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Use of Knowledge and Experience Gained from the Fukushima Daiichi Nuclear Power Station Accident to Establish the Technical Basis for Strategic Off-site Response

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This report provides a concise overview of knowledge and experience gained from the activities for environmental remediation after the Fukushima Daiichi (1F) accident. It is specifically tailored for international use, to establish or refine the technical basis for strategic, off-site response to nuclear incidents. It reflects JAEA's key role in the research associated with both remediation of contaminated areas and also the natural contamination migration processes in non-remediated areas, in collaboration with other Japanese and international organisations and research institutes.

Environmental monitoring and mapping to define boundary conditions in terms of the distribution of radioactivity and resultant doses, guides the resultant response. Radiation protection considerations set constraints, with approaches developed to estimate doses to different critical groups and set appropriate dose reduction targets. Decontamination activities, with special emphasis on associated waste management, provide experience in evaluation of the effectiveness of decontamination and the pros and cons of different approaches / technologies. The assessment of the natural behaviour of contaminant radionuclides and their mobility in the environment is now focused almost entirely on radiocaesium. Here, the impact of natural mobility in terms of self-cleaning / re-concentration in cleaned areas is discussed, along with possible actions to modify such transport or manage potential areas of radiocaesium accumulation.

Many of the conditions in Fukushima are similar to those following past contamination events in other countries, where natural self-cleaning alone has allowed recovery to such an extent that the original incident is now largely forgotten. Decontamination efforts in Japan will certainly accelerate this process. On-going remediation work is based on a good technical understanding of the movement of radiocaesium in the environment and this understanding is being translated into actions that enable the rapid return of evacuees and assures that they can safely resume their previous lifestyles. It does, however, need to be better integrated and much better communicated to the general public and other key stakeholders (foresters, fishermen, farmers etc.).

The report also provides a perspective on the future actions required to remediate all areas outside the 1F site, where continuing R&D is essential to facilitate return of residents to the most contaminated zones. The knowledge base also needs to be maintained and improved user interfaces developed, to allow it to serve as a tool for both research integration and as a resource for the international community.

Keywords: Fukushima Daiichi, Technical Basis for Strategic Off-site Response, Radiocaesium, Environmental Monitoring and Mapping, Radiation Protection, Decontamination Pilot Project, Waste Management, F-TRACE

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*MCM Consulting

福島第一原子力発電所事故後の環境回復の取り組みで得られた知見と経験の活用

日本原子力研究開発機構　福島研究開発部門　福島環境安全センター

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（2015 年 1 月 9 日　受理）

東京電力福島第一原子力発電所事故に伴い放出された放射性物質の地表への沈着状況等を踏まえ、除染等の環境回復の取り組みが行われてきた。これまでの環境回復の取り組みで得られた知識や経験は、公衆と環境の防護のための防災対策（原子力事故により重大な放射性物質の放出が発生しても公衆被ばくを抑制するように備えること）の技術基盤として整備することにより国内外での活用に資することが期待できる。日本原子力研究開発機構（原子力機構）は、事故直後から災害対策基本法の指定公共機関として活動を開始し、国からの受託による放射線モニタリングや除染モデル実証事業等を実施してきており、国内外の関係機関と協力しつつ環境回復に率先して取り組んできた。

放射線モニタリングとそれに基づく放射性物質の地表への沈着状況等のマッピングでは、住民の被ばく線量の推定や除染の計画立案等のための基本情報を整えた。これを踏まえ放射線防護では、線量の低減目標等を踏まえた被ばく線量推定の考え方に基づく評価を行った。除染モデル実証事業では、適切な廃棄物対策を講じて除染対象に応じた様々な手法や技術を適用し、それらの有効性について評価した。環境中に沈着した放射性セシウムの影響については、雨水による土壌の侵食や風化等の自然現象により徐々に環境が回復してきていることを示すとともに、河川敷きの土壌やダムの堆積物等に蓄積してきていることから、これらのモニタリングを踏まえ適切に管理することの重要性を指摘した。

自然現象による環境回復の進展はこれまで諸外国で経験したものと類似する側面もあり、除染の取組みは環境回復をさらに加速させている。原子力機構が取り組んでいる環境回復に係る調査研究は、避難住民の早期帰還や住民の安全・安心の確保に向けて、環境中での放射性セシウムの挙動の理解を深め、それを踏まえた沈着状況の将来予測や帰還住民の被ばく線量を評価するために鍵となる役割を担っている。環境回復で得られた知識や経験を総合的に取りまとめ、住民等に環境回復の取り組みの全体像を示しつつ適切に対話していくことが求められる。さらに、公衆と環境の防護のための防災対策のための技術基盤の整備のため、事故後の環境回復の取り組みについて俯瞰できるようにまとめておくことが重要である。

本報告書は、国内外での活用のため、主に原子力機構における環境回復の取組みに基づき得られた知識や経験を今後の環境回復の取り組みに向けた検討も含めまとめたものである。

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1.1 The Fukushima Daiichi core damage

The Great East Japan magnitude 9 megathrust earthquake and subsequent tsunami of the 11th March 2011 caused regional devastation along the entire northeast coast of Japan [1]. Despite major loss of life and destruction of infrastructure, the focus of environmental concerns following this event was the series of accidents at TEPCO's Fukushima Daiichi nuclear power plant (commonly referred to as 1F) which led to melt down of reactor cores in units 1-3 and extensive release of radioactivity.

The Boiling Water Reactor (BWR) units 1-3 successfully scrammed as a result of the earthquake. The connected unit 4 was defueled and two other newer units on site were under cold shutdown for planned maintenance at this time. The earthquake did, however, disrupt off-site power and on-site generators switched in to provide required cooling for units 1-3 and the associated fuel storage ponds for each of the units 1-4. The subsequent tsunami was, however, far larger than planned for and over-topped defences, flooding all emergency generators for units 1-4. The resulting total blackout extended beyond the lifetime of emergency batteries, leading to reactor core damage as indicated in Figure 1-1.

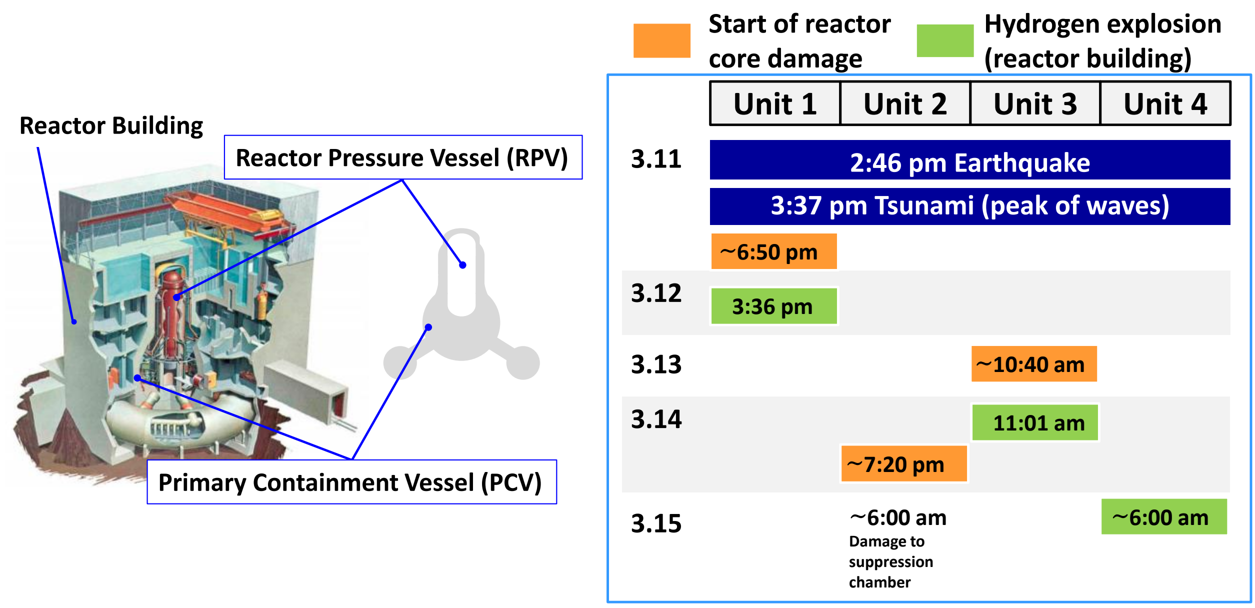


Figure 1-1 Sketch of main reactor structures for the unit 1-4 BWRs and estimated times of major events at the units following loss of on- and off-site power (right [2])

Core damage resulted in hydrogen formation, which in turn led to explosions in units 1 and 3 and, due to connections between the units, and also in the defueled unit 4. The background to the accident, its causes and its progression are described in detail elsewhere (e.g. [2]). It should be emphasised, nevertheless, that due to loss of power and damage to instrumentation, there are still considerable uncertainties associated with interpretations of how the accident developed, which are reported on, in updates provided by TEPCO (e.g. [3]).

1.1.1 Radioactivity releases from Fukushima Daiichi

Due to excessive pressure build-up within the reactor pressure vessels and the primary containment, these had to be vented on several occasions, releasing radioactive gases from stacks on site. This gas also leaked into the secondary containment and resulted in the major explosions that damaged the reactor buildings of units 1, 3 and 4. These events released a significant quantity of radioactivity into the environment. The radionuclides involved were predominantly noble gases and more volatile radionuclides, of which isotopes of iodine and caesium were the most radiologically significant. Because of failures of monitoring equipment, both on and off-site, estimates of total activity releases are associated with considerable uncertainties. Basically two approaches are used, either bottom-up, based on models of the core melt process or back calculation of releases from measured distribution of fallout using inverse modelling (e.g. [4]). Although values are uncertain probably by a factor of about 2, there is reasonable consensus that effectively all of the inventory of noble gases were released – equivalent to about 10 EBq (10^{19} Bq) of short-lived (5 day half-life) ^{133}Xe [5].

Releases of volatile I are lower, with the key safety-relevant isotope ^{131}I (8 day half-life) about two orders of magnitude less, ~ 200 PBq (2×10^{17} Bq). The most important volatile isotopes from the point of view of longer term contamination are ^{134}Cs (2.1 year half-life) and ^{137}Cs (30 year half-life): these were both released at a level of around 15 PBq [5], with the ^{134}Cs/^{137}Cs activity ratio around 1. Iodine and caesium can be transported in air over long distances, falling out onto land or sea as either dry or wet deposition.

Less volatile radionuclides would also have been released to some extent, possibly predominantly as aerosols and maybe associated with the hydrogen explosions. The activities of such releases have greater uncertainties, but have been estimated to be about 1% of the ^{137}Cs activity for fission products like ^{90}Sr and a further 4 orders of magnitude lower for actinides like ^{238}Pu [5]. Even if estimated releases are accurate, aerosols would be expected to be less stable in air and might fall out locally. This is consistent with a limited number of off-site measurements indicating ^{90}Sr activities of up to 4 orders of magnitude lower than ^{137}Cs (e.g. [6]) and extremely low levels of Pu isotopes, which are at a similar level to residual fallout from atmospheric bomb testing and are maybe indicative of transport by dust (e.g. [7]).

In the following sections, the focus is on the off-site contamination resulting from atmospheric deposition of I and Cs radioisotopes, which are the predominant health concerns after an accident. Nevertheless, in the future, particularly on or near the 1F site, a wider spectrum of isotopes may need to be considered. Additionally, in coastal areas, the impact of radioactivity that was released to sea should also be assessed for the sake of completeness. Although marine dilution will quickly reduce concentrations of dissolved radionuclides to negligible levels, continuous monitoring in coastal areas near 1F is required to ease public concern.

1.1.2 Regional fallout of volatile radionuclides

The releases of radioactivity from 1F occurred as a result of a series of specific events (venting, explosions) and the resulting transport and fallout of radionuclides is complex, depending on the weather conditions at the time of each event. The key meteorological characteristic is wind strength and direction, which determines how the radioactive plume develops. Fortunately, the wind was blowing eastwards, towards the open sea, during several of the releases (e.g. [8]). For cases where wind was blowing towards land (Figure 1-2, left), the computed trajectories are complex, illustrating the variability of winds at the time of year. In terms of fallout, the other key weather condition is precipitation (either rain or snow), as this tends to wash out radionuclides from the plume. The quantity and characteristics of fallout will be quite different depending on whether “dry” or “wet” deposition occurred and its subsequent behaviour will depend on the local topography and land use.

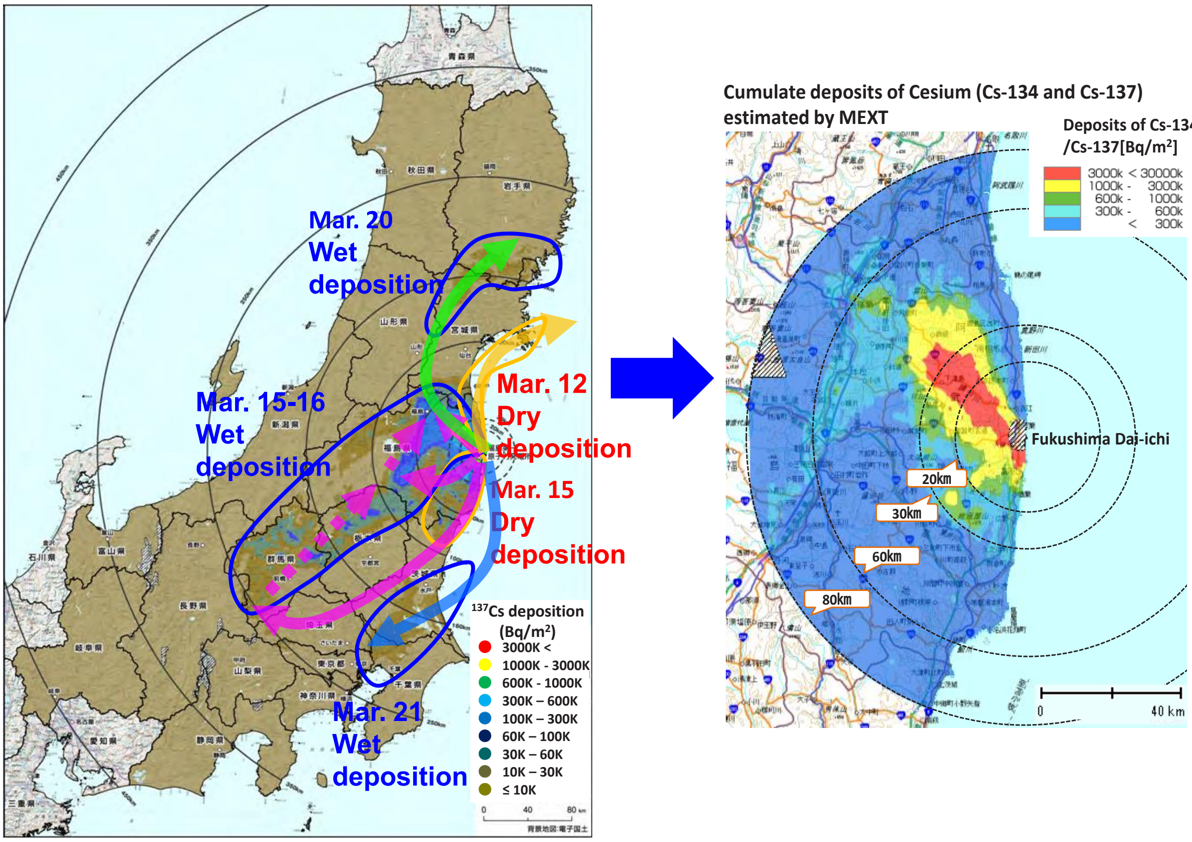


Figure 1-2 Key meteorological constraints on fallout for events leading to significant deposition on land (left [9]) and resultant cumulative deposits of radiocaesium (right [10])

Due to loss of much of the regional monitoring network, the representation of such plumes is predominantly based on atmospheric dispersion models. The expected major areas of fallout are, however, confirmed by maps of cumulative deposits of radiocaesium (Figure 1-2, right): such gamma-emitting radionuclides can be readily surveyed by aerial survey methods, supported by vehicle borne surveys where access is possible. Such maps clearly show highest activities in a zone to the northwest of 1F, with much lower contamination outwith this zone, even close to the stricken nuclear plant.

1.1.3 Contamination in context

From this summary it should be very clear that the releases from 1F were very different in nature to those from the Chernobyl accident. Despite both accidents assigned to the highest category (7, “severe accident”) of the IAEA International Nuclear and radiological Event Scale (INES), the quantity and nature of resultant contamination was very different. Chernobyl unit 4 experienced a power surge during a test shutdown, the core exploded and exposed the graphite moderator, which caught fire and burned for about 2 weeks. A large proportion of the total inventory of radioactivity in the core was dispersed outside the reactor site in the form of fine particulates, aerosols and volatiles in an atmospheric plume, which spread throughout Europe. Extremely high radiation fields and local contamination caused extensive (occasionally lethal) radiation sickness amongst the fire-fighters and other emergency workers who stabilised the remaining core and collected the most highly contaminated debris that was scattered about the vicinity (the remaining 3 reactors at this site continued to operate after the accident). There was also evidence of acute contamination of local populations, especially in the nearby town of Pripyat – which was not evacuated until more than 24 hours after the accident.

The fact that the units were scrammed prior to loss of power and that further time delays occurred before meltdown in the 1F case allowed significant decay of the shortest-lived radionuclides, which contribute most to early radiation fields. Even more importantly, the primary containment at 1F was effective in greatly limiting releases of even volatile radionuclides and ensured negligible loss of the most toxic, alpha-emitting actinides. Thus, although radiation levels were very high within the damaged reactors, exposure to workers was limited and thus helped avoid any case of acute radiation sickness. Releases of noble gases such as ^{133}Xe would have exceeded those at Chernobyl simply due to the larger power of the three 1F units [4]. However ^{133}Xe has little radiological significance as it is very effectively dispersed in the atmosphere and does not fall out or concentrate in the biosphere. Despite the larger reactor power, the total release of non-noble gas isotopes was about 10% of that from Chernobyl [11] and the impact of releases were further reduced by the fact that most of the releases (~ 80%) were dispersed over sea rather than land (e.g. [8]). After decay of radioiodine, the most contaminated areas around 1F are dominated by radiocaesium, with total activity decreasing significantly with time due to decay of shorter-lived, higher specific activity ^{134}Cs. This contrast with the exclusion zone around Chernobyl, which is completely different from Fukushima in that it contains the entire spectrum of radionuclides explosively released from the reactor core and subsequent fires.

With a focus on contamination, therefore, the immediate zone around Chernobyl is a poor analogue of the Fukushima Prefecture. If anything, the distant fallout of volatile radionuclides in Fenno-Scandinavia and the uplands of northern England and southern Scotland would have much more similarity to Fukushima, with the latter also having a more analogous climate (e.g. temperate coastal with significant seasonal storm events). In terms of fallout in the vicinity of a nuclear accident, the Windscale fire of 1957 is more similar to Fukushima than Chernobyl. Indeed, even though rated only as INES 5, the radiotoxicity of Windscale releases may well have been higher than those of 1F due to the highly toxic ^{210}Po also released [12].

1.2 **Responses to the accident**

1.2.1 Boundary conditions

It must be emphasised that the circumstances under which the 1F accident occurred were completely different to past reactor incidents, which occurred in isolation. Despite Japan's world-class reputation for disaster preparedness, the combination of, a giant tsunami caused by the largest earthquake since industrialisation and the melt-down of three reactors formed a "perfect storm", beyond any of the worst cases that had been considered. It has been reported [13] to have resulted in 19,074 deaths, 6,219 injured, and 2,633 people missing across twenty prefectures, as well as about 127,361 houses and residential buildings totally collapsed, with a further 273,268 houses and residential buildings 'half collapsed', and another 762,277 houses and residential buildings partially damaged. The earthquake and tsunami also caused extensive and severe structural damage in north-eastern Japan, including heavy damage to roads and railways as well as fires in many areas, and a dam collapse. Around 4.4 million households in north eastern Japan were left without electricity and 1.5 million without water. This humanitarian catastrophe influenced the availability and priority of emergency response resources and also greatly constrained communication, access and supply of services to both the 1F site and those charged with assessing and responding to radiation releases.

1.2.2 Evacuation

Despite the difficulties listed above, evacuation of populations within a 3 km radius of the plant was ordered within a few hours of the accident and before any releases of activity had occurred (Figure 1-1 and Figure 1-2). This area was expanded with time, as a result of growing awareness of the severity of the accident:

- 10 km radius (morning of March 12)
- 20 km radius (afternoon of March 12); “Restricted Area” (78,000 people)
- 20-30 km radius (voluntary evacuations from March 25); “Evacuation Prepared Area” (60,000 people)

Following aerial surveys and modelling that provided a better overview of local levels of contamination; the basis for evacuation was redefined in terms of a reference level of radiation dose (20 mSv y^{-1}) instead of distance from the plant. This led to evacuation of the community of Iitate, which lay outside the 20 km radius on April 22nd (this area was later termed the “Deliberate Evacuation Area”). Further cases (in Date and Minami Soma) then occurred in June as a result of identification of small locations where radiation levels exceeded the reference level (“Specific Spots Recommended for Evacuation”). These areas are shown in Figure 1-3 (left) along with the current classification of contained communities and the size of associated evacuated populations (right). It should be noted that the “nuclear” evacuees made up about 50% of the total population evacuated as a result of the tsunami, although expectations of being able to return and associated stress are somewhat different for the two groups [14].

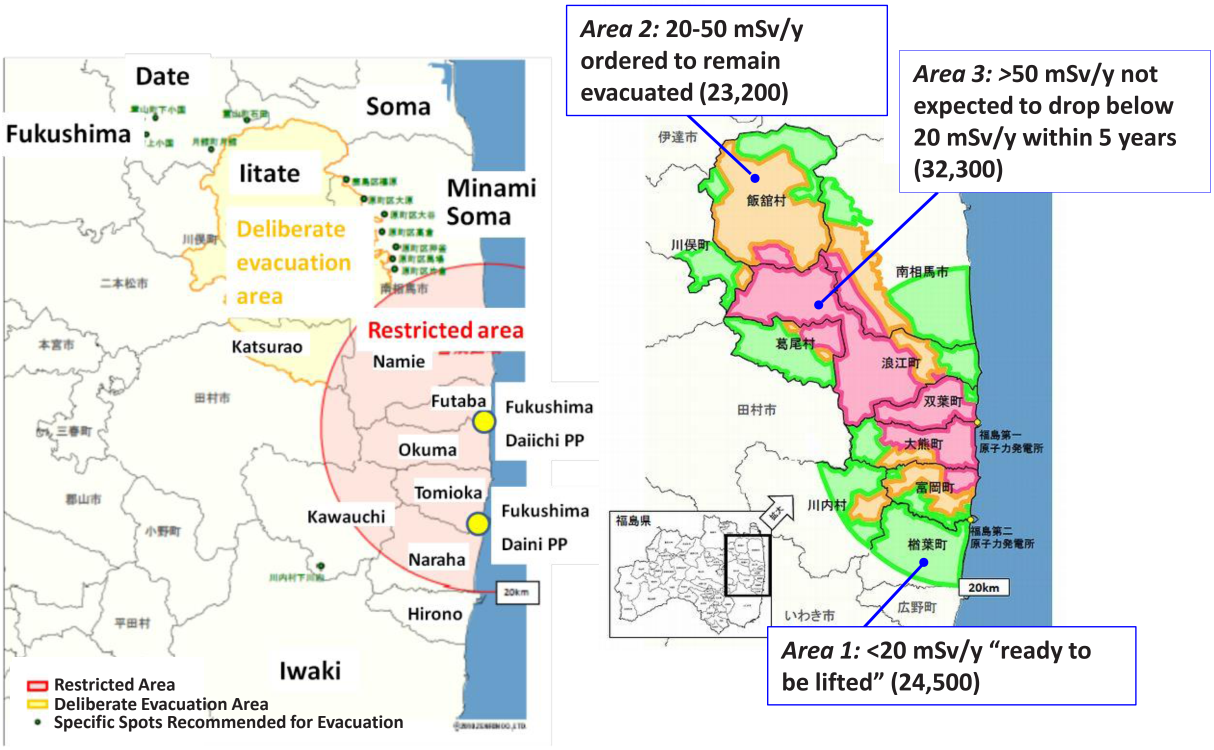


Figure 1-3 Designated evacuation areas as of April, 22 2011 (left [15]) and current classification (as of April 1, 2014), with the size of the associated evacuated population noted (right [16])

1.2.3 Other protection responses

In addition to evacuation, the use of potassium iodide (KI) to reduce the uptake of radioiodine to the thyroid was considered. Although KI was used for 1F workers and emergency response teams, due to prompt evacuation, threshold levels for administration were not reached for the general population. Difficulties of distribution of KI tablets during the period immediately after the accident did, however, highlight problems resulting from the regional loss of transport and communication infrastructure, which had not been taken into account in previous disaster planning.

A further rapid response to reduce radiological impact was imposition of strict regulatory limits on allowed contamination levels in food and water – initially based on assuring that resulting doses remain below a limit of 5 mSv y^{-1} (set on 20th March 2011). This was later reduced to an even more conservative limit of 1 mSv y^{-1} (on 1st April 2012).

As a result of all such measures, there is no indication that anyone either on or off site has died – or will die early – as a direct result of radiation dose received (again a major difference from Chernobyl). Indeed, estimated doses received by members of the public are generally low (in Fukushima Prefecture ranging from between 1 and 10 mSv). Therefore, any increase in an individual's risk of developing cancer (or any other radiation derived medical problem) in the future is also low. This reflects a consensus of both national and international expert organisations that present results suggesting that the increases in the incidence of human disease attributable to the additional radiation exposure from the 1F nuclear power plant accident are likely to remain below detectable levels (e.g. [17] [18]).

Despite the lack of radiological risk, it is clear that the process of evacuation is stressful and caused particular difficulties for vulnerable groups like the sick and the aged – for both "nuclear" and “non-nuclear” evacuees – leading to illness and death (e.g. [14]). Mental stress is now considered to be responsible for the greatest health problems, resulting from the accident [19]:

- Possible loss of or separation from family members
- Loss of property and business or employment
- Health concerns and societal stigma resulting from radiation exposures
- Depression, anxiety and post-traumatic symptoms

Such effects have been previously recorded after radiological accidents and conventional disasters that lead to large-scale evacuation (e.g. during a typhoon evacuation). In Japan, however, which already has a high suicide rate, further increases in the number of suicides is a special concern.

Communication is clearly a key issue. The difficulty of explaining radiation risks to the general public is already well known [14], but was further complicated by the confusion resulting from the complex conditions and communication failures in the immediate aftermath of the accident (e.g. [2]).

As a particular example, the government started communicating relocation and sheltering orders to the public based on 20 mSv y^{-1} (from April 22nd, 2011). It was thus difficult for the public to understand why a dose limit of 1 mSv y^{-1}, which was valid before the accident, could be exceeded after the accident – at a time when people expected to be better protected. In retrospect, it became clear that individuals responsible for informing the establishment of radiation protection guidelines during an accident should have agreed and communicated the technical criteria for establishing such guidelines in advance.

1.2.4 Lessons learned on emergency preparedness

Despite the extremely difficult conditions under which a response had to be developed, the Japanese government was able to substantially decrease radiation exposure risks to the public using standard protective actions. Sheltering in-place was not appropriate in this case (both due to extensive loss of services and physical damage caused by tsunami due to the earthquake and also limited protection provided by traditional Japanese houses). Nevertheless, rapid and stepwise-implemented evacuation, together with food and water restrictions was effective without having to resort to use of KI tablets. Recommendations for improvement in nuclear emergency preparedness identified on the basis of problems experienced to potentially compromise offsite emergency responses to Fukushima-scale events in the United States [19] included:

- Examine contingency planning for scenarios involving widespread loss of off-site electrical power and severe damage to critical infrastructure as part of any emergency preparedness plan
- Examine whether the real-time information regarding the condition of the plants needed to select protective actions would be available for all credible scenarios and, if not, assess how critical information could be determined by indirect methods or how decisions could be made without this information
- Test the effectiveness and scalability of emergency response plans by performing regular exercises at an appropriate scale with simulation of worst case scenario conditions

- Assess the balance of protective actions (e.g., sheltering in-place, evacuation and/or relocation) especially for vulnerable populations (children, ill, elderly and their caregivers) with explicit consideration of not only radiological risks but also social, psychological and economic impacts
- Review and improve existing plans for communicating with the public during a nuclear emergency, with a special focus on assuring messages are clear, consistent and appropriate.

It is important that external consideration of these lessons does not focus on the root causes of the accident – which may be relevant to the Pacific “Ring of Fire”, but less so to many other countries in different geological settings. The bottom line is that consideration of a nuclear emergency within the context of a major regional catastrophe has clearly received too little attention and such scenarios could be developed for any country on Earth, even if the initiating event might be very different (e.g. Katrina-scale hurricane, pandemic disease, war or civil conflict,…). Because of the novel conditions resulting from over-population, natural resource depletion, climate change, etc., basing scenarios on historical precedence can also be dangerous and it should be assured that the role of high impact scenarios is adequately assessed, even if their probabilities are low or even unknown [20].

1.3 Accident recovery

1.3.1 Initial ad hoc actions

Due to public concern, decontamination activities were rapidly initiated outside of the evacuation zones with a focus on high-sensitivity areas, such as schools and playgrounds. This was not based on any specific technical criteria, but simply a result of the fact that the presence of radiocaesium or enhanced gamma radiation is easy to measure with simple equipment. As initial fallout is predominantly associated with surfaces, reduction in local dose rate could be achieved by simple measures such as washing roofs, walls and impermeable surfaces, cutting and removing grass and foliage, removing surface soil layers, etc. There was little assessment of the impact of such actions on reduction of dose: the emphasis was more on improving the peace of mind of residents.

These decontamination activities were carried out primarily by local groups, mainly volunteers and local council employees, coordinated at a community or municipality level. Any required technical support for these activities was provided by organisations such as JAEA. Although there is some photo-documentation of such actions, there was no structured attempt to assess the cost-benefit of the different decontamination approaches used.

In the early time after the accident, actions were taken to remove contaminated material on-site to central stores in order to reduce doses to workers, but no actions were taken within the evacuated zone. There, the Self-Defense Forces, with the cooperation of the Ministry of the Environment, etc. conducted decontamination of the municipal offices of Naraha Town, Tomioka Town, Namie Town and Iitate Village (during December 7- December 19, 2011), which provided the bases of full-scale decontamination activities started in or after January 2012 as a project directly controlled by the Ministry of the Environment. Such a delay did, however, also allow very short-lived radionuclides (half-life of hours or days) to decay into insignificance (especially the biologically accumulated radioiodine), short-lived isotopes to decay significantly (especially ^{134}Cs) and self-cleaning processes to remove significant quantities of even long-lived isotopes from the accessible environment.

1.3.2 Regulatory basis for remediation of evacuated zones

A key component of preparation for clean-up of the evacuated zone was the establishment of the required regulatory basis, in particular the "Act on Special Measures Concerning the Handling of Radioactive Pollution" (promulgated in August 2011). This established a defined special decontamination area, consisting of the Restricted Area and the Deliberate Evacuation Area (**Figure 1-3**, left). This zone was later further subdivided into three areas based on the extent of contamination, which is very conservatively converted into an equivalent annual dose (August 2013: Figure 1-4, right):

- Area 1: < 20 mSv "ready to be lifted"
- Area 2: 20-50 mSv "ordered to remain evacuated"
- Area 3: > 50 mSv "not expected to drop below 20 mSv y^{-1} within 5 years".

Additionally "intensive contamination survey areas" were established, which included all other contaminated areas which would give rise to doses in the range of 1-20 mSv y^{-1}. The fundamental policy is summarised in Figure 1-4.

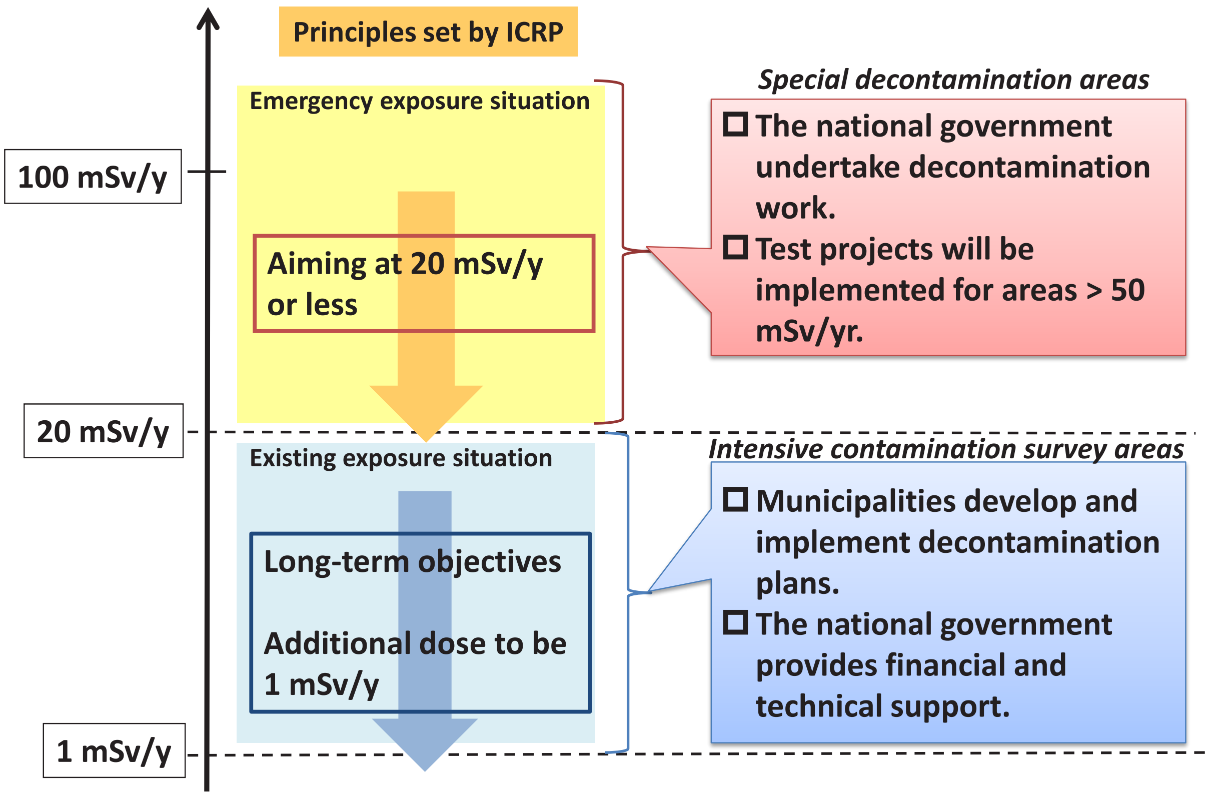


Figure 1-4 Illustration of the basis for the remediation policy

Specified decontamination of such areas is defined to include the cleaning of structures and removal of contaminated soil. The resulting removed soil and other contaminated wastes are to be stored at the remediation locations or at temporary sites, within about 3 years [21]. The National Government shall make utmost efforts to start the operation of the interim storage facility within about 3 years from the start of the full-scale transfer of the soil or waste to temporary storage facilities. Thereafter, contaminated soil and waste are to be gathered and placed into interim storage facilities until transferred to a long-term disposal site outside of the Fukushima Prefecture.

In order to go further and develop more specific guidelines for decontamination activities, existing generic guidelines on clean-up of contaminated land needed to be refined and tailored for the specific conditions in the Fukushima Prefecture. JAEA was thus chosen by the Government to conduct decontamination pilot projects (DPP) at 16 model sites in 11 municipalities, including the evacuated zones (September 2011-June 2012). The main challenges to implementation of full-scale decontamination were lack of both real-world examples of such work in relevant environments and also experience for planning and implementing decontamination technology appropriate to Japanese boundary conditions.

The decontamination pilot projects were extensively documented in Japanese [22] and have been summarised in English [23] [24]. Although emphasis was on in-situ tailoring of simple manual clean up approaches and commercial power tools to approach this challenge (Figure 1-5), further laboratory R&D also investigated the potential of alternative approaches to both surface decontamination and reduction in volume of resulting wastes. The DPP was tightly constrained in terms of the time and resources available, but served to:

- Check the availability and efficiency of both proven and new techniques and tools
- Investigate pros and cons of different approaches in terms of cost, work period, workforce, waste generated and radiation exposure of workers
- Establish waste management procedures, including volume reduction of wastes and treatment of any secondary waste produced
- Develop and test approaches to assure worker safety, providing appropriate radiation protection without compromising protection from conventional hazards associated with such work
- Establish optimal radiation monitoring technology to quantify levels of contamination of clean up targets before, during and after such work and also in resulting wastes
- Develop and record the required public communication to gain the permissions needed to allow decontamination to proceed and also explain the outcome of the work to the communities who would return to these locations.

Figure 1-5 Typical examples of decontamination actions during the DPP

The resulting knowledge base played a key role to support drafting of guidelines and manuals that can be used by the national government and local municipalities to optimise regional remediation work. Such manuals specify:

- Methods of investigating and measuring the status of contamination in specific surveyed areas
- Measures for decontamination and dose reduction
- Collection and transportation of removed soil and any other contaminated material or secondary wastes
- Storage of removed soil and other wastes.

A 1st Edition of the guidelines was issued in December, 2011. This was, however, recognised to be a “living document” and hence was followed by a 2nd Edition [25], expanded on the basis of knowledge and new technology obtained subsequently, issued on May, 2013. Further, on December, 2013, an Addendum focused on the important topic of Forest Management was issued.

1.3.3 Progress in decontamination

Although it has received little media coverage, decontamination work has been progressing steadily and, by the end of March 2014, about 50% of the planned clean up area in the special decontamination area had been covered. These initially targeted areas had lower levels of contamination (generally equivalent to < 20 mSv y^{-1}). Considering radioactive decay and self-cleaning, together with an average 40% dose reduction in inhabited areas due to the remediation actions, radiation exposure will be sufficiently low for evacuation orders to be lifted in the near future. Nevertheless, dose reduction alone is not sufficient to support the decision by evacuated populations to return, it will also be necessary to restore damaged infrastructure and abandoned services to provide a suitable living environment. This requires active communication and establishment of dialogue between the prefecture, municipalities and local inhabitants. Based on current planning, evacuation orders for much of this area will be lifted within the next couple of years (Figure 1-6).

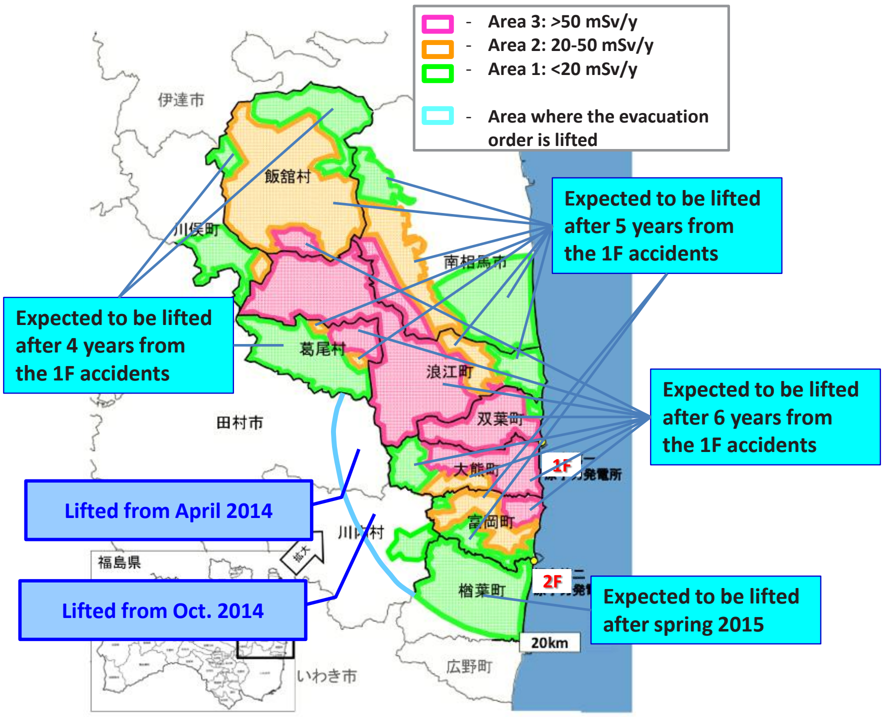


Figure 1-6 Expected dates for lifting the evacuation order (based on evacuation areas as of October, 1 2014 [26]) due to progress in the regional decontamination work

Work is now on-going or about to start in areas with higher contamination, equivalent to annual doses in the range of 20-50 mSv y^{-1}. This will be more challenging and, in general, the dates for lifting evacuation orders for this region have not yet been specified. No plans have been developed for decontamination of the highest dose areas (> 50 mSv y^{-1}) except decontamination model projects at 4 sites in Namie-town and 2 sites in Futaba-town in area 3 implemented from October 2013 to January 2014 [27], although the defined policy is that these will be remediated as soon as is practical after 5 years.

1.3.4 Waste management

One of the greatest challenges in decontamination is management of the huge quantities of resultant waste – estimated to be potentially in the order of 20 M m^3 [28]. As already considered in the DPP work, volume reduction is a key goal – either by reducing production of waste (e.g.

achieving required reduction of doses by deep ploughing of contaminated soil) or by recycling / reuse of material in which contamination is strongly bound (e.g. as ballast in construction projects). The former is, however, constrained by site characteristics (e.g. depth of hard pan) while the latter is limited by restrictions of movement of contaminated material. Nevertheless, there is great potential for reducing volumes if both public acceptance and the appropriate regulatory infrastructure can be gained (1st Cs workshop [29]).

A large fraction of the current waste arising from clean up comprises soil and vegetation contaminated with varying levels of radiocaesium. It would be possible to reduce volumes of vegetation, in particular, by incineration, as Cs is retained in the resulting ash: the problems here involve the cost and limited availability of suitable incineration plants and the high mobility of Cs in ash – which requires it to be immobilised prior to disposal.

During initial decontamination, waste and contaminated soil is stored on site in temporary facilities. Even within 3 years such storage is required to be monitored due to the instability of the material stored (both vegetation and organic-rich soil will biodegrade, producing gas, acidic leachates and volume changes that can disrupt storage structures) and the environmental conditions to be considered (earthquakes, typhoons, wet / dry and hot / cold cycles, etc.).

After temporary storage, specified waste can be sorted based on level of contamination and prepared for either conventional disposal (< 8 kBq kg^{-1}), "controlled disposal (< 100 kBq kg^{-1}) or placed in interim storage (> 100 kBq kg^{-1}) and all of the soil from decontamination in Fukushima Prefecture will be placed in interim storage, prior to disposal at a location outside Fukushima Prefecture within 30 years.

Although the siting and permitting processes have been underway, the Ministry of the Environment has identified potential storage locations situated in the vicinity of 1F [30]. For such locations, conceptual facility designs have been developed and tailored to site topography (e.g. [31]).

The period for the store is up to 30 years, so concepts of structure of storage facility is specified to ensure both radioactivity containment during storage and also ease of retrieval. To optimise operations and ensure stability of the emplaced material during storage, received soil and decontamination waste will be separated by type and contamination level, volume will be reduced to the extent practical (primarily by incineration) and then conditioned / packaged as required.

1.4 Goals and content of this report

The following chapters provide input for the international use of knowledge and experience gained from the Fukushima Daiichi accident in order to establish the technical basis for strategic, off-site response to nuclear incidents (outline illustrated in Figure 1-7).

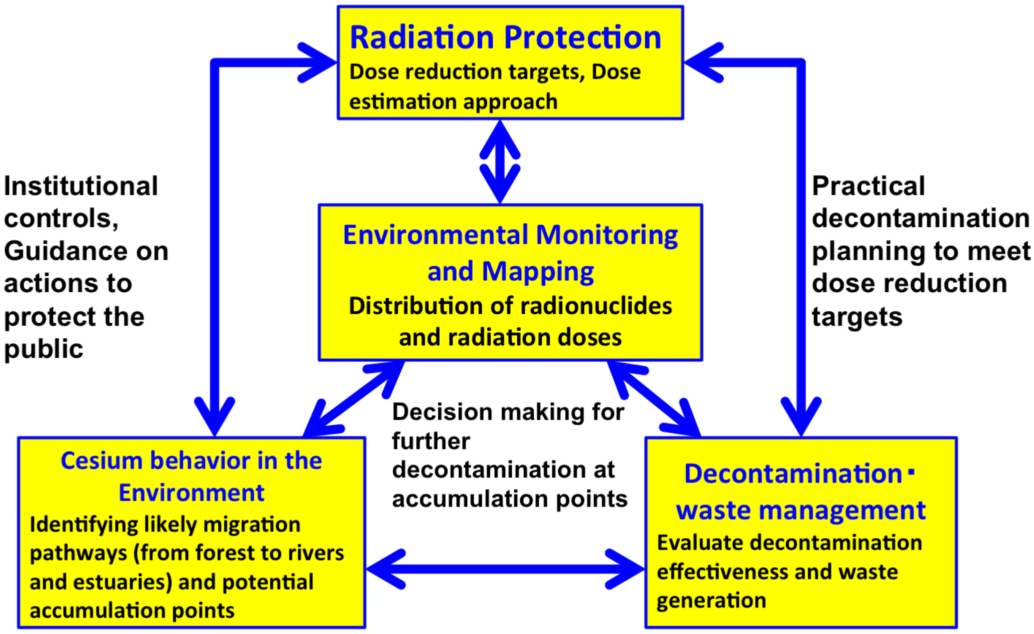


Figure 1-7 Overview of the contents of this report

The following Chapter describes the central role of environmental monitoring and mapping, which define the boundary conditions in terms of the distribution of radioactivity and resultant doses and thus guides the resultant response. Chapter 3 then outlines the constraints set by radiation protection, including approaches to estimate doses to different critical groups and set appropriate dose reduction targets. Chapter 4 overviews decontamination activities, with special emphasis on associated waste management. This includes experience in evaluation of the effectiveness of decontamination and the pros and cons of different approaches / technology. Chapter 5 considers the assessment of the natural behaviour of contaminant radionuclides and their mobility in the environment – here with special emphasis on radiocaesium. Here the impact of such natural mobility in terms of self-cleaning / re-concentration of cleaned areas is discussed along with possible actions to modify such transport or manage potential accumulation areas. The final concluding chapter summarises this experience with emphasis on the links between the main topics in terms of guidance, response planning and associated decision making. It also provides a perspective on the future actions to remediate all areas outside the 1F site.

The following explicit constraints on this report should be noted:

- It considers only technical aspects, as socio-political factors are considered too country-specific to be of general applicability.
- It focuses on specific activities rather than the work sequence in order to widen general applicability to possible future incidents with different boundary conditions.
- It takes over experience from Fukushima off-site work only, but notes associated limitations by reference to other sources of experience with different boundary conditions.

As this recovery work will continue over decades, the present report should be considered as a “living document”, which will be updated as further experience and knowledge is gained.

2 Environmental monitoring & mapping

Characterisation and mapping of fallout is an essential pre-requisite to initiating public protection measures and, subsequently, planning and implementing remediation actions. For the specific case of 1F, this is simplified because the radionuclides of greatest concern are gamma emitters and hence can be easily detected by a wide range of easily available equipment. The very availability and sensitivity of such equipment does, however, lead to some special communication issues: the fact that gamma rays are measurable is not equivalent to there being risks to health. This will, however, be discussed further in section 4.3. This section will focus on specific technical applications of radioactivity mapping at both regional and local scales, including:

- Radiation surveys
- Associated distribution modelling
- Structured evaluation of radionuclide distributions
- Assessing radionuclide distributions in terms of doses.

2.1 Radiation surveys

To estimate the impact of the accident and take appropriate countermeasures, it was necessary to obtain reliable and detailed information on contamination levels around the 1F site as quickly as possible – particularly because much of the original fixed emergency radiation monitoring network had been knocked out by the earthquake and tsunami. The usual method for characterising radionuclide fallout involves aerial surveys that monitor the gamma radiation, and the technology for this is well established for accident conditions [32]. In fact, it transpired that this approach was especially relevant to this accident, as the releases were completely dominated by volatile radionuclides and, discounting the radiologically insignificant noble gases, the key isotopes initially were thus ^{131}I, ^{134}Cs and ^{137}Cs, which are all gamma-emitters (simplified decay data in Table 2-1).

Table 2-1 Properties of key radionuclides

Isotope	Half-life	Gamma (keV)	Beta max (MeV)	Comment
^{131}I	8 days	364, 637,…	0.6, 0.8,…	Special concern due to concentration in the thyroid
^{134}Cs	2.1 years	605, 796,…	0.7,…	Because of the range of higher gamma energies, initially contributes more to measured dose than ^{137}Cs
^{137}Cs	30 years	662	0.5, 1.2	Gamma actually from short-lived daughter ^{127m}Ba

Immediately after the accident, an area of northeast Japan centred on 1F was surveyed aerially by a joint team from Japan (MEXT) and the US (DOE and USJF). This allowed a Deliberate Evacuation Area northwest of the site to be defined as a general area with an estimated external gamma dose rate greater than about 20 mSv y^{-1} (previously discussed in section 1.2.2).

Although such aerial surveys can be carried out rapidly, conversions of measurements to surface doses are associated with considerable uncertainties, especially for the complex terrain within the Fukushima Prefecture (variable topography and land use, extensive forest cover, areas with considerable tsunami damage). It was thus critical that these were supported and calibrated by more localised ground surveys with vehicle-borne equipment, complemented by focused point measurements and contamination sampling for laboratory analysis.

MEXT (responsible for national-scale mapping projects, which was taken over by the NRA) and JAEA have continued to perform aerial and ground surveys on a regular basis, establishing correlations between measurements made with a diverse range of techniques and equipment, as summarised in the following sections.

2.1.1 Aerial surveys

Aerial surveys initially focused on large, manned helicopters, but later also included utilisation of a range of remotely controlled, low flying aircraft. The characteristics of these different platforms are summarised in Table 2-2.

Table 2-2 Characteristics of different airborne survey systems

Survey area	Regional > 1000 km^2	Semi-regional > 100 km^2	Local > 1 km^2	Small < 1 km^2
Option	Manned helicopter	Unmanned airplane (UARMS)	Unmanned helicopter	Micro unmanned aerial vehicle (UAV)
Altitude	～300m	～150m	～50m	<10m
Features	Standardised methodology available for efficient regional surveys	Allows remote controlled long-time flight (e.g. 6hrs) Under development	Higher resolution mapping available	Allow focused surveys, e.g. above urban areas or in forests Under development
Illustrations				

There is clearly a trade-off between the ability to survey larger areas with a manned helicopter and the higher resolution available from lower-flying unmanned airplanes (drones) or remote-controlled aircraft (Figure 2-1). Other factors that may need to be taken into account in higher radiation zones include the potential dose to aircrew or remote vehicle operators.

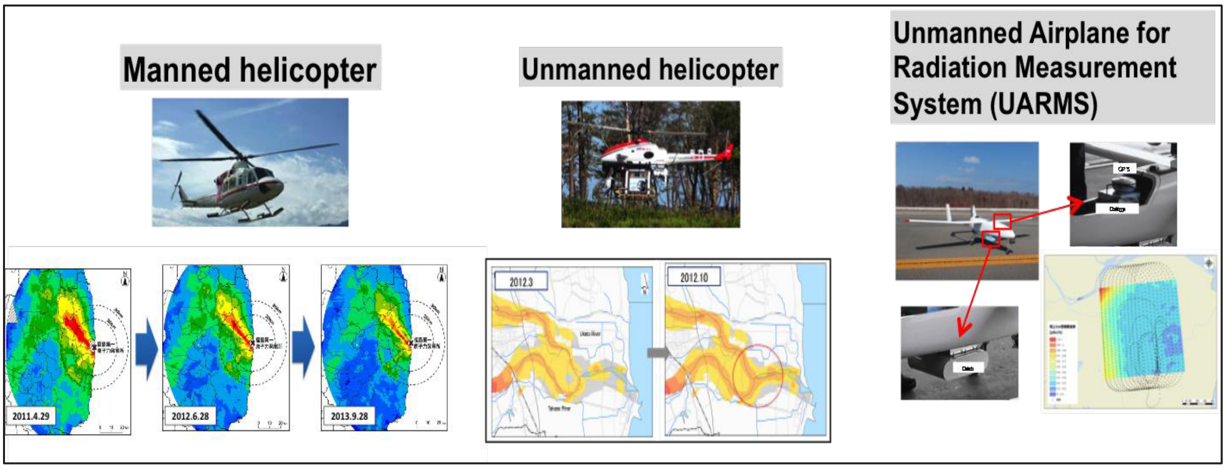


Figure 2-1 Typical survey results from different aerial measurement platforms

The principles of aerial gamma surveying are illustrated in Figure 2-2. The detector is generally a high efficiency scintillator (e.g. NaI(Tl)) or, occasionally, a high energy resolution semiconductor detector (e.g. CdTe), which is positioned within (or held below) the aircraft. The gamma spectrum is logged for a set time period and linked to a GPS system, while the aircraft flies at constant speed and height (to the extent that this is possible due to terrain and weather conditions). Spectral stripping allows the gamma contribution from radiocaesium isotopes to be quantified and then this can be converted into a map of excess gamma dose or estimated radiocaesium distribution using standard assumptions of homogeneous fallout and a flat terrain over the area sampled during the spectrum accumulation time.

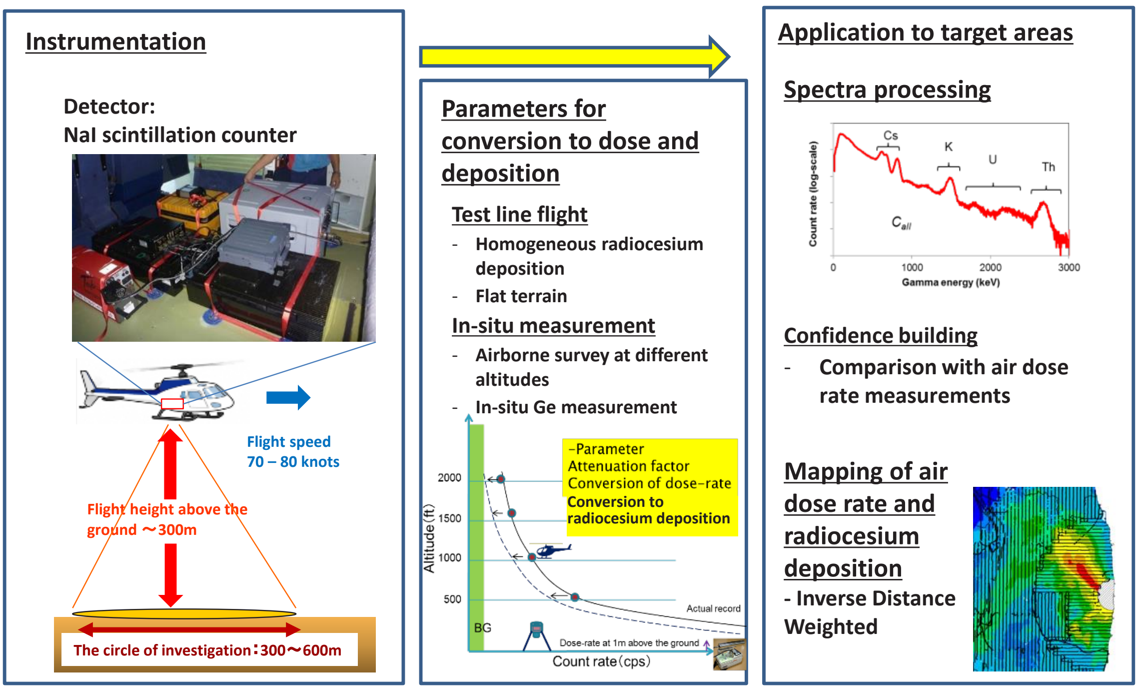


Figure 2-2 Principles of aerial gamma surveying

Regional surveys in the Fukushima area are clearly limited due to the complexity of the terrain, but repeated surveys give a clear picture of relative changes in contamination (Figure 2-3). Although the trend of decreasing dose is obvious, this can be difficult to interpret.

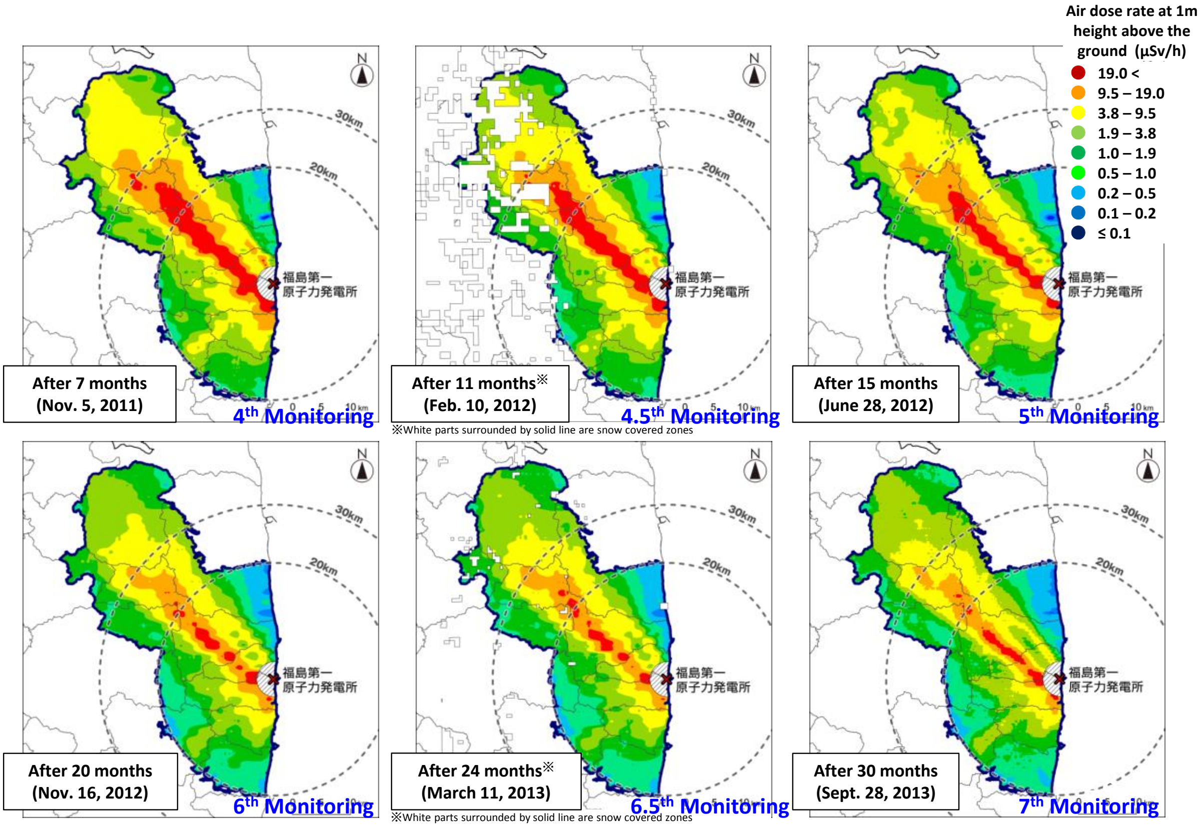


Figure 2-3 Results from repeated aerial gamma surveys on a regional scale (using map data in ArcGIS) [33]

One complication is clear from the maps produced 11 and 24 months after fallout occurred, where white areas indicate the presence of snow cover. Although the half-distance of ^{137}Cs gammas in air is about 70 m (distance required for absorption to reduce dose rate by a factor of 2), the half distance in water is only about 10 cm – thus thick layers of snow can significantly reduce measured gamma fluxes. Such effects are also caused by flooding or, in the case of Cs contained within a soil column, the degree of water saturation of the soil – significant factors in areas where rice is farmed in paddy fields, for example.

Despite such caveats, the trends for the entire region can be presented quantitatively, as in Figure 2-4. It is clear that the measured decrease is significantly greater than would be expected from radioactive decay alone (indicated by the red line).

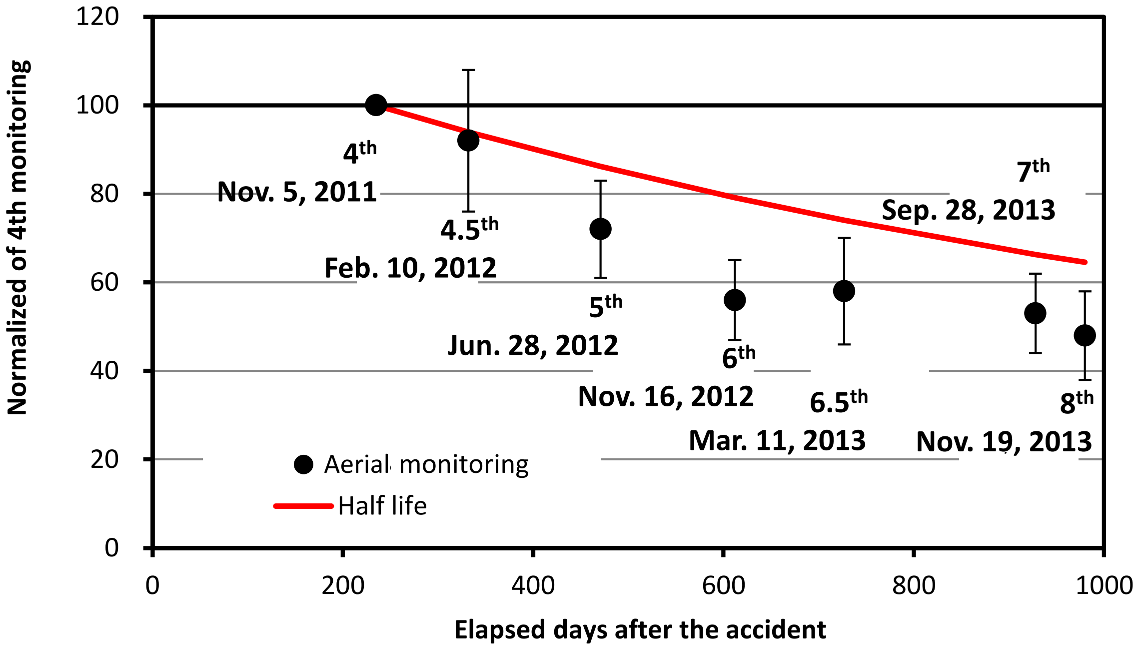


Figure 2-4 Trend of time variation in mean dose rate from the aerial surveys in evacuation areas, (normalised to the survey on November 5th 2011) compared to that expected from radioactive decay alone (red line) [33]

The reasons for this could include both ongoing clean-up actions in some areas, but also natural processes causing mobilisation of radiocaesium, e.g. removal by runoff, transport from tree crowns to litter or from surface to depth. Although these cannot be disentangled entirely without detailed studies on the ground, further details can be derived from focused studies of smaller regions with remote-controlled aerial monitoring systems. These have the advantages of being able to fly lower in more complex terrain than a manned aircraft and also collect data from areas where there might be a radiation risk to flight crews.

A good example of an application of remote controlled aerial gamma mapping of smaller areas involved surveys of the immediate vicinity of 1F conducted by JAEA (Figure 2-5).

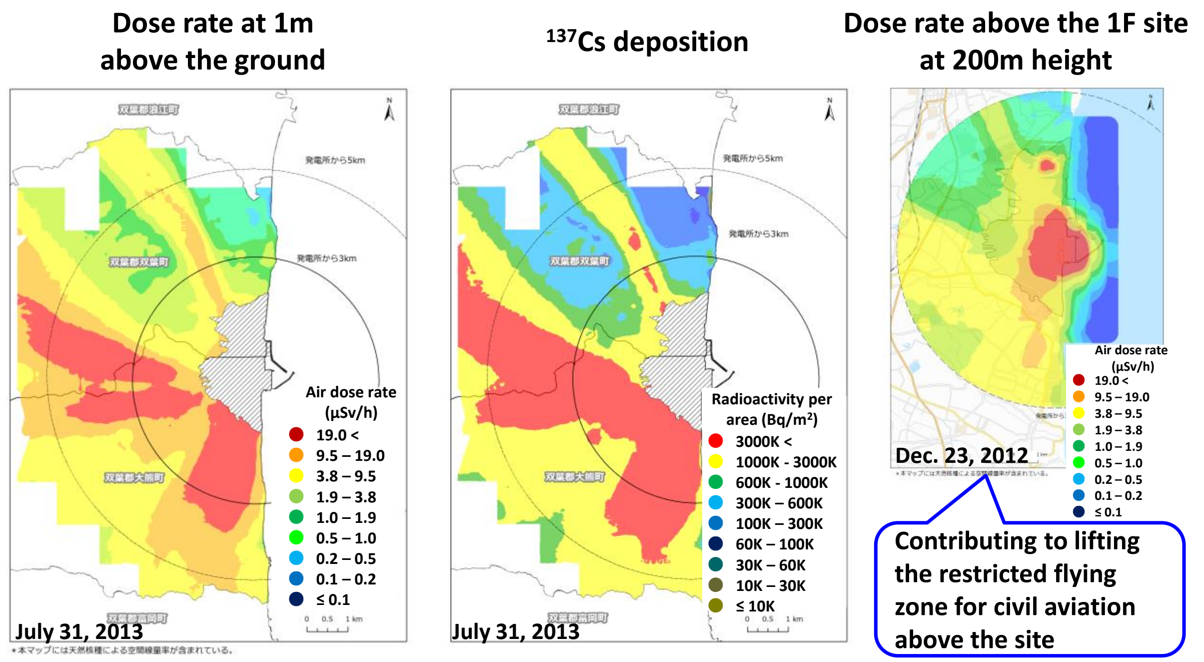


Figure 2-5 Examples of detailed measurements made by unmanned helicopter around the 1F site [34] [35]

Measurements directly over the plant in December 2012 contributed to lifting the restricted flying zone for civil aviation above the 1F site (Figure 2-5, right). Subsequent surveys allowed more detailed measurement of local dose rate distribution, which can also be interpreted in terms of ^{137}Cs contamination levels. Such small area surveys are particularly useful for measuring redistribution of contamination – e.g. as indicated in Figure 2-1 (middle image), where erosion and deposition of contaminated sediments in a flood plain can be seen.

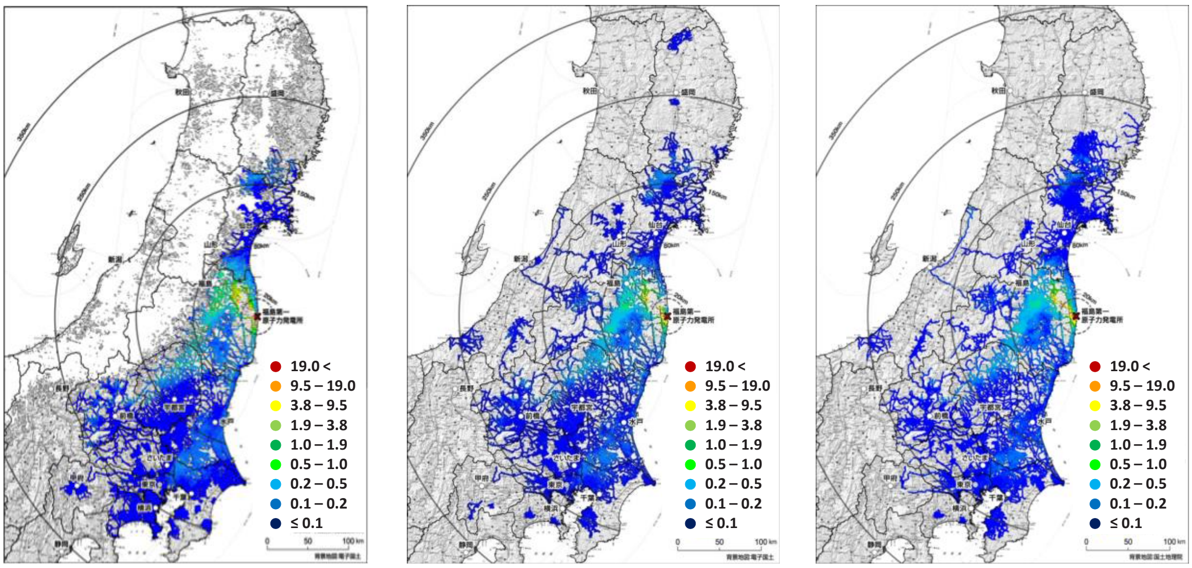
2.1.2 Surveys using road vehicles

A complementary approach to measurement of gamma dose rates from the air involves detector systems mounted in road vehicles. For example, gamma dose rates on roads were continuously measured by car-borne survey using the KURAMA system developed at Kyoto University (Figure 2-6).

Figure 2-6 Example of mobile gamma radiation monitoring system

Since the system is compact and easy to operate, a few hundred municipalities in potentially contaminated areas were asked to perform car-borne surveys using this equipment. The linked GPS system and mapping software allows integration of output to derive regional dose rate maps as shown in Figure 2-7. This not only allows distant areas with low contamination to be identified, but also confirms negligible fallout in most of the region surveyed.

Air dose rate at 1m height from the ground (μSv/h)



(from Dec. 2011 to March 2012) **(from Nov. 2012 to Dec. 2012)** **(from Nov. 2013 to Dec. 2013)**

Figure 2-7 Examples of dose rate maps derived from road vehicle surveys over large areas of northeast Japan [36] [37]

As with aerial surveys, data from car-borne detectors can be interpreted more easily in flat, featureless terrain, but is complex in the rugged topography, built-up areas and extensive forests typical of this region. Nevertheless, repeated surveys indicate trends in dose reduction due to decay, decontamination and natural "self-cleaning" processes.

2.1.3 Manual point measurements and small area surveys

Although much more manpower and resource intensive, the survey methods outlined in 2.1.1 and 2.1.2 above need to be complemented by manual field measurements and direct contamination measurements. Dose rates in air were measured by survey metres at 1 m above ground at several thousand locations; in general, flat fields expected to be undisturbed for an extended time were selected in order to investigate temporal changes in air dose rates due to natural weathering effects. As can be seen from the integrated maps presented in Figure 2-8, the measured distributions generally match those from the other survey methods and also show a trend of reducing dose rates with time.

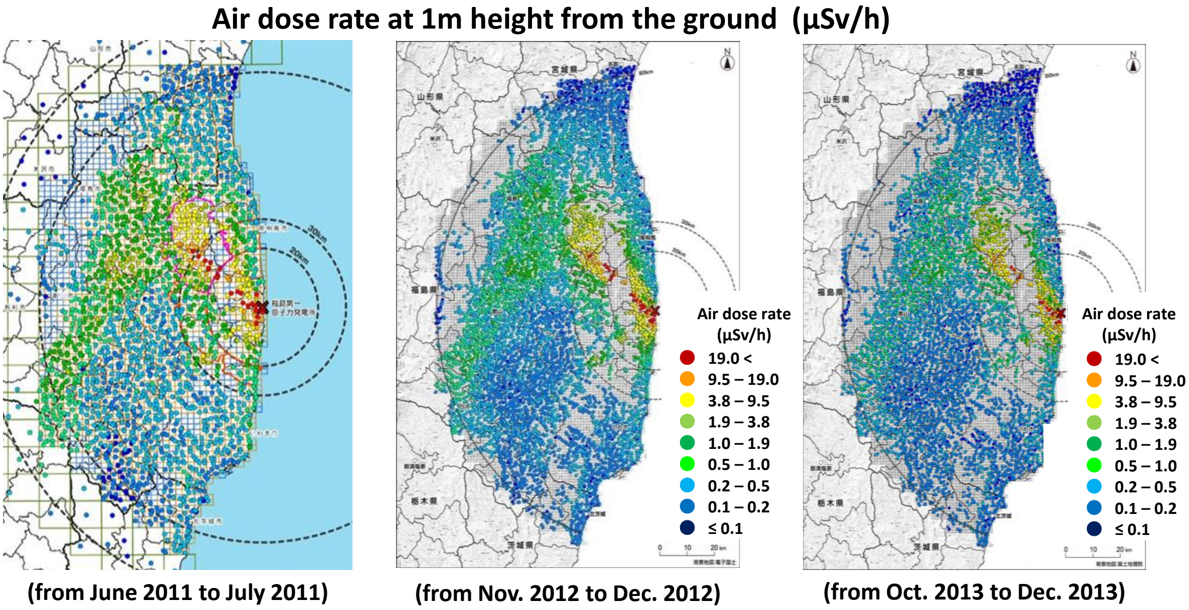


Figure 2-8 Examples of maps of point dose rate measurements made over different time periods in and around the area of 1F [38]

It can also be seen that, at early times when field work was restricted to a limited time, the sampling density was lower than is the case at later times. The time sequence of such measurements (Figure 2-9) shows an interesting contrast to that from the aerial surveys (Figure 2-4): here the decrease in activity of the 2 radiocaesium isotopes follows closely expected radioactive decay curves. This indicates that, in undisturbed flat fields, Cs mobilisation is negligible – a different situation to urban areas.

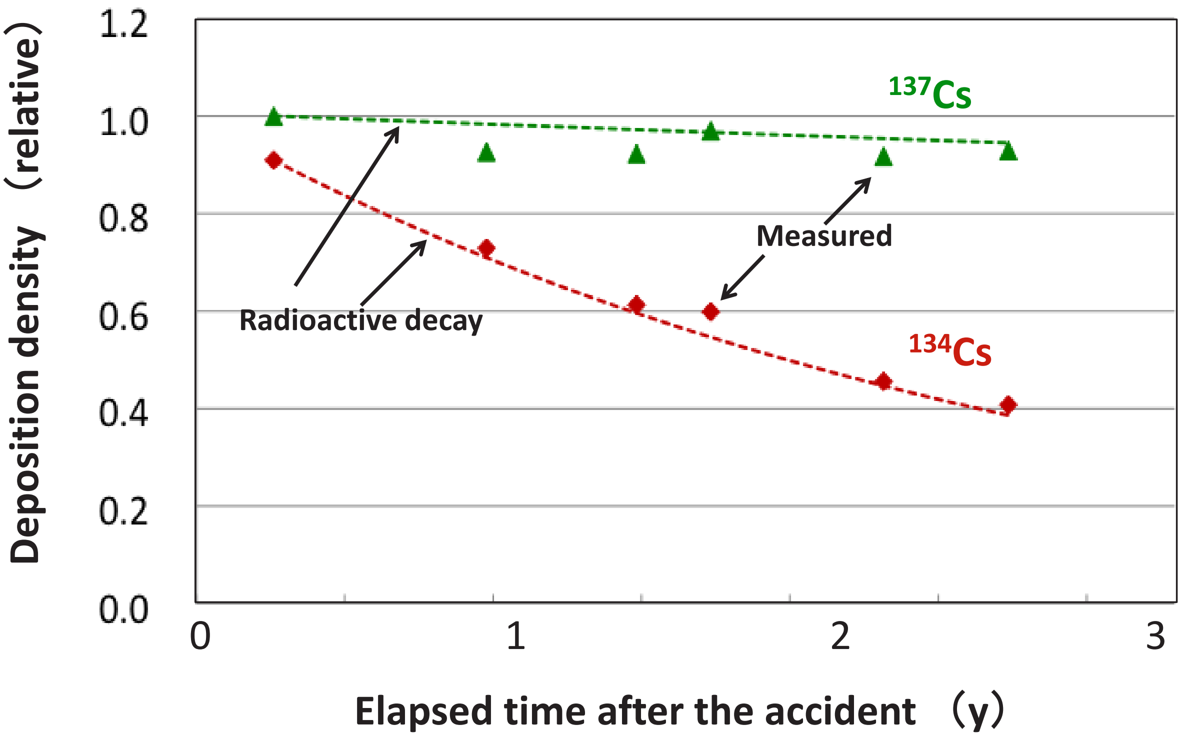


Figure 2-9 Measured average inventory (Bq m^{-2}) in flat fields as a function of time

Such measurements under well-controlled conditions can be used to calibrate gamma scanning methods. In addition, an option for scanning small areas of ground that are difficult to access involves manual backpack or "buggy" mounted equipment [23]. Although such equipment is mainly used within decontamination pilot projects, it has also been used to map dose rate distributions to support interpolations between point measurements and also to check for the existence of localised "hot spots" that can be missed by sparse measurement grids.

Although gamma dose point measurements give better defined data than survey methods, a number of assumptions are still needed to convert these into radionuclide contamination levels. Therefore, ~ 11,000 soil samples were collected at some 2,200 locations around the 1F site, which were analysed by high resolution gamma-ray spectrometry (using intrinsic Ge semiconductor detectors) at 21 different laboratories (from June through November 2011). To ensure reliability of the analysed data, an intercalibration was performed using standard samples; good agreements in estimated nuclide concentrations were observed among the participating institutes [39]. An example of a map of resultant output is shown in Figure 2-10, which represents directly measured fallout of ^{137}Cs, presented as Bq m^{-2}. Over the long term, this is clearly the most relevant isotope from the point of view of radiation risk. Similar maps were produced for ^{134}Cs, showing its faster decrease in concentration due to its relatively short half-life (2.1 years).

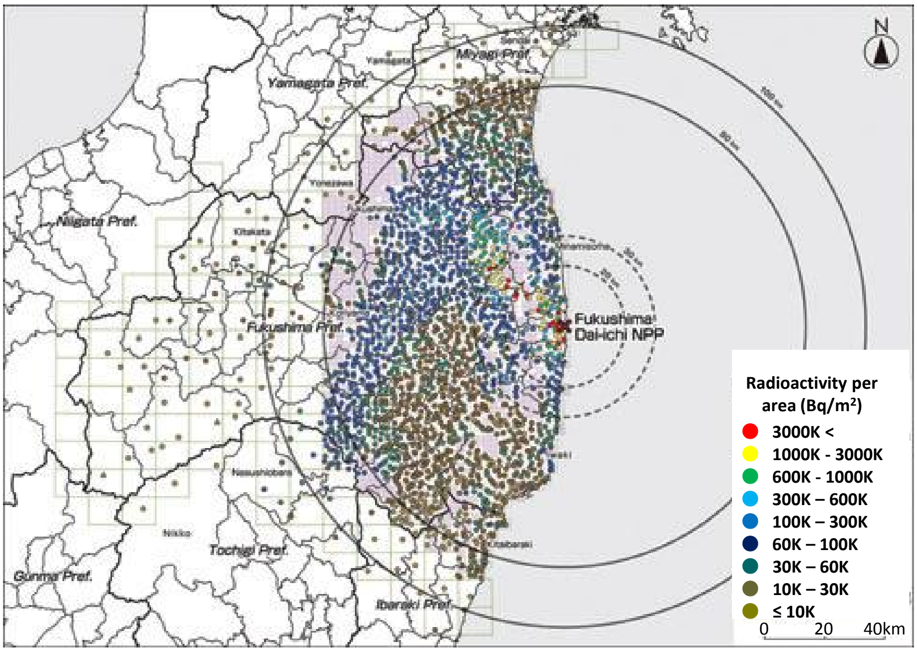


Figure 2-10 Map of measured values of ^{137}Cs deposition (decay corrected to a reference date of 14 June 2011) [40]

Maps were also produced for other measured gamma-emitters: ^{131}I and also some isotopes released only at much lower levels, in particular ^{110m}Ag and ^{129m}Te (half-lives 250 and 34 days, respectively). Despite large releases, due to its short half-life (8 days), ^{131}I quickly decayed to insignificance. Nevertheless, in a few hundreds of locations near 1F where these 3 isotopes could be measured, their activity ratios showed interesting trends. Activity ratios of ^{131}I and ^{129m}Te to ^{137}Cs are high in areas south of 1F, while those of ^{110m}Ag to ^{137}Cs are high in north-western areas. This is indicative of the differing characteristics of the releases that occurred at various times, from the different reactors.

In addition, alpha- and beta-emitting radionuclides were measured in ~ 100 soil samples selected in each campaign (from December 2011 through June 2012: [40] [41]). The number of measurements was restricted by the much greater time and effort needed for the chemical processing required to make such measurements. Nevertheless, deposition density maps were produced for the potentially hazardous isotopes ^{238}Pu, $^{239+240}$Pu, ^{89}Sr and ^{90}Sr. Although these radioisotopes could be measured in a few tens of samples, activity levels were generally extremely low. Indeed, the Pu isotope ratios indicated that the measurements actually reflected releases from 1F, but which resulted in comparable concentration in soil with remnants from nuclear weapons tests last century (e.g. [42]). In situ spectrometry using portable Ge detectors has the advantage of quantifying the average deposition density of radioactive nuclides by detecting the gamma rays coming from a wide area around the measurement location. Therefore, this method has been used since November 2011.

2.1.4 Synthesis

The survey methods outlined in the 3 sections above are complementary and contribute to managing initial accident response and also understanding the distribution and characteristics of contamination as a guide to planning subsequent decontamination or remedial actions. For example, Figure 2-11 integrates time series measurements from different survey methods, which indicates that the different approaches are picking up the signatures of different aspects of radiocaesium behaviour – especially when compared to the Cs inventory data presented in Figure 2-9. This will be discussed further in section 2.3 below.

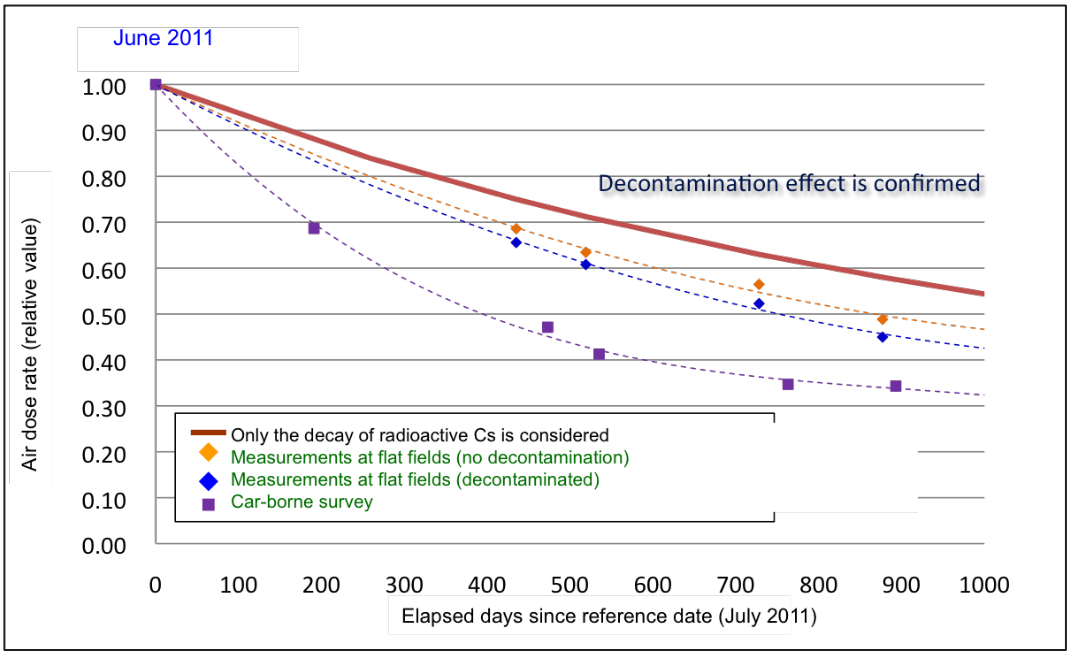


Figure 2-11 Variation of dose with time from different series of measurements

2.2 Fallout distribution modelling

The System for Prediction of Environmental Emergency Dose Information (SPEEDI) network system operated by MEXT is a key tool for calculating air concentrations and dose rates in the case of a nuclear accident [43]. Under expected conditions, SPEEDI would integrate data from on and off-site radiation measuring equipment with meteorological information to develop forecasts of expected radiological consequences.

Unfortunately, due to the disruption caused by the earthquake, tsunami and damage on 1F site, SPEEDI was not functioning to its full capacity after the accident. In particular, loss of on-site power made measurements of radioactive material releases through controlled release pathways (e.g., through the plant stack) impossible. Furthermore, considerable radioactive material releases from 1F plant were uncontrolled – e.g. as a result of hydrogen explosions. The release inventory was thus unknown and initial estimates of off-site atmospheric dispersion of radioactive noble gases and iodine used “reference” (or “guesstimated”) release rates [19].

Prediction of contamination distribution using aerial dispersion models (SPEEDI and some other models used in Japan and in other countries) was valuable, but limited in practice for this case, because critical ground stations for calibration of model output were mainly rendered inoperative by the earthquake and tsunami. Immediately after the accident, therefore, this input could be used only to complement aerial surveys on distribution of radionuclide deposition and guide immediate emergency responses for further potential release scenarios.

Under 1F conditions, inverse-modelling using SPEEDI played a key role in estimating total releases of the key isotopes of radioiodine and radiocaesium (e.g. [44]). This was especially important for ^{131}I shortly after the accident as, due to its lower gamma energy, it is more difficult to measure than the Cs isotopes but is much more of a radiological hazard due to its tendency to concentrate in the thyroid. It is thus considered important to determine what the potential health effects of such releases were.

Ground deposition maps of ^{131}I discharged from 1F were produced by a joint study of JAEA and the United States Department of Energy (DOE) National Nuclear Security Administration (NNSA). The study was conducted based on airborne monitoring data collected during the early stages of the accident by the DOE, and re-analysed to derive ^{131}I data [45] (Figure 2-12).

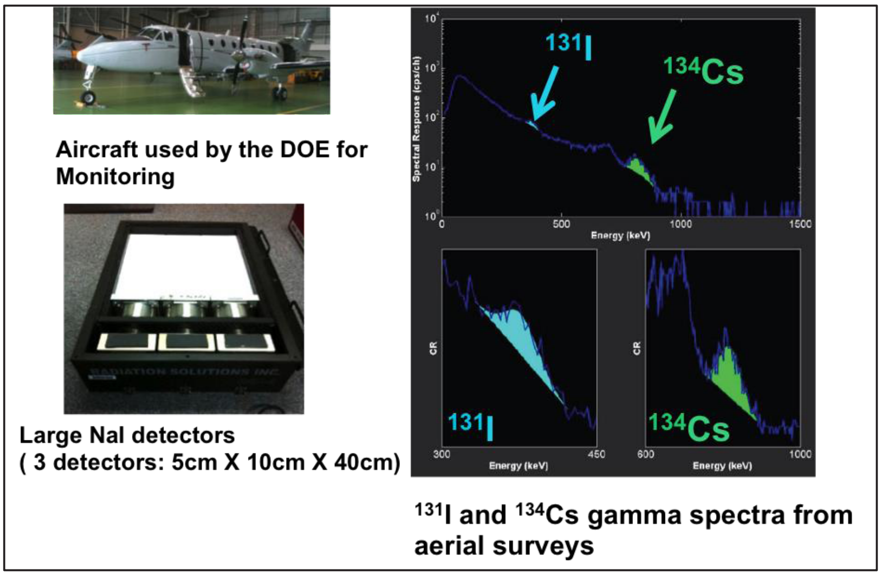


Figure 2-12 Equipment used and spectral analysis required to obtain ^{131}I distribution data [45]

The resulting ^{131}I distribution maps were used as input for SPEEDI inverse modelling to derive total releases and then detailed distribution maps related to specific release events (Figure 2-13). As a form of validation, the deposition map for ^{131}I obtained from soil samples shortly after the accident [40] has been extended using correlation of ^{131}I with still-measurable, long-lived ^{129}I (16 million year half-life) [41].

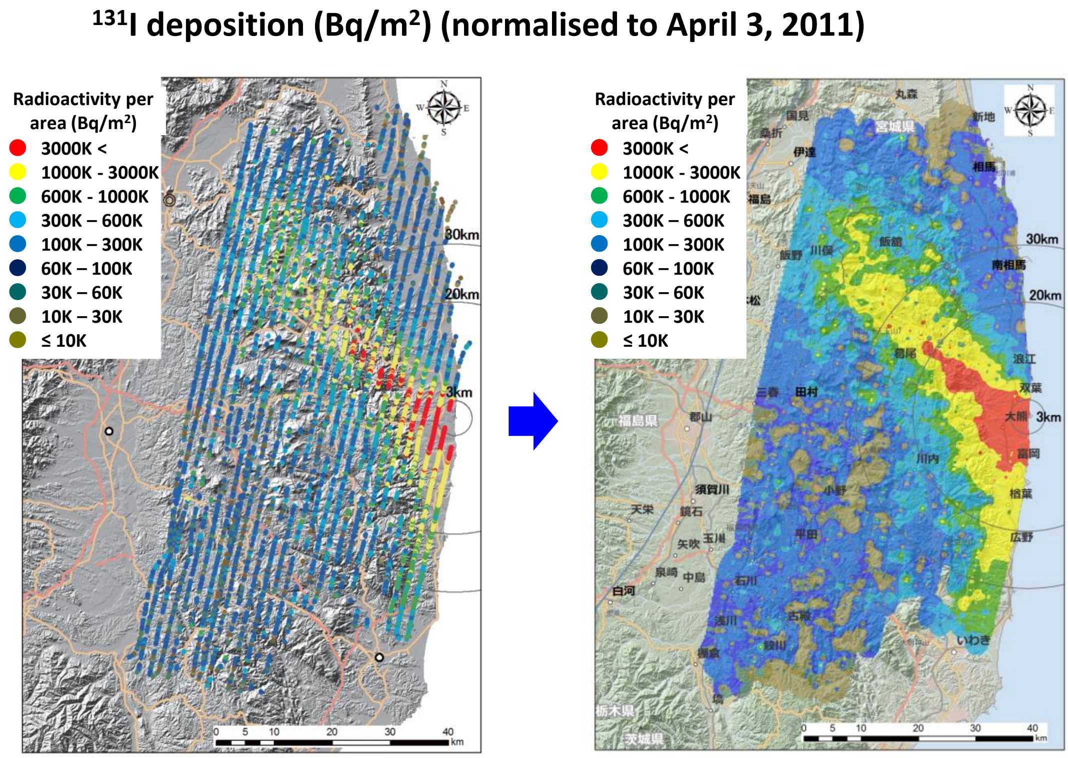


Figure 2-13 Use of aerial survey data to derive ^{131}I distributions used by SPEEDI inverse modelling to derive total releases and more detailed distribution maps [45]

Taken together with regional measurements of the ^{131}I / ^{137}Cs activity ratio, this allows a dose reconstruction trial to be carried out on the spatial scale of the affected areas of north-eastern Japan [46].

2.3 Structured evaluation of radionuclide distributions

It is well recognised that environmental monitoring and surveys of radioactivity are best achieved when two or more approaches are used in parallel (e.g. [47], which is in good agreement with the experience reported in the previous sections.

In cases like the 1F releases, where safety relevant radionuclides are gamma emitters, in situ, vehicular and airborne gamma-ray spectrometry allows rapid measurement of air doses over the entire contaminated region. When particular isotopes are of key significance to determine health risks, sophisticated analysis of the data may be required, complemented by modelling and sampling / radiochemical analysis (as discussed for ^{131}I in section 2.2 above). Nevertheless, these techniques generally give more spatially representative measurements, averaging out small scale heterogeneity. This must, however, also be recognised as a constraint, as local hot-spots may be missed unless very localised studies are carried out.

The accuracy of the standard interpretation of all gamma spectrometry surveys in terms of radionuclide inventory levels (Bq m^{-2}) depends on how closely contamination in the area involved corresponds to an idealised thin layer over an infinite flat plain. Important perturbing factors include shielding by snow or water (already discussed in section 2.1.1), vegetation / ground cover, depth distribution in soil and surface roughness / topography. Although empirical correction factors can be applied, these are all associated with significant uncertainties.

For the Fukushima Prefecture, vegetation is an important factor as about 70% of the land area is forested. For a given deposition of a gamma emitter in a forest, the measured flux in a detector will depend on the size and type of tree (deciduous or evergreen) and the distribution of fallout between foliage, leaf litter and soil – a distribution that will vary significantly with time for different kinds of forest.

For agricultural and other rural land, vertical activity distribution in the soil column has a major role in resultant air gamma fluxes together with, to a lesser extent, soil density and moisture content. Large numbers of measured profiles of radiocaesium concentration as a function of depth in different environments show a similar trend of a marked decrease with almost the entire inventory being contained within the upper 5 cm.

Following deposition from the atmosphere, radioactivity can penetrate into the soil and the vertical activity distribution can be approximated by a negative exponential (e.g. [47]):

$\boldsymbol{A}(\boldsymbol{x}) = A0 \cdot e^{(-x/\beta)}$, where

- $\boldsymbol{A}(\boldsymbol{x})$; the activity distribution with depth (Bq g^{-1})
- $\boldsymbol{x}$; the “mass depth” (cumulative mass per unit area) (g cm^{-2}): this effectively corrects for the changing porosity of soil with depth
- $\boldsymbol{A0}$; the activity concentration at the surface (Bq g^{-1})
- $\boldsymbol{\beta}$; a fit parameter termed the “relaxation mass depth” (g cm^{-2})

The values of β were derived approximately from depth profiles of 85 samples from an undisturbed plain most of which have a good fit with a negative exponential equation but some have a peak at a certain depth. Figure 2-14 shows that distributions of β evolve with time, which means that Cs penetrates slightly deeper with time.

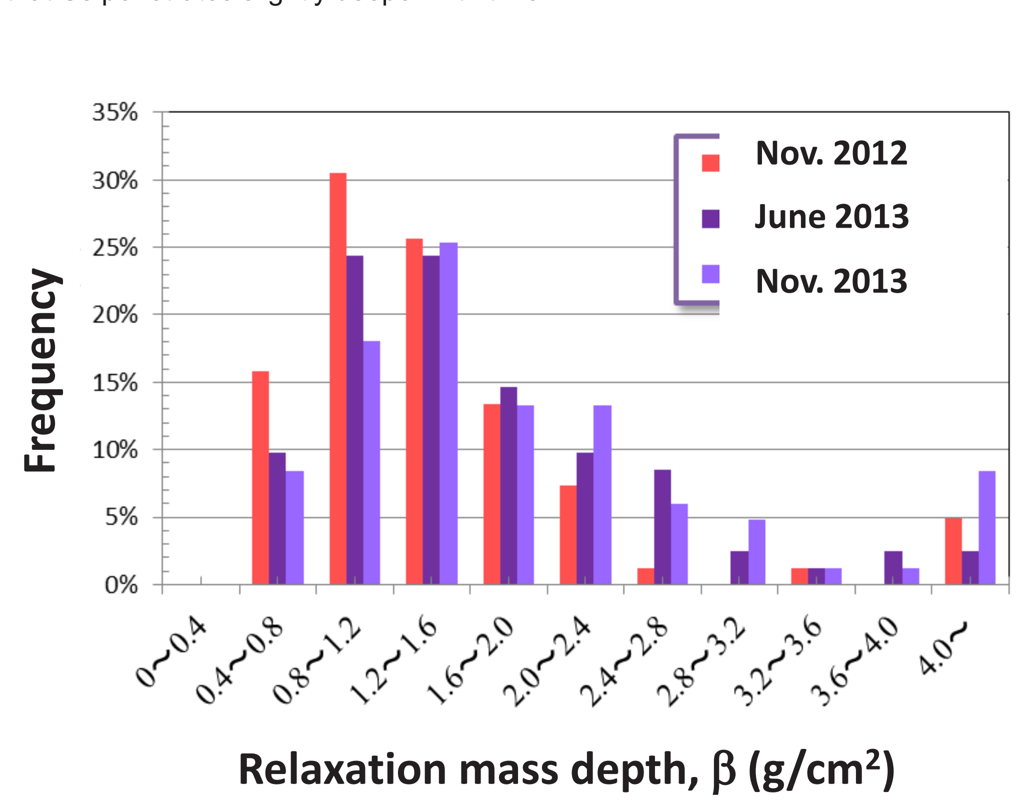


Figure 2-14 Temporal change in depth distribution [37] [48]

In some cases exponential curve fit parameters have been termed in analogy to Fickian diffusion. Nevertheless, it is very unlikely that molecular diffusion of Cs plays a significant role, given its very strong (almost irreversible) uptake onto clays [29]. The variable depth to which frost heaving and thawing, vertebrates, arthropods and annelids burrow and different plant roots and fungal mycelia penetrate are likely to explain detailed profiles on a case by case basis, even if these are simplistically modelled by empirical fit curves. Regardless of how it is modelled, the shielding effect of soil means that the deeper that Cs penetrates, the lower the surface gamma dose measured is for a specific inventory.

Also very important in most areas surveyed is taking into account topography and surface roughness caused by both natural and man-made structures. If surface contamination is completely homogeneous, this can be accounted for with a geometric correction model – but this is rarely the case in real life situations. If measurements are made with collimated shielding (which reduces the effects of complex local background), gamma fluxes from specific surfaces can be measured and used to interpret the total fluxes measured by unshielded detectors, but the correction is complex and subject to considerable uncertainties.

In conclusion, in situ, vehicular and airborne gamma surveys are very useful tools for measurements of air dose rates, but care is needed to interpret in terms of radiocaesium inventories with associated uncertainties. Therefore, detailed sampling and laboratory analysis of all components of relevant measurement environments is needed to calibrate the gamma fluxes measured. Nevertheless, despite such caveats, there is a clear correlation between measured Cs deposition and air gamma dose rate (Figure 2-15), showing that the measurements provide a consistent regional picture of the degree of contamination in undisturbed fields.

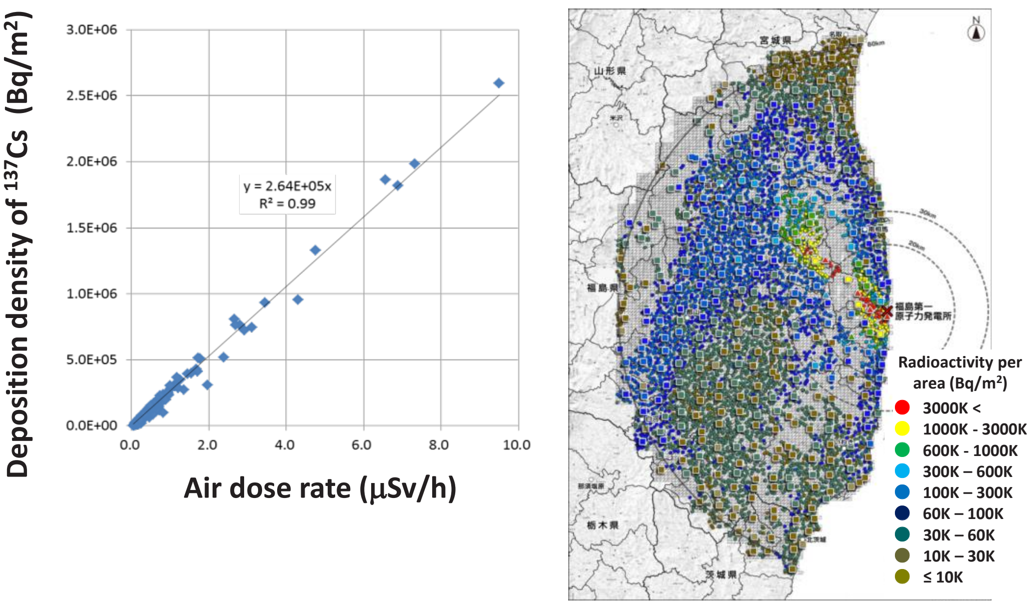


Figure 2-15 Correlation of measured ^{137}Cs deposition and air dose rate [39]

2.4 Assessing radionuclide distributions in terms of doses

Although the previous section outlines a comprehensive system of radiation measurement carried out over the last 3 years, that can be interpreted in terms of the decay and environmental behaviour of contaminant fallout, it does not directly contribute to answering questions of the local population in terms of the actual radiation dose that they are exposed to and how this will vary in the future. After decay of shorter-lived radionuclides, dose is now dominated by radiocaesium, which generally shows little bioaccumulation. Dose from ingestion and inhalation is much less significant due to strict food restrictions and Japan’s wet climate. Therefore, external gamma dose is the main focus for studies. In this section, only the distribution and evolution of local gamma dose rates is considered. Integration of such information to develop lifestyle-specific individual annual doses is considered in the following section.

2.4.1 Development of a predictive model

Development of a model to predict the evolution of air dose rate distribution in the 80 km zone was initiated in the fiscal year 2012 [49]. The aim was to allow prediction of the dose rate distribution throughout the region as a function of elapsed time up to 30 y, based on statistically analysed results of the environmental monitoring data accumulated in the projects. This is thus a completely empirical approach, without any attempt to link functions derived to the environmental behaviour of radiocaesium.

The model was initially based on the assumption that the time-dependent decrease of air dose rate in any specific setting can be approximated by a combination of two exponential functions, representing “fast” and “slow” reduction rates. The best-fit parameters for these exponential functions would be determined based on statistical analysis of the data set presented in section 2.1. It should be noted, however, that although such double exponential fit is obvious from past data for crops (e.g. [50]) and has been applied to grasslands ([51]), its wider applicability to other settings is only now being investigated in the Fukushima area.

In the first step of model development, continuous monitoring data at fixed locations during the first year after the accident were examined to judge whether they fit better to a double exponential decay with time or to a simpler single exponential. In fact, the data were found to be a better fit to the single exponential; indicating that the “slow component” of dose rate reduction was either inapplicable or unobservable over this time period. Such simple exponential fits allow a parameter termed the “environmental half-life” to be quantified. This is here defined as the half-life of the air dose rate corrected for the effects of radioactive decay.

As expected, analysis linked to geostatistical data shows that the environmental half-life clearly depends on land use. According to analysis of latest car-borne survey data, it may be that a slow component of the double exponential function is appropriate for some settings.

2.4.2 Development of an integrated database

Statistical analysis of an integrated database requires that measured data are recorded in standard formats which fully determine the characteristics of the measurement (location, date and time, type of equipment, ground cover, weather conditions, etc.). Ideally measurements should be directly linked to GPS and clock functions and linked to a digital photograph or video (very useful for investigating potential explanations for any outlying points). To facilitate this, an automatic data collection device utilising a cellular phone network was developed, which allowed logging and communicating data automatically and securely to a central database [52].

Quality control is essential; currently data obtained are checked by experienced staff before incorporation into the database. With the expanding volume of data included, it is important that such checks are automated to the extent possible, which can be facilitated by use of common QA guidelines by all teams involved plus regular measurement of blanks and standards and also, as required, laboratory and equipment intercalibration exercises.

The resulting database is open, allowing users to interactively create contamination maps by freely selecting the area of interest and the database components to be considered. The database still requires expansion to include data accumulated by different ministries and local governments, which were integrated within the platform accessed through [53]. In addition, further, user-friendly tools for data analysis and visualisation are planned based on this website.

2.4.3 Pilot study: real-time air dose data in Fukushima Prefecture

An example of a pilot study intended to provide easily understood, real-time information on air dose rates measured in residential areas is provided by a study utilising portable survey equipment mounted on public buses (Figure 2-16).

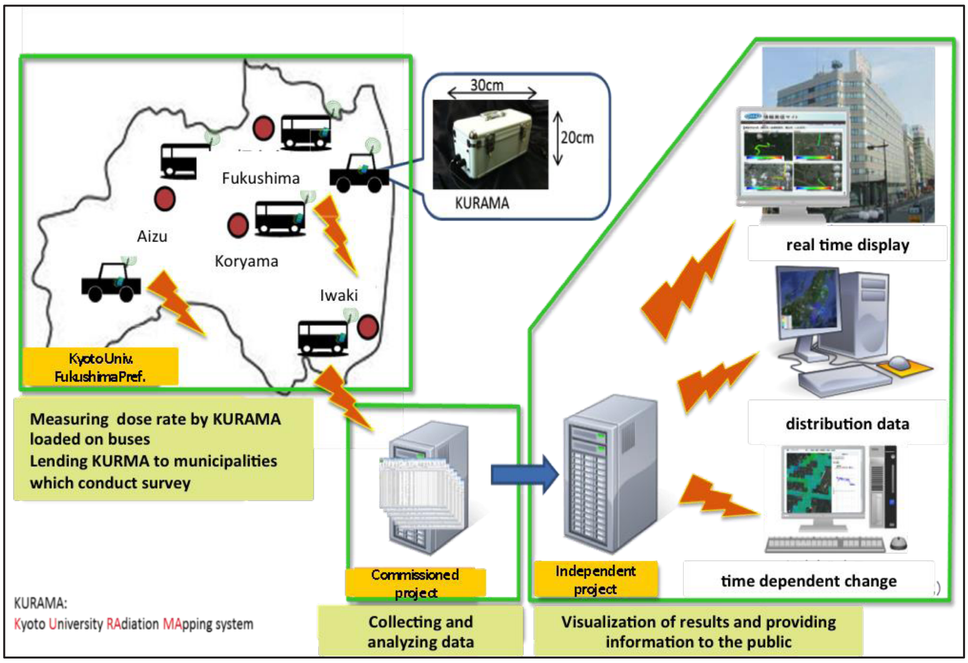


Figure 2-16 Overview of the Fukushima real-time dose monitoring system [54] [55]

This is promoted as a joint project between the Fukushima Prefecture and Kyoto University, who developed the KURAMA monitoring system. A key aspect of this project is automated data collection, wireless transmission, data analysis and data visualisation – allowing real-time updating of dose rate maps that can be accessed via the internet or viewed in displays in public locations. Additionally, changes in dose rate as a function of time can be viewed.

Surveys have been initiated in 4 cities within the Fukushima Prefecture and results have been open to the public since August, 2013. Apart from self-cleaning, this system allowed visualisation of decontamination efficiency (following decontamination work on a bus route along the National Route 4). The survey areas were expanded over the entire Fukushima Prefecture, involving about 30 buses from August 2014.

2.5 Future developments and recommendations

As noted in the introduction to section 2.4, emphasis to date is on assessing local gamma dose rates. This can be input to very simple models of shielding when indoors to allow conversion to an increase in annual dose rate – expressed in mSv y^{-1}. This is, however, very simplistic as it does not account for the varying exposure / shielding resulting from a lifestyle typical of this area. Nevertheless, with the data available, this could be assessed quantitatively or either representative of user-defined lifestyles by straightforward modification of existing tools.

A somewhat more challenging development is to develop complete dose estimates for those living in the area and, in particular, evacuees who are considering returning to their homes. Although strict food and water restrictions were effective, it is important that the public can access information on the impact of eating local food restricted from distribution into the market. This is especially the case for the few cases where Cs concentration is known – such as fungi, animals that consume them and some bottom-dwelling fish. A number of biosphere models exist that can allow such assessments to be made, but these need to be extended to interface with the contamination database and specific measurements of radiocaesium concentrations in food from areas with different contamination levels.

Overall, it can be seen that much progress has been made in monitoring contamination following the 1F accident and relating this to both immediate accident management and also long term recovery of the region. Development of equipment and, in particular, the tools to manage the resulting data could be of wide interest as part of the development of accident response plans and also, possible, planning for remediation of legacy contaminated sites. For a heavily populated area like Fukushima, communication with the public is particularly important and, although this was certainly a weak point immediately after the accident, it is an area where progress has been made recently. Successes in local communication have not, however, been matched at a national and international level. This is certainly an area in which further improvement is needed.

3 Radiation protection

The previous section focused on assessing the distribution of radiocaesium; this is now put in perspective by considering its impact in terms of dose to the population. Prior to this, however, the past impact of radioiodine and other short-lived radionuclides released from 1F is considered.

3.1 Radioiodine and other short-lived / low concentration / low toxicity isotopes

The dominant contributors to the gamma exposure from the 1F accident were previously noted to be ^{131}I, in the early period after the accident, and ^{134}Cs and ^{137}Cs later on [18] [56]. Nevertheless, a number of other radionuclides were released in significant quantities (Table 3-1). The dominant releases by far were noble gases, which were assumed to be entirely lost from damaged fuel. The most important isotope is ^{133}Xe, with total releases in the order of 10 EBq. Although there are considerable uncertainties in the estimated releases [4], this was a major release of ^{133}Xe, equivalent to that from a 1 Mt nuclear explosion [57].

Xe is, however, effectively inert and is rapidly dispersed in the atmosphere, hence considered of negligible radiological significance (a conclusion that applies to other, longer lived noble gases such as ^{85}Kr). Indeed, ^{133}Xe is used medically for assessing pulmonary function (e.g. [58]).

Table 3-1 Estimated radioactive releases into the atmosphere from 1F [5]

Nuclide	Half-life	Unit 1	Unit 2	Unit 3	Total
^{133}Xe	5.2 d	3.4×10^{18}	3.5×10^{18}	4.4×10^{18}	1.1×10^{19}
^{134}Cs	2.1 y	7.1×10^{14}	1.6×10^{16}	8.2×10^{14}	1.8×10^{16}
^{137}Cs	30.0 y	5.9×10^{14}	1.4×10^{16}	7.1×10^{14}	1.5×10^{16}
^{89}Sr	50.5 d	8.2×10^{13}	6.8×10^{14}	1.2×10^{15}	2.0×10^{15}
^{90}Sr	29.1 y	6.1×10^{12}	4.8×10^{13}	8.5×10^{13}	1.4×10^{14}
^{129m}Te	33.6 d	7.2×10^{14}	2.4×10^{15}	2.1×10^{14}	3.3×10^{15}
^{238}Pu	87.7 y	5.8×10^{8}	1.8×10^{10}	2.5×10^{8}	1.9×10^{10}
^{239}Pu	24,065 y	8.6×10^{7}	3.1×10^{9}	4.0×10^{7}	3.2×10^{9}
^{240}Pu	6,537 y	8.8×10^{7}	3.0×10^{9}	4.0×10^{7}	3.2×10^{9}
^{241}Pu	14.4 y	3.5×10^{10}	1.2×10^{12}	1.6×10^{10}	1.2×10^{12}
^{131}I	8.0 d	1.2×10^{16}	1.4×10^{17}	7.0×10^{15}	1.6×10^{17}

In terms of total releases, the next most significant isotope is ^{131}I, which is volatile and hence large releases from damaged fuel can be expected, even though a significant fraction will be captured by HEPA and active charcoal filters included in the gas venting system. Unlike the noble gases, I is associated with “fallout” – either as dry deposition or associated with precipitation (rain or snow). As an aerosol it can be inhaled and can also be ingested because it readily enters the food chain. Similar to stable iodine, ^{131}I is actively taken up by the thyroid gland, posing a particular cancer threat. The foetal thyroid gland concentrates iodine by 11–12 weeks gestation, so if radioactive iodine enters the mother’s blood stream after that period it can be taken up also by the foetal thyroid gland. The impact of this process can be reduced by issuing prophylactic KI tablets, which reduce the uptake of radioactivity into the thyroid. Assessments of the health impact of ^{131}I concentration by the thyroid are summarised in Table 3-2.

Table 3-2 Assessed internal dose to thyroid due to ^{131}I

Equivalent dose	Methods	References	Notes
8.3 mSv for 1 year old children living in Iitate village	Estimated by assuming ingestion of tap water (from March 16 to May 10, 2011)	[59]	To estimate the dose prevented by the application of countermeasures (tap water restrictions)
< 10 mSv (median) for all population and ~ 30 mSv (90% tile) for small children	Estimated on results of whole body measurements and dispersion simulation	[46]	
18 mSv* for > 2,000 residents of Namie Town	Direct measurement of the body	[60]	Whole body counting of ^{134}Cs by assuming a ratio of inhaled activity of ^{131}I and ^{134}Cs
20 mSv* (173 people)	Direct measurement of the body	[61]	Whole body counting of ^{131}I
33 mSv* (62 people)	Direct measurement of the body	[62]	Measurement of the neck of examinees by NaI(Tl) scintillation survey meter
27-66 mSv for adults and **44 mSv** for children	Measurement of bioassay samples	[63]	Urine samples

*the highest value

A general conclusion of UNSCEAR [56] is that "*no radiation-related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident. 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*".

For sake of completeness, health effects from other short-lived or low concentration radionuclides should be considered. Radionuclides deposited as fallout from atmospheric releases are assessed from the viewpoint of long-term exposure of the general public. Around the 1F site, about 10 anthropogenic radionuclides originating from the accident have been detected at significant concentrations. Soon after deposition, radionuclides deposited on the ground are assumed to form a plane source on the ground surface.

For this assessment, maximum nuclide deposition inventories (Bq m^{-2}) were used and external exposures and inhalation due to re-suspension were evaluated [64] [65]. Although it is somewhat simplistic as bio-concentration / food chain effects are not taken into account, the calculated accumulated effective doses for 50 years from June 2011 due to radionuclide deposition, allow the relative importance of different radionuclides to be estimated (Table 3-3). Although this is based on unduly conservative assumptions which do not intend to estimate realistic doses, this clearly shows that radiocaesium isotopes completely dominate, being responsible for a dose three orders of magnitude greater than all other isotopes combined.

Although it is important that such data are not over-interpreted, it should be noted that higher concentrations of isotopes other than I and Cs are very localised and, if of concern at all, would likely be limited only to restricted areas close to 1F site.

Table 3-3 Evaluation of radionuclide contribution to dose integrated over 50 years (from June 2011) [65]

Radionuclide	Maximum concentration ($Bq\ m^{-2}$)	Conversion factor* ($\mu Sv/Bq\ m^{-2}$)	Committed effective dose (μSv)	Normalised to ^{137}Cs committed effective dose
^{137}Cs	1.5×10^{7}	1.3×10^{-1}	2.0×10^{6} (2Sv)	1
^{134}Cs	1.4×10^{7}	5.1×10^{-2}	7.1×10^{5}	3.6×10^{-1}
^{131}I	5.5×10^{4}	2.7×10^{-4}	15	7.5×10^{-6}
^{89}Sr	2.2×10^{4}	2.8×10^{-5}	0.62	3.1×10^{-7}
^{90}Sr	5.7×10^{3}	2.1×10^{-2}	120	6.0×10^{-5}
^{238}Pu	4	6.6	26	1.3×10^{-5}
$^{239/240}Pu$	15	8.5	130	6.5×10^{-5}
^{110m}Ag	8.3×10^{4}	3.9×10^{-2}	3.2×10^{3}	1.6×10^{-3}
^{129m}Te	2.7×10^{6}	2.2×10^{-4}	600	3.0×10^{-4}

* [64] (Table E3: Conversion Factor CF4 was used.)

3.2 Radiocaesium: radioprotection issues

Cs is relatively volatile, although more effectively captured than I and hence the fractional release of the core inventory is less. ^{134}Cs and ^{137}Cs become the most relevant radioactive hazard from 1F after ^{131}I decays over the first few weeks. Cs also falls out from releases to air, although it tends to be strongly bound to surfaces, especially fine clays. It can be taken up into food and deposited material can be re-suspended into the air and inhaled (although this route of exposure is of less significance). Once caesium enters the bloodstream, it distributes relatively homogenously throughout human visceral and muscle tissues and hence causes radiation exposure to the entire body [56].

It is difficult to directly measure internal doses from radiocaesium (and other released radionuclides), so "operational quantities" are generally assessed, which allow such doses to be estimated. These include measurements of concentrations of Cs radioisotopes in air, food and water and measurements of the body burden by whole body counting or biopsies.

At the request of the Fukushima government, JAEA started whole-body counting of residents on July 11th, 2011, to assess radiation exposure after the accident (Table 3-4). The committed effective dose to 99.8% of the residents was found to be below 1 mSv even in the first year (from July 11th, 2011 to March 31st, 2012). There were only 23 subjects with a value greater than 1 mSv, and the maximum value recorded was 3 mSv. These values are low relative to background radiation and hence no significant health risks would be anticipated.

External gamma exposure, which results from radiation sources located at some distance from the body surface (e.g. deposited on the ground, suspended in the air), is generally a greater concern for radiocaesium. This kind of external irradiation can be reduced or even stopped by shielding or moving the radioactive source further away (or moving the person outside the radiation field, as happens during evacuation). Thus, although localised concentrations of radiocaesium can be expressed in terms of a dose rate ($\mu Sv\ h^{-1}$ as indicated in section 2), this has to be related to a representation of the lifestyle of the population in order to be converted into an annual effective dose and hence assessed in terms of potential health risks.

Table 3-4 Measured internal dose determined by whole-body scanning [66]

Date	Number of individuals measured			Committed effective dose	
	Age		Total	< 1 mSv	≥ 1 mSv
	< 18	≥ 18			
July 11th 2011 – March 31st, 2012	9,585	4,843	14,428	14,405	23
April 1st 2012 – March 31st, 2013	20,956	5,539	26,495	26,495	0
April 1st 2013 – March 31st, 2014	14,865	5,888	20,753	20,753	0
April 1st 2014 – July 31st, 2014	7,356	12	7,368	7,368	0
Total	52,762	16,282	69,044	69,021	23

The government of Japan uses a simple model to estimate annual exposure (e.g. for setting the evacuation standard of 20 mSv y^{-1}). This is taken from ambient dose rate measurements, based on the assumption that people spend 8 hours a day outdoors and 16 hours a day indoors, for the latter considering a dose reduction factor of 0.4. This type of calculation ideally requires averaging of external measured dose rates over a representative area (e.g. an entire village or town), but is often based on selection of particular areas that may be important for key population groups – e.g. measured playground dose rates for school children. It should also be noted that the assumed dose reduction factor is rather low, as it is based on no contamination on the basement of buildings and conservatively based on low protection of lightly built traditional wooden houses rather than the greater shielding provided by more common brick or concrete buildings.

The ambient dose rate is generally measured by gamma spectroscopic methods (in situ and airborne – see section 2) or NaI survey meters with energy compensation. Such measurements are very sensitive to the local distribution of contamination, topography and possible shielding structures – so may vary considerably over small distances. Further, in areas with relatively low contamination, it may be important to estimate the contribution to the dose measured resulting from natural radiation, so that it can be distinguished from artificial radiation due to the accident.

Alternatively, gamma dose rate can be estimated from measurement of radioactivity in soil, by using coefficients to convert areal concentration of radionuclides in soil to an ambient dose rate. Such soil concentrations can be accurately measured in samples taken to laboratories with low background and high-accuracy detectors, but are very sensitive to variability of deposition. It is commonly observed that radionuclide concentrations show distinct profiles as a function of depth. Therefore, the conversion factor can be derived by assuming an empirical exponential distribution as a function of soil depth.

The value of deriving dose rates from measured radiocaesium profiles is that these are expected to evolve as time elapses, in response to radioactive decay and radionuclide migration deeper into the soil. Either empirical or mechanistic models can forecast the extent of migration as a function of the environmental conditions and elapsed time after deposition [52] [37], allowing the future decrease of dose rates to be calculated.

3.3 Reference dose levels and reduction targets

A reference dose level for the protection of people living in contaminated areas should be selected in the lower part of the 1 - 20 mSv y^{-1} band, based on recommendations of ICRP for the management of this category of exposure situation [67]. Past experience has suggested that a typical value used for constraining the optimisation process in long-term post-accident situations is in the order of 1 mSv y^{-1}. It should be noted, however, that ICRP recommendations for the aftermath of severe accidents are currently being reassessed to capture lessons learned from the Fukushima accident [68]. The specific topics being considered include:

1. Justification for and optimisation of emergency decisions
2. Characterisation of the radiological situation
3. Protection of emergency and recovery responders
4. Decontamination and waste management strategy
5. Withdrawal of emergency protective action
6. Protection of pregnant women and children
7. Information sharing with stakeholders
8. Emergency and recovery preparedness.

In terms of the first point, a reference level in an emergency exposure situation set to specify the areas evacuated was a conservatively calculated effective dose of 20 mSv y^{-1} (as described in section 1.2). The goals set for decontamination actions and lifting the evacuation orders are, however, very sensitive and require careful balancing of technical arguments against the need to reassure the public.

The situation is illustrated in Figure 3-1, which shows the calculated health impact (expressed as an additional risk of cancer) as a function of increase in annual dose over background. For values above about 100 mSv y^{-1}, the graph is based on a range of published evidence and can be considered well established.

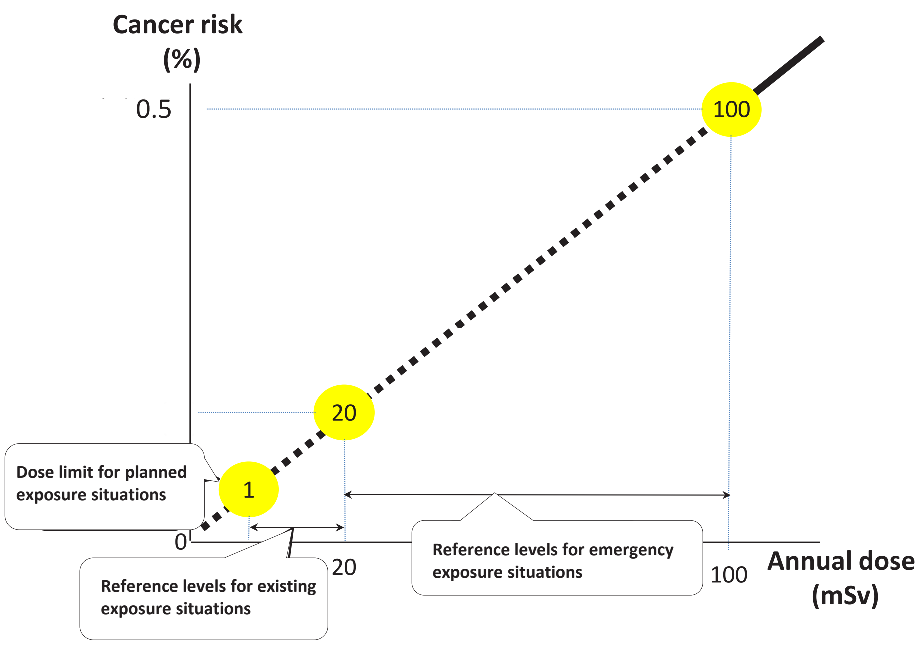


Figure 3-1 Schematic representation of increase in cancer risk as a function of additional annual dose

However, the risk of cancer development from radiation at levels of 100 mSv y^{-1} or lower is considered so slight according to international consensus that the risk is concealed by carcinogenic effects from other causes [69]. In the figure, the dotted line is a linear extrapolation to lower doses – termed the linear no threshold (LNT) model. This can be argued to be the best practical approach to managing risk from radiation exposure and commensurate with the 'precautionary principle'. However, the probabilistic nature of stochastic effects and the properties of the LNT model make it impossible to derive a clear distinction between 'safe' and 'dangerous', and this creates some difficulties in explaining the control of radiation risks [70].

The communication problems are clear when the natural variations in natural background radiation dose are considered. Average natural background radiation dose in Japan (≈ 2.1 mSv y^{-1}; [56]) is low relative to average medical exposure in Japan (≈ 3.9 mSv y^{-1}; [71]). It is considerably less than specific regions at higher altitude and with geological settings containing higher natural radioactivity. Despite extensive studies, no evidence has been obtained that there is any health detriment from living in an area of higher background – or from employment that leads to higher radiation exposure in this range (e.g. air crews, mountain guides). In terms of very low additional doses, the scientific consensus is probably best summarised as: *"The Scientific Committee does not recommend multiplying very low doses by large numbers of individuals to estimate numbers of radiation-induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels"* [72].

National policy in Japan can be summarised as [73]:

- The NSC has applied 20 mSv y^{-1} as the basis for designation of the Deliberate Evacuation Area. This is equivalent to the lowest level of dose band of 20 to 100 mSv (acute or annual) for the ICRP recommended reference level in an emergency exposure situation.
- A reference level for optimisation of the protective actions should be selected from the lower part of 1 to 20 mSv y^{-1} band recommended by the ICRP for the management of existing exposure situations. In order to improve the situation in a step by step manner, a provisional reference level can be fixed within this band, but the target of the exposure dose in the long term should be 1 mSv y^{-1}.

It is emphasised that this does not mean either that 1 mSv y^{-1} is derived as a clear distinction between 'safe' and 'dangerous' or that 1 mSv y^{-1} will be achieved only by decontamination. 1 mSv y^{-1} is a reference level to effectively implement protective actions such as radiation monitoring, health surveillance, the management of contaminated foodstuffs and decontamination, which aim to reduce individual doses below the reference level [74]. Nevertheless, this is a difficult concept to communicate to the general public, who can interpret this goal as indicating that previous levels did not provide sufficient safety.

3.4 **Models for assessing success of dose reduction**

From the discussion of the previous section, it is evident that reference dose levels are set in a very conservative manner. It is thus important that the models used to assess such doses are as realistic as possible. A very simple model approach (Figure 3-2, upper) was useful as an indicator to guide community wide decontamination, as applied to the Intensive Contamination Survey Area.

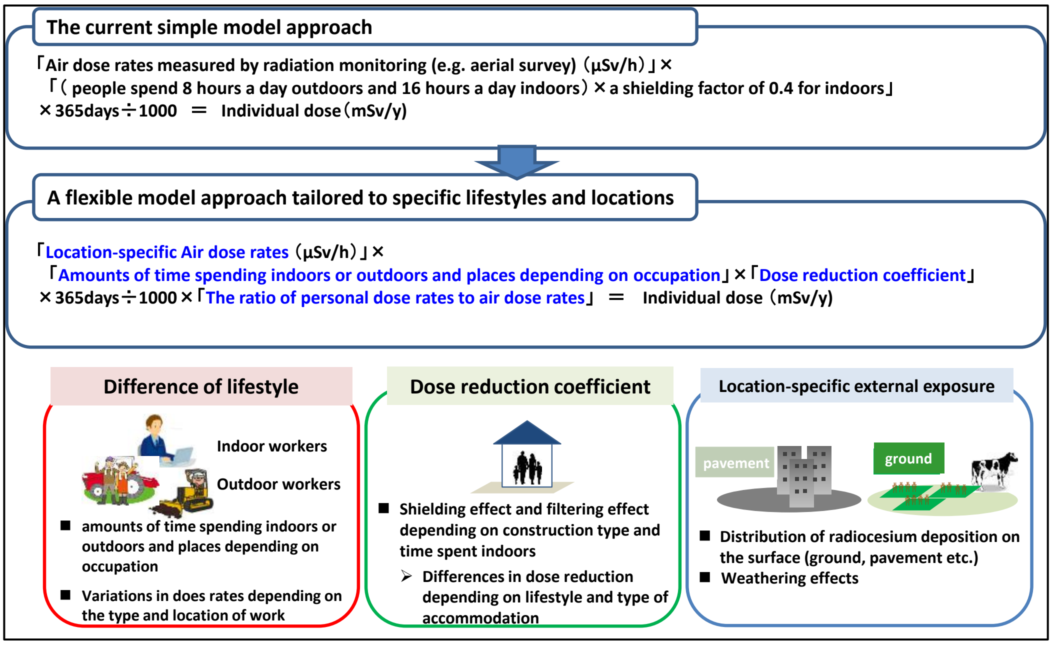


Figure 3-2 Required improvement of dose estimation models [75]

Here 99 municipalities in 8 prefectures were designated on the basis of measured air dose rates over 0.23 μSv h^{-1}, calculated to be equivalent to over 1 mSv y^{-1}. Nevertheless, a more refined approach should be used in the future.

The Nuclear Regulation Authority of Japan [76] formulated practical measures of radiation protection for the evacuees who will return to their homes, based on best scientific and technological understanding. In this report they focus on personal dose as follows:

- It has been acknowledged that personal dose rates vary depending on individual daily life and that personal dose data directly measured by municipalities tend to be significantly lower than the exposure doses estimated from air dose rates based on the simple model approach.
- It is necessary to implement measures to reduce individual exposure dose and health care depending on the personal dose data.

JAEA has developed a more flexible model to improve radiation protection planning for return of populations to the evacuated area, based on a combination of dosimetry, lifestyle questionnaires and supporting studies. A starting point for model improvement was comparison of directly measured and estimated external cumulative radiation doses: these showed that measurements by personal dosimeters were much less than the estimates from the simple model. There are two key components to this, the simplifications involved in direct consideration of measured external gamma doses by commercial electronic dosimeters and realistic integration of exposure as a function of lifestyle.

To examine the former, conventional dosimeter measurements were compared to those using a “slab phantom”, which more realistically assesses the impact of radiation on the human body [77]. From this work (Figure 3-3), it was concluded that cumulative personal dose equivalent for adults could be estimated from cumulative air doses at 1 m height multiplied by 0.7 (for the investigated areas; three mountainous areas in evacuated zones).

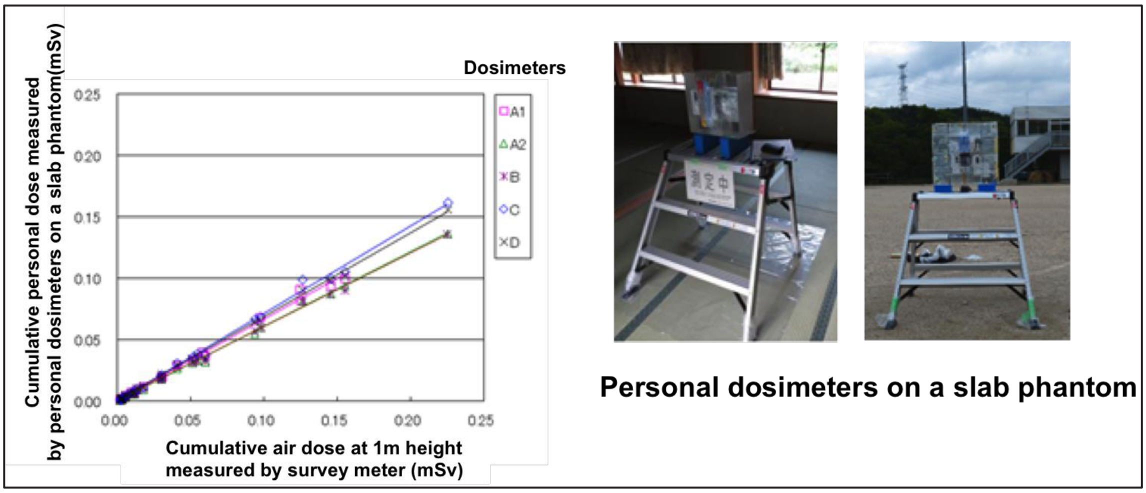


Figure 3-3 The ratio of personal dose rates to air dose rates [77]

A further contribution to model improvement was better determination of dose reduction due to assuming no contamination in buildings and shielding effects provided by different types of buildings [78]. This showed clearly that the factor of 0.4 assumed for dose reduction was relevant even for a wooden house and an extreme under-estimate of the shielding provided by more substantial buildings (Figure 3-4).

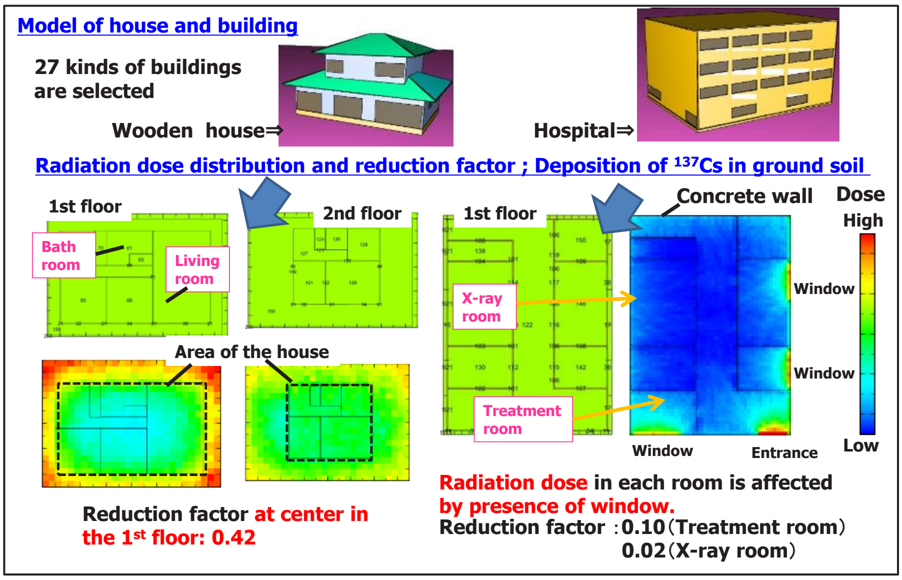


Figure 3-4 Model estimates of dose reduction factors due to shielding within different kinds of building [78]

If contribution of natural background radiation can be adequately separated from ambient dose rates, dose reduction factor can be more relevantly estimated for estimating personal dose. Finally, lifestyle contributions were assessed. As indicated in Figure 3-5, groups with very different lifestyles were issued with personal dosimeters to record accumulated radiation exposure. In addition, monitored inhabitants filled in lifestyle questionnaires to record amounts of time spent indoors or outdoors.

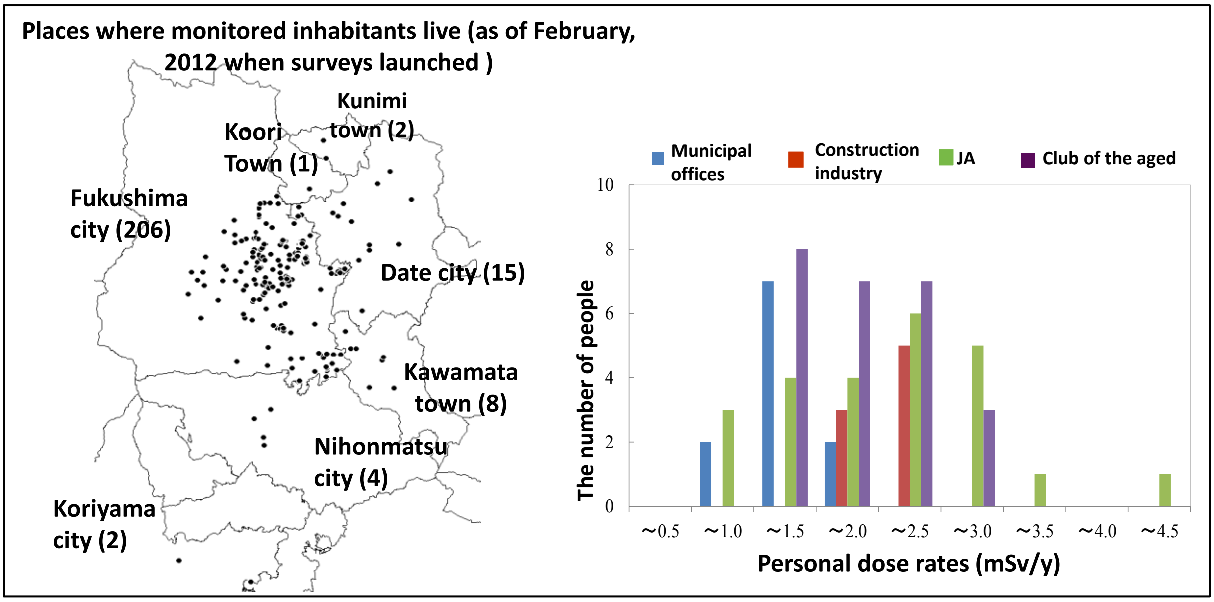


Figure 3-5 Basis of lifestyle survey [79]

From the defined lifestyles, external doses could be modelled and compared with those measured (Table 3-5). The results showed clearly that doses scaled with time spent outdoors. However, the improved model (based on the questionnaire) resulted in doses significantly lower than the simple model – but still provided over-estimates compared to directly measured doses. The difference between the simple model and measured dose rate, ranged from factors of 2 to 3.

Table 3-5 Comparison of dose rate estimated by simple model and that recorded by personal dosimeter [79]

Lifestyle	Time outdoors (h)	Average estimate based on air dose rates (mSv y^{-1})	Average personal dose rate (mSv y^{-1})
Municipal offices	0.8	2.1	1.3
Construction industry	7.2	3.2	2.0
Japan Agricultural Cooperatives (JA)	6.5	3.3	2.1
Club of the aged	2.0	2.4	1.9
Simple model approach	8.0	4.6	-

The results of such an analysis can be expressed in the form:

$$E = \Sigma\, c \bullet D(p) \bullet t(p)$$

where

E: total effective dose

c: conversion coefficient from ambient dose to effective dose

D(p): ambient dose at location p

t(p) : residence time at location p

If external dose is measured by personal dosimeters, Σ D(p)•t(p) can be derived with relatively small uncertainties. Conversion coefficients need to be carefully examined on the basis of simulation results, since they change according to several conditions such as source energy, source distribution, environmental configuration, body size and so on.

An alternative is to estimate external dose from ambient dose equivalent rate measurements. The procedures involved are simple, but inherently result in larger uncertainties. The derived D(p) depends on each location; it is difficult to define representative values for larger areas and to combine these with realistic estimates of t(p) and appropriate c values. Nevertheless, as ambient dose can be related to the evolution of the distribution of the radiocaesium, it offers a potential approach to treat time dependency of D(p). Although the principles are simple to state (e.g. Figure 3-6), the derivation of conversion coefficients in a rigorous manner is challenging [80].

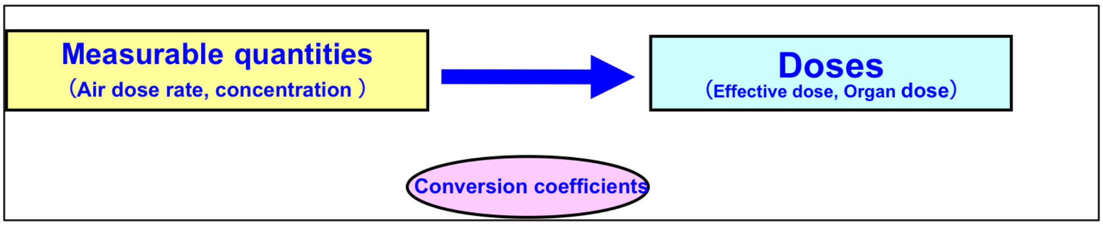


Figure 3-6 Principle of deriving doses from measurable quantities (or their extrapolations in time)

Even if the radionuclide distribution in the environment could be estimated reasonably accurately, the conversion factor has to consider the impact of topography and shielding on the resultant gamma energy spectrum and the resultant air kerma as a function of height. In practice, the inherent natural variability may be captured by a probabilistic approach – which might also be applied to the t(p) variability even for individuals with similar lifestyles. Ideally, to put results in context, the external gamma dose contributions from radiocaesium, any other artificial radionuclides and naturally occurring radionuclides (especially ^{40}K and the members of the ^{238}U, ^{232}Th and ^{235}U natural decay series), should be individually calculated.

Even if the ambient dose equivalent can be estimated, to convert this into an effective dose, details of the individual involved are required as there can be significant variations depending on age, sex, body size and even if a person is standing or lying down. As indicated in Figure 3-7, it is particularly important to recognise that conversion factors for a baby can be quite different to those for an adult, and that these will vary according to the distribution of the radiation source.

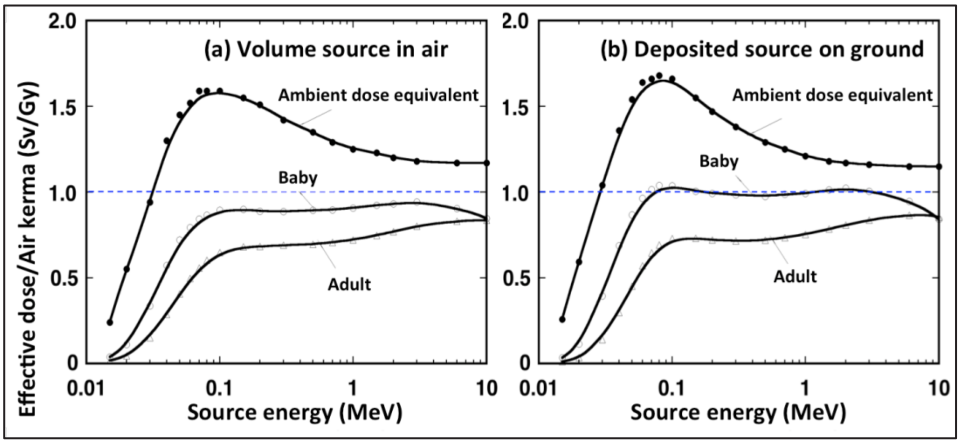


Figure 3-7 Dose conversion coefficients for environmental gamma rays [81] [82] [83]

In any case, the ambient dose equivalent considerably over-estimates the effective dose in all cases.

3.5 Future developments and recommendations

Although the situation with regard to dose estimation is relatively simple for gamma-emitting radionuclides like ^{134}Cs and ^{137}Cs, which do not significantly concentrate in the body, there are large uncertainties associated with making accurate estimates of the effective dose accumulated by individuals. The total annual dose is greatly influenced by the heterogeneous distribution of contamination and the impact of shielding – which both result in a large sensitivity to individual lifestyles. Even when doses are measured directly by personal dosimeters, corrections need to be applied to account for inherent conservatisms associated with these simple measurements.

In the light of such uncertainties, the judgements of limits set for evacuation and goals defined for decontamination can be seen to be extremely conservative. Although this is a reasonable application of the precautionary principle, it can lead to concern of the general public and lead to problems when attempting to make decisions that involve trade-offs between costs/environmental impacts of clean up procedures with the resultant benefits in terms of reduction of already very small doses.

It would certainly be beneficial to develop models which more realistically simulate doses accumulated on an individual level, possibly also responding to the need to provide input to answer common stakeholder concerns (e.g. including estimates of the very small dose contributions from eating local foodstuffs with low contamination levels). As importantly, more effort has to be directed to the very difficult job of openly and clearly communicating health effects of low radiation doses to non-specialists, which requires training scientists to proactively communicate [84].

4 Decontamination and waste management

The previous chapters have covered the measurement of contamination and the work carried out to put this in context, in terms of the resultant dose to exposed populations. As noted in Chapter 1, after evacuation, decontamination was a high priority in order to reduce doses to sensitive groups outside the evacuated zone and to accelerate return of evacuees to close to normal lifestyles in their original communities. Because of the lack of experience in such decontamination – not only in Japan, but internationally – it was important to develop the tools and methodology to carry this work out in a structured and efficient manner. This work has been extensively documented in Japanese [22] and summarised in English in the Decontamination Pilot Project (DPP) report [23] [24] as described in the following section. In this chapter, emphasis will be placed on the lessons learned from the DPP work in terms of both future remediation work in Japan and also application to emergency preparedness worldwide and decontamination of specific legacy contaminated sites.

Here it should be emphasised that the DPP includes all techniques to reduce dose to populations. This represents conventional usage in Japan and is adopted throughout this section, although not consistent with IAEA definitions [85], which distinguish:

- Decontamination: the complete or partial removal of contamination by a deliberate physical, chemical or biological process.
- Remediation: 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.

The DPP aims are, however, consistent with safety requirements for remediation as defined by the IAEA [86]:

- Remedial actions aiming at the reduction of exposure to the public are subject to the application of the three radiation protection principles, namely, justification, optimisation and limitation
- Thus, any action has to be justified, so remedial actions should do more good than harm
- It has to be ensured that remedial actions are commensurate with risks and that they are expected to yield sufficient benefits to individuals and to society that outweigh the cost of such action and any harm or damage caused by the action.

4.1 **The DPP report**

The DPP report comprises 2 parts, the first describing the background, work plan and output from the Decontamination Pilot Project and the second summarising recent developments in regional decontamination, supporting R&D and international support initiatives.

4.1.1 Part 1

Part 1 initially provides the context for the DPP, which is determined by Japanese national policy for environmental decontamination following the 1F accident. This, in turn, leads to definition of the goals of, and expected output from, this project. Although JAEA supported early ad hoc actions to reduce doses in sensitive areas outside the evacuated zone (schools, kindergarten, play areas, etc.), the first focused study of decontamination technology was carried out by JAEA on the basis of a Government mandate of August 2011. This work was carried out at 2 sites (Date City and Minami Soma City) where the radiation dose was relatively low (outside of both the restricted and the deliberate evacuation areas). The sites were both small (~0.03 km^2), but included a wide variety of clean-up targets (e.g. houses, farm buildings, agricultural fields, vegetable gardens, wooded hillside, a playground for children, roads, natural / artificial drainage features, etc.) in topographic settings typical of this region. Although constrained by a short timeframe and limited budget, such work provided experience in the characterisation of contamination, planning and implementing remediation and quantifying the impact of different approaches which provided a technical basis for the DPP.

JAEA was chosen by the Government to conduct decontamination pilot project within all 12 municipalities that contained evacuated areas, although it was not possible to agree locations in one case (Futaba town) and hence first decontamination here was postponed to a later stage. The total allocated budget for this programme was 10.1 Billion Yen: including management and coordination costs, the field decontamination work itself and the subsequent synthesis to develop the input for regional decontamination. On the basis of open tendering in which a number of general contractors were asked to submit proposals for decontamination work (including planning and evaluation), three consortia were selected by JAEA: the Taisei Joint Venture (JV), the Kajima JV and the Obayashi JV.

To select the target areas for the Decontamination Pilot Project, land use type and physical geographical features in different options were considered. An important criterion in selection of a target area for decontamination work was to ensure that there was enough free space available to house and construct a temporary storage site (for the wastes arising) and the associated infrastructure accompanying such construction. This eventually resulted in identification of 16 model sites in 11 municipalities (Figure 4-1), including highly contaminated locations in the evacuated zones, where work was carried out over the period of September 2011 until June 2012.

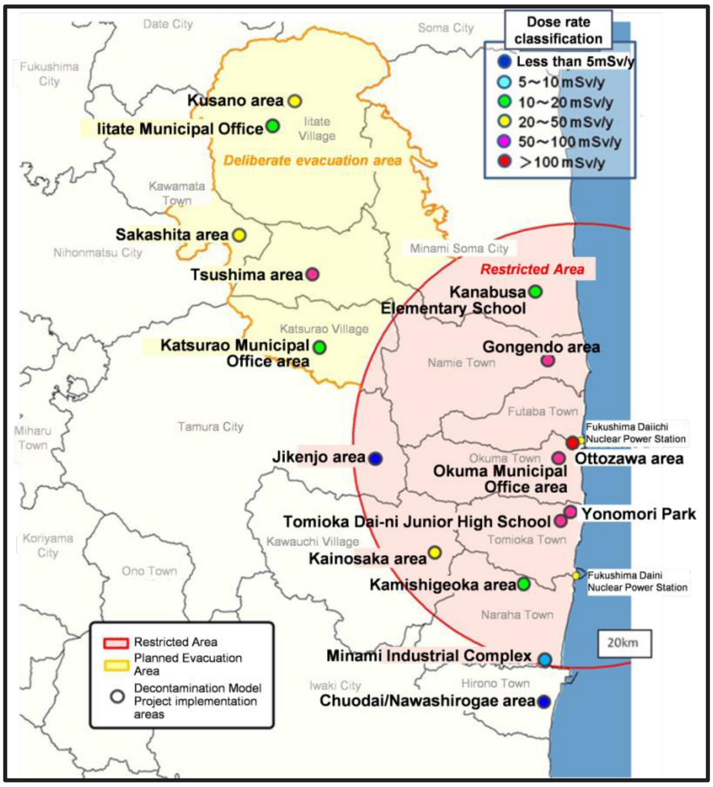


Figure 4-1 Map illustrating locations selected for decontamination with the affected areas; Average annual air dose rate data are also indicated (as of January 2012) [23]

The very short duration of the Decontamination Pilot Project was further complicated by the special problems resulting from the need to obtain permission to work on private property, the logistics of working in evacuated areas with often damaged infrastructure and cold winter conditions.

With emphasis on building experience for planning and implementing decontamination technology appropriate to Japanese boundary conditions, the JVs were encouraged to apply different technology to the targets specified. This allowed the pros and cons of variants to be assessed, which supported drafting of guidelines and manuals that could be used by the national government and local municipalities to optimise subsequent regional remediation work. The DPP thus led to a knowledge base on:

- The availability and efficacy of proven and new techniques
- Cost, work period, workforce, waste generated and radiation exposure of workers for each technique examined
- Management of resultant waste, including volume reduction, treatment of secondary waste and temporary storage until centralised interim storage becomes available
- Worker safety, both conventional and radiation protection
- Radiation monitoring (before, during and after contamination)
- Public communication

Although the decontamination pilot projects were extensively documented in Japanese [22], the DPP report includes summaries of all techniques applied as “yellow pages” appended to Part 1. It is not sensible to repeat details from the DPP report, but some general observations are worthy of note.

In terms of initial site characterisation, although the pilot projects were set up under extreme time pressure, which did not allow optimisation of procedures or standardisation of measurement protocols, manuals were developed to guide sampling and field measurement and independent quality assurance checks were introduced. Unlike conventional civil engineering work, it was difficult to visually assess the progress of large-scale decontamination work. Therefore, during clean-up, the surface dose rate was often monitored to check the effectiveness of procedures, particularly during removal of hotspots. Integration of electronic maps, geographical information (land use, etc.) and measured radiometric data worked well, producing fast and efficient approaches to assessing the relative distribution of radioactivity (or dose rate) in any remediation area.

For residential areas, a special focus for buildings was roof cleaning and, especially, the hotspots found in gutters, drains and other locations where runoff could collect or be collected. In general, simple manual techniques were generally found to be sufficient for dose reduction. Although high pressure water jets were tested and achieved good reductions in dose rate, care had to be taken to prevent water penetration of tiled roofs. Depending on the reduction in dose rate required for roads and paved surfaces, techniques that achieved good results included: high to ultra-high pressure jet washing (up to about 200 MPa), brushing, abrasion and, as a last resort, complete resurfacing.

A range of techniques were tested for agricultural land, including various options for soil removal (e.g. top soil stripping, sometimes with initial solidification) or soil profile inversion (e.g. deep ploughing). In many cases soil inversion was found to be as effective as soil removal and had the added advantage of preserving soil, which is an important resource, and producing no waste - thereby making this a particularly cost effective technique. However, the extent to which it could be applied was limited by both technical requirements in terms of contamination levels and also practical constraints – in particular the depth of the plough pan (an impermeable layer often found in Japanese agricultural land, especially paddy fields [87]). The resultant decision tree used to select appropriate treatment approaches is illustrated in Figure 4-2.

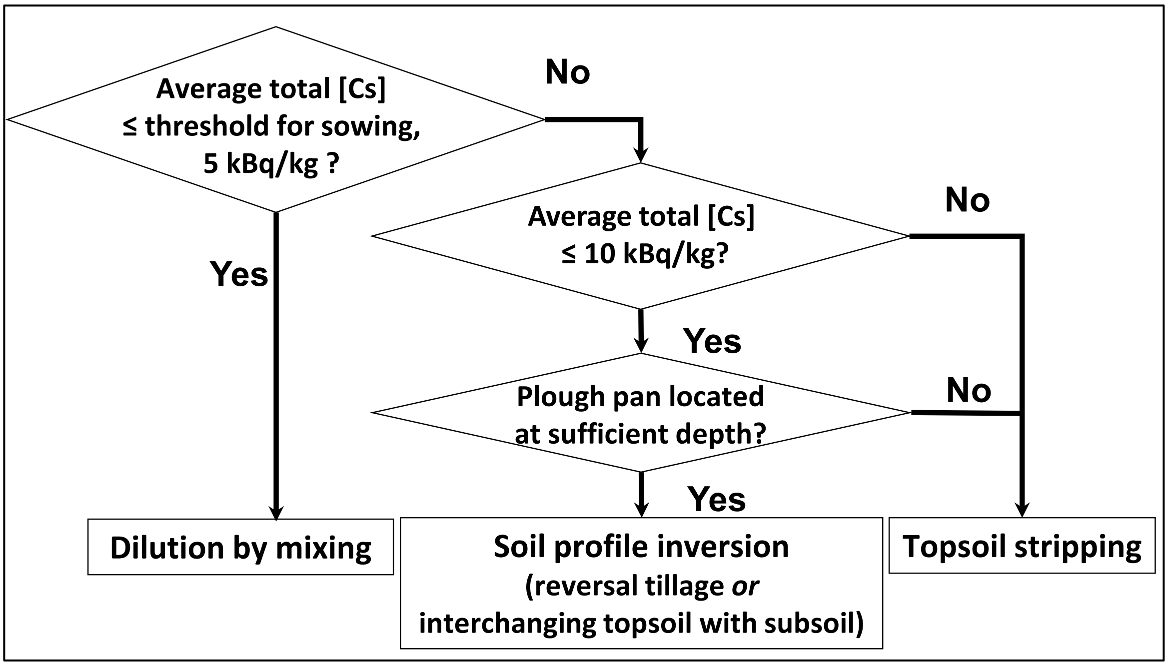
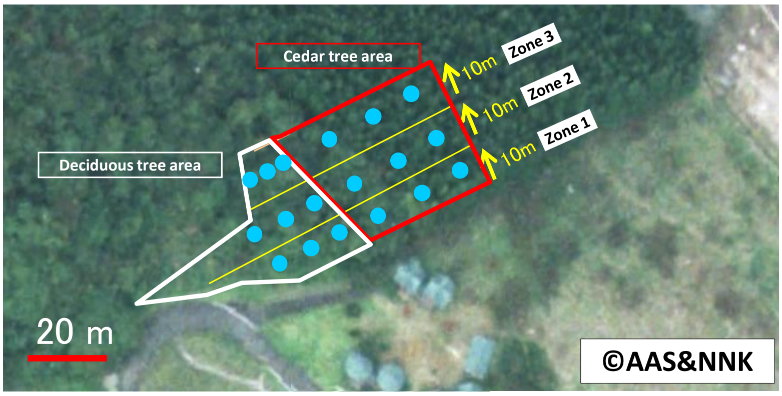


Figure 4-2 Decision tree for selecting appropriate decontamination approaches for agricultural land [23]

Forests form a large fraction of the evacuated zone but, within the DPP, emphasis was on wooded areas in the vicinity of residential areas; decontamination was thus focused on reducing the radiation dose in the living environment of nearby residents. From this perspective, it was generally sufficient to remove litter (fallen leaves, ground cover, etc.) for about 10 - 20 m in from the edge of the forest (Figure 4-3), but this range needs to be determined on a site-specific basis.



μSv/h

Location	Zone	Before clean-up		After clean-up			
				Mowing and leaf litter removal		Humus layer removal	
		1cm	1m	1cm	1m	1cm	1m
cedar tree area	1	3.1	2.7	2.3	1.4	1.7	1.4
	2	3.0	2.7	2.4	1.9	1.6	1.6
	3	3.1	2.7	2.1	1.7	1.4	1.4
Deciduous tree area	1	3.3	2.9	2.4	2.0	1.5	1.6
	2	4.0	3.0	2.4	2.0	1.7	1.6
	3	3.8	3.0	2.2	1.9	1.6	1.5

Figure 4-3 Impact of different decontamination options on dose in a residential area bordering forest [88]

Apart from target-specific experience, it was also generally noted that the fractional reduction in dose rate of any target tended to depend also on the original dose rate before decontamination (Figure 4-4).

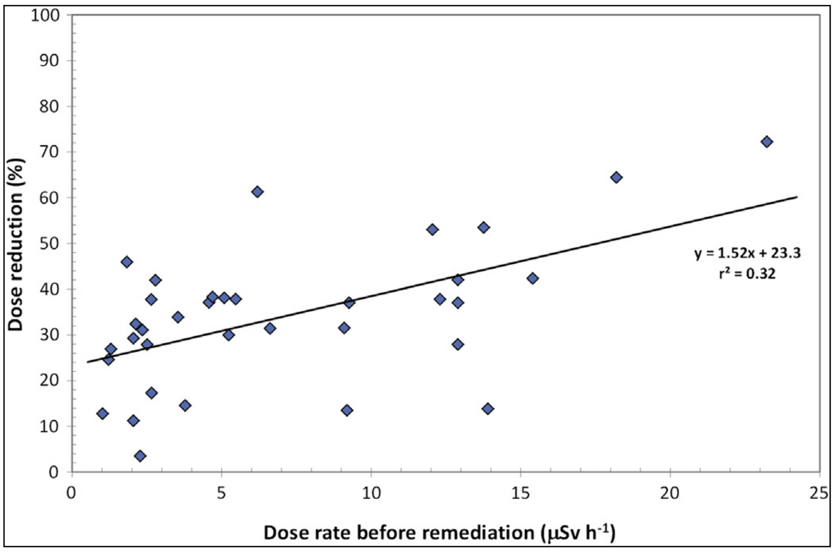


Figure 4-4 Observed reduction in dose rate as a function of measured dose rate before remediation [89]

Although the correlation is weak and for sites with low contamination levels (Tamura city and Hirono town) particular emphasis was placed on reduction of the volume of waste produced, the trend is not unsurprising as these external gamma dose measurements include contributions from natural background radiation and fallout from atmospheric testing of nuclear weapons, which will be little or not at all influenced by decontamination actions. Additionally, any measurement integrates dose from a very wide range of distinct sources surrounding the measuring location, some of which may be non-treated areas (NB the half distance of ^{137}Cs gammas in air is about 70 m). The impact of both these features will tend to be larger for less contaminated sites, when the local contribution to dose is low.

A key aim of the DPP was to examine options to reduce the volumes of waste produced and ensure that any water used could be cleaned to the extent that it could be discharged to normal drainage. Solid wastes resulting from decontamination were packaged in standard flexible plastic containers, labelled and stored at the temporary storage sites. The designs of such temporary stores were tailored to available sites, but all included measures to assure mechanical stability (e.g. graded cover with soil) and prevent releases to groundwater (impermeable base and cap, gravity flow drainage including catch tanks and radiation monitors). The facilities at the temporary storage sites have been monitored since then, to check performance is maintained and, in case of any problems, ensure that appropriate actions are taken.

4.1.2 Part 2

Part 2 provides an overview of how the output from the DPP has been used to form the basis for full-scale regional remediation of the evacuated areas, which is ongoing under the responsibility of the Ministry of the Environment (MoE). This includes experience in project planning (Figure 4-5), site characterisation, decontamination and quantification of its effectiveness, communication and waste management.

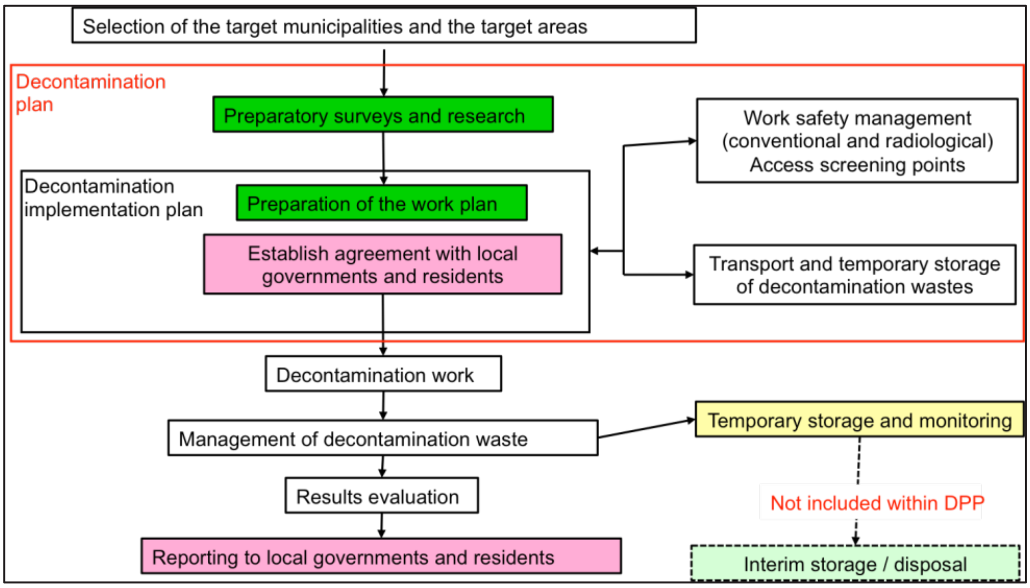


Figure 4-5 Outline project planning and work flow, based on DPP [23]

An overview is also provided of the status of work as of September 2014. Further updates are available on the MoE homepage [90]. As noted already in section 1.3.3, the work in the lower contaminated areas is proceeding well; the evacuation order for two of these areas was lifted (Tamura on 1st April 2014 and Kawauchi on 1st October 2014) and significant progress has been made in several others.

In particular for Naraha and Kawauchi, the critical steps of securing temporary storage sites and obtaining consent of land and property owners are effectively complete; at other locations the ability to store waste produced may actually be one of the main constraints on decontamination activities. For completeness, however, it should be noted that other work aims at re-establishing critical infrastructure for the entire region, with an initial focus on the Joban Expressway.

Overall, the results of regional remediation have matched expectations based on the smaller scale DPP work. The trend of decreased fractional dose rate reduction in less contaminated sites was also evident.

However, the extent of dose reduction for forest was relatively low, which reflects the experience from the JAEA DPP work and also understanding of the environmental behaviour of Cs in such environments. The MoE reviewed the progress and policy of decontamination work on September 2013 and stated expansion of procedures to the management of forest decontamination including locations such as forest surrounding residential areas. If removal of organic surface material (e.g. litter or litter and humus) from the 20 m peripheral zone was found to have limited effect, further removal of organic debris (e.g. humus depending on what was initially removed) from the initial 5 m zone was performed [91].

4.2 Special issues associated with future decontamination planning

Although it was seen that the fractional dose reduction in more contaminated areas was generally larger, as future phases of work move into more contaminated areas, even higher decontamination factors will be needed in response to high local dose rates. Such decontamination should, ideally, also be achieved by more efficient tools and technology, which reduce the volumes of waste produced and doses to the workers involved. Focused R&D is required that combines exploitation of experience gained in the regional decontamination work with advances in understanding of contamination and the technology used to remediate high dose rate locations noted in section 1.3.3.

In essence, there are 3 issues to be considered:

- To what extent can existing approaches be optimised in order to provide the increases in performance required?
- Are new techniques and approaches available that, given the specific boundary conditions for the higher contaminated sites, may be developed to meet requirements?
- If decontamination involves an unreasonable investment of resources or has potential for serious environmental degradations, can redefinition of land use lead to a solution that is acceptable to stakeholders?

It should be emphasised that consideration of such issues is ongoing at the present time and, as yet, no conclusions have been reached. Nevertheless, it is worth considering these 3, potentially complementary, approaches in more detail.

4.2.1 Further development of existing technology

As described in detail in the DPP report, the techniques applied to date in the regional remediation predominantly involve low technology, manual cleaning using equipment that can be taken over directly – or in slightly modified form – from other applications. This is sensible from a technical point of view, allowing rapid mobilisation at reasonable cost, but also provides a social benefit to communities by providing employment for those displaced by evacuation (either from the contaminated zone or as a result of the huge devastation caused by the tsunami). As experience is gained using this equipment, options for improvement will be noted and, indeed, this is a part of the QA systems used by all organisations involved in this work.

A particular challenge involves cleaning surfaces, as natural washing increasingly removes any readily mobilised contamination and, with time, immobilised Cs tends to become more strongly bound or penetrate further into surfaces. It is thus expected that low pressure washing and simple wiping / brushing of surfaces will increasingly need to be replaced by high pressure washing and surface abrasion (e.g. ice, dry ice, iron shot). R&D is required to develop the required technology, with a focus on problems identified with current approaches (e.g. damage of structures due to high pressures, production of secondary wastes, slow rate of cleaning). This may well be a simple evolution from use of general purpose vehicles to those specifically designed for decontamination under the conditions in Fukushima Prefecture. Although increasing use of tailored equipment may reduce manpower requirements, this may have benefits in terms of reducing both conventional working risks and also doses to workers in more contaminated zones.

As indicated previously in Figure 4-2, minimisation of removal of soil will be increasingly difficult as contamination levels increase. From a technical point of view, the focus on concentration in soil is rather simplistic, as Cs behaviour is very dependent on clay content and, in principle, different management options could be justified for clay-rich and organic-rich soils. Nevertheless, surface removal is likely to be increasingly required for higher dose zones and hence techniques for optimising this process are required (e.g. a variable depth cutter could be combined with a gamma-scanner to allow only the highest activity layer to be removed). Although it may increase complexity, combinations of thin layer stripping and soil profile inversion could be considered (possibly involving some kind of combined function machine) with the aim of preserving soil as a resource for returning communities and minimising waste production.

Although self-cleaning of easily mobilised contamination has benefits, this also means that, increasingly, radiocaesium is building up in locations where such mobile material is trapped – i.e. natural and artificial drainage systems. Although most land run-off may eventually end up in the sea, where it is diluted to insignificance, trapping in locations that could give rise to population exposure (agricultural and domestic drains, sewerage, pond sediments) may need increased consideration as more heavily contaminated areas are remediated, requiring tailoring of current technology.

4.2.2 Novel approaches

As described in the DPP report, the field decontamination projects were complemented by a range of fundamental R&D projects that examined the potential of more novel / high technology approaches to decontamination and waste volume reduction. This work showed that, for the DPP boundary conditions, some of the techniques studied would provide little benefit due to high cost, low efficiency or long timescale required for sufficient decontamination. For the case of the most highly contaminated zones, it is worth reconsidering this assessment, particularly as significantly longer timescales may now be considered. In this case, an option would be some form of phytoremediation – removal of contaminant by a "hyper-accumulating" organism [92]. Although Cs does not tend to be concentrated within organisms, there are some exceptions such as fungi, mosses and lichens (e.g. [93]).

In principle, such an approach could be applied to both agricultural land [94] and forest ecosystems [95], but it should be borne in mind that indigenous species will be required not only for accumulated concentration but also for decontamination effectiveness (DF) and efficiency.

As noted in the previous section, run off of Cs is a concern – not only in terms of providing a process to concentrate contamination, but also as a mechanism for re-concentration in areas that have already been cleaned up. In the latter regard, a particular concern involves the river banks and flood plains beside larger rivers, which tend to be heavily used for recreation e.g. playing fields (Figure 4-6) walking paths, etc.

Figure 4-6 Baseball being played on a flood plain (an example in Fukushima city)

The problem arises only during periods of flooding associated with very high rainfall (e.g. during typhoons) or rapid snow melt. To avoid repeated decontamination, it is worth considering catchment-level integrated water course management, which could combine ordinary dam management, river flow management (e.g. via embankments, dredging or levees) and provision of flood areas (e.g. nature reserves – see following section).

4.2.3 Redefinition of land use

In previous contamination incidents, control of land access / use has tended to be the major approach used to reduce population radiation exposure [96] [97]. In Japan, the high economic and cultural value of coastal land and the relatively low level of contamination has allowed this to be considered only as a temporary measure, as specified in the plan for return of evacuees as discussed in section 1.3.2. Nevertheless, for the most contaminated areas and those very close to the 1F site, it is worth considering re-zoning, especially if this can be seen to have benefits for the returning residents.

In the Chernobyl exclusion zone, biodiversity has increased considerably in even the most highly contaminated areas, allowing this area to be considered as a nature refuge [98]. For the very much lower levels of contamination in Fukushima, such nature reserves could serve as a valuable cultural resource.

Centralised interim storage sites for decontamination waste are already planned for this area and how such sites are utilised after the planned 30 years storage is worth considering. More generally, the problems of surface contamination with radiocaesium are much less significant for industrial sites compared to agricultural or residential areas. For heavy industry, ground cover with concrete is common, which would reduce the need for decontamination before construction. This would be particularly the case for licensed nuclear sites – e.g. a central decommissioning centre of the Studsvik (Sweden) type [99] - a facility that could be in great demand to provide services to the 1F site. Although industrialisation would change the nature of the locations involved, this could provide benefits in terms of long-term employment.

4.3 Special issues associated with communication

Communication has been a critical issue in the aftermath of the 1F accident – both nationally and internationally [100]. For the specific case of decontamination, challenges start with obtaining permission from local government (mayors of local municipalities and heads of administrative districts) and land / property owners to allow work to take place and, in particular, to construct temporary waste stores. Briefing sessions with communities and the use of a clear and simple consent form helped to facilitate this process.

While work is ongoing and after it is completed, it is important to explain what has been done to assure residents that they can safely return to their homes. Materials for explaining remediation to stakeholders and providing the basis for establishing dialogue with them have been developed, including plans of remediation and temporary storage and explanation of the effectiveness of remedial measures. In addition to a wide range of conventional communication techniques (meetings, school visits, telephone helpline, brochures,… - described in more detail in the DPP report), the internet has been widely used. Although most material is available in Japanese, English summaries are provided by JAEA [101] and associated links [102].

Despite some successes in establishing dialogue with stakeholders, the communication of risks associated with low levels of radiation has been difficult – matching general international experience (e.g. [103]). Although remediation goals expressed in terms of long-term reduction in additional gamma dose to 1 mSv y^{-1} may be a reasonable strategy, it is difficult to explain that levels between 5 and 20 mSv y^{-1} are considered to be safe and within the range of natural variability of radiation exposure which is known to have no measurable health impact. Given that there is still a tendency to focus on incorrect comparisons with Chernobyl and exaggerate problems on the 1F site, it is not surprising that non-specialists find the mixed messages very confusing. It is evident that more needs to be done, possibly with more effort to put Fukushima contamination into context by comparisons with the UK, Fenno-Scandinavia and the southern Alps, rather than the Ukraine.

In the future, there is also a need to establish dialogue in order to generate consensus on the best way to remediate the higher contaminated areas nearer to the 1F site (preceding section) and also long-term management of decommissioning wastes (following section). It is clear that, in both these cases, technical arguments need to be balanced against socio-political and financial issues and that many non-technical stakeholders (especially local communities) must be involved in (“buy into”) the decision-making process. This may require some changes in the normal roles in such procedures, but this should be encouraged if it leads to a better outcome for all involved

[2]. Nevertheless, it will require that all options of the kind discussed in this chapter are fully understood, along with their pros and cons – which will be a major communication challenge. Useful experience that might help here could be derived from public dialogue associated with siting nuclear waste repositories – e.g. in Switzerland [104].

4.4 Waste management challenges

As noted above, during the DPP work, a range of options were investigated to reduce the volumes of solid waste produced and avoid all production of liquid wastes. In this and the subsequent regional decontamination, the waste management options available were greatly constrained by the need to carry out work as quickly as possible and the practical requirement to store all wastes at their point of production. Continuing clean-up efforts are generating large volumes of contaminated soil and waste of which the total volume is estimated to be between 16 and 22 Mm^3 [28], which must be managed in a safe and cost-effective manner, wherever possible implementing waste volume reduction.

As discussed previously, all options to minimise removal of soil should be considered. If soil is removed, future reuse of soil for construction purposes should be considered, if constraints in terms of allowable organic and clay content can be managed. As Cs is very strongly bound to most soils, use as ballast or infill might provide options for both reducing total costs and also minimising environmental impact. In areas near the coast, tsunami defence projects might be a possible target. Another option, if current regulatory hurdles could be cleared, would be use of off-site soil as ground cover or infill on 1F site. An example of such an application might be if a decision was made to infill the 1F harbour in order to immobilise contaminated sediment, where large volumes of contaminated soil could be used as bulk infill before a cap of clean soil, asphalt or concrete is applied.

For waste in temporary storage, a key concern is degradation of barriers. The wastes stored – especially organic materials – are inherently unstable and will degrade with time. The containment barriers (clay, thin plastic sheeting) are not inherently robust to both the effects of waste degradation and also external perturbations from extreme weather conditions (typhoons, hot-cold temperature cycles). In the interim, it may be required to regularly assess the condition of existing temporary stores (e.g. gamma and geometry scans).

Assuming that storage sites perform as planned, the waste containers can simply be lifted out when central interim storage facilities become available and directly transported by truck. Indeed, as soon as interim storage is available, it would be beneficial to transport generated remediation wastes to the central site(s) immediately, avoiding the temporary storage step. This would simplify the material flow.

For the centralised interim store(s), the key challenges will again focus on organic material and hence an incineration plant is included in the concept. This would ideally be designed to make use of the heat produced (e.g. for drying soil designated as waste) to optimise the conditioning and packaging of the ash. Ash from incineration of wood or organic waste corresponds to about 1% of the original weight [105] and hence significantly concentrates the included ^{137}Cs.

Cs will be present as a trace component associated with K in such ash, which is highly soluble. Conventional cementation will thus result in a matrix which performs poorly with respect to leaching by groundwater. As long as the cement is kept out of contact with water after curing (e.g. within a steel drum), this would not be a problem. Given the solubility of Cs and its potentially higher mobility in the presence of K, however, it is important that a solution is developed that is appropriate for final disposal. Fundamentally, the options are:

- Accepting limitations of a standard cement matrix / steel drum and developing disposal designs that assure acceptable performance based on the properties of the site and the complete engineered barrier system
- Improving performance by use of additives; although there is some relevant international literature and practical experience, this will probably require some focused R&D to develop optimised solutions
- Improving performance by developing container options that may assure longer lifetimes under humid conditions (e.g. heavy-duty plastics as used in the chemicals industry)
- Considering alternative isolation matrices for ash. There is international expertise in use of bitumen and a number of resins, but again R&D may be needed to develop a solution tailored to Japanese boundary conditions.
- Dissolution of Cs from ash and immobilisation in an alternative matrix. The expertise developed in handling contaminated water on the Fukushima Daiichi site could be relevant here.

This last option highlights the potential synergies involved if off-site waste management is integrated with management of the generally more problematic waste on-site.

In terms of facility design for final disposal, it is advantageous if this is done in a structured top-down manner, rather than simply attempting to take over designs from other projects. A considerable knowledge base on disposal of different types of waste exists in Japan and this can be mined to help the planning process. Potentially as important, knowledge management tools have been developed and implemented and these could help formalise the design process and link it to the required safety case. Two particular tools may be useful here – requirements management and argumentation modelling.

Requirements management provides a formal approach to identify the key constraints on the disposal facility and determine what conflicts may be present. Identifying inevitable requirement conflicts at an early stage, is useful to allow the advantages and disadvantages of different concept, design and operational plans to be listed and trade-offs considered to develop an optimised system in an iterative manner.

Linking technical aspects of design and operational planning to other pragmatic requirements (e.g. quality assurance) and the coupled safety case might be facilitated by argumentation modelling. Such a model allows the key issues that influence performance to be highlighted. Although it is anticipated that the site will remain under active institutional control for its planned lifetime, the occurrence of perturbations due to typhoons and earthquakes – and in some locations possibly flooding or tsunamis – cannot be precluded. The requirements of allowing waste to be easily retrieved yet providing robust performance for all potential disruption scenarios will be a significant challenge.

Although waste retrieval is planned within 30 years, no fixed concept for subsequent disposal yet exists. Indeed, greater integration of management of all radioactive wastes generated on- and off-site may provide benefits if a regulatory basis could be provided and if it was acceptable to stakeholders [106].

4.5 Recommendations

Possibly one of the key lessons learned from the decontamination work is that, despite many incidents causing local, regional or global contamination over the last 5 decades or so, there is very limited experience that can be drawn on to support remediation of the type planned and implemented within the Fukushima Prefecture. Indeed, although radiocaesium has been a major component of several past incidents and it is one of the most widely studied radioisotopes, decontamination has rarely been attempted in the past and emphasis has instead been placed on reducing health impacts by controlling specific foods, restricting land use and monitoring self-cleaning of the environment. Because of the unique knowledge base produced, recommendations are worth considering for the 4 main topical areas involved: site characterisation, decontamination, waste management and communication.

4.5.1 Site characterisation

To facilitate effective contamination monitoring, on the basis of experience to date it can be recommended that:

- Plans for monitoring are developed based on site-specific constraints and with consideration of staged implementation before, during and after remediation,
- Equipment allowing continuous profiling with automatic data-logging is used as much as possible, with detailed point measurement / sampling used for calibration,
- Monitoring includes sediment in rivers, pond, lakes, etc., as radiocaesium is often transported to such environmental compartments associated with erosion of surface soil,
- A special focus is identification of hot-spots, which could require special precautions for workers or be priority targets for clean-up.
- From a perspective of future plans, it can be further recommended that:
  - For farmland and forests, contamination monitoring is tailored to remediation options, both in terms of what is measured where, but also the timing of monitoring (related to plant growth cycles),
  - The effectiveness of some remediation options may change dramatically with time after contamination (e.g. removal of leaf litter) and these may be special focuses for monitoring,
  - A comprehensive programme for foodstuff monitoring is implemented to allow total dose models to be developed.

In addition, although the focus has been on the terrestrial environment, radiation monitoring in the coastal marine environment has included water, sediment and a wide range of seafood. This has been used to monitor self-cleaning by decay, dilution and dispersion.

4.5.2 Decontamination

To facilitate the choice of optimal decontamination technology it is recommended that:

- Focus is on simple approaches that can be implemented with available equipment and relatively inexperienced manpower,

- Wherever possible, aim to avoid waste production, recycle waste or minimise the volume produced. In particular, contaminated water should be cleaned to a level allowing free release into normal (or industrial) drainage,
- In order to compare options, practical experience is needed to determine decontamination efficiencies, cleaning rate, manpower requirements, costs, environmental impact, etc. under representative conditions,
- All options are considered subject to specified boundary conditions. The spectrum involved extends considerably if slow remediation is acceptable (e.g. phytoremediation),
- All potentially negative side-effects of remediation technology in terms of both risk of spread of contamination and environmental degradation are assessed and explicitly included when comparing options.

Further, in terms of planning and implementation, it is recommended that:

- Planning teams are familiar with the practicalities of managing major projects, but also the special requirements of handling radioactive materials (assuring that any required training is provided),
- Selecting approaches / tools includes explicit consideration of the pros and cons of alternatives, which can be facilitated by a simple, user-friendly database of options,
- Scheduling is carefully considered both in terms of minimising risks of recontamination and also logistical optimisation,
- The process of gaining required permissions is simplified to the extent possible,
- Manuals are produced to standardise planning of all remediation actions,
- A central knowledge base is established to allow communication of lessons learned between all those working in remediation projects,
- For work involving major expenditure, the contracting process is appropriate and transparent.

4.5.3 Waste management

To develop an optimised waste management programme it is recommended that:

- All possible options to avoid waste production while reducing radiation exposure to acceptable levels should be considered,
- Waste volume reduction should be considered, especially when it may increase stability with regard to required storage / disposal (e.g. incineration of organic waste),
- Aqueous waste streams are decontaminated to allow free discharge, if at all possible,
- The entire process of storage and disposal should be optimised to reduce both operational phase and post-closure risks.

Although it may be considerably constrained by regulatory or socio-political boundary conditions, if possible, there may be benefits if responsibility for all waste management activities is assigned to an experienced organisation or group who can develop a holistic overview and contribute to total programme optimisation.

4.5.4 Communication

To facilitate effective communication it is recommended that:

- Communication is treated as a top priority, recognising that risks to health from fear can be greater than those due directly to radiation,
- The impact of modern media is taken into account in order to assure messages reach key stakeholders, especially the evacuees and those living in neighbouring communities,
- For cases where public acceptance is critical to implementation of remediation, emphasis is placed on developing effective dialogue.

If possible, it may be advantageous if a single organisation is charged with the task of coordinating all remediation communication to ensure consistency of messages, user-friendliness of materials, active facilitation of dialogue.

5 Assessing natural mobilisation of Cs in the environment

The previous chapter outlined regional decontamination of radiocaesium, emphasising that this is occurring on a scale never attempted before. Nevertheless, it is neither possible nor necessary to decontaminate the entire area where fallout occurred. In particular, most of the prefecture is covered by forest (about 70%), which is both difficult and costly to clean up except where surrounding residential areas. Further, natural mobilisation processes have already transferred a fraction of the fallout inventory to river, dam, pond and, eventually estuarine and coastal marine sediments – which are also unsuitable clean-up targets. It is thus necessary to complement decontamination with a rigorous quantification of natural mobilisation of Cs in the environment – both to understand self-cleaning of contaminated environments and also to provide a basis for managing any possible risk of such processes re-concentrating areas that have already been decontaminated.

This chapter first provides the background to, and current status of, the F-TRACE project carried out by JAEA to assess such natural mobilisation. This work is then put in context by considering future challenges, which includes integrating JAEA work with that of the many other R&D organisations and universities, who are involved in related studies.

5.1 Background to F-TRACE

The JAEA study of long-term assessment of Transport of Radioactive Contaminants in the Environment of Fukushima is referred to as F-TRACE [107] [108]. It includes assessing radiocaesium transport processes as illustrated in Figure 5-1, including:

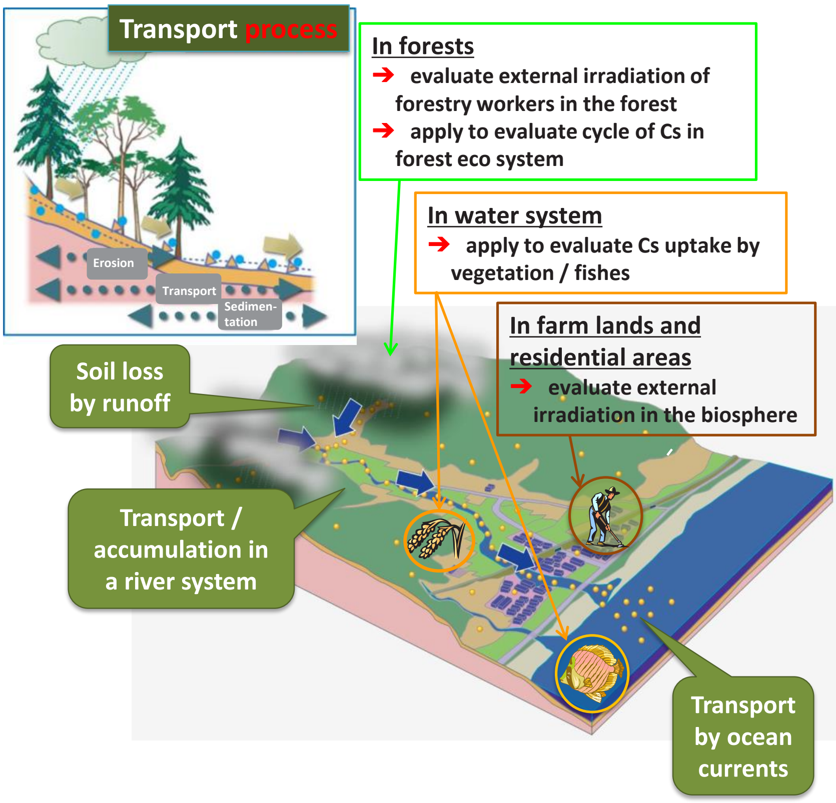


Figure 5-1 Overview of processes studied in F-TRACE [109]

- Distribution between different surface environment compartments following initial dry or wet fallout: wash off from foliage and other unreactive surfaces, uptake / binding onto other materials - especially clay-rich soils;
- Subsequent migration of radiocaesium in open ground (both natural and agricultural land), with a focus on the transfer of Cs bound to soil and sediments due to terrain erosion, the seasonal variation of this process (roles of snow melt and high rainfall events) and the restraining impact of vegetation;
- Gradual migration of the large fraction of the radiocaesium inventory captured by forest canopies to ground by rain wash-off and leaf fall, transfer within the litter layer and eventual capture (in most cases) by the forest soil layer underneath;
- Catchment-scale movement of Cs-loaded suspended sediments in the aquatic environment, through streams, rivers and estuaries into the coastal marine environment, accounting for trapping in ponds, lakes and dams. Here transfer back to the terrestrial environment (mainly flood plains during periods of high river flow) and potential options to counter this (e.g. via dam management, river levees) is also considered.

Such understanding is integrated with a focus on understanding current and future doses resulting from direct radiation exposure (e.g. to forestry workers, farmers, those using flood plains for recreation) and also uptake into the food chain (crops, fish, wild mushrooms, etc.).

The studies have been carried out at model sites selected in highly contaminated areas located northwest and southwest of the 1F site. These include representatives of all key environmental zones, including forests, river systems, dam lakes, ponds and estuaries (covering the 7 main river systems in the coastal area of the Fukushima Prefecture) – Figure 5-2.

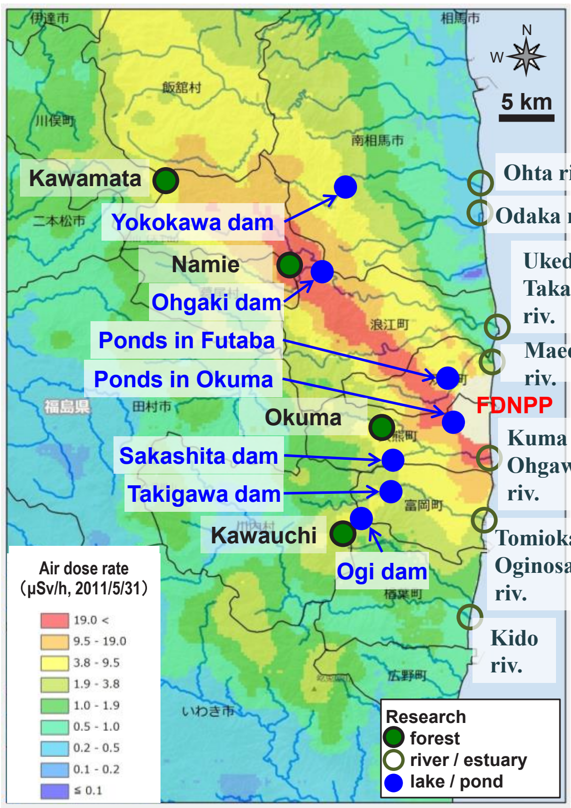


Figure 5-2 Map of main F-TRACE field study sites

The specified objectives of the studies are to:

- develop models to quantify transport behaviour of particulate-bound radiocaesium from forests to sea through river systems,
- assess and forecast future evolution of air dose rates and Cs uptake within the food chain,
- propose and test measures to mitigate any potentially significant external exposure.

An example of the kind of integrated data set that is produced for a study site is provided in Figure 5-3. At this particular location (Oginosawa River / Ogi Dam), the upper part of the figure illustrates general site characteristics associated with this generally forested landscape at this time period, about 2.5 years after contamination. Negligible concentrations of radiocaesium in lake water confirm expectations that, in this system, transfer is dominated by particulate or colloidal phases.

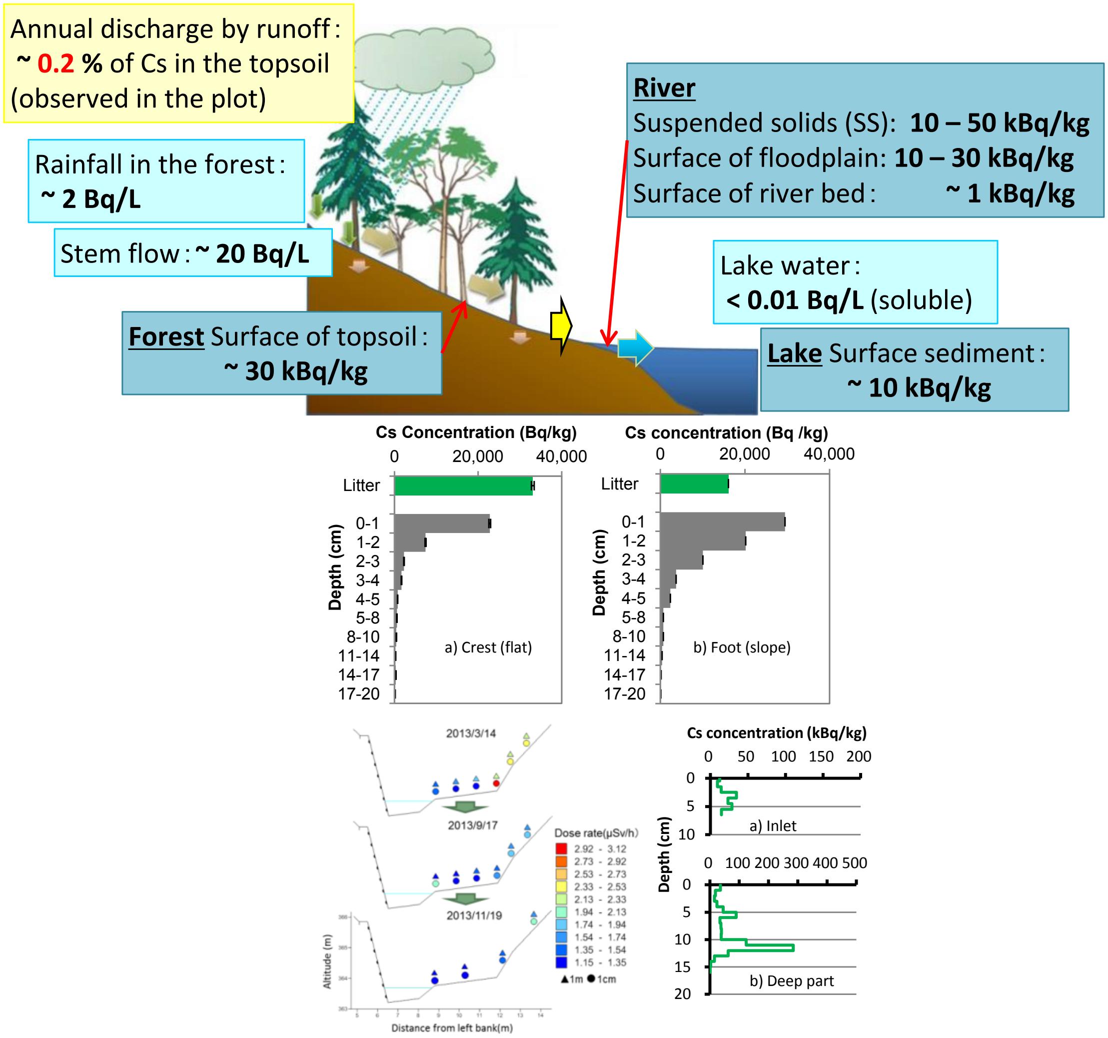


Figure 5-3 Example of integrated data set for a study site (Oginosawa River / Ogi Dam) illustrating general site characteristics (upper); soil profiles from a local cedar forest (middle) taken from the crest (left) and foot (right) of a hill; evolving dose rates measured on the river flood plain (lower left) and sediment profiles from the dam (lower right) measured at the inlet (upper) and deepest part of the dam [107] [109]

Soil profiles from local forest dominated by Japanese cedar, an evergreen tree, illustrate both the gradual transfer from the litter layer to soil and transfer within the soil profile (Figure 5-3, middle). Although the exponential depth profile is reminiscent of those resulting from diffusion, in this case water penetration is more likely to be responsible. Comparison of profiles from upper and lower parts of a slope (left and right, respectively) also illustrates the consequences of erosion and soil slumping, gradually transferring surface contaminated soil down gradient [108].

The evolving dose rates measured on the river flood plain (Figure 5-3, lower left) illustrate, in this case, the impact of various natural remediation mechanisms which can include, in addition to radioactive decay, erosion of surface contamination, dispersion of such activity through the soil column or burial by less contaminated material – or a mixture of several of these mechanisms. Both depth profiles of contamination and models of local sediment redistribution are required to develop the more detailed understanding required for quantitative predictive models [110] [111] [112] [113].

With particulate transport in surface waters playing such an important role, it is important to understand how sediment is moved or trapped during river flow. For example, profiles from the Ogi dam (lower right) measured at the inlet and deepest part of the reservoir show the effects of sediment capture, with high activity material representing first runoff after initial fallout possibly preserved as a buried layer in deeper waters [114]. The existence of such material is an important constraint when considering normal dam management practices.

The situation in the small, rather shallow Ogi dam can be compared to that in the larger Ogaki Dam (Figure 5-4).

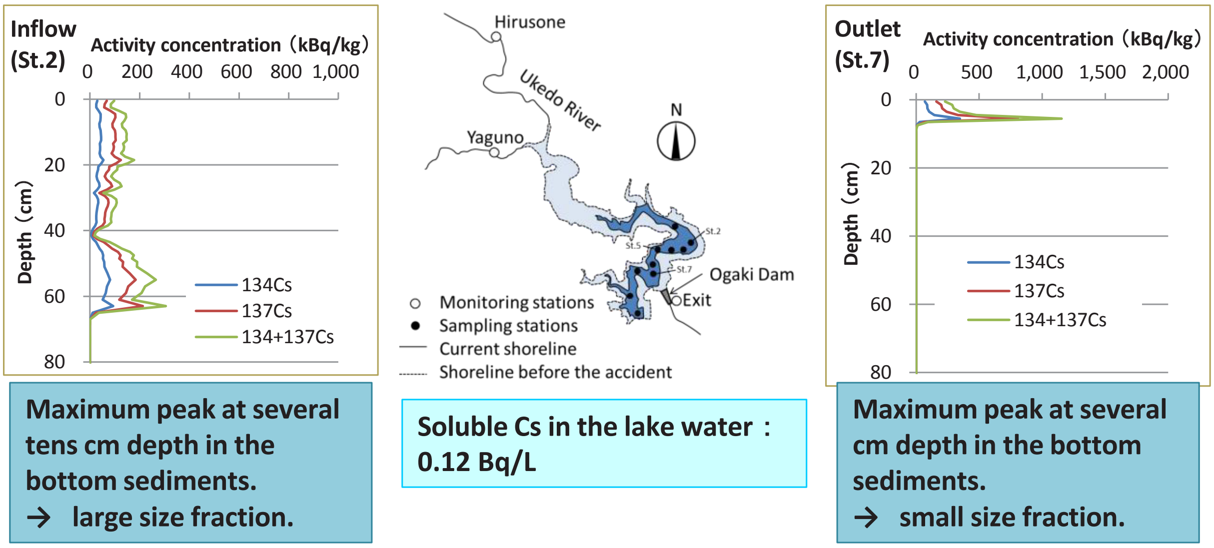


Figure 5-4 Comparative data set for another study site (Ogaki Dam) [115]

The differences in the profiles can be explained by the fact that, for the latter, slowing of water velocity at the inflow causes deposition of most of the suspended load – building up a thick layer of contaminated sediment. Very little suspended material is carried as far at the outlet, but this corresponds to the smallest size fraction, which also tends to have the highest radiocaesium loading. The thinner layer of contaminated sediment thus has a higher peak activity.

Another comparative example from further down river is taken from the Ukedo River basin (Figure 5-5). Here there is little change in doses measured in the flood plain, possibly reflecting a dynamic system in which general removal by erosion is balanced by re-concentration by individual flooding events. River bed sediments show a slightly decreasing trend, which may represent transport into the estuary, where dilution / burial with uncontaminated coastal marine material will occur.

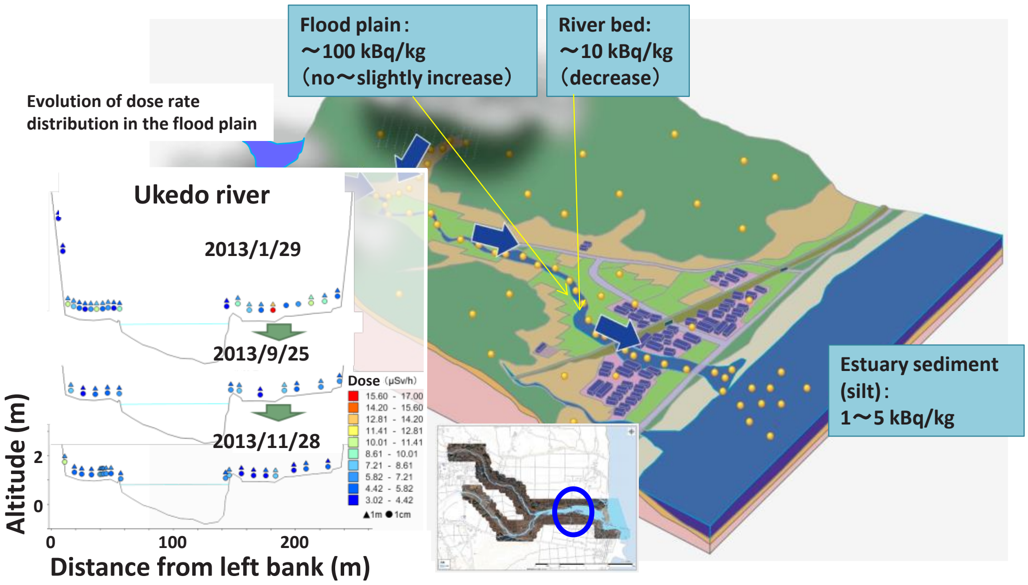


Figure 5-5 Comparative data set for the Ukedo River basin and estuary [109]

As the mouth of the river is approached, however, the situation becomes more complex as the influence of tides causes fluctuating water chemistry and flocculation of fine suspensions / colloids. This area is also subject to more complicated influences from events such as strong typhoons, combining initial storm surges (sometimes called “meteotsunamis”) of marine water with later high flows of river water. These effects are on top of the process of gradual recovery of estuarine topography which, in many cases, was greatly transformed by the Great Tohoku tsunami.

In addition to such regional studies to characterise and, eventually, quantify regional-scale radiocaesium mobility, very detailed investigations focus on transport mechanisms at a micro scale. A good example here is an investigation of Cs redistribution within forest soils (Figure 5-6), which is especially important given the large extent of forests and the impracticality of decontaminating them. Indeed, for all deciduous forests and most evergreens, by now inventory in foliage is negligible and hence the interest is how Cs in soil might be either transferred to deeper soil layers or, possibly, into a root zone where uptake by biota may occur.

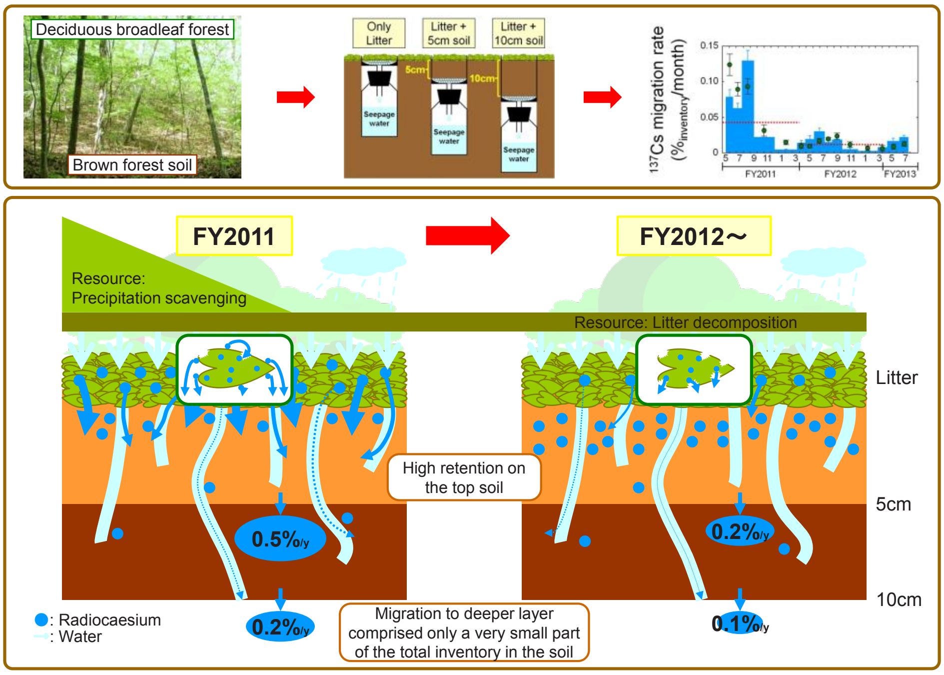


Figure 5-6 Detailed studies of Cs transport in forest soils [116]

As indicated in Figure 5-6, biodegradation of litter is now the rate-determining step for transfer to upper soil layers, with displacement of a small fraction of this material by water infiltration causing slow transfer to greater depths. As is known from past studies of Cs fallout, it is critically important to consider the ecology of different types of forest when planning, implementing and interpreting such work [95]. Nevertheless, important general observations are that > 90% of Cs fallout remains within the upper 5 cm of forest soil. In the event that such material is transferred to surface waters, associated Cs is effectively irreversibly bound (when expressed as a “Kd”, this would be > 10^6 l/kg – but it should be emphasised that Kd is strictly applicable only in the case of fast, reversible sorption, which is clearly not the case here [117].

Overall, therefore, the F-TRACE project and related studies are developing a comprehensive knowledge base on Cs transport mechanisms in specific Fukushima environments, which can form the basis of rigorous future dose forecasts and planning of any counter-measures required to reduce such doses – as considered further in the following section.

5.2 Future Challenges

Understanding the processes influencing the current and future distribution of radiocaesium is only a starting point for developing the tools to support return of evacuees to the contaminated zones and allowing them to live a normal lifestyle. Specific challenges that are focused for on-going and future work include management of the contaminated forests that represent such a large proportion of the land surface in this region and are also an important resource for the forestry industry, tourism and exploiting the wild foodstuffs that were such an important part of the culture of this area (e.g. mushrooms).

This area is also characterised by the main river catchments that define the populated zones and, in particular, important agricultural and recreational land and also freshwater fisheries. Management of aquatic systems is thus a key component to allow local populations to recover the lifestyles they had prior to evacuation. A special issue associated with this is the possibility of radiocaesium re-concentration in the environment – either in decontaminated areas or those that are subject only to natural mobilisation processes. Based on such understanding, current and future risks can be assessed and effective counter-measures developed. These are now discussed in more detail.

5.2.1 Forest management guidance

Fundamentally, countermeasure options to reduce doses within forest areas range from complete restriction of access (as applied in other contamination accidents such as Chernobyl or Mayak [118]) to some form of comprehensive decontamination. Both of these options have specific advantages and disadvantages, which must be assessed for Fukushima-specific boundary conditions. Complete restriction of access would have major impacts to the locally important forestry industry, tourism and the normal lifestyle of residents. It also introduces possible hazards to this intensively managed forest ecosystem, for example increasing the risk of forest fires (possibly more of a risk than in the past as a result of climate change), which could potentially cause extensive re-concentration of Cs in surrounding areas.

On the other hand, it should be noted that large scale decontamination, with removal of trees and soils, is not only extremely expensive, but could also cause major environmental degradation as a result of increased soil erosion and landslides, reduction of biodiversity and degradation of soil nutrient and water retention functions. The potential for reduction of radiation dose to specific users of the forest, feasibility, cost, possible ecological effects and social acceptability of all countermeasure options thus, need to be taken into account before an optimised management programme can be developed. This will inevitably involve a combination or modification of the above two options [119].

This approach could be considered to be consistent with MoE guidelines, which note that, from the perspective of reducing the radiation dose in the living environment of residents near the forest, it is sufficient to restrict decontamination actions to about a 20 m perimeter of the forest (exact value determined on the basis of local conditions). Further decontamination efforts provide no net benefit. The situation with respect to both re-establishment of the forestry industry and the extent of opening / restricting recreational activities in the forest is trickier and is a focus of on-going work, supported by input from the international community [84].

5.2.2 Surface water transport

The understanding of radiocaesium transport in aquatic systems provides direct input to guide management / decontamination of riverbanks, flood plains, ponds, etc. which are an important part of the living environment of residents [120]. For example, a common case in this region is that riverbanks are utilised as parks or playgrounds. Understanding of existing radiocaesium distributions, natural self-cleaning processes and site-specific potential for re-concentration (Figure 5-7) supports decisions on whether decontamination is needed or not (based on comparison of ambient doses with those in the surroundings) and, when doses may significantly increase following heavy rain, judgement of whether / what kind of counter-measures are required.

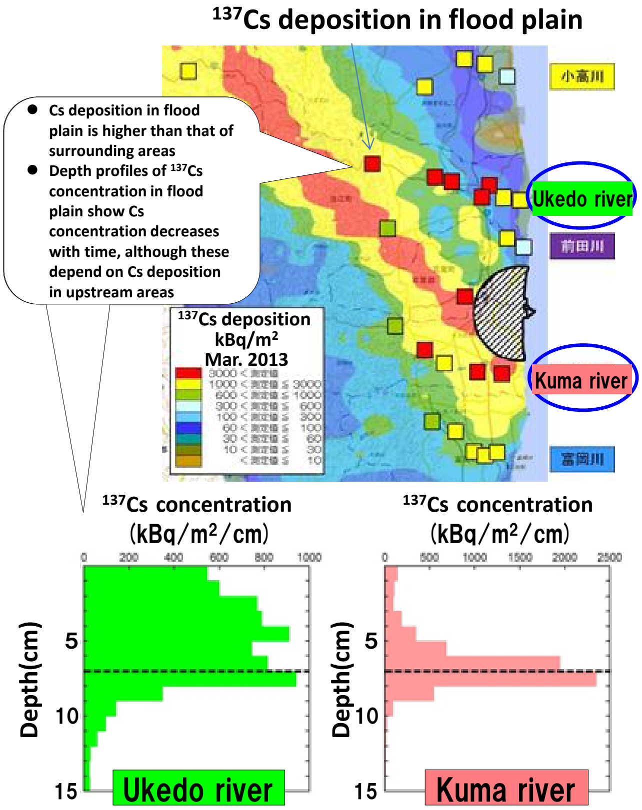


Figure 5-7 Detailed understanding of flood plain contamination to support management decisions [121]

Ponds are also a common feature of this landscape, but here concerns arise in the event of dry weather rather than wet. In any case where ponds located at residential areas and parks can dry out, the potential impact of contaminated sediments needs to be assessed, in terms of direct radiation doses. When ambient doses could significantly increase in such an event, a basis of technical understanding is needed to support decisions on whether / how any decontamination should be carried out. For these and other relevant aquatic environments, it is important that a long-term monitoring programme is implemented to confirm that ambient dose rates are decreasing as expected and, in case of anomalies, these are quickly spotted and appropriate responses implemented, thus building the experience into the knowledge base that improves future forecasting ability.

Finally, because public involvement in decision making is key to building acceptance, there is a need to communicate an understanding of risks to residents and other stakeholders. This provides the basis for open and productive dialogue and encourages an active role of residents in guiding and implementing the recovery process – especially for the aquatic ecosystem, which plays such a central economic and cultural role in this region.

5.2.3 Possible re-concentration mechanisms

Although the general tendency in natural systems is to self-clean as dilution, dispersion and decay reduces contamination concentrations, there are cases when Cs mobilisation can cause re-concentration. Identifying such situations and developing appropriate responses is thus a critical component of regional remediation. The most important processes here, for the case of radiocaesium are predominantly physical, due to the fact that Cs is mainly mobilised tightly bound onto solid phases. Under such circumstances, any process that can concentrate finer sediment – especially the clay fraction – can lead to enhanced Cs concentrations. This was already illustrated in the Ogaki Dam example (Figure 5-4) discussed in the previous section. It is thus important to understand not only processes that cause transport of sediment in aquatic systems, but also those that may cause particle size fractionation (e.g. Figure 5-8).

This requires an understanding of both re-concentration processes that can occur under normal flow conditions (e.g. due to colloid destabilisation in estuaries, scavenging fine material at fresh-brackish water interfaces) but also the traps for fine particles that may exist during the particular high-flow events that dominate Cs transport in this environment (e.g. slack water, vegetation in flood plains,…).

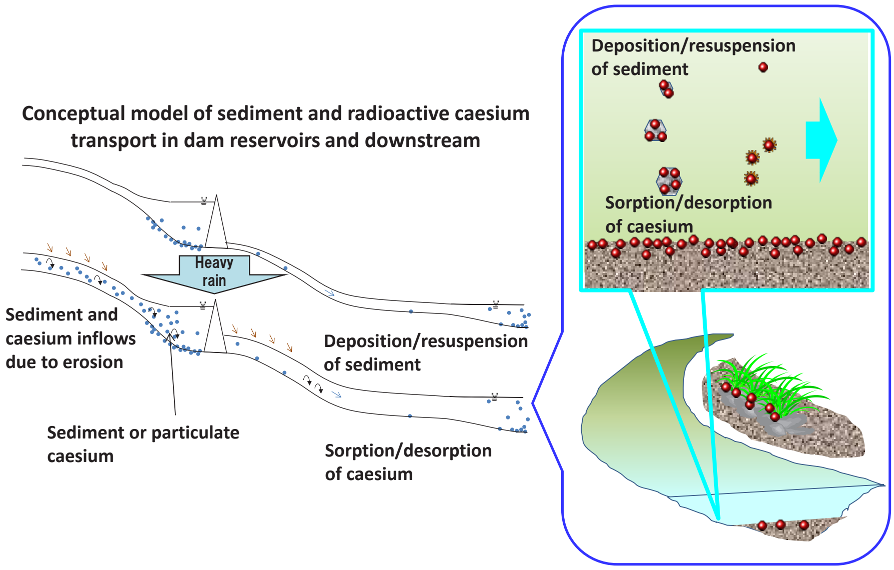


Figure 5-8 Illustration of a potential re-concentration scenario

Because of the generally low biological concentration of Cs, such a mechanism is generally unimportant for this element. A notable exception, however, is high levels of concentration by fungi, mosses and lichen with fungi being particularly important in forest ecosystems [95] [122]. When considering long term evolution of environments with significant fungal biomass, where fungi are significant components of the local diet (as can be the case in Fukushima) and when bio-remediation is being considered, this particular re-concentration mechanism should be carefully assessed.

5.2.4 Counter-measures

The understanding of Cs transport / re-concentration highlighted in the previous sections supports development of appropriate countermeasures – but requires a more quantitative basis if these are to be tailored to site-specific problems. Thus, recognition that radiocaesium transport occurs mainly during flood events and that the finest sediment fraction carries the highest contaminant concentrations needs to be captured in a quantitative model that both explains the current situation and also provides some predictive capability [123] [124]. This is illustrated in Figure 5-9, for the specific case of Ogaki Dam, which has been discussed in previous sections.

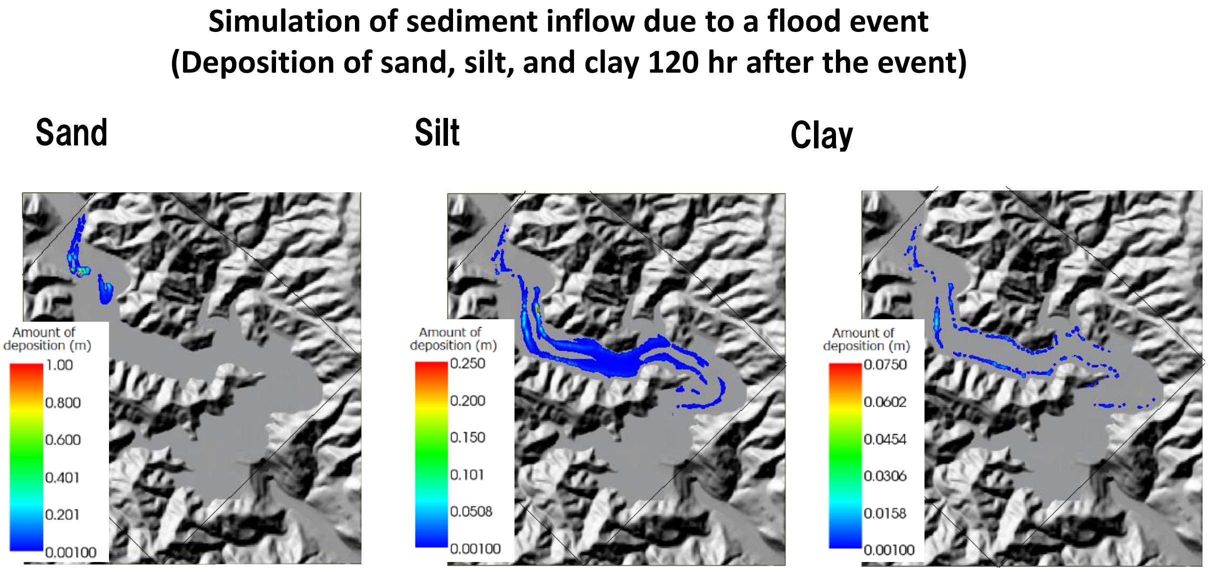


Figure 5-9 Quantitative modelling of sediment capture in Ogaki Dam (map drawn using Digital Elevation Model data provided by the Geophysical Survey Institute) [124] [125]

As highlighted in Figure 5-9, the hydrodynamics of this system result in sediment fractionation and concentration of the deposition of finest material in specific locations. This is in agreement with observations of existing sediment profiles (Figure 5-4 and Figure 5-10), confirming that the mechanistic model is capturing key characteristics of this specific environment.

Such a model can then be combined with scenarios for possible management of the dam, which would normally be based on balancing water requirements downstream, water inflow and sediment control, resulting in considerable variations in reservoir extent (Figure 5-10). This then allows dam management to be implemented as a tool to support control of movement of contaminated sediment and reduction of risks of increased dose rates to local residents.

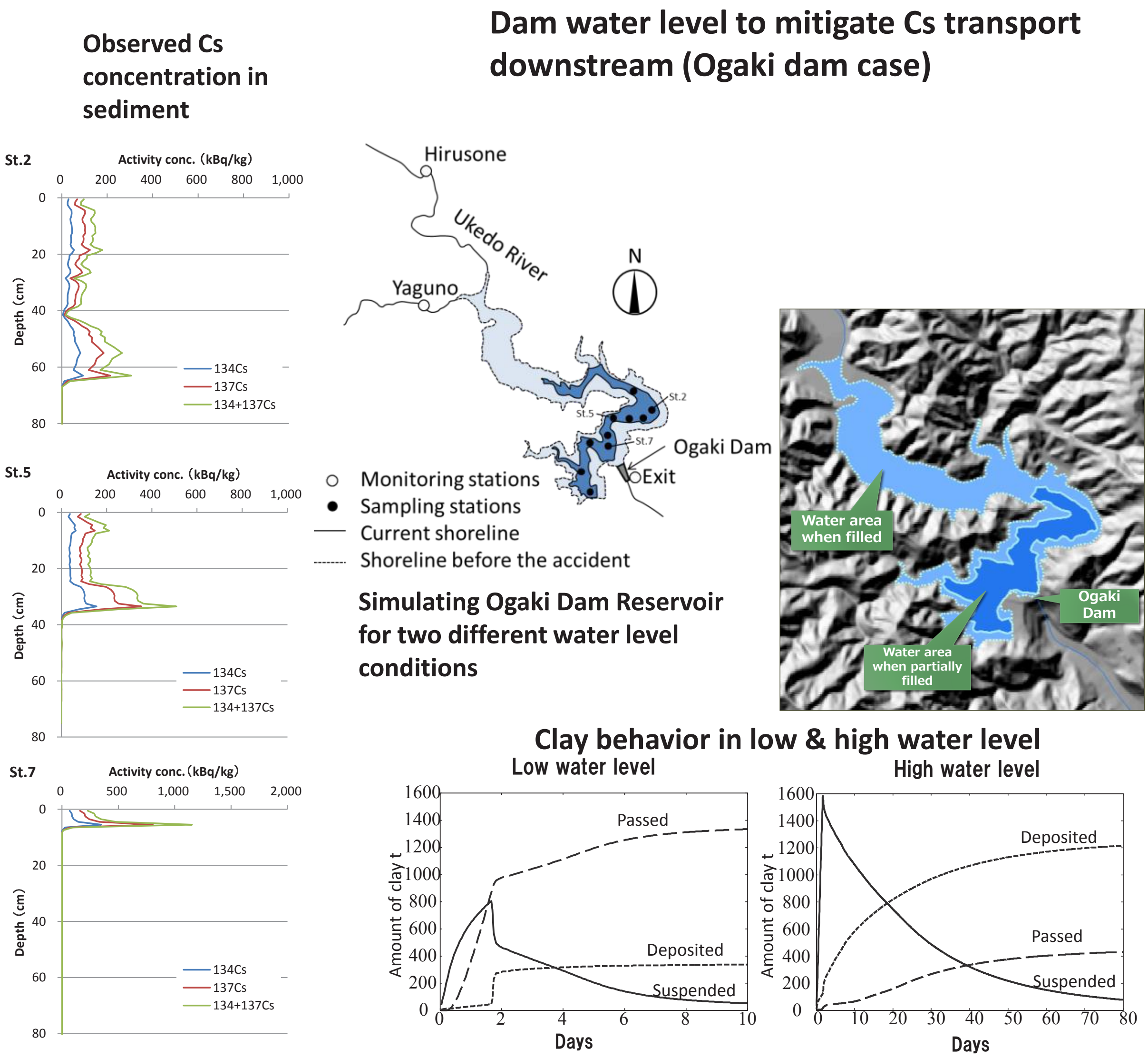


Figure 5-10 Background to assess management options for Ogaki Dam [124]

At present, managing counter-measures runs on a rather ad hoc basis, constrained by both the availability of suitable data and the limitations of both the scenarios considered and the models used to assess them. Nevertheless, with time this shows continual improvement and, with appropriate support, should gradually evolve into a holistic regional contamination management system.

5.3 Sinks in the coastal marine environment

The focus of decontamination work is entirely on land contaminated by 1F fallout, but recovery of the region must also consider the coastal marine environment, as this is both an important economic resource and, for the Japanese people, a key cultural asset.

A positive aspect of the conditions during development of the releases from 1F is that winds were generally blowing towards the east, meaning that a much lower fraction off fallout occurred on land compared to other inland accidents like Chernobyl and Mayak [126] (Figure 5-11). Although the extent of such deposition was significant in absolute terms, it occurred over a very large area of the Pacific Ocean, where dilution and dispersion quickly reduced concentrations to negligible levels (e.g. [127]). The media have highlighted some cases of ocean transport bringing activity to the West coast of the USA, but the levels are trivial and can be distinguished from ambient bomb-fallout levels due only to the extremely high sensitivity with which ^{134}Cs can now be measured (e.g. [127]).

From mass balance calculations alone, it is clear that oceanic contamination is of no radiological concern, but the situation in the coastal marine environment is less clear. This not only received direct localised discharges as a result of direct release of radioactive water from 1F during the early stages of the accident, but is the ultimate sink of much of the runoff from land. Even here, dissolved Cs is of little concern as the coastal current will effectively dilute concentrations to insignificance – but Cs bound to solid phases may be retained locally and its impact needs to be assessed – especially in light of not only important coastal fisheries, but also extensive aquaculture of a wide range of seafood, including shellfish and seaweeds which may be able to access sediment-bound radiocaesium.

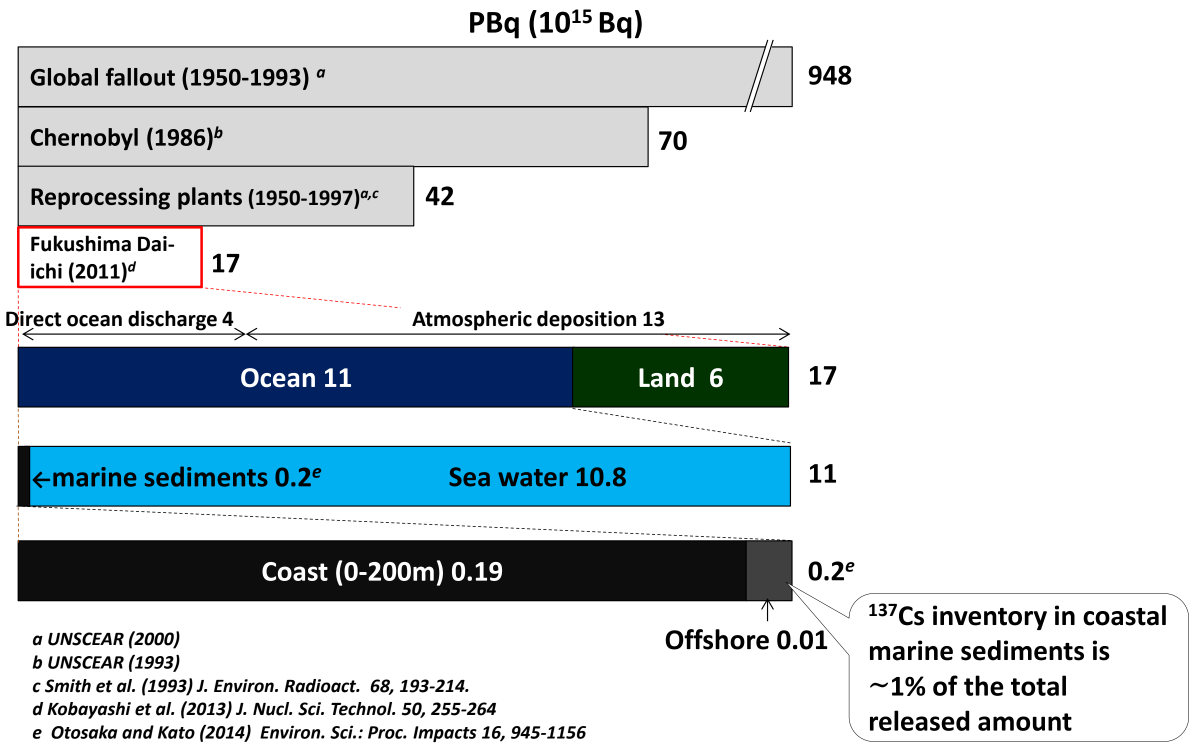


Figure 5-11 Overview of the coastal radiocaesium inventory [128]

Assessment of dissolved and particulate radiocaesium transfer from estuaries into the coastal marine environment is summarised in Figure 5-12 [129]. Since the 1F accidents, significant levels of anthropogenic radionuclides have been detected in seabed sediments off the east coast of Japan [130]. The approximate amount of accident-derived radiocaesium in seabed sediments off Fukushima, Miyagi and Ibaraki prefectures was estimated from a sediment integration algorithm [129]. Approximately 6 months after the accident, more than 90% of the radiocaesium inventory had accumulated in areas less than 200 m depth. The large inventory found in the coastal sediments was attributed to effective adsorption of dissolved radiocaesium onto suspended particles that settled out directly to sediments in the early post-accident stage [129]. Although rivers are also an important source of supply of radiocaesium to coastal regions, this flux was much lower than that of the above-mentioned process within the first 6 months of the accident [129]. Because of the dominant role of fine particulates, collection of undisturbed sediment cores is especially critical (e.g. [131]). Therefore, a multi-corer (equipped with a slow penetration gravity corer) was used for undisturbed sediment sampling in the aforementioned study [129].

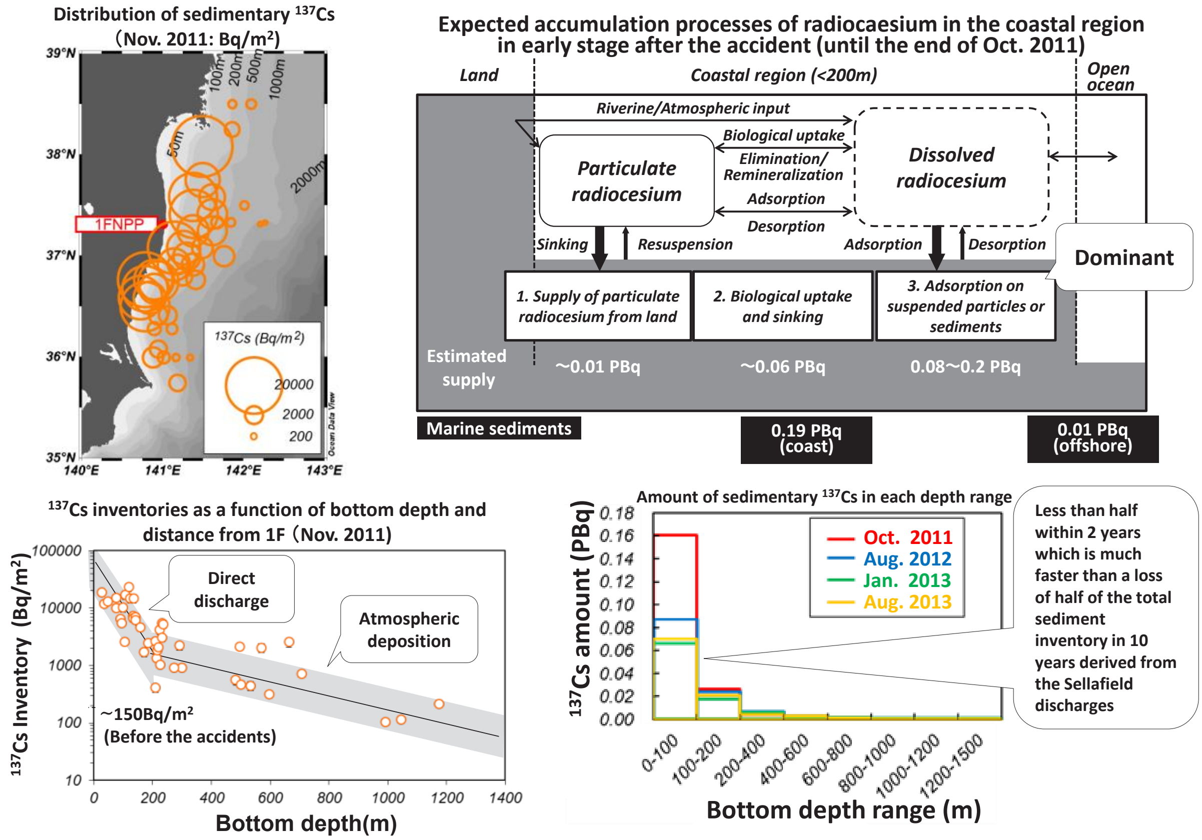


Figure 5-12 Assessment of radiocaesium in the offshore Fukushima coastal environment [129]

Unlike the terrestrial environment, where external doses dominate, the radiological significance of contamination of the coastal marine environment focuses entirely on uptake into the food chain. As noted above, the ecological niche of different marine organisms and their ability to take up particulate-bound Cs into edible components defines their significance in terms of human dose. Regardless, limitations on consumption are set on a more simplistic measure of total radiocaesium activity per unit body weight – which is set at a very low value at present (100 Bq kg^{-1} – less than the natural ^{40}K activity in bananas). Nevertheless, even based on this measure, it is clear that the self-cleaning of marine environments is very effective (Figure 5-13).

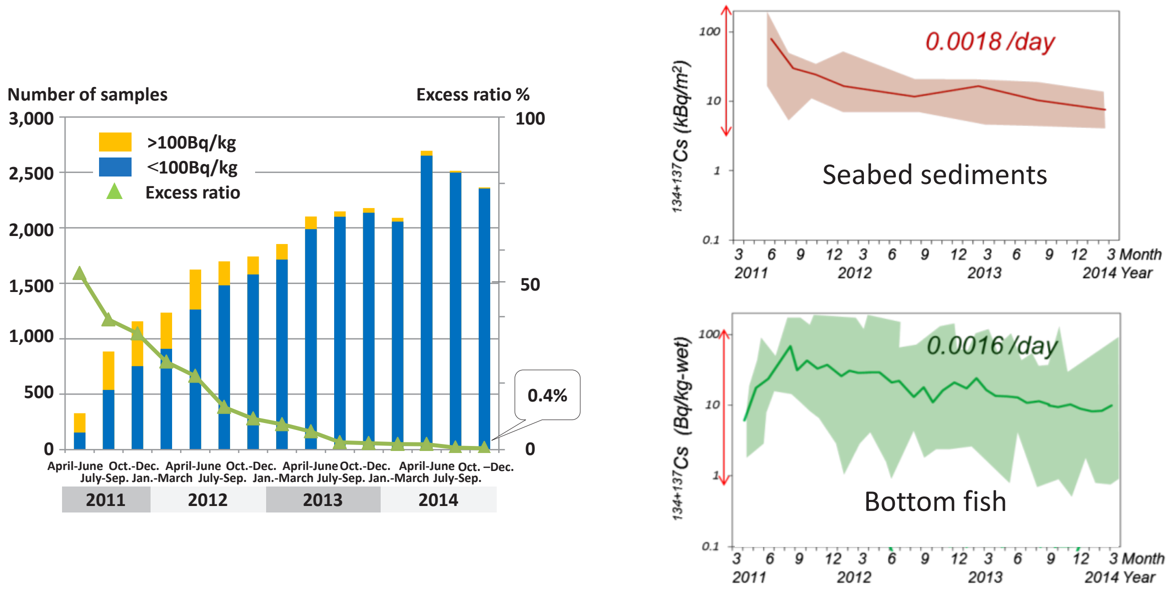


Figure 5-13 Evolution of radiocaesium concentration in fish (left [132], right [133])

5.4 Recommendations

For any large scale contamination of a region which contains large extensive forests or other areas with limited population access (wetlands, beaches, etc.), it is clearly neither necessary nor cost-effective to attempt to decontaminate the entire area: effort should be focused on targets where the benefits in terms of dose reduction to residents are greatest. Nevertheless, if the decision is taken to allow certain areas to “self clean” – the effectiveness of this process needs to be understood - and also its possible impact on other areas that have been decontaminated.

The F-TRACE project provides a blueprint for such a supporting study of natural radionuclide mobilisation processes, in terms of both its technical content and its focus on providing support for the end goal of returning evacuees to a normal lifestyle as soon as possible. In particular, it highlights that goals need to be tailored to local concerns, which are defined not only by the nature of the contamination incident, but also from local physical, geographical, climatic and socio-political boundary conditions.

Implementation of F-TRACE – and its direct support of the return of evacuees – has shown both strengths and weaknesses of the approach. A definite strength was the speed at which such a large project was implemented, a weakness was the fact that – as a direct result of such haste – methodology and technology had to be developed under extreme time pressure (“reinventing the wheel”) rather than fully benefiting from the extensive international knowledge base on radiocaesium contamination.

It has to be recognised that the JAEA F-TRACE team were aware of such limitations and rapidly instituted annual “International Cs workshops” [29] [84] to directly access such expertise. They also initiated bilateral collaboration agreements with organisations having appropriate expertise in Europe and the USA and took advantage of access to experience resulting from Chernobyl via the IAEA. Here it has to be noted that the advantages of access to a wider knowledge base had to be balanced against the fact that much of it was for deposition / geography / climate conditions that were of little relevance to Fukushima.

Another initiative to access international experience and provide support to inexperienced field teams involved an external QA review, carried out by a group with extensive experience in radiocaesium contamination of an environment with similar topological, climatic and ecological conditions developed over the last 4 decades. This provides both access to appropriate methodology and technology, but also test cases that can be used to validate the predictive ability of the quantitative models that are being developed.

Possibly the biggest remaining challenge involves integration of the work of the many different organisations that are involved in related studies in this region. The individual work programmes for such studies were generally developed independently, reflecting funding from different government ministries. Despite common goals, integration is extremely difficult due to the range of technology, equipment, experience, reporting protocols, etc. of the participant organisations. To resolve this situation will require both implementation of appropriate technology (possibly based on advanced knowledge management tools already established in Japan) and also a commitment from the upper-level funding organisations to work together. This purely administrative challenge is likely to be typical of those that all nations will be confronted with when facing such a challenge.

6 Summary & Conclusions

6.1 Socio-political boundary conditions

Although this report is predominantly technical in nature, the transferability of experience and technology from nuclear decontamination in Japan to other countries or other clean-up applications has to be assessed considering also the particular socio-political boundary conditions in Japan. Key aspects of Japanese culture that were regularly commented on by foreign observers were national resilience in the face of disaster, obedience to instructions from authorities and preparedness to make individual sacrifices for the common good. Thus, there was no sign of the panic, civil disobedience, looting, etc. The discipline of the evacuation process and the stoicism of those evacuated certainly contributed to the success of this operation and the implementation of a structured, stepwise decontamination process.

Despite the fact that it was overwhelmed by the “perfect storm” of a giant earthquake, a huge tsunami and reactor melt-downs, Japan´s world-class natural hazard response system provided a strong basis on which to structure resultant disaster management, again aided by the public familiarity with natural disasters that arises from their location on the Pacific “ring of fire”.

In terms of mobilisation of the resources needed for both on-site recovery and off-site decontamination, Japan benefited from extensive nuclear infrastructure which allowed required manpower and equipment to be rapidly mobilised. This was further helped by Japan´s extensive international network in the nuclear field, which meant that required foreign support was also available any time required.

Finally, of course, it has also to be noted that Japan is both fully developed and economically powerful, allowing the financial burden of regional remediation to be borne. Thus, although the general principles highlighted in this report are quite general, their application may vary significantly between countries. Indeed, for smaller countries or those with less developed nuclear infrastructure, the lessons learned from 1F decontamination may be best considered on a regional rather than national basis.

6.2 Current status and future challenges for decontamination and recovery in Japan

Many of the conditions in Fukushima are similar to those following contamination in other countries, where natural self-cleaning has allowed recovery. Decontamination efforts in Japan will certainly accelerate this process. On-going remediation work is based on a good technical understanding of the movement of radiocaesium in the environment and this understanding is being translated into actions that enable the rapid return of evacuees and assures that they can safely resume their previous lifestyles.

Specifically with regard to study of the redistribution of radiocaesium and assessing its impact on the restoration of agricultural land, it was clear that tools exist to rapidly measure the movement of contamination at both regional and local scales, consistently showing reduction of doses at a rate greater than would be expected by radioactive decay alone. This is in agreement with models which predict that, although deposited Cs is strongly bound to surface soil, it can be transported slightly deeper into the soil column by physical processes or bioturbation, or partially washed away during heavy rainfall.

With respect to radiocaesium behaviour in forests, experience in Fukushima was consistent with that from distant fallout from Chernobyl in Fenno-Scandinavia, the UK and the southern European Alps. This confirmed the special challenges resulting from the greater complexity of forest ecosystems compared to the agricultural land that has been the focus of most radioecological work in the past. Nevertheless, integration of foreign and Japanese knowledge provides a strong basis for developing plans to effectively manage contaminated forests in order to revitalise the forestry industry and allow returning residents to make use of forest resources.

Clean-up efforts are generating huge volumes of contaminated soil and vegetation waste, which must be managed in a safe and cost-effective manner, wherever possible implementing waste volume reduction. Future reuse of soil for construction purposes is an important option, if constraints in terms of allowable organic and clay content can be managed.

For waste management in particular, but also all other aspects of recovery of Fukushima, communication with stakeholders and establishing dialogue with them is critical, e.g. communicating clearly risks and benefits of different options.

Towards accelerating the return of evacuees and revitalisation of the essential forestry, agriculture and fishery industries of the region, the combination of short-term and long-term countermeasures is important for restoration, e.g. dam operation optimisation for short-term contamination management, natural self-cleaning of the forest as a long-term management goal, use of phytoremediation for more heavily contaminated zones, etc.

JAEA plays a key role in the research associated with remediation of the contaminated area around the 1F site, working together with a number of Japanese and international organisations and research institutes. Japanese work is building a knowledge base which can support rapid return of evacuees and allow them to have a normal lifestyle. It does, however, need to be better integrated and much better communicated to the general public and other key stakeholders (foresters, fishermen, farmers etc.). Relevant international analogue experience (e.g. distant fallout from Chernobyl, local fallout from the Windscale fire) might help here. It was recognised that R&D efforts such as the F-TRACE programme were essential for increased system understanding, prediction of future Cs migration via modelling and risk assessment as well as for research integration. Forecasting future evolution of radiation exposure can be based on a holistic view of system understanding, including processes in the coastal marine environment, management of highly contaminated areas and improvements in decontamination techniques.

To develop the technical basis for strategic off-site response, relevant information should be gathered, based on lessons learned from Fukushima environmental remediation as summarised in this report. In order to foster international collaboration, such experience needs to be made available in a more user-friendly friendly form utilising an advanced knowledge management system (KMS).

6.3 Lessons for emergency preparedness and response to future contamination events

Possibly the main lesson to be learned from this incident in terms of emergency preparedness is that basing all planning on past experience is dangerous in a world where large populations and sensitive infrastructure are increasingly located in zones at risk from natural catastrophes. “Black swans” – events that are possible but not considered because that have never been previously experienced – need to be more comprehensively covered in disaster response plans.

For the specific case of regional radioactive contamination, whether due to an accident at a power plant or other nuclear facility or as a result of an act of war or terrorism, advance planning can greatly minimise consequences and aid recovery. Such planning should include three components – training of response teams, establishing communication channels / material and setting required regulatory infrastructure in place.

A system of civil defence or disaster response already exists in most developed countries and here the requirement may be only to develop a wider range of scenarios to be considered. Although the probability of a Fukushima-scale accident may be very low, its large consequences justify it receiving careful consideration. Learning from 1F, it is important that too much focus is not placed on the cause of the accident, rather effort should be placed on response should the unimaginable occur. A good example of this approach is the response to 1F by the Swiss nuclear regulator ENSI [134].

There is no doubt that communication was one of key issues to be improved in the response to the 1F meltdowns. Problems were experienced at every level – local, regional, national and international. To be fair, no past accident of this type has been well communicated (e.g. [135] or has received such extensive media coverage, which continues to the present day. It has to be recognised that, in many cases, fear of radiation causes larger health impacts than radiation itself [19] and so reduction of such fear is an important component of any disaster response plan.

Despite the growing technological sophistication of the general public, “radiophobia” is common throughout the world. This has to be explicitly recognised and public education in relevant areas strengthened prior to any future event, so that affected populations can weigh information received in a more balanced manner.

Although the Japanese government reacted quickly to pass acts for decontamination, implementation was challenging to cover cleanup activities and, in particular, the movement, storage and disposal of resultant wastes for the latter of which an act passed on November 2014 for specifying that a disposal site shall be located outside of the Fukushima Prefecture. If put in place in advance for further development of a regulatory framework, it would not only have facilitated decontamination, but would also have been made on a technical basis for assuring safety.

6.4 Lessons for decontamination of legacy sites

Extensive areas of radioactively contaminated land exist around the world as a result of past accidents, mining, military activities and past industrial practices – including waste disposal in ways that do not meet current standards. Although large efforts have been made to decontaminate some locations (e.g. US superfund sites [136]), management is more often limited to restricting public access and allowing self-cleaning to naturally reduce contamination levels. The Fukushima work demonstrates that large scale decontamination can be carried out cost-effectively if the value of the land is sufficiently high, although Japanese boundary conditions in terms of the nature of contamination and the technology applied may not be transferable to most of the sites involved.

Possibly more generally useful is the extensive database on the environmental behaviour of radiocaesium, as this is a common contaminant in other places. Although Cs has been extensively studied in the past, the integrated regional assessment which follows transport from forested mountains to a coastal marine environment is unique and may be useful for other countries with similar geographic and climatic conditions.

6.5 Future knowledge transfer activities

As noted in section 6.2, development of a knowledge base is planned to transfer the extensive experience already gained in Fukushima to guide future work and also support improving emergency response planning in other countries. Already a huge volume of data has been accumulated and this will expand considerably over coming decades. The only way in which this can be sensibly handled is by taking full advantage of modern knowledge management tools – which are already well established in JAEA (e.g. [137]) as a result of past work related to radioactive waste disposal. To facilitate access, these KM tools are probably best structured around an internet-based communication platform. Establishing a fully functional system will require significant investment in the required software tools – but also major internal knowledge transfer efforts to ensure that required quality assurance and standardisation of data collection protocols are implemented. Nevertheless, the benefits will be considerable – both in terms of maximising the usefulness of work carried out by facilitating its integration with related studies and also by making it fully accessible to both national stakeholders and the international scientific community.

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Appendix

Glossary

The terminology used in this report includes both universally used technical terms (e.g. [138] [139] [140]), in addition to terms specific to this report.

Decontamination	Actions taken in an attempt to reduce the radiation dose. This could be the removal of soil for example, or the removal of radioactive contaminants by washing, blasting or perhaps the use of peeling agents. Measures that are undertaken to reduce radiation dose that do not involve the removal of radioactive contaminants e.g. soil turnover, are in many instances referred to as remediation. However, in this document all methods to reduce dose, whether they involve the removal of contaminated material or not, are referred to as decontamination.
Decontamination factor	The percentage reduction in a radioactivity point measurement after decontamination work has been performed.
Dilution & dispersion	Processes of redistribution of radioactivity which leads to a decrease in its concentration.
Disposal	Isolation of the waste from the human environment, in this case within a specially engineered barrier system and / or underground in a suitable geological setting.
Environmental half-life	The time required for a radionuclide (e.g. ^{137}Cs) lost from surface soil or other land use targets to deplete the inventory by half due to environmental processes such as weathering, which is distinct from loss due to radiological decay.
Hotspots	Locations where radioactivity is significantly higher than the local average, due to either initial deposition or subsequent concentration.
Incineration	Waste treatment process that involves the combustion of flammable wastes in order to minimise waste volume and reduce their vulnerability to degradation during storage.
Interim storage	Intended to be a specially engineered storage facility where decontamination wastes will be moved to from current temporary storage until a final disposal concept has been agreed upon. Currently the centralised interim storage facilities (1 or more) are planned to hold waste for a period of up to 30 years.

Linear no threshold model The hypothesis that the risk of stochastic effects is directly proportional to the dose for all levels of dose and dose rate (below those at which deterministic effects occur).

Monitoring Here covers all measurement of radioactivity, generally performed on a regular basis after initial characterisation. Monitoring may be performed on a regional basis (e.g. aerial monitoring) or on a more local basis (e.g. after decontamination activities).

Quality Assurance (QA) Planned and systematic processes aimed at providing confidence in a product and its suitability for its intended purpose. In this case the product is the outcome of the decontamination work.

Radiocaesium An unstable isotope (of which there are 11 major ones) of caesium (Cs). ^{137}Cs and ^{134}Cs are the isotopes of most concern in the context of post-Fukushima accident remediation.

Runoff Natural flow of water over land, enabling movement of particles (and associated radionuclides) into aquatic systems.

Self-cleaning The process whereby there is removal of radioactive contaminants from the terrestrial environment by natural processes (e.g. erosion and transport to sea) or natural reduction in effective dose (e.g. by bioturbation transporting the contaminant to depth in soil).

Sorption The interaction of an atom, molecule or particle with the solid surface at a solid–solution (or a solid–gas) interface.

Stakeholder Any party who has an interest in the decontamination work.

Temporary store A specially engineered storage facility (located at each of the decontamination sites). The waste will then be transported to centralised interim storage facilities, which were planned to commence receiving the waste in January 2015.

Acronyms

DPP	Decontamination Pilot Project - decontamination work carried out within the evacuation zone by JAEA in order to examine the applicability of decontamination techniques on a larger scale. Initially, the first decontamination projects undertaken by JAEA to demonstrate the effectiveness of a range of decontamination techniques were known as the “decontamination model project” and then the “decontamination demonstration project”. The name was changed to DPP to reflect the fact that these initial test projects were just the beginning of R&D into decontamination methodology for the regional decontamination work.
DF	Decontamination Factor
DOE	United States Department of Energy
ENSI	Swiss Federal Nuclear Safety Inspectorate
EPA	Environmental Protection Agency
GPS	Global Positioning System
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
1F	Fukushima Daiichi (“ichi-efu” in Japanese)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
JAEA	Japan Atomic Energy Agency
JV	Joint Venture
KMS	Knowledge Management System
KURAMA	Kyoto University Radiation Mapping System - GPS-aided mobile radiation monitoring system with CsI(Tl) scintillation counter
LNT	Linear No Threshold
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MoE	Ministry of the Environment
NAIIC	National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission
NAS	National Academy of Sciences
NIRS	National Institute of Radiological Sciences
NRA	Nuclear Regulation Authority
NSC	Nuclear Safety Commission of Japan
SPEEDI	System for Prediction of Environmental Emergency Dose Information
TEPCO	Tokyo Electric Power Company
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USJF	United States Joint Forces
WHO	World Health Organization

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度 (a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立法メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率 (b)	（数字の） 1	1
比透磁率 (b)	（数字の） 1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m^2/m^2
周波数	ヘルツ (d)	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	m^{-2} cd
放射性核種の放射能 (f)	ベクレル (d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト (g)	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		s^{-1} mol

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	m^{-3} sA
表面電荷	クーロン毎平方メートル	C/m^2	m^{-2} sA
電束密度，電気変位	クーロン毎平方メートル	C/m^2	m^{-2} sA
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	kg^{-1} sA
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}$ mol

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^9	ギガ	G	10^{-12}	ピコ	p
10^6	メガ	M	10^{-15}	フェムト	f
10^3	キロ	k	10^{-18}	アト	a
10^2	ヘクト	h	10^{-21}	ゼプト	z
10^1	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	$1ha=1hm^2=10^4m^2$
リットル	L，l	$1L=11=1dm^3=10^3cm^3=10^{-3}m^3$
トン	t	$1t=10^3$ kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	$1eV=1.602\ 176\ 53(14)\times10^{-19}J$
ダルトン	Da	$1Da=1.660\ 538\ 86(28)\times10^{-27}kg$
統一原子質量単位	u	1u=1 Da
天文単位	ua	$1ua=1.495\ 978\ 706\ 91(6)\times10^{11}m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1MPa=100kPa=10^5Pa$
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	$1\ Å=0.1nm=100pm=10^{-10}m$
海里	M	1 M=1852m
バーン	b	$1\ b=100fm^2=(10^{-12}cm)2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}$ J
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1Pa\ s$
ストークス	St	$1\ St=1cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	$1\ sb=1cd\ cm^{-2}=10^4cd\ m^{-2}$
フォト	ph	$1\ ph=1cd\ sr\ cm^{-2}\ 10^4lx$
ガル	Gal	$1\ Gal=1cm\ s^{-2}=10^{-2}ms^{-2}$
マクスウェル	Mx	$1\ Mx=1G\ cm^2=10^{-8}Wb$
ガウス	G	$1\ G=1Mx\ cm^{-2}=10^{-4}T$
エルステッド (c)	Oe	$1\ Oe \triangleq (10^3/4\pi)A\ m^{-1}$

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R=2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
ガンマ	γ	1 γ =1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	µ	$1\ µ=1µm=10^{-6}m$

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