UNSCEAR United Nations Scientific Committee on the Effects of Atomic Radiation

DEVELOPMENTS SINCE THE 2013 UNSCEAR REPORT ON THE LEVELS AND EFFECTS OF RADIATION EXPOSURE DUE TO THE NUCLEAR ACCIDENT FOLLOWING THE GREAT EAST-JAPAN EARTHQUAKE AND TSUNAMI

A 2017 white paper to guide the Scientific Committee's future programme of work

EVALUATING RADIATION SCIENCE FOR INFORMED DECISION-MAKING

UNITED NATIONS

DEVELOPMENTS SINCE THE 2013 UNSCEAR REPORT ON THE LEVELS AND EFFECTS OF RADIATION EXPOSURE DUE TO THE NUCLEAR ACCIDENT FOLLOWING THE GREAT EAST-JAPAN EARTHQUAKE AND TSUNAMI

A 2017 white paper to guide the Scientific Committee's future programme of work

UNITED NATIONS
New York, 2017

This document is available on the UNSCEAR website at www.unscear.org.
Any inquiries regarding this document should be sent to the UNSCEAR secretariat (unscear@unscear.org).

This publication has not been formally edited.

CONTENTS

The attachment cited in this white paper is electronically available for download in English only from http://www.unscear.org/unscear/en/publications/Fukushima_WP2017.html

EXECUTIVE SUMMARY

This summary is based on the report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the seventy-second session of the United Nations General Assembly.[1]

[…]

At its sixty-fourth session (29 May to 2 June 2017), the Committee recalled its assessment of the exposures and effects due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami, as presented in its report to the sixty-eighth General Assembly in 2013[2] and the supporting detailed scientific annex.[3] It had concluded in that report that, in general, doses were low and that therefore associated risks were also expected to be low. A discernible increase in cancer incidence in the adult population of Fukushima Prefecture that could be attributed to radiation exposure from the accident was not expected. Nevertheless, the report noted a possibility that an increased risk of thyroid cancer among those children most exposed to radiation could be theoretically inferred, although the occurrence of a large number of radiation-induced thyroid cancers in Fukushima Prefecture—such as occurred after the Chernobyl accident—could be discounted because absorbed doses to the thyroid after the accident at Fukushima were substantially lower. It had also concluded that no discernible changes in birth defects and hereditary diseases were expected and that any increased incidence of cancer among workers due to their exposure was expected to be indiscernible because of the difficulty of confirming a small increase against the normal statistical fluctuations in cancer incidence. The effects on terrestrial and marine ecosystems were expected to have been transient and localized.

Following its assessment, the Committee put in place arrangements for follow-up activities to enable it to remain abreast of additional relevant information as it was published. The Committee's reports of the sixty-second and sixty-third sessions to the seventieth and seventy-first sessions of the General Assembly, respectively, included the Committee's findings from its follow-up activities up to the relevant time in each case.

The Committee has continued to identify further information that had become available up to the end of 2016, and systematically appraised relevant new publications to assess their implications for the Committee's 2013 report. A large proportion of these new publications have again confirmed the main assumptions and findings of the Committee's 2013 report. None of the publications have materially affected the main findings in, or challenged the major assumptions of, the Committee's 2013 report. A few have been identified for which further analysis or more conclusive evidence from additional research is needed. On the basis of the material reviewed, the Committee sees no need, at the current time, to make any change to its assessment or its conclusions. However, several of the research needs identified by the Committee have yet to be addressed fully by the scientific community.

The Committee has requested that the findings be issued electronically on its website as a non-sales publication in English and that, subject to available resources, its publication be fostered in Japanese.

---

[1] *Official Records of the General Assembly, Seventy-second session, Supplement No. 46* (A/72/46).

[2] *Official Records of the General Assembly, Sixty-eighth session, Supplement No. 46* and corrigendum (A/68/46 and Corr.1).

[3] *Sources, Effects and Risks of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2013 Report to the General Assembly*, vol. I, annex A (United Nations publication, Sales No. E.14.IX.1).

I. INTRODUCTION

1. The Committee had assessed radiation exposures of the public, workers and non-human biota that resulted from the 11 March 2011 accident at the Fukushima Daiichi nuclear power station (FDNPS), considered the health implications, and presented its findings in its annual report to the United Nations General Assembly in August 2013.[4] The United Nations subsequently published the Committee's findings and the detailed scientific annexes underpinning them on 2 April 2014 [U2]. The publication (referred to hereafter as the "2013 report") was well received by the General Assembly, governments, the scientific community and the media/public in Japan.

2. The Committee's assessment had, in general, been based on information disclosed or published before the end of October 2012. Subsequently, much additional relevant information has been published or become available and this is likely to continue for the foreseeable future. The Committee has remained abreast of such developments because they may have implications for the results of its assessment (for example in corroborating, challenging or refining its findings and/or contributing to addressing identified research needs) and intends to continue to do so; this will enable the Committee to take informed and timely decisions on the need to refine or update its previous findings. The Committee expects that providing sound scientific appraisal of new material will also help *(a)* those affected by the accident to better understand the situation and *(b)* inform decision-making.

3. Accordingly, at its sixty-first session (21–25 July 2014), the Committee had requested the secretariat to "submit for consideration at its sixty-second session (1–5 June 2015) preliminary plans […] for follow up activities to update and consolidate some of the findings and conclusions of the Committee's assessment of the radiological consequences of the Fukushima Daiichi accident". It also asked the secretariat to "promptly develop a standing mechanism to stay aware of new scientific developments in the follow-up to the accident. That mechanism should be based on the ad hoc arrangements that had been developed for conducting its recent assessment of the accident". It also asked the secretariat to "report annually on the implications for the Committee's programme of work".

4. In response, the secretariat developed a project plan of follow-up activities, which was endorsed by the Committee and is being implemented. The project comprises two phases: Phase I, a systematic and ongoing review of new information; and Phase II, an update of the 2013 report at an appropriate time. The overall aim of Phase I (up to at least 2016 and beyond) is to "keep the Committee regularly apprised of the implications of new publications and research activities related to the accident with a view to initiating a formal update of the 2013 report (i.e. Phase II) at an appropriate time". The more specific objectives of Phase I include:

(a) To systematically keep the overall radiological situation on the FDNPS accident under review by collecting and appraising published information;

(b) To collect and evaluate progress made in, and plans for, major research projects and programmes related to pending questions;

[4] *Official Records of the General Assembly, Sixty-eighth session, Supplement No. 46* and corrigendum (A/68/46 and Corr.1).

(c) To promptly identify inconsistencies between information issued after October 2012 and the 2013 report;

(d) To conduct ad hoc analyses to help clarify the situation and which could be used subsequently in any update of the 2013 report;

(e) To respond to questions and critiques of the 2013 report;

(f) To report annually to the Committee at its regular sessions on the outcomes of the above.

5. At its sixty-second session, the Committee agreed to the publication of a white paper[5] setting out: *(a)* an assessment of the implications of new scientific developments (up till the end of 2014) for the findings of the 2013 report; and *(b)* a commentary on general themes raised in the few critiques made of the 2013 report. In addition, two electronic attachments were made available providing additional technical information that supplemented the 2013 report. This first white paper was published in October 2015 [U4]. At its sixty-third session, the Committee agreed on the publication of a second white paper setting out a further assessment of the implications of new scientific developments (since the first white paper and up to the end of 2015) for the findings of the 2013 report. This second white paper was published in October 2016 [U5].

6. This third white paper sets out a further assessment of the implications of new scientific developments (since the second white paper and up to the end of 2016)[6] for the findings of the 2013 report. It provides a summary of the main outcomes of the follow-up activities that underpin the findings reported by the Committee to the General Assembly. As before, the white paper includes reviews of published information, but (further to specific objective *(b)* in paragraph 4 above) it also includes a summary of major relevant research projects and programmes underway in Japan. The white paper provides an overview of the aims of these projects and programmes and when they are expected to provide information of particular value to any update of the 2013 report.

II. EVALUATION OF NEW INFORMATION

7. The scope of new information analysed by the Committee in its first white paper was, in general, restricted to publications in English in peer-reviewed journals that had not been included or referenced in the 2013 report (i.e. published after October 2012, the cut-off date that had been generally adopted for information analysed in the report), but which had become available or published before the end of 2014. The second white paper covered information not previously considered that had become available or published before the end of 2015. This third white paper covers information not previously considered that became available or was published before the end of 2016. The scope of both the second and this white paper was extended to include not only publications in peer-reviewed journals, but also peer-reviewed conference papers, reports issued by regional/national institutes/organizations, government

[5] White papers are documents developed for the Committee to guide its future programme of work and that the Committee has decided to share with the wider community.
[6] Publications considered for this white paper comprised those which had not been reviewed in the previous white papers and which had become available up to the end of 2016, including publications which had been made available online. This white paper therefore includes some publications with an earlier publication date than 2016 and some with a final publication date in 2017.

departments/ministries, learned societies, utilities, and similar bodies,[7] reports issued by intergovernmental organizations, and major compilations[8] (and/or analyses) of data from official and other sources. In practice, in preparing this white paper, only one publication was identified for review from these additional categories: a report by the Science Council of Japan [S9].

8. The approach the Committee used to identify, screen and appraise new information was as described in the first white paper, with the exception of the introduction of an additional topical area, that of transfer through the terrestrial and freshwater environments (as in the second white paper). In screening potentially relevant publications and selecting those that should be subject to more detailed appraisal, particular consideration was given to whether the publication had the potential to:

- Challenge[9] or confirm the assumptions in the 2013 report;
- Affect the main findings of the 2013 report; or
- Address research needs either identified in the 2013 report or in topical areas where a wide consensus was emerging.

While all publications meeting the above criteria have been appraised, the content of this white paper has a greater focus on new information that may potentially challenge the assumptions and main findings of the 2013 report, rather than on new information which confirms these assumptions and main findings. It also highlights some of the more relevant information which has become available that addresses identified research needs and would be valuable to any future assessment of the radiological impacts of the accident at FDNPS. However, it is not intended to provide a comprehensive overview of all new information relating to the FDNPS accident.

9. The following chapters describe the main outcomes of the screening and appraisal of new sources of information for each topical area in turn. In each case, a brief recapitulation is provided of the findings of the 2013 report, because these provide the context for the review, as well as of the conclusions of the previous white papers. This is followed by a summary of the outcomes of the appraisals, and conclusions about the implications both for the 2013 report and any follow-up activities. Chapter X then sets out overall conclusions from the appraisals and includes a tabular summary of those sources of new information deemed to make a significant contribution to addressing identified research needs. Finally, chapter XI summarizes major relevant research projects and programmes underway in Japan and is supported by an electronic attachment.

[7] In exceptional cases, the scope was extended to scientific reports issued by non-governmental organizations.
[8] Large amounts of data continue to be generated and published at relatively frequent intervals by various Japanese organizations, and it would not be practicable to include all of these for review within this project. Consideration has, therefore, been limited to more substantive compilations of data that have the potential to be useful in the context of any future re-assessment or in extending the scope of any such re-assessment.
[9] A publication would be considered to challenge an assumption in the 2013 report or materially affect its conclusions if its implications were sufficient to warrant the Committee considering issuing an addendum to the 2013 report.

III. UPDATES ON RADIONUCLIDE RELEASES TO ATMOSPHERE, DISPERSION AND DEPOSITION

A. Recapitulation of the 2013 report

10. The Committee had reviewed estimates of total releases to the atmosphere of ^{131}I and ^{137}Cs (the two most significant radionuclides from the perspective of exposures of people and the environment). These estimates had ranged generally from 100 to 500 petabecquerels (PBq) for ^{131}I and from 6 to 20 PBq for ^{137}Cs. The averages of the published estimates were about 10% and 20%, respectively, of the corresponding releases to the atmosphere estimated for the Chernobyl accident. Much of the released material was dispersed over the Pacific Ocean, but, depending on the meteorological conditions, a fraction was dispersed over eastern mainland Japan, and radioactive material was deposited on the ground by means of *(a)* dry deposition, and *(b)* wet deposition with rain, fog and snow. The main deposition on land occurred to the north-west of the FDNPS site, but significant deposition also occurred to the north, south and west of the FDNPS site.

11. In general, the Committee had relied on measurements of the deposition densities of radionuclides as the basis for its estimates of doses to the public from external exposure and from inhalation. However, where measurement data were unavailable for the periods when exposures occurred (e.g. for evacuees) and could no longer be obtained, the Committee had needed to use an estimate of the source term (including the temporal patterns of release rates) together with appropriate atmospheric transport, dispersion and deposition modelling (ATDM) to estimate levels in the environment and resulting doses to people. The Committee had chosen a published source term for this purpose [T7]. The releases of the radiologically dominant radionuclides ^{131}I and ^{137}Cs in this source term were 120 and 8.8 PBq, respectively. While at the lower end of the range of published estimates, and possibly an underestimate of the total release, the Committee had considered this source term as the most appropriate for estimating doses incurred as a result of dispersion over the land mass of Japan (see paragraphs B15–B16 in [U2]).

B. Findings of review of new publications

12. The first and the second white papers concluded that no publications had been identified in this area that materially affected the main findings or challenged the major assumptions of the 2013 report; several publications confirmed the assumptions in whole or part. One publication [K4] was identified which provided a refinement of the source term estimate used in the 2013 report, and the Committee recommended the use of this source term in preference in future studies, although its use was not expected to alter significantly the doses estimated in the 2013 report. The Committee noted that new data that were becoming available had the potential to significantly improve source term estimates and estimates of the levels of radionuclides in the air and deposited on the ground. A detailed comparison of these new data with those used in the 2013 report would be needed to fully understand their implications.

13. Of the publications considered in this third white paper, 28 were reviewed in detail. Many confirmed the assumptions and findings of the 2013 report in whole or in part. The main implications of the findings of these publications are summarized below.

14. Chino et al. [C2] identified which reactor units were the dominant sources of atmospheric releases at different times during the major release period of 12–21 March 2011. They also determined which reactor unit was the source of releases that resulted in deposition

on to specific areas of the Japanese mainland. The findings were based on ^{134}Cs:^{137}Cs activity ratios derived from deposition density measurements, and information about the ratios in the fuel of the different reactor units. The study was not able to identify definitively which events at FDNPS resulted in large releases, but emphasized the scientific value of improved understanding of this issue and the need for further collaborative research work in this area. A similar approach has also been presented by Jäckel et al. [J1] using data to the north-west of FDNPS and Snow et al. [S10] who added ^{135}Cs:^{137}Cs activity ratios observed in the south-west of FDNPS. Radionuclide deposition densities very close to (within 500 m of) FDNPS were found to be dominated by contributions from reactor unit 2, whereas deposition densities at greater distances towards the north and west were found to be more dominated by contributions from reactor units 1 and 3. All three reactor units were found to contribute to the deposition densities at greater distances towards the south-west.

15. Furthermore, based on the above analysis, Chino et al. [C2] presented a minor update of the Katata et al. [K4] source term relating solely to the period of 20 March to 21 March 2011. They estimated a slightly lower release of ^{137}Cs over this period compared to the previous estimate, but little change in the total amount of ^{137}Cs released. This small change to the Katata et al. source term should be taken into account in future studies.

16. Yumimoto et al. [Y10] used the source term originally estimated by Terada et al. [T7] to derive a new source term estimate using inverse modelling and a large set of deposition density monitoring data recorded by aircraft. The authors then compared predicted concentrations of ^{137}Cs in air using this source term with those measured by collection of suspended particulate matter on filter tape [O13, T12]. Yumimoto et al. were better able to reconstruct ground level concentrations in air than previous studies, especially for 15 March 2011.

17. Hanna and Young [H1] summarized briefly the current state-of-the-art techniques for identifying the locations and/or magnitude of releases to atmosphere based on observations and modelling of wind fields and atmospheric transport. They recommended that the research community across many disciplines should move towards harmonization of methodologies and terminologies via outreach to organizations that can influence the direction of public policy on science. They proposed that special issues on source term estimation could be organized in peer-reviewed journals with the goal of harmonizing methods, and that special sessions at scientific conferences could be organized on this topic.

18. Girard et al. [G2] analysed the impact of uncertainties of model input and model parameters on the predictions of atmospheric dispersion models. They used an estimate of the release to atmosphere from the FDNPS accident to study the influence of uncertain model inputs on gamma dose rates estimated using a Eulerian atmospheric transport, dispersion and deposition model. They carried out a variance-based sensitivity analysis to understand which input parameters had the greatest influence on estimates of gamma dose rates. The results underline the need for further research to understand the influence of input uncertainty and uncertainty propagation through atmospheric dispersion modelling.

19. The Science Council of Japan [S9] evaluated and compared several models used to analyse the transportation and deposition of radioactive materials released during the FDNPS accident. The inter-comparison covered regional-scale and global-scale atmospheric transport, dispersion and deposition models as well as ocean dispersion models. One of the findings was that deposition of ^{137}Cs on to the mainland of Japan, as assessed with different regional-scale models, was about 27±10% of the total emission. The global-scale model comparison indicated that wet deposition over the globe was 93±5% of the total ^{137}Cs emissions assumed in the models. The models considered were found to be capable of depicting the main features of

observed radioactive material distributions. All of these findings are consistent with the assumptions and findings of the 2013 report.

20. Fujiwara [F1] confirmed the feasibility of retrospectively reconstructing deposition densities of ^{131}I from the measured deposition densities of ^{129}I, as had been presented earlier by Muramatsu et al. [M13]. While Muramatsu et al. had applied their approach for the area within 80 km of FDNPS, where the concentrations of the two iodine radionuclides in soil were found to be strongly correlated, the new study demonstrated that this approach—with some modifications—was also feasible in areas far from FDNPS, where deposition densities of ^{131}I and ^{129}I were relatively low.

21. Hirose [H7] reviewed the information available on releases of radionuclides from the FDNPS accident to the atmosphere and to the ocean and their subsequent transport, dispersion and deposition based on many papers published between 2011 and 2016. The author confirmed several of the assumptions and key findings of the 2013 report and the 2015 and 2016 white papers. For example, he concluded from several publications that about 80% of the total atmospheric release of ^{137}Cs deposited on to the North Pacific Ocean. He also confirmed the value of the Tsuruta et al. [T12] publication (which presented ^{137}Cs concentrations in air at ground-level in the Fukushima and Kanto area derived from an analysis of filter-tapes of air pollution monitoring stations). From a review of several publications, Hirose suggested that the particle size of the ^{131}I bearing particles may have differed from those bearing radiocaesium, and therefore that the dispersion and deposition behaviour of ^{131}I bearing particles may have differed from those bearing ^{134}Cs and ^{137}Cs. While the assumption in the 2013 report had been that particulate iodine and caesium behaved in a similar way during the atmospheric transport and deposition, the effects of any differences in particle size suggested by Hirose are likely to be small compared with those due to assumptions about the chemical form of radioiodine (see [U5], paragraphs 15–16).

22. Hirose [H6] investigated the monthly ^{137}Cs deposition at monitoring stations in the Kanto and south Tōhoku regions. The author concluded from the results that emissions of radioactive material from FDNPS to atmosphere still continued in spring 2013, although the ^{137}Cs emission rates were about four orders of magnitude smaller than during the initial release. Steinhauser et al. [S11] have pointed out that secondary releases of radioactive materials are possible—even years after the accident—because of decommissioning and dismantling activities on the FDNPS site. This possibility was not discussed as an alternative explanation for the monitoring results presented by Hirose. Steinhauser et al. further noted, as have Igarashi et al. [I2] and Ochiai et al. [O1], that resuspension can lead to continuing concentrations of ^{137}Cs in air and its re-deposition.

23. Ochiai et al. [O1] studied the resuspension of caesium deposition in the years after the accident. They showed that coarse and fine ^{137}Cs-bearing particulates have different origins and behaviours in the resuspension process. The authors introduced a new resuspension factor that was a little smaller than the annual mean resuspension factors observed after the Chernobyl accident in Europe. The study confirmed the assumption made in the 2013 report that resuspension did not significantly contribute to the long-term exposure of the public.

24. Mikami et al. [M5] measured deposition densities and activity ratios of ^{110m}Ag, ^{134}Cs and ^{137}Cs at a large number of locations across Fukushima Prefecture and several neighbouring prefectures. They confirmed that deposition densities of ^{110m}Ag were several orders of magnitude smaller than those of ^{134}Cs and ^{137}Cs. The authors found that there was little change in ^{134}Cs and ^{137}Cs deposition densities between March and December 2012, indicating that there was little migration of radiocaesium deposited on to the soil, especially in a horizontal

direction, although this may be because of the topography of the selected measurement locations (open and flat terrain). They also reported on spatial variations in the ratio ^{134}Cs:^{137}Cs, which they attributed to multiple releases with different nuclide ratios. Such data on ^{134}Cs:^{137}Cs ratios have been used by Chino et al. [C2] for linking deposition in specific areas with releases from the different reactor units.

25. Sato et al. [S6] demonstrated that the concentration of radiocaesium in soil varied greatly within a small area: the average ratio (over 27 locations) of the maximum to the minimum measured concentration in five soil samples from an area 7 m by 7 m was about five. Such information about spatial variability can improve understanding of the relationship between measured concentrations in soil samples and estimated doses to the public.

26. Satou et al. [S7] reported that they had isolated four radioactive solid particles from surface soil taken from a site 20 km north-west of FDNPS. According to the authors, these particles were larger and more radioactive than—but had similar chemical composition to—those observed in previous studies [A1, A2, Y1]. These previous studies found caesium-bearing particles which consisted of water-insoluble “glassy spherules”, several micrometres in diameter, containing the elements caesium, oxygen, iron and zinc (Satou et al. and Yamaguchi et al. both additionally found silicates in the caesium-bearing particles). In contrast, Kaneyasu et al. [K2] reported that radiocaesium was attached to sulphate aerosols of submicron size and soluble in water. Abe et al. [A1] concluded that such particles may originate from the nuclear fuel, whereas Salbu and Lind [S4] argued that the absence of long-lived gamma-emitting refractory fission products and the absence of transuranic elements indicated that the particles could not have originated from spent nuclear fuel. One explanation for these differences might be that the physical and chemical forms of the radiocaesium emitted during the FDNPS accident varied considerably. This explanation is supported by Miyamoto et al. [M7] who found three peaks at less than 0.5, 0.94 and 7.8 micrometres in the distribution of the activity median aerodynamic diameter for ^{134}Cs and ^{137}Cs. More research is needed to fully understand the physical and chemical properties of the caesium-bearing particles and aerosols released, because these properties will influence deposition processes, estimates of inhalation doses and the future behaviour of radiocaesium in the environment.

27. Sakaguchi et al. [S1] performed measurements of ^{236}U, plutonium isotopes, and ^{134}Cs and ^{137}Cs in samples of black-coloured road dusts from high radiation areas in Fukushima Prefecture (at distances between 3 and 35 km from FDNPS). They found very high concentrations of ^{134}Cs and ^{137}Cs in all samples and detected $^{239+240}$Pu and ^{236}U at low levels. According to the authors, the observed activity ratios for ^{236}U:$^{239+240}$Pu indicated that trace amounts of uranium and plutonium were released from the fuel cores. They also estimated that 3.9×10^6 Bq of total uranium and 2.3×10^9 Bq of $^{239+240}$Pu were released in total from FDNPS. This is consistent with the finding of the 2013 report that the fractional releases of plutonium and uranium were many orders of magnitude smaller than those of the volatile elements caesium and iodine.

28. Terasaka et al. [T8] estimated concentrations of different radionuclides in air in the early stage of the FDNPS accident for six locations in Ibaraki Prefecture from pulse height distributions measured with thallium-doped sodium iodide (NaI(Tl)) scintillation detectors. This work is similar to a previous study by Hirayama et al. [H4], who assessed the time distribution of ^{131}I concentration in air from measurements made at several monitoring posts in Fukushima Prefecture. Further analysis is required to judge whether the Terasaka et al. study confirms the findings of the 2013 report.

C. Potential implication of new publications

29. The Committee has noted the continuing progress being made in understanding the releases to the atmosphere, including particle sizes and the releases of radionuclides other than isotopes of iodine and caesium. New data and analyses are also continuing to improve estimates of the levels of radionuclides in the air and deposited on the ground. The Committee does not expect the new information to have significant implications for the findings of the 2013 report, but this would need to be confirmed by more detailed analysis.[10]

30. The Committee has identified that research in the following specific areas would have the greatest potential to contribute to addressing the needs identified in the 2013 report:

(a) Continuing to investigate the modelling of wet deposition in atmospheric transport and dispersion models;

(b) Investigating the influence of input uncertainty and uncertainty propagation through atmospheric dispersion modelling;

(c) Continuing to improve inverse and reverse modelling to estimate the source term;

(d) Improving current estimates of the source term making use of all available measurement data;

(e) Continuing to use all available measurement data and ATDM to improve understanding of how the time distribution of release rates relates to events in the different FDNPS reactor units;

(f) Extending the reconstruction of ^{131}I deposition from ^{129}I measurements to the remaining soil samples;

(g) Extending the measurements of radionuclide concentrations on filter tapes from air quality monitoring stations to the remaining filter samples;

(h) Analysing and comparing the data on ^{131}I, ^{134}Cs and ^{137}Cs concentrations in air against existing previous monitoring and modelling results;

(i) Continuing to investigate the physical and chemical properties of caesium-bearing particles and aerosols deposited after the FDNPS accident.

IV. UPDATES ON RADIONUCLIDE RELEASES TO WATER, DISPERSION AND DEPOSITION

A. Recapitulation of the 2013 report

31. The Committee had concluded that the direct discharges and releases from FDNPS to the ocean mainly occurred during the first month following the accident, and that the continuing releases were unlikely to affect the Committee’s assessment of doses to the public

[10] The new data reported in several of the publications cited above (e.g., better measurements of ^{137}Cs in soils, its particle size distribution and its resuspension) will be useful for any future re-assessment of doses to members of the public.

significantly. The Committee had judged that these direct releases were about 10–20 PBq for ^{131}I and 3–6 PBq for ^{137}Cs, mainly on the basis of estimates derived using three-dimensional modelling. In addition, the Committee had judged that the release to the ocean due to deposition from the atmosphere was about 60–100 PBq for ^{131}I and 5−8 PBq for ^{137}Cs, with only a small percentage of this occurring within a radius of 80 km from FDNPS. The Committee had concluded that measured levels of ^{137}Cs in seawater near the FDNPS site declined rapidly from a peak of 68,000 Bq/L (6.8×10^7 Bq/m^3) on 7 April 2011 and were generally below 200 Bq/L (2×10^5 Bq/m^3) by the end of April, after which the rate of decrease was much smaller. Concentrations decreased rapidly with distance from the coast: at 15 km and 30 km offshore from the FDNPS site, they were about 100 times and 1,000 times lower, respectively, than near the FDNPS site. The measured levels of ^{137}Cs in sediment generally lay between 10 and 1,000 Bq/kg of dry sediment, except in the port of FDNPS, where measured levels were much higher.

32. At the time the 2013 report was finalized, radioactive water had still been leaking on the site, and groundwater had been transporting radionuclides into the aquatic environment. The Committee had also noted the appearance of significant amounts of fission and activation products in stagnant water in the basements of the reactor and turbine buildings. The Committee had identified that key priorities for scientific research were to improve the characterization of the leaks and releases to the aquatic environment, and forecasting and quantifying the long-term transport and mixing of these releases.

B. Findings of review of new publications

33. The Committee concluded in the first and second white papers that its findings in this area of the 2013 report remained valid and were largely unaffected by new information that had since been published. It noted several publications that would contribute to an improved understanding of the release and subsequent dispersion of radionuclides in the marine environment.

34. Of the publications considered in this third white paper, seven have been reviewed in detail. None contradicted the findings of the 2013 report, and several confirmed the assumption of a general decreasing trend in direct discharge to the ocean. Several publications addressed identified research needs. Their contributions are summarized in the following paragraphs.

35. Two publications derived new estimates of the releases of radiocaesium to the Pacific Ocean. Inomata et al. [I4], using optimal interpolation of the measured concentrations of ^{134}Cs in seawater, estimated the inventory of this radionuclide in the North Pacific to be 15.3±2.6 PBq at the end of March 2011. About half of this inventory was to be found in the coastal region near FDNPS. Tsubono et al. [T10] carried out an ensemble analysis of simulations of radionuclide dispersion to evaluate the uncertainties linked to the chaotic behaviour of the ocean. Based on a regression between simulated and observed ^{134}Cs concentrations, the total ^{134}Cs flux into the North Pacific was estimated at 16.1±1.4 PBq. The flux of ^{137}Cs can be inferred to be comparable, because the activity ratio of ^{134}Cs to ^{137}Cs in the releases was around unity [U2]. These estimates are broadly consistent with the upper end of the range of estimates for ^{137}Cs release (directly to the sea plus deposition from the atmosphere) set out in the 2013 report.

36. During May and October each year from 2013 to 2015, Fukuda et al. [F2] analysed the dissolved ^{137}Cs concentrations in seawater within a distance of 30 km from the coast of FDNPS. They showed that the concentrations were one to two orders of magnitude higher than those

before the accident. Concentrations were highest within 5 km of the coast (20 to 220 Bq/m^3), but these showed high variability with time. Concentrations tended to decrease with increasing distance from the coast, reaching 2–4 Bq/m^3 at 30 km. Two possible sources for the relatively high concentrations and high temporal variability were identified: heavy rainfall increasing the input into the ocean from rivers; and increased discharges of contaminated water to the open sea from the FDNPS harbour facility.

37. In September 2013, Castrillejo et al. [C1] reported on concentrations of ^{90}Sr in seawater samples taken off the coast of Fukushima Prefecture. The highest concentrations in surface water were found close to FDNPS and were between 0.8 and 8.9 Bq/m^3, suggesting continuing releases of ^{90}Sr from FDNPS. Estimates made by Castrillejo et al. indicated that the inputs from continuing releases from FDNPS probably exceeded the inputs from rivers by two to three orders of magnitude. Compared to measurements made in June 2011, concentrations in September 2013 were one order of magnitude lower for ^{90}Sr and 2−3 orders of magnitude lower for radiocaesium. Castrillejo et al. considered this relative enrichment in ^{90}Sr to be either the result of inputs from groundwater or from leaks of tanks containing water from which caesium had been removed.

38. The transport of radiocaesium over long distances in the Pacific Ocean was monitored during the summer of 2012 along a trans-Pacific line from the Arctic to Antarctic Oceans [K11]. Caesium-134 was only observed between 25 and 63°N (at the northern edge of the Bering Sea), indicating that ^{134}Cs released as a result of the FDNPS accident had not been transported to the Arctic Ocean by the summer of 2012. The north–south distribution found by Kumamoto et al. [K11] was consistent with the results of ATDM modelling of deposition of releases to atmosphere on to the ocean. In measurements made about two years later, in 2014, between 45 and 50°N, Inoue et al. [I6] found that ^{134}Cs concentration had not decreased in the area of the Oyashio current, indicating that radiocaesium was being continually transported to this area. At the same time, Kumamoto et al. [K12] found that the elevated concentration of ^{134}Cs observed in 2012 to the north of the Kuroshio Front (35–40°N) had disappeared, probably because of its eastward propagation along the surface current towards the North American coast. At the eastern edge of the Pacific basin, off the west coast of the North American continent, southward transportation of released radiocaesium was not observed. In the western subtropical area, the released radiocaesium had reached about 15°N by 2014 (compared to 18°N in 2012) with a maximum concentration at around 200 m depth, indicative of a southward transport in the water mass called Subtropical Mode Water. Because of the mode of formation of this water mass, Kumamoto et al. [K11] inferred that the origin of the ^{134}Cs in this water mass was probably deposited from the atmosphere to the south of the Kuroshio Current (between 30 and 35°N).

39. Nagao et al. [N1] measured concentrations of ^{137}Cs in the Niida River (about 25 km to the north of FDNPS) of between 0.025 and 4.18 Bq/L between May 2011 and November 2012. Concentrations were generally found to decrease with time, although higher values were superimposed on this decreasing trend during high river flows, attributed to rainfall events. Naulier et al. [N4] analysing ^{137}Cs in six coastal catchments showed that, during low to moderate river discharge flows, the main carrier of radiocaesium in the deposited sediment and suspended sediment was the particulate organic matter, whereas during extreme flooding it was the mineral phase.

C. Potential implication of new publications

40. The Committee has concluded that its findings in this area of the 2013 report remain valid and are largely unaffected by new information that has since been published. The Committee has noted several publications that will contribute to an improved understanding of the release and subsequent dispersion of radionuclides in the marine environment.

V. UPDATES ON THE TRANSFER OF RADIONUCLIDES IN TERRESTRIAL AND FRESHWATER ENVIRONMENTS

A. Recapitulation of the 2013 report

41. In the 2013 report, the Committee had modelled transfers through the terrestrial and freshwater environments to estimate doses to members of the public from ingestion of foodstuffs for the second year after the FDNPS accident onwards. The Committee had estimated these doses using the FARMLAND model [B1]. This model was used to predict the migration of deposited radionuclides into the soil and their subsequent uptake into food products. Some modifications had been made to the model to account for East-Asian agricultural conditions (especially for rice, vegetables and fruit), but many radiological and agricultural parameter values based on Northern European data had been retained.

42. In the 2013 report, the food categories with the highest per capita intake by weight for adults, included in the assessment of doses from ingestion for the second year onwards, had been rice, “other vegetables” (assumed to be in the leafy green vegetables category), wheat and wheat products (assumed to be in the cereals category), fruit and milk. The aim had been to make realistic estimates of doses and the focus had been on assessing average doses to representative groups in the population; therefore, consumption of wild food products, such as game animals, mushrooms, and freshwater fish, had not been considered.

43. On the basis of these assumptions, and that food restrictions remained in place, the Committee had estimated doses from ingestion for periods after the first year that were one to two orders of magnitude lower than those from external exposure to deposited radionuclides. Several subsequent studies, in which the internal exposure of people has been estimated more directly from human measurements, have confirmed the dominance of the external exposure pathway, and have indicated that doses from ingestion estimated using the FARMLAND model were more likely overestimates than underestimates (see section VI below).

44. The Committee had identified the need to better characterize the distributions of doses to the public and to better quantify the uncertainties in the dose estimation as priorities for future research. In this context, notwithstanding the minor contribution that ingestion of foodstuffs had made to estimated doses, better information on the transfer of radionuclides to foodstuffs, and specifically regional and national parameters for models would be useful for future assessments of the consequences of the FDNPS accident and to assess the impacts of food restrictions and remedial measures. In addition, such information would be helpful to improve understanding of the potential impact of environmental remediation programmes.

B. Findings of review of new publications

45. The Committee had not explicitly considered new publications on transfers through the terrestrial and freshwater environments in its first white paper. In the second white paper the Committee's review was confined to papers published in 2015 with priority given to the transfer pathways of radiocaesium (which had made the dominant contribution to ingestion doses after the first year) to food products. The Committee concluded from its review that its assumptions and findings in this area of the 2013 report remained broadly valid. For this third white paper, the Committee has reviewed similar information published in 2016 as well as considering some other relevant papers published after the accident that it had not previously considered.

46. Of the publications considered in this third white paper, 32 have been reviewed in detail. The main implications of the findings of these publications are summarized below.

1. Radiocaesium migration in soil

47. In the 2013 report, migration of radiocaesium into deeper layers of well-mixed soil used for crop production had been assumed to be slow, with, for example, only about 7% migrating below the top 30 cm of well-mixed soils after 10 years. No data have yet been identified for agricultural soils that show radiocaesium attributable to the FDNPS accident at soil depths below 30 cm.

48. The partition coefficient (K_d) provides an indication of the bioavailability of a radionuclide in soil; a high K_d denotes strong sorption and, therefore, low bioavailability. Konoplev et al. [K9] reported that measured values of the K_d for radiocaesium between suspended soil particles and water published in five papers since the FDNPS accident varied between 1.1×10^5 and 11×10^5 L/kg; these values were one to two orders of magnitude higher (indicating much lower bioavailability) than values found in areas affected by the Chernobyl accident in the first few years after it occurred. The difference was attributed to *(a)* the higher proportion of clays in the prevailing soils and sediments in areas affected by releases from FDNPS and *(b)* the presence of radiocaesium associated with glass particles, which have been reported in areas affected by the FDNPS accident.

49. Mishra et al. [M6] measured lower K_d values (varying from around 80 to 320 L/kg for 10 cm depth soil samples) in three undisturbed grassland sandy soils (which would be expected to bind radiocaesium to a lesser extent than soils with higher clay contents) in other areas of Japan. The vertical migration of radiocaesium was found to be slow with more than 90% of the radiocaesium retained within the upper 5 cm layer.

50. Konoplev et al. [K9, K10] focused on Okuma town soils within 10 km of FDNPS and parts of the Niida river, and reported that, in both of these areas, small amounts of ^{134}Cs and ^{137}Cs were detected in some of the soils at soil depths of more than 20 cm. The vertical migration of radiocaesium in undisturbed forest and grassland soils near the FDNPS site was faster than that in soils within the 30 km zone of the Chernobyl nuclear power plant for a similar time interval. Possible reasons for both these differences include higher precipitation, more bioturbation and higher soil temperatures. In undisturbed soils, faster vertical migration of radiocaesium has been reported in forest soil compared to grassland soil [K10].

51. Uematsu et al. [U1] found that Japanese soils appeared to have a lower affinity for binding radiocaesium than temperate European soils with similar soil clay and exchangeable

potassium contents, possibly owing to differences in mineralogy. They considered that soil characteristics generally used in existing mechanistic models were not a good basis for predicting the transfer of radiocaesium from soil to grass. Further soil characteristics need to be incorporated into models to be suitable for Japanese soils.

52. Mukai et al. [M11, M12] have identified partially vermiculated (or weathered) biotite, as found in soils in Fukushima Prefecture, to be a more effective binder for radiocaesium than other micaceous minerals or organic matter.

53. Kitamura et al. [K7] developed three-dimensional models of the river basins of five catchments in Fukushima Prefecture to estimate water flow rates, suspended sediment concentrations and accumulated sediment erosion and deposition. They found that the majority of annual sediment migration in the basins occurred over storm periods, so typhoons were the main vectors for redistribution. Evrard et al. [E4] showed that, between 2012 and 2015, there had been a decrease of around 90% in the contribution of radiocaesium in upstream soils to radiocaesium concentrations in sediment transiting the coastal plains. The occurrence of typhoons and decontamination efforts in various tributaries of the Niida River have resulted in some temporary increases in local radiocaesium concentrations. However, the much lower contribution of radiocaesium from upstream soils to coastal plain sediment in November 2015 indicates that the source of the easily erodible radiocaesium may have been removed by decontamination, diluted by subsoils, or eroded and transported to the Pacific Ocean.

2. Radiocaesium transfer from soil to crops

54. Values of the concentration ratio (CR [11] – the ratio of the concentration of a radionuclide in the food product to its concentration in soil to 20 cm depth on a dry weight basis) for the transfer of radiocaesium from soil to brown rice, or data that can be used to derive the CR, have been reported by Yang et al. [Y5], Endo et al. [E3], Wakabayashi et al. [W3], Ohmori et al. [O7], Tsukada and Ohse [T11], and Eguchi et al. [E2]. Most data in these publications for rice sampled from 2011 to 2014 suggest that the CR for brown rice may have been higher (by up to around one order of magnitude) than that assumed in the 2013 report. The changes of ^{137}Cs concentration in rice over time between 2012 and 2014 were similar to those predicted by the FARMLAND model [W3, Y5].

55. Kusaba et al. [K14] confirmed earlier data showing that, in the first three years after deposition, radiocaesium adhered to bark surfaces was a more important source of radiocaesium in fruit than radiocaesium in soil. From 2011 to 2014 the ^{137}Cs concentration in apples declined at a faster rate than would be predicted by the FARMLAND model. The CR for apples in the period 2012–2014 was similar to that predicted by the model.

56. In 2012, Win et al. [W6] measured ^{137}Cs uptake in 97 cultivars of the azuki bean, which is the second most important legume consumed in Japan and is an important crop in Fukushima Prefecture. Tenfold differences in CR were noted between cultivars, and the CR values—allowing for reductions with time and soil depth corrections—were mostly lower than that assumed in the FARMLAND model.

[11] The transfer of radiocaesium from soil to crops is normally quantified using the concentration ratio (CR), often denoted F_v, and also sometimes called the transfer factor (TF). Some authors used the term TF and/or slightly different soil depths so, where relevant, the impact of the different depth has been taken into account in the reviewed CR values.

57. Djedidi et al. [D1] measured the CR for a large number of *Brassica* cultivars in field trials conducted in 2013. For field mustard, Indian mustard and oilseed rape, the CR values for ^{137}Cs were relatively high and most of them exceeded the assumed value for leafy green vegetables in the FARMLAND model. From May 2011 to May 2013 the reduction in the ^{137}Cs concentration in tea leaves was greater than that predicted by the FARMLAND model for leafy green vegetables [H5].

58. Sunaga and Harada [S13] developed a magnetic analyser method for estimating soil adhesion on plants and applied it to some rye crops. They found that the radiocaesium concentration was linearly correlated with the amount of adhered soil and that plants with a higher yield had relatively less adhered soil. The adhered soil accounted for about half of the total radiocaesium concentration of Italian rye grass, which—with lower yields and plant lengths—had a high soil loading. The highest values measured for both forage and Italian rye grass were one order of magnitude smaller than that assumed by the FARMLAND model for hay/silage or for pasture.

59. For agricultural animals, a study conducted early in spring 2011 showed that milk of housed dairy cows had much lower concentrations of ^{131}I, ^{134}Cs and ^{137}Cs compared with those that were outdoors on pasture [K8]. Manabe et al. [M4] noted that most farm animals are kept in closed barns in Japan. This is confirmed by information readily available at the website of the Ministry of Agriculture, Forestry and Fisheries of Japan. For example, of the 14,800 dairy cattle in Fukushima Prefecture after the accident only 720 grazed outdoors [M1, M2]. The transfer coefficients for radiocaesium measured in four studies in controlled conditions with housed cows [H2, K8, O8, O9] were similar to those assumed in the FARMLAND model. A transfer coefficient measured for pigs fed rice [O6] was the same as that assumed in the FARMLAND model.

3. Radiocaesium transfer to food products not considered in the 2013 report

60. Fuma et al. [F4] considered monitoring data from 2011 to 2015 and reported that the annual mean radiocaesium concentrations in bamboo shoots gradually decreased with time, but the rate of reduction was slower than that for agricultural produce.

61. Wada et al. [W2] summarized compiled data for sixteen species of freshwater fish from an extensive monitoring programme conducted by Fukushima Prefecture. A higher proportion of freshwater fish than marine fish had radiocaesium concentrations that exceeded the level at which food restrictions applied, especially in the first two years after the accident [W2]. In 2014, food restriction levels were only exceeded in areas with the highest deposition densities, and maximum radiocaesium concentrations did not exceed 750 Bq/kg wet weight.

62. Cultured fish are more commonly eaten in Japan than “wild” fish collected from lakes and rivers. Cultured fish had considerably lower radiocaesium concentrations than wild fish [Y3] partially because radiocaesium transfer to freshwater fish is mainly via the food chain whereas cultured fish are fed with commercial pellets [W2]. A correlation was reported between radiocaesium deposition density and radiocaesium concentrations in various freshwater fish species [A5], especially along the higher deposition area to the north-west of FDNPS. Radiocaesium concentrations in lake fish were generally higher than in those from rivers [W2]. There has been a considerable reduction with time since 2011 in the radiocaesium concentrations in wild fish species [A5, I3, W2].

63. Wada et al. [W2] found that the radiocaesium concentrations in different freshwater fish species and changes with time were specific to area and habitat. They were affected by fish-feeding strategies, life cycles, and features of water bodies such as the lower turnover time in lakes than rivers. For example, there was a trophic level effect such that radiocaesium concentrations generally declined in the order: carnivorous (e.g. salmonids) > omnivorous > herbivorous > planktivorous species [A5, I3, W2]. A relatively high concentration ratio (fish to water) for Ayu (a salmonid) was reported in 2011, and the intake of algae with associated sediment was identified as the most important pathway for ^{137}Cs transfer into Ayu [I3]. The retention time of ^{137}Cs inside Ayu was relatively short, whereas for other salmonids it was much longer [W2].

64. Tagami et al. [T1] reported high transfer of radiocaesium to a range of wild animal species (particularly bears, wild boar, sika deer and the copper pheasant) in five prefectures between 2011 and 2015, and long effective half-lives. Similarly, high transfers to hunted animals occurred in Europe after the Chernobyl accident.

C. Potential implication of new publications

65. The Committee has concluded that its assumptions and findings in this area of the 2013 report remain broadly valid. New information specific to Japanese conditions has become available on transfers of radioactive material in soils and into foods. This information would be more appropriate for any future assessment of the FDNPS accident than parameter values based on European conditions (which had been used in the 2013 report in the absence of more relevant alternatives). Use of this information may lead to changes in the time-dependence of the doses from ingestion of foods predicted for the second year after the accident onwards and in the relative importance of different foodstuffs. For example, the contribution of animal products to doses from ingestion of foods over the longer term is likely to have been overestimated, because of the conservative assumption that some agricultural animals graze on pasture whereas most farm animals in Japan are housed. However, the Committee expects that the overall effect on predicted doses due to ingestion for the second year onwards would be minor, mainly because of the continued application of food restrictions. In addition, measurements on people (see chapter VI below) have confirmed that internal exposure was very small compared with external exposure, and suggested that the doses from ingestion of foods as predicted in the 2013 report for the second year onwards were likely to have been overestimates.

66. The following areas of research would be particularly beneficial in providing better regional and national parameters on the transfer of radionuclides to foodstuffs for future assessments and in improving understanding of the potential impact of environmental remediation programmes:

(a) Continued study of the migration of radiocaesium in agricultural, freshwater and forest environments and their transfer into various agricultural, aquatic and wild foods (especially in the categories of rice and “other vegetables”, freshwater fish, hunted animals, wild plants and mushrooms);

(b) Further development of spatial and temporal models of environmental transfer processes specific to the diversity of food produced and consumed in Japan to support the prediction of long-term ingestion doses, addressing, in particular: feeding and management regimes of key domestic agricultural animals and wild animals; and the potential long-term contribution of transfer of radiocaesium in rivers and lakes to food products;

(c) Continued monitoring of long-term changes with time in radiocaesium concentrations in various agricultural and wild foods;

(d) Continued study of the effectiveness of remediation measures in reducing radiocaesium transfer from soil to agricultural products.

VI. UPDATES ON EVALUATION OF DOSES FOR THE PUBLIC

A. Recapitulation of the 2013 report

67. The Committee's aim had been to make realistic estimates of doses to defined groups of individuals considered representative of the different subsets of the Japanese population. For the assessment of doses from external exposure, the Committee had used models with parameter values mostly derived from European studies after the Chernobyl accident, and validated with numerous individual measurements by thermoluminescent dosimeter conducted in the affected Bryansk region of Russia. The Committee had used these models in its 2013 report in combination with population-averaged deposition densities of radionuclides for Japanese districts or prefectures, derived by combining measurements of radionuclide deposition densities with the density of population. Data on population densities as well as on age compositions and occupancy factors for different groups of the Japanese population had been based on the 2010 Japanese census.

68. For the assessment of doses to the public from internal exposure, the Committee had considered two exposure pathways, inhalation and ingestion. Exposure from inhalation had been assessed only from radionuclides in the passing radioactive plume, with subsequent inhalation of resuspended radionuclides considered insignificant. Exposure from inhalation of radionuclides in the passing plume had been estimated from measurements of deposition density using ratios of the concentrations of radionuclides in air to deposition density levels derived using the assumed source term and ATDM.

69. Intakes of radionuclides in food and drinking water in the first year following the accident had been assessed using the database of food and drinking water measurements carried out in Fukushima Prefecture and other prefectures of Japan. This database included many measurements made for food inspection purposes and therefore had some bias associated with the sampling: samples with potentially elevated concentrations were more likely to have been selected. However, at the time of preparation of the 2013 report, no other food measurements had been available.

70. For subsequent years, a modified form of the FARMLAND model [B1] had been applied for estimating the transfer of radionuclides through terrestrial food chains, with some transfer coefficients adjusted for the conditions and agricultural practices of contemporary Japan. The model had been used in combination with input data on population-averaged deposition densities of radionuclides for Japanese districts or prefectures.

71. For residents of evacuated communities, where it had not been possible to use measurements of radionuclide concentrations in the environment, the Committee had estimated time-varying concentrations of radionuclides in the environment using the assumed source term for releases to the atmosphere and ATDM. Doses from external exposure and from inhalation had then been estimated for the periods before, during and after evacuation using

scenarios representing the movements of residents derived from the results of a survey using questionnaires.

72. Measurements of radionuclides in people, such as whole-body and thyroid measurements, provide a direct source of information on internal exposure. However, at the time of preparation of the 2013 report, the number of thyroid measurements had been limited (about 1,100 persons) and these data could only be used to corroborate modelled doses to the thyroid in a few settlements. In addition, data from whole-body measurements had become available to the Committee at a late stage of the 2013 report preparation, and comprehensive data analysis had not been possible. Nevertheless, some assessment of doses from internal exposure based on human measurements had been carried out by the Committee and were presented in the 2013 report (see paragraphs 116–118 of [U2]). These had indicated that estimates of doses from internal exposure based on whole-body measurements were substantially lower than those based on modelling.

B. Findings of review of new publications

73. In the first and second white papers, the Committee concluded that its findings in this area remained valid and were largely unaffected by new information that had been published subsequently. By far the majority of the new publications broadly supported or confirmed the main assumptions made in, and the findings of, the 2013 report. Further whole-body measurements had given added weight to the statement made in the 2013 report that effective doses from ingestion of radionuclides in foodstuffs may, in practice, have been much lower than those estimated theoretically.

74. Of the publications considered in this third white paper, 11 were reviewed in detail. The main implications of the outcome of this review are summarized below.

1. External exposure

75. Realistic assessments of current and future individual doses from external exposure are needed as an input into decisions to lift the evacuation order in affected areas in Fukushima Prefecture and allow people to return. Naito et al. [N3] used personal electronic dosimeters (D-Shuttle) along with the Global Positioning System and Geographic Information System to relate individual doses from external exposure to ambient doses, and activity-patterns of individuals. The dosimeters of the 142 participants provided 29,550 hourly exposure data points that were used for analysis. The results showed that the additional (i.e. relative to background) individual doses from external exposure were well correlated with the additional (relative to background) ambient dose determined from an airborne monitoring survey. From the results of linear regression analysis, Naito et al. [N3] suggested that the additional individual doses from external exposure were numerically on average about one fifth that of the additional ambient doses. The reduction factors (the ratios of the additional individual doses to the additional ambient doses) were calculated to be on average 0.14 and 0.32 for time spent at home and outdoors, respectively, which is in good agreement with the model used in the 2013 report [U2]. The contribution to the total individual dose due to external exposure from that received during each type of activity (i.e. at home, in other buildings, outdoors, in transport, and other) was in good agreement with the fraction of time spent daily in each type of activity. The results contributed to an improved understanding of how realistic estimates of individual dose from external exposure can be derived from measurements of ambient doses from airborne monitoring and information about the time individuals spend on different

activities. The data will be useful in any assessment of future cumulative doses after the return of residents to evacuation order areas in Fukushima Prefecture.

76. Sakumi et al. [S3] measured individual doses to workers from external exposure in the evacuated village of Iitate during an 11-month period in 2013 (see chapter VII below). From the maximum dose measured for these workers, the authors estimated the annual dose from external exposure for a hypothetical resident who returned to Iitate village in 2013 to be about 10 mSv, but this was based on the unrealistic assumption that the individual stayed outdoors 24 hours a day during the year. A more realistic estimate based on the model used in the 2013 report for an outdoor worker would be about 5 mSv in 2013 and 3 mSv in 2015 [I1, U2].

77. Malins et al. [M3] developed a tool that calculates ambient dose equivalent rates at 1 m above the ground based on a model that accounts for ^{134}Cs and ^{137}Cs soil deposition density, depth profile and horizontal distribution within the ground. Good correlation was found between predicted dose rates and dose rates measured with survey meters in Fukushima Prefecture in areas with radiocaesium deposition from the FDNPS accident. Reductions seen in dose rates in air above flat, undisturbed fields in Fukushima Prefecture were consistent with radioactive decay and downward migration of caesium into soil; the predictions of the tool were in good agreement both with the measurements and with the model used in the 2013 report [U2]. The tool could also be useful in making realistic estimates of future doses from external exposure.

78. Ishikawa et al. [I8] assessed time spent outdoors (an important factor in estimating doses from external exposure) for residents of Iitate village from information collected in the Basic Survey conducted by Fukushima Medical University in Fukushima Prefecture [I7]. From 3,400 responses to the questionnaire collected from residents in Iitate village, the authors randomly selected a total of 240 responses in accordance with the distribution of the original population by age groups, and estimated the average time spent outdoors per day. The arithmetic mean for the 170 individuals for whom there was a full set of data on behaviour for four months was 2.08 (95% CI: 1.64, 2.51) hours. This is a much smaller value than commonly assumed in many dose assessments, although a value of 2.4 hours had been adopted for indoor workers in the 2013 report [U2].

2. Internal exposure

(a) Assessment of early intakes and doses

79. Three substantial papers [K5, K6, T5] have been published addressing the difficult issue of estimating thyroid doses from internal exposure resulting from intake of short-lived radionuclides (mainly ^{131}I) in the absence of early environmental and human measurements.

80. Kim et al. [K6] presented an assessment of the doses from internal exposure to 174 residents living near FDNPS at the time of the accident based on whole-body measurements performed by the National Institute of Radiological Sciences (NIRS) during the period between 27 June and 28 July 2011. The 174 subjects consisted of 125 adults and 49 children and included 90 individuals from Namie town, a municipality within the 20 km evacuation zone. The number of subjects in whom both ^{134}Cs and ^{137}Cs were detected was relatively small: 28.8% for the adults and 4.1% for the children. A significant gender difference in the radiocaesium concentrations in the whole body (males > females) was observed for adults but not for children. The committed effective dose (CED) from ^{134}Cs and ^{137}Cs was

calculated by correcting individual whole-body measurements for body size, and assuming intake was by acute inhalation of compounds easily soluble in the lungs on 12 March 2011, when the first explosion occurred at FDNPS. The resulting 90th-percentile of the CED distribution for adults was around 0.1 mSv and the maximum CED (0.63 mSv) was found for an elderly male. Comparable CED results were obtained from other whole-body measurements subsequently performed by the Japan Atomic Energy Agency (JAEA) in a similar manner to that of NIRS. Based on measurements of ^{131}I in the thyroid made by Tokonami et al. [T9] on a different group of adult subjects from the same and neighbouring municipalities, Kim et al. evaluated an intake ratio of ^{131}I to ^{134}Cs of around three to five. Kim et al. then used the average intake ratio of 3.8 to estimate the median and maximum equivalent doses to the thyroids of adult subjects of their study as 3.5 mSv and 84 mSv, respectively. For comparison, in the 2013 report, the settlement-average absorbed dose to the thyroid in the first year after the accident for adults evacuated from Namie town was estimated to be 34 mGy [U2]. There are some reservations associated with this approach, particularly the use of intake ratios of ^{131}I to ^{134}Cs derived from whole-body and thyroid measurements made by different research groups with different study subjects, and the authors did not assess the uncertainty associated with the use of the average value derived. The ratio of the concentrations of ^{131}I to ^{134}Cs measured in soil was very different in some locations (e.g. to the south of FDNPS) than in others [U2], and intake scenarios may not be the same for different age groups. The authors acknowledged the uncertainties associated with their approach and plan further studies on the relationship between individual doses from internal exposure and personal behaviour after the accident.

81. Kim et al. [K5] reported on other estimates made by NIRS of the dose to the thyroid due to internal exposure for residents of Fukushima Prefecture. This estimation was performed using a combination of information from direct thyroid measurements of 1,080 children (^{131}I) made at the end of March 2011, about 3,000 whole-body measurements of adults (^{134}Cs, ^{137}Cs) made between 11 July 2011 and 31 January 2012, and ATDM simulations of ^{131}I concentrations in air for areas where no direct measurements were available. By comparing estimated doses to the thyroid of children due to ^{131}I with CEDs to adults due to ^{134}Cs and ^{137}Cs for those locations (Iitate village and Kawamata town) where estimates of both were available from direct measurements, an intake ratio of ^{131}I to ^{137}Cs of three was derived. The ratio was then applied to the whole-body measurement information for other municipalities to estimate thyroid doses for these municipalities. The highest doses to the thyroid from internal exposure were estimated for residents of Futaba town, Iitate village and Iwaki City and were mostly below 30 mSv. The authors compared their estimates with the somewhat higher values in the 2013 report but noted that the latter included doses from ingestion, whereas the authors' method did not. The likely overestimation of doses to the thyroid (owing to the assumed intake by ingestion) was acknowledged in the 2013 report and confirmed by analyses undertaken by IAEA [I1] that showed that inhalation was by far the largest contributor to exposure of the thyroid. The 2013 report estimates also took account of even shorter-lived radionuclides (^{132}I, ^{132}Te and ^{133}I), as well as ^{131}I. This study is associated with similar reservations to the study described in the previous paragraph. To address remaining issues, including the dose contribution from ingestion, the authors proposed a new dose estimation method using data on personal behaviour and presented examples of the preliminary analyses.

82. Tani et al. [T5] calculated ^{131}I concentrations in breast milk of nursing mothers in Ibaraki Prefecture, based on a biokinetic model for iodine and scenarios for time-varying intakes due to inhalation of ambient air and to ingestion of tap water, and using relevant measurements of ^{131}I concentrations in air and in tap water. The authors compared the calculated ^{131}I concentrations in breast milk with those measured in a small number of samples obtained from volunteers living in Fukushima Prefecture and neighbouring prefectures shortly

after the accident in 2011 and found general agreement. Tani et al. then estimated equivalent doses to the thyroids of breast-fed infants (assuming that the infants consumed 800 mL of breast milk every day) of 10–11 mSv for Mito City and Kasama City and 1.1–1.8 mSv for Tsukuba City and Moriya City. Tani et al. suggested that breast milk consumption could therefore be a major contributor to thyroid equivalent dose from internal exposure for breast-fed infants in areas where concentrations of ^{131}I in air were relatively low; however, the authors pointed out that further studies including personal behaviour surveys would be necessary to estimate individual doses.

(b) Assessment of current exposures

83. Orita et al. [O11] evaluated the current concentrations of radiocaesium in local foods collected in Kawauchi village, which is located less than 30 km from FDNPS, in order to assess doses to the public from ingestion and to minimize public anxiety regarding internal exposure after the accident. The number of samples exceeding the regulatory limit for radiocaesium (100 Bq/kg for general foods) was 5 out of 4,080 samples for vegetables (0.1%), 652 out of 1,986 samples for edible wild plants and fungi (32.8%), and 8 out of 647 samples for fruits (1.2%). The study confirmed that the annual effective doses from internal exposure as a result of ingesting these foods were low, ranging from 22 to 43 μSv for adults. The authors considered that comprehensive long-term follow-up studies should take place to clarify trends in radiocaesium concentrations in local foods and CEDs in Fukushima-area residents.

84. Aono et al. [A4] studied the dynamics of radionuclide concentrations in some agricultural products of Japan and in seafoods collected off Fukushima Prefecture after the accident. The concentration of ^{134}Cs plus ^{137}Cs in spinach produced across the whole of Japan rapidly declined from a range of between 10 and 10,000 Bq/kg in spring 2011 to between 1 and 100 Bq/kg in 2012 and between 1 and 10 Bq/kg in 2013–2014. In contrast, the concentration of ^{134}Cs plus ^{137}Cs in mushrooms produced or collected from all over Japan showed little reduction in the first three years after the accident, remaining in the range of 3 to 300 Bq/kg in 2013–2014. Many concentrations of radionuclides measured in mushrooms continued to exceed regulatory levels established in April 2012. The concentration of ^{134}Cs plus ^{137}Cs in common skate collected around FDNPS between 2013 and 2015 was measurable but mostly below regulatory levels. Concentrations of radiocaesium in agricultural foods and marine fish were generally found to be below the Japanese regulatory levels, but radiocaesium concentrations above this level continued to be found in edible wild plants, wild mushrooms and game such as boar meat. The authors considered that long-term kinetic studies of radionuclides in terrestrial and marine environments were important both for the assessment of doses to the public from ingestion and for the prevention of unacceptable intakes of radionuclides via the food chain.

3. Remediation

85. As the Committee noted in the first and second white papers, decontamination of settlements in the evacuated Special Decontamination Area and inhabited Intensive Contaminated Survey Area has been in progress since 2012. However, it continues to be the case that dose-rate measurements made before and after remediation have not yet been published in peer-reviewed literature. The Committee continues to note the importance of assessing decontamination effectiveness in terms not only of dose rate reduction but also of the reduction in the annual effective dose from external exposure of residents, both individually and collectively.

86. Howard et al. [H11] compared a range of different features relevant to remediation following the Chernobyl and FDNPS accidents, including the characteristics of the distribution of radionuclides and the landscapes affected, the radiological criteria applied, the designation of areas to be remediated and the remediation measures adopted. For both accidents, the long term goal of remediation has been an additional annual individual effective dose of less than 1 mSv, although there were differences in when this goal was applied. The scale of remediation activities has been comparable in the two cases, even though the radiological consequences of the FDNPS accident for the public were much lower. Some key reasons for this are that:

(a) The radiological criteria for remediation applied in Japan have been lower than those applied in the former USSR, and have therefore had relatively higher associated costs;

(b) Lower limits have been adopted for radionuclide concentrations in food in Japan;

(c) A decision was made to remediate the evacuated land in Japan.

87. After the Chernobyl accident, the balancing of averted collective dose against remediation costs was an important part of the remediation strategy. In Japan, remediation of affected districts has been justified and implemented based on radiological and/or social and cultural considerations.

88. The tool developed by Malins et al. [M3] for the calculation of ambient dose equivalent rate at 1 metre above the ground (see paragraph 77 above) could be useful for remediation planning. Simulations of three remediation methods to reduce dose rates in air for farmland soil using this tool demonstrated that topsoil removal and layer interchange strategies had similar levels of effectiveness, and both methods were more effective than reverse tillage.

C. Potential implication of new publications

89. The Committee has concluded that its findings in this area of the 2013 report remain valid and are largely unaffected by new information that has since become available. The majority of the new publications broadly support or confirm the main assumptions made in—and the findings of—the 2013 report, in particular:

(a) Doses to the general public in Japan continue to decline in line with the findings of the 2013 report;

(b) Doses to the general public in Japan from external exposure, determined by personal dose measurements or dose-rate measurements combined with national shielding factors for buildings and exposure scenarios, are in general agreement with the findings of the 2013 report. Papers published in 2016 further clarified external exposure patterns and determined appropriate values for parameters in relevant models;

(c) There were no publications in 2016 on large-scale measurements of current whole-body contents of ^{134}Cs and ^{137}Cs of residents of affected areas, but the Committee has previously noted that the dose from internal exposure of residents of Fukushima Prefecture and neighbouring prefectures from current ingestion of caesium radionuclides with food is generally low [U4, U5]. Concentrations of radiocaesium in agricultural foods have declined rapidly since 2011, whereas concentrations in edible wild plants, wild mushrooms and game such as boar meat have decreased more slowly;

(d) Progress has been made in retrospective assessment of doses from internal exposure due to early intake of radionuclides, especially of ^{131}I for children.

90. The Committee has identified the following areas as having the greatest potential to contribute to addressing the research needs identified in the 2013 report:

(a) Continue to measure the dose rates due to external exposure to deposited material in various environments, forecast and track changes over time;

(b) Determine parameter values necessary for national and regional models of doses (e.g. shielding parameters of buildings; time spent outdoors and indoors in various building types in different seasons, and as a function of age and social group; and parameters related to the system of food production and distribution, and consumption habits of cultivated and wild foods);

(c) Measure individual doses from external exposure of residents of towns with elevated deposition of radionuclides in order to validate dosimetric models and obtain an experimental basis for uncertainty analysis;

(d) Continue efforts on thyroid dose reconstruction for 2011;

(e) Further conduct in vivo measurements of caesium radionuclides in people with different food habits to support refinement in the estimation of current doses from internal exposure and their uncertainties;

(f) Measure concentrations of caesium radionuclides in various agricultural and wild foods as a function of time after the FDNPS accident;

(g) Quantify the impact of environmental remediation programmes (decontamination, agricultural measures and others) both in terms of reduction of environmental radiation indicators (dose rate, radionuclide concentrations, and so on) and averted dose to residents from external and internal exposure;

(h) Better characterize the distributions of modelled doses to the public, expressing variability between individuals using probabilistic approaches, and compare them with human measurements.

VII. UPDATES ON EVALUATION OF DOSES FOR WORKERS

A. Recapitulation of the 2013 report

91. The main aim of the Committee's work had been to judge the extent to which the individual doses reported in Japan provided a true and reliable measure of the doses actually incurred by workers, and therefore the extent to which the reported doses could support a reliable commentary on the implications for health. By the end of October 2012, the Tokyo Electric Power Company (TEPCO) had reported statistics on doses to about 25,000 workers at the FDNPS site, most of whom were employed by contractors. According to TEPCO's reports, the average effective dose to FDNPS workers over the first 19 months after the accident had been about 10 mSv. About 34% of the workforce had received effective doses over this period above 10 mSv, while 0.7% of the workforce (corresponding to 173 individuals) had received effective doses more than 100 mSv. The highest reported effective dose was 679 mSv for the TEPCO worker who had also received the highest reported CED due to internal exposure

(590 mSv). Dose statistics had been reported separately for a few hundred emergency services workers.

92. The Committee's independent assessments of the doses due to internal exposure for 12 workers (out of a total of 13) who had CEDs due to internal exposure higher than 100 mSv had confirmed that they had received absorbed doses to the thyroid due to inhalation of ^{131}I in the range of 2 to 12 Gy.

93. The reliability of the internal exposure assessments for the much larger number of workers with lower assessed internal exposures had been evaluated by performing independent assessments for randomly selected samples of workers.

94. The Committee had confirmed the reliability of assessments reported by TEPCO for those of its workers where ^{131}I in the body had been detected. However, for most of the workers, in vivo monitoring of ^{131}I in the thyroid had not started until the second half of May 2011, and in many cases this delay had meant that ^{131}I could no longer be detected. For the same reason, the contribution to internal exposure from intakes of shorter-lived radionuclides such as ^{132}Te and ^{133}I could not be reliably assessed. The Committee had been unable to confirm the reliability of the assessments reported by TEPCO for those of its workers for whom ^{131}I had not been detected in the body, nor the reliability of the internal exposure assessments reported by contractors for their workers.

95. The Committee had judged that the major factor potentially affecting the reliability of external exposure assessments had been the sharing of electronic personal dosimeters during March 2011 (because the majority of the dosimeters had been lost in the tsunami flood), with only one worker in a team wearing a dosimeter for many missions.

96. The Committee had had insufficient information on beta irradiation to make an informed assessment of doses to the eye lens of workers (paragraph 143 in [U2]).

B. Findings of review of new publications

97. The Committee concluded in the first and second white papers that its findings in this area of the 2013 report remained valid and were largely unaffected by new information that had been published. While significant changes had been made to doses estimated for some workers since the 2013 report (see [U4] and [U5]), the Committee did not expect that these would materially affect its main findings, although this would need to be confirmed by a fuller analysis.

98. Of the publications considered in this third white paper, three have been reviewed in detail. One publication by Yasui [Y7] presented recommendations for the design of a large-scale epidemiological study on workers, developed in a meeting of experts convened by the Japanese Ministry of Health, Labour and Welfare (MHLW); when published, results of the study would almost certainly be relevant for any follow-up assessment to the Committee's 2013 report. A second publication [Y6] reported on the establishment of a dose registration system for decontamination workers and presented dose statistics for the period April 2011 to December 2014. A third publication [S3] reported results of individual measurements of effective dose due to external exposure for workers in the village of Iitate during 2013; data for workers and dose predictions for returning evacuees derived from the worker data could be useful in any follow-up assessment.

99. The worker epidemiological study described by Yasui [Y7] aims to examine adverse health effects in a target group of approximately 20,000 FDNPS emergency workers. No results from the study have yet been published, but a pilot study has been completed, and the full-scale study commenced in April 2015. The study will continue for the lifetime of the workers in the target group. A comprehensive re-evaluation of doses from external exposure and internal exposure was proposed at the meeting of experts, as was an analysis of the reliability and validity of assessed doses. The experts also recommended biological dosimetry (specifically, chromosomal tests using the fluorescence in situ hybridization method) for workers whose effective doses exceeded 100 mSv. Although the study is comprehensive in its coverage, and its design is thorough, the Committee considers that two aspects of the study design relating to dosimetry warrant further consideration:

(a) The study recommends the estimation of cumulative effective dose up to the point of health examination as the measure of exposure. The Committee believes it would be more appropriate to identify the health effects to be investigated, and then identify the appropriate measure of exposure for that health effect. The measure of exposure in radiation epidemiology studies is usually the set of absorbed doses to specified organs received in each year of exposure, rather than CED, and the organs specified (e.g. thyroid) are selected on the basis of a consideration of the health effects to be investigated (e.g. thyroid cancer);

(b) For many workers, the delay in commencing thyroid monitoring meant that thyroid doses from intakes of ^{131}I could not be reliably assessed. These doses will be re-evaluated in the study but large uncertainties in their values are likely to remain. An assessment of the implications of these uncertainties for the expected outcomes of the study would better inform judgements on the adequacy of its design.

100. The proposed comprehensive re-evaluation of worker doses means that the study should be able to address several of the research needs for worker dosimetry identified in the 2013 report.

101. Yasui [Y6] also reported on the establishment in December 2013 of a central dose registration system for workers engaged in decontamination projects in special decontamination areas. From the doses registered, Yasui presented distributions of effective doses for each 3-month period between April 2011 and December 2014 and distributions of effective doses by sex and by age for each of the years 2012, 2013 and 2014. The number of decontamination workers progressively increased from 11,058 in 2012 to 34,611 in 2014, and the average effective dose for these workers increased from 0.5 mSv in 2012 and 2013 to 0.7 mSv in 2014. The maximum effective doses were 13.9 mSv, 6.7 mSv, and 10.4 mSv in 2012, 2013 and 2014, respectively. The results presented confirm that doses to decontamination workers were low.

102. Sakumi et al. [S3] reported results of individual measurements of effective dose from external exposure for 64 workers in the village of Iitate made during an 11-month period in 2013. Although Iitate is within the deliberate evacuation area, the Japanese Ministry of Environment permitted some companies to continue working there. Sakumi et al. reported that the workers were present in Iitate for 10 hours per day and 5 days per week. Measurements were made with photoluminescence glass dosimeters. Sakumi et al. reported that 70% of the workers received an annual effective dose of less than 2 mSv, and that all of the workers with an annual effective radiation dose of more than 3 mSv worked outdoors for almost 10 hours in each working day. The maximum effective dose was 3.6 mSv for a worker working outdoors close to a road in the centre of Iitate. The mean and median doses were 1.73 and 1.53 mSv,

respectively. The paper addresses an identified research need, although for a time period later than that covered by the 2013 report.

C. Potential implication of new publications

103. The Committee has concluded that its findings in this area of the 2013 report remain valid and are largely unaffected by new information that has been published so far.

104. The proposed comprehensive re-evaluation of doses discussed by Yasui [Y7] should be able to address several of the research needs for worker dosimetry identified in the 2013 report. No new information was identified that would enable the Committee to reach informed judgments on the exposure of the lens of the eye, and further research in this area would be particularly valuable.

VIII. UPDATES ON HEALTH IMPLICATIONS FOR WORKERS AND PUBLIC

A. Recapitulation of the 2013 report

105. The Committee had expected health risks resulting from the FDNPS accident to be far lower than those for the Chernobyl accident, owing to the substantially lower doses received by the public and workers. No deterministic effects from radiation exposure had been observed among the public and none had been expected. No increase in spontaneous abortions, miscarriages, perinatal mortality, birth defects or cognitive impairment had been expected from exposures during pregnancy. Nor had a “discernible increase in heritable disease among the descendants of those exposed from the accident” (paragraph 224 of [U2]) been expected. No discernible radiation-related increases in rates of leukaemia or breast cancer (two of the most radiogenic cancer types), nor in other types of solid cancer besides possibly thyroid cancer, had been expected. A large excess of thyroid cancer due to radiation exposure, such as occurred after the Chernobyl accident, could be discounted, because the estimated thyroid doses due to the FDNPS accident were substantially lower than those sustained around Chernobyl. However, the sensitive ultrasound-based thyroid screening of those aged 18 years or younger[12] at the time of the accident had been expected to detect a large number of thyroid cysts and solid nodules, including a number of thyroid cancers “that would not normally have been detected without such intensive screening” (paragraph 225 of [U2]). However, similar even slightly higher rates of cysts and nodules had been found in the prefectures of Aomori, Yamanashi and Nagasaki that had not received significant radionuclide deposition from the accident. The substantial numbers that had already been observed in the Fukushima Health Management Survey (FHMS)[13] had been considered likely to be due to the sensitivity of the screening and not to radiation effects.

[12] Previous white papers had reported that screening was of those under 18 years old at the time of the accident, but this has subsequently been clarified as those aged 0–18 years at the time of the accident.

[13] The Fukushima Health Management Survey is a large programme of health questionnaires and health screening conducted by Fukushima Medical University with Japanese government funding. The FHMS includes: a comprehensive health check, and lifestyle and mental health assessment, for all residents from the evacuation zones; recording of all pregnancies and births among all women in the prefecture who were pregnant on 11 March 2011; and repeated thyroid ultrasound examinations for all children of the prefecture of ages 0–18 at the time of the accident.

106. Among FDNPS emergency workers, deterministic effects had been considered unlikely, but the Committee had not been able to preclude the possibility of hypothyroidism, or to assess the risk of cataracts (owing to insufficient information on doses to the lens of the eye from beta irradiation). Although 2−3 excess cancers could be inferred over the lifetime among the 173 workers with doses greater than 100 mSv (mainly from external exposure), the Committee had considered it unlikely that such increased incidence of cancer due to irradiation would be discernible. The Committee had judged the magnitude of any inferred risk of thyroid cancer among workers to be such that any increase in incidence due to radiation exposure would likely not be discernible.

107. The Committee had noted that the major health impacts that had been observed among the general public and among workers were mental health problems and impaired social well-being [U4]. The Committee did not assess health effects unrelated to radiation exposure: estimation of the occurrence and the severity of such health effects was beyond the Committee’s mandate.

B. Findings of review of new publications

108. The Committee concluded in the first and second white papers that its findings in this area of the 2013 report remained valid and were largely unaffected by new information that had since been published. A study reviewed in the second white paper which appeared to challenge the Committee’s findings regarding radiogenic thyroid cancer risk was found to be seriously flawed.

109. Of the publications considered in this third digest, 20 have been reviewed in detail. The publications served to strengthen or complement the findings of the 2013 report. Three publications [N2, S14, S15] provided updated information on thyroid cancer screening in the FHMS programme of clinical and ultrasound examinations among those who were aged 18 years or younger at the time of the FDNPS accident, focusing on the detection rates of thyroid cysts, nodules and cancers in Fukushima Prefecture. They demonstrated an appreciable elevation, caused by sensitive ultrasound screening, in the number of detected thyroid cancers. Three publications [O5, S14, S15] compared the rates of thyroid cancer detection in areas of Fukushima Prefecture that had received relatively high, medium or low levels of radiation exposure. One publication [K1] reported on the biological modelling of two different pathways for thyroid cancer development, distinguished by expression levels of a particular gene that tend to differentiate sporadic from radiogenic papillary thyroid cancers. Of note is a publication [Y7] describing plans for the study of the FDNPS worker cohort.

110. The first round of screening of 300,476 children and adolescents aged 18 years or younger at the time of the FDNPS accident has now been completed with a high participation rate (81.7%). The results are reported in several papers. Two papers [S14, S15] reported that 2,294 individuals had nodules larger than 5 mm, cysts larger than 20 mm, or needed confirmatory examination based on clinical and ultrasound examination. Nagataki [N2] indicated 116 confirmed or suspected thyroid cancers (38.6 per 100,000) based on fine needle aspiration cytology (FNAC); 102 of these cases were subject to surgery and 100 cases were diagnosed as papillary thyroid cancers, one as a poorly differentiated cancer, and one as a benign tumour. There was a skewed distribution of tumour sizes, with a mean of 13.9 mm (range 5.1–45 mm). The mean age at exposure to ^{131}I from the accident was 14.9 years for the thyroid cancer cases, with no case younger than 6 years. All the papillary cancers were of the classical type [S15]; in contrast, following the Chernobyl accident, the solid variant type was frequently found in irradiated children [Z1]. A second round of screening has examined

270,379 individuals (as of 30 June 2016), most of whom were included in the first round, and detected an additional 59 (21.8 per 100,000) suspected thyroid cancers by FNAC [N2].

111. Several papers compared the prevalence of thyroid cancer in areas of Fukushima Prefecture with a range of levels of exposure to radionuclides released as a result of the accident. Neither Ohira et al. [O5] nor Suzuki [S14] found any statistically significant differences in thyroid cancer prevalence for those from the highest or middle exposure areas, compared to the lowest exposure area. For example, Suzuki found thyroid cancer prevalences of 33, 39 and 35 per 100,000 in the highest, medium and lowest-exposure areas within Fukushima Prefecture, respectively. When Suzuki et al. [S15] further subdivided the low exposure area into low and lowest, the odds ratios (ORs) were all non-significant: 1.22 (95% CI: 0.55, 2.7), 1.21 (95% CI: 0.64, 2.3), 1.19 (95% CI: 0.58, 2.4) for the high (evacuation zone), medium and low exposure areas, respectively, compared to the lowest exposure area. Though these papers divided the exposure areas differently, none of them found any relationship between thyroid cancer prevalence and exposure level. Katanoda et al. [K3] reported that the observed prevalence of thyroid cancer in the FHMS compared to the expected prevalence was about 20-fold higher, which the authors attributed to an ultrasound screening effect, because the thyroid doses and other considerations make it implausible that it was an effect of radiation exposure.

112. Ohira et al. [O5] compared the estimated doses from external exposure for the 56 thyroid cancer cases with those for the remainder of the subset of about 129,300 of those screened for whom individual doses had been estimated. Compared to those with estimated doses from external exposure of less than 1 mSv, the ORs for risk of thyroid cancer were 0.76 (95% CI: 0.43, 1.35) for those with estimated doses in the range 1 to 2 mSv, and 0.24 (95% CI: 0.03, 1.74) for those with estimated doses greater than or equal to 2 mSv. Suzuki et al. [S15] indicated that, of 63 confirmed or suspected thyroid cancer cases with estimated doses from external exposure, 71% had doses less than 1 mSv and none had doses greater than 2.2 mSv. However, similar, more meaningful, comparisons cannot be made for doses to the thyroid, because no estimates of these are available. In the absence of thyroid doses, caution should be exercised in interpreting the results of Ohira et al. [O5].

113. Other papers highlighted concerns about possible over-diagnosis of thyroid cancer because of sensitive thyroid screening of general populations with ultrasound and about aggressive treatment of small thyroid cancers. From international temporal trends in thyroid cancer incidence, Vaccarella et al. [V1] showed the effect of large-scale screening in increasing thyroid cancer incidence in Australia, the Republic of Korea, the United States, and a number of countries in Europe. Park et al. [P1] analysed extensive thyroid cancer data from a number of clinics in the Republic of Korea from 1999 and 2008, during which time there was a large increase in thyroid cancer incidence in the country. They estimated that about 94% of the increase in incidence was due to the national programme to promote population ultrasound screening. In 2014, when a public awareness campaign against routine population screening was initiated in the Republic of Korea, the number of cases of thyroid cancer surgery fell by 35% in one year. Leboulleux et al. [L1] pointed out that many of the small papillary thyroid cancers found by ultrasound screening have indolent, benign behaviour. Since surgery has monetary costs and potential medical and psychological risks, they advocated “watchful waiting” rather than surgery for some small cancers; however, no consensus has been achieved regarding this suggestion. Nagataki [N2] recommended further research to identify molecular markers that can distinguish aggressive from indolent papillary thyroid cancers.

114. Thyroid screening is a complex issue and judgements on its scope, nature and/or continuation following the accident at FDNPS require considerations of factors that go far beyond the purely scientific issues alone (e.g. those of a socio-economic, public health, legal, ethical or human

rights nature).[14] Should the screening continue, the systematic collection and storage of biopsy material (including related information on exposures) and open access to it for meritorious research, would help investigations to be made of biomarkers and molecular signatures of radiation-induced thyroid cancer (i.e. in a similar manner to the Chernobyl Tissue Bank).

115. Kaiser et al. [K1] put forward the hypothesis that childhood radiation-induced thyroid cancer develops in a multistage pathway that is distinct from the carcinogenesis pathway of sporadic thyroid cancers (in contrast to the single-pathway hypothesis of Williams [W5]). They modelled the Chernobyl thyroid cancer data and found that over-expression of the *CLIP2* gene statistically distinguished radiation-associated thyroid cancers occurring before age 20 from sporadic ones. Future research to find and model predictive biomarkers for radiogenic thyroid cancer may shed new light on the pathogenesis of radiogenic thyroid cancer.

116. One paper purported to show increases in perinatal mortality associated with radiation exposure by comparing prefecture-wide rates before and after the FDNPS accident, using sophisticated modelling methods [S8]. However, the study is flawed in that the authors designated six prefectures as a “severely contaminated” area for comparison with other areas, whereas most of those prefectures received radiation exposures from the accident that were small compared to normal background radiation exposure. In addition, as the authors admit, this was an observational study that does not allow causal inference.

117. A study of self-reported psychological distress among those evacuated as a result of the FDNPS accident showed a positive correlation between radiation levels in their home locality and the frequency of distress [K13]. However, as noted in the 2013 report, psychological distress is a general indirect effect of catastrophic events and should not be attributed to radiation exposure itself; such effects do not fall within the Committee’s mandate.

118. A number of papers have compared health changes in evacuees from before their evacuation with afterwards or according to the duration of evacuation [E1, H3, O2, O3, O4]. They observed increases in such health conditions as the frequency of metabolic syndrome, dyslipidaemia, hypertension, weight gain, psychological distress and alcoholism that could be associated with evacuation. Of particular concern was the documented increase in mortality among the institutionalized elderly within the first year after evacuation[15] [Y8]. The Committee recognizes that these can be indirect effects of evacuation, stress and associated lifestyle changes, consequent to a radiation accident or other catastrophe, but such effects of evacuation are beyond the scope of the Committee’s considerations.

119. In 2016, the Japanese government awarded compensation to two occupationally exposed nuclear power plant workers. Both had been employed at FDNPS following the accident where they had accumulated part of their exposure. One was diagnosed with leukaemia and the other with thyroid cancer. The Committee has informed on the elements of scientific attribution of malignancies to radiation exposure (see annex A of the 2012 report [U3]). Scientific attribution is not equivalent to legal imputation in an occupational context. Therefore, the granting of these awards (and, likewise, others granted previously or in the future to occupationally exposed workers) does not imply a scientifically proven cause–effect relationship between radiation exposure and any particular case of cancer. Rather, it is the

---

[14] Broader issues relevant to decisions on the continuation and/or implementation of thyroid screening in the Fukushima Prefecture have been addressed in various forums, for example, [Y4] and [N5].

[15] Including 12 people who died in transit during the evacuation and 50 who died as refugees immediately after transport.

result of the application of a scheme,[16] developed several decades ago by the Japanese government, for industrial accident compensation insurance [M8]; knowledge and understanding of the effects of radiation has since improved considerably.

120. Experts convened by the MHLW have planned a long-term epidemiological and health monitoring study of FDNPS emergency workers [Y7]. Accurate cumulative measures of radiation dose, before, during and after the FDNPS emergency work, are to be obtained. The study plans to maintain a long-term follow-up of the approximately 20,000 workers, with periodic, well-standardized health examinations. The experts recommended that standard health data on the indicators measured and the laboratory tests carried out as part of the compulsory annual medical examination be compiled every year, and that a thyroid ultrasound examination, lens opacity examination and special tests for kidney function, infectious diseases and systemic inflammation be conducted every 3-5 years for those workers exposed to over 100 mSv as a result of the accident. The thyroid outcomes of interest include thyroid cancer, hypothyroidism and autoimmune thyroiditis. The experts also recommended that questionnaire information should be obtained periodically on potential confounding factors: medical history, lifestyle and socio-demographic data, psychological stresses, and exposure to other toxic agents. They further recommended that arrangements be made to link the workers to the MHLW national mortality (cause of death) database and the new national tumour registry. Storage of part of the blood samples was also suggested for assessing future markers of disease or for other research purposes. To help prevent arbitrary statistical analysis, they recommended that researchers report the full set of both statistically significant and null differences.

121. The Committee has the following concerns relating to the scientific value of this study:

(a) Because only 173 workers received as much as 100 mSv during emergency operations, the statistical power of the study will likely be too low to fulfil the study's aspiration to distinguish cumulative dose from dose-rate effects, although information on additional occupational radiation exposure before and after emergency operations, plus medical exposures, will be obtained to estimate lifetime doses;

(b) The study may be compromised by low participation rates, given that radiation workers are already receiving compulsory annual medical examinations, and that contract radiation workers are very transient and it may be difficult to keep track of their whereabouts.

---

[16] In 1976, the Japanese government established the basis for the award of compensation to occupationally exposed workers through the Industrial Accident Compensation Insurance scheme [M8]. The initial focus of the scheme was leukaemia. According to this scheme, leukaemia may be deemed eligible for medical compensation by a medical review panel if the dose was at least 5 mSv times the number of years between (first) exposure and diagnosis of the malignancy. A similar scheme applies for certain other lympho-haematopoietic malignancies with modification based on their comparative radiosensitivity. Up to the end of 2016, some 15 nuclear power plant workers in Japan had been granted compensation under this scheme for lympho-haematopoietic malignancies, of which about half were leukaemia. Two of these 15 workers were employed at FDNPS following the accident.

Solid cancer may be deemed eligible for medical compensation by a medical review panel if the effective dose was at least 100 mSv, the time between (first) exposure and diagnosis of the malignancy was 5 years or more, and there was no other aetiology than radiation. These criteria are kept under continuing review and may be revised in light of new scientific evidence. In 2016, one worker was granted compensation for thyroid cancer; he was in his forties, had been involved in with work on radiation since 1992, including employment at FDNPS between March 2011 and April 2012, and his cumulative effective dose was about 150 mSv, of which 139 mSv was received while working at FDNPS.

Despite the potentially limited scientific value of the study, the Committee acknowledges that it may be considered justified to address the health concerns of the workers affected.

C. Potential implication of new publications

122. The Committee has concluded that its findings regarding health effects of radiation exposure from the FDNPS accident in the 2013 report remain valid and are largely unaffected by new information that has since been published.

123. The Committee has noted, and will remain abreast of, ongoing research and investigations into the health implications of the accident, as reported from the FHMS being carried out in Fukushima Prefecture and other sources. It has identified the following specific areas, in particular, where further data or information would have the potential to contribute to addressing the research needs identified in the 2013 report:

(a) Provision by the FHMS of more detailed breakdowns of the numbers of young people screened, and of confirmed/suspected thyroid cancers by tumour size, and by age at irradiation, age at screening, and sex, because this would permit more accurate comparisons with parallel data from young people screened but unexposed;

(b) Completion of estimation of dose from external exposure for the young people in the FHMS thyroid screening study, especially those with suspected or confirmed thyroid cancers; this would permit an improved analysis by exposure level that would provide a stronger basis for inference than comparisons with other populations who may differ from the FHMS study in age, sex, screening protocols and other factors;

(c) Linkage of outcome information—including mortality and incidence of thyroid cancer, other cancer and non-cancer diseases, birth defects, and clinical and laboratory findings—with radiation exposure and information on age, sex and other risk factors, to permit the most informed assessment of health experience and risk; this would maximize the capability to address important questions that both scientists and the public may have;

(d) Provision of systematic data on the health of the FDNPS emergency workers, with cooperation by the government and nuclear industry to facilitate a high follow-up rate, so as to develop a high-quality assessment of potential radiation effects, while also considering possible confounding by lifestyle, toxic exposures and pre-existing medical conditions.

IX. UPDATES ON EVALUATION OF DOSES AND EFFECTS FOR NON-HUMAN BIOTA

A. Recapitulation of the 2013 report

124. The Committee had estimated radiation doses due to the accident to non-human biota through applying suitable models. The corresponding estimates of effects due to the radiation exposure had then been inferred by synthesizing the Committee's generic evaluations of dose–effect relationships. Exposures of both marine and terrestrial non-human biota following the accident had been, in general, too low for acute effects to be observed, although some exceptions had been considered possible because of local variability. The Committee had concluded that, in general, population-relevant effects on non-human biota in the marine environment would have been confined to areas close to where highly radioactive water was discharged and released into the ocean. Although the Committee had been unable to exclude a risk of effects to individuals of certain terrestrial species, in particular mammals, it had considered observable effects at the population level to be unlikely. It had concluded that any radiation effects would have been constrained to a limited area where the deposition density of radioactive material was greatest, and that, beyond this area, the potential for effects on biota was insignificant.

125. The Committee had made reference to studies in which effects in various terrestrial biota had been observed in areas with enhanced levels of radioactive material as a result of the FDNPS accident [H8, M9, M10]. It had noted that the substantial impacts reported for populations of wild organisms from these studies were inconsistent with the main findings of the Committee's theoretical assessment. The Committee had expressed reservations about these observations, noting that uncertainties with regard to dosimetry and possible confounding factors made it difficult to substantiate firm conclusions from the cited field studies.

B. Findings of review of new publications

126. The Committee concluded in the first and second annual white papers that its findings in this area of the 2013 Fukushima report remained broadly supported by the available evidence. However, it recognized potential limitations in its approach owing to reliance largely on laboratory-based rather than field studies. It identified a need for multidisciplinary field studies tailored to analyse the impacts of ionizing radiation on populations of wild organisms interacting under the conditions prevalent within ecosystems in areas with enhanced levels of radioactive material.

127. Of the publications considered in this third white paper, 21 have been reviewed in detail. The main implications of the findings of these publications are summarized below.

128. Several authors [T6, V2, V3] have applied kinetic transfer models to releases from the FDNPS accident to provide further insights into the temporal evolution of radionuclide concentrations in different environmental compartments. Tateda et al. [T6] carried out an analysis that they believed indicated that the observed slow decline of concentrations of ^{137}Cs in benthic fish off southern Fukushima could be explained by radiocaesium transfer to such fish from benthic invertebrates via ingestion. Vives i Batlle et al. [V3] provided an overview of an intercomparison that was undertaken for eight models (including one steady state model and

two kinetic models used in the 2013 report) designed to predict the radiological exposure of marine biota. The inter-comparison showed that, although there was, in some cases, significant variability between the models because of parameter and methodological differences, the predictions for some key indicators of exposure, e.g. radiocaesium concentrations in most organisms, were remarkably similar (often within one order of magnitude). This suggests that both kinetic models used in the 2013 report provided reasonably robust predictions of marine biota exposures in the initial period post-accidental release.

129. Several reviewed papers concerned studies of the concentrations of radionuclides in, and their transfer to, non-human biota [A3, F3, T1, T2, T4, W1, W2]. The results were generally consistent with the input data sets used for the environmental impact assessment carried out for the 2013 report, having, in some cases, been drawn from the same or related information sources. All of the above-mentioned studies, including the kinetic transfer modelling work, as well as other more indirectly relevant studies on transfer [S12, U1] and post-deposition processes [S5, T3], may be useful in refining the models used in the 2013 report in any follow-up assessment.

130. Qiu et al. [Q1] presented data on concentrations of radiocaesium and radiosilver in wharf roaches (*Ligia* sp.) sampled from various coastal locations, including the coast of Fukushima Prefecture, in 2011 and 2012. Samples generally contained low levels of the radionuclides—rarely exceeding 100 Bq/kg fresh weight—and therefore much lower than those assessed in the 2013 report. However, the study of Qiu et al. [Q1] indicated that substantial bioaccumulation of ^{110m}Ag may have occurred in some locations: a ^{110m}Ag:^{137}Cs activity ratio in excess of one was found for one Fukushima Prefecture coastal location (which is about one to two orders of magnitude greater than the ratio in coastal sediments). Given that silver has a relatively high concentration ratio for fish, it is therefore plausible that ^{110m}Ag may have been more important than assumed in the 2013 report. Horiguchi et al. [H10] also measured relatively elevated concentrations of ^{110m}Ag in shellfish, but the ^{110m}Ag:^{137}Cs ratios were even higher in this study: for example, ^{110m}Ag:^{137}Cs ratios in the limpet and rock shell were reported as being 1.5–54.2 and 13.6–15.7, respectively. However, in view of the relatively low ^{110m}Ag concentration in marine sediment relative to ^{137}Cs noted by IAEA [I1] and ^{110m}Ag:^{137}Cs ratios in marine biota rarely exceeding unity as noted by Qiu et al. [Q1], the elevated values of ^{110m}Ag as reported by Horiguchi et al. [H10] appear to be outliers and would benefit from further investigation.

131. Two papers [T2, V2] appeared to support the finding of the 2013 report that the contribution of radionuclides in marine sediment to exposures of marine biota in the initial period after the accident was negligible compared to other sources.

132. Okano et al. [O10] studied large Japanese field mice (*Apodemus speciosus*) in Fukushima Prefecture, focusing on apoptosis in germ cells and abnormal sperm morphologies. They concluded that radiation exposure did not cause substantial male subfertility during 2013 and 2014. The study provides evidence to support the main findings of the 2013 report that regional population impacts on non-human biota were not likely. However, the sampling sites used in the study were generally not in the areas of highest radionuclide deposition, although one site was in a location with ambient dose equivalents (30 months after the accident) exceeding 10 μGy/h.

133. Horiguchi et al. [H10] studied population densities and diversity of various intertidal organisms (e.g. echinoderms, crustaceans, and bivalves) in coastal regions along the eastern Japanese seaboard in the environs of FDNPS in the period 2011–2013. The authors found that the number of intertidal species decreased significantly at coastal locations closer to FDNPS.

Furthermore, no rock shell (*Thais clavigera*) specimens were collected within a distance of approximately 30 km from FDNPS in 2012. The fact that this particular species of gastropod was observed at many other sites affected by the tsunami suggested to the authors that there was a clear causal link between the absence of this organism and the FDNPS accident. The number of species and population densities in the intertidal zones, surveyed in 2013, were much lower at sites near, or within several kilometres south of, FDNPS compared to other more distant sites, and lower than in 1995, especially in the case of arthropoda. Nonetheless, the authors of this work also highlighted the complexity of establishing a definite causal link because of various potential direct impacts, such as physical harm from the tsunami, and toxicity from chemicals and radionuclides in the releases that occurred immediately after the accident. There also appear to be some questions regarding radionuclide determinations in this study, given the extremely high relative values of ^{110m}Ag that have been reported (see paragraph 130 above). Nonetheless, the results of the biological survey, per se, appear to be robust and provide further support to the argument that the assessment in the 2013 report may have been simplistic in not accounting for ecosystem complexity when quantifying environmental risk.

134. Hiyama et al. [H9] provided further evidence to suggest that the high abnormality rates observed in the pale grass blue butterfly were induced by “anthropogenic radioactive mutagens”. However, Otaki [O12] synthesized the results from several studies of the effects on the same species of butterfly following the FDNPS accident, and reported that ionizing radiation was unlikely to be the exclusive source of the environmental disturbances observed.

135. Yoschenko et al. [Y9] observed significant increases in morphological abnormalities in young trees of the species Japanese red pine (*Pinus densiflora*) in areas with elevated radionuclide deposition densities following the FDNPS accident. This is consistent with earlier studies [W4] reported in the second white paper [U5], which found morphological abnormalities in Japanese fir trees. As noted in the second white paper [U5], accumulated doses in vegetation in areas with relatively high densities of deposited radionuclides were estimated in the 2013 report to be similar to those at which disturbances in growth, reproduction and morphology of conifers had been observed following the Chernobyl accident. The implications of the presence of morphological abnormalities on tree population integrity is not well established.

C. Potential implication of new publications

136. The Committee’s assessment of the transfer of radionuclides released as a result of the FDNPS accident to non-human biota and consequent environmental exposures remains broadly supported by numerous publications. Although the study of Horiguchi et al. [H10] potentially challenges the findings of the 2013 report in the observation of large population level impacts in the intertidal zone, there are questions over some of the data presented in this work that need to be resolved, as noted above, before definitive conclusions can be drawn. Geras’kin [G1] noted that there does seem to be mounting evidence to suggest that radiation exposure can result in disruption of ecological interactions between components of ecosystems, which may act as a trigger of perturbation and lead to consequences that may differ from those expected from direct effects observed at the organism level. As noted in earlier white papers [U5], there may be questions in relation to how calculated dose-rates are interpreted, and, in particular, whether it is sufficient to focus on end points that do not take full account of the complexity of ecosystem interactions. The identified need for follow-up studies investigating the dose response at higher levels of biological organization (e.g. the population level) which take due account of biota interactions within ecosystems remains valid.

X. CONCLUSIONS OF APPRAISAL OF NEW PUBLICATIONS

137. Of the new sources of information appraised for this third white paper, a large proportion confirmed one or other of the major assumptions in the 2013 report. None materially affected the main findings in, or challenged the major assumptions of, the 2013 report. Those that had the potential to do so, albeit subject to further analysis or confirmation from studies of better quality, are summarized briefly below.

A. Potential challenges to 2013 report

138. The study of Horiguchi et al. [H10] potentially challenges the findings of the 2013 report in the observation of large population level impacts on non-human biota in the intertidal zone. However, there are questions over some of the data presented in this work, which need to be resolved before definitive conclusions can be drawn. Further studies [G1, H9, O12] have added to the evidence suggesting that irradiation can result in disruption of ecological interactions between components of ecosystems. Studies that take due account of biota interactions within ecosystems continue to be needed.

B. Contributions to research needs

139. Table 1 summarizes those publications that have been judged to have made a significant contribution to addressing the research needs identified in the 2013 report. Progress is being made in many areas, but several of those research needs have yet to be addressed fully by the scientific community (at least in peer-reviewed publications).

Table 1. Publications considered to make a significant contribution to one or other identified research need

Research need	*Publications deemed to make a high contribution to research need*	*Publications deemed to make a medium contribution to research need*
RELEASES TO ATMOSPHERE, DISPERSION AND DEPOSITION		
Improve estimates of amount and characteristics of releases to atmosphere as a function of time	[C2, S7, S9, T8]	[F1, G2, H7, J1, K2, M5, M7, O1, S1, S4, S10, Y1, Y10]
RELEASES TO WATER, DISPERSION AND DEPOSITION		
Measure and improve characterization of leaks of radioactive water and releases to aquatic environment over time	[C1, F2, I4, T10]	
Forecast and quantify long-term transport and mixing of releases and consequent exposures through aquatic pathways	[K11, K12]	[I5]
TRANSFER THROUGH TERRESTRIAL AND FRESHWATER ENVIRONMENTS		
Collate relevant information on transfer parameter values for food chain pathways	[K8, M11, W2, Y2]	[D1, E3, E4, F4, I3, K7, K9, K14, M6, M12, O6, O9, S13, T1, U1, W3, W6, Y3, Y5]
DOSES TO THE PUBLIC		
Measure dose rates due to external exposure to deposited material in various environments, forecast and track changes over time and quantify impact of environmental remediation programmes		[M3, N3]
Conduct in vivo measurements of radionuclides in people to support refinement in the estimation of doses and their distribution and to estimate current and future levels of exposure		[K5, K6, T5]
DOSES TO WORKERS		
Quantify the uncertainties in reported doses to workers, considering the work histories of individual workers		[S3, Y6, Y7]
HEALTH IMPLICATIONS		
Continue the ongoing health survey in Fukushima Prefecture	[N2]	[S2]
Analyse and quantify the impact of ultrasonographic surveys on the apparent incidence of thyroid cancer in Fukushima Prefecture	[O5, S14, S15]	
DOSES AND EFFECTS FOR NON-HUMAN BIOTA		
Measure and assess the environmental exposures typical for certain species of non-human biota, and further analyse whether radiation exposure was an important factor in causing environmental effects reported in field studies but which were inconsistent with the Committee’s assessment	[H9, H10, O10, T1, W1, W2, Y9]	[A3, F3, O12, Q1, S12, T2, T4, V2, V3]

XI. COLLECTION AND EVALUATION OF MAJOR RESEARCH PROJECTS AND PROGRAMMES

140. One of the specific objectives in the plan for follow-up activities (see paragraph 4) was "to collect and evaluate progress made in, and plans for, major research projects and programmes related to pending questions". This objective was not addressed systematically in either of the previous white papers, where the focus was on the review of published information. Awareness and/or the evaluation of on-going and planned major research projects or programmes will be beneficial for the Committee's follow-up activities in two respects: firstly, in providing advance warning of studies, the outcomes of which may have a material impact on the findings of the 2013 report; and, secondly, in better informing judgements on if, and if so when, it may be appropriate to update the 2013 report, i.e. moving from Phase I (review of new information) to Phase II (update of the 2013 report) of the plan for follow-up activities (see paragraph 4).

141. Research projects and programmes being carried out, or funded by, Japanese organizations represent by far the majority of ongoing and planned research on the accident at FDNPS. These have been evaluated based on meetings with the Japanese research community.

142. Two meetings were held with the Japanese research community in November 2016. The purposes of the meetings were: to exchange views on gaps, uncertainties and research needs that had the potential to improve assessments of the health and environmental impact of the accident at FDNPS; to become better informed of major Japanese research projects/programmes, in particular their scope, objectives, current status, envisaged outcomes and duration; and to establish mechanisms to enable effective dialogue and exchange of information between the Committee's experts and the Japanese research community. One meeting was held in Tokyo for those projects/programmes being carried out or funded at a national level; a second meeting was held in Fukushima City for those projects/programmes being carried out largely under the auspices of the Fukushima Prefecture. Members of the Committee's Expert Group and Japanese Working Group attended both meetings, together with lead researchers for each project/programme and representatives of a number of organizations that had commissioned/funded the research.

143. The scope, content and outcomes of these meetings are briefly described in an electronic attachment to this white paper. Particular attention is given to the extent to which the research projects/programmes address the research needs identified in the 2013 report. Table 2 presents a summary of the major Japanese research projects/programmes, setting out the main objectives, the envisaged outcomes which address these research needs and the timescales for each. It is based on information initially compiled by the Committee's Japanese Working Group supplemented by information presented during the two meetings. Many of the research projects/programmes, at least as currently formulated, will be completed within the next few years (i.e. before 2020) and have the potential to enhance significantly the quality, robustness and/or comprehensiveness of current estimates of, inter alia: the magnitude and characteristics of the release of radioactive material, the doses to the public resulting from the accident at FDNPS, and the health implications.

Table 2. Major Japanese research projects and programmes

Short description of research programme (Sponsor or Lead)	*Objectives*	*Key outcomes addressing UNSCEAR research needs*	*Results envisaged by*
Interdisciplinary study on inhalation exposure and risk assessment based on measured concentrations of radionuclides in air following the nuclear accident (Ministry of the Environment, MOE)	To make best use of databases of measurements of concentrations of radioactive material in the air and ATDM to better quantify concentrations in air where people were located during the accident, and, thereby, assess inhalation doses in the early phases of the accident	Improved estimates of doses to members of the public from inhalation and their uncertainties	Mid-2018
Comprehensive study to assess radiation doses to residents from the FDNPS accident (MOE)	Address uncertainties in the source term and modelling by using improved ATDM results, measurement data on dose rates in air, and an updated source term Reconstruct doses to members of the public (in particular, in the early phases of the accident) from internal and external exposure	New source term for releases to the atmosphere Improved estimates of doses to members of the public, particularly in the early phases of the accident, from inhalation, ingestion and external exposure	Mid-2017
Survey on the distribution of radioactive materials (Ministry of Education, Culture, Sports, Science and Technology, MEXT, Nuclear Regulation Authority, JAEA)	Create maps of the dose rate in air and radionuclide deposition density Clarify the characteristics of deposition Study radiocaesium migration in the environment Develop a model to predict the air dose rate distribution Make data available to the public	Maps of dose rates in air and radionuclide deposition densities on the ground Improved understanding of how deposition occurred and how it varied in time and space Predictions of air dose rates up to 30 years after the accident Publicly available database integrating various environmental monitoring data	Research continuing with publication as appropriate
Studies on releases of radioactive water from the FDNPS accident to the ocean environment (JAEA)	Characterize releases to the aquatic environment, including groundwater, and ultimately the Pacific Ocean, over time Forecast and quantify the long-term transport and mixing of these releases Assess consequent exposures through aquatic pathways	Releases to the ocean by source (direct releases, deposition from the atmosphere, inputs from rivers and groundwater) and over time Understanding of transport and dispersion in the ocean	Mid-2019
Studies on the transfer of radionuclides in the terrestrial environment (MEXT, JAEA)	Assess the migration of radionuclides in the terrestrial environment	Calculation tools and parameter values for modelling transfers of radionuclides in the terrestrial environment in Japan	2018, with outcomes of further research to follow

Short description of research programme (Sponsor or Lead)	*Objectives*	*Key outcomes addressing UNSCEAR research needs*	*Results envisaged by*
Studies on radionuclide transport in the terrestrial and aquatic environment and exposure of wildlife (Fukushima University)	Understand radionuclide transport in the terrestrial and aquatic environment, the physiochemical forms of radionuclides, the long-term behaviour of radionuclides in rivers, reservoirs and the marine environment, and the long-term behaviour of radionuclides in the ecosystem Assess the effects of chronic exposure of wildlife populations to radiation from the accident	Parameter values for modelling transfers of radionuclides in the terrestrial and aquatic environments in Japan and for estimating doses to members of the public from ingestion of foodstuffs Improved estimates of long-term doses to and effects on non-human biota	Research continuing with publication as appropriate
Studies on the radiation effects on wild animals and plants (MOE)	Understand the effects of the radioactive materials released from FDNPS on natural ecosystems	Assessment of the exposures of non-human biota and effects as a result of the FDNPS accident	2012 to 2015 survey reported in 2016. Research continuing with publication as appropriate
Fukushima Health Management Survey (Fukushima Prefecture and Fukushima Medical University)	Provide dose estimates for the residents of Fukushima Prefecture, including estimates of the dose from external exposure for the first four months after the FDNPS accident Assess and monitor the health and well-being of residents of Fukushima Prefecture through a comprehensive health check for people living in evacuation areas, thyroid screening for all children in the prefecture, monitoring of mental health and lifestyle changes, and a pregnancy and birth survey	Estimates of doses to members of the public from internal exposure and from external exposure Evidence on changes in health and well-being	Research continuing with publication as appropriate
Nuclear Emergency Workers Health Study (MHLW, Radiation Effects Research Foundation)	Estimation of individual doses and monitoring the health status of emergency workers including estimates of doses from external and internal exposure during the emergency period, a comprehensive health check-up, thyroid screening by ultrasonography, a cataract (lens opacity) study, a mental health survey, and storage of biological samples	Improved estimates of doses to workers from internal and external exposure Evidence on changes in health and well-being of workers	Baseline survey expected complete in 2019

ACKNOWLEDGEMENTS

In approving this white paper for publication, the Committee wishes to acknowledge with gratitude the help of the experts directly involved in undertaking follow-up activities relating to levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami.

Senior technical advisers

W. Weiss (Germany) and M. Akashi (Japan)

Expert group

M. Balonov (Russian Federation), C. Estournel (France), G. Etherington (United Kingdom), F. Gering (Germany), B. Howard (United Kingdom), R. Shore (United States), S. Solomon (Australia), P. Strand (Norway)

Japanese working group

Technical support: K. Kodama (Japan)

Members: T. Aono (Japan), M. Chino (Japan), K. Ozasa (Japan), S. Saigusa (Japan), K. Sakai (Japan), T. Takahashi (Japan), H. Yasuda (Japan)

Critical reviewers

J. Brown (United Kingdom), J. Chen (Canada), N. Harley (United States), G. Hirth (Australia), J.-R. Jourdain (France), F. Mettler (United States), B.I. Min (Republic of Korea), H. Nies (Germany), S. Shinkarev (Russian Federation), K.S. Suh (Republic of Korea), H. Vandenhove (Belgium)

Project manager

G.N. Kelly (United Kingdom)

REFERENCES

A1 Abe, Y., Y. Iizawa, Y. Terada et al. Detection of uranium and chemical state analysis of individual radioactive microparticles emitted from the Fukushima nuclear accident using multiple synchrotron radiation X-ray analyses. Anal Chem 86(17): 8521-8525 (2014).

A2 Adachi, K., M. Kajino, Y. Zaizen et al. Emission of spherical cesium-bearing particles from an early stage of the Fukushima nuclear accident. Sci Rep 3: 2554 (2013).

A3 Aono, T., Y. Ito, T. Sohtome et al. Observation of radionuclides in marine biota off the coast of Fukushima prefecture after TEPCO's Fukushima Daiichi nuclear power station accident. pp.115-123 in: Radiation Monitoring and Dose Estimation of the Fukushima Nuclear Accident. (S. Takahashi, ed.) Springer, Tokyo, 2014.

A4 Aono, T., S. Yoshida and M. Akashi. Initial and present situation of food contamination in Japan after the accident at the Fukushima Dai-Ichi nuclear power plant. Radiat Prot Dosim 171(1): 14-19 (2016).

A5 Arai, T. Radioactive cesium accumulation in freshwater fishes after the Fukushima nuclear accident. Springerplus 3(1): 479-491 (2014).

B1 Brown, J. and J.R. Simmonds. FARMLAND a dynamic model for the transfer of radionuclides through terrestrial foodchains. NRPB-R273. National Radiological Protection Board, Chilton, 1995.

C1 Castrillejo, M., N. Casacuberta, C.F. Breier et al. Reassessment of (90)Sr, (137)Cs, and (134)Cs in the coast off Japan derived from the Fukushima Dai-ichi nuclear accident. Environ Sci Technol 50(1): 173-180 (2016).

C2 Chino, M., H. Terada, H. Nagai et al. Utilization of (134)Cs/(137)Cs in the environment to identify the reactor units that caused atmospheric releases during the Fukushima Daiichi accident. Sci Rep 6: 31376 (2016).

D1 Djedidi, S., K. Kojima, N. Ohkama-Ohtsu et al. Growth and (137)Cs uptake and accumulation among 56 Japanese cultivars of Brassica rapa, Brassica juncea and Brassica napus grown in a contaminated field in Fukushima: Effect of inoculation with a Bacillus pumilus strain. J Environ Radioact 157: 27-37 (2016).

E1 Ebner, D.K., M. Ohsawa, K. Igari et al. Lifestyle-related diseases following the evacuation after the Fukushima Daiichi nuclear power plant accident: a retrospective study of Kawauchi Village with long-term follow-up. BMJ Open 6(7): e011641 (2016).

E2 Eguchi, T., T. Ohta, T. Ishikawa et al. Influence of the nonexchangeable potassium of mica on radiocesium uptake by paddy rice. J Environ Radioact 147: 33-42 (2015).

E3 Endo, S., T. Kajimoto and K. Shizuma. Paddy-field contamination with ^{134}Cs and ^{137}Cs due to Fukushima Dai-ichi nuclear power plant accident and soil-to-rice transfer coefficients. J Environ Radioact 116: 59-64 (2013).

E4 Evrard, O., J.P. Laceby, Y. Onda et al. Quantifying the dilution of the radiocesium contamination in Fukushima coastal river sediment (2011-2015). Sci Rep 6: 34828 (2016).

F1 Fujiwara, H. Observation of radioactive iodine ((131)I, (129)I) in cropland soil after the Fukushima nuclear accident. Sci Total Environ 566-567: 1432-1439 (2016).

F2 Fukuda, M., T. Aono, S. Yamazaki et al. Dissolved radiocaesium in seawater off the coast of Fukushima during 2013–2015. J Radioanal Nucl Chem 311(2): 1479-1484 (2016).

F3 Fuma, S., Y. Kubota, S. Ihara et al. Radiocaesium contamination of wild boars in Fukushima and surrounding regions after the Fukushima nuclear accident. J Environ Radioact 164: 60-64 (2016).

F4 Fuma, S., Y. Watanabe, Y. Kubota et al. Radiocaesium contamination of bamboo shoots in Fukushima and surrounding regions after the Fukushima nuclear accident. J Radioanal Nucl Chem 311(1): 219-223 (2017).

G1 Geras'kin, S.A. Ecological effects of exposure to enhanced levels of ionizing radiation. J Environ Radioact 162-163: 347-357 (2016).

G2 Girard, S., V. Mallet, I. Korsakissok et al. Emulation and Sobol' sensitivity analysis of an atmospheric dispersion model applied to the Fukushima nuclear accident. J Geophys Res Atmos 121(7): 3484-3496 (2016).

H1 Hanna, S.R. and G.S. Young. The need for harmonization of methods for finding locations and magnitudes of air pollution sources using observations of concentrations and wind fields. Atmos Environ 148: 361-363 (2017).

H2 Hashimoto, K., K. Tanoi, K. Sakurai et al. The radioactivity measurement of milk from the cow supplied with the meadow grass grown in Ibaraki-prefecture, after the nuclear power plant accident. Radioisotopes 60(8): 335-338 (2011). (Japanese).

H3 Hashimoto, S., M. Nagai, S. Fukuma et al. Influence of post-disaster evacuation on incidence of metabolic syndrome. J Atheroscler Thromb 24(3): 327-337 (2017).

H4 Hirayama, H., H. Matsumura, Y. Namito et al. Estimation of time history of I-131 concentration in air using NaI(Tl) detector pulse height distribution at monitoring posts in Fukushima prefecture. Trans At Energy Soc Japan 14(1): 1-11 (2015). (Japanese).

H5 Hirono, Y. and K. Nonaka. Time series changes in radiocaesium distribution in tea plants (Camellia sinensis (L.)) after the Fukushima Dai-ichi Nuclear Power Plant accident. J Environ Radioact 152: 119-126 (2016).

H6 Hirose, K. Two-years trend of monthly ^{137}Cs deposition observed in Kanto and south Tohoku areas, Japan: effects of the Fukushima Dai-ichi nuclear power plant accident. J Radioanal Nucl Chem 303(2): 1327-1329 (2015).

H7 Hirose, K. Fukushima Daiichi Nuclear Plant accident: Atmospheric and oceanic impacts over the five years. J Environ Radioact 157: 113-130 (2016).

H8 Hiyama, A., C. Nohara, S. Kinjo et al. The biological impacts of the Fukushima nuclear accident on the pale grass blue butterfly. Sci Rep 2: 570 (2012).

H9 Hiyama, A., W. Taira, M. Iwasaki et al. Geographical distribution of morphological abnormalities and wing color pattern modifications of the pale grass blue butterfly in northeastern Japan. Entomol Sci 20(1): 100-110 (2017).

H10 Horiguchi, T., H. Yoshii, S. Mizuno et al. Decline in intertidal biota after the 2011 Great East Japan Earthquake and Tsunami and the Fukushima nuclear disaster: field observations. Sci Rep 6: 20416 (2016).

H11 Howard, B.J., S. Fesenko, M. Balonov et al. A comparison of remediation after the Chernobyl and Fukushima Daiichi accidents. Radiat Prot Dosim 173(1-3): 170-176 (2017).

I1 IAEA. The Fukushima Daiichi accident. Technical volume 5/5: Post-accident recovery. International Atomic Energy Agency. Vienna, 2015.

I2 Igarashi, Y., M. Kajino, Y. Zaizen et al. Atmospheric radioactivity over Tsukuba, Japan: a summary of three years of observations after the FDNPP accident. Progress in Earth and Planetary Science 2(1): 44 (2015).

I3 Iguchi, K., K. Fujimoto, H. Kaeriyama et al. Cesium-137 discharge into the freshwater fishery ground of grazing fish, ayu Plecoglossus altivelis after the March 2011 Fukushima nuclear accident. Fish Sci 79(6): 983-988 (2013).

I4 Inomata, Y., M. Aoyama, T. Tsubono et al. Spatial and temporal distributions of (134)Cs and (137)Cs derived from the TEPCO Fukushima Daiichi Nuclear Power Plant accident in the North Pacific Ocean by using optimal interpolation analysis. Environ Sci Process Impacts 18(1): 126-136 (2016).

I5 Inoue, M., H. Kofuji, K. Fujimoto et al. Delivery mechanism of (134)Cs and (137)Cs in seawater off the Sanriku Coast, Japan, following the Fukushima Dai-ichi NPP accident. J Environ Radioact 137: 113-118 (2014).

I6 Inoue, M., Y. Shirotani, S. Nagao et al. Migration of the FDNPP-derived ^{134}Cs and ^{137}Cs along with ^{226}Ra and ^{228}Ra concentrations across the northwestern North Pacific Ocean. J Environ Radioact 162-163: 33-38 (2016).

I7 Ishikawa, T., S. Yasumura, K. Ozasa et al. The Fukushima Health Management Survey: estimation of external doses to residents in Fukushima Prefecture. Sci Rep 5: 12712 (2015).

I8 Ishikawa, T., S. Yasumura, A. Ohtsuru et al. An influential factor for external radiation dose estimation for residents after the Fukushima Daiichi Nuclear Power Plant accident-time spent outdoors for residents in Iitate Village. J Radiol Prot 36(2): 255-268 (2016).

J1 Jäckel, B.S., A. Bevilacqua, G. Ducros et al. Land contamination activity data interpretation from Fukushima Daiichi accident. Nucl Eng Des 300: 28-33 (2016).

K1 Kaiser, J.C., R. Meckbach, M. Eidemuller et al. Integration of a radiation biomarker into modeling of thyroid carcinogenesis and post-Chernobyl risk assessment. Carcinogenesis 37(12): 1152-1160 (2016).

K2 Kaneyasu, N., H. Ohashi, F. Suzuki et al. Sulfate aerosol as a potential transport medium of radiocesium from the Fukushima nuclear accident. Environ Sci Technol 46(11): 5720-5726 (2012).

K3 Katanoda, K., K. Kamo and S. Tsugane. Quantification of the increase in thyroid cancer prevalence in Fukushima after the nuclear disaster in 2011--a potential overdiagnosis? Jpn J Clin Oncol 46(3): 284-286 (2016).

K4 Katata, G., M. Chino, T. Kobayashi et al. Detailed source term estimation of the atmospheric release for the Fukushima

Daiichi Nuclear Power Station accident by coupling simulations of an atmospheric dispersion model with an improved deposition scheme and oceanic dispersion model. Atmos Chem Phys 15(2): 1029-1070 (2015).

K5 Kim, E., O. Kurihara, N. Kunishima et al. Internal thyroid doses to Fukushima residents-estimation and issues remaining. J Radiat Res 57 (Suppl 1): i118-i126 (2016).

K6 Kim, E., O. Kurihara, N. Kunishima et al. Early intake of radiocesium by residents living near the TEPCO Fukushima Dai-Ichi nuclear power plant after the accident. Part 1: Internal doses based on whole-body measurements by NIRS. Health Phys 111(5): 451-464 (2016).

K7 Kitamura, A., H. Kurikami, K. Sakuma et al. Redistribution and export of contaminated sediment within eastern Fukushima Prefecture due to typhoon flooding. Earth Surf Process Landforms 41(12): 1708-1726 (2016).

K8 Kobayashi, M., K. Suzuki, S. Miyamoto et al. Urgent study on the contamination of radionuclides in milk of dairy cows following the accident at the Fukushima Daiichi Nuclear Power Plant in Japan. Nihon Chikusan Gakkaiho 83(1): 57-64 (2012). (Japanese).

K9 Konoplev, A., V. Golosov, G. Laptev et al. Behavior of accidentally released radiocesium in soil-water environment: Looking at Fukushima from a Chernobyl perspective. J Environ Radioact 151 (Pt 3): 568-578 (2016).

K10 Konoplev, A.V., V.N. Golosov, V.I. Yoschenko et al. Vertical distribution of radiocesium in soils of the area affected by the Fukushima Dai-ichi nuclear power plant accident. Eurasian Soil Sci 49(5): 570-580 (2016).

K11 Kumamoto, Y., M. Aoyama, Y. Hamajima et al. Meridional distribution of Fukushima-derived radiocesium in surface seawater along a trans-Pacific line from the Arctic to Antarctic Oceans in summer 2012. J Radioanal Nucl Chem 307(3): 1703-1710 (2016).

K12 Kumamoto, Y., M. Aoyama, Y. Hamajima et al. Fukushima-derived radiocesium in the western North Pacific in 2014. J Radioanal Nucl Chem 311(2): 1209-1217 (2017).

K13 Kunii, Y., Y. Suzuki, T. Shiga et al. Severe psychological distress of evacuees in evacuation zone caused by the Fukushima Daiichi nuclear power plant accident: The Fukushima Health Management Survey. PLoS One 11(7): e0158821 (2016).

K14 Kusaba, S., K. Matsuoka, K. Abe et al. Effect of soil surface management on radiocesium concentrations in apple orchard and fruit. Hort J 85(1): 30-36 (2016).

L1 Leboulleux, S., R.M. Tuttle, F. Pacini et al. Papillary thyroid microcarcinoma: time to shift from surgery to active surveillance? Lancet Diabetes Endocrinol 4(11): 933-942 (2016).

M1 MAFF. 2012 livestock statistics. Ministry of Agriculture, Forestry and Fishery, Japan. [Internet] Available from (http://www.e-stat.go.jp/SG1/estat/List.do?lid=000001105713) on 1 January 2017. (Japanese).

M2 MAFF. 2011 livestock statistics. Ministry of Agriculture, Forestry and Fishery, Japan. [Internet] Available from (http://www.e-stat.go.jp/SG1/estat/List.do?lid=000001099430) on 1 January 2017. (Japanese).

M3 Malins, A., H. Kurikami, S. Nakama et al. Evaluation of ambient dose equivalent rates influenced by vertical and horizontal distribution of radioactive cesium in soil in Fukushima Prefecture. J Environ Radioact 151 (Pt 1): 38-49 (2016).

M4 Manabe, N., T. Takahashi, M. Endo et al. Effects of “Clean Feeding” management on livestock products contaminated with radioactive cesium due to the Fukushima Daiichi Nuclear Power Plant accident. pp.77-90 in: Agricultural Implications of the Fukushima Nuclear Accident (T.M. Nakanishi and K. Tanoi, eds.). Springer, Tokyo, 2016.

M5 Mikami, S., T. Maeyama, Y. Hoshide et al. Spatial distributions of radionuclides deposited onto ground soil around the Fukushima Dai-ichi Nuclear Power Plant and their temporal change until December 2012. J Environ Radioact 139: 320-343 (2015).

M6 Mishra, S., S.K. Sahoo, P. Bossew et al. Vertical migration of radio-caesium derived from the Fukushima Dai-ichi Nuclear Power Plant accident in undisturbed soils of grassland and forest. J Geochem Explor 169: 163-186 (2016).

M7 Miyamoto, Y., K. Yasuda and M. Magara. Size distribution of radioactive particles collected at Tokai, Japan 6 days after the nuclear accident. J Environ Radioact 132: 1-7 (2014).

M8 ML. Criteria for approving occupational/ non-occupational diseases related to ionizing radiation disease. Director-General's notice No. 810. Ministry of Labour, Japan, 8 November 1976. (Japanese).

M9 Møller, A.P., A. Hagiwara, S. Matsui et al. Abundance of birds in Fukushima as judged from Chernobyl. Environ Pollut 164: 36-39 (2012).

M10 Møller, A.P., I. Nishiumi, H. Suzuki et al. Differences in effects of radiation on abundance of animals in Fukushima and Chernobyl. Ecol Indic 24: 75-81 (2013).
M11 Mukai, H., A. Hirose, S. Motai et al. Cesium adsorption/desorption behavior of clay minerals considering actual contamination conditions in Fukushima. Sci Rep 6: 21543 (2016).
M12 Mukai, H., S. Motai, T. Yaita et al. Identification of the actual cesium-adsorbing materials in the contaminated Fukushima soil. Appl Clay Sci 121-122: 188-193 (2016).
M13 Muramatsu, Y., H. Matsuzaki, C. Toyama et al. Analysis of ^{129}I in the soils of Fukushima Prefecture: preliminary reconstruction of ^{131}I deposition related to the accident at Fukushima Daiichi Nuclear Power Plant (FDNPP). J Environ Radioact 139: 344-350 (2015).
N1 Nagao, S., M. Kanamori, S. Ochiai et al. Migration behavior of ^{134}Cs and ^{137}Cs in the Niida River water in Fukushima Prefecture, Japan during 2011–2012. J Radioanal Nucl Chem 303(2): 1617-1621 (2015).
N2 Nagataki, S. Minimizing the health effects of the nuclear accident in Fukushima on thyroids. Eur Thyroid J 5(4): 219-223 (2016).
N3 Naito, W., M. Uesaka, C. Yamada et al. Relationship between individual external doses, ambient dose rates and individuals' activity-patterns in affected areas in Fukushima following the Fukushima Daiichi Nuclear Power Plant accident. PLoS One 11(8): e0158879 (2016).
N4 Naulier, M., F. Eyrolle-Boyer, P. Boyer et al. Particulate organic matter in rivers of Fukushima: An unexpected carrier phase for radiocesiums. Sci Total Environ 579: 1560-1571 (2017).
N5 Nippon Foundation. Recommendations: the Fifth International Expert Symposium in Fukushima on Radiation and Health. [Internet] Available from (http://www.nippon-foundation.or.jp/en/news/articles/2016/img/60/1.pdf)
O1 Ochiai, S., H. Hasegawa, H. Kakiuchi et al. Temporal variation of post-accident atmospheric ^{137}Cs in an evacuated area of Fukushima Prefecture: Size-dependent behaviors of ^{137}Cs-bearing particles. J Environ Radioact 165: 131-139 (2016).
O2 Oe, M., S. Fujii, M. Maeda et al. Three-year trend survey of psychological distress, post-traumatic stress, and problem drinking among residents in the evacuation zone after the Fukushima Daiichi Nuclear Power Plant accident [The Fukushima Health Management Survey]. Psychiatry Clin Neurosci 70(6): 245-252 (2016).
O3 Ohira, T., M. Hosoya, S. Yasumura et al. Evacuation and risk of hypertension after the Great East Japan earthquake: The Fukushima Health Management Survey. Hypertension 68(3): 558-564 (2016).
O4 Ohira, T., M. Hosoya, S. Yasumura et al. Effect of evacuation on body weight after the Great East Japan earthquake. Am J Prev Med 50(5): 553-560 (2016).
O5 Ohira, T., H. Takahashi, S. Yasumura et al. Comparison of childhood thyroid cancer prevalence among 3 areas based on external radiation dose after the Fukushima Daiichi nuclear power plant accident. Medicine 95(35): e4472 (2016).
O6 Ohmori, H., Y. Sasaki, K. Tajima et al. Radioactive caesium concentrations in pigs fed brown rice contaminated by the Tokyo Electric Power Company Fukushima Daiichi nuclear power plant. Livestock Sci 159: 156-160 (2014).
O7 Ohmori, Y., M. Kajikawa, S. Nishida et al. The effect of fertilization on cesium concentration of rice grown in a paddy field in Fukushima Prefecture in 2011 and 2012. J Plant Res 127(1): 67-71 (2014).
O8 Oinuma, H., K. Yanai, H. Matsuyama et al. Inhibitory effect of zeolite and bentonite on absorption radioactive cesium in daily cattle. Tohoku J Agric Res 65: 89-90 (2012). (Japanese).
O9 Oinuma, H., M. Saito, Y. Oda et al. Effect of zeolite supplementation on the transfer of radioactive cesium from diet in dairy cows. Nihon Chikusan Gakkaiho 84(3): 333-339 (2013). (Japanese).
O10 Okano, T., H. Ishiniwa, M. Onuma et al. Effects of environmental radiation on testes and spermatogenesis in wild large Japanese field mice (Apodemus speciosus) from Fukushima. Sci Rep 6: 23601 (2016).
O11 Orita, M., K. Nakashima, N. Hayashida et al. Concentrations of radiocesium in local foods collected in Kawauchi village after the accident at the Fukushima Dai-ichi Nuclear Power Station. Sci Rep 6: 28470 (2016).
O12 Otaki, J.M. Fukushima's lessons from the blue butterfly: A risk assessment of the human living environment in the post-Fukushima era. Integr Environ Assess Manag 12(4): 667-672 (2016).
O13 Oura, Y., M. Ebihara, H. Tsuruta et al. A database of hourly atmospheric concentrations of radiocesium (^{134}Cs and ^{137}Cs) in suspended particulate matter collected in March 2011 at 99 air pollution monitoring stations in eastern Japan. J Nucl Radiochem Sci 15(2): 1-12 (2015).

P1 Park, S., C.M. Oh, H. Cho et al. Association between screening and the thyroid cancer "epidemic" in South Korea: evidence from a nationwide study. Br Med J 355: i5745 (2016).

Q1 Qiu, X., S.L. Undap, M. Honda et al. Pollution of radiocesium and radiosilver in wharf roach (*Ligia* sp.) by the Fukushima Dai-ichi Nuclear Power Plant accident. J Radioanal Nucl Chem 311(1): 121-126 (2016).

S1 Sakaguchi, A., P. Steier, Y. Takahashi et al. Isotopic compositions of (236)U and Pu isotopes in "black substances" collected from roadsides in Fukushima prefecture: fallout from the Fukushima Dai-ichi nuclear power plant accident. Environ Sci Technol 48(7): 3691-3697 (2014).

S2 Sakai, A., T. Ohira, M. Hosoya et al. White blood cell, neutrophil, and lymphocyte counts in individuals in the evacuation zone designated by the government after the Fukushima Daiichi Nuclear Power Plant accident: the Fukushima Health Management Survey. J Epidemiol 25(1): 80-87 (2015).

S3 Sakumi, A., R. Miyagawa, Y. Tamari et al. External effective radiation dose to workers in the restricted area of the Fukushima Daiichi Nuclear Power Plant during the third year after the Great East Japan Earthquake. J Radiat Res 57(2): 178-181 (2016).

S4 Salbu, B. and O.C. Lind. Radioactive particles released to the environment from the Fukushima reactors-Confirmation is still needed. Integr Environ Assess Manag 12(4): 687-689 (2016).

S5 Sasaki, Y., H. Abe, K. Mitachi et al. The transfer of radiocesium from the bark to the stemflow of chestnut trees (Castanea crenata) contaminated by radionuclides from the Fukushima Dai-ichi nuclear power plant accident. J Environ Radioact 161: 58-65 (2016).

S6 Sato, I., M. Natsuhori, J. Sasaki et al. Local variation of soil contamination with radioactive cesium at a farm in Fukushima. Jpn J Vet Res 64(1): 95-99 (2016).

S7 Satou, Y., K. Sueki, K. Sasa et al. First successful isolation of radioactive particles from soil near the Fukushima Daiichi Nuclear Power Plant. Anthropocene 14: 71-76 (2016).

S8 Scherb, H.H., K. Mori and K. Hayashi. Increases in perinatal mortality in prefectures contaminated by the Fukushima nuclear power plant accident in Japan: A spatially stratified longitudinal study. Medicine (Baltimore) 95(38): e4958 (2016).

S9 SCJ. A review of the model comparison of transportation and deposition of radioactive materials released to the environment as a result of the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant accident. Sectional Committee on Nuclear Accident, Science Council of Japan, Tokyo, 2014.

S10 Snow, M.S., D.C. Snyder and J.E. Delmore. Fukushima Daiichi reactor source term attribution using cesium isotope ratios from contaminated environmental samples. Rapid Commun Mass Spectrom 30(4): 523-532 (2016).

S11 Steinhauser, G., T. Niisoe, K.H. Harada et al. Post-accident sporadic releases of airborne radionuclides from the Fukushima Daiichi Nuclear Power Plant site. Environ Sci Technol 49(24): 14028-14035 (2015).

S12 Sugiura, Y., M. Shibata, Y. Ogata et al. Evaluation of radiocesium concentrations in new leaves of wild plants two years after the Fukushima Dai-ichi Nuclear Power Plant accident. J Environ Radioact 160: 8-24 (2016).

S13 Sunaga, Y. and H. Harada. Simple method for estimating soil mass loading onto plant surface using magnetic material content as a soil indicator - Influence of soil adhesion to vegetation on radioactive cesium concentration in forage. J Environ Radioact 164: 125-132 (2016).

S14 Suzuki, S. Childhood and adolescent thyroid cancer in Fukushima after the Fukushima Daiichi Nuclear Power Plant accident: 5 years on. Clin Oncol (R Coll Radiol) 28(4): 263-271 (2016).

S15 Suzuki, S., S. Suzuki, T. Fukushima et al. Comprehensive survey results of childhood thyroid ultrasound examinations in Fukushima in the first four years after the Fukushima Daiichi Nuclear Power Plant accident. Thyroid 26(6): 843-851 (2016).

T1 Tagami, K., B.J. Howard and S. Uchida. The time-dependent transfer factor of radiocesium from soil to game animals in Japan after the Fukushima Dai-ichi nuclear accident. Environ Sci Technol 50(17): 9424-9431 (2016).

T2 Tagami, K. and S. Uchida. Consideration on the long ecological half-life component of ^{137}Cs in demersal fish based on field observation results obtained after the Fukushima accident. Environ Sci Technol 50(4): 1804-1811 (2016).

T3 Takada, M., T. Yamada, T. Takahara et al. Spatial variation in the (137)Cs inventory in soils in a mixed deciduous forest in Fukushima, Japan. J Environ Radioact 161: 35-41 (2016).

T4 Tanaka, S., K. Hatakeyama, S. Takahashi et al. Radioactive contamination of arthropods from different trophic levels in hilly and mountainous areas after the Fukushima Daiichi nuclear power plant accident. J Environ Radioact 164: 104-112 (2016).

T5 Tani, K., O. Kurihara, E. Kim et al. Implementation of iodine biokinetic model for interpreting I-131 contamination in breast milk after the Fukushima nuclear disaster. Sci Rep 5: 12426 (2015).

T6 Tateda, Y., D. Tsumune, T. Tsubono et al. Status of (137)Cs contamination in marine biota along the Pacific coast of eastern Japan derived from a dynamic biological model two years simulation following the Fukushima accident. J Environ Radioact 151 (Pt 2): 495-501 (2016).

T7 Terada, H., G. Katata, M. Chino et al. Atmospheric discharge and dispersion of radionuclides during the Fukushima Daiichi Nuclear Power Plant accident. Part II: verification of the source term and analysis of regional-scale atmospheric dispersion. J Environ Radioact 112: 141-154 (2012).

T8 Terasaka, Y., H. Yamazawa, J. Hirouchi et al. Air concentration estimation of radionuclides discharged from Fukushima Daiichi Nuclear Power Station using NaI(Tl) detector pulse height distribution measured in Ibaraki Prefecture. J Nucl Sci Technol 53(12): 1919-1932 (2016).

T9 Tokonami, S., M. Hosoda, S. Akiba et al. Thyroid doses for evacuees from the Fukushima nuclear accident. Sci Rep 2: 507 (2012).

T10 Tsubono, T., K. Misumi, D. Tsumune et al. Evaluation of radioactive cesium impact from atmospheric deposition and direct release fluxes into the North Pacific from the Fukushima Daiichi nuclear power plant. Deep-Sea Res Part I Oceanogr Res Pap 115: 10-21 (2016).

T11 Tsukada, H. and K. Ohse. Concentration of radiocaesium in rice and irrigation water, and soil management practices in Oguni, Date, Fukushima. Integr Environ Assess Manag 12(4): 659-661 (2016).

T12 Tsuruta, H., Y. Oura, M. Ebihara et al. First retrieval of hourly atmospheric radionuclides just after the Fukushima accident by analyzing filter-tapes of operational air pollution monitoring stations. Sci Rep 4: 6717 (2014).

U1 Uematsu, S., H. Vandenhove, L. Sweeck et al. Variability of the soil-to-plant radiocaesium transfer factor for Japanese soils predicted with soil and plant properties. J Environ Radioact 153: 51-60 (2016).

U2 UNSCEAR. Sources, Effects and Risks of Ionizing Radiation. Volume I: Report to the General Assembly and Scientific Annex A. UNSCEAR 2013 Report. United Nations Scientific Committee on the Effects of Atomic Radiation. United Nations sales publication E.14.IX.1. United Nations, New York, 2014.

U3 UNSCEAR. Sources, Effects and Risks of Ionizing Radiation. Report to the General Assembly and Scientific Annexes A and B. UNSCEAR 2012 Report. United Nations Scientific Committee on the Effects of Atomic Radiation. United Nations sales publication E.16.IX.1. United Nations, New York, 2015.

U4 UNSCEAR. Developments since the 2013 UNSCEAR Report on the Levels and Effects of Radiation Exposure due to the Nuclear Accident following the Great East-Japan Earthquake and Tsunami. A 2015 white paper to guide the Scientific Committee's future programme of work. United Nations Scientific Committee on the Effects of Atomic Radiation. United Nations, New York, 2015.

U5 UNSCEAR. Developments since the 2013 UNSCEAR Report on the Levels and Effects of Radiation Exposure due to the Nuclear Accident following the Great East-Japan Earthquake and Tsunami. A 2016 white paper to guide the Scientific Committee's future programme of work. United Nations Scientific Committee on the Effects of Atomic Radiation. United Nations, New York, 2016.

V1 Vaccarella, S., S. Franceschi, F. Bray et al. Worldwide thyroid-cancer epidemic? The increasing impact of overdiagnosis. N Engl J Med 375(7): 614-617 (2016).

V2 Vives i Batlle, J. Dynamic modelling of radionuclide uptake by marine biota: application to the Fukushima nuclear power plant accident. J Environ Radioact 151 (Pt 2): 502-511 (2016).

V3 Vives i Batlle, J., N.A. Beresford, K. Beaugelin-Seiller et al. Inter-comparison of dynamic models for radionuclide transfer to marine biota in a Fukushima accident scenario. J Environ Radioact 153: 31-50 (2016).

W1 Wada, T., T. Fujita, Y. Nemoto et al. Effects of the nuclear disaster on marine products in Fukushima: An update after five years. J Environ Radioact 164: 312-324 (2016).

W2 Wada, T., A. Tomiya, M. Enomoto et al. Radiological impact of the nuclear power plant accident on freshwater fish in Fukushima: An overview of monitoring results. J Environ Radioact 151 (Pt 1): 144-155 (2016).

W3 Wakabayashi, S., S. Itoh, N. Kihou et al. Influence of water management and fertilizer application on (137)Cs and (133)Cs uptake in paddy rice fields. J Environ Radioact 157: 102-112 (2016).

W4 Watanabe, Y., S. Ichikawa, M. Kubota et al. Morphological defects in native Japanese fir trees around the Fukushima Daiichi Nuclear Power Plant. Sci Rep 5: 13232 (2015).

W5 Williams, D. Thyroid growth and cancer. Eur Thyroid J 4(3): 164-173 (2015).

W6 Win, K.T., A.Z. Oo, K. Kojima et al. Genotypic difference in (137)Cs accumulation and transfer from the contaminated field in Fukushima to azuki bean (Vigna angularis). J Environ Radioact 158-159: 138-147 (2016).

Y1 Yamaguchi, N., M. Mitome, A.H. Kotone et al. Internal structure of cesium-bearing radioactive microparticles released from Fukushima nuclear power plant. Sci Rep 6: 20548 (2016).

Y2 Yamaguchi, N., I. Taniyama, T. Kimura et al. Contamination of agricultural products and soils with radiocesium derived from the accident at TEPCO Fukushima Daiichi Nuclear Power Station: monitoring, case studies and countermeasures. Soil Sci Plant Nutr 62(3): 303-314 (2016).

Y3 Yamamoto, S., K. Mutou, H. Nakamura et al. Assessment of radiocaesium accumulation by hatchery-reared salmonids after the Fukushima nuclear accident. Can J Fish Aquat Sci 71(12): 1772-1775 (2014).

Y4 Yamashita, S. and G. Thomas. Thyroid Cancer and Nuclear Accidents: Long-Term Aftereffects of Chernobyl and Fukushima. Academic Press, 2017.

Y5 Yang, B., Y. Onda, Y. Wakiyama et al. Temporal changes of radiocesium in irrigated paddy fields and its accumulation in rice plants in Fukushima. Environ Pollut 208(Pt B): 562-570 (2016).

Y6 Yasui, S. Establishment of the central radiation dose registration system for decontamination work involving radioactive fallout emitted by the Fukushima Daiichi APP accident. J Occup Environ Hyg 13(10): D166-D174 (2016).

Y7 Yasui, S. A recommended epidemiological study design for examining the adverse health effects among emergency workers who experienced the TEPCO Fukushima Daiichi NPP accident in 2011. J Occup Environ Hyg 13(5): D77-D88 (2016).

Y8 Yasumura, S. Evacuation effect on excess mortality among institutionalized elderly after the Fukushima Daiichi nuclear power plant accident. Fukushima J Med Sci 60(2): 192-195 (2014).

Y9 Yoschenko, V., K. Nanba, S. Yoshida et al. Morphological abnormalities in Japanese red pine (Pinus densiflora) at the territories contaminated as a result of the accident at Fukushima Dai-Ichi Nuclear Power Plant. J Environ Radioact 165: 60-67 (2016).

Y10 Yumimoto, K., Y. Morino, T. Ohara et al. Inverse modeling of the 137Cs source term of the Fukushima Dai-ichi Nuclear Power Plant accident constrained by a deposition map monitored by aircraft. J Environ Radioact 164: 1-12 (2016).

Z1 Zablotska, L.B., E.A. Nadyrov, A.V. Rozhko et al. Analysis of thyroid malignant pathologic findings identified during 3 rounds of screening (1997-2008) of a cohort of children and adolescents from Belarus exposed to radioiodines after the Chernobyl accident. Cancer 121(3): 457-466 (2015).

unscear.org

In 1955 the United Nations General Assembly established the Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in response to concerns about the effects of ionizing radiation on human health and the environment. At that time fallout from atmospheric nuclear weapons tests was reaching people through air, water and food. UNSCEAR was to collect and evaluate information on the levels and effects of ionizing radiation. Its first reports laid the scientific grounds on which the Partial Test Ban Treaty prohibiting atmospheric nuclear weapons testing was negotiated in 1963.

Over the decades, UNSCEAR has evolved to become the world authority on the global level and effects of atomic radiation. UNSCEAR's independent and objective evaluation of the science are to provide for—but not address—informed policymaking and decision-making related to radiation risks and protection.

V.17-06738