(the committed effective doses estimated from whole body counting were negligible, see below), resulting in effective dose levels that are comparable with typical background effective dose levels.

Figure 4.9 illustrates this analysis for two cities in the affected areas for which annualized information was available. The analysis reconfirmed that the annual personal dose equivalents are low, with average effective doses below 1 mSv per year, providing 95% confidence that people incurred effective doses below 5 mSv.

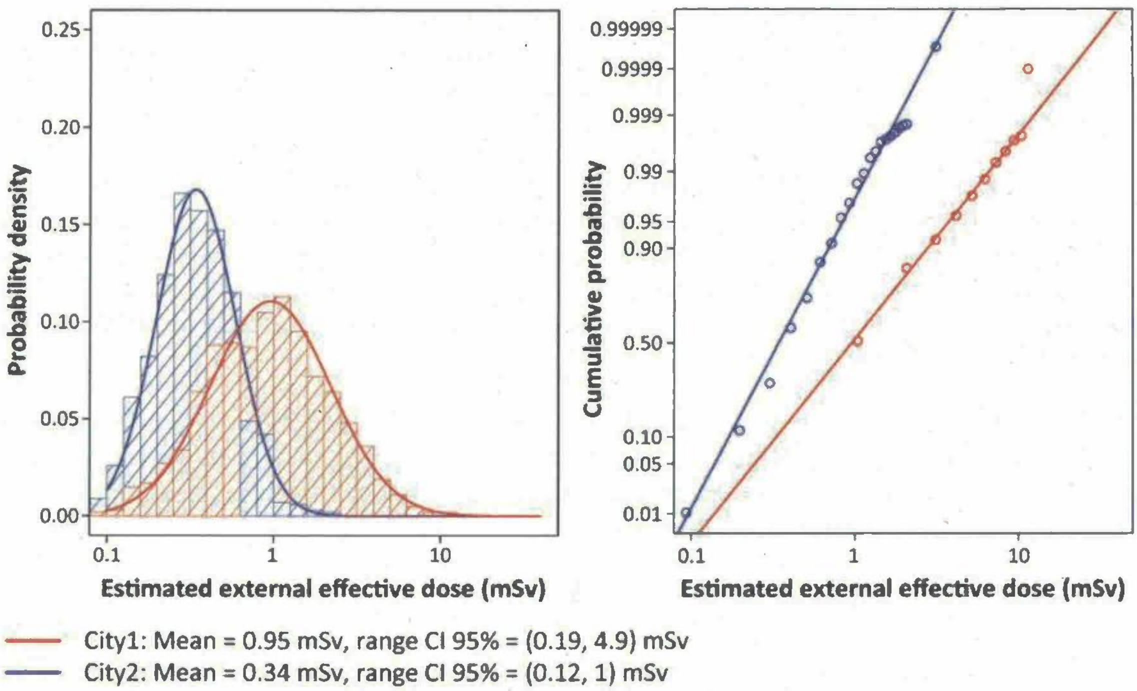

FIG. 4.9. Probability distribution of monitored personal dose equivalents of members of the public during 2011 provided by the Government of Japan for two cities in the affected area for which annualized data were available. For city 1 the normalized idealized probability density distribution is illustrated (red colour); for city 2 the normalized idealized probability density is illustrated (blue colour); for both cities the accumulative probability distribution is illustrated (see Box 4.6). The distribution shows that personal dose equivalent are low, with averages below 1 mSv per year, providing 95% confidence that individuals who incurred effective doses in those cities sustained doses below 5 mSv.

Internal exposure

Measurements of intake of radionuclides using whole body counting were made by the NIRS, the JAEA and other organizations in Japan.

After the accident, monitoring was carried out on more than 200 000 residents in various locations within Fukushima Prefecture. The levels were generally lower than the very low detection limits of the whole body counters, indicating little or no intake of radionuclides into the body. As a result, it was neither possible nor necessary to undertake detailed statistical analysis of these data.

Where it was possible to convert measured intakes to effective dose, making assumptions about the timing and nature of the intake, the vast majority of estimates of the committed effective dose were less than 1 mSv [215]. The estimated effective dose commitment from whole body counting measurements of ^{134}Cs and ^{137}Cs was reported to be lower than around 1 mSv in 99% of the residents [211].

Many whole body counting measurements were carried out several months after the accident [216, 217] and are therefore often only applicable to ^{134}Cs and ^{137}Cs, due to the short half-life of ^{131}I. Given the importance of intakes of ^{131}I both through inhalation and ingestion in the first month following the accident, this made judgements on internal exposure difficult. However, it was possible to detect ^{131}I in measurements of evacuees and short term visitors to Fukushima Prefecture carried out at Nagasaki University [218]. The highest estimated thyroid absorbed dose was 20 mGy (i.e. a thyroid equivalent dose of 20 mSv), with a corresponding effective dose of around 1 mSv.

The internal doses incurred in the initial period were dependent on whether people ate locally produced food or food from elsewhere, or drank tap water, during the first few days, before restrictions were fully put in place. Market basket surveys suggested that exposures from the consumption of milk, food and water were very low, as locally produced milk and food products were not distributed to shelters and only bottled water was used for drinking and preparing *baby formula*.

Exposure from the consumption of vegetables was low as very few, if any, locally produced vegetables grown outdoors were being eaten; it was early spring, before the growing season. Effectively, the only locally produced vegetables consumed were those grown in greenhouses, which were not contaminated.

Doses to the thyroid gland in children

In the aftermath of a nuclear accident involving substantial releases of ^{131}I, doses to the thyroid gland in children are an important public health concern. The main potential pathway for thyroid doses in children is usually the intake of milk containing ^{131}I.

However, the typical intake of ^{131}I via cows' milk was very low following the accident, owing to a number of factors. Dairy practices in Japan, such as generally sheltering cattle,prevented the ingestion of ^{131}I by dairy cows. The intake of ^{131}I via milk was also limited by the relatively low contribution of milk to the diet of infants and by the strict restrictions on the consumption of milk imposed by the authorities following the accident. While there were alternative ^{131}I ingestion pathways such as the consumption of leafy vegetables and drinking water, especially in the very early period following the release, the prompt restrictions on drinking water and food limited the intake via these pathways.

As a result of these factors, the intake of ^{131}I by children is likely to have been low, and mainly attributable to inhalation. However, there were uncertainties associated with the estimates of ^{131}I intakes and thyroid equivalent doses in children in the first few days following the accident.

Thyroid equivalent doses to children were estimated by monitoring levels of external radiation from ^{131}I activity in the gland. These levels were measured on the skin, near the thyroid, of children from areas where thyroid doses were predicted to be high. A limited number of these direct measurements were reported for the weeks following the accident. The results of one study, in which 1080 measurements were made on children aged 1–15 years in Iwaki City, Kawamata Town and Iitate Village in the period 26–30 March 2011, are summarized in Fig. 4.10 [219].

The highest ambient dose equivalent rate measured near the thyroid of one year old children was 0.0001 mSv per hour, which would be consistent with an absorbed dose to the thyroid of approximately 50 mGy (a thyroid equivalent dose of 50 mSv). It was reported that thyroid equivalent doses, determined in March 2011 using an NaI (Tl) scintillation survey meter in children in the evacuation zone and 'deliberate evacuation areas', were lower than around 10 mSv in 95.7% of children (with a maximum of 43 mSv) [219]. It is likely that all doses were lower than the generic optimized intervention value for iodine prophylaxis of 100 mGy of avertable committed absorbed dose to the thyroid due to radioiodine established in the 1996 BSS [144]. They were also lower than the projected dose of 50 mSv in the first seven days for iodine thyroid blocking established in the revised BSS [203] as generic criteria for protective actions and other response actions in emergency exposure situations to reduce the risk of stochastic effects. In comparison, the absorbed doses by thyroid of children following the Chernobyl accident ranged up to several thousand mGy [174, 183], nearly 100 to 1000 times higher.

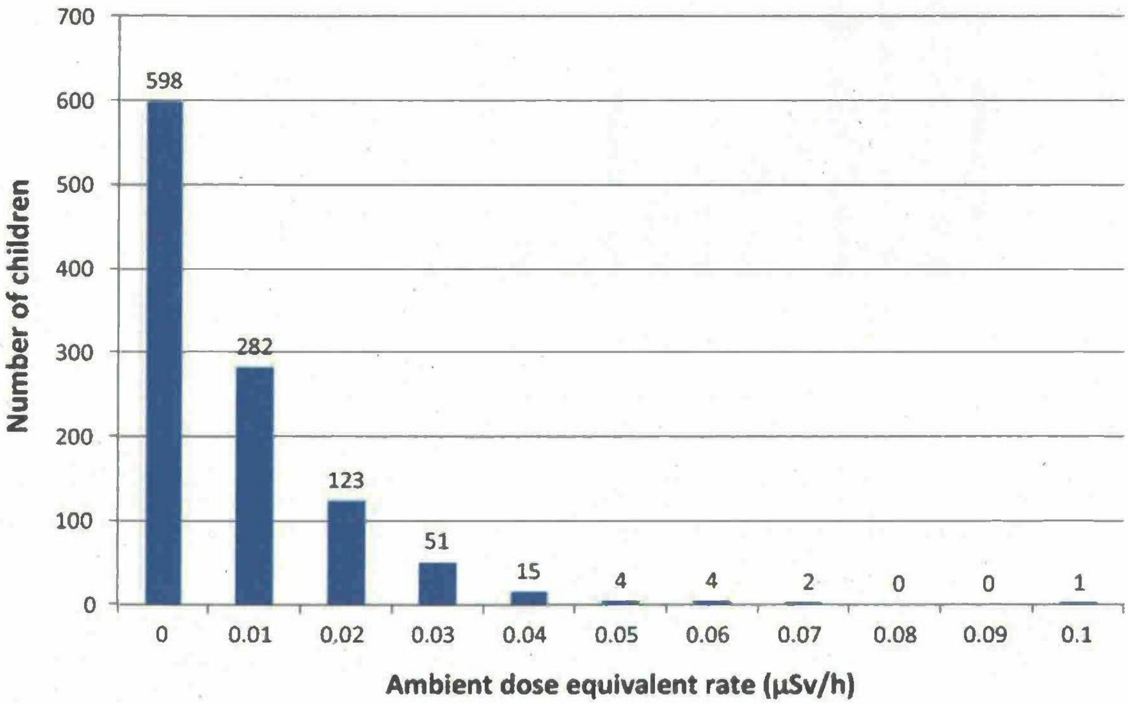

FIG. 4.10. Distribution of net value of measured dose rate in thyroid gland estimated by subtracting the background value from the reading value [219], i.e. the net ambient dose equivalent rates at the thyroid gland, in 1080 children aged 0-15 years. For 99% of the children tested, the ambient dose equivalent rate measured near the thyroid was 0.000 04 mSv per hour or less, corresponding to a thyroid equivalent dose of approximately 20 mSv or less.

4.3.2 Occupational exposures

Following the accident, on-site emergency workers were immediately subjected to extremely harsh working conditions and very high radiation levels as they sought to stabilize the reactors. In the period from March 2011 to March 2012, 174 of the approximately 23 000 workers on the site exceeded the original effective dose criterion in an emergency of 100 mSv, six of whom exceeded the (temporarily revised) effective dose criterion in an emergency of 250 mSv. No workers exceeded an effective dose of 100 mSv in subsequent years. One worker[95] exceeded the occupational annual effective dose limit of 50 mSv in the period from April 2012 to March 2013 [208]. Figure 4.11 presents the comparison of effective doses incurred by emergency workers at the Fukushima Daiichi NPP between March 2011 and October 2014.

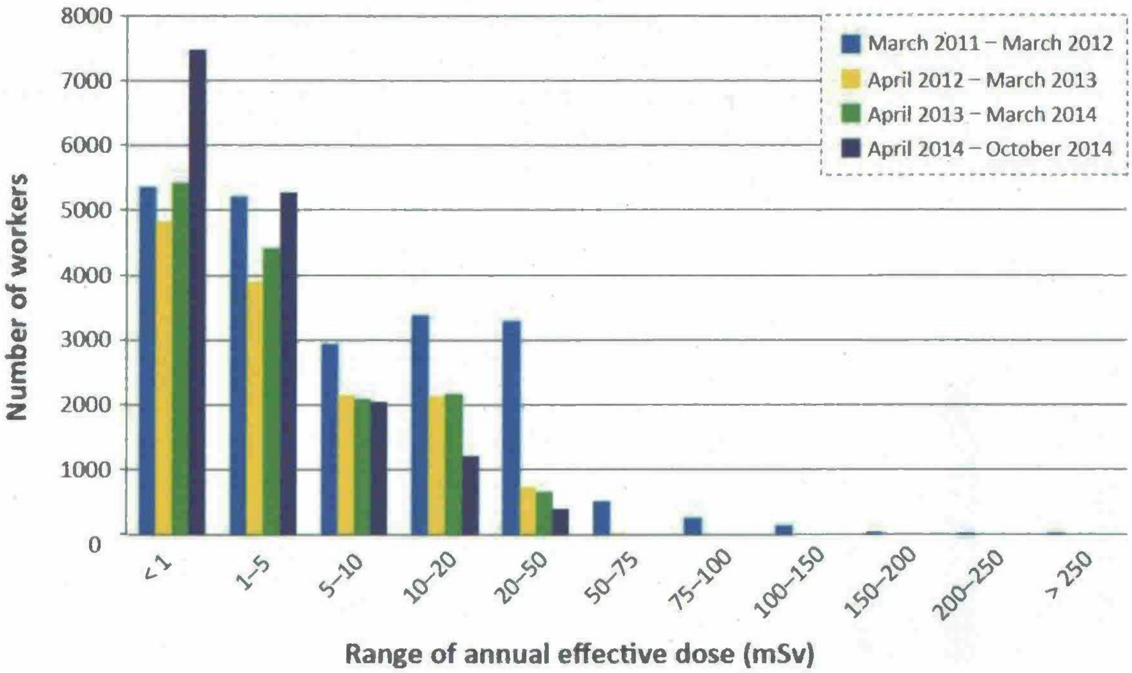

FIG. 4.11. Comparison of effective dose for emergency workers at the Fukushima Daiichi NPP site between March 2011 and October 2014 (TEPCO employees and contractors). High effective doses occurred over the year following the accident. By 2012, effective doses to workers were low, and were comparable with those incurred in normal operations [220].

The personal dose equivalent values for both TEPCO workers and contract workers were submitted by TEPCO and were statistically analysed. The results are presented in Fig. 4.12.

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95 This worker was categorized as having been subjected to the emergency dose limit of 100 mSv instead of to the occupational dose limit of 50 mSv per year.

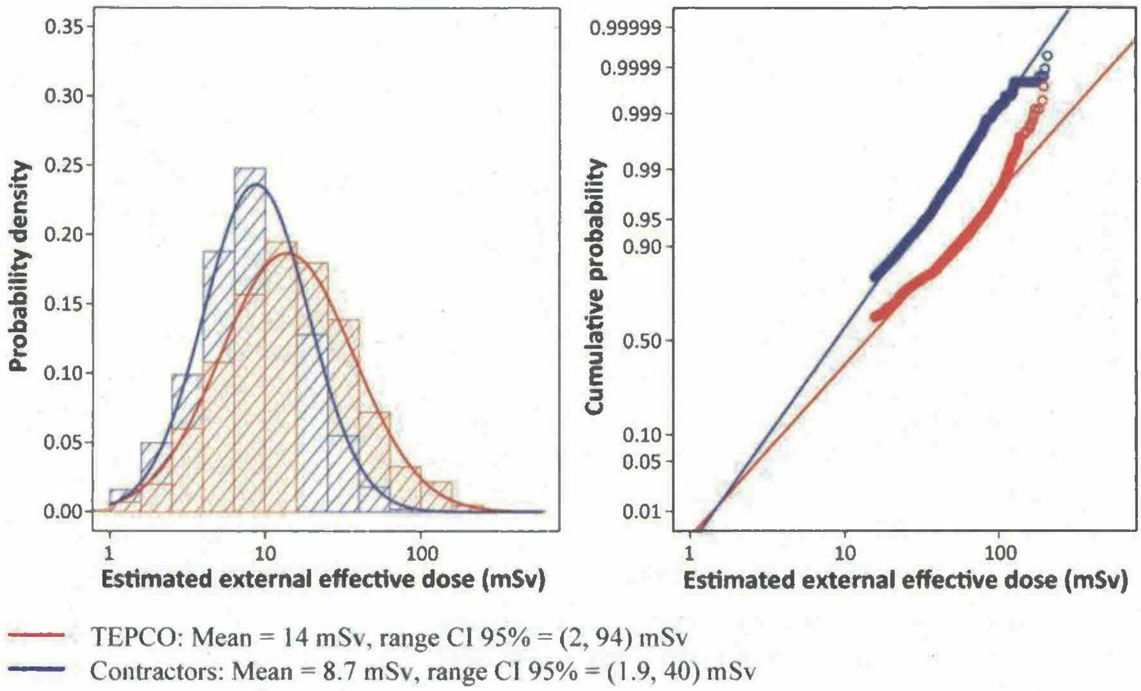


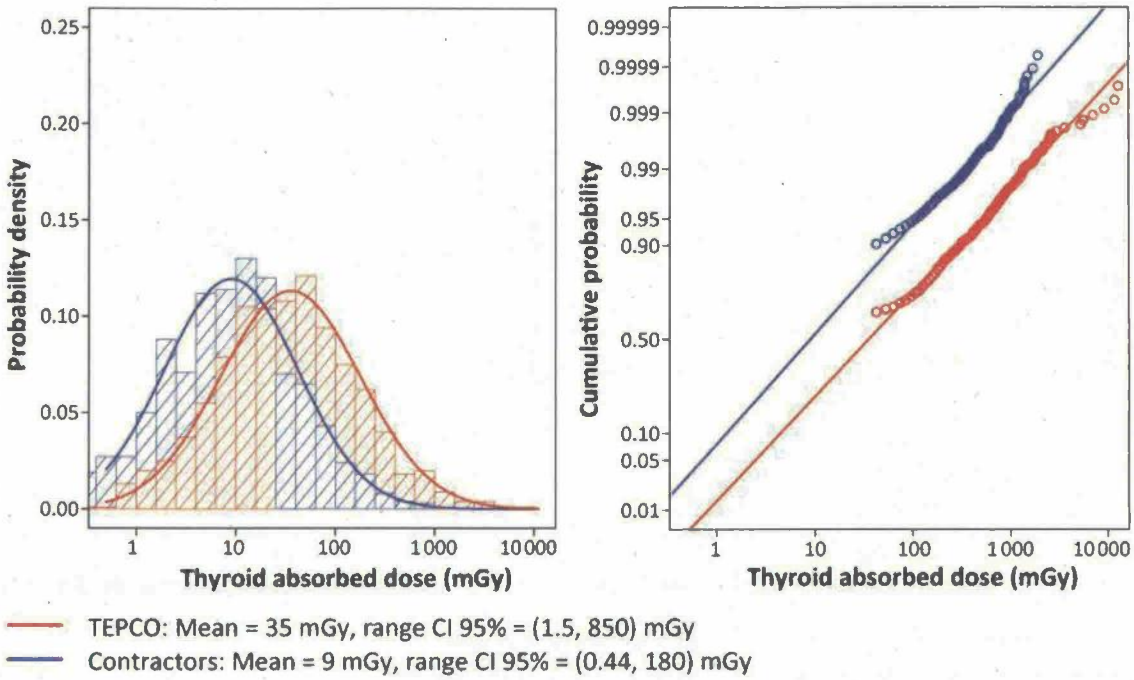
FIG. 4.12. Normalized idealized probability density distribution and cumulative probability distribution (see Box 4.6) of personal dose equivalent monitored for workers from TEPCO and contracted workers for 2011. Doses for TEPCO workers were generally higher than those of contract workers because TEPCO employees were working in higher dose areas [220].

In the early phase, the main contributor to effective doses, in particular to the doses incurred by the six on-site emergency workers who exceeded the temporarily revised dose criterion for emergency workers, was internal exposure from the intake of radionuclides. This was caused by challenges associated with harsh emergency working conditions, improper use of respirators and insufficient training.

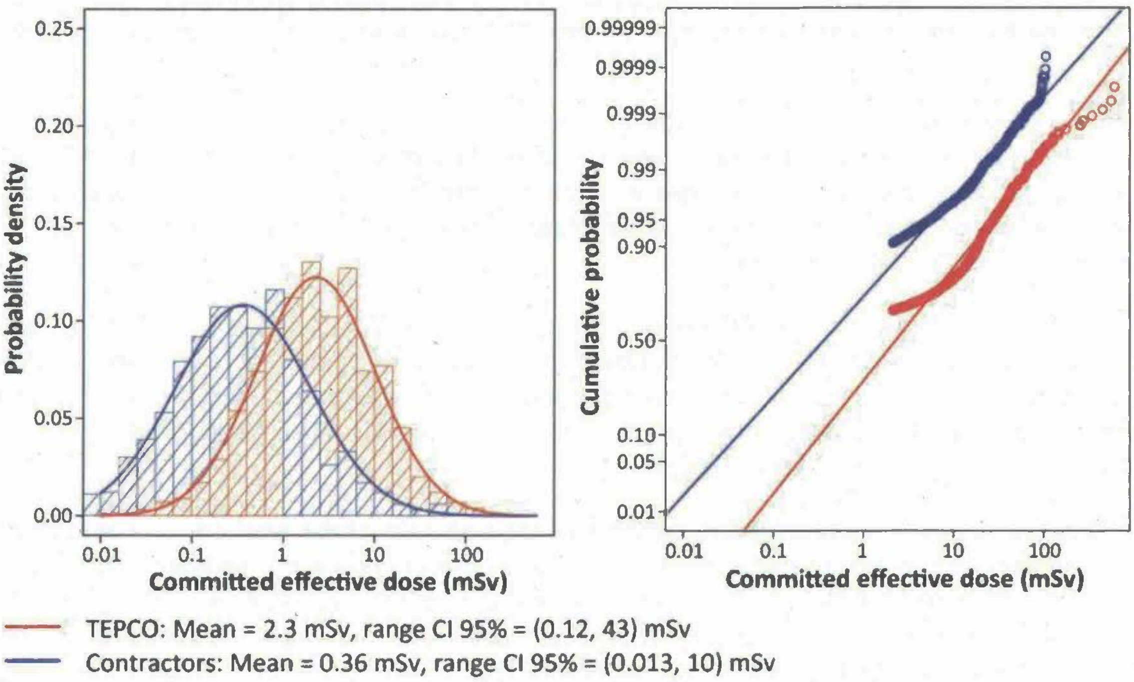
The internal doses were mostly thyroid equivalent doses from inhaled ^{131}I. Although the majority of workers at the Fukushima Daiichi NPP received thyroid equivalent doses below 100 mSv, 1757 workers received thyroid equivalent doses above this level, with 17 workers receiving thyroid equivalent doses above 2000 mSv and two receiving thyroid equivalent doses in excess of 12 000 mSv [221].

There are several uncertainties associated with the estimates of the workers' radiation doses due to internal exposure, particularly with thyroid equivalent doses. For instance, the scenario that was assumed for the incorporation of radionuclides into the body (e.g. the timing) is crucial for internal dose estimation. There was also some time lag in undertaking thyroid measurements due to the emergency operations and general post-accident conditions. The MHLW conducted a re-evaluation of the committed effective dose of emergency workers. The Ministry has promoted the standardization of methodologies of cautious assessments of internal dose in order to avoid underestimates of doses as much as reasonably achievable [222].

The statistical analysis of the distribution of the reported thyroid absorbed doses and of the estimated committed effective doses due to internal exposure is presented in Fig. 4.13.



(a)



(b)

FIG. 4.13. Normalized idealized probability density distribution and cumulative probability distribution of internal doses (see Box 4.6). (a) Thyroid absorbed dose; and (b) the consequent committed effective dose. The higher than expected distribution in the lower doses may imply that doses equivalent to the detection level were assigned to all people for whom radioactivity was undetectable [220].

The occupational exposures of workers on-site are consistent with the findings of UNSCEAR. Re-assessments of doses to TEPCO workers and contractors, which became available after the publication of the UNSCEAR report, were used in the statistical analysis of doses in this report, reducing the uncertainties. Some uncertainties remain about doses from short lived radionuclides, the influence of high background radiation in early whole body counting measurements, delays in thyroid measurements and the sufficiency of the bioassay information. Organizations in Japan are working to further reduce the uncertainties in the occupational dose assessment, specifically in the internal exposure assessments (e.g. Ref. [223]).

Firefighters, police and Japan Self-Defense Force personnel were also involved in a range of on-site emergency activities (see Section 3). No members of this group received effective doses in excess of 100 mSv, and the majority received effective doses of less than 10 mSv. Of over 8000 personnel who worked off the site, for whom dosimetric information was available, five received effective doses in excess of 10 mSv but less than 20 mSv. The maximum effective dose recorded for police officers working off-site was around 5 mSv.

Personnel from other countries helped in the emergency. Available data show that, among those from the USA who assisted or performed environmental monitoring in the Fukushima area, the maximum effective dose received was 0.12 mSv for US military personnel and 0.068 mSv for US Department of Energy staff [224], all below regulatory limits. Among IAEA staff members who participated in environmental monitoring and provided advice on protection and safety, the mean effective dose was around 0.5 mSv, while one staff member received an effective dose of around 2.5 mSv from external exposure.

4.4. HEALTH EFFECTS

No early radiation induced health effects were observed among workers or members of the public that could be attributed to the accident.

The latency time for late radiation health effects can be decades, and therefore it is not possible to discount the potential occurrence of such effects among an exposed population by observations a few years after exposure. However, given the low levels of doses reported among members of the public, the conclusions of this report are in agreement with those of UNSCEAR to the UN General Assembly. UNSCEAR found that "no discernible increased incidence of radiation-related health effects are expected among exposed members of the public and their descendants" (which was reported within the context of the health implications related to "levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami"). Among the group of workers who received effective doses of 100 mSv or more, UNSCEAR concluded that "an increased risk of cancer would be expected in the future. However, any increased incidence of cancer in this group is expected to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence".

The Fukushima Health Management Survey was implemented to monitor the health of the affected population of Fukushima Prefecture. This survey is aimed at the early detection and treatment of diseases, as well as prevention of lifestyle related diseases. At the time of writing, an intensive screening of children's thyroid glands is taking place as part of the survey. Highly sensitive equipment is being used, which has detected asymptomatic thyroid abnormalities among a significant number of surveyed children (which would not have

been detectable by clinical means). The abnormalities identified in the survey are unlikely to be associated with radiation exposure from the accident and most probably denote the natural occurrence of thyroid abnormalities in children of this age. The incidence of thyroid cancer in children is the most likely health effect after an accident involving significant releases of radioiodine. Because the reported thyroid doses attributable to the accident were generally low, an increase in childhood thyroid cancer attributable to the accident is unlikely. However, uncertainties remained concerning the thyroid equivalent doses incurred by children immediately after the accident.

Prenatal radiation effects have not been observed and are not expected to occur, given that the reported doses are well below the threshold at which these effects may take place. Unwanted terminations of pregnancy attributable to the radiological situation have not been reported. Concerning the possibility of parents' exposures resulting in hereditary effects in their descendants, UNSCEAR concluded that, in general, "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure".

Some psychological conditions were reported among the population affected by the nuclear accident. Since a number of these people had suffered the combined impacts of a major earthquake and a devastating tsunami as well as the accident, it is difficult to assess to what extent these effects could be attributed to the nuclear accident alone. The Fukushima Health Management Survey's Mental Health and Lifestyle Survey shows associated psychological problems in some vulnerable groups of the affected population, such as increases in anxiety and post-traumatic stress disorders. UNSCEAR estimated that "the most important health effect [from the accident] is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation" [96].

A comprehensive health check of the affected population is being carried out under the Fukushima Health Management Survey described in Box 4.2. The programme aims at the early detection and treatment of diseases, as well as the prevention of lifestyle related diseases. Additional tests, such as differential leukocyte counts, are being performed in addition to routine general medical check-ups at the workplace or by the local government [225].

4.4.1 Early radiation induced health effects

Radiation exposure can induce health effects caused by the killing of cells. The severity of these effects increases with dose, and they can range from skin injuries to the collapse of vital tissues. Most of these effects occur early after a dose is incurred above threshold levels that are known for each potential effect. The available information indicates that no individual received a dose at or above these threshold levels to cause acute radiation effects as a result of the accident. Two workers were exposed on their legs from contaminated water from the turbine hall. The skin equivalent doses of these workers were reported to be lower than the

[96] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Sources, Effects and Risks of Ionizing Radiation, UNSCEAR 2013 Report, Volume I, Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, United Nations, New York (2014), http://www.unscear.org/docs/reports/2013/14-06336_Report_2013_Annex_A_Ebook_website.pdf.

estimated threshold for deterministic effects[97] [81] and the applicable international limits[98] [227].

UNSCEAR already observed that "no radiation related deaths or acute diseases are apparent among workers and the general public exposed to radiation from the accident" [228].

4.4.2 Potential late radiation induced health effects

Under the severe circumstances and conditions of the accident, of the approximately 23 000 workers involved in emergency operations, the number exceeding a dose of 100 mSv was 174. UNSCEAR concluded that among this group "an increased risk of cancer would be expected in the future. However, any increased incidence of cancer in this group is expected to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence" [229].

With reference to potential late effects among members of the public, international estimates were published before this report (see Box 4.1). WHO issued a hypothetical estimate[99] of additional lifetime risks over baseline rates for the development of leukaemia, breast cancer, thyroid cancer and all solid cancers for the population in the locations with the highest dose rates, which was based on the WHO preliminary dose estimates[100] [151, 152].

UNSCEAR, following its updated dose estimate, reported that

> "The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants" [228].

[97] ICRP estimates for the exposure of the skin are that an early response, such as early transient erythema, is seen a few hours after doses of >2000 mGy, when the exposed area is relatively large. The ICRP also estimates that the approximate threshold doses are as follows: early transient erythema 2000 mGy, main erythema reaction 6000 mGy, temporary epilation 3000 mGy, permanent epilation 7000 mGy, dry desquamation 14 000 mGy, moist desquamation 18 000 mGy, secondary ulceration 24 000 mGy, late erythema 15 000 mGy, ischaemic dermal necrosis 18 000 mGy, dermal atrophy (first phase) 10 000 mGy, telangiectasia 10 000 mGy, and dermal necrosis (late phase) >15 000 mGy [226].

[98] The recommended occupational dose limit for skin in planned exposure situations is an equivalent dose of 500 mSv/year, averaged over 1 cm^2 area of skin regardless of the area exposed (see Table 6 in Reference [134] and Schedule III in Reference [203]). The generic criterion established for acute doses to the skin, for which protective actions and other response actions are expected to be undertaken under any circumstances to avoid or to minimize severe deterministic effects, is 10 000 mGy incurred in a 100 cm^2 dermis (skin structures at a depth of 40 mg/cm^2 (or 0.4 mm) below the surface) (see Table IV.1 in Reference [203]).

[99] Given the limited information available at the time, the assessment contained a number of conservative assumptions. WHO indicated that "all efforts were made to avoid any underestimation of doses" and that "some possible dose overestimation may have occurred" [151].

[100] WHO's health risk assessment estimated that "in the two most affected locations of Fukushima prefecture, the preliminary estimated radiation effective doses for the first year ranged from 12 to 25 mSv" and that, on the basis of these estimates, "in the highest dose location, the estimated additional lifetime risks for the development of leukaemia, breast cancer, thyroid cancer and all solid cancers over baseline rates are likely to represent an upper bound of the risk as methodological options were consciously chosen to avoid underestimation of risks. For leukaemia, the lifetime risks are predicted to increase by up to around 7% over baseline cancer rates in males exposed as infants; for breast cancer, the estimated lifetime risks increase by up to around 6% over baseline rates in females exposed as infants; for all solid cancers, the estimated lifetime risks increase by up to around 4% over baseline rates in females exposed as infants; and for thyroid cancer, the estimated lifetime risk increases by up to around 70% over baseline rates in females exposed as infants. These percentages represent estimated relative increases over the baseline rates and are not estimated absolute risks for developing such cancers" [152].

Before reporting on the accident, UNSCEAR had informed the UN General Assembly that "increases in the incidence of health effects in populations cannot be attributed reliably to chronic exposure to radiation at levels that are typical of the global average background levels of radiation" [172]. The information available indicates that members of the public incurred annual doses that were not higher than annual doses due to typical background levels of radiation. This indicates that no discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants, in agreement with UNSCEAR estimates.

This estimate is also generally applicable to the special case of adult thyroid cancer. In adult life, this risk is very much lower than that from radiation exposure in childhood (see the discussion of thyroid effects in children below). Given the reported radiation equivalent doses to the thyroid, it is unlikely that there would be a discernible increase in thyroid cancers among the adult population.

For the few workers who received high thyroid equivalent doses (see Section 4.3.2), an increased risk of developing thyroid disorders could be inferred. These thyroid equivalent dose levels can reduce the function of the gland to such an extent that hypothyroidism ensues. Hyperthyroidism is not expected because the reported thyroid equivalent doses are below the level of around 15 000 mSv above which such effects could occur. Effects for low and medium thyroid equivalent doses, typical of the range of doses received by the emergency workers, are difficult to quantify, and the potential for and magnitude of effects remains unclear.

4.4.3 Radiation effects in children

The potential for radiation effects in children is an issue of special concern. International recommendations and standards for radiation protection take account of children in an exposed population. For radiation protection purposes, they postulate a potential nominal radiation risk for an entire population, i.e. a population including children[101], that is about 30% higher than the postulated risk for an adult population (such nominal risks have been estimated on the basis of epidemiological studies of populations exposed to high radiation doses) [134, 230].

Thyroid effects in children

For thyroid cancer, children are more radiosensitive than adults. For a given intake of radioiodines, the dose to the thyroid for infants is eight or nine times as large as that for adults. A substantial environmental presence of ^{131}I can result in thyroid cancer in children. The normal incidence of some types of thyroid cancer in children is low and the sensitivity of children's thyroid glands to radiation is high. Owing to this higher sensitivity, in the aftermath of the accident it was important to undertake follow-up screening in order to detect early any potential increase in the incidence of this type of cancer [231].

The results of three years of thyroid ultrasound examinations performed under the Fukushima Health Management Survey were reported [232]. The screening covered roughly 370 000 children aged 0–18 years at the time of the accident. This initial screening was followed by

[101] The term 'children' includes those exposed as infants, children and adolescents.

complete thyroid examinations from 2014 onwards, and the residents will be monitored regularly in subsequent years.

The examinations use highly sensitive ultrasound sonography equipment for screening the thyroid gland. The screening has detected asymptomatic[102] thyroid abnormalities — nodules, cysts and cancers — that would have gone undetected if asymptomatic children had been screened using standard equipment. Similar results were obtained when the same screening was carried out on children living far away from the areas affected by the accident [233]. The latency time for radiation induced thyroid cancer is longer than the four years that have elapsed since the accident, at the time of writing. In many cases, thyroid cancers were found in children in the late teenage years but no cases were found in the most vulnerable group of children who were aged under five years on 11 March 2011. The proportion of suspicious or malignant cases was almost the same among regions in Fukushima Prefecture in the initial screening conducted in 2011–2013 [234]. These factors suggest that the thyroid abnormalities detected in the survey are unlikely to be associated with radiation exposure due to the accident.

On the basis of the data made available on indirect measurements of external dose equivalent due to activity in the thyroid (see Fig. 4.10), thyroid equivalent doses in children appear to have been low. For the levels of doses reported, increases in thyroid cancer in children would not be attributable to radiation exposure.

4.4.4 Prenatal radiation induced health effects

A 'prenatal (or 'antenatal') effect of exposure' is the term used to refer to effects of radiation on the embryo and foetus. At absorbed doses under 100 mGy, lethal effects of irradiation in the pre-implantation period of embryonic development are considered to be very infrequent, and there is an absorbed dose threshold of around 100 mGy for the induction of other effects [235, 236, 237]. Absorbed doses to the embryo and foetus that could be attributable to the accident were much lower than the threshold absorbed dose for the occurrence of these effects.

The pregnancy survey carried out as part of the Fukushima Health Management Survey (see Box 4.2) helped the provision of appropriate medical care and support to mothers, who were given a Maternal and Child Health Handbook between 1 August 2010 and 31 July 2011, and to their children. This survey is being updated every year to take account of new data, particularly on pregnancy and births [167]. The aim was to collect data that might improve obstetrical and prenatal care and to support women who were pregnant or gave birth in Fukushima Prefecture following the accident. On the basis of the survey results, there were no significant adverse outcomes, and the incidences of stillbirth, pre-term birth, low birth weight and congenital abnormalities were found to be similar to those elsewhere in Japan [238].

UNSCEAR reported to the UN General Assembly that "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation" [172]. Therefore, the findings in this report indicate that no heritable effects will be attributable to the accident.

[102]Asymptomatic effects are those that produce no symptoms, i.e. nothing that indicates a condition of disease, in particular nothing apparent to the children, to their parents or even to doctors.

Following accidents involving significant potential for radiation exposure, some pregnant women seek medical advice on whether or not their pregnancy should be terminated. In the case of Fukushima Daiichi accident, a study by the Obstetrics and Gynaecology Department of the Fukushima Medical University reported that no such elective terminations had been carried out in the aftermath of the accident [238, 239].

4.4.5 Psychological consequences

Although not directly attributable to radiation exposure, psychological consequences were considered in this report. UNSCEAR reported that:

> "…the most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation. Effects such as depression and post-traumatic stress symptoms have already been reported." [153]

A number of studies on psychological conditions following the Fukushima Daiichi accident have been performed. These studies focused largely on pregnant women and mothers of infants, rescue and cleanup workers, and evacuees. Some psychological consequences have been detected in the affected population [240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250][103]. According to these studies, communication and dissemination of accurate information to the public at an early stage and during the development of the accident contributed to the alleviation of undesired psychological reactions [155].

The largest study is the Mental Health and Lifestyle Survey conducted as part of the Fukushima Health Management Survey [254], which aims at providing adequate care mainly for evacuees who are at a higher risk of developing mental health problems such as post-traumatic stress disorder, anxiety and stress. The questionnaires contained standard measures of symptoms of post-traumatic stress disorder and psychological distress (anxiety) as well as questions about concerns regarding radiation exposure and adversity resulting from the earthquake and tsunami (e.g. loss of family or relatives, damage to houses, loss of employment, decrease in income, movement within or outside Fukushima Prefecture).

The results of the Mental Health and Lifestyle Survey were published [242]. They confirmed that the affected population experienced considerable distress and symptoms of post-traumatic stress disorder. The survey indicated that "socio-demographic data showed that many evacuee households were separated after the disaster and had to move several times", suggesting this was a cause of psychological conditions.

Two other methods were used to assess the mental health status of adult evacuees [255, 256] and an additional survey was performed to assess alcoholism [257]. These surveys indicated that mental health symptoms were substantially worse than would be expected from surveys of the general population [243]. Children's mental health status was assessed using another

[103] Psychological consequences have been detected in other traumatic situations and may include depression, post-traumatic stress responses, chronic anxiety, sleep disturbance, severe headaches and increased smoking and use of alcohol, as well as dysfunctional behaviour such as intense anger, despair, extreme anxiety about health, and feelings of stigmatization and discrimination. As demonstrated after previous accidents, such as the Chernobyl accident, the majority of people affected are generally resilient to psychological conditions, but exceptions have been reported in a number of studies [174, 251, 252, 253].

questionnaire approach [258, 259], which suggested some psychological difficulties among the surveyed children, but with relative improvements year by year.

Studies were also performed on the affected workers. A study comparing workers at the Fukushima Daiichi and Fukushima Daini NPPs in April–June 2011 found significantly more symptoms of general psychological distress and post-traumatic stress responses among Fukushima Daiichi workers (see Fig. 4.14). In both groups of workers, there were also statistically significant associations between experiencing discrimination and slurs and symptoms of both these conditions.

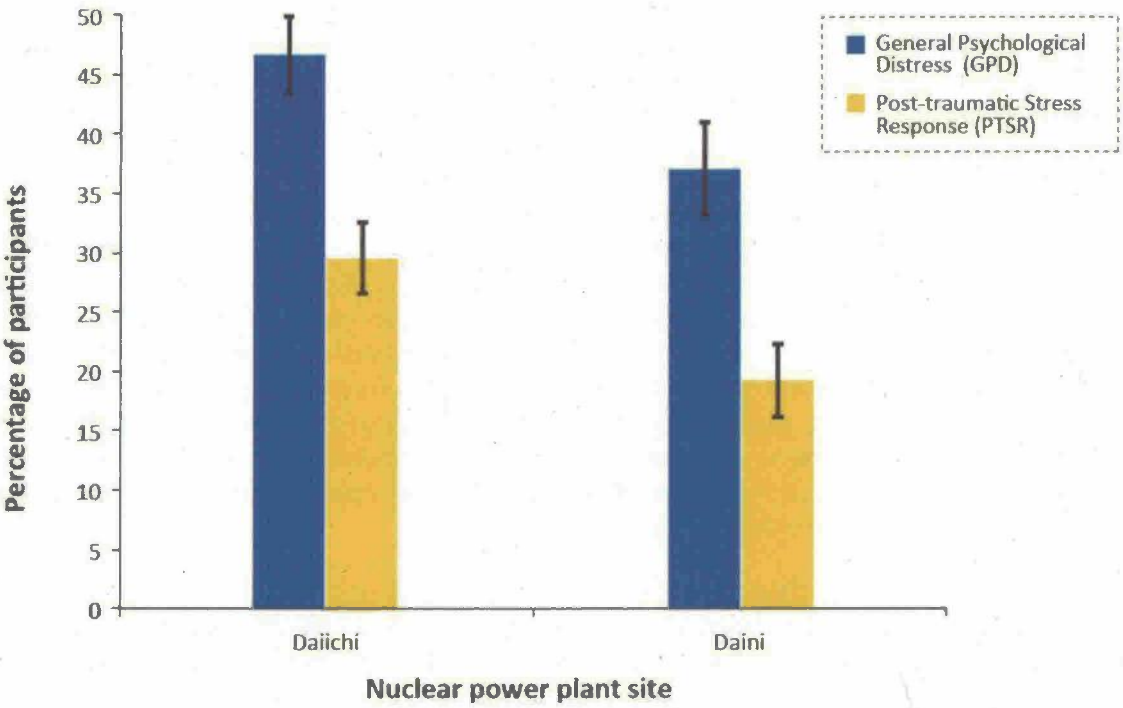


FIG. 4.14. Percentage of workers at the Fukushima Daiichi and Fukushima Daini NPPs reporting psychological distress, April 2011 [248].

4.5. RADIOLOGICAL CONSEQUENCES FOR NON-HUMAN BIOTA

No observations of direct radiation induced effects in plants and animals have been reported although limited observational studies were conducted in the period immediately after the accident. There are limitations in the available methodologies for assessing radiological consequences but, based on previous experience and the levels of radionuclides present in the environment, it is unlikely that there would be any major radiological consequences for biota populations or ecosystems as a consequence of the accident.

Protection of the environment[104] includes “the protection and conservation of: non-human species, both animal and plant, and their biodiversity; environmental goods and services. The term also includes the production of food and feed; resources used in agriculture, forestry, fisheries and tourism; amenities used in spiritual, cultural and recreational activities; media, for example soil, water and air; and natural processes, such as carbon, nitrogen and water cycles” [203]. The earthquake and tsunami caused significant environmental stress to the terrestrial and marine environments along the north-eastern coast of Honshu [260, 261][105].

The immediate priority following the accident was the protection of people rather than species in the environment, for which exposures are not easy to control. Although residents within a 20 km radius of the plant were evacuated in order to reduce their radiation exposures, the exposure of non-human organisms inhabiting these areas was unavoidable. The approaches used in this report to assess the potential radiological impact of the accident on non-human organisms were those recommended by the ICRP [230, 263]. The estimated exposures were then compared with information on the impact of such exposures on different types of plants and animals as published in the literature (see Ref. [264, 265]).

The overall uncertainties associated with the types of models applied in this assessment are large, particularly where assumptions about environmental transfers are involved [266]. These assessment methodologies tend to be based on simple assumptions and uncertainties are usually taken into account by the use of conservative assumptions. The benchmarks used to relate calculated doses to radiation effects are primarily related to chronic rather than acute exposures and to a limited range of individual organisms, rather than populations or ecosystems. The current methodologies do not take account of interactions between components of ecosystems or the combined impact of radiation and other environmental stressors. There is a need for improvements in both the assessment methodologies and in the understanding of radiation induced effects to ecosystems.

The estimated absorbed doses were highest for plants during the first weeks after the accident, but remained below levels at which acute effects would be anticipated. The relevant reference levels were exceeded for some terrestrial reference organisms (such as pine, grass, deer and rats) in the early phase following the accident. However, no overall impact on the populations of these organisms or the ecosystems has been observed.

Earlier publications by UNSCEAR [267, 268] reported that minor damage could occur in conifers at doses below 1.2 Gy while more serious damage, leading to death, could occur at doses in the range of 10–20 Gy. From the assessed doses it is possible to infer that any direct lethal effects are unlikely on wild grass as it is more radioresistant. For the terrestrial animals, the estimated dose rates in the early phase indicated that there is a low probability of reproductive disturbances.

Although dose rates exceeded some reference values in the early phases of the accident, no impact on animal and plant populations and ecosystems is expected. Long term effects are also not expected as the estimated short term doses were generally well below levels at which highly detrimental acute effects might be expected and dose rates declined relatively rapidly after the accident.

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[104] In this report, the term ‘environment’ refers to ‘the conditions under which people, animals and plants live or develop and which sustain all life and development, especially such conditions as affected by human activities’ [203].

[105] Other reports of the effect of the tsunami on the ecosystems can be found in [262].

4.6. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of the radiological consequences of the accident.

— **In case of an accidental release of radioactive substances to the environment, the prompt quantification and characterization of the amount and composition of the release is needed. For significant releases, a comprehensive and coordinated programme of long term environmental monitoring is necessary to determine the nature and extent of the radiological impact on the environment at the local, regional and global levels.**

The quantification and characterization of the source term of the accident at the Fukushima Daiichi NPP proved to be difficult. Prompt monitoring of the environment provides confirmation of the levels of radionuclides and establishes the initial basis for protecting people. The results can be used to inform the public and to develop strategies for response and recovery activities. It is also important to continue environmental monitoring to verify that there are no further significant releases of radionuclides and to provide information to decision makers and other stakeholders on the possible redistribution of radionuclides in the environment over time.

— **Relevant international bodies need to develop explanations of the principles and criteria for radiation protection that are understandable for non-specialists in order to make their application clearer for decision makers and the public. As some protracted protection measures were disruptive for the affected people, a better communication strategy is needed to convey the justification for such measures and actions to all stakeholders, including the public.**

There is a recognized need for simple explanations of a number of radiation protection issues, including:

- Differences between the concepts of dose limits and reference levels and the associated rationale.
- Criteria for the justification of protective measures and actions aimed at averting radiation doses in the long term, in particular when they involve significant disruptions to normal life.
- Specific situations relating to the radiation protection of workers in an emergency.

The principles of radiation protection are based not solely on science, but also on value judgements based on ethical principles. In some circumstances, protective measures and actions involve protracted social disruption. Under these circumstances, the potential benefit from avoiding radiation doses must outweigh the individual and social detriment caused by the protective measures and actions themselves. It is important to explain to stakeholders the justification for long-standing radiation protection measures and actions.

— **Conservative decisions related to specific activity and activity concentrations in consumer products and deposition activity led to extended restrictions and associated difficulties. In a prolonged exposure situation, consistency among international standards, and between international and national standards, is**

beneficial, particularly those associated with drinking water, food, non-edible consumer products and deposition activity on land.

The Japanese authorities established measures for controlling the presence of radioactive substances in consumer products, which were generally more stringent than the available international guidance. The current international system for controlling radioactivity in consumer products is governed by distinct guidance, e.g. the Codex Alimentarius for food (including bottled water) in international trade, IAEA safety standards for food and drinking water for use in an emergency, WHO guidelines for drinking water in existing exposure situations and IAEA safety standards for non-edible products for exemption purposes. There is a need for consistency in the international standards for acceptable levels of radioactivity in products for public consumption in order to facilitate their application by regulatory bodies and their understanding by the public. National standards need to be in line with international standards, where this is feasible. Moreover, there is a need for criteria for dealing with the protracted presence of radionuclides on land.

— **Personal radiation monitoring of representative groups of members of the public provides invaluable information for reliable estimates of radiation doses and needs to be used together with environmental measurements and appropriate dose estimation models for assessing public dose.**

The early estimation of doses was based on environmental measures and modelling, resulting in some conservative assumptions on doses incurred and projected.

Personal monitoring of ^{131}I in the thyroids of children needs to be undertaken as soon as possible following radioiodine releases to the environment, owing to the short half-life of this radionuclide. Personal monitoring of external radiation and the internal presence of the longer lived radionuclides (e.g. ^{137}Cs) needs to be undertaken as soon as feasible and to continue over time, as appropriate.

In the absence of personal radiation measurements, modelling of environmental and ambient data may be needed to estimate the radiation doses incurred by individuals. In these cases, the uncertainties associated with the assumptions used in the models need to be clearly explained, particularly if the results are being used to inform decision making on protective measures and actions or to estimate the potential for radiation induced health effects.

— **While dairy products were not the main pathways for the ingestion of radioiodine in Japan, it is clear that the most important method of limiting thyroid doses, especially to children, is to restrict the consumption of fresh milk from grazing cows.**

The estimates of thyroid doses to children following the accident were low. This was the result of a combination of factors, including the time of year (before the growing season), agricultural practices in Japan, low consumption of cows' milk by infants and the controls on milk consumption that were immediately introduced. These factors contributed to the low level of intake of ^{131}I.

— **A robust system is necessary for monitoring and recording occupational radiation doses, via all relevant pathways, particularly those due to internal exposure that may be incurred by workers during severe accident management activities. It is**

essential that suitable and sufficient personal protective equipment be available for limiting the exposure of workers during emergency response activities and that workers be sufficiently trained in its use.

Early and continued direct measurements of the radiation exposure and the levels of radionuclides incorporated by emergency workers are the most valuable approach for obtaining information for estimating radiation risks and potential health effects and for optimizing protection. There is a need to monitor and register occupational radiation doses through a robust system of personal dosimeters and measurements. Monitoring of ^{131}I in the thyroid needs to be undertaken as soon as possible.

Immediately following the Fukushima Daiichi accident, the provision of personal protective equipment for restricting the exposure of workers and monitoring was difficult.

— **The risks of radiation exposure and the attribution of health effects to radiation need to be clearly presented to stakeholders, making it unambiguous that any increases in the occurrence of health effects in populations are not attributable to exposure to radiation, if levels of exposure are similar to the global average background levels of radiation.**

In the case of the Fukushima Daiichi accident, doses to members of the public were low and comparable to typical global average background doses. There is a need to clearly inform the public, particularly the people affected, that no discernible increased incidence of radiation related health effects is expected among exposed members of the public and their descendants as a result of the accident.

An understanding of radiation and its possible health effects is important for all those involved in an emergency, in particular for physicians, nurses, radiation technologists and medical first responders. This needs to be ensured through appropriate education and training of medical professionals in the topics of radioactivity, radiation and health effects associated with radiation exposure.

— **After a nuclear accident, health surveys are very important and useful, but should not be interpreted as epidemiological studies. The results of such health surveys are intended to provide information to support medical assistance to the affected population.**

The Fukushima Health Management Survey provides valuable health information for the local community, helping to ensure that any health effects are detected quickly, and that appropriate actions are taken to protect the health of the population. The overall results of health checks may provide important information, but they should not be misinterpreted as the results of an epidemiological assessment.

— **There is a need for radiological protection guidance to address the psychological consequences to members of the affected populations in the aftermath of radiological accidents. A Task Group of the ICRP has recommended that "strategies**

for mitigating the serious psychological consequences arising from radiological accidents [should] be sought"[106].

Psychological conditions have been reported as a consequence of the accident. This has been a repeated issue in the aftermath of accidents involving radiation exposure. In spite of its importance, these consequences have not been recognized in international recommendations and standards on radiological protection.

— **Factual information on radiation effects needs to be communicated in an understandable and timely manner to individuals in affected areas in order to enhance their understanding of protection strategies, to alleviate their concerns and support their own protection initiatives.**

Arrangements at the national and local level need to be put in place to share information in an understandable manner with the public who may be affected by accidents with radiological consequences. The arrangements need to allow for person to person dialogue, so that individuals can seek clarifications and express their concerns. These arrangements will require the concerted efforts of the relevant authorities, experts and professionals in supporting and advising the affected individuals and communities. Sharing information is important when conveying decisions to protect these individuals, including the support of their own initiatives.

— **During any emergency phase, the focus has to be on protecting people. Doses to the biota cannot be controlled and could be potentially significant on an individual basis. Knowledge of the impacts of radiation exposure on non-human biota needs to be strengthened by improving the assessment methodology and understanding of radiation-induced effects on biota populations and ecosystems. Following a large release of radionuclides to the environment, an integrated perspective needs to be adopted to ensure sustainability of agriculture, forestry, fishery and tourism and of the use of natural resources.**

It may be difficult to substantially reduce doses to non-human biota because of the impracticability of introducing countermeasures. Impact assessments for plants and animals in the aftermath of accidents such as that at the Fukushima Daiichi NPP require consideration of numerous potential stressors — radiation exposure being one of many. Consideration also needs to be given to the potential for the build-up and accumulation of long lived radionuclides in the environment and how this might affect plants and animals over multiple generations.

[106] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Report of ICRP Task Group 84 on Initial Lessons Learned from the Nuclear Power Plant Accident in Japan vis-à-vis the ICRP System of Radiological Protection (2012), http://www.icrp.org/docs/ICRP%20TG84%20Summary%20Report.pdf.

5. POST-ACCIDENT RECOVERY

Immediately following the accident at the Fukushima Daiichi NPP, priority was given to stabilizing conditions at the plant and protecting the public through actions that included sheltering and evacuation of residents in the affected areas and restrictions on food[107] and drinking water. As work progressed and conditions at the site were stabilized, greater emphasis was placed on recovery from the accident, including the revitalization of community and infrastructure.

This section considers progress in post-accident recovery up until March 2015 as well as plans for the future. It considers, primarily, the existing exposure situation that followed the emergency phase.

5.1. OFF-SITE REMEDIATION OF AREAS AFFECTED BY THE ACCIDENT

The long term goal of post-accident recovery[108] is to re-establish an acceptable basis for a fully functioning society in the affected areas. Consideration needs to be given to remediation[109] of the areas affected by the accident in order to reduce radiation doses, consistent with adopted reference levels. In preparing for the return of evacuees, factors such as the restoration of infrastructure and the viability and sustainable economic activity of the community need to be considered.

Prior to the Fukushima Daiichi accident, policies and strategies for post-accident remediation were not in place in Japan, and it became necessary to develop them in the period after the accident. The remediation policy was enacted by the Government of Japan in August 2011[110]. It assigned responsibilities to the national and local governments, the operator and the public and created the necessary institutional arrangements for the implementation of a coordinated work programme.

A remediation strategy was developed and implementation began. The strategy specifies that priority areas for remediation are residential areas, including buildings and gardens, farmland, roads and infrastructure, with emphasis on the reduction of external exposures.

External dose from radionuclides deposited on the ground and other surfaces is the main pathway of exposure. The remediation strategy is therefore focused on decontamination activities to reduce the levels of radiocaesium present in priority areas, thereby reducing the potential for such exposures. Internal doses continue to be controlled by restrictions on food, as well as through remediation activities on agricultural land.

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[107] Including restrictions on the distribution and sale of food, the use of agricultural land and the collection of wild food products (see Section 3.3.).

[108] Post-accident recovery includes: remediation of areas affected by the accident; the stabilization of damaged on-site facilities and preparations for decommissioning; the management of contaminated material and radioactive waste arising from these activities; and community revitalization and stakeholder engagement.

[109] Remediation is defined as any measures that may be carried out to reduce the *radiation exposure* from existing *contamination* of land areas through actions applied to the *contamination* itself (the *source*) or to the *exposure pathways* to humans.

[110] The 'Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District–Off the Pacific Ocean Earthquake that Occurred on March 11, 2011'.

Following the accident, the authorities in Japan adopted a 'reference level' as a target level of dose for the overall remediation strategy. This level was consistent with the lower end of the range specified in international guidance. The application of a low reference level has the effect of increasing the quantity of contaminated materials generated in remediation activities, and thereby increasing the costs and the demands on limited resources. The experience obtained in Japan could be used in developing practical guidance on the application of international safety standards in post-accident recovery situations

Two categories of contaminated areas were defined, on the basis of additional annual doses estimated in the autumn of 2011. The national government was assigned responsibility for formulating and implementing remediation plans in the first area (the 'special decontamination area') — within a radius of 20 km of the Fukushima Daiichi site and in areas where additional annual doses arising from contamination on the ground were projected to reach 20 mSv in the first year after the accident. The municipalities were given responsibility for implementing remediation activities in the other area (the 'intensive contamination survey area'), where the additional annual doses were projected to exceed 1 mSv but to remain below 20 mSv. Specific dose reduction goals were set, including a long term goal of achieving an additional annual dose of 1 mSv or less.

5.1.1. Establishment of a legal and regulatory framework for remediation

Following the accident, a policy on recovery and remediation was established by the Government of Japan through the enactment of the 'Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District–Off the Pacific Ocean Earthquake that Occurred on March 11, 2011', in August 2011 [129]. The Act includes provisions for prioritization of sites to be remediated, allocation of funds to carry out the remediation work and involvement of stakeholders in the overall process.

The first steps in developing a remediation programme are the definition of appropriate reference levels and the establishment of a remediation strategy to achieve the required reduction in the radiation exposure of members of the public. International guidance recommends that a reference level be selected from the range of additional dose of 1-20 mSv/y, depending on the prevailing circumstances (Box 5.1) [134, 203, 269][111].

It is important in setting reference levels within this range that they are not too high, which could jeopardize the required safety objective, or too low, which could result in a less than optimal use of limited resources. In the initial stages of remediation in Japan in 2011, the Government of Japan set reference levels that were intentionally low [270, 271], and a long term goal for residents, following remediation, of an additional dose of no more than 1 mSv/y was adopted [272]. This is the lowest value in the range given in international guidance (Box 5.1).

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[111] A pre-publication version of the interim edition of the International Basic Safety Standards was available at the time of the accident [269]. IAEA Safety Standards Series No. GSR Part 3 [203] was subsequently published in 2014.

Box 5.1. Reference level for remediation

The 'reference level' is the target dose for the overall remediation strategy, but it is not a dose limit. International guidance [134, 269] recommends reference levels in the range of 1 to 20 mSv/y for additional exposure of a member of the public in 'existing exposure situations', depending on the prevailing circumstances.

Reference levels are established by the government, the regulatory body or another relevant authority, according to the arrangements in the national regulatory framework. Reference levels in post-accident situations are used to identify optimal strategies for remediation. These strategies will ensure that remediation is performed through the efficient use of available human, technical and financial resources to achieve the best outcomes in the protection of the affected communities.

Specific actions applied to reduce environmental contamination and radiation doses to people are generally guided by derived 'remediation action levels'. Usually, these are specified in terms of easily measurable quantities, such as ambient gamma dose rates (μSv/h) or deposited activity per unit area (Bq/m^2), and derived from the reference levels by using models and assumptions about people's living habits and about the behaviour of radionuclides in the environment.

The high level of conservatism in the approach used to estimate doses to people was illustrated by an assessment by UNSCEAR [153]. The estimated doses are based on the activity per unit area of ^{134}Cs and ^{137}Cs, taking into account the decline of activity due to decay, the loss of activity due to weathering from surfaces and the shielding factor typical for wooden houses. Calculations undertaken for the purpose of this report, using the same methodology used by UNSCEAR [153, 273], indicated that the average additional radiation doses in 2012 in large parts of the intensive contamination survey area (see Section 5.1.2) would have been well below 1 mSv/y.

5.1.2. Remediation strategy adopted

The remediation strategy was influenced by the fact that internal doses following the accident were largely avoided by implementing restrictions on food and drinking water. As a consequence, the remediation actions described here were primarily concerned with decontamination efforts to reduce the levels of external doses.

The Government of Japan's remediation strategy set an approach for the rapid reduction of radiation dose, prioritizing remediation in residential areas, on farmland and in forest areas adjacent to residential or agricultural areas [129, 272]. To facilitate this, in August 2011, it classified the land to be remediated as follows:

— *Special decontamination area* (Fig. 5.1, left). This area overlaps the former 'restricted areas', i.e. the evacuation zone within a 20 km radius of the Fukushima Daiichi NPP, and the former 'deliberate evacuation areas', which were situated beyond the 20 km radius from the plant where the additional annual dose for individuals could exceed 20 mSv in the first year after the accident. Within the special decontamination area, the national government has the responsibility of formulating and implementing remediation plans.

— *Intensive contamination survey area* (Fig. 5.1, right). This area includes those municipalities where the additional radiation dose in the first year was estimated to be between 1 and 20 mSv for individuals in some parts of the municipality[112]. Municipalities conduct monitoring surveys to identify areas requiring decontamination and carry out remediation activities in these areas, with the national government providing financial and technical support.

In 2012 and 2013, the areas in which evacuation orders had been issued were further subdivided into the following three categories on the basis of the estimated annual total dose to people inhabiting the area, if any (Fig. 5.1, left) [274, 275]:

— ***Area 1 (green).*** Areas where evacuation orders were ready to be lifted. The estimated annual dose was expected to be 20 mSv or less.

— ***Area 2 (orange).*** Areas in which residents were still not permitted to live. The estimated annual dose was expected to exceed 20 mSv.

— ***Area 3 (red).*** Areas to which it was anticipated that residents would not be able to return for a long time. The estimated annual dose was over 50 mSv, and the average annual dose over the period of six years after the accident was expected to be more than 20 mSv.

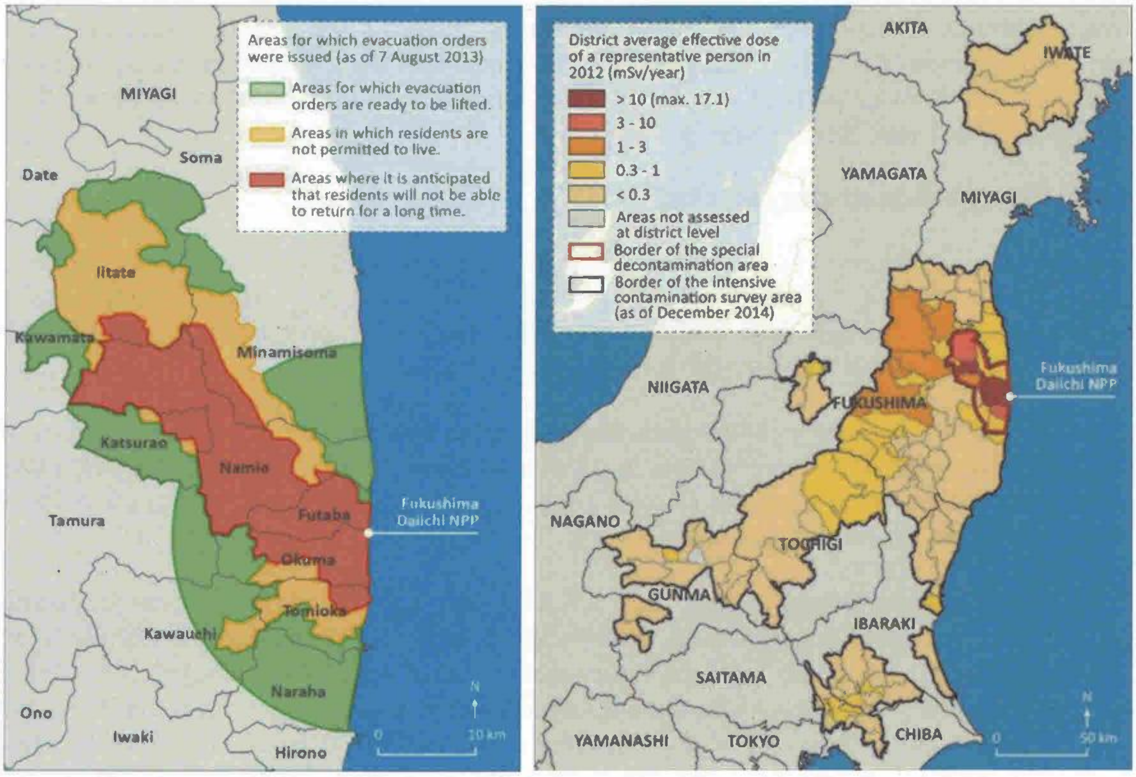

FIG. 5.1. The map on the left shows the subdivision of the evacuation zone as of 7 August 2013 [276]. The map on the right shows the designation of the 'special decontamination area' and the 'intensive contamination survey area' (as of December 2014) and indicates the average additional radiation doses in 2012.

[112] An ambient dose rate of 0.23 μSv/h was used as the radiological criterion for this area. This dose rate corresponds to a conservatively estimated additional effective dose of 1 mSv in one year.

5.1.3. Progress in remediation

A number of pilot projects were undertaken in 2011. The JAEA initially performed a series of small scale studies at two sites outside the evacuated zones to assess the effectiveness of decontamination in achieving reductions in dose rate for various types of surfaces (e.g. streets, roofs, walls and lawns) [277]. Later studies considered the feasibility of decontamination of larger areas in the evacuated zones, assessed the effectiveness of these measures in reducing ambient gamma dose rates and explored the implications for worker safety and waste management.

These pilot studies played an important role in planning and implementing remediation strategies. They provided information on the effectiveness and applicability of decontamination techniques and helped to establish procedures for the radiation protection of workers [278].

Commonly implemented remediation measures following the Fukushima Daiichi accident are listed in Table 5.1. Topsoil removal, which generates a large amount of waste, was widely used in the first years of remediation.

TABLE 5.1. COMMONLY IMPLEMENTED REMEDIATION MEASURES

Target	Remediation measures
Houses, buildings	— Removal of deposits from the roof, deck and gutters — Wiping roofs and walls — Vacuum sanding — High pressure washing
Schoolyards, gardens and parks	— Topsoil removal — Weed/grass/pasture removal
Roads	— Removal of deposits in ditches — High pressure washing
Gardens and trees	— Mowing — Removal of fallen leaves — Removal of topsoil — High pressure washing — Paring tree surfaces
Farmlands	— Tillage reversal — Topsoil removal — Soil treatment (e.g. enhanced application of fertilizer) — Soil hardening and removal — Weed/grass/pasture removal
Animal production	— Control of radiocaesium levels in animal feed
Forests and woodland	— Removal of fallen leaves and lower twigs — Pruning

Remediation strategies were later implemented in both the intensive contamination survey area and the special decontamination area, and significant progress was made. By the end of 2014, decontamination in most parts of the intensive contamination survey area outside Fukushima Prefecture was almost complete (in about 80% of the municipalities). In the intensive contamination survey area within Fukushima Prefecture, around 80% of the public facilities, 60% of residential houses and 40% of roads had been decontaminated [279].

Within the special decontamination area, decontamination plans had been completed in four municipalities in March 2015 (Tamura, Kawauchi, Naraha and Okuma). Decontamination of residential areas had also been completed in two more municipalities (Katsurao and Kawamata) and had almost been completed in Iitate [279]. Most decontamination plans in both decontamination areas 1 and 2 within Fukushima Prefecture were due to be completed before the end of March 2016, although some were due to continue into 2017 (Fig. 5.2).

Investigations performed in residential areas of Tamura and Naraha municipalities showed that ambient gamma dose rates had been reduced by an average of 36% and 46%, respectively. Gamma dose rates (see text in Box 5.1) were determined by measuring ambient dose rates at a distance of 1 metre from the decontaminated surfaces, both before and after remediation actions. Average dose rate reductions in the two municipalities following remedial actions in farmlands, forests and roads were between 21% and 44% [279].

The data indicate that the reduction of ambient gamma dose rates is more significant in areas with higher initial dose rates. After remediation, the gamma dose rates continue to decline owing to the natural processes of weathering and radioactive decay.

Unit costs for decontamination in the special decontamination areas directly controlled by the national government ranged from around 1100 JPY/m^2 (forests) to approximately 5500 JPY/m^2 (parks) [280].

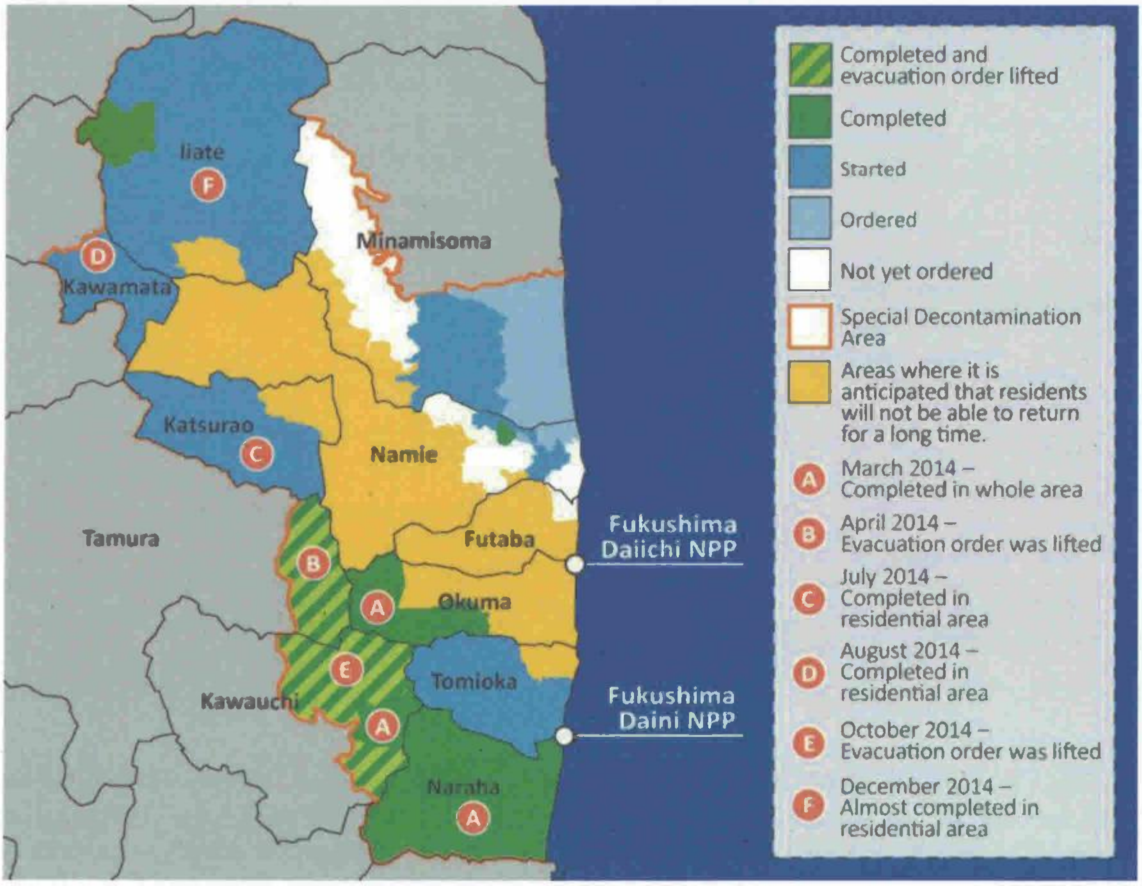

FIG. 5.2. Progress of remediation in the special decontamination areas up to December 2014 [279].

Examples of remediation are shown in Fig. 5.3.

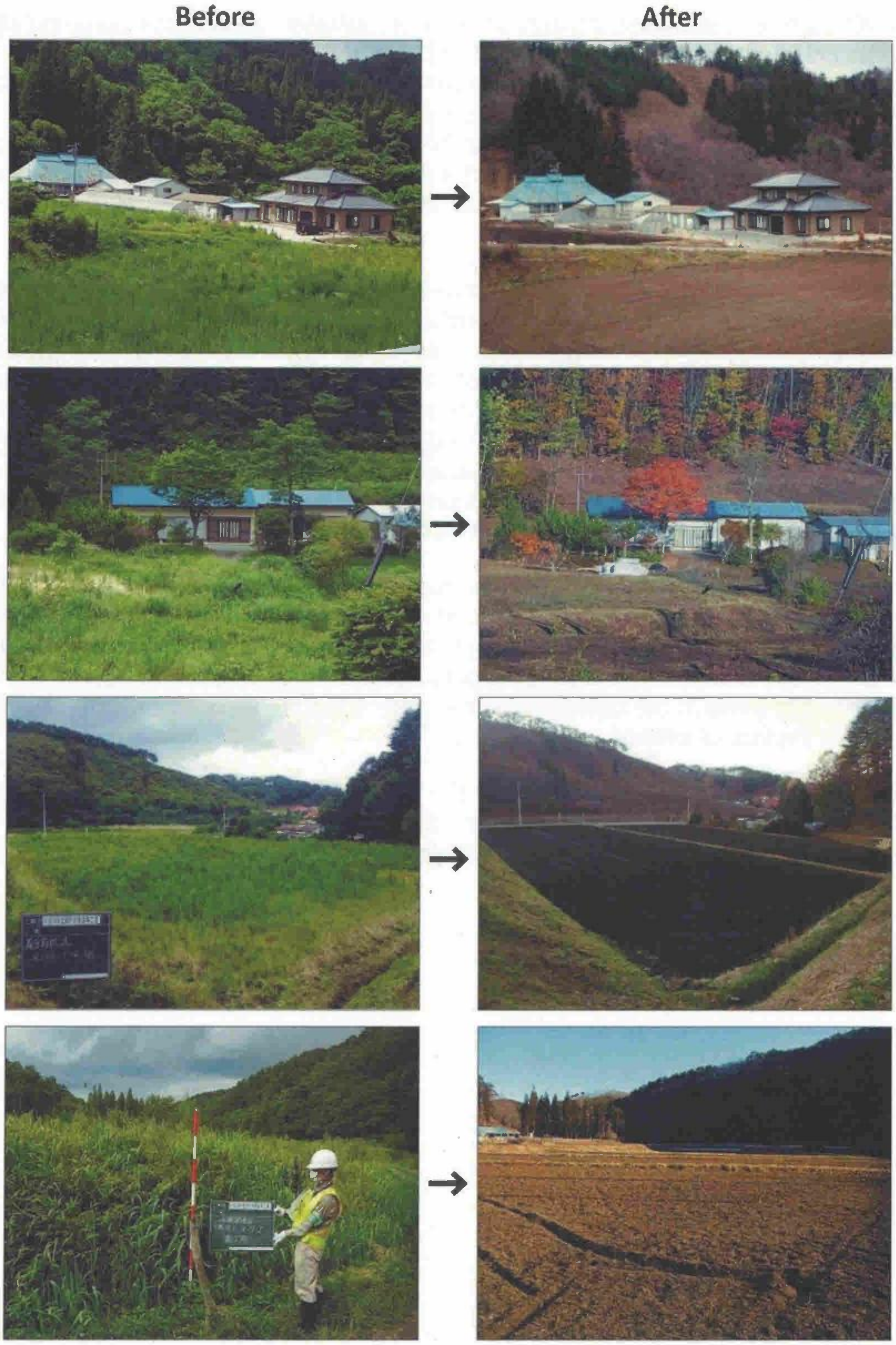

FIG. 5.3. Landscapes before and after remediation in Tamura city (photos courtesy of the Ministry of the Environment, Japan).

5.2.ON-SITE STABILIZATION AND PREPARATIONS FOR DECOMMISSIONING

A comprehensive, high level strategic plan for stabilization and decommissioning of the damaged NPP was developed jointly by TEPCO and the relevant Japanese Government agencies. The plan was first issued in December 2011 and subsequently revised twice to reflect the experience gained and an improved understanding of the conditions of the damaged NPP, as well as the magnitude of the future challenges. The strategic plan addresses the complex nature of on-site work and includes: the approach to ensure safety; measures toward decommissioning; systems and environments to facilitate the work; and research and development requirements.

At the time of writing, safety functions had been re-established and structures, systems and components were in place to reliably maintain stable conditions. However, there was a continuing need for control of ingress of groundwater to the damaged and contaminated reactor buildings. The resulting contaminated water was being treated to remove radionuclides to the extent possible and stored in more than 800 tanks. More sustainable solutions are needed, considering all options, including the possible resumption of controlled discharge to the sea. Final decision making will require engaging relevant stakeholders and consideration of socioeconomic conditions in the consultation process, as well as implementation of a comprehensive monitoring programme.

Plans for the management of spent fuel and fuel debris were developed and removal of fuel from spent fuel pools began[113]. A conceptual model of future activities for removing fuel debris was also developed, which takes account of the many preliminary steps required, including visual confirmation of the configuration and composition of the debris. The high radiation dose levels in the damaged reactors meant that no such confirmation had been possible at the time of writing.

Japanese authorities have estimated that the timescale for completing decommissioning activities is likely to be in the range of 30–40 years. Decisions regarding the final conditions of the plant and site will be the subject of further analysis and discussions.

[113] Removal of fuel from the Unit 4 spent fuel pool was completed in December 2014.

Box 5.2. Stabilization and post-accident decommissioning

The term 'decommissioning' refers to the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility.

In practical terms, decommissioning is the progressive removal of the facility's structures, systems and components. Under normal circumstances, decommissioning of an NPP is a planned activity that is initiated after the decision has been taken to end operations. Post-accident decommissioning presents a different set of challenges: the condition of the facilities and the status of the fuel and the plant equipment need to be first determined and a path forward decided. This may require development of new technologies and methodologies.

If reactor shutdown is the consequence of an accident, the facility needs to be brought to a safe configuration (stabilization) before an approved final decommissioning plan is put into effect. Stabilization comprises actions required to ensure that the plant structures (such as the buildings that house the damaged reactors), systems (such as electrical supply systems) and components (such as pumps or motors) are put in a stable condition and can operate for as long as may be required.

5.2.1. Strategic plan

Following the emergency phase, TEPCO and the relevant government agencies established a strategic plan — the 'Roadmap towards Restoration from the Accident at TEPCO Fukushima Daiichi Nuclear Power Station' — for stabilization and decommissioning activities [281]. The plan was first issued in December 2011 and subsequently revised twice to take account of the greater experience and improved understanding of the on-site conditions [282]. It is a comprehensive, high level strategic plan for those supervising the recovery. Decommissioning is projected to be completed on a timescale of 30–40 years, according to Japanese authorities' estimates.

The plan describes the strategic approach for areas of work concerning:

— **The approach to ensuring safety**, which includes strategic objectives for reducing risks and optimizing the removal of fuel and fuel debris.

— **Mid-term and long-term measures toward decommissioning**, which include plans for the removal of fuel and fuel debris from each reactor unit. These plans are sufficiently flexible to address the possible range of conditions that may be revealed as more information is gained in the processes of removing fuel and fuel debris.

— **Systems and environment to facilitate work**, for which TEPCO established an organization for centralized monitoring of the health and radiation exposure of workers. Efforts to improve radiation protection of workers continued and plans were put in place for managing and ensuring the availability of a trained workforce throughout the decommissioning process.

— **Research and development**, which is necessary as much of the work to be accomplished at the Fukushima Daiichi NPP is the first of its kind, requiring equipment and technology that has yet to be developed or used on a large scale. The International Research Institute for Nuclear Decommissioning was established to develop technologies for nuclear decommissioning, promote cooperation with international and domestic organizations on nuclear decommissioning and develop human resources for research and development.

5.2.2. Preparations for decommissioning

Shortly after its establishment [283], the NRA developed a new regulatory framework for the regulation of so-called disaster experienced facilities, which need special measures to prevent further accidents and to ensure nuclear security. On 7 November 2012, the NRA designated the Fukushima Daiichi NPP as 'Specified Reactor Facilities', which are facilities where a nuclear accident has occurred and special regulations commensurate with the prevailing conditions at the facility are stipulated.

This designation allowed the NRA to require TEPCO to develop a plan to implement the actions outlined in the strategic plan [281]. TEPCO's Implementation Plan was submitted in December 2012 [284] and was subsequently approved. TEPCO is responsible for carrying out the actions specified in the Implementation Plan. The execution of these actions is reviewed by the NRA.

Additionally, the NRA developed a regulatory requirement for managing the additional effective dose at the site boundary in February 2014 and identified actions in 'Measures for Mid-term Risk Reduction at TEPCO's Fukushima Daiichi NPS' in February 2015 [285].

TEPCO established stable conditions at the site to maintain protection and safety and allow progress toward decommissioning [281]. Important support functions, such as normal and backup electrical supplies, were re-established and upgraded. Fundamental safety functions were also re-established. Arrangements to ensure the long term reliability of stable conditions include:

- Monitoring plant conditions;
- Cooling the fuel and fuel debris;
- Maintaining nuclear subcriticality;
- Controlling levels of hydrogen;
- Ensuring structural stability of the reactor buildings;
- Controlling water ingress to the reactor buildings and preventing leakage to the environment;
- Ensuring essential electrical power supplies;
- Ensuring the fulfilment of fundamental safety functions over the long term.

Important safety functions were re-established and upgraded, for example, by installing multiple backup features and replacing and/or upgrading mobile and temporary systems to augment permanent ones. The situation on the site remains complex, and careful monitoring and control is required to ensure continued stable conditions.

5.2.3. Management of contaminated water

Water that enters damaged reactor buildings becomes contaminated and poses a particularly challenging problem due to the large volumes involved. At the time of writing, water continued to enter the reactor buildings at the Fukushima Daiichi NPP in two ways: water injection into the reactor cores for cooling purposes and ingress of groundwater. Characterizing and managing this water continued to be necessary (Fig. 5.4).

Before the accident, groundwater flowing from the mountainside to the rear of the Fukushima Daiichi NPP was pumped at a rate of approximately 850 m^3/d from sub-drains located around the buildings of Units 1–4 to control the groundwater level. As a consequence of the accident, the sub-drains and pumps that previously suppressed building buoyancy and prevented groundwater from entering the buildings ceased operation [286].

After the accident, approximately 400 m^3/d of uncontaminated groundwater flowed into the buildings. Approximately 400 m^3/d of water is circulated through the Unit 1–3 reactors for cooling. The groundwater that enters the buildings is mixed with the circulating water used for cooling the reactors, leading to a total volume of approximately 800 m^3/d of contaminated water that has to be managed. Approximately 400 m^3/d of this water is re-injected into the reactors for cooling the fuel and fuel debris, and the remaining 400 m^3/d is stored in the contaminated water storage tanks [282].

The water is treated to remove radionuclides, with the exception of tritium, which cannot be removed [287]. The treated water was stored on the site in 826 tanks (as of 12 February 2015) [280].

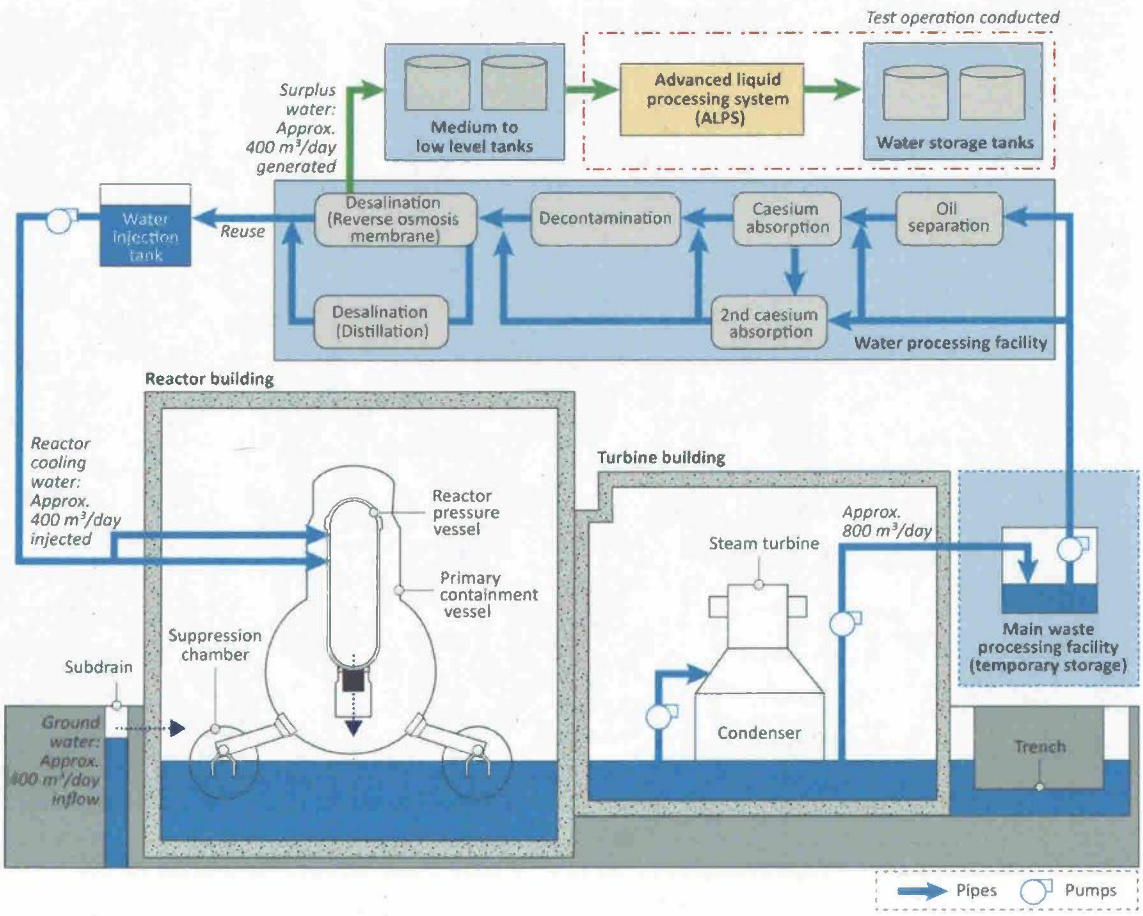

FIG. 5.4. Management of contaminated water on the site [288].

Various water management techniques have been deployed, or were being planned, including improvement and installation of additional treatment systems and storage tanks, the restoration of the subdrain system and the installation of sea side impermeable walls. Uncontaminated groundwater from uphill of the damaged facilities is being bypassed around the facilities and into the ocean (Fig. 5.5) [289]. In addition, a cryogenic 'frozen' wall on the mountain side of the reactor buildings was under construction to prevent further water ingress. A cryogenic wall on the sea side of the reactor buildings was also planned.

FIG. 5.5. Illustration of water management efforts. Storage tanks for contaminated water are shown on the left [290].

With the approval of the NRA and the acceptance of the relevant stakeholders, including Fukushima Prefecture and the fishing industry, TEPCO began discharging the bypassed uncontaminated groundwater directly to the sea in May 2014 [289]. This measure reduced the volume of water requiring treatment.

The large quantities of contaminated water on the site present a variety of risks. Owing to malfunctions of tanks, pipes and valves or during heavy rainfall, leaks of radioactively contaminated water from components were observed. In some cases, the leaks led to releases of radionuclides to the sea. The identification of such leaks triggered more intensive monitoring, both on the site as well as in the marine environment [291]. Although measures were being implemented to stop or reduce the leakage, more sustainable solutions are needed, considering all options, including the possible resumption of controlled discharges to the sea. As a result of the IAEA Review Missions [292, 293], TEPCO was advised to perform an assessment of the potential radiological impact of the release of water containing tritium and any other residual radionuclides to the sea. It was also recognized that final decision making would require engaging all stakeholders, including TEPCO, the NRA, the national government, the Fukushima Prefecture government, local communities and others, and that there was a need to consider socioeconomic conditions in the consultation process and to implement a comprehensive monitoring programme to ensure that there was no detrimental impact on human health and the environment [292, 293]. In this context, further guidance on the application of international guidance for discharges in post-accident situations would be beneficial.

5.2.4. Removal of spent fuel and fuel debris

The preparation for decommissioning the accident damaged facilities includes the removal of spent fuel and new fuel assemblies from storage pools inside the damaged reactor buildings. TEPCO began removing the fuel in the storage pool inside the Unit 4 reactor building to the common fuel pool in November 2013. The operation was completed in December 2014 [288].

It will require several years to remove the spent fuel and new fuel assemblies from the storage pools in Units 1–3. A more accurate estimate of the time needed is dependent on the progress in removing the debris resulting from the explosions, preparing the upper structure of Units 1–3 for access, providing supports for equipment and structures for removal, and other measures. The spent fuel will be placed in a common pool for temporary storage.

Removal and management of debris from the melted fuel in the reactor core is a much more complex challenge. Visual confirmation of the configuration and the composition of the damaged fuel ('fuel debris') resulting from the accident has not been possible due to the high radiation dose levels in the damaged reactors. Available analyses indicate that most of the fuel in Unit 1 melted and that some penetrated the bottom of the reactor pressure vessel to the primary containment vessel, whereas in Units 2 and 3, fuel also melted, but a greater proportion remained within the reactor pressure vessels [9].

At the time of writing, the Government of Japan was sponsoring conceptual studies on ways of gaining access to and removing fuel debris [282, 294]. A conceptual model for future activities for removing fuel debris has been developed, which takes account of the many preliminary steps required, including:

(1) **Reduction of radiation levels in the reactor buildings.** Access by workers to the spaces inside the reactor buildings is difficult because of high dose rates and rubble

and contaminated dust that have been scattered inside them. Decontamination, in many instances with remotely operated equipment, will be needed to make access possible.

(2) **Repair of the primary containment vessels containing water**. An investigation will be conducted and the required equipment will be developed to stop water leakage from the containment vessels, after which the water levels will be monitored and maintained as needed for subsequent operations.

(3) **Characterization of the conditions inside the primary containment vessels.** Removal of the fuel debris requires determining the exact locations of the pieces of fuel debris. Equipment to investigate the conditions inside the containment vessels will be developed and the necessary information, such as the locations, distributions and shapes of the pieces of fuel debris, will be obtained.

(4) **Characterization of the conditions inside the reactor pressure vessels.** This includes the distribution of fuel debris, levels of radioactivity, as well as the physical configuration of the damaged pressure vessels.

(5) **Development of technologies for the removal of fuel debris.** The preconditions for removal of fuel debris will be identified, leading to the development of technologies and equipment to open the reactors, remove structural impediments inside the reactor pressure vessels and remove fuel debris.

(6) **Water management.** Beyond cooling and boron control, careful water management will be necessary as the approach to the removal of fuel debris progresses. For example, additional means will be needed for removal of particulate material that becomes suspended in water as a result of the removal operations.

(7) **Packaging, transfer and storage of fuel debris.** As debris is removed from the reactor pressure vessels and the primary containment vessels, it will need to be placed in shielded containers. The containers will need to be removed from the reactor buildings and placed in interim storage on the Fukushima Daiichi site until a final decision on their disposition has been taken.

(8) **Prevention of nuclear criticality of fuel debris.** Evaluations will be conducted and monitoring techniques put in place to preclude any possibility of nuclear criticality within the debris.

(9) **Accounting for, and control of, nuclear material in the fuel debris.** Accountability is required for fissionable material, in conformity with the safeguards agreement between Japan and the IAEA and with Japanese domestic law. Because the standard methods cannot be applied to the fuel debris, accountability measures will be established before the fuel debris is removed from the reactors.

Fuel debris will be removed while submerged in water to provide shielding and to minimize radioactive releases to the air. The high levels of radiation and contamination, and the unknown distribution and properties of the fuel debris, mean that much of the work will need to be conducted by use of remotely operated equipment. Strategies for removal of fuel debris will need to be adjusted as data become available regarding the conditions of the fuel and fuel debris, as will plans to design, engineer and build appropriate equipment.

5.2.5. Decommissioning end state for the site

Under normal (non-accident) circumstances, the end state of an NPP is defined and described in the licence application and subsequent supporting documents. Two strategies for achieving a plant end state are generally available: immediate dismantling and deferred dismantling, which is sometimes referred to as safe storage. Under exceptional circumstances, e.g. following a nuclear accident, entombment may also be considered [295].

A nuclear accident may invalidate prior decommissioning planning owing, for example, to the need to stabilize structures, systems and components before the new decommissioning plan can be developed. Decommissioning plans, removal of the fuel debris and options for the final end state of the site depend on the nature of the accident, and will include consideration of the status of: nuclear residues, particles and radioactive materials remaining within the facilities; spent fuel and fuel debris in storage; and solid radioactive waste and processed water in storage [296]. The interests of stakeholders obtained, for example, through an appropriate public consultation process, will also influence the planning and execution of the decommissioning.

It is currently not possible to predict the end state of the Fukushima Daiichi NPP [294]. It may be noted that none of the three plants elsewhere in the world that experienced the most severe fuel damage in previous accidents have yet achieved the final end state for complete decommissioning [296] (Box 5.3).

Box 5.3. Status of decommissioning of damaged nuclear facilities

The three facilities elsewhere that have experienced the most severe fuel damage in previous accidents are Windscale (United Kingdom), Three Mile Island (USA) and Chernobyl (Ukraine). Their status at the time of writing was as follows:

The Windscale pile, damaged in an accident in 1957, was in a care and maintenance condition, with a plan to place it in safe storage in the next few years and with final decommissioning planned to occur around 2050.

The unit damaged at the Three Mile Island NPP in 1979 was in a safe storage mode, with a plan for complete dismantlement and site remediation within the next 20 years.

Chernobyl Unit 4, severely damaged in the accident in 1986, was in the process of being placed in a condition of safe storage, with final decommissioning projected for around 2050.

A final decision on the end state to be achieved at the Fukushima Daiichi site will need to consider many factors, including the future use of the land, possible radiation doses to the decommissioning workers, the waste that would be generated and options for the waste conditioning and disposal.

5.3. MANAGEMENT OF CONTAMINATED MATERIAL AND RADIOACTIVE WASTE

Stabilization of a damaged NPP and the on-site decontamination and remediation efforts in the surrounding areas results in large quantities of contaminated material and of radioactive waste. The management of such material — with its varying physical, chemical and radiological properties — is complex and requires significant efforts.

Following the Fukushima Daiichi accident, there were difficulties in establishing locations to store the large amounts of contaminated material arising from off-site remediation activities. Several hundred temporary storage facilities had been established in local communities. Efforts to establish an interim storage facility were continuing.

5.3.1. Managing the waste

A large amount of waste (known as 'disaster waste') was generated by the earthquake and tsunami, some of which was contaminated (predominantly by ^{134}Cs and ^{137}Cs) as a result of releases from the Fukushima Daiichi NPP. On-site stabilization activities have increased the inventory of contaminated material and of solid and liquid radioactive waste necessitating management, while off-site remediation activities have increased the amount of contaminated material.

> ***Box 5.4. Radioactive waste***
>
> Radioactive waste is material for which no further use is foreseen that contains radionuclides with a content or concentration above a specified level. Disposal is the internationally recognized end point for the management of radioactive waste. However, storage of some radioactive waste for periods of tens of years is often necessary while disposal facilities are being developed. Certain types of radioactive waste (low level radioactive waste) can be disposed of in 'near surface' waste disposal facilities.

The management (i.e. pre-treatment, treatment, conditioning, transport, storage and future disposal) of large amounts of waste with differing physical, chemical and radiological properties presents a challenge. Equipment, activities and facilities have had to be developed and/or modified under circumstances made more difficult by the loss of infrastructure caused by the earthquake and tsunami and by high radiation levels. Amendments to legislation and to the national approach to waste management were also necessary [129, 272, 283, 297].

5.3.2. Off-site activities

Off-site remediation was initiated with the objective of reducing external exposures. The remedial actions included the removal of topsoil and vegetation and the decontamination of public and residential areas. The size of the area requiring remediation was influenced by the radiological criteria and action levels adopted, which also had implications for the amount of contaminated material requiring management.

In general, a low reference level results in a larger generation of contaminated material. It is estimated that the stockpile of soil and other contaminated material generated from remediation activities after the accident will be approximately 16–22 million m^3 after the reduction in volume by incineration of plants and trees [279].

The stages of the waste management process used in Fukushima Prefecture are illustrated in Fig. 5.6. The management of waste generated in the remediation activities involves its collection in temporary storage facilities near the locations for decontamination. Many hundreds of temporary storage facilities have been constructed. After temporary storage, this waste will be transported into the interim storage facility. Some of the material has contamination at levels that are sufficiently low to allow the use of existing infrastructure for the disposal of municipal solid waste (e.g. municipal incinerator facilities and waste landfills). However, the process of obtaining the agreement of municipalities to use conventional incinerators to reduce the volume of off-site contaminated material has proved to be difficult.

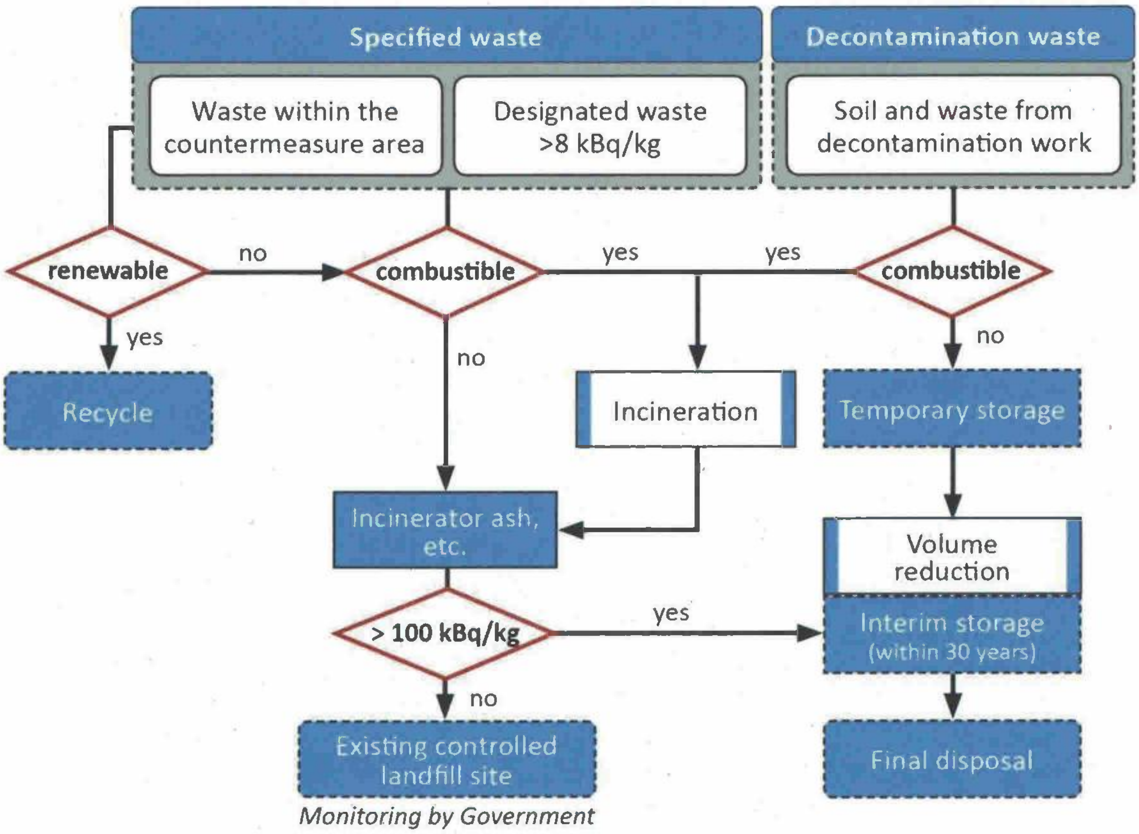

FIG. 5.6. Flow chart for the management of specified waste and decontamination waste in Fukushima Prefecture [298].

There were delays in site selection for temporary and interim storage facilities. Obtaining the agreement of the local population has been a contributing factor in the siting delays. However, following discussions of national and local government officials with local residents and landowners, the plan to construct an interim storage facility was accepted in Okuma in December 2014 and in Futaba in January 2015. In January 2015, the Ministry of the Environment (MOE) confirmed plans and arrangements for pilot-scale transport of contaminated soil to the interim storage facility from March 2015 [279]; for testing purposes, these transports started on 13 March 2015.

5.3.3. On-site activities

At the Fukushima Daiichi NPP, large amounts of contaminated solid and liquid material as well as radioactive waste have been generated following various recovery activities. For example, as of 30 November 2014, 131 900 m^3 of debris and 79 700 m^3 of trees were being stored on the site [299, 300]. The generation of these large amounts of contaminated material and radioactive waste has required the establishment of effective strategies for waste management. In particular, there has been a need to develop facilities for treatment and storage of many hundreds of thousands of cubic metres of contaminated and treated water as well as for solid waste resulting from the treatment processes and the clearing of large areas of land. Part of the strategy for on-site waste management, including the facilities for water treatment and storage, is illustrated in Fig. 5.7.

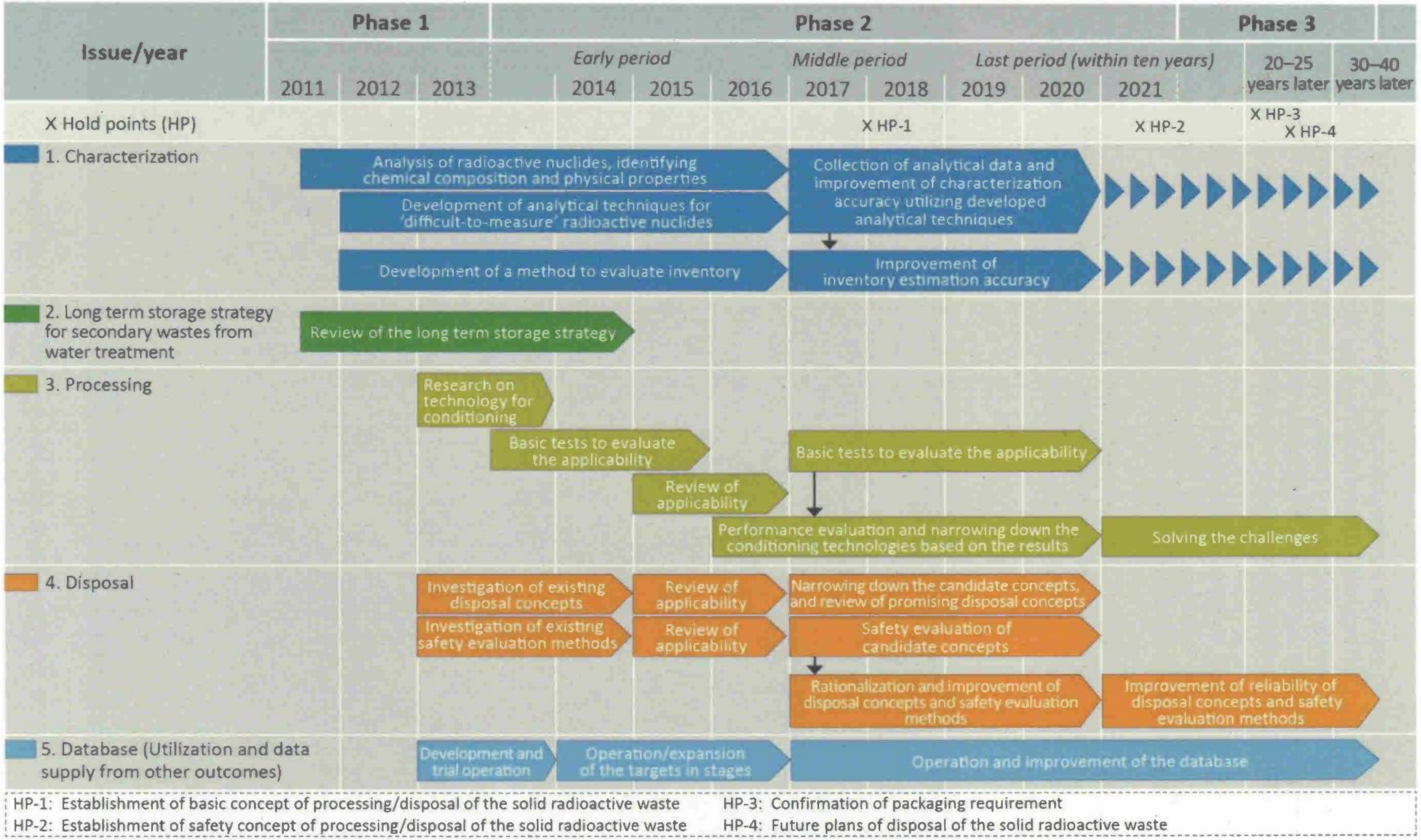

FIG. 5.7. Part of the strategy for on-site waste management [294].

There is a continuing need for storage capacities for various types of solid and liquid waste streams (Fig. 5.8). Consequently, volume reduction has become an important component in the management of on-site waste, e.g. through waste avoidance, installation of incinerators, and reuse and recycling of materials. Additional waste is expected from the decommissioning of the NPP [301]. The types and amounts of waste will depend on the approach adopted.

There have been efforts to move radioactive waste away from the site boundary in order to limit dose rates at the boundary to less than 1 mSv/y. These activities have no impact on public exposure as there is no public presence at the site boundary [302].

The management of waste on the site poses many complex challenges, requiring further research and development. As new capabilities are obtained, a strategy for final disposal of on-site waste will need to be considered, involving decisions for both the near term and the long term [303].

FIG. 5.8. Aerial view of the on-site area showing the water storage tanks [304].

5.4. COMMUNITY REVITALIZATION AND STAKEHOLDER ENGAGEMENT

The nuclear accident and radiation protection measures introduced in both the emergency and post-accident recovery phases have had significant consequences for the way of life of the affected population. Evacuation and relocation measures and restrictions on food involved hardships for the people affected. The revitalization and reconstruction projects introduced in Fukushima Prefecture were developed from an understanding of the socioeconomic consequences of the accident. These projects address issues such as reconstruction of infrastructure, community revitalization and support and compensation.

Communication with the public on recovery activities is essential to build trust. To communicate effectively, it is necessary for experts to understand the information needs of the affected population and to provide understandable information through relevant means. Communications improved in the aftermath of the accident and the affected population became increasingly involved in decision making and remediation measures.

The accident and the protective actions introduced in both the emergency phase and the recovery phase impacted the way of life of populations in the areas affected. By 30 January 2015, the number of evacuees was around 119 000, compared with a peak of around 164 000 in June 2012. The hardships associated with evacuation, relocation and restrictions on food are substantial [274, 275].

The earthquake, the tsunami and the accident resulted in the destruction, degradation or disuse of infrastructure (including schools, hospitals and commercial enterprises), had an impact on business and trade and brought about demographic changes through the evacuation of large numbers of people. It was reported that young families were more likely to remain evacuated, and the elderly were more likely to return to their homes [305]. Recovery and revitalization plans at the national and local levels recognize the importance of physical and socioeconomic reconstruction and address issues such as reconstruction of infrastructure, community support and compensation [275].

The particular challenges for people living in temporary accommodation include a range of issues of general physical and mental well-being that are associated with high levels of unemployment and the difficulties associated with provisional accommodation [245]. The total number of evacuees living in temporary accommodation as a result of the earthquake, tsunami and nuclear accident is not known precisely but, by June 2013, 16 800 temporary housing units had been constructed and nearly 24 000 families were living in accommodation rented by the prefectural government [275]. In addition, there were plans to build 2586 units of permanent public housing by 2015 for people affected by the earthquake and tsunami. For those evacuated in the response to the accident, 4890 units of permanent public housing were planned [280].

5.4.1. Socioeconomic consequences

Evacuation resulted in the loss of farms and businesses. Fishing ceased within 30 km of the site (reduced to 20 km at the end of September 2011). Agricultural and other commercial activities have ceased in an area of about 700 km^2 outside the special decontamination area [275, 306, 307].

Socioeconomic consequences in the agricultural sector and other enterprises were also seen outside the special decontamination area and the intensive contamination survey area. In addition to the loss of employment and of livelihoods for those affected, restrictions on food, export losses involving food and consumer goods, the costs of monitoring to demonstrate compliance with radiological criteria and payment of compensation to people affected have also had an effect. Indirect socioeconomic consequences include those arising from the loss of consumer confidence, not only in food products, but also in commodities from and businesses in the affected areas [275, 306, 308].

The combination of earthquake, tsunami and nuclear accident had a direct effect on the Japanese economy. Exports fell by 2.4% in April 2011 compared with the level in April 2010. At the same time, imports increased, especially those of fuels, chemicals and food, resulting in a deficit in the trade balance in April and May 2011 [306]. Imports of fossil fuel remained at a higher level at the time of writing. [309].

Although at the time of the accident Japan was not party to any of the conventions on civil liability for nuclear damage (it joined the Convention on Supplementary Compensation for Nuclear Damage (CSC) on 15 January 2015), legislation enacted in 1961 was consistent with the basic principles of nuclear liability as embodied in those conventions. Under this legislation, TEPCO was exclusively liable for nuclear damage caused by the Fukushima Daiichi accident [310]. Its liability was unlimited in amount. Following the accident, TEPCO was not granted exemption from liability by the Government and Parliament on the assumption that the exemption clause related to a grave natural disaster, as specified in the Act on Compensation for Nuclear Damage, was inapplicable in this case. Various means to allow TEPCO to meet its obligations towards the victims of the accident have been implemented, including provisional compensation payments as an emergency measure, the provision of financial support to TEPCO by the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF), and NDF becoming the controlling shareholder of TEPCO. Moreover, the creation of the Dispute Reconciliation Committee for Nuclear Damage Compensation and the issuance of legally non-binding guidelines provided a mechanism for prompt out of court settlements of compensation for nuclear damage.

The established compensation policy applies to those ordered to evacuate and also covers impacts on livelihood and way of life, loss of profits due to restrictions and loss of trust by consumers, and infrastructure changes for people remaining in the area. In addition, there are specific provisions for parents with young families and for pregnant women [311].

According to guidelines established in December 2011, people subject to evacuation received compensation of the order of JPY 100 000 per person and per month. Additional compensation of about JPY 900 000 per person will be paid to those returning to live in the areas affected within a year after the lifting of the evacuation order [312].

5.4.2. Revitalization

A number of initiatives to stimulate the revitalization of Fukushima Prefecture have been implemented with government and local support. These include the reconstruction of infrastructure, housing and transport. Some actions focus on regaining consumers' trust in products, while also promoting local pride and tourism. Recognizing that the availability of work and employment is also a driving factor for the return of residents (or for the settlement of new populations), other initiatives focus on rebuilding businesses as well as creating new commercial opportunities.

Revitalization initiatives and reconstruction activities linked to recovery range from those at national government level to initiatives by non-governmental organizations and local communities. The Government of Japan established a Reconstruction Agency; Fukushima Prefecture has initiated various activities including the establishment of the Centre for Environmental Creation [240, 275]; and the Fukushima Revitalization Headquarters was set up by TEPCO in 2013. All projects aim to combine radiation protection actions with broader societal aspects, such as revitalization of infrastructure and public engagement and – in the case of the Revitalization Headquarters – compensation [313].

The actions vary across the prefecture, often depending on the engagement of local leaders and the different challenges within the region. Examples of successful revitalization initiatives include cooperation between peach growers and distributors and the food industry to restore public trust in food produced in Fukushima Prefecture [275, 314].

5.4.3. Engagement of and communication with stakeholders

Engagement of stakeholders has increased and strategies for consultation and involvement have improved as remediation and recovery actions have progressed. The response to the accident has provided a number of examples that show the benefits of involving affected populations in activities for recovery, from consultation and dialogue to remediation actions (so-called self-help actions).

Open and effective communication with the public is an essential part of revitalization. An information hub for the area on decontamination (Decontamination Information Plaza) was opened in Fukushima City in January 2012 as a joint project of Fukushima Prefecture and the MOE [315].

Other communication activities at the local level include dialogues between experts and the public and specific advice for self-help actions. These activities have helped to restore communication with Fukushima residents and to rebuild trust.

A flow chart of the implementation process for remediation and associated interactions with stakeholders is shown in Fig. 5.9. All steps in the development of plans and their implementation included stakeholder participation and consultation. In the case of remediation of privately owned land, agreement is required from the landowners before any remediation activities can be started.

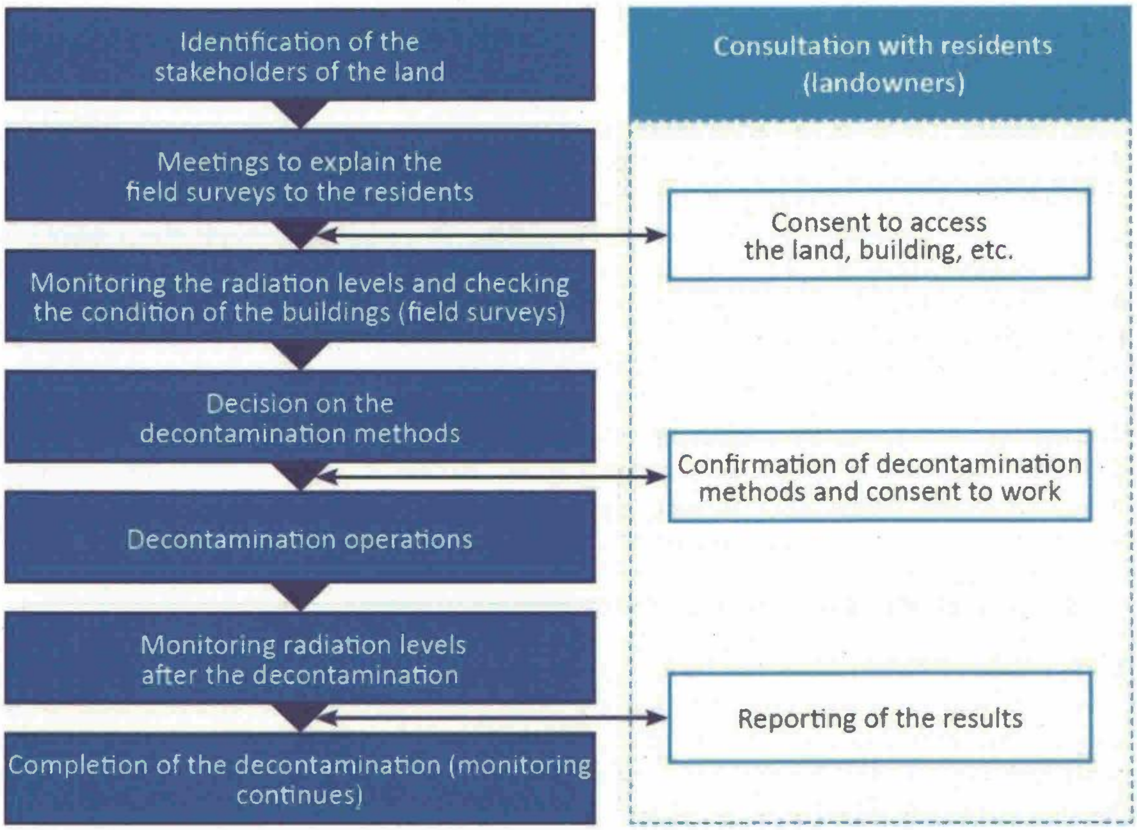

FIG. 5.9. Flow chart of the process for remediation and for consultation with residents [316].

In a nuclear accident, the media, in both traditional and new forms, play an important role in communicating with the public. The Fukushima Daiichi accident was characterized by a high level of media coverage, through the Internet, social media and, in the initial phase, through continuous TV and radio broadcasts. The coverage of the accident lasted for several months, focusing mainly on problems linked to the accident site, but also on the protective actions taken by Japanese authorities. Social media intensified reporting on the event, as well as disseminating the views of individuals and non-governmental organizations. A considerable amount of information was available, of varying quality and levels of credibility [313].

Radiation safety experts needed to learn what kind of information the public was requesting, and to provide it in an understandable manner. Critical questions asked by the affected communities and by the media focused on what levels of radiation are 'safe' [317].

5.5. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of the post-accident activities.

— **Pre-accident planning for post-accident recovery is necessary to improve decision making under pressure in the immediate post-accident situation. National strategies and measures for post-accident recovery need to be prepared in advance in order to enable an effective and appropriate overall recovery**

programme to be put in place in case of a nuclear accident. These strategies and measures need to include the establishment of a legal and regulatory framework; generic remediation strategies and criteria for residual radiation doses and contamination levels; a plan for stabilization and decommissioning of damaged nuclear facilities; and a generic strategy for managing large quantities of contaminated material and radioactive waste.

These strategies and measures need to include:

- The establishment of a legal and regulatory framework that specifies the roles and responsibilities of the various institutions to be involved. This framework needs to address off-site remediation, on-site stabilization and preparations for decommissioning, management of contaminated material and radioactive waste, and community revitalization and stakeholder engagement.
- Generic remediation strategies and criteria (reference and derived action levels) for residual radiation doses and contamination levels.
- A plan for the stabilization of conditions on the site of a damaged nuclear facility and preparations for its decommissioning.
- Development of a generic strategy for managing large quantities of contaminated material and radioactive waste, supported by generic safety assessments for storage and disposal facilities.
- Sufficient flexibility to ensure that the management of post-accident conditions can be adapted in response to changing conditions and acquired information and experience.

— **Remediation strategies need to take account of the effectiveness and feasibility of individual measures and the amount of contaminated material that will be generated in the remediation process.**

Having established reference levels for residual radiation doses and contamination levels, it is essential to control carefully the amount of contaminated material generated by implementing the remediation strategy in order to minimize the amount of waste to be managed. The absence of preparations for recovery from a nuclear accident in Japan meant that, initially, large volumes of potentially contaminated material were generated. As time elapsed and planning developed, remediation actions were optimized, leading to improved control of the amount of waste to be managed.

Pilot projects were useful in determining both the effectiveness of particular remediation techniques and the amount of waste generated by particular techniques. Pilot projects also contributed to establishing procedures for radiation protection of workers.

— **As part of the remediation strategy, the implementation of rigorous testing of and controls on food is necessary to prevent or minimize ingestion doses.**

The systematic implementation of rigorous testing of and controls on food after the accident demonstrated that ingestion doses can be kept at low levels.

To establish confidence in locally produced food, local monitoring stations were set up to allow people in affected areas to bring food to be measured. This control of ingestion doses simplified the recovery by allowing remediation to focus on techniques that reduce external doses.

— **Further international guidance is needed on the practical application of safety standards for radiation protection in post-accident recovery situations.**

Further practical guidance is needed on the application of the IAEA safety standards in existing exposure situations. The reference levels adopted for the early post-accident years need to be periodically reviewed and modified, as appropriate, to the changing radiological conditions. The guidance needs to include a methodology for the selection of case and site specific reference levels, in terms of dose and derived quantities, as well as mechanisms to integrate technical and scientific advice with other socially relevant factors to establish a coherent, transparent and collectively accepted decision making process.

— **Following an accident, a strategic plan for maintaining long term stable conditions and for the decommissioning of accident-damaged facilities is essential for on-site recovery. The plan needs to be flexible and readily adaptable to changing conditions and new information.**

Preparations for the decommissioning of a facility damaged in an accident would first involve stabilization to ensure that structures, systems and components are in place to reliably maintain stable conditions for the long term until their functions are no longer needed. Post-accident preparations for decommissioning take decades. Arrangements are necessary to maintain the necessary expertise and workforce throughout this entire period.

Decision making on interim decommissioning stages and on the final conditions of the site and the damaged reactors need to include a dialogue with stakeholders. Decision making on decommissioning depends on the conditions of the damaged reactors, fuel and debris, which cannot be determined in the period immediately following an accident. Factors to be considered in decision making include: dose levels for workers in decommissioning; the volumes and types of waste generated; and the efforts necessary for waste treatment. In the early stage of cleanup activities, it is unrealistic to predict the final conditions of the plant site, but expectations and plans for the land need to be considered in the decision making process.

— **Retrieving damaged fuel and characterizing and removing fuel debris require solutions that are specific to the accident and special methods and tools may need to be developed.**

A reactor accident involving damage to nuclear fuel results in particular conditions in the reactor that are unique to the accident. The removal and management of damaged fuel elements and of debris from melted fuel are complex tasks. The debris needs to be characterized, removed, packaged and placed in storage until disposal is implemented, under difficult conditions, associated largely with high radiation levels.

— **National strategies and measures for post-accident recovery need to include the development of a generic strategy for managing contaminated liquid and solid material and radioactive waste, supported by generic safety assessments for discharge, storage and disposal.**

A waste management strategy is needed for the implementation of pre-disposal management (for example, handling, treatment, conditioning and storage) of accident generated contaminated material and radioactive waste. It also needs to identify appropriate routes for the disposal of materials. Waste management strategies may involve the use of existing processing, storage and disposal facilities, such as incinerators or leachate controlled landfills. However, other approaches may be necessary, depending on the volumes and characteristics of the waste involved. The development of such strategies could be supported by the development of a generic safety case.

Strategies for the post-accident management of large volumes of contaminated water are also necessary, including consideration of its controlled discharge to the environment. Although there is international guidance for discharges during the normal operation of nuclear facilities, further guidance on its application in post-accident situations is needed.

— **It is necessary to recognize the socioeconomic consequences of any nuclear accident and of the subsequent protective actions, and to develop revitalization and reconstruction projects that address issues such as reconstruction of infrastructure, community revitalization and compensation.**

Nuclear accidents and the protective and remedial actions introduced in both the emergency phase and the post-accident recovery phase, with the objective of reducing doses, have far reaching consequences on the way of life of the affected population. Engagement of stakeholders at various stages of remediation and recovery is essential.

— **Support by stakeholders is essential for all aspects of post-accident recovery. In particular, engagement of the affected population in the decision making processes is necessary for the success, acceptability and effectiveness of the recovery and for the revitalization of communities. An effective recovery programme requires the trust and the involvement of the affected population. Confidence in the implementation of recovery measures has to be built through processes of dialogue, the provision of consistent, clear and timely information, and support to the affected population.**

Governments need to provide a realistic description of a recovery programme to the public that is consistent, clear and timely. A variety of information channels, including social media, need to be used to reach all interested groups.

Perceptions of radiation risks and answers to questions about 'safe' radiation levels have many dimensions, including scientific, societal and ethical. These answers need to be clearly communicated to relevant communities through educational programmes — ideally before an accident has occurred.

It is important that the affected population receives support for local recovery efforts. Support for self-help actions related to remediation and for rebuilding businesses can increase involvement in the recovery programme, and build the trust of the affected population.

6. THE IAEA RESPONSE TO THE ACCIDENT

This section provides an overview of key IAEA activities following the Fukushima Daiichi accident, both in the immediate phase and in the longer term. These include initial activities, IAEA missions to Japan, the Ministerial Conferences on Nuclear Safety and the IAEA Action Plan.

The IAEA is the depositary for the Convention on Nuclear Safety and its role is to provide the Secretariat for the meetings by convening, preparing and servicing these meetings, as well as transmitting relevant information to the Contracting Parties. The activities related to the meetings of the Contracting Parties to the Convention on Nuclear Safety following the Fukushima Daiichi accident are also presented in this section.

6.1. IAEA ACTIVITIES

6.1.1. Initial activities

The responsibility for responding to a nuclear or radiological emergency and for the protection of workers, the public and the environment, rests with the operating organization at the level of the facility concerned, and with the affected State at the local, regional and national levels.

The IAEA has a central role in the international framework[114] for emergency preparedness and response. This role includes: (1) notification and official information exchange through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision and facilitation of international assistance upon request; and (4) coordination of the inter-agency response[115].

The IAEA discharges this role through its Incident and Emergency System (IES). This system includes a 24-hour contact point and an operational focal point, the Incident and Emergency Centre (IEC).

At 06:42 UTC[116] on 11 March 2011, the IAEA activated the IES following a notification from the IAEA's International Seismic Safety Centre. This notification indicated the occurrence of an earthquake, the potential for damage at four NPPs[117] on the north-eastern coast of Japan and the risk of a tsunami [318]. At 07:21 UTC, the IAEA established initial

[114] The international emergency preparedness and response framework at the time of the accident consisted of: (a) international legal instruments and agreements, in particular the Convention on Early Notification of a Nuclear Accident (Early Notification Convention) and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention); (b) IAEA safety standards and technical guidance in the area of emergency preparedness and response; and (c) international operational arrangements and tools, in particular the Emergency Notification and Assistance Technical Operations Manual (ENATOM), the IAEA Response and Assistance Network (RANET), and the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

[115] The primary coordinating body for nuclear and radiological emergencies is the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE). This body was established following the Chernobyl accident in 1986 and currently includes 18 international organizations. One of the primary roles of IACRNE is the development and maintenance of the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN 2010 at the time of the accident).

[116] Coordinated Universal Time, which is nine hours behind Japan Standard Time.

[117] Fukushima Daiichi and Fukushima Daini of the Tokyo Electric Power Company (TEPCO), Onagawa (Tohoku Power Company) and Tokai (Japan Atomic Power Company).

communication with the official contact point designated by Japan under the Early Notification Convention and the Assistance Convention.

In the initial days of the accident, it became evident that the reactors and the fuel in the spent fuel pools at the Fukushima Daiichi NPP could be at risk of severe damage. Consequently, the IAEA established teams to evaluate key nuclear and radiological safety issues. The IAEA Laboratories[118] reviewed environmental data provided by the Japanese authorities on monitoring of the marine environment and received terrestrial environment samples for independent analysis.

The Director General of the IAEA visited Tokyo from 17 to 19 March for high level consultations, to express the solidarity of the international community and its full support to Japan in dealing with the consequences of the earthquake, tsunami and nuclear accident, and to convey offers of assistance from more than a dozen countries. The Director General also discussed the possibility of the IAEA providing or coordinating specific types of assistance, such as expert missions and fact finding missions, and emphasized the importance of transparency and the timely provision of official information by Japan.

On 28 March, at a special briefing on the accident for IAEA Member States, the Director General announced that a high level IAEA Conference on Nuclear Safety would take place in Vienna before the summer. He stated that it was "vitally important that we learn the right lessons from what happened on 11 March and afterwards, in order to strengthen nuclear safety throughout the world" [319].

Between 18 March and 18 April, at the request of Japan, the IAEA sent four radiological monitoring teams to Japan to help validate the results of the more extensive measurements taken by the Japanese authorities. The teams undertook measurements at a number of locations inside and outside the 20 km evacuation zone around the Fukushima Daiichi NPP and in the vicinity of Tokyo. A senior IAEA official was sent to Japan to coordinate the relevant IAEA activities and to transmit offers of assistance from Member States to the Japanese authorities. IAEA liaison officers were sent to Tokyo to facilitate and improve communication with Japan's regulatory body, which at that time was NISA.

A joint Food Safety Assessment Team from the IAEA and FAO visited Japan from 26 to 31 March. The team provided advice and assistance to the authorities at the national and local levels on technical issues relating to food safety and agricultural countermeasures. Advice was provided on sampling and analytical strategies and interpretation of monitoring data to ensure that reliable, continuous updates could be provided on the extent of food contamination in the affected areas. These data were used for the development of mitigation and remediation strategies by the Japanese authorities.

An IAEA team of experts on boiling water reactors was sent to Japan on 3 April, concluding its work on 12 April. The team toured both the Fukushima Daiichi and Fukushima Daini sites, meeting plant personnel in order to better understand the accident, the mitigation actions taken up to that time and the basis of the major decisions that had been made. They also held meetings with staff of several government offices and had detailed technical discussions with TEPCO and NISA in Tokyo.

[118] The IAEA Laboratories, located in Seibersdorf, Austria, and in Monaco, specialize in evaluating terrestrial and marine environmental samples, respectively.

The first statement by the IAEA on the accident was made public less than three hours after the earthquake on 11 March. Five additional statements were published later that day, conveying information received from Japan. More than 120 updates were published up to 22 April 2011. The IAEA held 16 news conferences between 14 March and 2 June 2011, in addition to those held during the Director General's visit to Japan. The IAEA's public information activities also included responding to thousands of telephone calls and providing detailed technical responses to hundreds of queries from the media.

The IAEA posted daily briefings for Member States and the public on its public website. These briefings covered: the status of Units 1–6 at the Fukushima Daiichi NPP; radiation monitoring data for radionuclides such as ^{131}I, ^{134}Cs and ^{137}Cs; the results of radiation monitoring of food and information on restrictions on the distribution and consumption of food and drinking water; and data on monitoring of the marine environment. The IAEA also provided briefings on the accident to the Permanent Missions of IAEA Member States in Vienna.

6.1.2. IAEA missions to Japan

Based upon an agreement with the Government of Japan, an International Fact Finding Expert Mission was undertaken by experts from the IAEA and Member States from 24 May to 2 June 2011. The mission gathered information for a preliminary assessment of the accident at the Fukushima Daiichi NPP and on events at other sites (Fukushima Daini and Tokai Daini). In addition, generic safety issues associated with natural events were identified that needed further exploration or assessment on the basis of the IAEA safety standards.

The scope of the mission included: external events of natural origin; plant safety assessment and the application of defence in depth; plant response after an earthquake and tsunami; management of a severe accident; management of spent fuel in a severely degraded facility; emergency preparedness and response; and radiological consequences. The mission findings [320] included 15 conclusions and 16 lessons, which were reported to the IAEA Ministerial Conference on Nuclear Safety in June 2011.

Other IAEA missions to Japan are summarized in Table 6.1.

Following the recommendation of the second decommissioning mission, projects were started to enhance transparency and to provide independent assessments of monitoring of the marine environment by Japan. Proficiency tests were conducted at the IAEA Environment Laboratories in Monaco to monitor the performance and analytical capabilities of participating laboratories. The results of the marine monitoring programme are regularly updated on the IAEA's website.

TABLE 6.1. IAEA MISSIONS TO JAPAN

Date	Mission	Objectives
7–15 October 2011	International mission on Remediation of Large Contaminated Areas Off-site the Fukushima Daiichi NPP [321]	Assist Japan's plans to remediate large areas contaminated by the accident. Review Japan's ongoing remediation strategies, plans and activities, including contamination mapping. Share findings with the international community to disseminate lessons from the accident.
23–31 January 2012	Mission to review NISA's Approach to the Comprehensive Assessments for the Safety of Existing Power Reactor Facilities [322]	Review (at the request of the Japanese Government) NISA's Comprehensive Assessments for the Safety of Existing Power Reactor Facilities, and the results of the licensee's assessments.
30 July–11 August 2012	Expert mission to the Onagawa NPP [323]	Examine the performance of systems, structures and components following the earthquake and tsunami.
15–22 April 2013	International peer review of the Mid- and Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 (first mission) [324]	Review the 'Decommissioning Roadmap'; challenges; condition of the reactors; management of waste; protection of employees; and structural integrity of reactor buildings and other structures.
14–21 October 2013	Follow up international mission on Remediation of Large Contaminated Areas Off-site the Fukushima Daiichi NPP [271]	Evaluate the progress of ongoing remediation work in Japan and to provide advice on addressing remediation challenges.
6–12 November 2013	Expert visit on marine monitoring	Observe seawater sampling and data analysis in Fukushima (7 and 8 November 2013) and meet the relevant Japanese authorities in Tokyo to collect information on marine monitoring conducted by Japan under its Sea Area Monitoring Plan.
25 November–4 December 2013	International peer review of the Mid- and Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 (second mission) [292]	Focus on TEPCO's removal of fuel assemblies from reactor Unit 4's spent fuel pool and contaminated water management issues.
10–16 September 2014 and 4–14 November 2014	Expert mission on marine monitoring confidence building and data quality assurance	Focus on availability of marine monitoring results.
8–15 February 2015	International peer review of the Mid- and Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 (third mission)	Focus on TEPCO's removal of fuel assemblies from Unit 4's spent fuel pool and contaminated water and waste management issues.

6.1.3. IAEA Ministerial Conference on Nuclear Safety

In June 2011, a Ministerial Conference on Nuclear Safety was convened by the Director General at IAEA Headquarters with the objective of strengthening nuclear safety by drawing on the lessons from the accident. The conference provided an opportunity to undertake, at the ministerial and senior technical levels, a preliminary assessment of the accident. The conference also considered actions for safety improvements, issues regarding emergency preparedness and response, and implications for the global nuclear safety framework.

The outcome was a Ministerial Declaration on Nuclear Safety [325], which outlined a number of measures to further improve nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. It also expressed the firm commitment of IAEA Member States to ensure that these measures were taken. The key measures were to: