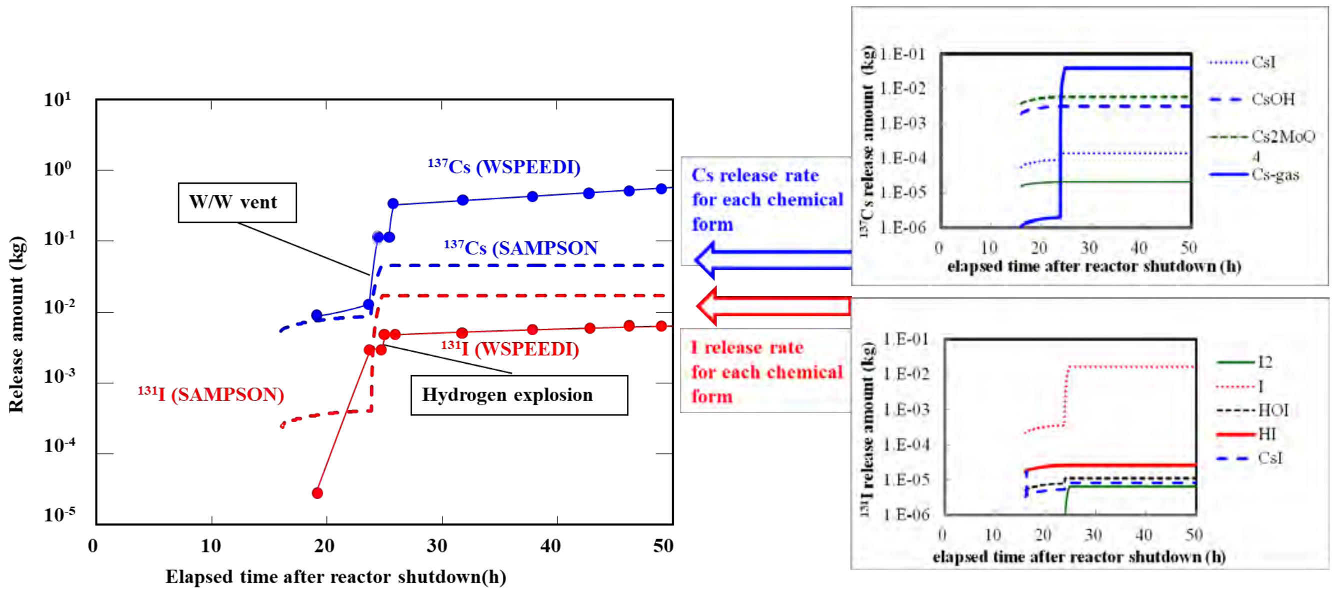
*) IRSN (2011) SYMBIOSE: A Simulation Platform for Performing Radiological Risk Assessments.



Reference Figure 2　Outline of the SA analysis code, SAMPSON

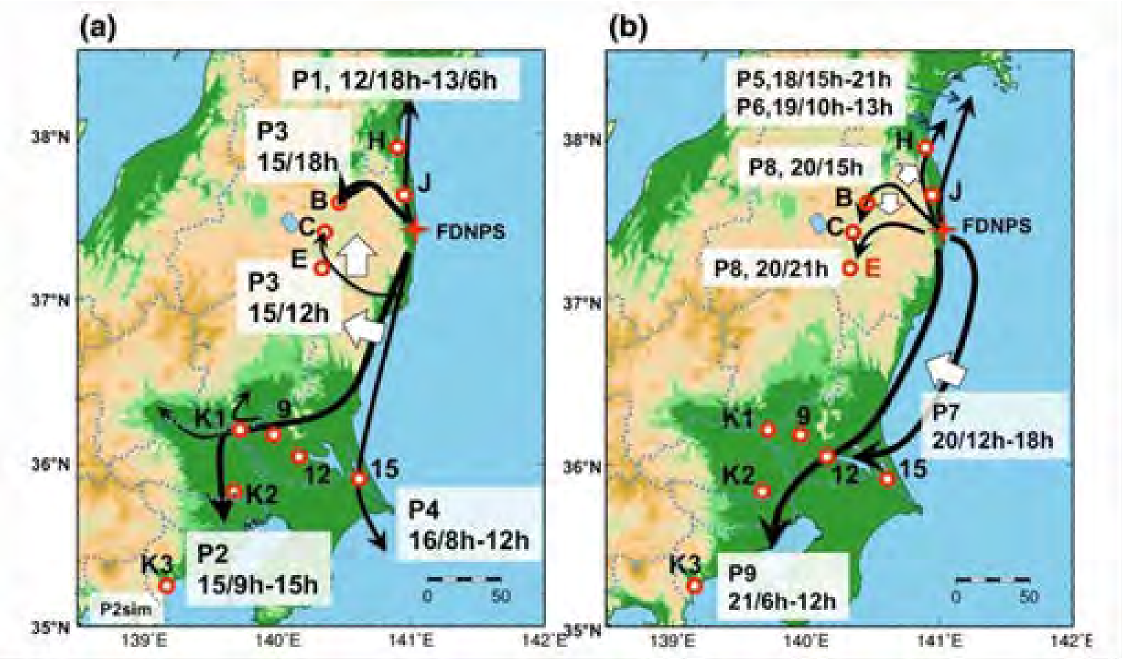
Reference Figure 2: Overview of the SA analysis code SAMPSON

Source: Fig. 1 in Reference (22), which illustrates the main functions of SAMPSON code components.



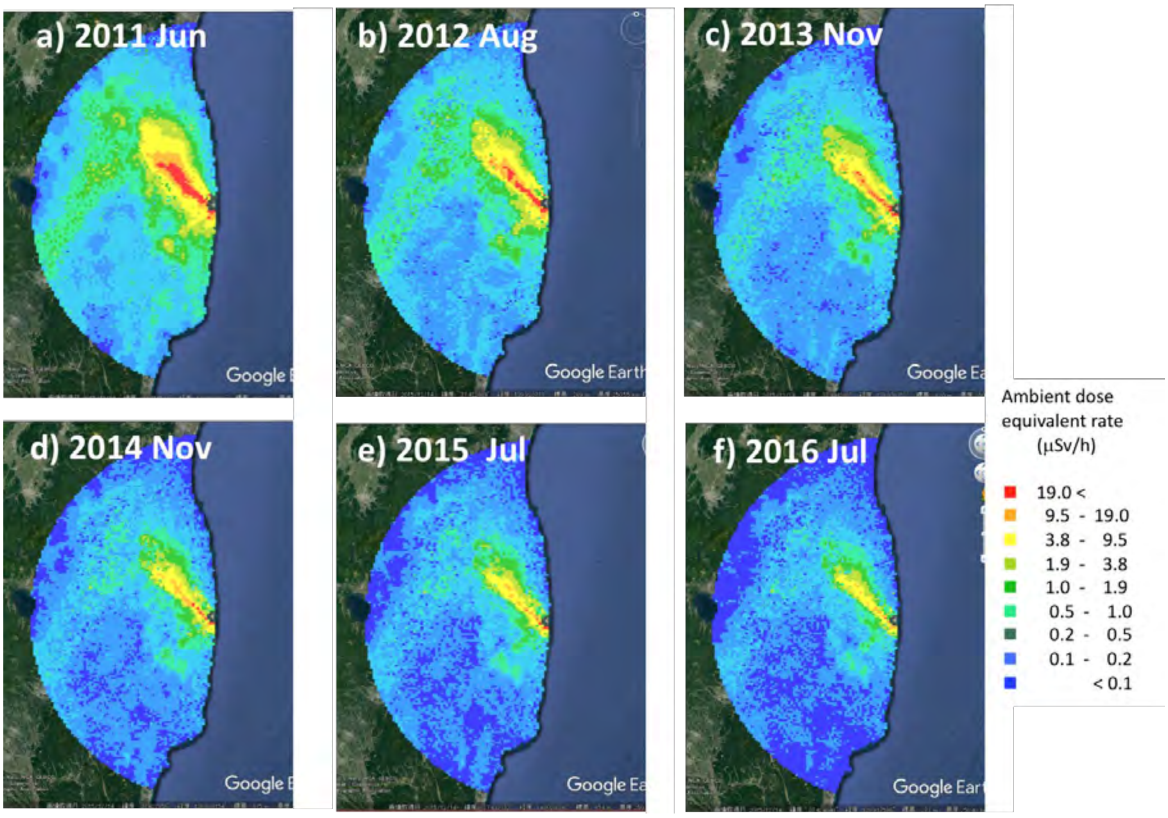
Reference Figure 3　FP release to the environment - Comparison of SAMPSON and WSPEEDI results

Source: Excerpt from "FP behavior analysis in the containment vessel under accident conditions - current status of SAMPSON analysis for Unit 1", Document 1-1 of the 24th term of the Informal Working Group on "Exchange of accident and environmental information", showing the temporal changes in FP emissions from Unit 1 calculated with the SAMPSON code.



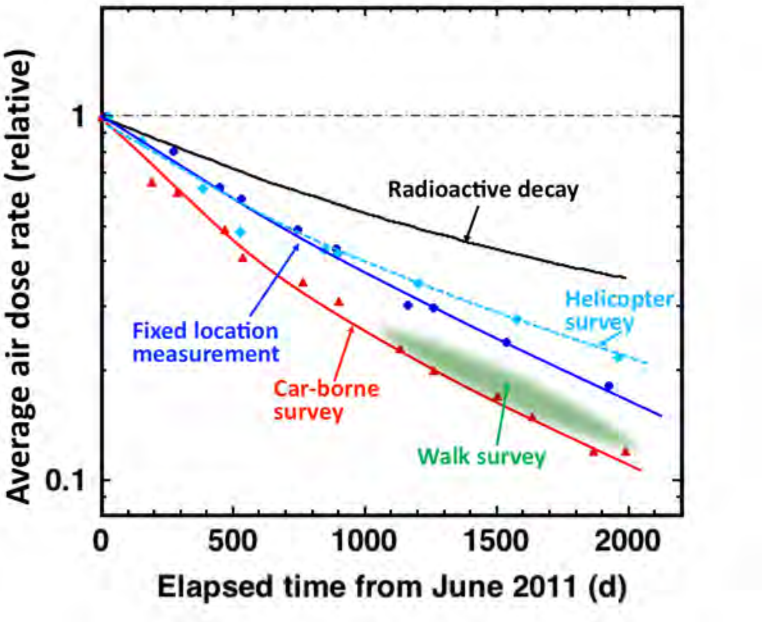
Reference Figure 4 Main plume pathways in the early post-accident period

Source: Nakajima et al. 2017 [26] Fig. 15



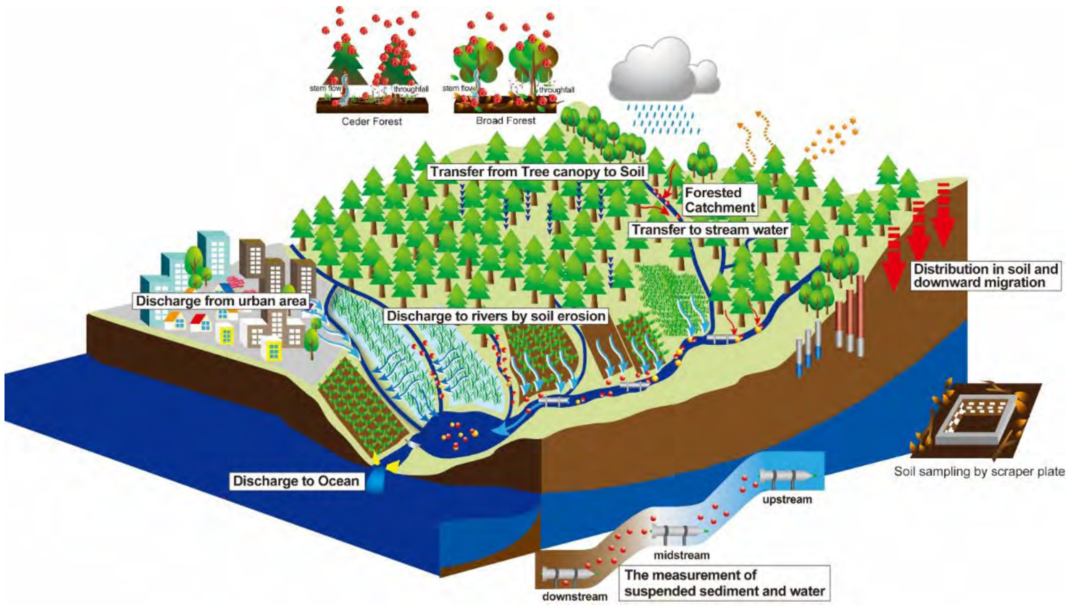
Reference Figure 5 Changes in air dose rate distribution within an 80 km radius of the Fukushima Daiichi Nuclear Power Plant over time (Saito et al. 2019 [47])

The maps were created by simple integration of the data obtained by fixed-location measurements in undisturbed fields and those by helicopter surveys



Reference Figure 6 Changes in average air dose rates over time within an 80 km radius of the Fukushima nuclear power plant (Saito et al. 2019 [47])

Decreasing tendency of air dose rates due to radiocesium was evaluated by subtracting contribution from natural gamma rays.



Reference Figure 7 Schematic diagram of radioactive material transfer survey on land

Source: "Interdisciplinary Research on the Environmental Fate of Radionuclides Discharged by the Fukushima Nuclear Power Plant Accident", Grant-in-Aid for Scientific Research