JAEA-Review
2014-052

JAEA-Review

Remediation of Contaminated Areas in the Aftermath of the Accident at the Fukushima Daiichi Nuclear Power Station: Overview, Analysis and Lessons Learned
Part 2: Recent Developments, Supporting R&D and International Discussions

Fukushima Environmental Safety Center

Sector of Fukushima Research and Development

March 2015

Japan Atomic Energy Agency

日本原子力研究開発機構

Remediation of Contaminated Areas in the Aftermath of the Accident at the Fukushima Daiichi Nuclear Power Station: Overview, Analysis and Lessons Learned Part 2: Recent Developments, Supporting R&D and International Discussions

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(Received December 3, 2014)

In the wake of the Great Tohoku earthquake and tsunami, which resulted in significant damage to the Fukushima Daiichi nuclear power station, considerable radioactive discharge and deposition occurred. Populations were evacuated from the zones that received the most deposition and overarching "Special Measures" laws established the Ministry of the Environment (MOE) as the department responsible for decontamination to remediate the environment.

Major challenges to implementing full-scale environmental decontamination were the absence of real-world examples and also lack of experience in planning and implementing decontamination technology appropriate to the physical and social boundary conditions in both Japan and Fukushima.

The Japan Atomic Energy Agency (JAEA) was thus charged with conducting "Decontamination Pilot Project" to examine the applicability of decontamination technologies, with a special focus on reducing dose rates and thus allowing evacuees to return to re-establish their normal lifestyles as quickly as possible, whilst simultaneously maintaining worker safety.

The Decontamination Pilot Project was implemented at 16 sites in 11 municipalities within the evacuated zone, including locations that received the highest deposition. Despite tight boundary conditions in terms of timescale and resources, the Decontamination Pilot Project provides a good basis for developing recommendations on how to assure decontamination efficiency and worker safety whilst additionally constraining costs, subsequent waste management and environmental impacts. The Decontamination Pilot Project has thus played a key role in the drafting of guidelines and manuals that are currently being used as a source of reference by the national government, local municipalities and the contractors performing regional decontamination.

Part 1 of this report summarises the Decontamination Pilot Project, providing the background required to put this work in context for an international audience. In this Part 2, the subsequent application of output from these projects to regional remediation now being conducted by the MOE and municipalities, is discussed, along with a status update on such work (including radioactivity monitoring), an overview of associated JAEA's R&D and international input to / review of regional environmental decontamination in Fukushima.

Keywords: Fukushima Daiichi, Decontamination Pilot Project, Radiocaesium, Regional Decontamination, Supporting R&D, International Input and Context

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福島第一原子力発電所事故後の環境修復の取り組み：概要、分析および教訓
その２：広域除染の現状、除染技術開発、除染をめぐる国際的な議論

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

（2014 年 12 月 3 日　受理）

東日本大震災に伴う東京電力福島第一原子力発電所事故により、大量の放射性物質が発電所敷地内外を汚染させ、多数の人々が避難生活を余儀なくされている。事故後、除染に関する「放射性物質汚染対処特別措置法」が成立し、この法律に基づいて環境省および自治体主導の大規模な環境除染が進行中である。

そのような広域の環境の除染はこれまで世界的に例がない。むろん、日本そして福島に特有の地形的・社会的条件下における除染の計画や実施の経験はない。避難者の帰還・生活の再興を促すためには線量を低減させる必要があり、環境除染の技術の早急な実証を迫られた。

日本原子力研究開発機構は内閣府より「除染モデル実証事業」を受託し、避難区域内の 11 市町村 16 か所の試験対象エリアにおいて、除染技術の適用性、発生する廃棄物の管理、作業員の安全確保策など広域環境除染に関する広範な試験を行った。限られた時間および人的資源の下で行われたにも関わらず、この大規模なモデル事業は、個々の除染技術の適用性や効果について詳細で現実的なデータを得たのみならず、除染作業員の安全確保、コストの制約、発生する除染物の取扱いなど、広域除染に関するさまざまな情報を総合した知識基盤を提供することとなった。実際このモデル実証事業の成果は、現在環境省と自治体が進めている広域環境除染のためのガイドラインやマニュアルに反映されている。

除染モデル実証事業の結果については、事業終了後に詳細な報告書として政府に提出されている。一方、本レポートは諸外国の専門家を読者と想定して書かれたものであり、除染モデル実証事業の概要をその 1 に、また除染モデル実証事業で得られた成果の広域除染に対する反映、モデル実証事業終了後の継続的な線量測定などフォローアップの結果、日本原子力研究開発機構が関わった除染技術開発、広域除染の現況、および福島における除染に関する国際的な議論などをその 2 にとりまとめた。

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PREFACE

In the wake of the Great Tohoku earthquake and tsunami, which resulted in significant damage to the Fukushima Daiichi nuclear power station, considerable radioactive contamination occurred, both on and off-site. Populations were evacuated from the most contaminated zones and overarching “Special Measures” laws established the Ministry of the Environment as the department responsible for decontamination of the evacuated areas.

Major challenges to implementing full-scale decontamination were the absence of real-world examples (most previous radiocaesium releases to the environment have undergone natural self-cleaning processes only) and also lack of experience for planning and implementing decontamination technology appropriate to Japanese boundary conditions. JAEA was thus charged with conducting a range of studies within the “decontamination pilot project” to examine the applicability of decontamination technologies within the evacuated zones. A special focus was on reducing dose rates, thus allowing evacuees to return to re-establish their normal lifestyles as quickly as possible, whilst simultaneously maintaining worker safety.

The decontamination pilot project was implemented at 16 sites in 11 municipalities within the evacuated zone, including highly contaminated locations. Despite tight boundary conditions in terms of timescale and resources, the decontamination pilot project provides a good basis for developing recommendations on how to assure decontamination efficiency and worker safety whilst additionally constraining costs, subsequent waste management and environmental impacts. The decontamination pilot project has thus played a key role in the drafting of guidelines and manuals that are currently being used as a source of reference by the national government, local municipalities and the contractors performing regional decontamination.

Part 1 of this report summarises the decontamination pilot project, providing the background required to put this work in context for an international audience. In Part 2, the subsequent application of output from this project to regional remediation is discussed, along with a status update on such work, an overview of associated R&D and international input to / review of this work.

1. Input of JAEA Decontamination Pilot Project to regional decontamination activities

The background, planning, implementation and results from the JAEA Decontamination Pilot Project (JAEA DPP) are summarised in Part 1 of this report and are not repeated here. This section focuses on how input from the JAEA DPP was utilised for support of subsequent regional decontamination activities and, in particular, the associated guidelines produced by the Ministry of the Environment (MOE), which has responsibility for such work as indicated in Figure 1-1[1)].

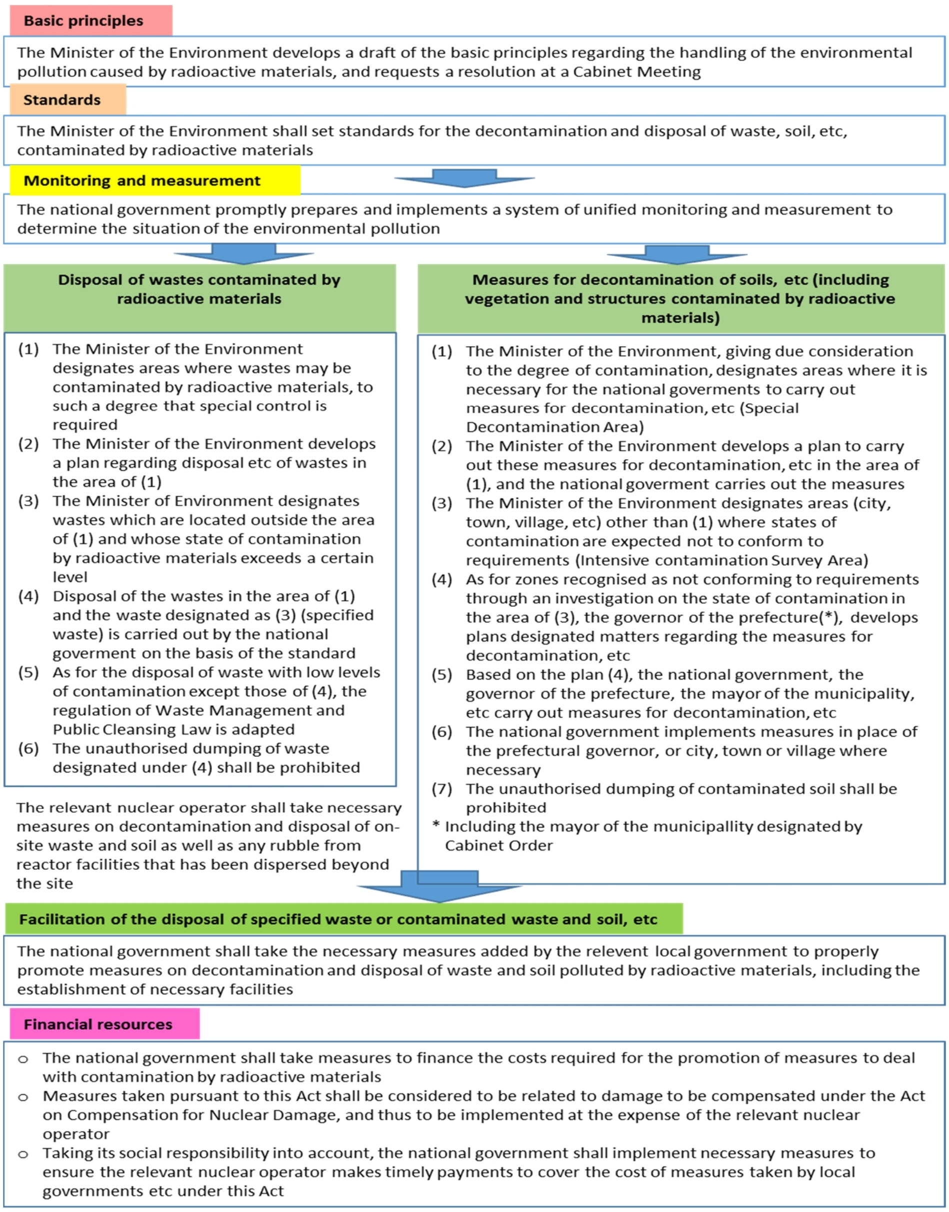


Figure 1-1: MOE responsibilities as defined in the "Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District – Off the Pacific Ocean Earthquake that Occurred on March 11, 2011"[1)]

These extensive documents (Decontamination Guidelines[2)] and Guidelines for Waste[3)]) are mainly available only in Japanese and include guidelines for decontamination (4 parts, over 250 pages) and for waste characterisation and management (6 parts, ~ 400 pages). The Decontamination Guidelines were prepared for one of the 2 designated areas for decontamination (see below) and not areas with "especially high radiation doses".

1.1 Policy, planning and co-ordination

Although the "Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District – Off the Pacific Ocean Earthquake that Occurred on March 11, 2011" (henceforth referred to as the "Act") came into force in August of 2011, the "Basic Principles" did not come into force until the 1st of January 2012. After the new policy framework for off-site decontamination came into being, decontamination work was progressively implemented under the responsibility of the national government. Under the "Act" areas for decontamination were categorised into 2 sub categories: the "Special Decontamination Area" (responsibility of the national government) and the "Intensive Contamination Survey Area" (responsibility of each individual municipality with financial and technical support being provided by the national government). As of June, 2013, there were 100 municipalities in 8 prefectures, designated under the "Act" within which an additional 1 mSv per year above natural background had been recorded. For reference, the average natural background radiation for Japan is about 1.5 mSv y^{-1} (the global average is ~ 2.4 mSv y^{-1}).

The fundamental decontamination policy for the "Special Decontamination Area" that was devised for financial years 2012 and 2013 is outlined as follows. Implementation of the decontamination work was undertaken according to aerial dose rates that were divided into 3 specific ranges of annual dose:

- **Areas < 20 mSv y^{-1}:** aim to reduce the additional exposure (above background) to < 1 mSv y^{-1} (long-term goal)
- **Areas between 20 and 50 mSv y^{-1}:** aim to reduce the dose in both residential and agricultural areas to < 20 mSv y^{-1} by the end of FY 2013
- **Areas > 50 mSv y^{-1}:** demonstration projects to be implemented in order to determine future decontamination policy

The policy for decontamination of these areas after FY 2014 is firstly to reduce the annual dose to 1 mSv y^{-1} above background as a long term goal. Secondly, to evaluate the results from 2 years of decontamination work, with actions to be taken if necessary (including a revision of policy and implementation for all decontamination work procedures).

These are shown in Figure 1-2[4)] and correspond to the areas evacuated following the accident. It is important to note that the decontamination goals are conservative (1 mSv y^{-1} is two thirds of the average background radiation in Japan, which is already low by international standards - e.g. the average dose from natural radiation in Finland is 8 mSv y^{-1}): the IAEA has suggested that exposure below 20 mSv y^{-1} has no significant health effects[5)].

The Special Decontamination Area (Figure 1-2) was designated by the MOE and includes 11 municipalities that are in either the (former) restricted zone or planned evacuation zone. The plan for decontamination work to be carried out within the Special Decontamination Area was also the remit of the MOE and had 3 main goals:

- Specification of the principles and objectives for the implementation of decontamination measures
- Consultation with heads of related administrative bodies
- Determination of local government opinion

After these 3 goals had been fulfilled, the National Government implemented measures for decontamination work that was to be undertaken by the MOE in co-operation with the relevant ministries (e.g. the Ministry of Land, Infrastructure, Transport and Tourism, the Ministry of Agriculture, Forestry and Fishery, and the Reconstruction Agency, which deals with overall restoration in addition to decontamination).

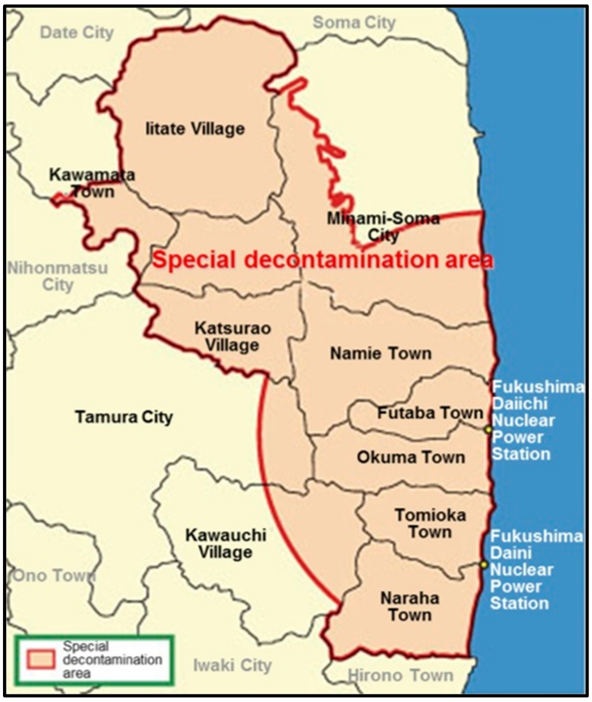


Figure 1-2: Map of the Special Decontamination Area[4)]

In practice, the goals are reformulated in a more pragmatic manner to the following:

- areas with an additional exposure of > 20 mSv y^{-1} (above that received from medical or natural radiation) to undergo a stepwise and rapid reduction in aerial dose rates based on the ICRP 2007 recommendations[6)]
- areas with an additional exposure of < 20 mSv y^{-1} (long term goal to reduce to ≤ 1 mSv y^{-1}) to be categorised separately for adult and children:
    - for adults the aim was to reduce the estimated annual dose by 50% in 2 years, by August 2013
    - for children the aim was to reduce the estimated annual dose by 60% in 2 years, by August 2013

These revised dose reduction goals were to be brought about by a combination of radioactive decay, natural removal processes and decontamination procedures and, for the first time, clearly recognised that natural system self-cleaning and radioactive decay contribute towards reducing radiation exposure. Although the longer-lived ^{137}Cs (30 year half-life) now dominates the measured radioactivity, the higher gamma dose from shorter-lived ^{134}Cs (2 year half-life) means that decay of the latter has had a large effect in dose reduction (e.g. (7)).

As is well documented in the JAEA DPP work – and confirmed in the JAEA Caesium workshop[8)] – Cs binds very strongly to soil and, in particular, clay minerals. This initially leads to concentration of radiocaesium within the surface layer of soil; however this layer is vulnerable to erosion during periods of high rainfall and in addition soil from this layer may also be transported deeper into the ground via bioturbation. Both of these processes will act to reduce surface gamma doses. In addition to the evacuated zones, other areas where the additional gamma dose exceeds 1 mSv y^{-1} (assessed as equivalent to 0.23 μSv h^{-1}) have also been mapped and designated as the “Intensive Contamination Survey Area” (Figure 1-3). The Intensive Contamination Survey Area contains a total of 100 municipalities in 8 prefectures (Chiba, Fukushima, Gunma, Ibaraki, Iwate, Miyagi, Saitama and Tochigi).

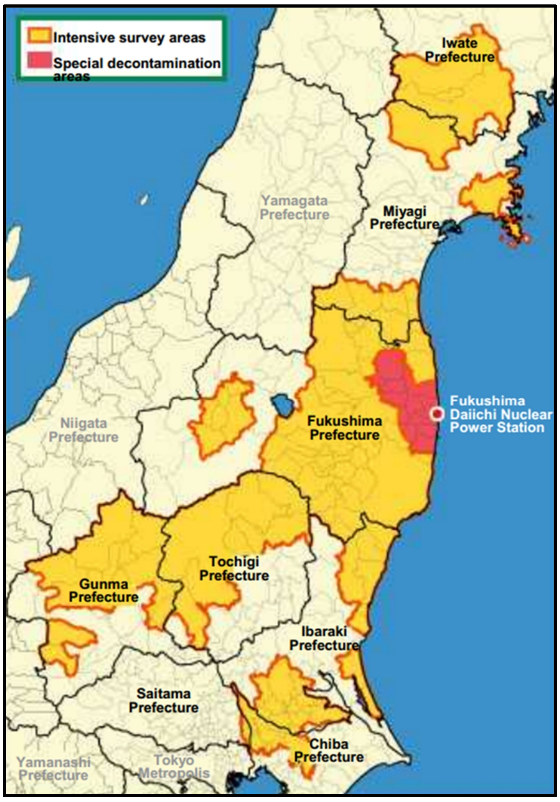


Figure 1-3: Map and concept for management of Intensive Contamination Survey Area[4)]

In principle, the processes for planning and implementing decontamination are similar to those for the Special Decontamination Area, but the responsibility for this work varies depending on the formal assignment of control of the land, as is detailed in the following breakdown of the framework for decontamination. Once again the designation of the Intensive Contamination Survey Area was carried out by the MOE and radioactivity surveys and measurements and decontamination planning were the responsibility of the heads of each of the individual municipalities. Various organisations were responsible for the implementation of decontamination work on land that was managed within the Intensive Contamination Survey area. These organisations included:

1. the national government
2. the individual prefecture
3. the municipality
4. a person or entity as set forth in the Ordinance of the MOE e.g. independent administrative agencies, national universities

Any other land managed by an organisation other than those listed in above was the responsibility of the municipality in which the land is located.

In terms of implementation, as was the case for the JAEA DPP, the MOE contracts remediation work to major engineering companies. This work is carried out under intense media scrutiny and was re-assessed in response to criticism at the beginning of 2013, with a re-launch of the programme including stronger control measures.

The overall policy is also continually reviewed in the light of lessons learned. In September 2013, this led to expansion in two particular areas – follow-up actions after decontamination is complete and management of contaminated forest. In both these cases, a key aim was to respond to public concern and hence communication is an important part of their implementation. Follow-up measures after decontamination work was completed included:

- Air dose rate monitoring to ensure that any reduction in air dose rate was maintained.

- Decontamination of areas that had been decontaminated and re-contaminated or areas that had not been previously decontaminated.
- Risk communication, undertaken based on discussions at the Nuclear Emergency Response Headquarters
- Monitoring of rivers and lakes.

1.2 Outline of the Ministry of the Environment Guidelines

1.2.1 Radiometric surveys

The topic of carrying out radiometric surveys of sites is provided in volume 1 of the MOE Decontamination Guidelines[2], while sampling of sites to determine contamination levels in materials that will be declared as waste is covered in the Guidelines for Waste[3].

The site survey guidelines focus on measurement of air dose at specific points (1 m or 50 cm above surface: the former for general areas and the latter for areas where children would be present) based on simple measurements with dosimeters, GM counters or scintillation counters. Rather than being prescriptive, the guidelines emphasise general principles (e.g. more intensive measurement in sensitive areas like schools and playgrounds – Figure 1-4 and practical aspects associated with the avoidance of contamination of detectors and forms for measurement recording. Experience from the JAEA DPP is captured in general recommendations, e.g. in terms of identification of hotspots where Cs run-off may accumulate (e.g. gutters, drains, etc.).

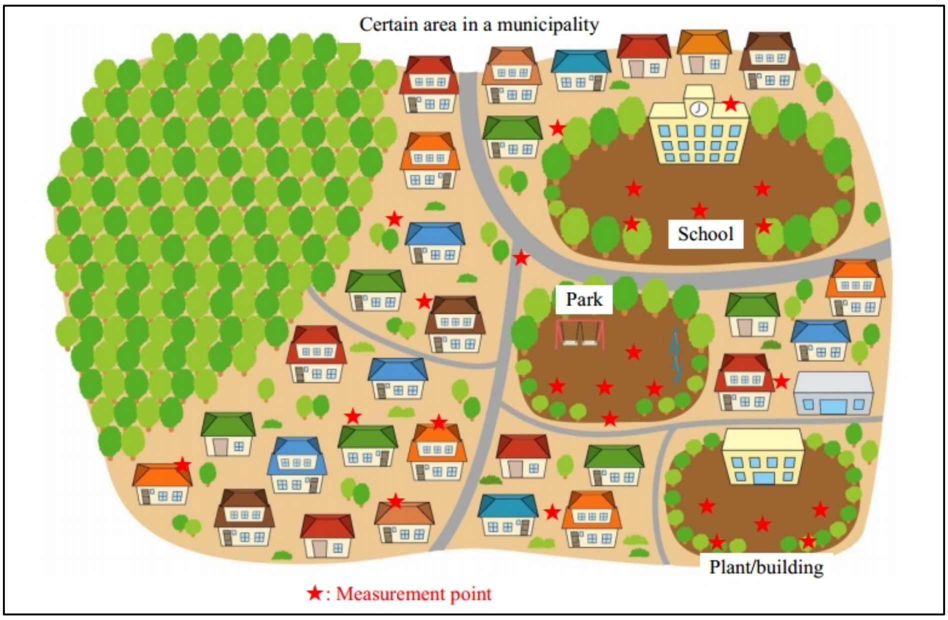


Figure 1-4: Concept for establishing measurement points[2]

These Guidelines also include measurement of surface contamination levels (at a height of 1 cm) with a shielded GM detector and illustrate how contributions to the total count rate from local gamma, beta and surrounding background can be distinguished. Importantly, the uncertainties associated with measurements are emphasised (contribution of background and impact of local shielding, impact of water content on surface count rate measurements) along with the importance of having staff with appropriate experience to carry out such work.

More specific techniques associated with the measurement of hotspots are covered in the MOE's Decontamination Guidelines (Part 2 – e.g. gamma camera, Figure 1-5).

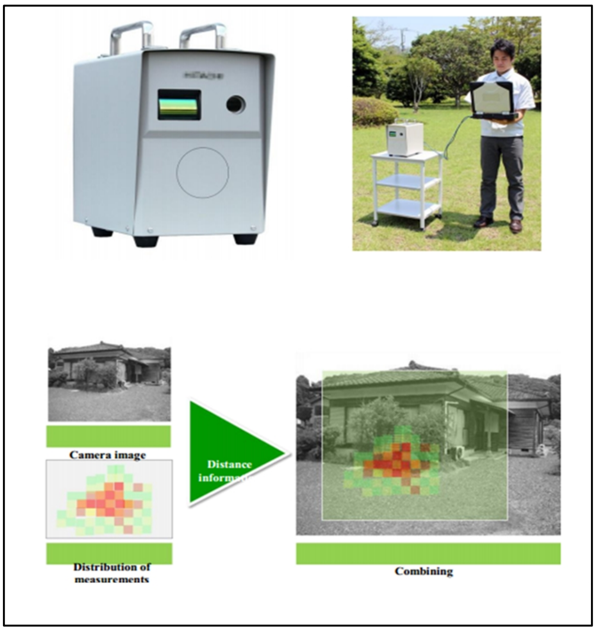


Figure 1-5: Use of gamma camera to identify hotspots[2)]

Guidelines for Waste[3)] Part II covers sampling, measurement and recording of Cs radioactivity in a range of solids, including sludge, ash and organic materials. Further requirements for dose measurements associated with waste handling, transport and storage are covered in Parts II-IV. Part V provides more details on radiation measurement technology and, as such, there is some overlap with Decontamination Guidelines Part 1. Nevertheless, the Part V of Guidelines for Waste focuses on application to measurement of doses from waste or during its transport and storage, indicating where and how measurements should be made and recorded (some overlap with Decontamination Guidelines Parts 3 and 4: Figure 1-6).

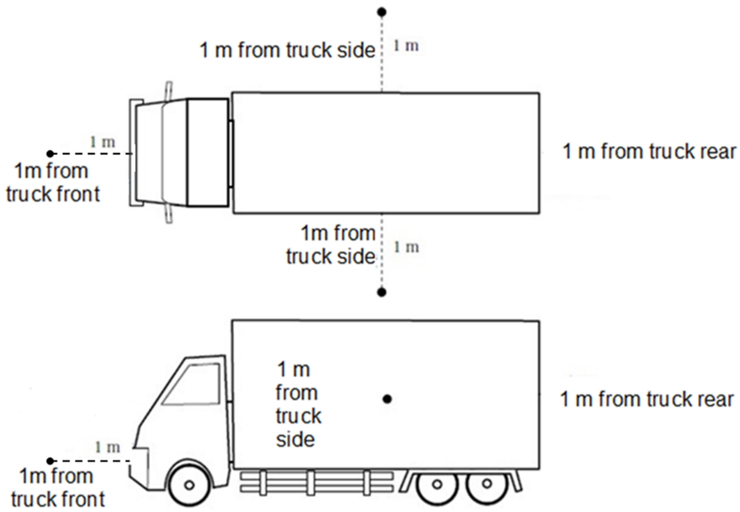


Figure 1-6: Example of specified radiation dose measurement points around a truck used for waste transport
This figure has been modified from one originally produced by the Ministry of the Environment[9)]

1.2.2 Waste management

The characterisation, volume reduction / conditioning, packaging, transport and storage of waste resulting from remediation is highly sensitive and is included in both Decontamination Guidelines Parts 3 and 4 and, in more detail, in the 6 parts of Guidelines for Waste. Focusing on the latter, waste characterisation (Parts I) has already been discussed in section 1.1 above. Part II covers characterisation, labelling, storage, transport and disposal of waste from industrial treatment facilities (e.g. incinerators, melters, thermal decomposition units) and defines free release limits for water and off-gasses and allowance for solid disposal in conventional landfill or other disposal facilities (appropriate mainly to intensive contamination areas).

Part III of Guidelines for Waste covers collection, transport and storage of more contaminated waste, specifying also radiation protection requirements. Special management requirements are defined, related not only to the concentration of radiocaesium in solid waste, but also associated chemotoxic hazards (particularly presence of asbestos). In terms of storage facilities, specific concerns related to different waste types are also defined (e.g. heat, gas generation and slumping from organic wastes), along with specified counter-measures to problems (e.g. storage geometries to prevent spread of fires (Figure 1-7).

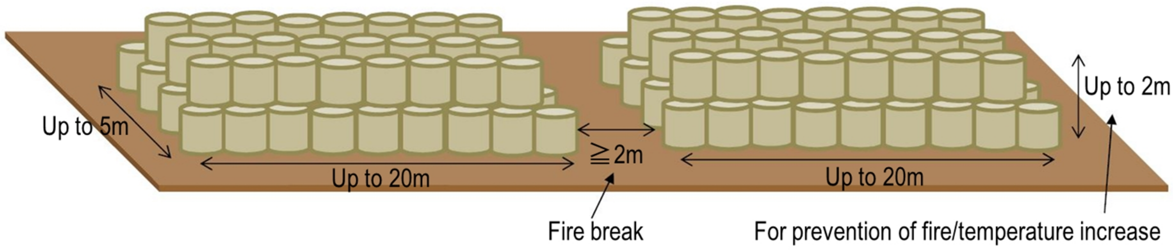


Figure 1-7: Illustration of initial storage geometry for flammable wastes to minimise fire risk
This figure has been modified from one originally produced by the Ministry of the Environment[3].

In many cases, especially for higher radioactivity wastes, engineered storage structures are required and guidelines for their design and construction are provided. These are particularly aimed at ensuring structural stability (under both normal conditions and during earthquakes), allowing for controlled drainage and avoiding gas pressurisation (e.g. Figure 1-8).

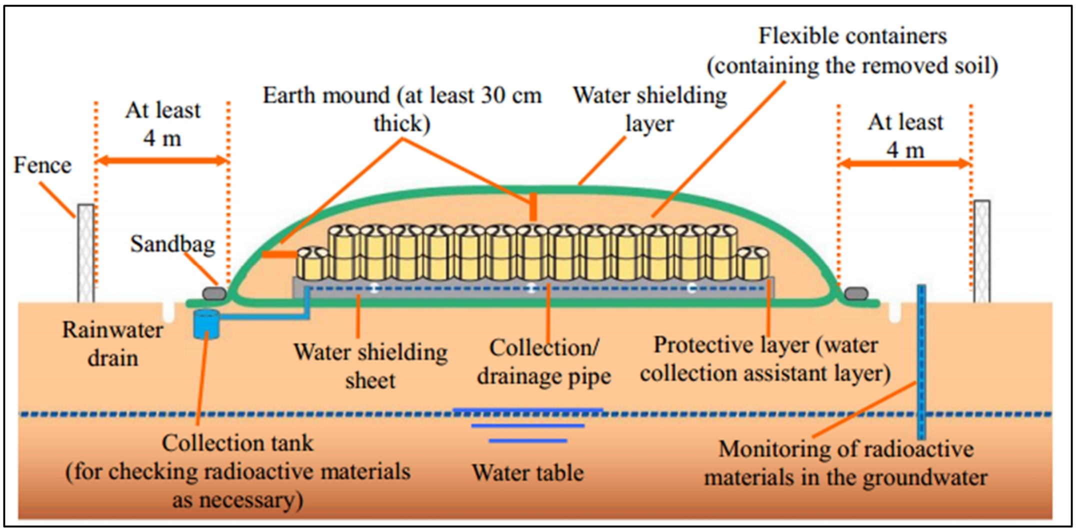


Figure 1-8: Illustration of storage design requirements for managing water / drainage[2]

In terms of radiation protection, shielding requirements and separation from housing (or respect distance for boundary fences) are also specified for surface storage of different quantities and radioactivity levels of waste (e.g. Figure 1-9), as are protective clothing requirements for working in environments with different levels of contamination and also procedures for accident management (e.g. road accidents during waste transfer).

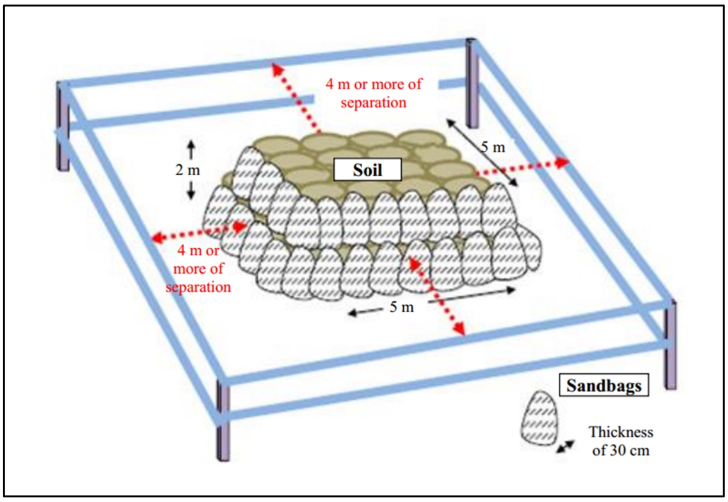


Figure 1-9: Illustration of required isolation distance for waste having an average concentration of 20 kBq kg^{-1} 2)
External shielding is provided by uncontaminated soil or bags of sand

Part VI of the Guidelines for Waste is, in effect, a synthesis of volumes 1-5 which also includes forms used to specify waste storage facilities and examples of their completion for different kinds of stores. Relevant standards for waste transport, treatment (e.g. incineration) and landfill disposal (for lower radioactivity material) are also included here, along with required documentation. For disposal, this also includes monitoring and record-keeping requirements, along with prohibitions (e.g. sea dumping) and punishments for non-compliance.

1.2.2.1 Long-term monitoring

As noted in 1.1, revised MOE policy now requires long-term monitoring of sites after decontamination work has been completed. Such monitoring systems will be implemented at all sites but, as yet there are, of course, no results from the regional decontamination work. Nevertheless, such monitoring has been carried out at the JAEA DPP sites and the results are shown in Figure 1-10 (normalised to the measured value immediately after decontamination in all cases).

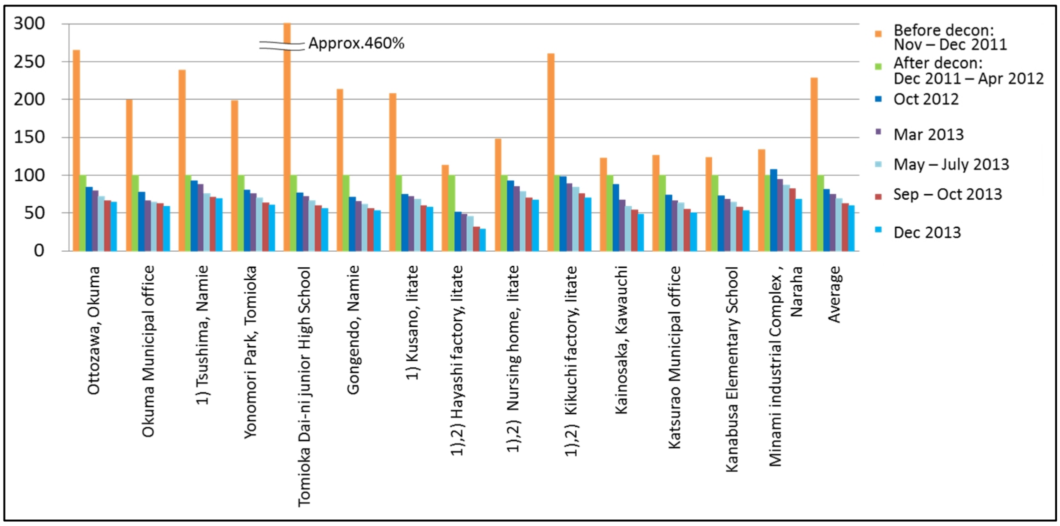


Figure 1-10: Results of long-term monitoring at the JAEA DPP sites
The value immediately after decontamination (green column) is normalised to 100%. 1) Measured values just after decontamination work (winter, 2011) in Tsushima, Namie and Iitate may be lower due to shielding from snow cover. 2) These areas were parts of target areas in Iitate village.

Although there some fluctuations (notably Naraha), the general trend is of continuously decreasing doses as a result of self-cleaning and radioactive decay.

It should be emphasised that the original set of MOE guidelines were prepared for areas of low radiation dose only (low, in this instance, is defined by areas that were not decontaminated under governmental control). Experience from the JAEA DPP (and later decontamination work) provided input for the 2nd edition of the MOE guidelines, but more significant input was incorporated into the MOE work specifications for the special decontamination areas (further detail on this is given in the following section 1.3).

1.3 Decontamination methodology for the Special Decontamination Area and input from the JAEA DPP

1.3.1 Decontamination work specification

In terms of technology, the experience gained in the JAEA DPP is captured in the MOE Decontamination Guidelines 2nd edition. Modifications of standard decontamination technology were used in the JAEA DPP, due to the fact that radiation doses were higher in these areas relative to the initial test sites at Minamisoma City and Date City (Part 1 of this report, section 2.1). In addition to examining the effectiveness of various decontamination methodologies (via reduction in dose rates), the versatility and speed of methods used were also taken into account. These modified methods were added to the MOE's portfolio of decontamination techniques, thus providing them with a suite of techniques for a range of different targets, which could be adopted for both lower and higher radiation dose areas.

Here an overview of work plans and descriptions of appropriate technology are provided for relevant targets, combining conceptual drawings with illustrations of how these would be implemented (e.g. Figure 1-11). The Guidelines also include practical aspects of how decontamination areas are controlled by use of barriers and how contaminated tools and clothing are managed.

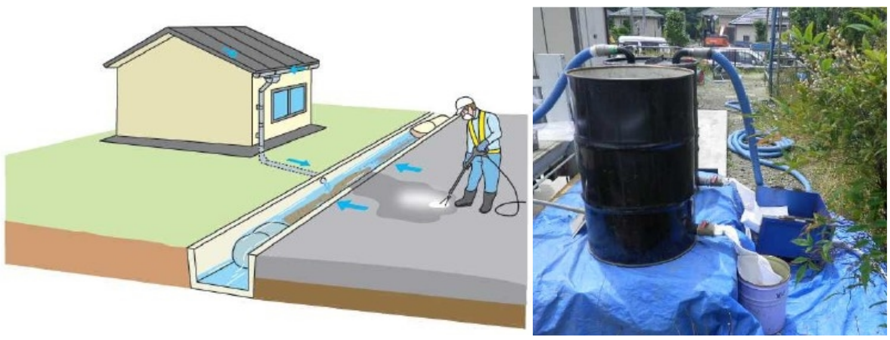


Figure 1-11: Concept of capture and decontamination of water used for washing and an illustration of how this is done in practice[2)]

For different types of target, the Guidelines also provide indications of the locations where measurements are made to assess the effectiveness of decontamination (Figure 1-12). Experience with implementation of such work is described in detail in the following section.

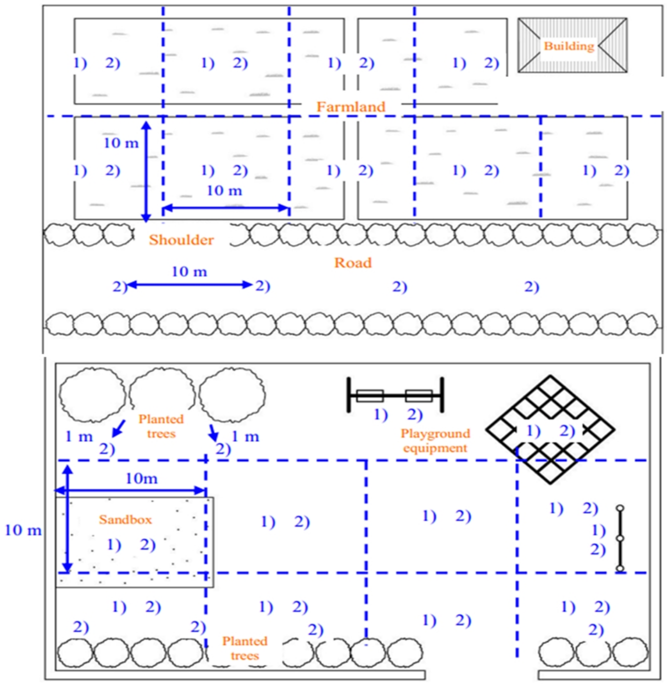


Figure 1-12: Indication of measurement locations for farmland (above) and parkland (below)
1) = dose rate at 1 m, 2) = radioactivity in cpm measured using a GM detector.
This figure has been modified from one originally produced by the Ministry of the Environment[2).

Expansion of procedures to the management of forest decontamination included:

- Forest surrounding residential areas – if removal of organic surface material from the 20 m peripheral zone was found to have limited effect, further removal of organic debris from the initial 5 m zone was performed.
- If air dose rates at residences were still high even after the 20 m zone in the surrounding forest had been decontaminated (e.g. where homes were situated in valleys) provision was made to extend the 20 m decontamination zone.
- Collaborative measures for contamination management between the Forestry Agency (charged with forestry management) and the MOE (charged with monitoring and developing countermeasures for run-off (including soil particles) from forestry)
- Mushroom farming (mushroom farms are commonly found in forests close to residential areas in Japan).

1.4 Overview

The MOE Guidelines, especially for decontamination, capture experience gained within the JAEA DPP at a general level, but do not provide the detail required to establish an optimised remediation programme. In particular, the pros and cons of different decontamination technologies and their cost, time and Waste Management requirements are not included (as provided in the "YELLOW PAGES" appended to Part 1 of this report). In terms of work components considered above, supporting information needed from the JAEA DPP summary includes:

- Site characterisation and monitoring (Part 1, section 2.2): applicability and advantages of various continuous profiling techniques, particularly if these are linked to GPS data and incorporated directly into a GIS database. Depth profiling of Cs in soil and other surfaces to determine applicability of different remediation options (methodology for sampling and analysis, interpretation of uncertainties).

- Decontamination technology (Part 1, section 2.4): range of options for management of contaminated soil without waste generation (mixing or profile inversion), decontamination approach to forests depending on whether deciduous or evergreen, different approaches to treatment of contaminated surfaces (roofs, roads, etc.) depending on materials and depth of penetration of contamination.
- Temporary storage site design (Part 1, section 2.6): tailoring of design to the contamination level of waste and the topography of the specified storage site.

In the following chapter, implementation of both Guidelines and JAEA DPP experience within the regional decontamination programme is described.

2. Regional decontamination

This overview provides a summary of the status of work as of September 2013. Further updates are available on the MOE homepage[1)]. As outlined in section 1.1, work is ongoing in parallel in both the “Special Decontamination Area” and the “Intensive Contamination Survey Area”, which are considered separately here.

2.1 Special Decontamination Area

An indication of progress with decontamination of the Special Decontamination Area is presented in Figure 2-1.

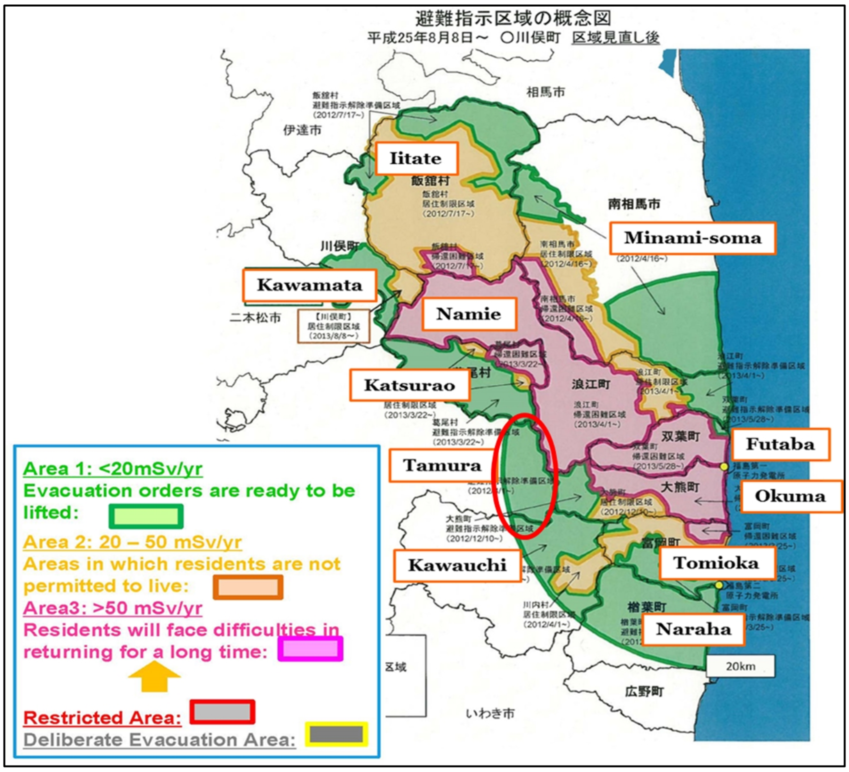


Figure 2-1: Classification of Special Decontamination Area

Since production of this map the evacuation order for Tamura City (red oval) has been lifted. This figure has been modified from one originally produced by Ministry of the Environment[10)]

The areas highlighted in the map fall into the following categories:

- Green: areas where the evacuation order is ready to be lifted (< 20 mSv y^{-1}).
- Amber: areas where residents can visit in during daytime hours (20 - 50 mSv y^{-1}).
- Red: areas where residents will be unable to return in the near future (> 50 mSv y^{-1}).

The evacuation order for one of these areas was lifted (Tamura) on 1st April 2014 and significant progress has been made in several others (Table 1). 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.

A breakdown of the decontamination targets for sites in which work is ongoing (or completed) is provided in Table 2. This again indicates that considerable progress has been made at the sites for which storage sites have been secured, whilst at other locations the ability to store waste produced may actually be one of the main constraints on decontamination activities.

Table 1: Overview of decontamination progress as of October 2014[10)]

Town	Population (approx.)	Decontamination area (10^3 m^2) (approx.)	Progress of decontamination activities			
			Decontamination plan	Temporary storage site	Landowners contacted	Decontamination activities
Tamura	400	5 000	Apr 2012	Secured	Completed	Completed June 2013
Naraha	7700	21 000	Apr 2012	Secured	Completed	Completed March 2014
Kawauchi	400	5 000	Apr 2012	Secured	Completed	Completed March 2014
Okuma	400	4 000	Dec 2012	Secured	Completed	Completed March 2014
Minami - soma	13 300	61 000	Apr 2012	~80% secured	~50%	In progress
Iitate	6 000	56 000	May 2012	secured	~90%	In progress
Kawamata	1200	16 000	Aug 2012	~90% secured	Almost complete	In progress
Katsurao	1400	17 000	Sep 2012	secured	Almost complete	In progress
Namie	18 800	33 000	Nov 2012	~30% secured	~50%	In progress
Tomioka	11 300	28 000	June 2013	~90% secured	~90%	In progress
Futaba	300	2 000	July 2014	Under coordination	Under preparation	Under preparation

Table 2: Breakdown of decontamination progress by target area within each town as of November 2014[10)]

Land use	Tamura	Naraha	Kawauchi	Minami-soma	Iitate	Kawamata	Katsurao	Namie	Okuma	Tomioka
Residential	100%	100%	100%	5%	46%	100%	100%	6%	100%	6%
Farmland	100%	100%	100%	2%	14%	15%	27%	6%	100%	1%
Forest	100%	100%	100%	20%	25%	38%	99%	10%	100%	8%
Road	100%	100%	100%	0.4%	10%	4%	6%	12%	100%	53%

Further details of the decontamination work are provided in sections 2.2-2.4, with particular emphasis on the completed work at Tamura. 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. As shown in Figure 2-2, a plan for stepwise decontamination / reopening of this key access route to the region during 2014 or shortly after has been established.

Decontamination was integrated with reconstruction and maintenance as required, in particular associated with the repair of earthquake damage. Decontamination work was completed in June 2013 and currently reconstruction work is in progress. The target air dose rate for the Joban Expressway after decontamination was ≤ 3.8 $\mu Sv\ h^{-1}$ (equivalent to annual dose 20 mSv) for areas that had an initial dose rate of between 3.8 - 9.5 $\mu Sv\ h^{-1}$ and ≤ 9.5 $\mu Sv\ h^{-1}$ (equivalent to annual dose 50 mSv) for areas more than 9.5 $\mu Sv\ h^{-1}$. Different decontamination techniques were used in low and high dose areas (e.g. high-pressure water jet-based washing for low dose areas and shot blasting for high dose areas). In the areas which have already been reopened, the target dose rates were successfully met. Although in some remaining areas target dose rates were not met by initial decontamination, it is expected that as a result of further reconstruction work, the air dose rates will be reduced to the targets specified.

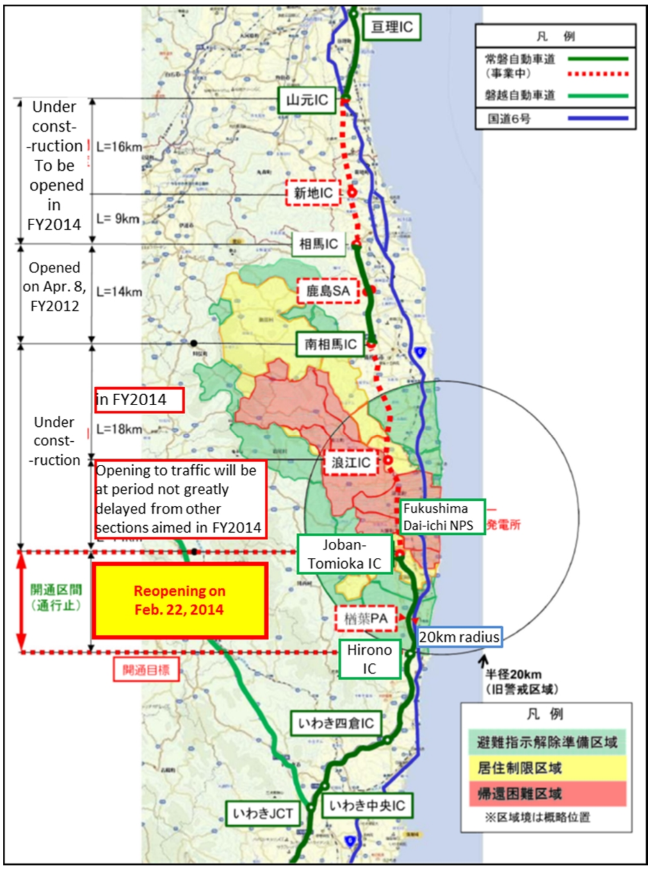


Figure 2-2: Plan for decontaminating / re-opening the Joban Expressway[10)]

2.2 Intensive Contamination Survey Area

One hundred and four municipalities, designated as lying within the Intensive Contamination Survey Area, are required to implement monitoring surveys and formulate decontamination implementation plans, which stipulate target areas, decontamination methods and contractors to carry out this work. As of November 2014, 94 municipalities had completed plans for decontamination and 17 had completed decontamination[10)]. However, due to the large areas to be considered, prioritisation is important – which is supported by an assessment of the significance of actions in terms of reducing risks to public health. As a result, implementation is most advanced for schools, public areas, houses and farmland – with roads, forest, etc. lagging somewhat behind (Table 3). Completion of this work is expected within 2-5 years in the different geographical areas included.

The MOE integrates information on progress by different municipalities in their progress report[10)] and also facilitates communication between these communities on “Good Practice” – which includes both practical aspects of decontamination (e.g. volume reduction) and also material for communication with the public (Figure 2-3).

2.3 Detailed decontamination experience

As noted above, Tamura is a site within the Special Decontamination Area where work is complete and hence is a good example to illustrate how experience from the JAEA DPP (Part 1 of this report, Chapters 2 & 3) and the procedures set up within the Guidelines (Chapter 1 above) are actually put into practice. Although only available in Japanese, a comprehensive overview of the work is provided on the associated website[11)]. This includes the original decontamination plan, archived progress reports, monitoring data (including interactive maps), photographic records of decontamination (including interactive views of time progress of work) and details of the waste stored.

Table 3: Summary of progress in the Intensive Contamination Survey Area by target, distinguishing those within and outside Fukushima prefecture[10)]

Outside Fukushima prefecture (end December 2013)	Percentage of total decontamination projects under planning	Percentage of planned projects that have been implemented to date
Schools and nurseries	Complete	Almost complete
Park, Sport facilities	Almost complete	Almost complete
Residential houses	~90%	~90%
Other facilities	~80%	~80%
Roads	~90%	~90%
Farmlands & meadows	Complete	Almost complete
Forests (in living areas)	Almost complete	~50%
Within Fukushima prefecture (end December 2013)	**Percentage of total decontamination projects under planning**	**Percentage of planned projects that have been implemented to date**
Public facilities, etc.	~80%	~80%
Residential houses	~90%	~60%
Roads	~70%	~30%
Farmlands & meadows	~90%	~70%
Forests (in living areas)	~80%	~30%

Figure 2-3: Exchange of experience between municipalities and integration within the "Good Practice Collection"[10)]

2.3.1 Overview of Decontamination work

As indicated in Figure 2-4, the work at Tamura is focused on the built-up and farmed areas extending along valleys penetrating wooded hills. This project lasted almost 1 year and involved an effort of around 120,000 person-days, with a maximum number of 1,300 workers employed in this effort.

The work period lasted from the 5th July 2012 until the 28th June 2013. The decontamination target areas included both forested (20 m from the forest periphery) and residential areas in both the Furumichi and Miyakoji districts. In total, ~230 000 m^2 of residential buildings, ~100 km of road, ~1.3 million m^2 of farmland and ~2 million m^2 of forest were decontaminated. A map of the current level of dose in this area is provided in Figure 2-5, which also provides an indication of the decrease provided by the decontamination activities.

The net effect of decontamination is summarised in Figure 2-6. Measurement of count rate at 1 cm with a collimated GM detector gives a measure of relative reduction in surface contamination, which demonstrates a generally high level of decontamination.

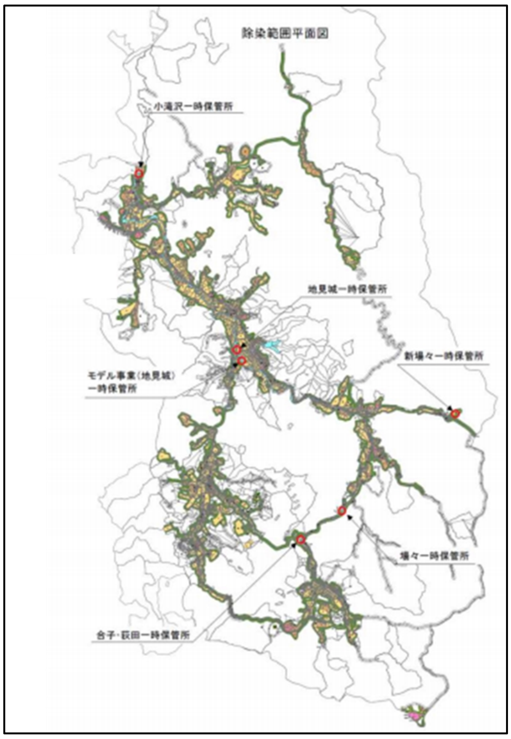


Figure 2-4: Overview of Tamura decontamination[10)]

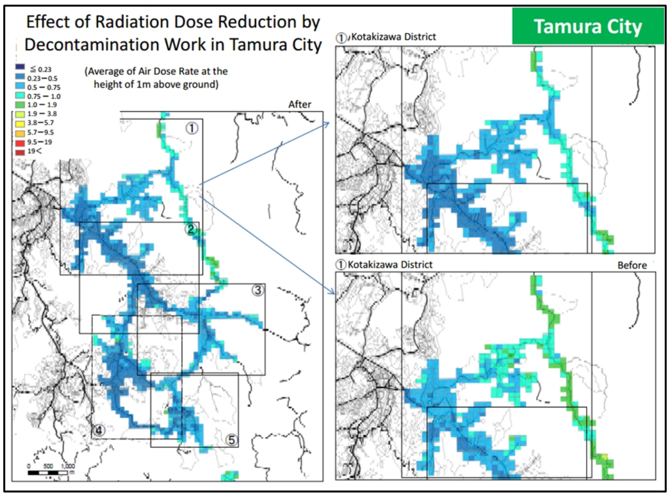


Figure 2-5: Overview of air dose rate distribution after decontamination and comparison of final (upper right figure) with initial (lower right figure) values for Kotakiwaza District in Tamura City[10)]

In terms of dose rate at 1 m, decontamination has a significant effect, but it is clearly less dramatic, particularly in terms of removing the few cases at the upper end of the range. This is an inherent consequence of the geometry of the narrow valleys being remediated as, because of the large range of gammas in air (half distance of 70 m), the air dose rate may include significant contributions from surrounding areas (mainly forest) that are not decontaminated or even from waste that may be stored in the vicinity.

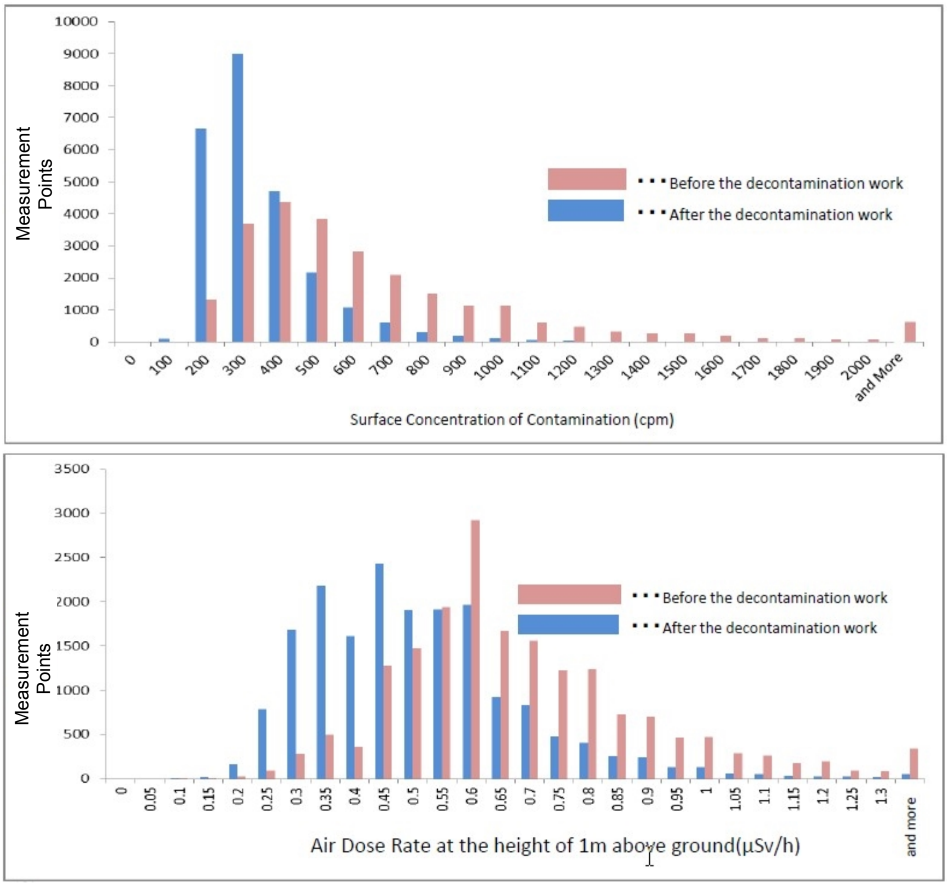


Figure 2-6: Overview of the net effect of decontamination in terms of reduction of surface concentration of contamination (upper) and air dose rate at 1 m above surface (lower)[10)]

2.3.2 Specific decontamination targets

The topography of this location is clear from Figure 2-7, which also shows the situation before and after decontamination for representative farmland. As can be seen, the main actions are removal of heavily over-grown vegetation and ground cover and also, in some cases, mixing or removal of topsoil. The undergrowth and litter of the surrounding forest are also extensively cleared, to within 20 m of the forest edge.

In terms of dose rate at 1 m, decontamination has a significant effect, but it is clearly less dramatic, particularly in terms of removing the few cases at the upper end of the range. This is an inherent consequence of the geometry of the narrow valleys being remediated as, because of the large range of gammas in air (half distance of 70 m), the air dose rate may include significant contributions from surrounding areas (mainly forest) that are not decontaminated or even from waste that may be stored in the vicinity.

For other decontamination targets, the focus is on manual washing and physical removal of contaminated material, as was the case in the JAEA DPP (Figure 2-8). This general approach was also carefully applied to sensitive targets such as shrines and cemeteries.

Figure 2-7: Illustration of farmland decontamination[10)]

Figure 2-8: Illustration of decontamination work in progress[10,12)]

An overview of the effectiveness of decontamination work, broken down by specific targets, is provided in Table 4. As noted in section 2.2.1, such dose rate measurements tend to underestimate the effect of surface decontamination. Nevertheless, it is clear that the largest dose reductions were achieved in the most critical locations – residential land and farmland with the highest initial contamination levels. It is also clear that the potential to further reduce dose at the sites with the lowest contamination is limited – probably due to the fact that self-cleaning has already washed away any readily removed caesium from these locations.

In Tamura, as also in other locations being decontaminated, the extent of dose reduction for forest was particularly low. This reflects the experience from the JAEA DPP work and also understanding of the environmental behaviour of Cs in such environments (further discussed in section 3.5). As discussed in section 1.1, this is reflected in the current reconsideration by the MOE of the policy for treatment of forested areas.

Table 4: Overview of decontamination results for different targets as a function of initial level of contamination[13)]

Land use type	Dose rate range before decontamination (μSv h^{-1})	Number of measurement points	Average dose rate before decontamination (μSv h^{-1})	Average dose rate after decontamination (μSv h^{-1})	Dose rate reduction
Residential land	≥ 1.0	484	1.19	0.54	54%
	0.75-1.0	1235	0.83	0.49	40%
	0.5-0.75	2973	0.60	0.40	34%
	< 0.5	1772	0.40	0.31	23%
Farmland	≥ 1.0	119	1.11	0.74	34%
	0.75-1.0	708	0.83	0.59	29%
	0.5-0.75	1711	0.60	0.46	24%
	< 0.5	458	0.43	0.36	15%
Forest	≥ 1.0	680	1.17	0.80	31%
	0.75-1.0	1147	0.84	0.66	21%
	0.5-0.75	1814	0.62	0.53	15%
	< 0.5	338	0.43	0.40	7%
Roads	≥ 1.0	222	1.20	0.87	28%
	0.75-1.0	690	0.83	0.60	27%
	0.5-0.75	2021	0.60	0.44	26%
	< 0.5	1255	0.40	0.32	21%

2.3.3 Temporary waste storage

As the contamination levels are relatively low, simple designs for temporary storage sites are sufficient (Figure 2-9), and soil cover to provide radiation shielding is not required. This is shown by measurements of radiation dose at the site boundary before, during and after waste emplacement (Figure 2-10).

Figure 2-9: Site during operational and temporary storage phases[13)]

Data on the emplaced waste volumes and dose rates at temporary storage facilities within the decontamination area are given in Table 5.

In no case does the waste significantly increase doses at the site boundary or could radiocaesium be detected during monitoring of either storage site drainage or surrounding groundwater.

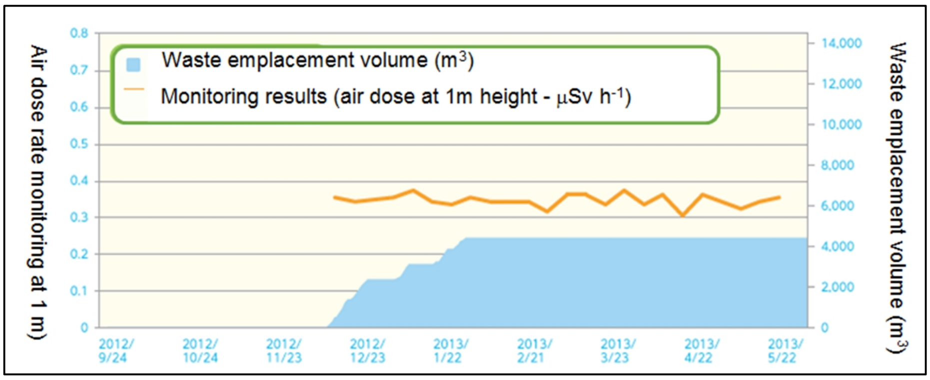


Figure 2-10: Air dose rate monitoring at 1 m (orange line) during waste emplacement (blue profile)[13)]

Table 5: Data on Tamura temporary storage sites (modified from (10))

Tamura district	Air dose rate after installation (1 m)	Air dose rate (27th May 2014)	Removed soil (m^3)
Kotakizawa	0.36	0.36	4 100
Jikenjo	0.32	0.38	2 700
Jikenjo (JAEA DPP)	0.38	0.34	2 600
Shin-Baba	0.60	0.56	8 000
Baba	0.40	0.45	2 000
Goshi, Ogita	0.39	0.43	12 000

2.4 Interim storage and disposal

Wastes arising in the Fukushima prefecture are largely categorised into two groups: the first is waste generated by the earthquake and tsunami and the second group is waste arising from decontamination activities (both groups are contaminated with radiocaesium). The Guidelines for treatment and disposal of waste are summarised in Figure 2-11. The treatment flow for specified waste (tsunami and earthquake waste) is depicted in the left-hand side of Figure 2-11 and the waste from decontamination activities is outlined on the right-hand side of the Figure. Management of caesium contaminated waste is determined by concentration, normally expressed in Bq kg^{-1} total radiocaesium.

The nomenclature in the English translation in the Figure below, describes, "specified waste", as an aggregate of waste from the "Contaminated Waste Management Areas" and "designated waste". Waste from the "Contaminated Waste Management Areas" is that generated in the Special Decontamination Area. The "designated waste" defines the types of waste which are mainly incineration ash, rice straw, compost, sludge from water purification and sewage sludge (with a radiocaesium concentration > 8 kBq kg^{-1}). Waste from the "Contaminated Waste Management Areas" that is only slightly contaminated (≤ 8 kBq kg^{-1}) is treated in the same way as waste arising from outside the Special Decontamination Area (i.e. normal municipal waste). It is assumed that combustible waste will be incinerated and that the resulting ash, slag, etc. will be solidified in a container and then, together with non-combustible waste, will go for disposal in a leachate-controlled landfill site, if the concentration of radiocaesium is ≤ 100 kBq kg^{-1}; otherwise the waste will go to interim storage.

The waste generated from decontamination in the Fukushima prefecture is represented on the right-hand of Figure 2-11. As noted in section 2.2.3 above, waste is emplaced in local temporary storage (conceptual designs for these facilities are shown in Figure 2-12), after which it will be moved to interim storage, which is planned to commence receiving waste in January 2015.

Figure 2-11 also shows an option of direct incineration of burnable waste from decontamination activities, with the resultant solids being treated in the same way as those from the "designated waste" stream. Currently, this does not occur and all solid waste from these areas goes to temporary storage. However, incineration test facilities are in operation by the MOE, in order to acquire preliminary data before commencing future large scale incineration.

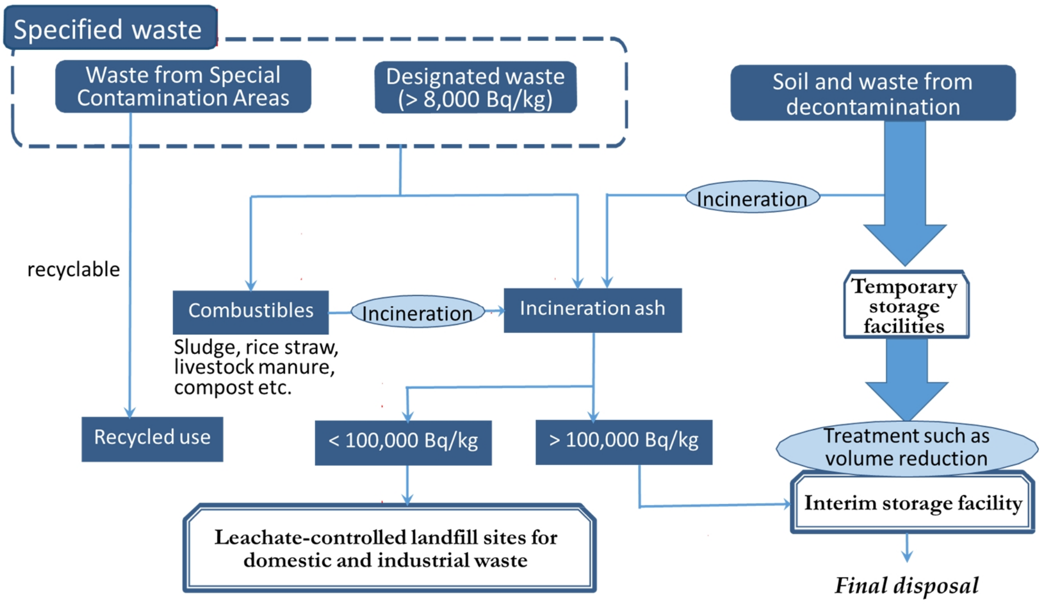


Figure 2-11: Overview of waste treatment options for waste arising in the Fukushima prefecture
This figure has been modified from one originally produced by the Ministry of the Environment[14].

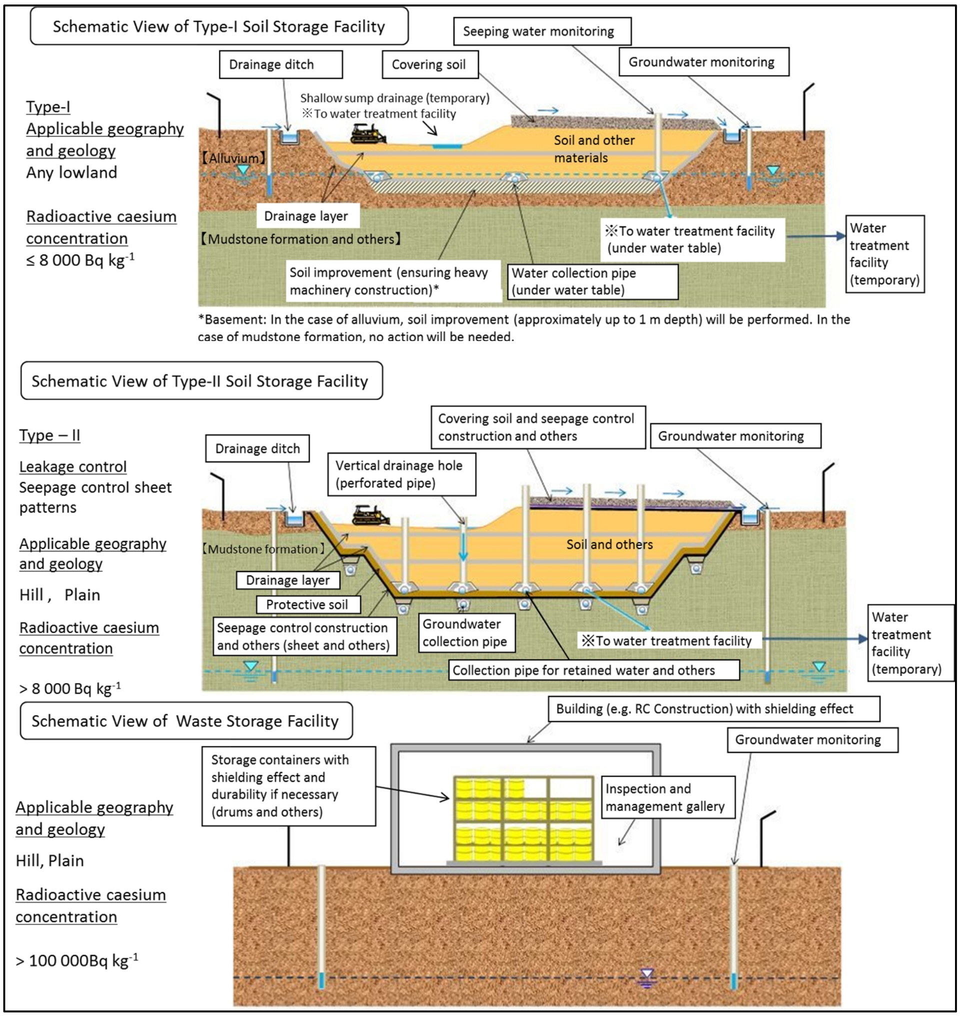


Figure 2-12: Conceptual drawings of storage facilities for “specified waste”[10]

The interim storage facility (or facilities) is still at the planning stage. A general concept for such a site is illustrated in Figure 2-13. Depending on the degree to which waste production can be reduced, the volume of waste to be managed would lie in the range of 15 – 30 million m^3.

The interim storage facility will have a design lifetime of 30 years, after which waste will be removed for final disposal at a location as yet to be defined. This thus leads to considerable challenges in ensuring that packaged waste will be both stable over this period and be easily and safely recovered and transported thereafter. Drilling work has been done at sites in Okuma, Naraha and Futaba during 2013. As the Governor of Fukushima prefecture requested the MOE to review the plan to consolidate facilities in Okuma and Futaba, the interim storage facility is currently being considered at 2 sites.

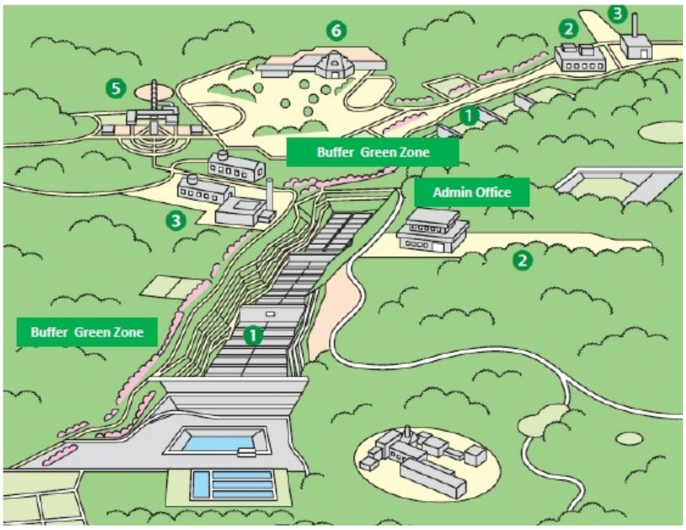


Figure 2-13: Concept for an interim storage facility

1 storage area, 2 waste reception & segregation facility, 3 volume reduction facility, 4 monitoring system (spread throughout area), 5 R&D facility, 6 public information centre[15)]

3. Supporting R&D

A wide range of R&D is being carried out in Japan to develop improved technology for monitoring contamination, carrying out site decontamination, waste volume reduction and improving understanding of the environmental behaviour of radiocaesium. This is sponsored by several government departments and carried out by many different research organisations, universities and contractors. In the following, currently ongoing R&D carried out by JAEA is introduced for radiation monitoring and mapping (3.1), decontamination and waste management technology (3.2) and environmental behaviour of radiocaesium (3.3). Supporting documentation in English is available to download at (16). Work more directly linked to agriculture is summarised by Nakanishi and Tanoi[17].

3.1 Radiation monitoring and mapping

A comprehensive overview of national and regional radiation monitoring data is provided by the Nuclear Regulation Authority website[18] and much of the data that can be found here was provided by JAEA staff. More details of the technology for regional aerial radiation monitoring, calibration, uncertainty analysis and extensive maps of results are provided by JAEA[19].

For more detailed survey of smaller regions, JAEA has studied a range of unmanned aerial measurement systems (e.g. Figure 3-1), including micro aerial vehicles for ~100 m scale survey. These

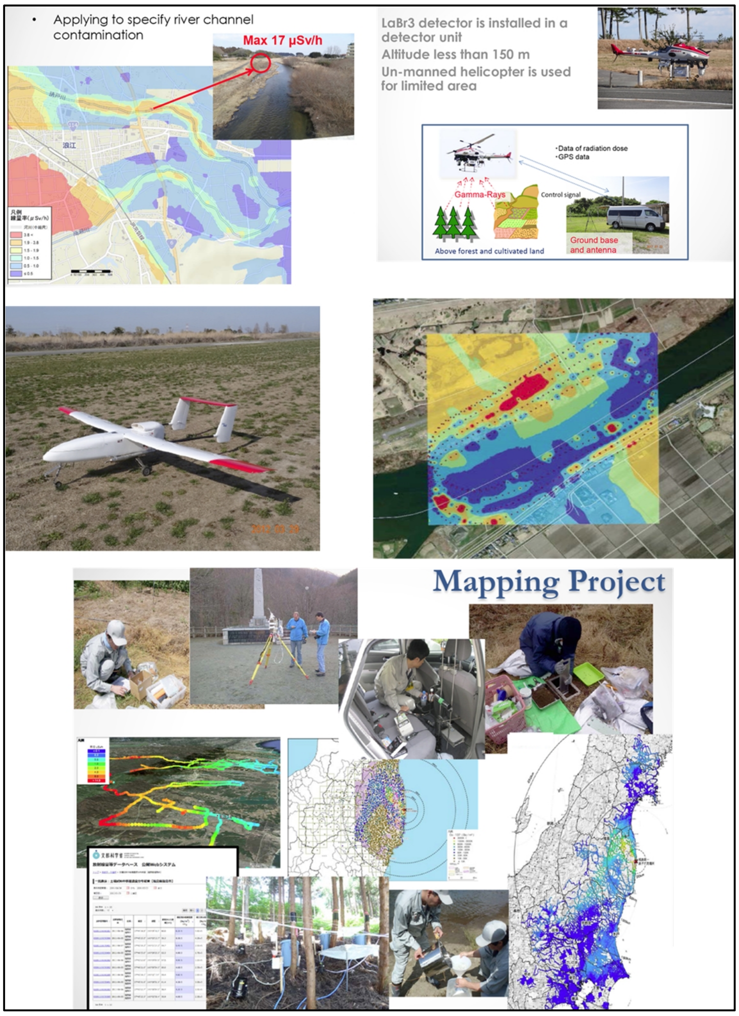


Figure 3-1: Developed measurement systems by JAEA
Top: Survey with an autonomous unmanned helicopter (AUH); Middle: Drone-based survey system and radiation map using improved visualisation approach; Bottom: Illustration of activities within the MEXT mapping project

can rapidly survey sites and identify any hotspots present. R&D is currently on-going to further develop aerial mapping technology, along with the data management systems to improve visualisation of results (Figure 3-1, middle). Aerial systems are complemented by a number of ground-based measurements using motor vehicles, buggies, backpacks and point measurements (both in-situ and sampling, plus laboratory measurement). JAEA coordinates a major effort by MEXT to integrate measurements carried out by a number of different organisations and integrate them within a common database (Figure 3-1, bottom).

Because of the range of techniques used, intercalibration and establishment of reference measurement sites are important to assure data can be integrated in a common database. Efforts in this direction have been initiated[7)] and will be extended as part of a recent bilateral collaboration between SUERC (the Scottish Universities Environmental Research Centre) and JAEA[20)].

JAEA have invested considerable resources and time into developing a system by which the general public can view air dose rates (in real time) within a number of highly populated residential areas in Fukushima prefecture. This is a joint project undertaken with the assistance of Kyoto University and the Fukushima prefecture (Figure 3-2). Portable radiation survey meters have been installed on route buses in the cities of Aizu-Wakamatsu, Iwaki, Koriyama and Fukushima City.

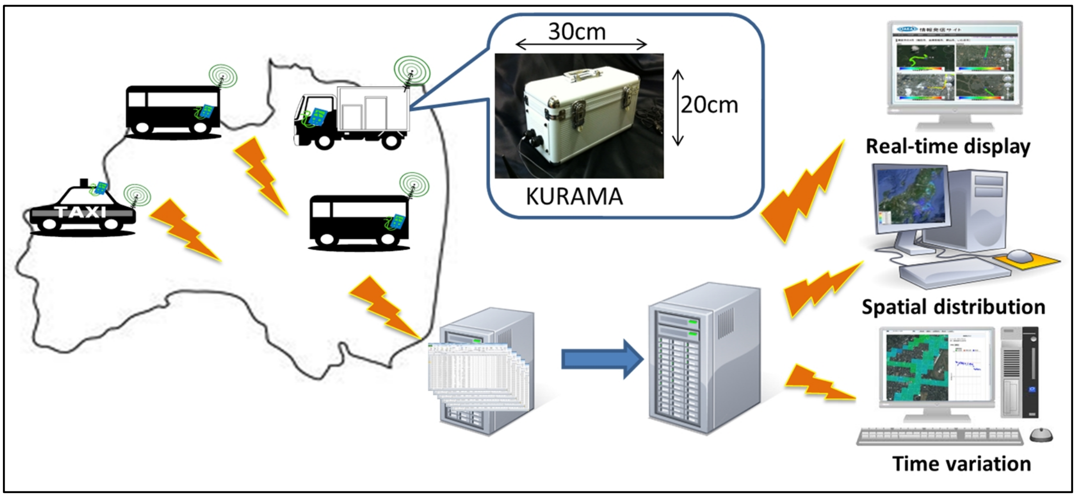


Figure 3-2: Capture of real time radiation dose measurements. Air dose rates are measured by KURAMA (Kyoto University RAdiation MApping system) survey meters installed on various vehicles

This means that the radiation doses can be recorded along many major and minor arterial routes in each of these cities. Data collection, processing and analysis is automated and the data can be viewed over a wide range of spatial and temporal dimensions and the output linked to widely available and easy to use web based geographical information programme linked to satellite images and aerial photographs, e.g. Google earth (Figure 3-3: see also (21)).

In several cases this information is displayed in public areas in order that the general public can have easy access to it. For example, JAEA have set up a large monitor on the ground floor of the Unix building in the centre of Fukushima city (houses JAEA offices). Members of the public can freely enter the building and view dose rates in the city in real time (Figure 3-4). This is an example of one of many approaches JAEA are developing in an attempt to foster good public relations through effective communication.

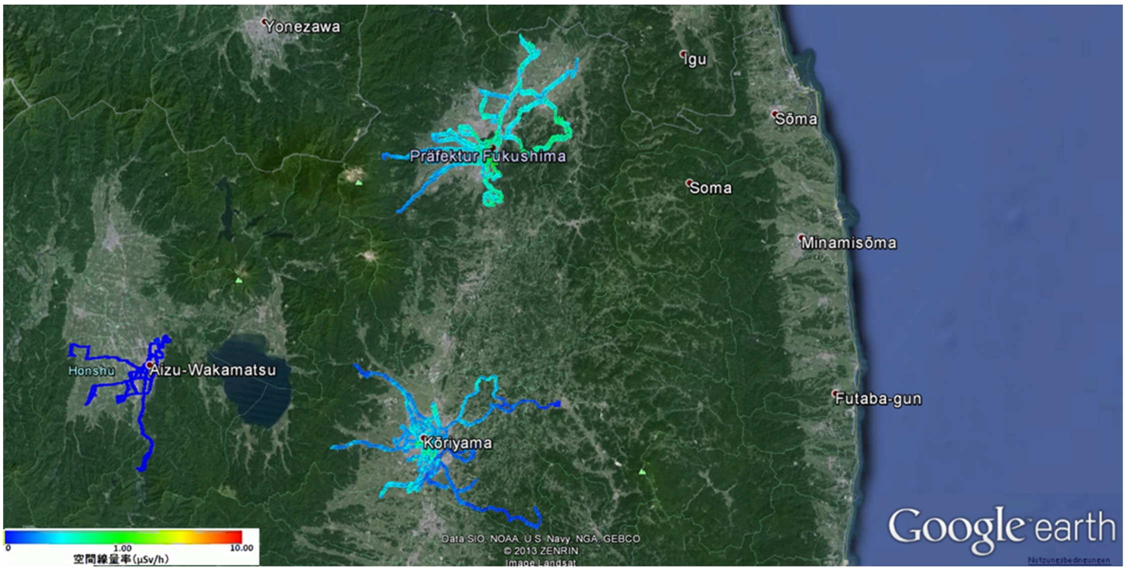


Figure 3-3: Example of real time dose measurements linked to a web based geographical information system
Credits: Data SIO, NOAA, U.S. Navy, NGA, GEBCO ©2013 ZENRIN Image Landsat

Figure 3-4: Real time radiation dose displayed for 4 cities within the Fukushima prefecture in an area easily accessible to the general public

3.2 Decontamination and waste management technology

On 4 separate occasions, the Japanese government invited proposals for R&D work to support investigation of alternative decontamination or waste volume reduction technology. JAEA was commissioned by the Cabinet Office (1st call) and by the MOE (2nd, 3rd and 4th calls) to participate. The first call included 25 funded projects, and these formed part of the JAEA DPP (Table 6).

As can be seen, these projects cover a range of decontamination targets and, for each of these, different technical approaches are examined (e.g. for soil, as shown in Table 7).

Each approach was assessed in terms of effectiveness of decontamination, often including consideration of different implementation options (e.g. number of washing cycles). Consideration of the complete system flow (e.g. Figure 3-5) allows a mass balance to be developed which includes materials requirements (e.g. water use) and all primary and secondary wastes generated (e.g. from water cleaning and contamination of equipment).

Table 6: Summary of decontamination technology R&D projects (1st call)

Target	Method*		No.
Soil	Heat treatment	Removal of Cs by rotating furnace-based sublimation	1
	Wet Separation	Small-scale separation system (pump and sieve)	2
		Ball mill/drum washer	3
		Crusher and washer system	4
		Separation followed by heating at 700 °C	5
		Crusher and washer system, cavitation washing	6
		Washing and separation using micro-bubbles, high-pressure water jet	7
	Chemical treatment	Oxalic acid-based elution of Cs	8
Sewage sludge	Elution	Organic reagent treatment	9
Playgrounds, roads and buildings	Stripping	Paint stripping	10
	Washing	Nano-bubble water treatment	11
		Molecular cluster ozone water	12
		Ultra-high pressure waterjet (280 MPa)	13
	Blasting	Alumina slurry blasting	14
Tsunami debris	Washing	Surface abrasion in water	15
		Separation (sieving) of frozen (with dry ice) soil particles	16
Organic matter volume reduction	Conversion into manure	Aerobic fermentation at ≥ 100°C	17
		Aerobic fermentation at 50-60°C	18
Water	Sorption	Zeolite blocks	19
		Iron ferrocyanide	20
Forests and timber	Stripping & solidification	Cement paint stripping	21
	Washing	Water wash / incineration	22
		High-pressure water jet washing of unpeeled logs	23
	Tree thinning	Air dose measurements during tree thinning work	24
	Undergrowth clearing	Vacuuming and monorail transportation	25

Table 7: Details of soil decontamination approaches

Decontamination technique		Separation	Grinding	Washing	Heating
1	Removal of Cs by rotating furnace-based sublimation	x	x	x	✓
2	Small-scale separation system using a special pump and a sieving machine	✓	x	✓	x
3	Ball mill/drum washer	✓	✓	✓	x
4	Crusher and washer system	✓	✓	x	x
5	Separation followed by heating at 700 °C	✓	x	x	✓
6	Crusher and washer system, cavitation washing	✓	✓	✓	x
7	Washing and separation using micro-bubbles, high-pressure water jet	✓	✓	✓	x
8	Oxalic acid-based elution of Cs	x	x	✓	x

Because of the requirement to capture and treat washing water, techniques which minimised (e.g. approach 14 in Table 6) or avoided water use completely (e.g. approaches 10 & 16 also Table 6) were of interest. Comparison of water washing with alternatives considered both the equipment and time requirements (Figure 3-6) and also the effectiveness of the technology in reducing contamination for different surfaces and operational parameters (e.g. Figure 3-7).

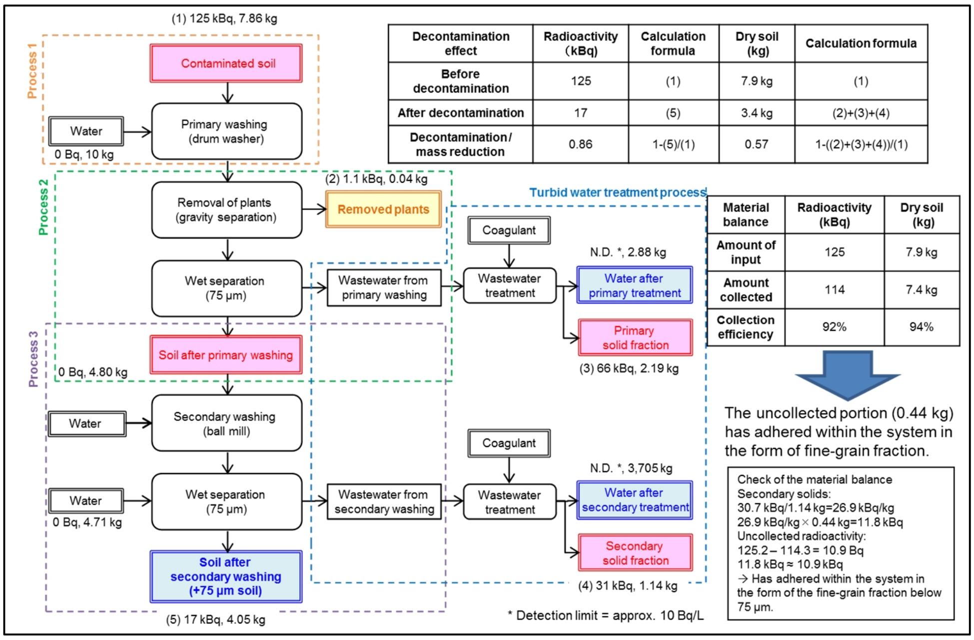


Figure 3-5: Flow chart for assessing characteristics of soil decontamination approach

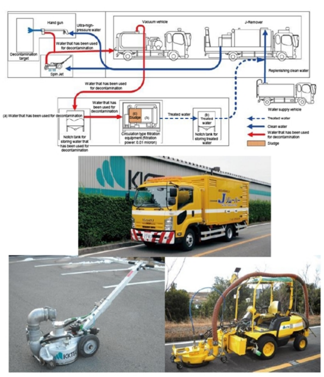
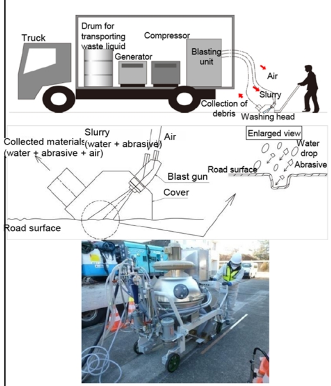
Method	Ultra-high-pressure water jet	Wet blasting
Conditions	Pressure; up to 280 MPa Water volume: 30 L/min	Blasting material: alumina
Water treatment	Coagulation and precipitation + filter (UF + activated charcoal)	None
Work speed	62 m²/h	24 m²/h
Equipment		

Figure 3-6: Comparison of road decontamination approaches

As can be seen from Figure 3-7, however, more intensive cleaning may provide greater decontamination, but also physically damage the surface and hence careful cost benefit analysis must be applied.

An overview of the general technology assessment is provided in Table 8 and a more extensive overview of the output from this work is available at (22).

At present, continual development of decontamination technology is a component of the regional remediation project, which is based on experience gained from full-scale application. A focus for ongoing R&D is waste volume reduction – particularly contaminated vegetation and soil. An update on the progress of this work was provided at the recent "Cs workshop"[8], from which it is clear that the very strong binding of Cs to soil minerals – in particular clays – greatly limit the potential applicability of either

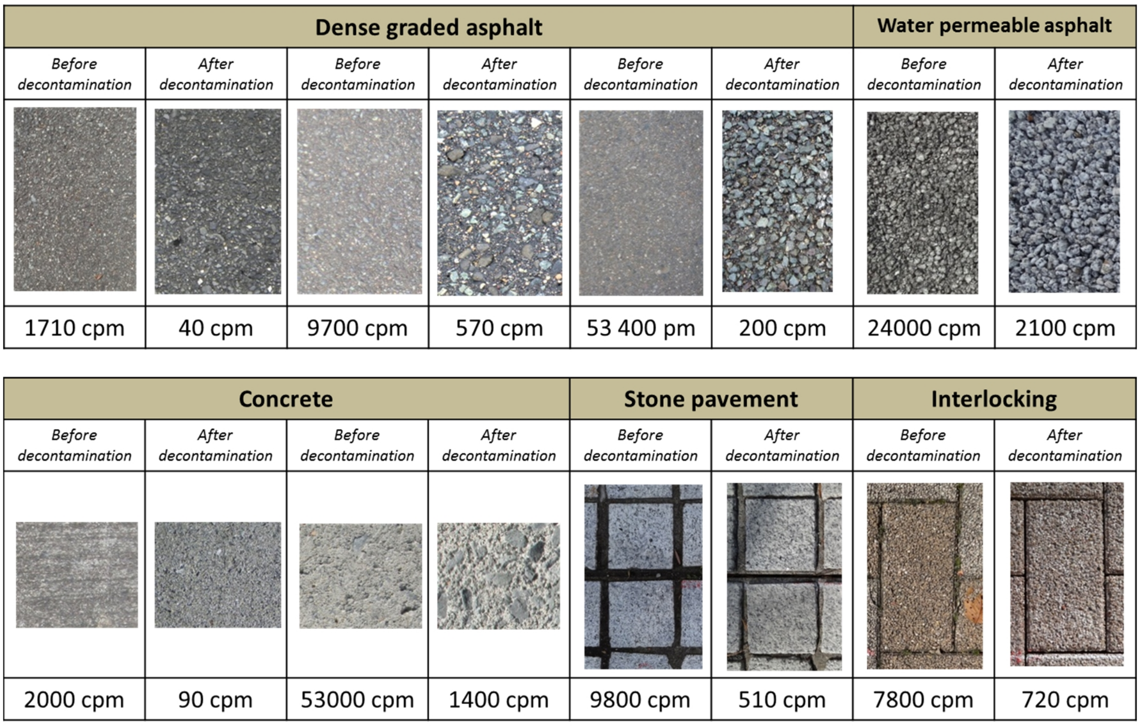


Figure 3-7: Comparison of decontamination of different surfaces

chemical or thermal decontamination methods. However such evidence for the irreversibility of Cs uptake can be used to support arguments for in-situ soil mixing or profile inversion or utilisation of contaminated soil as in-fill for construction projects.

Finally, meta-analysis of the overall effectiveness of the decontamination programme should be mentioned (e.g. (23)), although in-depth cost analysis for decontamination technology development has not been performed in JAEA DPP. Such analyses evaluate both the financial costs of different decontamination scenarios (Table 9) and the net results in terms of dose reduction to returning populations (Figure 3-8).

Yasutaka et al.[23)] found that the cost of decontamination per person for each unit area varied greatly depending on both the population density and the type of land use. For example, compared with urban areas having high population densities, agricultural areas had higher decontamination costs per person.

3.3 Environmental behaviour of radiocaesium

Many universities and research institutes from Japan and around the world study the environmental behaviour of radiocaesium, making it possibly the best studied of all radio-isotopes, with extensive background literature extending from the middle of the last century. In terms of local studies focused on Fukushima, a key initiative is the "Long-term assessment of Transport of Radioactive Contaminants in the Environment of Fukushima" (F-TRACE) run by JAEA. As defined in December 2012, F-TRACE was planned with 8 components, 4 focused on specific environments (river, dam, estuary and forest) and 4 on infrastructure and coordination (analytical equipment, follow-up monitoring, radionuclide migration and migration control).

As indicated in Figure 3-9, the overall aim of F-TRACE is to develop an understanding of the natural processes influencing the mobility of Cs in areas which have not been decontaminated – predominantly forested hills and mountains.

Quantification of such processes in models allows the impact on local populations to be assessed in terms of additional radiation dose as a result of all exposure mechanisms resulting from their normal lifestyle. On the basis of potential dose, the need for counter-measures to reduce this can be assessed and the practicality of approaches to constrain Cs transport assessed. For the specific case of radiocaesium, a critical factor influencing its mobility is its strong uptake onto surfaces (Figure 3-10).

Table 8: Overall assessment of technology R&D projects (listed in Table 6)

Target	Method	No.	Decontamination effectiveness	Investment in equipment	Waste volume	Cost	Comments
Soil	Heat treatment	1	High	Necessary	Very low	High	Handling of removed soil containing high concentrations of radioactive Cs needs to be addressed. Cost reduction required.
	Wet separation	2	Moderate	Existing	Low	Moderate	Only a small number of tests were performed, further data acquisition required.
		3	Moderate	Necessary	Moderate	Low	Investment required before implementation.
		4	Moderate	Necessary	Moderate	Low	Technique needs to be optimised for treatment of highly contaminated soil.
		5	Limited	Necessary	Moderate	Low	Separation brings about a decontamination effect. Subsequent heat treatment did not affect.
		6	Moderate	Necessary	Moderate	Low	Investment required before implementation.
		7	Moderate	Necessary	Moderate	Moderate	Investment required before implementation.
	Chemical treatment	8	Moderate	Existing	Very small	High	Needs to be more cost effective before implementation.
Sewage sludge	Elution	9	Limited	Necessary	Moderate	No data	Only a small number of tests were performed, further data acquisition required.
Parks, roads and buildings	Stripping and peeling	10	Moderate	Not necessary	Low	Low	Can be applied immediately.
	Water wash	11	Limited	Necessary	Low	High	No increase in decontamination effect relative to water alone.
		12	Limited	Necessary	Low	High	Worker safety measures required for application of this treatment.
	High-pressure water jet	13	High	Existing	Low	Moderate	Can be applied immediately.
	Stripping and peeling	14	Moderate	Existing	Low	Moderate	Can be applied immediately.
Debris	Washing	15	Moderate	Necessary	Low	Moderate	Selection of a more optimal grinding material could improve decontamination effect and reduce waste arising.
		16	Limited	Necessary	Moderate	Moderate	Decontamination effect is low, but no waste water generation.
Vegetation and cow manure	Conversion into manure (see Table 6 for °C)	17	No data	Necessary	No data	No data	Only a small number of tests were performed, further data acquisition required.
		18	No data	Necessary	Moderate	Moderate	Tests were performed on dry vegetation (wood and leaves) only. Wet vegetation tests needed.
Water	Collection	19	Limited	Necessary	Moderate	Moderate	Only one type of artificial zeolite was tested. Tests on alternative zeolites needed.
	Adsorption, coagulation	20	High	Existing	Low	Moderate	Applicable as a high-performance purification system for large volumes of water. Management of spent iron ferrocyanide not included here - needs to be addressed.
Forests and timber	Solidification, peeling	21	Limited	Not necessary	Large	High	Same decontamination effect as wet brushing.
	Washing	22	Moderate	Existing	Low	Moderate	Decontamination is achieved with washing but incineration required to reduce waste volume.
		23	Moderate	Existing	Low	Low	Timber data still required, but water treatment can be applied immediately.
	Thinning	24	No data available				Data acquisition needed on dose reduction related to forest decontamination work.
	Undergrowth removal	25	No data	Existing	No data	Moderate	Improvements are necessary regarding testing for removal of soil.

Table 9: Unit cost for storage phase of decontamination and total of all the unit costs considered in the present analysis (modified from (23))

Land use	Abbr.	Decontamination option	Unit cost (JPY m^2) Interim storage[a]			Total[b]		
			D1	D2	D3	D1	D2	D3
Agricultural	A1	Vegetation and topsoil removal (5cm)	2215	7220	8150	5447	10452	11382
	A2	Vegetation and topsoil removal (5cm)	2215	7220	8150	5122	10127	11057
	A3	Interchanging topsoil with subsoil	0	0	0	310	310	310
	A4	Ploughing	0	0	0	33	33	33
Forest	F1	Removal of fallen leaves and humus	992	2882	5300	3221	5111	7529
Residential	RB1	Whole decontamination	450	1500	1500	2620	3670	3670
Roads	RS1	Shot blasting	90	300	300	654	864	864

a Three options are assumed for interim storage: D1 assumes combustible waste to be subjected to volume reduction and different types of disposal for high-elution materials (isolation-type disposal) and low-elution materials (control-type disposal) are used. D2 assumes combustible waste to be subjected to volume reduction and isolation-type disposal for both high-elution and low-elution materials is used. D3 assumes no volume reduction and isolation-type disposal is used for all waste.

b Total consists of clean-up and storage cost

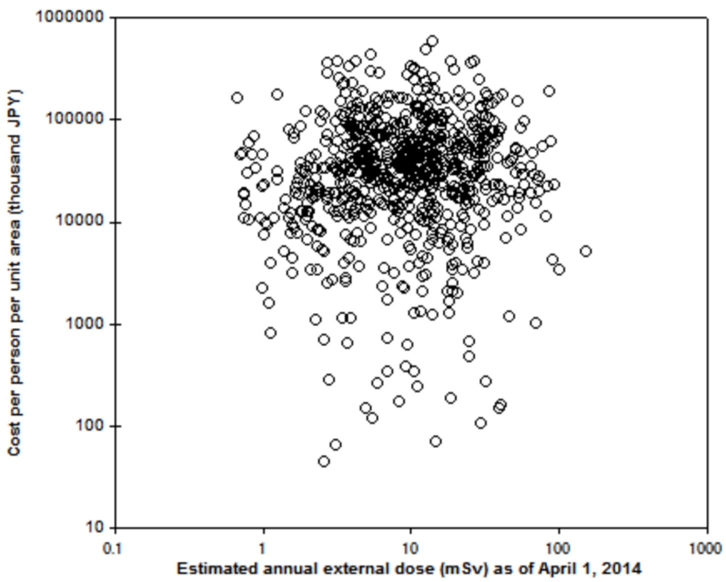


Figure 3-8: Relationship between the estimated cost of decontamination and the estimated initial annual external dose in the special decontamination areas in Fukushima[23)]

Cost per person per unit area was calculated by the population of the unit area. Population data are based on the 2010 Population Census

For forested areas, much of the deposition is initially intercepted by foliage – which remains a significant component of the total inventory for evergreen trees. For deciduous trees – which had less foliage at the time of deposition in March 2010 and which have lost any initially contaminated leaves – this has already been transferred to leaf litter and, as such litter degrades, is increasingly moved into surface soil.

Litter degradation and subsequent transport within the soil column is greatly influenced by both micro- and macro-biological activity, which shows significant seasonal variations. Cs concentration in soil porewater is generally very low, but transport occurs via erosion of organic debris and fine soil particulates – again seasonal, being correlated mainly with periods of highest rainfall associated with typhoons. As the water table is close to the surface throughout Fukushima, both dissolved and particulate transport is predominantly associated with surface water flow.

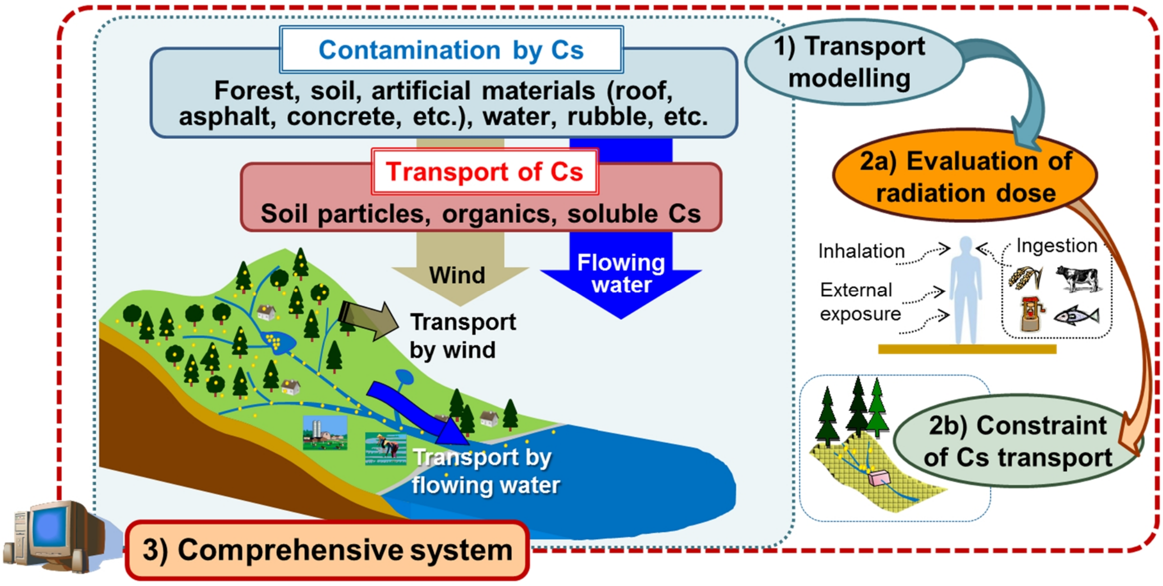


Figure 3-9: Overview of the F-TRACE research programme

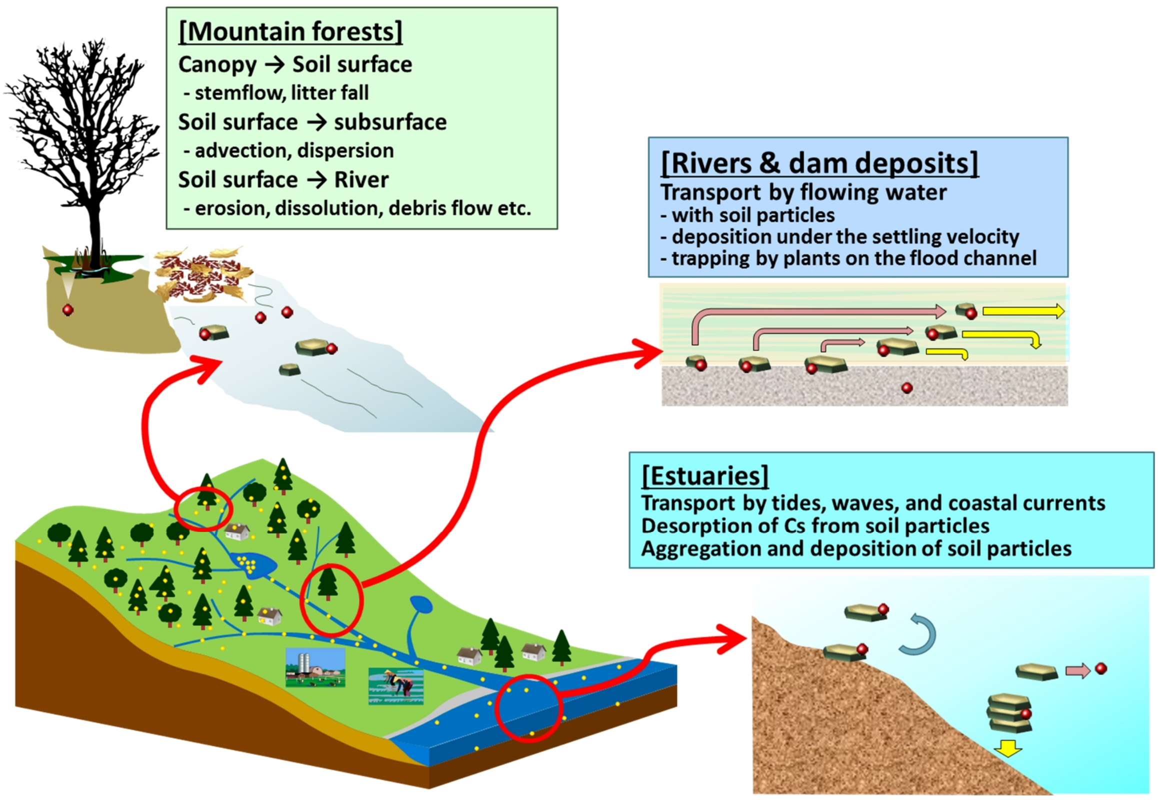


Figure 3-10: Key factors influencing Cs mobility

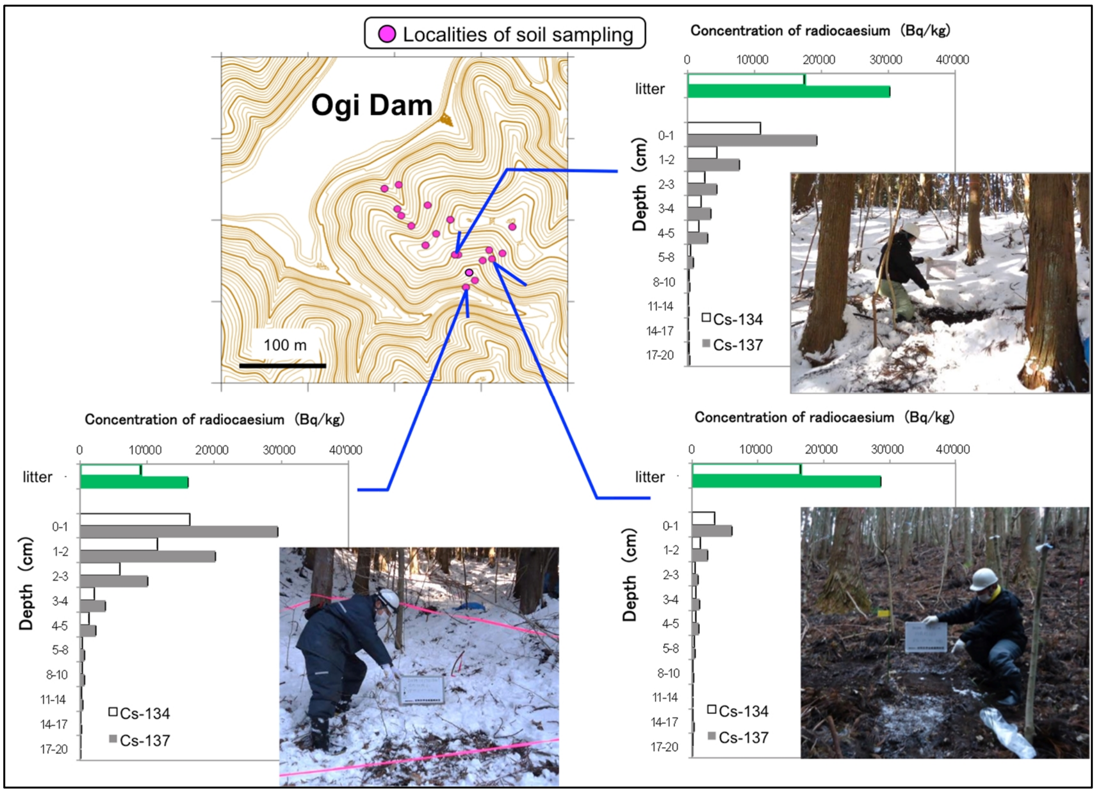


Figure 3-11: Quantification of Cs transport in a forested area of the Ogi Dam field site

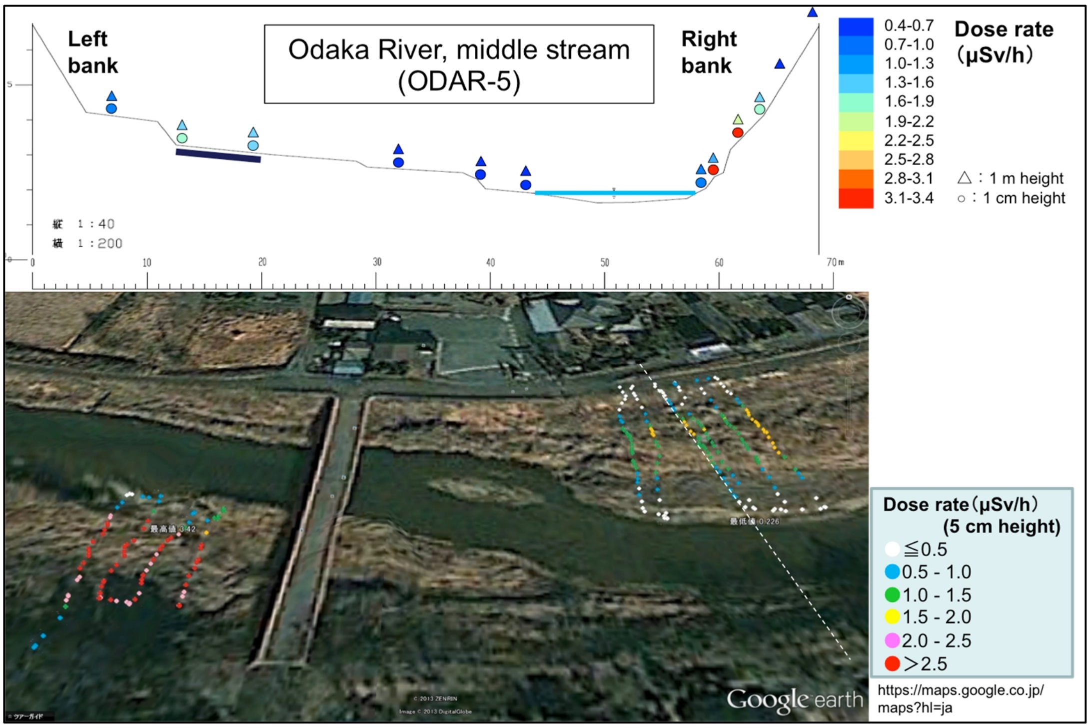


Figure 3-12: Varying Cs concentrations in different locations of the sediments of the Odaka River
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As example of the type of data collected to develop system understanding of Cs transport in a forested ecosystem is illustrated in Figure 3-11. Radiocaesium concentrations are measured in the litter zone and as a function of depth in underlying soil within a catchment draining into the Ogi Dam. This is complemented by measurement of Cs depth profiles in sediment at a range of locations in the Ogi reservoir in order to construct a mass balance of flow of eroded materials and associated radiocaesium.

As indicated in Figure 3-10, within a river system, transport of Cs depends on balances between sorption / desorption processes on suspended particulates / colloids and settling / remobilisation of such particles as a function of water flow velocity. The latter processes are studied in the lower reaches of several rivers, where deposition is very dependent on location on the river bank and the varying river profile as a function of runoff – especially during extreme rainfall events (Figure 3-12).

In general, uptake of Cs on suspended particulates is expected to be effectively irreversible and colloids to be stable in freshwater systems. The situation may be more complicated in estuaries, however, where increasing salinity may displace sorbed Cs and cause colloids to coagulate. Because of the particular sensitivity of the coastal marine environment in Japan, due to extensive fishing and aquaculture, this area is extensively studied (e.g. Figure 3-13) in order to determine the final destination of runoff Cs as a function of different estuary structures.

F-TRACE also includes studies of counter-measures that can be introduced if natural Cs mobilisation processes are considered to be a possible cause of radiation exposure to the public. A number of measures including traps and filters (Figure 3-14) are being examined to capture the particulates that are the main vector for Cs transport. Based on characterisation of the performance of such technology, these can be introduced into regional transport models to determine their impact on reduction of contamination of sensitive areas and resultant dose to resident populations. An update of work performed within the F-TRACE project and an overview of related work is provided in the record of the recent Cs workshop[8,24].

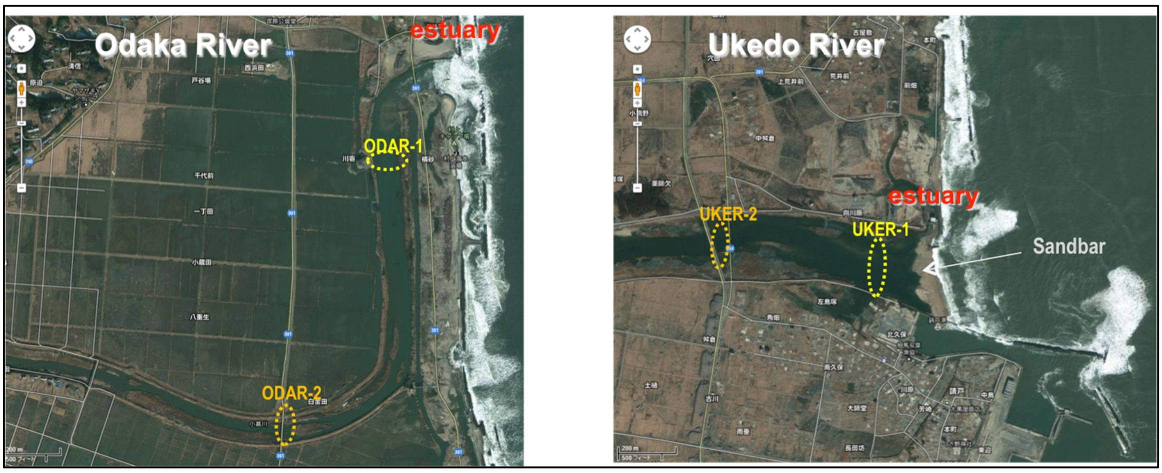

Figure 3-13: Varying structure of studied estuaries
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In addition to trying to constrain movement of radiocaesium, JAEA placed great importance on trying to identify potential improvements to the decontamination work. A better mechanistic understanding of the key environmental properties of Cs and how these relate to mobility and uptake, providing information that will be useful for both waste volume reduction and determining the stability of caesium in stored decontamination wastes. There is a huge knowledge base in the international literature demonstrating the affinity of clay minerals present in soils for radiocaesium. A number of techniques were used by JAEA to elucidate the uptake mechanism of Cs onto clay minerals. These included scanning electron microscopy (SEM), successive over-relaxation (SOR) analysis, X-ray absorption fine structure spectroscopy (XAFS) and scanning transmission X-ray microscopy (STXM) as illustrated in Figure 3-15.

In tandem with the research on Cs sorption mechanisms, various approaches to waste volume reduction were trialled (Figure 3-16 illustrates a few examples).

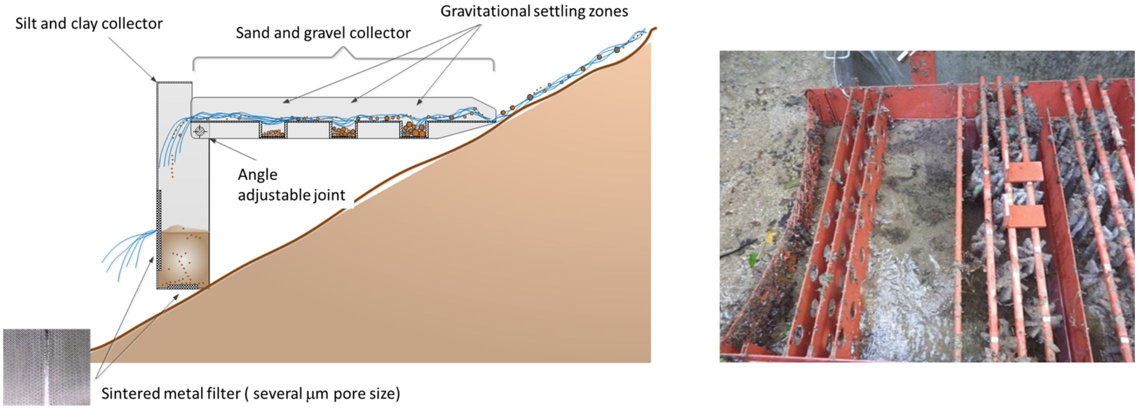

Figure 3-14: Sediment traps (left) and filters (right) as counter-measures to reduce Cs transport

Approaches tested included both physical treatments (e.g. wet separation, incineration) and a range of chemical treatments (e.g. soil washing, oxalic acid extraction). Desorption of Cs from soil components such as clay minerals is extremely difficult and therefore it is better to treat Cs sorption as irreversible. Thus, it follows that physical techniques would offer most promise if such waste volume reduction was considered cost-effective.

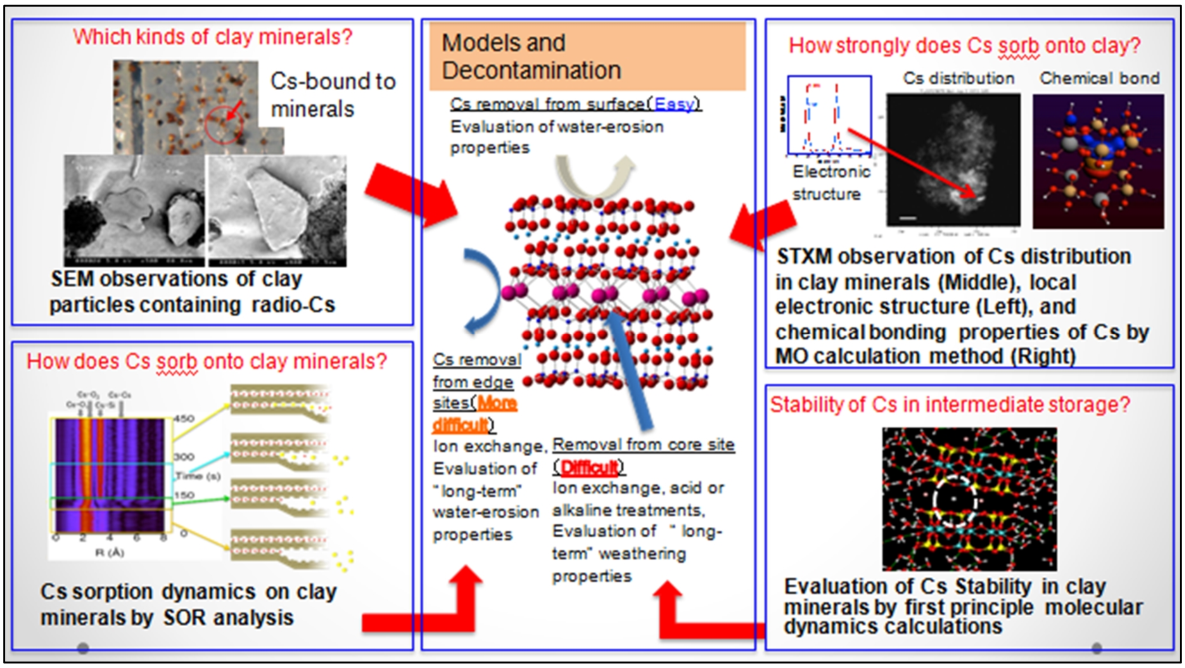

Figure 3-15: Investigating Cs sorption mechanisms onto clay minerals

3.4 Communication

Poor communication was a major criticism levelled at almost all national and international organisations associated with the Fukushima Daiichi accident and its aftermath. As a result, communication has been identified as a major initiative for JAEA Fukushima Environmental Safety Center[25]. Work carried out is reported regularly in information bulletins, most of which are also available in English[26]. This website also provides access to a web-based information platform on the JAEA Decontamination Pilot Project, “Cleanup navi”[27], video clip for the activities by JAEA Fukushima Environmental Safety Center[28], and a JAEA library of background information on the Fukushima Daiichi accident[16].

A further initiative here is the MOE “Decontamination Information Plaza”[29]. The amount of information available in English is limited, but much more is available from the visitor site close to Fukushima city main train station or the associated Japanese web site[30].

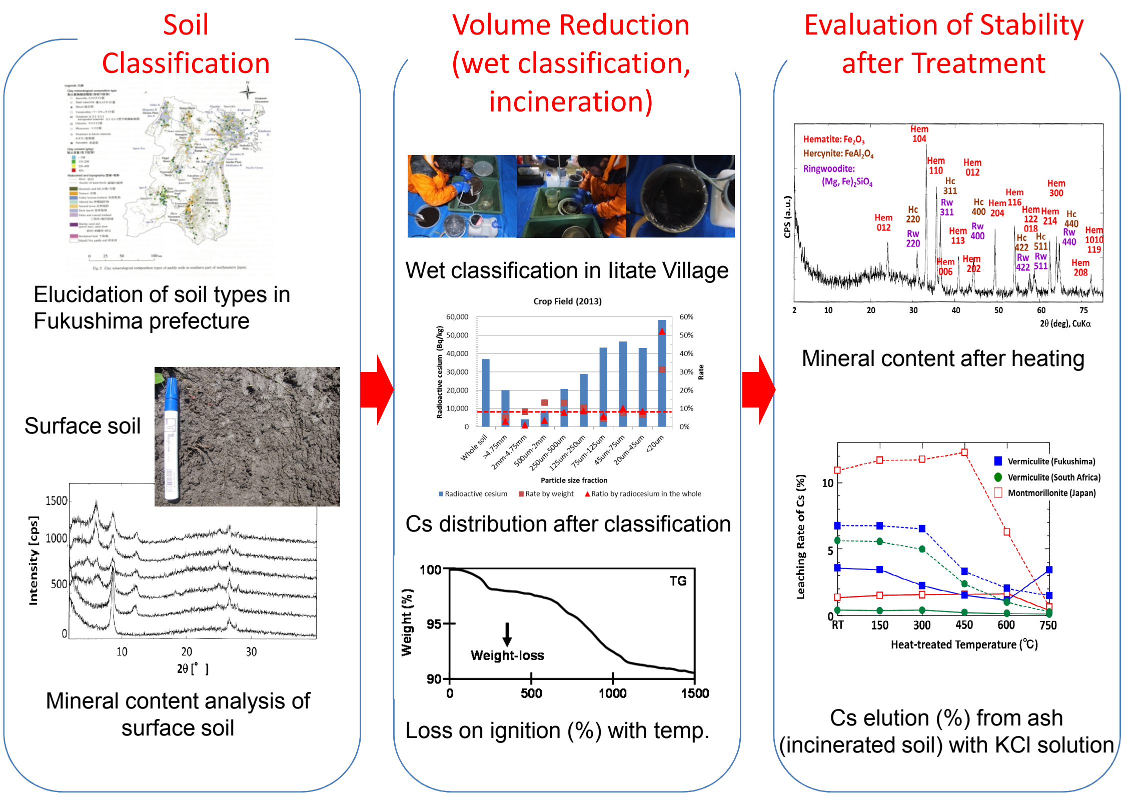

Figure 3-16: Various approaches trialled for volume reduction of soil waste

4. International input and context

The causes of, and response to, the Fukushima Daiichi accident have been of great interest to the international nuclear community, who have emphasised the importance of providing assistance based on relevant experience elsewhere, but also learning from Japan in order to minimise the risk of similar accidents in the future. Indeed, Japanese experience with large-scale decontamination work is seen also to be relevant to the general problem of remediation of legacy contaminated sites, which are scattered around the globe.

In this section, focus is primarily on international support as provided by the IAEA (4.1) and the US Department of Energy (USDOE, 4.2) and Environmental Protection Agency (EPA, 4.2). The EU has had an extensive collaboration programme on decontamination and recovery from nuclear accidents and the context provided by this is discussed in section 4.3. Other relevant input from international organisations or provided within major meetings or conferences is summarised in section 4.4.

4.1 IAEA

After the Great East Japan Earthquake on 11 March 2011, the International Atomic Energy Agency (IAEA) conducted two main missions to provide overall assessment of recovery, which was supported by a number of technical meetings and working groups covering more specialist topics. This section focuses on the former while information on other relevant IAEA activities can be found on their website[31)], with some key documentation available on (32).

The first "Fact Finding Mission", took place from 24th May to 2nd June 2011 in Tokyo and in Fukushima prefecture[33)]. During the IAEA Mission, a team of nuclear experts reported that they received excellent cooperation from all parties, receiving information from many relevant Japanese ministries, nuclear regulators and operators. The Mission also visited three affected nuclear power plants to gain an appreciation of the status of the plants and the scale of the damage. The facility visits allowed the experts to talk to the operator staff as well as to view the on-going restoration and remediation work. The Mission gathered evidence and undertook a preliminary assessment and developed preliminary conclusions as well as highlighting lessons to be learned.

The Mission conclusions relevant to the source of the accident and subsequent off-site remediation can be summarised as:

- Given the extreme circumstances of this accident, the local management has been conducted in the best way possible as Japan has a well organised emergency preparedness and response system. An effective response was reached even in unexpected situations and prevented a larger impact of the accident on the health of the general public and facility workers. Nevertheless, complicated structures and organisations can result in delays in urgent decision making.
- At the same time, there were insufficient defence-in-depth provisions for tsunami hazards: hazards were underestimated, the additional protective measures were not sufficient to cope with the high tsunami heights, severe accident management provisions were not adequate to cope with multiple plant failures.
- Short term immediate measures at Fukushima Daiichi Nuclear Power Station need to be planned and implemented. Until that time, high priority measures against external hazards need to be identified using simple methods in order to have a timely plan. As preventive measures will be important but limited, both on-site and off-site mitigation measures need to be included in the plan. In addition, a suitable follow up programme on public exposures and health monitoring would be beneficial.
- An updating of regulatory requirements and guidelines should be performed reflecting the experience and data obtained during the Great East Japan Earthquake and Tsunami. They should also consider the periodic alignment of national regulations and guidance to internationally established standards and guidance for inclusion of new lessons learned from global experiences of the impact of external hazards.

- A follow-up mission should look in detail at lessons to be learned from the emergency response on and off the site, seek lessons used to provide large scale radiation protection in response to the Fukushima accident, and assist in any further development of the Japanese nuclear regulatory system.

The second International Mission on remediation of large contaminated areas off-site the Fukushima Daiichi Nuclear Power Station, took place from 14th to 21st October 2013 in Tokyo and the Fukushima prefecture[33,34]. This Mission focused on remediation in the Special Decontamination Area ("restricted area"), as it was not considered under the scope of the previous Mission, and on following up on progress regarding the advice provided by the previous mission to enhance remediation planning and implementation in all the affected areas.

The Follow-up Mission had the following three objectives:

- To provide assistance to Japan in assessing the progress made with the remediation of the Special Decontamination Area (not included in the previous mission of 2011) and the Intensive Contamination Survey Area;
- To review remediation strategies, plans and works, in view of the advice provided by the previous mission on remediation of large contaminated off-site areas; and
- To share its findings with the international community as lessons learned.

The Team considered that the remediation of large contaminated areas represented a huge effort and recognised that Japan was allocating enormous resources to developing strategies and plans and implementing remediation activities. The Team was pleased to see good progress in the coordination of remediation activities with reconstruction and revitalisation efforts.

The mission highlighted progress, reporting it as:

- The Team acknowledges the institutional arrangements implemented by Japan to address the remediation needs of the areas affected by TEPCO's Fukushima Daiichi accident. The Team appreciates that Japan makes enormous efforts to implement the remediation programme in order to reduce exposures to people in the affected areas, to enable, stimulate and support the return of people evacuated after the accident, and to support the affected municipalities in overcoming economic and social disruptions.
- The Team has seen many examples of good practice in stakeholder involvement, with demonstrable evidence that successful communication and engagement processes are being adopted at the national, prefectural and municipal level.
- The Team acknowledges that a large amount of crucial information (especially in relation to dose rates) has been produced since the accident that will help to drive decision making processes.
- The Team also acknowledges monitoring of data in order to assess the status of the environmental contamination. The Team acknowledges that the NRA has set up a team to conduct a study on 'Safety and Security Measures towards Evacuees Returning Home'. It is beneficial to continue the measurement of individual external exposure doses for Fukushima prefecture residents, to confirm the expected decreasing trend and justify the remediation decision. Some measures, not only for decontamination but for exposure reduction measures, health management and rebuilding daily life, can be undertaken after evacuation orders are lifted, until additional individual dose exposure decreases gradually towards the long-term dose reduction goal of 1 mSv y^{-1}. A comprehensive aquatic monitoring programme is also implemented.
- Great progress was achieved in decontamination of farmlands (the intensive monitoring shows that much of the land can produce food below the reference level for permissible radioactivity) and forests.
- The Mission Team found significant progress in the development and implementation of temporary storage facilities by Municipalities and the National Government for contaminated materials generated by on-going remediation activities. The Team found that incineration, a technique that is being used as a technology for volume reduction of contaminated material, is very effective.

The Mission concluded with the following advice:

- The relevant institutions in Japan are encouraged to assess the benefits that could be derived from a more active participation of the Nuclear Regulation Authority (NRA) in the review of remediation activities.
- Japanese institutions are encouraged to increase efforts to communicate that, in remediation situations, any level of individual radiation dose in the range of 1 to 20 mSv per year is acceptable and in line with the international standards and with the recommendations from the relevant international organisations, e.g. ICRP, IAEA, UNSCEAR and WHO. The government should strengthen its efforts to explain to the public that an additional individual dose of 1 mSv y^{-1} is a long-term goal, and that it cannot be achieved in a short time, e.g. solely by decontamination work. The Team believes that communicating the entire remediation and reconstruction programmes, and how the various components interact (for example, trade-offs between reducing exposure and increasing waste volumes), could reduce some uncertainties and provide greater confidence in the decisions being made.
- There needs to be continued movement towards the use of individual doses, as measured with personal dosimeters, to support remediation decisions.
- The Team notes that by taking into consideration the natural processes leading to reduced availability of radiocaesium to crops, there is potential to further optimise the application of remediation measures and still produce safe foods.
- The Team recommends continuing the optimisation of the remediation of forest areas around residential areas, farmland and public spaces by concentrating efforts in areas that bring greatest benefit in reducing doses to the public and avoid damage to the ecological functioning of the forest where possible.
- The Team recommends continuing the monitoring of freshwater and marine environments, and suggests that these data be interpreted within the context of processes known to affect the concentrations of radiocaesium in water, sediment and biota.
- The Mission Team encourages the responsible organisation(s) to carry out appropriate demonstrations of the safety of the facilities and activities for the management of contaminated materials, in particular for long-term activities, and to allow for their independent evaluation.

4.2 US DOE and EPA

A range of input from the US was provided after the accident, much of which was related to stabilisation of the damaged reactors and managing on-site problems (e.g. (35)). US State Department's Embassy Science Fellowship Program was used to provide expert support to Japan's Ministry of the Environment (MOE) in its decontamination efforts in areas outside of the Daiichi Nuclear Power Station. The programme duration was from February to March 2013. The presentation summarising the main conclusions of this programme can be found online[36)].

The overall intent was to draw upon US DOE and US EPA remediation experience to:

- Share methods and lessons learned
- Offer suggestions for enhancing Japan's off-site decontamination efforts, and
- Identify areas for future collaboration.

In terms of radiation protection, it was recommended to:

1. Develop re-population and dose reduction framework and implementation processes for application at a community specific level.
2. Establish a radiation dosimetry program for residents who return to evacuated areas to provide the best information possible for understanding and managing population radiation exposure.
3. Regularly review environmental monitoring results, dosimetry results and impacts from decontamination efforts to adapt the framework in Recommendation #1.

4. Establish an Expert Advisory Group on radiation protection to provide technical assistance to prefectural and municipal government officials, and to provide necessary information to the public and stakeholder groups.

The following recommendations were given for the decontamination processes:

- Develop and ensure application of a set of standard protocols for measuring the effectiveness of decontamination methods for all applicable targets of decontamination (e.g. roads, soil, etc.).
- Conduct a systematic analysis of the existing performance data to identify potential factors or practices that could improve effectiveness of future decontamination efforts and that identifies situations where specific practices are not likely to be effective.
- Develop and maintain a comprehensive catalogue of decontamination technology performance (based on systematic methods for assessing effectiveness).
- Enhance existing processes for facilitating the development and maturing advanced decontamination technologies.

Waste management needs improvement in the following directions:

- Expedite implementation of Temporary Storage Facilities (TSFs) in Intensive Decontamination Survey Areas and in Special Decontamination Area.
- Develop a waste inventory forecasting and tracking capability that incorporates a systems approach.
- Promptly implement modular, expandable Interim Storage Facilities (ISFs).
- Conduct systematic evaluation of treatment options for stabilisation and/or volume reduction of decontamination waste.
- Develop final disposal standards and regulations for decontamination waste.

The following recommendations were given for environmental monitoring:

- Develop and implement an overall environmental monitoring plan that strengthens the linkage between the purpose/need for data and the data collection and management protocols
- Enhance the data management systems to improve the consistency of data storage methods and accessibility to facilitate visualisation and multi-disciplinary data evaluation and analysis
- Conduct periodic reviews and evaluations of monitoring data to ensure appropriate feedback with other strategic functions including efforts to optimise decontamination strategies, efforts to improve understanding of caesium behaviour in the environment, and efforts to optimise the long-term monitoring program

Remediation strategy can be improved by:

- Conducting a systematic review of the decontamination work that has been completed to date (cost, effectiveness, waste generation, etc.) to provide the information base for extrapolating to implementation of the remaining decontamination work.
- Developing the baseline definition of the total set of decontamination work that needs to be completed.
- Developing and maintaining an overall remediation strategy complete with life cycle cost estimates, resource allocation strategies (e.g. manpower, etc.) and analysis of critical strategic alternatives.

And last, but not least, there is an immediate need to develop more effective processes for public involvement in remediation system decisions (e.g. site selection for treatment and storage facilities, re-population strategies for evacuated areas). To obtain this goal, approaches for adapting Citizen Advisory Board concepts for use in Japan should be discussed, expert groups should be commissioned to review current public involvement practices and provide expert recommendations for implementing the effective approaches needed. In addition US-Japan information exchange opportunities (e.g. Iitate Village and Bunker Hill Superfund site) should be identified.

4.3 EU projects

The decontamination work carried out in Japan can be assessed for completeness of coverage by comparison with generic plans for contaminated site remediation. Of particular use here is the report of the EU project "EURANOS": "Generic handbook for assisting the management of contaminated inhabited areas in Europe following a radiological emergency"[37). This academic handbook was translated by the Atomic Energy Society of Japan and turned into a decontamination catalogue with the addition of target areas that were specific to Japan and not included in the EURANOS report (e.g. paddy fields). The catalogue can be found in Japanese at (38).

The multi-national project EURANOS, funded by the European Commission and 23 European Member States, started in April 2004 and ended in July 2009, and the main objective and conclusions of the project are available online[39)]. Key objectives of the project were to collate information on the likely effectiveness and applicability of a wide range of countermeasures, to provide guidance to emergency management organisations and decision makers on the establishment of an appropriate response strategy and to further enhance advanced decision support systems, in particular, "RODOS"[40)], through feedback from their operational use.

The main goal of the project was the enhancement of the technical, methodological and strategic approaches for national and cross-border emergency management and rehabilitation in Europe, which is not directly related to the current situation in Fukushima. For example, a website[41)] was developed and intended to be a European portal to provide information and knowledge relevant for radiological and nuclear off-site emergency management and rehabilitation. In addition, demonstration activities were a core element and stakeholders were involved in all the parts of the project.

Although rather academic, this study has the advantage of being integrated within a larger project on decision-making ("RODOS"), which leads to a particularly structured approach to remediation planning. In addition, one of the case studies included is based on regional scale contamination of ^{137}Cs, so it provides a perspective on a structured approach to assessment of different remediation options, even if the details of the example are not particularly relevant (focused on a city park).

The EURANOS handbook[37)] introduces a classification of inhabited areas and the surfaces involved (Figure 4-1), which can be compared to the range of targets within the 11 municipalities in the restricted area.

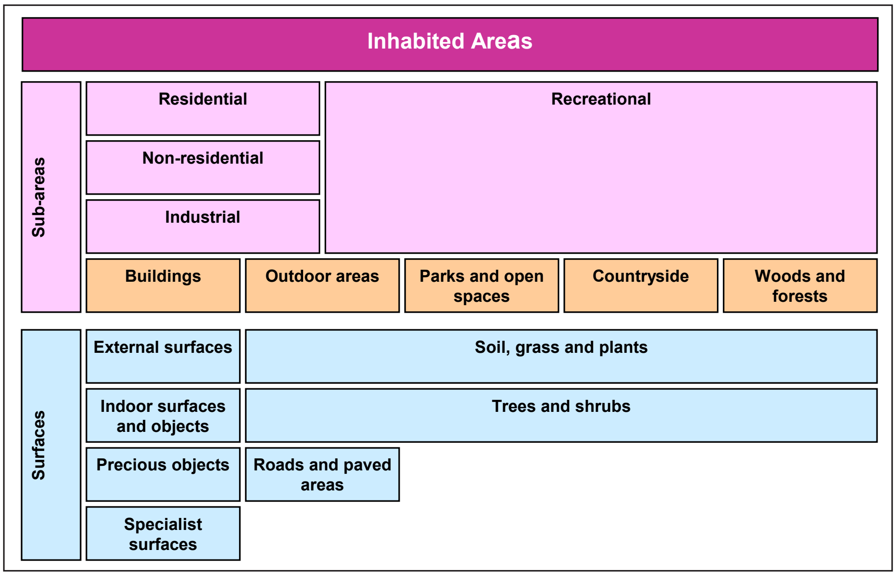

Figure 4-1: Link between types of inhabited area and surfaces (Figure 1.3, EURANOS handbook[37)])

It can be seen that most of these are covered, especially if “non-residential / industrial” sub-areas are taken to include schools and public community buildings, which are well represented in the JAEA DPP. The strange term “specialist surfaces” actually refers to metals, plastics, etc., which are also covered.

The exceptions are indoor surfaces and objects, which can be explained by the form of fallout involved, which meant that indoor contamination was generally of minor significance, but this may be an issue that needs to be addressed at locations nearer the FDI site. Also, in the work to date, there has been little consideration of precious objects, although these will need to be considered at a later stage (e.g. associated with shrines and temples).

For each of the specific targets, lists of remediation approaches are presented in the handbook and are actually hyperlinked to standard format descriptions in the original pdf document. For the example of external surfaces of buildings (Figure 4-2), again the list here can be compared to the options tested in the JAEA DPP and most are clearly covered.

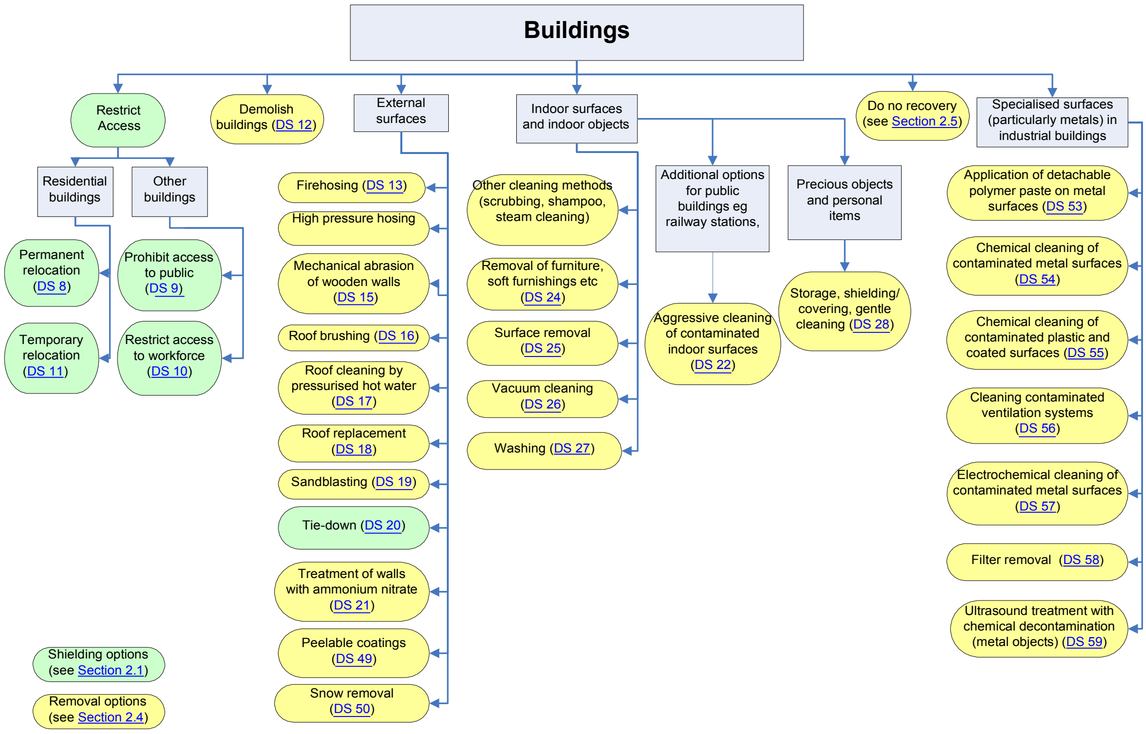

Figure 4-2: Examples from the EURANOS handbook (Figures 2.1[37])

The “tie down” option (immobilisation: fixing contamination to the surface) is not appropriate for radiocaesium contamination (more relevant for alpha emitters), snow removal is not an issue and roof replacement is not considered to be needed for any of the sites examined. Ammonium nitrate treatment, specifically noted as an option for removing radiocaesium contamination, has not been tested, but might be considered in the future.

4.4 Other organisations

Some of the key input provided by national governments and other international organisations is collected in (42).

FAIRDO[43] is an action research project launched in June 2012 for the purpose of offering advice and guidance in a timely and appropriate manner for the effective implementation of initiatives for full scale decontamination undertaken by the national, prefectural and municipal governments from 2012 onwards (see 2nd discussion paper[44]) which can be downloaded from the website). The research team is composed of academic experts from Japan who are actively involved in decontamination and reconstruction in Fukushima through various channels, as well as European researchers who played a central role in the EURANOS project (described in 4.3 above). The main aim is to review the issue of decontamination among the overall policies concerning reconstruction and regeneration of the hometowns as well as looking at the rehabilitation and rebuilding of the lives of the people affected by the disaster. Throughout the project period of two years, it conducted research concerning the three themes of effective governance on decontamination, development of decontamination plans that reflect local conditions, and communication that promotes collaboration with the local residents.

The main conclusions were:

1. Municipalities made huge efforts to undertake the unprecedentedly large project, of clearing up radioactive materials scattered across a huge area. Despite various problems, such as insufficient human resources, knowledge and experience, substantial progress had been made. Some of the municipalities undertook decontamination activities shortly after the accident and accumulated valuable knowledge about decontamination technologies, modes of communication with the residents and consensus-building. However such knowledge and experience was not shared with other municipalities.
2. Municipalities and decontamination operators need to communicate with the local people and form an agreement with them on a number of issues such as the targets and expected effectiveness of decontamination, temporary storage of waste material.
3. Rehabilitation of the lives of those affected requires a wide range of conditions to be met besides the reduction of radiation. The policies to reconstruct or maintain such conditions as compensation, infrastructure redevelopment, administrative services and employment support are decided differently yet are closely interlinked.
4. In order to have concrete options and take action, residents need clearer prospects of the conditions needed to rehabilitate their lives. Some of the issues can be addressed by proceeding further with decontamination activities. However, there needs to be a change in the way of thinking on overall reconstruction policies, including decontamination. In other words, the aim “to restore the status quo” needs to be abandoned.

FAIRDO’s key messages are summarised as:

Message 1 “Re-examine the scope of decontamination”

The ambient/surface radiation level is one of many conditions required for rehabilitating the lives of those people affected by the disaster. Decontamination needs to be conducted at appropriate levels that are balanced with measures that are in place to achieve other conditions.

Message 2 “Participation of residents and assurance of choices”

The decisions of individuals and families regarding the rehabilitation of their lives should be treated with the utmost respect. Additionally, public participation should be assured in the collective decision-making process for reconstructing areas and regenerating communities. To respect the decisions of individuals or families, and ensure participation in consensus building, it is necessary to provide opportunities for exchanging information and having discussions.

FAIRDO’s actions:

1. Initiatives for participatory and consensus building:
   - Preparation of regional round table discussions
   - Utilisation of simulation tools (including RODOS model, etc.) for plan formulation and consensus-building
   - Utilisation of brief assessment for consensus-building on temporary storages
2. Promotion of information exchange and information-sharing between stakeholders to reduce the burdens of the initiatives mentioned above:

- Establishment of an information platform

4.5 Overview

In general, international review input has been useful to put Japanese decontamination work in context and provide independent support for the measures implemented. For the general public, especially due to loss of confidence in the Japanese nuclear industry, such international support is extremely important in building acceptance, particularly for communities that will return to the evacuated areas.

In terms of more specific input, usefulness of such reviews is constrained by the major differences in the boundary conditions under which decontamination experience has been developed in other countries (e.g. contaminated groundwater in desert sites in the USA, dispersed reactor core in a continental location around Chernobyl). This limitation is compounded by a common lack of understanding of Japanese legal, social and cultural requirements, which must be respected when developing solutions to the decontamination and waste management challenges.

Potentially the most useful approach is when foreign experts work together in a team with their Japanese colleagues. There are a number of models for such focused knowledge transfer, including the FAIRDO project described above, the JAEA Cs workshops[8,24)] and focused bilateral collaborations (e.g. JAEA with SUERC, IRSN). It is expected that, building on such experience, involvement of international experts and organisations can be utilised more efficiently in the future.

5. Summary & conclusions

The types and concentrations of volatile radionuclides released to the Japanese environment from the Fukushima Daiichi nuclear accident were similar to radionuclide releases from some past accidents (e.g. distant Chernobyl fallout and the Windscale fire, both over northern Europe) but no environmental remediation was performed in these cases. Indeed, even areas with much higher levels of contamination (e.g. exclusion zone around Chernobyl, Mayak) often received little clean-up. Experience from other releases of radiocaesium to the environment such as that from the Hanford site in the United States, cannot be directly extrapolated to Japan as the boundary conditions are completely different (the Hanford site is situated in an area of continental, flat desert whilst Japan has a mountainous topography that is covered in lush forests growing in a coastal, temperate climate). Additionally Japan is often subject to extreme weather events, such as typhoons, that play an important role in the mobilisation of radionuclide contamination in the environment.

The decontamination work undertaken by JAEA was the first of its kind. Nowhere in the world has decontamination work on such a scale been attempted and thus there was no real life experience available from which to draw; this was one of a number of major challenges faced by JAEA. Another challenge for JAEA (and later MOE) was the fact that an accident on such a scale had not been anticipated and hence no appropriate plans, guidelines or legal framework were in place to cover either the decontamination work or the associated management of waste arising from this. Although the MOE had guidelines available before the accident in 2011, these were really only applicable to low dose radiation areas and therefore the JAEA DPP were instrumental in providing the experience and knowledge required for the much more extensive regional decontamination effort. Indeed, the tacit knowledge gained from the JAEA DPP provided input to many decontamination work specification procedures for the Special Decontamination Area.

JAEA also undertook a wide ranging R&D programme with the two-fold aim of increasing the efficiency of decontamination methodologies and minimising waste volume production. For waste volume reduction, physical techniques such as incineration were found to be the most effective for vegetation. Many chemical techniques were trialled for Cs removal from soil but, as has now been demonstrated by JAEA experimental work (presented at the 1st JAEA international Cs workshop[8)], Cs is so strongly bound to the lattice of clay minerals present in soil that uptake is virtually irreversible. Thus it was demonstrated that physical techniques such as size fractionation or wet separation are preferable (and more cost effective) than chemical treatments.

Although JAEA and the MOE were first to undertake decontamination work on such a large scale after a nuclear accident, support from a number of international organisations such as the IAEA[33,34)] and the

US EPA was provided and a number of recommendations have been made. Particular emphasis was placed on the need to be able to communicate with the general public on the negligible health impacts of the low dose rates in the decontaminated areas.

In addition to decontamination work, JAEA thus also undertook a number of public communication projects including making technology available in its Fukushima city office that shows dose rates in 4 cities of the Fukushima prefecture in real time. Another highlight was the creation of a user friendly website “Cleanup navi” available in English[27)] as well as Japanese[45)] that provides information on the decontamination work and also has some very good background information on the basics of radioactivity.

It is clear that it will be several years before off-site decontamination allows return of all evacuees and that on-site decommissioning will take even longer, but the JAEA Decontamination Pilot Project form a solid basis for the iterative development of the technology and communication toolkit that will facilitate this.

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Appendix: ABBREVIATIONS

AUH	Autonomous unmanned helicopter
DF	Decontamination Factor
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.
DSS	Decision support systems
EURANOS	European approach to nuclear and radiological emergency management and rehabilitation strategies
FDI	Fukushima Daiichi (in Japan often simply 1F – “ichi-efu”)
GIS	Geographical information system
GPS	Global positioning system
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (Radioprotection and Nuclear Safety Institute)
ISF	Interim storage facility
JAEA	Japan Atomic Energy Agency
MEXT	Ministry of Education, Culture, Sports, Science and Technology (Japan)
MOE	Ministry of the Environment (Japan)
SEM	Scanning electron microscopy
SOR	Successive over relaxation
STXM	Scanning transmission X-ray microscopy
SUERC	Scottish Universities Environmental Research Centre
TSF	Temporary storage facility
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
WHO	World Health Organization
XAFS	X-ray absorption fine structure spectroscopy

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	$1L=1l=1dm^3=10^3cm^3=10^{-3}m^3$
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	$1\ µ=1µm=10^{-6}m$

（第8版，2006年改訂）