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Current and Emerging Post-Fukushima Technologies, and Techniques, and Practices for Wide Area Radiological Survey, Remediation, and Waste Management

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Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

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Executive Summary

Technologies to survey and decontaminate wide-area contamination and manage the subsequent radioactive waste have been developed and implemented following the Chernobyl nuclear power plant release and the breach of a radiological source resulting in contamination in Goiânia, Brazil. These civilian examples of radioactive material release provided some of the first examples of urban radiological remediation. Many emerging technologies have recently been developed and demonstrated in Japan following the release of radioactive cesium isotopes (Cs-134 and Cs-137) from the Fukushima Dai-ichi nuclear power plant in 2011. Information on technologies reported by several Japanese government agencies such as the Japan Atomic Energy Agency (JAEA), the Japanese Ministry of the Environment (MOE) and the National Institute for Environmental Science (NIES), together with academic institutions and industry have been summarized and are compared to recently developed, deployed and available technologies in the United States.

The technologies and techniques presented in this report may be deployed in response to a wide area contamination event in the United States. In some cases, additional research and testing is needed to adequately validate the effectiveness of the technology over wide areas. Survey techniques can be deployed on the ground or from the air, allowing a range of coverage rates and sensitivities. Survey technologies also include those useful in measuring decontamination progress and mapping contamination. Decontamination technologies and techniques range from non-destructive (e.g., high pressure washing) and minimally destructive (plowing) to fully destructive (surface removal or demolition). Waste minimization techniques can greatly impact the long-term environmental consequences and cost of remediation efforts.

Recommendations on technical improvements to address technology gaps are presented together with observations on remediation in Japan.

Acronyms

3-D	3-dimensional
AMS	Aerial Measuring System
ASPECT	Airborne Spectral Photometric Environmental Collection Technology
Bq/kg	Becquerel(s) per kilo-gram
Ci	Curie (unit of radioactivity)
cm	centimeter(s)
cpm	counts per minute
Cs	cesium
CsI-Tl	thallium-doped cesium iodide
CsCl	cesium chloride
d	day(s)
DHS	Department of Homeland Security
DF	decontamination factor
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DPP	Decontamination Pilot Plan
DSRC	Dedicated Short Range Communications
EPA	U.S. Environmental Protection Agency
EU	European Union
FSU	Former Soviet Union
g	gram(s)
GIS	Geographic Information System
GM	Geiger-Müller
GMT	Geiger–Müller tube
Gy	Gray (unit of absorbed dose)
h	hour(s)
HEPA	high-efficiency particulate air
HPGe	high-purity Germanium
I-131	iodine-131
IAEA	International Atomic Energy Agency
ICSA	intensive contamination survey area
IND	improvised nuclear device
INES	International Nuclear and Radiological Event Scale
ISF	Interim Storage Facility
ITRC	Interstate Technology Regulatory Council
JAEA	Japan Atomic Energy Agency
JPY	Japanese Yen (currency)
JREC	Japan Radiation Engineering Co.
kBq	kilo-Becquerel(s)
kCi	kilo-Curie(s)
km	kilo-meter(s)
KURAMA	Kyoto University RAdiation MApping
LLNL	Lawrence Livermore National Laboratory
L/m^2	liter(s) per meter squared
m	meter(s)

mCi/kg	milliCurie(s) per kilogram
m/s	meter(s) per second
MEXT	Ministry of Education, Culture, Sports, Science & Technology (Japan)
mm	millimeter(s)
Mm^3	million cubic meter(s)
MOE	Ministry of the Environment (Japan)
MPa	mega-Pascal(s) (unit of pressure)
mph	mile(s) per hour
mSv/h	milliSievert(s) per hour
mSv/y	milliSievert(s) per year
μSv/h	microSievert(s) per hour
MSW	municipal solid waste
NaI-Tl	thallium-doped sodium iodide
NIES	National Institute for Environmental Studies (Japan)
NPP	nuclear power plant
PMMA	polymethylmethacrylate
PSF	plastic scintillation fiber
PVT	polyvinyl toluene (plastic scintillator)
QAPP	quality assurance project plan
R/h	Roentgen(s) per hour (unit of dose-rate)
RDD	radiological dispersal device
SDA	special decontamination area
SUV	sports utility vehicle
Sv/h	Sievert(s) per hour (unit of dose-rate)
TBq	terra-Becquerel(s) (unit of radioactivity)
UAV	unmanned aerial vehicle
UK	United Kingdom
US	United States
y	year(s)
$	US Dollar

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1. Introduction and Background

After detonation of a radiological dispersal device (RDD) or an improvised nuclear device (IND), an accidental radiological release from a nuclear facility such as a nuclear power plant (NPP), or the breach of a radiological source, radioactive contamination may be dispersed over a wide area, affecting a variety of land uses from rural and agricultural to urban. The scale of nuclear events is determined by the International Atomic Energy Agency (IAEA) using the International Nuclear and Radiological Event Scale (INES). A description of IAEA INES levels is given in Table 1.1, and radiological equivalence to radioactive iodine-131 (I-131) for radionuclide releases to the atmosphere is shown in Table 1.2.

Table 1.1. Definition of IAEA INES Levels > 3 based on Activity Released (reproduced from IAEA, 2013)

IAEA INES Level	Definition	Additional Notes
7	An event resulting in an environmental release corresponding to a quantity of radioactivity radiologically equivalent to a release to the atmosphere of more than several tens of thousands of terra-Becquerels (TBq) [> 100 kilo-Curies (kCi) range] of I-131.	This level corresponds to a large fraction of the core inventory of a power reactor, typically involving a mixture of short- and long-lived radionuclides. With such a release, stochastic health effects over a wide area, perhaps involving more than one country, are expected, and there is a possibility of deterministic health effects. Long-term environmental consequences are also likely, and it is very likely that protective action such as sheltering and evacuation will be judged necessary to prevent or limit health effects for members of the public.
6	An event resulting in an environmental release corresponding to a quantity of radioactivity radiologically equivalent to a release to the atmosphere of the order of thousands to tens of thousands of TBq [tens of kCi] of I -131.	With such a release, it is very likely that protective action such as sheltering and evacuation will be judged necessary to prevent or limit health effects on members of the public.
5	An event resulting in an environmental release corresponding to a quantity of radioactivity radiologically equivalent to a release to the atmosphere of the order of hundreds to thousands of TBq [< 10 kCi] of I-131.	As a result of the actual release, some protective action will probably be required (e.g., localized sheltering and/or evacuation to prevent or minimize the likelihood of health effects).
4	An event resulting in an environmental release corresponding to a quantity of radioactivity radiologically equivalent to a release to the atmosphere of the order of tens to hundreds of TBq [Ci to kCi range] of I-131.	For such a release, protective action will probably not be required, other than local food controls.

According to IAEA (2013):

> *I-131 is used because the scale was originally developed for nuclear power plants and I-131 would generally be one of the more significant isotopes released... The actual activity of the isotope released should be multiplied by the factor given in Table 1.2 and then compared with the values given in the definition of each level. If several isotopes are released, the equivalent value for each should be calculated and then summed.*

Table 1.2. Radiological Equivalence to I-131 for Radionuclide Releases to the Atmosphere (reproduced from IAEA, 2013)

Isotope	Multiplication factor	Isotope	Multiplication factor
Americium-241	8,000	Rubidium-106	6
Cobalt-60	50	Strontium-90	20
Cesium-134	17	Tellurium-132	0.3
Cesium-137	40	Uranium-235(S) [a]	1,000
Tritium	0.02	Uranium-235(M) [a]	600
Iodine-131	1	Uranium-235(F) [a]	500
Iridium-192	2	Uranium-238(S) [a]	900
Manganese-54	4	Uranium-238(M) [a]	600
Molybdenum-99	0.08	Uranium-238(F) [a]	400
Phosphorus-32	0.2	Natural uranium	1,000
Plutonium-239	10,000	Noble gases	Effectively 0

[a] Lung absorption types: S — slow; M — medium; F — fast. If unsure, use the most conservative value.

A summary of accidental radioactive cesium isotope releases (Cs-134 and Cs-137) above the International Atomic Energy Agency (IAEA) INES level 4 are shown in Table 1.3.

Table 1.3. Examples of Large Accidental Releases of Cs-137 to the Environment

Source of Cs-137 Release	Cs-137 Released		Equivalent Mass of Cs-137, g [a]	Area Affected	References	IAEA INES Level
	TBq	kCi		km[2,b]		
Windscale NPP, United Kingdom 1957	20	0.541	6.14	500	Devell and Johansson, 1994	5
Chernobyl NPP, Ukraine 1986	85,000	2,300	26,100	> 200,000	Thakur et al., 2013	7
Goiânia, Brazil 1987	50.9	1.38	15.6	~ 1	IAEA, 1988	5
Fukushima Dai-ichi NPP, Japan 2011	7,000 – 20,000	190 – 540	2,200 – 6,100	13,000	IAEA, 2015b	7

[a] The mass of Cs-137 released in each case is calculated using a specific activity of 88 Curies/gram (Ci/g).
[b] km = square kilometers

Such accidents (which include releases from Windscale, Chernobyl and Fukushima Dai-ichi nuclear power plants) result in wider consequences to people and the environment beyond the local level and involve release of large quantities of radioactive material with a high probability of significant public exposure. In addition to releases from NPPs, Cs-137 is also found in radiological sources used in medical and industrial irradiators, typically in the form of cesium chloride (CsCl) in double-encapsulated stainless steel tubes, which also present an environmental threat if the material is not properly protected or disposed of securely. For example, a 50.9 TBq, equivalent to 1.375 kCi Cs-137 source removed from a teletherapy machine in Goiânia, Brazil, was breached and led to substantial cleanup efforts (IAEA, 1988).

A vast array of surfaces will require a survey and subsequent monitoring to determine the extent of contamination, potential stabilization to prevent resuspension, decontamination and monitoring, or disposal. Monitoring, containment and remediation techniques and technologies were developed by several countries in response to nuclear accidents resulting in dispersed radioactive material. A fire at the Windscale Pile reactor in 1957 resulted in the release of fission and activation products across portions of the United Kingdom (UK). Restrictions on sale, consumption and disposal of milk and farm animals were enforced, but no significant decontamination efforts were performed beyond the fence-line. Sections 1.1, 1.2 and 1.3 examine the remediation and recovery efforts employed in the former Soviet Union (primarily Ukraine and Belarus), Brazil and Japan following urban and rural radiological releases. Emerging technologies developed and demonstrated in Japan for surveying, decontamination and waste treatment are described in Section 2.

1.1 Quality Assurance

A Quality Assurance Project Plan (QAPP) was previously developed by LLNL and approved by the U.S. Environmental Protection Agency (EPA) in 2014 to include a literature review of remediation technologies and identification of gaps (LLNL, 2014a). There are four potential sources of information that will be used to understand technical gaps, and these sources are ranked in order of reliability:

1. Peer-reviewed journal articles and conference abstracts;
2. Government reports;
3. Commercial vendor reports; and
4. Commercial and community web sites.

By nature of their review by peers, journal articles and some conference abstracts are considered trusted sources of information. Similarly, reports published by government agencies such as US EPA, US Department of Energy (DOE) and the Interstate Technology Regulatory Council (ITRC) are considered highly trustworthy. International governmental reports were also utilized, including those from the UK and European Union (EU) as well as the Japanese Atomic Energy Agency (JAEA) and the International Atomic Energy Agency (IAEA), particularly the reports relating to the response following Fukushima and Chernobyl. While the Goiânia event is not a radiological release from a nuclear power plant, this event does provide another example of radiological contamination on a smaller scale, more representative of an area impacted by the detonation of an RDD. Some EU countries have developed recovery handbooks to aid in the recovery from radiological incidents (Public Health England's Radiological Recovery Handbook is an excellent example). Commercial vendor reports were considered in the survey if data and claims made are reasonable, and tests were carried out appropriately. Often, commercial vendors/manufacturers perform product testing in collaboration with other research agencies. Finally, data available on commercial websites and community web sites were searched for relevant information, although this information should carry minimal weight in analyzing technology gaps.

1.2 Chernobyl Wide Area Contamination and Remediation

Response in the Former Soviet Union (FSU) following the accident at Chernobyl involved evacuation of impacted areas and application of clay to surfaces (clay having the natural ability to bind soluble cesium). Figure 1-1 shows the areas heavily impacted by the release of Cs-137 fission product from Chernobyl (IAEA, 2006), and Table 1.4 shows the estimated relative surface activity concentration of different radionuclides after release from the Chernobyl event.

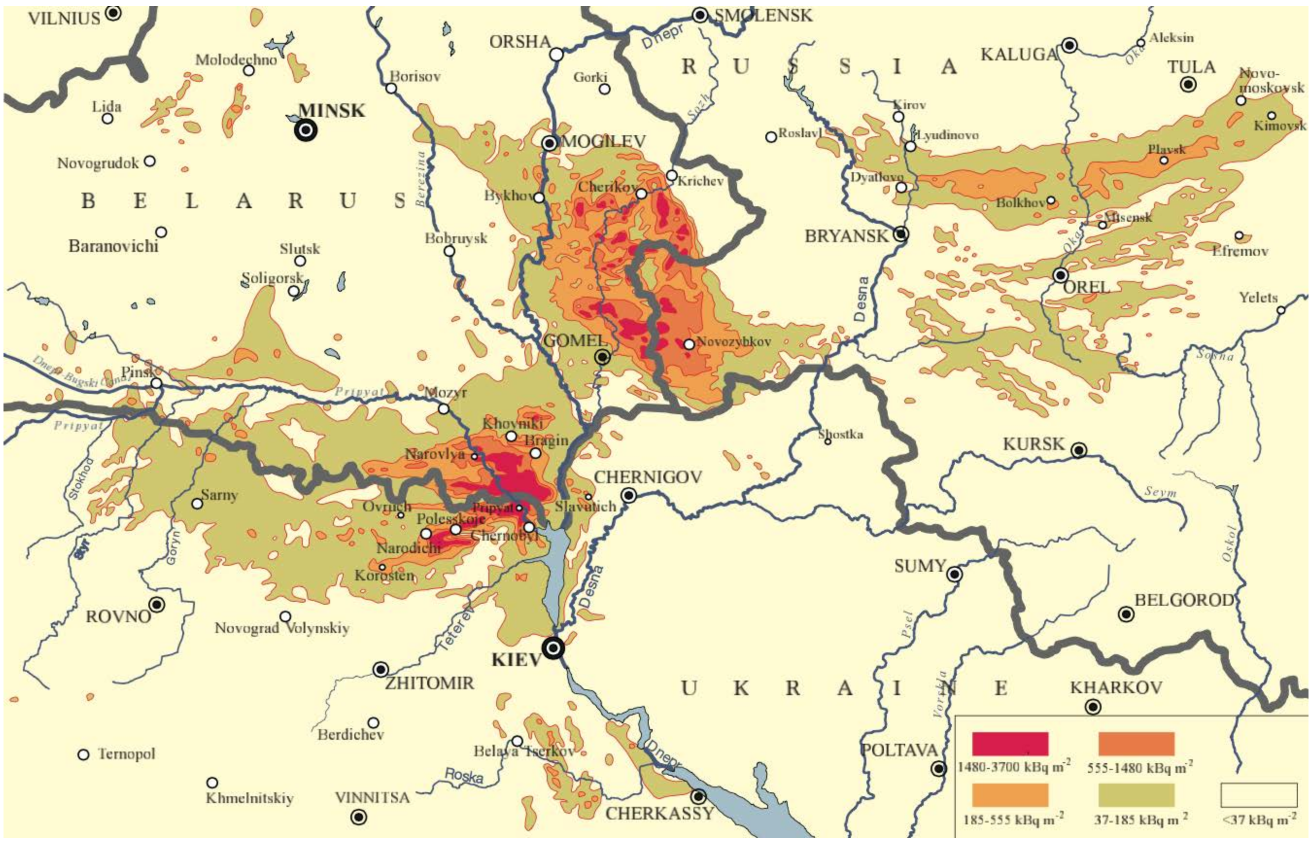

Figure 1-1. Surface Ground Deposition of Cs-137 in the Immediate Vicinity of the Chernobyl Nuclear Reactor (IAEA, 2006)

Some 5,000 tons of boron, dolomite, sand, clay and lead were dropped onto the burning core by helicopter in an effort to extinguish the blaze and limit the release of radioactive particles[1]. Vovk et al. (1993) and Ahn et al. (1995) demonstrated decontamination of building surfaces (including those in urban areas affected by Chernobyl) using naturally occurring clays from Korea and Ukraine. Cities such as Pripyat, which remains deserted 30 years after the Chernobyl accident, serve as an example of the difficulty of remediating and repopulating following a wide area release. The FSU instead chose to abandon Pripyat and relocate to Slavutych before the dissolution of the Soviet Union. However, substantial remediation efforts have been applied in several of the countries most affected by the fallout from Chernobyl. An excellent review of the environmental consequences of the Chernobyl accident

[1] World Nuclear http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/chernobyl-accident.aspx (last accessed in June 2016)

after 20 years of experience is provided by IAEA (2006). IAEA reports that a significant fraction of the dose received by people was from radioactive contamination located in the soil, on coated surfaces such as asphalt and concrete and to a small extent, on building walls and roofs. The most effective decontamination technologies used to reduce dose were those that removed the upper layer of soil. The contributions from different urban surfaces to human dose (and subsequent dose reductions) are determined by settlement and house design, construction material, population habits, mode of radionuclide deposition (wet versus dry), the radionuclide, the physicochemical composition of the fallout and time (IAEA, 2006).

Table 1.4. Estimated Relative Surface Activity Concentration for Different Radionuclides after Release from the Chernobyl Nuclear Power Plant (April 26, 1986).

		Activity per Unit Area Relative to Cs-137			
Isotope	**Half-life***	**Western Plume (near zone)**	**Northern Plume (near zone)**	**Southern Plume (near zone)**	**Cs Hotspots (far zone)**
Sr-90	28.5-years	0.5	0.13	1.5	0.014
Zr-95	64.0-days	5	3	10	0.06
Mo-99	66.0-hours	8	3	25	0.11
Ru-103	39.35-days	4	2.7	12	1.9
Te-132	78.0-hours	15	17	13	13
I-131	8.02-days	18	17	30	10
Cs-137	30.0-years	1.0	1.0	1.0	1.0
Ba-140	12.79-days	7	3	20	0.7
Ce-144	284.8-days	3	2.3	6	0.07
Np-239	2.355-days	25	7	140	0.6
Pu-239	24,400-years	0.0015	0.0015	—	—

Recreated from IAEA, 2006 and sources therein (Izrael et al., 1990).

***Half-life: the time required for the radioactivity of a specified isotope to decrease to half its original value.**

For dry deposition, traditional street cleaning, vegetation removal and soil plowing are efficient and inexpensive methods for significantly reducing dose. Cleaning of walls and roofs also significantly decreases dose, but these techniques are generally expensive and labor-intensive. For wet deposition, gardens and lawns should be given decontamination priority since removing contamination from vegetation near residential areas can result in a significant reduction in dose, using techniques such as mowing, strimming (weed-whacking) and trimming which are effective, quick and cheap methods. Large-scale decontamination was performed for several years following the Chernobyl event, including washing buildings, cleaning residential areas, removing contaminated soil and decontaminating bodies of open water (those subject to deposition and contamination such as outdoor swimming pools, lakes, rivers, reservoirs, etc.), with special attention paid to kindergartens, schools, hospitals and other public areas. To suppress dust resuspension in the early phase, organic dust suppression solutions were sprayed over contaminated plots, and streets were watered both to prevent dust and to remove contamination to the sewer system. IAEA (2006) also reports that since 1990, almost all large-scale decontamination in the FSU ceased. However, some decontamination activities continue in Belarus, including public areas and buildings, villages and houses, and some industrial buildings and equipment (IAEA, 2006; Antsipov et al., 2000). The IAEA (2006) provides the following set of major and simple long-term decontamination strategies (quote):

a) *Removal of the upper 5 to 10 cm layer (depending on the activity–depth distribution) of soil in courtyards in front of residential buildings, around public buildings, schools and kindergartens, and from roadsides inside a settlement. The removed soil layer contains much of the contamination and should be placed into holes specially dug on the territory of a private homestead or on the territory of a settlement. The clean soil from the holes should be used to cover the decontaminated areas. Such a technology excludes the formation of special burial sites for radioactive waste.*
b) *Private fruit gardens should be treated by deep plowing or removal of the upper 5 to 10 cm layer of soil…*
c) *Covering the decontaminated parts of courtyards, etc., with a layer of clean sand, or, where possible, with a layer of gravel to attenuate residual radiation.*
d) *Cleaning or replacing of roofs…*

For soil, the procedure can include plowing to dilute contamination from the topsoil, reseeding and/or application of fertilizers and lime to dilute uptake in plants. When used together, these techniques provide an effective treatment for rural farmland. For forests, remediation efforts are typically labor-intensive, slow and expensive. Techniques can be either administrative (restrict access, logging, hunting, etc.) or technology-based. Fire prevention is largely administrative (since fires are typically started by human actions) and is important to prevent widespread resuspension. Technology-based approaches include early clear cutting and replanting or self-regeneration to reduce tree contamination. However, the technology-based approaches may result in a higher dose to workers. Soil improvement is another approach to mitigate contamination, requiring improved tree growth to dilute contamination in the topsoil and decrease uptake in edible fruits. The application of phosphorus and potassium fertilizers may also reduce uptake in trees and herbs and promote plant growth, although it can have negative ecological effects (IAEA, 2006).

For aquatic systems, IAEA (2006) reports that most radionuclides may be removed from drinking water supplies during the water treatment process. Suspended particles can be removed during treatment and soluble contamination can be removed by passing through activated charcoal and zeolite filtration systems. Dredging bodies of water was performed after the Chernobyl event but was found to be mostly ineffective due to high flow rates and contaminant solubility. Zeolite-containing dykes were also constructed and were found to be minimally effective for small rivers and streams.

Substantial information on a variety of remediation techniques is provided by Roed et al. (1995), including remediation data on the following surfaces tested in the FSU following Chernobyl:

- **Roads**
  - Fire hosing
  - Road surface planing/shaving
  - Vacuum sweeping
- **Walls**
  - High-pressure washing
  - Sand blasting (wet and dry)
  - Clay treatment
  - Ammonium nitrate spraying
  - Coatings
  - Power-tool assisted sanding
  - Manual scraping
- **Roofs**
  - High-pressure washing
  - Clay treatment
  - Cleaning with rotating brush
  - Replacement of roof
- **Asphalt and concrete surfaces**
  - High-pressure washing
- **Flagstones**
  - Manually turn
- **Indoor surfaces**
  - Vacuum cleaning, scraping, brushing

The following topsoil removal techniques and virgin soil treatments are evaluated in Roed et al. (1995):

- **Topsoil**
  - Front-loader
  - Bulldozer
  - Grader
  - Manual digging
  - Turf harvester (large and small)
  - Lawn mower (mulcher)
  - Soil size fractionation
- **Virgin rural soil**
  - Ordinary plowing
  - Deep plowing
  - Skim and burial plowing

Similarly, the following forest area remediation techniques are evaluated in Roed et al. (1995):

- Litter removal
- Grinding mower
- Debarking wood
- Wood pulp treatment

The properties evaluated in Roed et al. (1995) for each technology include:

- **Constraints (pre-requisites)**
- **Number of operators**
- **Productivity**
- **Mode of operation**
- **Efficiency**
- **Wastes generated**
  - Solid
  - Liquid
  - Activity per volume
  - Toxicity
- **Benefits**
- **Cost**
  - Manpower
  - Tool investment cost
  - Discount
  - Consumables
  - Overheads
  - Scale of application
  - Specific exposure
  - Inhalation/external dose relation
  - Number of man-hours needed

1.3 Goiânia Urban Remediation and Restoration

In Goiânia, Brazil, the containment of a Cs-137 irradiation source from a disused clinic was compromised in 1987, resulting in 249 people contaminated, four deaths, six doses above a few gray (Gy, several hundred rads). Figure 1-2 shows the areas impacted by the release.

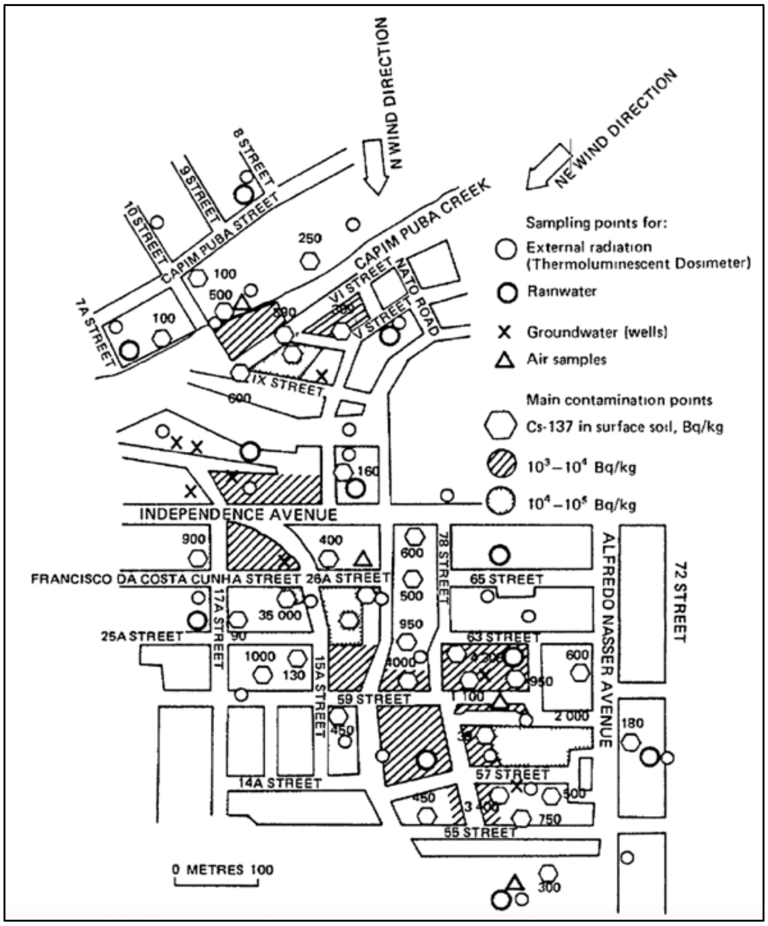

Figure 1-2. Principal Sites of Goiânia Contamination (recreated from IAEA, 1988).

The Goiânia event and subsequent response are well documented in IAEA (1988). Surveying found that the top 1.5 cm of soil retained on average 60% of the Cs-137, so removal of topsoil was implemented. Surveying employed several monitors including Geiger-Müller (GM) tubes, proportional counters and scintillation detectors. Proportional counters were found to have poor robustness. Scintillation counters designed for geological surveying provided low limits of detection, fast response time and were very useful in determining hot-spots. To protect against the ambient environment (including contamination and rain-water), monitors were placed in plastic bags, which hindered handling and reading. The cesium chloride source was hydrated, resulting in dissolution of Cs-137 and subsequent migration into porous materials such as soils, buildings and skin. Contaminated top layers of soil dried and formed radioactive dust that was spread further and created an inhalation hazard. Chemical decontamination was performed for surfaces generating exposure rates of 15 Roentgens per hour (R/h), a calculated equivalence of 131 milliSieverts per hour (mSv/h) and 3.87 milliCuries of radioactive cesium per kilogram of soil (mCi/kg).

Decontamination efforts included 85 homes, 45 public places (including pedestrian areas, shops, swimming pools, and bars) and approximately 50 vehicles.

For vegetation, dust deposition on leaves could be reduced by 50% simply by washing, while pruning of trees followed by disposal of fruit was also effective. Soil was acidified with hydrochloric acid and alum followed by Prussian blue. This treatment was also used to decontaminate clay or cement floors, walls, roofs, asphalt, paper and clothes. An organic solvent was added first to remove grease on floors or tables, and sodium hydroxide was employed first with detergents for synthetic floors and personal objects. Creams and gels containing Prussian blue resin were applied to delicate items including furniture and television screens. Enamel, granite and other silicate surfaces required pre-treatment with hydrofluoric acid. Building contents were removed, and a determination was made as to whether items were valuable (financially or personally) before being decontaminated or disposed of. Interior surfaces (including walls, floors and inner roofs) were cleaned with high-efficiency filtered vacuums to remove dust that accounted for more than 90% of the radioactivity. Exterior surfaces such as floors, roofs, walls and vehicles were subjected to pressure washing with water, although this was 50% effective.

1.4 Fukushima Wide Area Contamination

A more progressive and comprehensive approach to remediation has been implemented in Japan following the accident at the Fukushima Dai-ichi NPP. In March 2011, approximately 2,700 to 11,000 kCi Iodine-131, 190 to 540 kCi Cesium-137 and 160,000 to 320,000 kCi Xenon-133 (IAEA, 2015a) were released from the reactors and deposited over a wide area. A range of activities is given for each due to uncertainties in source terms, which have been reduced based on excluding early (and less certain) estimates of the amount of radionuclides released (IAEA, 2015a).

The land affected was primarily forest and agricultural but did include major urban cities such as Fukushima City. Evacuations in the most impacted areas involved approximately 120,000 people, with a restricted "exclusion area" established at a distance of 20 km from the Fukushima Dai-ichi NPP and a planned evacuation area northwest of the site corresponding to a dose rate of at least 20 milliSieverts per year (mSv/y) (SRNL, 2013), together forming the "special decontamination area" (SDA) as shown in the left panel of Figure 1-3 (IAEA, 2014). Within the SDA, zones were created based on dose, as shown in the right panel of Figure 1-3:

- < 20 mSv/y – residents returned to homes (green)
- 20 to 50 mSv/y – residents restricted to maintaining house, land, agriculture only during daytime (yellow)
- >50 mSv/y –residents prohibited from returning to area (pink)

The SDA incorporates land in 11 municipalities. The area includes all of Naraha Town, Tomioka Town, Okuma Town, Futaba Town, Namie Town, Katsurao Village and Iitate Village, and parts of Tamura City, Minamisoma City, Kawamata Town and Kawauchi Village municipalities (IAEA, 2015b).

Additionally, an intensive contamination survey area (ICSA) was identified in which the dose rate was estimated to be between 1 and 20 mSv/y. The ICSA includes wider regions of the Fukushima Prefecture, in addition to portions of Gunma, Tochigi, Chiba, Ibaraki, Miyagi and Iwate Prefectures.

Within the SDA, decontamination efforts were led by the Japanese government. Outside the SDA (where residents were not evacuated, and including the ICSA), decontamination was performed by municipal (local) governments.

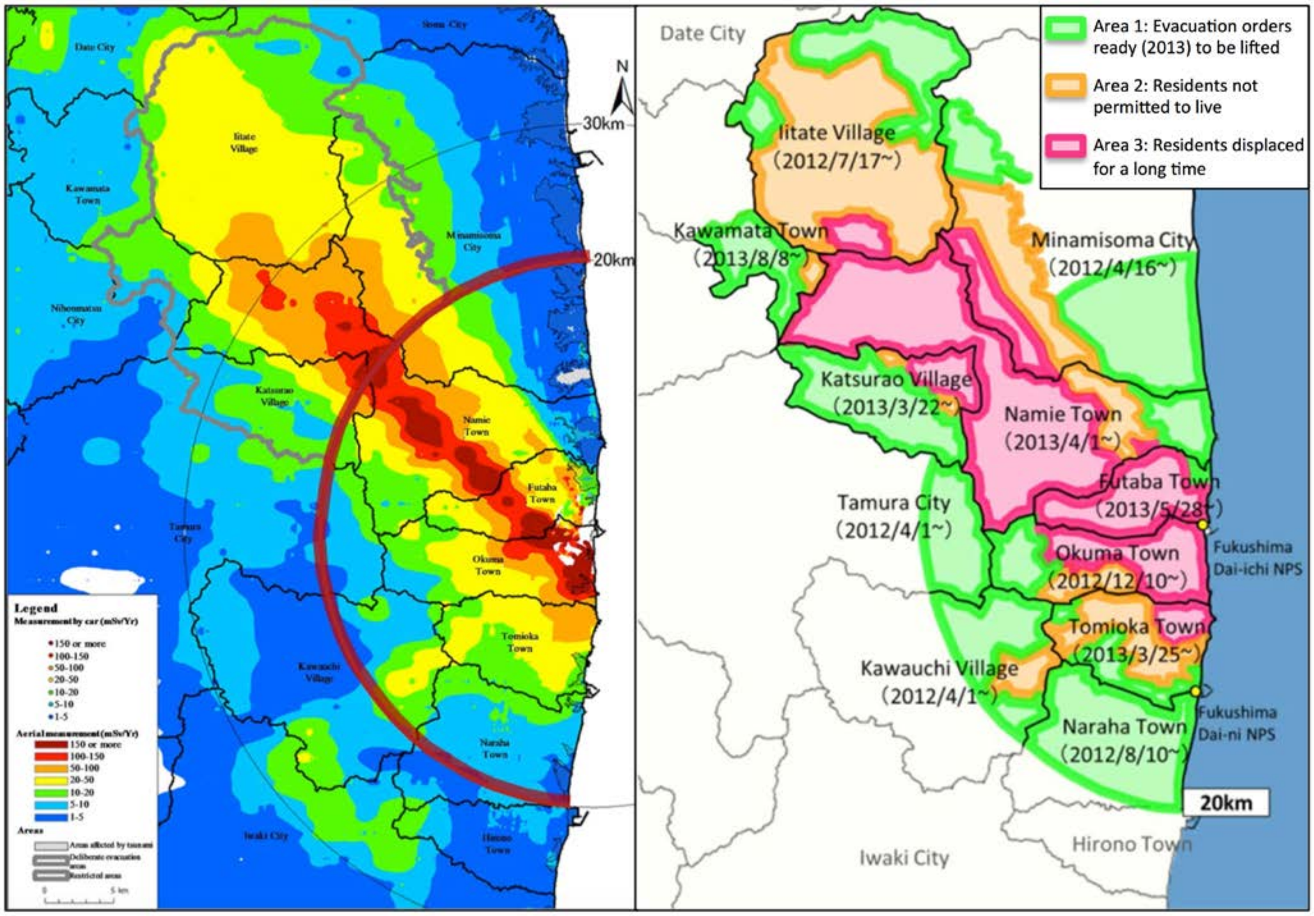

Figure 1-3. Dose and Evacuation Areas Following the Fukushima Dai-ichi NPP Release (IAEA, 2014)

A significant body of work by IAEA and EPA was developed prior to the events in Japan, including a technology reference guide for radiologically contaminated sites and surfaces (IAEA, 1999; EPA, 2006) and a report on treating contaminated media (EPA, 2007). A review of traditional decontamination strategies deployed in Chernobyl, Goiâna and Fukushima has been developed by Kaminski et al. (2016). Not surprisingly, decontamination of agricultural land and building exteriors in Japan mirrored the decontamination of agricultural land and building exteriors previously demonstrated following events in Chernobyl and Goiânia, including washing of exterior surfaces and removal of vegetation. A substantial body of work has also already been collected, demonstrated and evaluated by Japan's Ministry for the Environment and the Japan Atomic Energy Agency as well as scientists, engineers and scholars from other organizations such as NIES, the Universities of Tokyo and Kyoto and private industry to understand the extent of contamination and determine the best remediation strategies. The remediation strategies currently employed and *emerging technologies* are further discussed in Section 2.

2. Current and Emerging Technologies and Techniques in Japan Following the Fukushima Dai-ichi Accident

In response to the Fukushima Dai-ichi NPP accident in March 2011, MOE initiated a demonstration program for decontamination techniques to elicit potentially new technologies and to provide an opportunity to demonstrate such techniques to the public (MOE, 2012; 2013a; 2014a; 2014b). The demonstrations included verifying decontamination efficiency, cost efficiency, and safety. Beginning in 2011 (and revised each year since), the program selects promising and emerging decontamination techniques via a review committee consisting of subject matter experts. Selected techniques are tested and verified independently at suitable contaminated sites. Technical advice and evaluation of decontamination techniques are reported by the Headquarters of Fukushima Partnership Operations and JAEA.

JAEA Decontamination Pilot Plans (DPPs) have been implemented at 16 sites in 11 municipalities to address the lack of real-world examples for promising technologies and to provide additional experience appropriate to Japanese boundary conditions. The pilot projects provided valuable information for each technology (Miyahara et al., 2015), including:

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

2.1 Survey and Characterization

Surveying and characterization of the radionuclides of interest, the activity and the geographic/topologic distribution is vital to understanding and planning for both stabilization (to prevent migration or resuspension) and decontamination. Monitoring is also needed during decontamination (to evaluate progress) and after decontamination (clearance). Surveys can be aerial or ground-based, each type having pros and cons. Aerial mapping of the contamination can cover large areas quickly and is not dependent on road/terrain. However, aerial surveys do not have the same precision in area that ground-based surveys can provide. Conversely, ground-based surveys can be slow to perform and are limited by access for a given terrain (e.g., road or rail). Personnel-based surveying can also be performed using backpack-style meters. Several U.S. government agencies such as DOE, Department of Defense (DOD) and EPA have survey capabilities, including ground-based detection in cars, trucks and vans, and aerial vehicles such as planes and helicopters.

2.1.1 Aerial Surveys

Since the initial wide area surveys of northeastern Japan by the Ministry of Education, Culture, Sports, Science & Technology (MEXT) and DOE in 2011 to define the evacuation zones, JAEA and MEXT have performed significant work to test and characterize a range of airborne survey systems including manned and unmanned aerial vehicles. The characteristics of each system are given in Table 2.1 (Miyahara et al., 2015), together with images of each airborne technology demonstrated in Japan in Figure 2-1.

Table 2.1. Characteristics of JAEA Airborne Survey Systems (reproduced from Miyahara et al., 2015)

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

Figure 2-1. Airborne Survey Systems Corresponding to Table 2.1 (Miyahara et al., 2015)

Manned aerial vehicles typically fly at higher altitudes, covering larger areas faster, but producing lower resolution images. By contrast, micro-UAVs can cover significantly less area than the larger aircraft but can fly much closer to the ground, providing finer resolution. UAVs also offer the ability to go into otherwise inaccessible locations such as under tree lines, between buildings, under bridges, etc. The UAV technology also has the ability to map contamination on buildings (e.g., high-rise walls/roofs), which could greatly assist in the planning for and execution of decontamination and subsequent clearance measurements. Clearly, the cost, fuel usage, range, maintenance, ground support and pilot qualifications increase from small UAVs to unmanned helicopters, planes and manned aerial vehicles such as fixed wings or helicopters. Researchers at Chiba University in Japan also demonstrated a low cost UAV with a highly efficient spatial radiation monitoring system to survey low-ground regions and residential areas, as well as forests and wasteland where walking survey was previously impossible (MOE, 2013a). Their technology, which flies between 1 and 3 meters (m) above the ground, also includes a Geographic Information System (GIS) and a hyper-spectral aerial photographing system that can obtain a continuous spectrum between the visible and near infrared region to determine land cover classification.

The regional manned helicopter fielded by JAEA is similar to the aerial survey equipment deployed as DOE's fixed wing and helicopter Aerial Measuring System (AMS)[2], EPA's Airborne Spectral Photometric Environmental Collection Technology (ASPECT)[3] and other commercially available standoff detection systems as detailed in Table 2.2 (DHS, 2013). It is recommended that the deployment of radiation detection on UAVs be further evaluated in the U.S.

Table 2.2. Characteristics of Example Airborne Standoff Radiation Detectors (DHS 2013)

Company	Product	Gamma Detectors	Dimensions L x W x H (cm)	Weight (kg)	2013 Cost ($k)	Product Website
Mirion Technologies Inc.	SPIR-Ident Mobile Monitoring System™	NaI-Tl*	33 x 43 x 89	117.9	285	www.mirion.com, accessed June, 2016
Nucsafe, Inc.	ARDIMS Aerial Pod System™	NaI-Tl	33 x 185 x 185	81.6	n/a	www.nucsafe.com, accessed June, 2016
Rad Solution Inc.	RS-500 Digital Airborne Gamma-Ray Spectrometer	NaI-Tl	74 x 56 x 28	113.4	n/a	www.radiationsolutions.ca, accessed June, 2016

n/a: not available
***NaI-Tl: thallium-doped sodium iodide**

2.1.2 Ground-Based Surveys

Of the 58 techniques that were selected by MOE between 2011 and 2014, only two techniques were in the survey and characterization category and one of these techniques was ground-based technology to simplify the measurements for radioactivity concentrations in containers. The Toshiba Corporation developed an integrated device that measures activity, surface dose rate and the shape of the container unit in the field and calculates the total activity in the container. This technique, demonstrated with incineration ash and soil (Figure 2-2), improves working efficiency and reduces the radiation exposure to workers. Using two germanium detectors, the device can account for heterogeneity, measuring to within an error of 35%, with detection limits of 770 Becquerels/kilogram (Bq/kg) of Cs-137 after just one minute (MOE, 2013a). Longer count times will improve statistics (MOE, 2013a).

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[2] http://www.nnsa.energy.gov/aboutus/ourprograms/emergencyoperationscounterterrorism/respondingtoemergencies-0-0, accessed June, 2016.
[3] https://www.epa.gov/emergency-response/aspect, accessed June, 2016.

Figure 2-2. Toshiba's Simplified Method for Measuring Radioactivity Concentration per Container (MOE, 2013a)

In 2012, Hitachi-GE Nuclear Energy developed a plastic scintillation fiber (PSF) that operates for four hours continuously with a rechargeable battery that can measure air dose rate as far as 20 m in a few seconds.[4] The work was published in 2014 (Gamo et al.), providing examples of using 1, 7 and 12 PSF bundles to measure contamination along a roadway gutter, and potential applications on a building wall, a tree, a pond and attached to a vehicle to survey roads. The technology is paired with GE's SOPHIDA™ and D-phod Viewer™ software with mesh sizes of 10 m and 1 m, respectively.

Recent work by JAEA has investigated the application of PSF to various contaminated areas resulting from the Fukushima Dai-ichi NPP. A 19-fiber, 12 meter long PSF array was placed across a field, straddling the boundary between contaminated and decontaminated land. The results showed a clear delineation between the two areas (Todani, 2011). At the same time, measurements of radiation dose rates were made in Minamisoma City and Date City, Japan using PSF and identifying where high doses were collocated over cracks in asphalt pavement (JAEA, 2011a). Similarly, a 20-m long bundle of 10 polystyrene 1 millimeter (mm) in diameter PSFs with polymethylmethacrylate (PMMA) cladding was manually moved along outdoor surfaces at schools at a rate of 0.1 meters per second (m/s), equivalent to 0.2 miles per hour (mph), allowing the two-dimensional mapping of Cs-137 before and after decontamination (Torii and Sanada, 2013). In the same paper, the technique was also applied to the front of a construction vehicle (e.g., IHI CL45 compact track loader) and performed the mapping of a 2,000-m^2 area within one hour. Assuming a road lane width of three meters, the corresponding speed of the motorized application was 0.4 mph. Additional studies were documented using PSF to measure the contamination at the bottom of a pond in the Fukushima Prefecture using a 20 m submerged PSF bundle (JAEA, 2014a). JAEA extended the length to 50 m PSF, and the submerged PSF bundle was used to monitor leakage from contaminated water tanks at the Fukushima Dai-ichi NPP (JAEA, 2014b; JAEA, 2015c).

Sanada et al. (2015) utilized nineteen bundled, 1 mm diameter, 20 m length Kuraray SCSF-3HF PSFs to measure Cs-137 sediments under the water in irrigation ponds that had collected falling rain in the

[4] http://enformable.com/2012/05/ge-developing-fiber-optic-gamma-radiation-dose-rate-detection-and-measurement-system/, accessed June, 2016.

Fukushima prefecture. The results compared well with sediment cores withdrawn after measurement with PSF. Subsequent measurements taken after decontamination were integrated with GIS maps to demonstrate monitoring of decontamination efficacy. Example JAEA PSF applications are shown in Figure 2-3, showing: (A) PSF equipment (with Photomultiplier Tube, PMT) supplied by Japan Radiation Engineering Co. (JREC), (B) Application of PSF to survey pond sediments, (C) Application of PSF to survey forest soil, and (D) Application of PSF to measure outdoor urban surfaces, e.g., a school playground utilizing a system built by JREC Co. Ltd., and P-SCAN software to process data.[5]

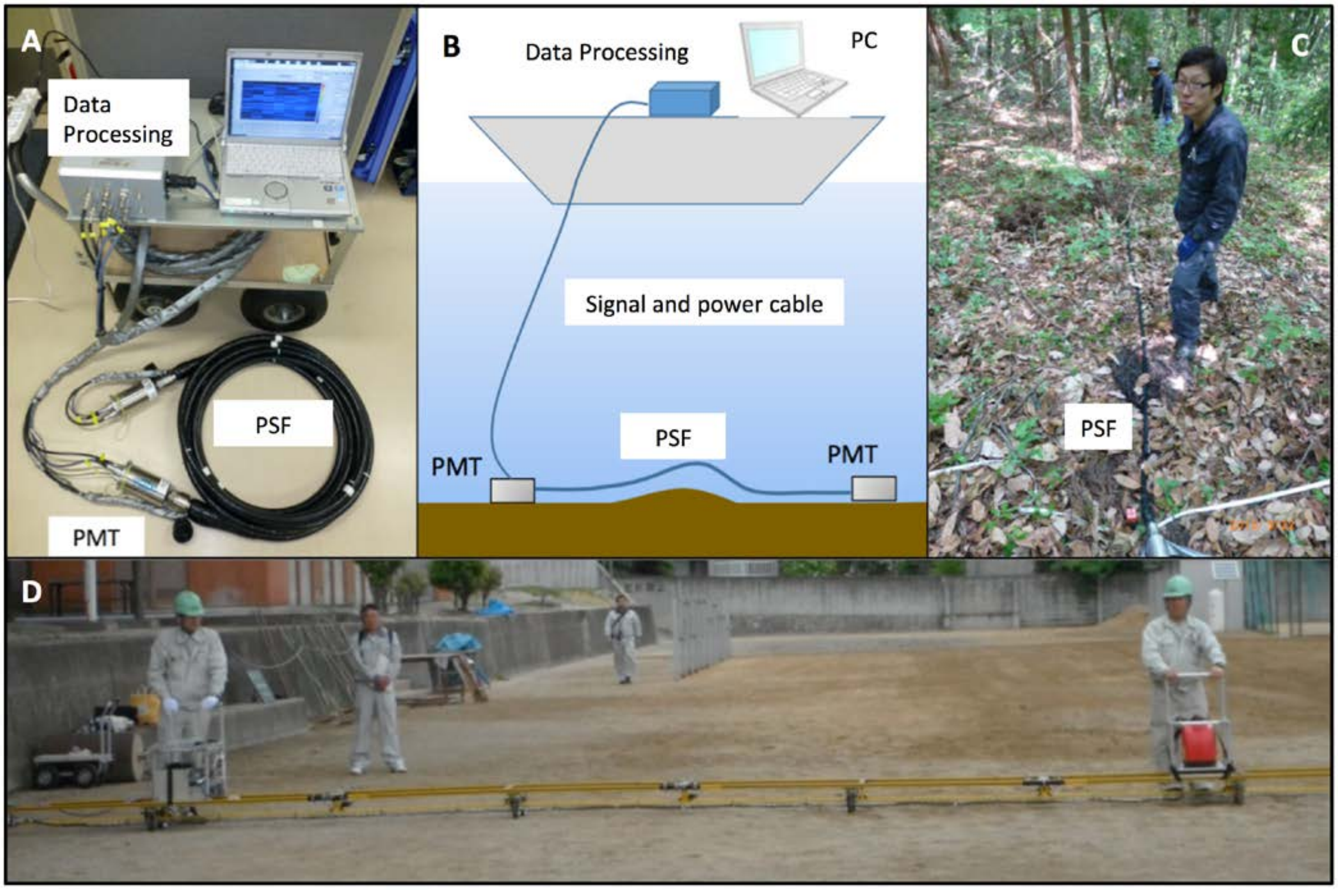

Figure 2-3. JAEA Application of PSF in Post-Fukushima Surveys (reproduced from JAEA)

IHI Corporation attached a PSF to a turf stripper to measure and remove contaminated soil, demonstrating the capability in Okuma Town and Soma City, Japan. The technique promises two-dimensional mapping, evaluation of depth profile, turf removal, reduction in soil or turf waste volume and reduction in work hours (MOE, 2012). The application of PSF on vehicles should be investigated in US studies, particularly those vehicles capable of performing decontamination or stabilization of contamination on surfaces.

[5] http://fukushima.jaea.go.jp/english/topics/pdf/topics-fukushima050e.pdf, last accessed in June 2016.

JAEA have also applied modern detection technology to a sports-utility-vehicle (SUV) with GPS, fielded from the Sasakino Analytical Laboratory, shown in Figure 2-4. The detection systems on the vehicle can measure both low and high dose rate ranges, specifically 0.01 to 10 microSieverts per hour (μSv/h) using a shielded NaI-Tl scintillation detector and up to 100,000 μSv/h using semi-conductor detector technology. Dust and gas sampling can measure alpha- and beta- emitting radionuclides in airborne particles and capture radioactive iodine. The vehicle can transfer data real-time to a base station, can travel off-road (particularly important for emergency response) and has a moveable searchlight for night operation. Discussions with JAEA also determined that driving through contaminated areas resulted in vehicle contamination that was not easily removed with typical vehicle washing. Additionally, air-filters and cabin filters became contaminated. Similar issues should be considered in US deployments of such response vehicles.

Figure 2-4. JAEA Monitoring Vehicle

Survey equipment has also been developed at the Kyoto University. The KURAMA (Kyoto University RAdiation MApping) System measures a dose every three seconds and is deployed in a minivan with GPS and linked to Google Earth. However, KURAMA requires an operator and a complicated setup. Subsequently, KURAMA-II has been developed in a compact (30 x 20 centimeter [cm]), lightweight form with autonomous pulse-height spectra utilizing a thallium-doped cesium iodide (CsI-Tl) scintillation detector. Both systems have been demonstrated successfully in contaminated areas in the Fukushima region. By deploying KURAMA-II instruments in 28 buses, two prefecture cars and 19 service-operated cars, data are transmitted real-time to JAEA and displayed on a large screen in the JAEA Fukushima Office lobby (Tanigaki, 2015). Kyoto University and JAEA have now deployed 100 KURAMA-II instruments across eastern Japan. KURAMA-II is small enough to deploy on a motorcycle (as shown in Figure 2-5) and backpack (Tsuda et al., 2015; Tanigaki, 2015).

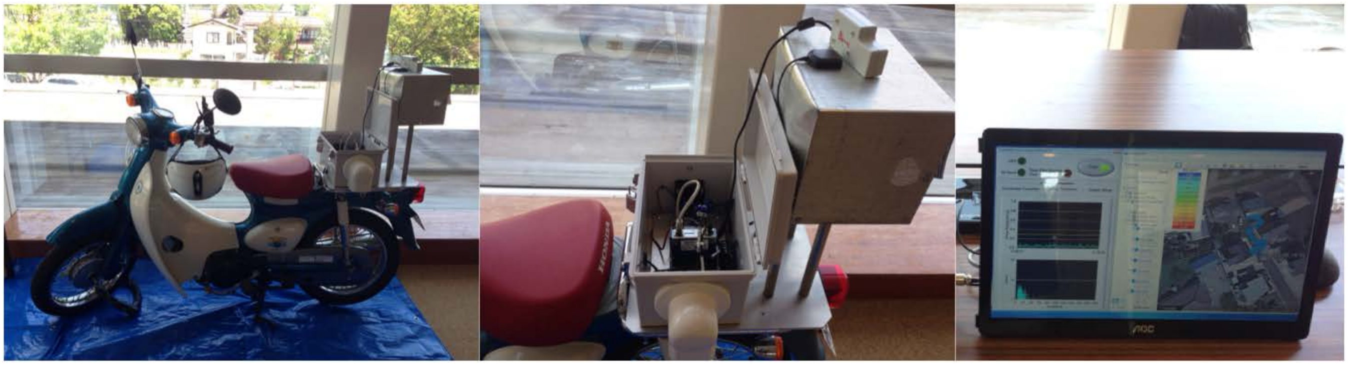

Figure 2-5. A Demonstration of KURAMA-II

The KURAMA-II program has the potential to be expanded to include other service vehicles, including garbage trucks, street sweepers, and mail and parcel delivery trucks. Such detectors with real-time feedback have the potential to "crowd-source" data if the program were to be expanded. Such a network of highly portable, service-vehicle mounted detectors with real-time feedback to inform both government and residents about dose may be useful for U.S. response to wide-area radiological emergencies.

By comparison, several stand-off radiation search detectors were evaluated in a market survey report by DHS (2013), the characteristics of which are shown in Table 2.3 and that can be deployed on vehicles.

Table 2.3. Characteristics of Example Ground-based Standoff Radiation Detectors (DHS, 2013)

Company	**Product**	**Gamma Detectors**	**Dimensions L x W x H (cm)**	**Weight (kg)**	**2013 Cost ($k)**	**Product Website**
Bubble Technology Inc.	FlexSpec Mobile™	Left/right directionality, NaI-Tl	99 x 137 x 91	249.5	195 – 260	www.bubbletech.ca, accessed June, 2016
FLIR Radiation Inc.	iFind Compton Camera 442™	Two-plane measurement, truck/trailer mounted, NaI-Tl and PVT	203 x 130 x 193	900.4	600 – 1,200	www.flir.com, accessed June, 2016
Innovative American Technology Inc.	Mobile Radiation Verification System™	Vehicle mounted or stand-alone 360-degree horizontal field of view, NaI-Tl	64 x 114 x 99	105.2	175	
Innovation American Technology Inc.	Rapid Deployment Radiation Verification System™	NaI-Tl	71 x 81 x 81	68.0	75	
Mirion Technologies Inc.	SPIR-Ident Mobile Monitoring System™	NaI-Tl	33 x 43 x 89	117.9	285	www.mirion.com, accessed June, 2016

Company	Product	Gamma Detectors	Dimensions L x W x H (cm)	Weight (kg)	2013 Cost ($k)	Product Website
Nucsafe Inc.	Guardian Predator Portable Radiation Detection Kit™	NaI-Tl, CsI-Tl, PVT, GMT	71 x 56 x 36	30.8	n/a	www.nucsafe.com, accessed June, 2016
ORTEC	Detective-200™	HPGe	38 x 25 x 43	21.3	95 - 380	www.ortec-online.com, accessed June, 2016
Radiation Solutions Inc.	RS-700 Mobile Radiation Monitoring System	NaI-Tl	69 x 15 x 18	31.8	n/a	www.radiationsolutions.ca, accessed June, 2016
Thermo Fisher Scientific Inc.	Matrix Mobile ARIS™	NaI-Tl	n/a	n/a	n/a	www.thermoscientific.com, accessed June, 2016

CsI-Tl: thallium-doped cesium iodide; GMT: Geiger-Müller tube; HPGe: high purity germanium; NaI-Tl: thallium-doped sodium iodide; PVT: polyvinyl toluene; n/a: not available

Additional information on emerging standoff detection technologies is provided in DHS (2013). EPA has a ground-based version of the ASPECT aerial detector. Known as ASPHALT, the system can be placed on a pickup truck, SUV or other vehicle and uses up to three 3 x 3 inch lanthanum bromide crystals to obtain better resolution than aerial systems and hand-held devices due to the crystal size (U.S. EPA, 2014). Similarly, DOE has ground-based versions of AMSs, known as KIWI, consisting of an array of eight 2 x 4 x 16 inch sodium iodide detectors positioned at three feet from the ground, and has a view of approximately 10 feet in diameter allowing high spatial resolution mapping of contamination (U.S. EPA, 2014).

Specifically, advanced imaging tools for locating radioactive sources use gamma cameras and Compton imaging, both of which when paired with image software improve the probability of distinguishing between the source and background radiation. Such techniques are designed to identify radioactive material concentrated in a single location, with the background radioactivity spread over a large area. Combining visual images with gamma measurements makes locating areas of elevated radioactive contamination easier, particularly for those with little training in gamma measurement. An example gamma camera application was recommended in the MOE decontamination guidance (MOE, 2013b) and is shown recreated in Figure 2-6.

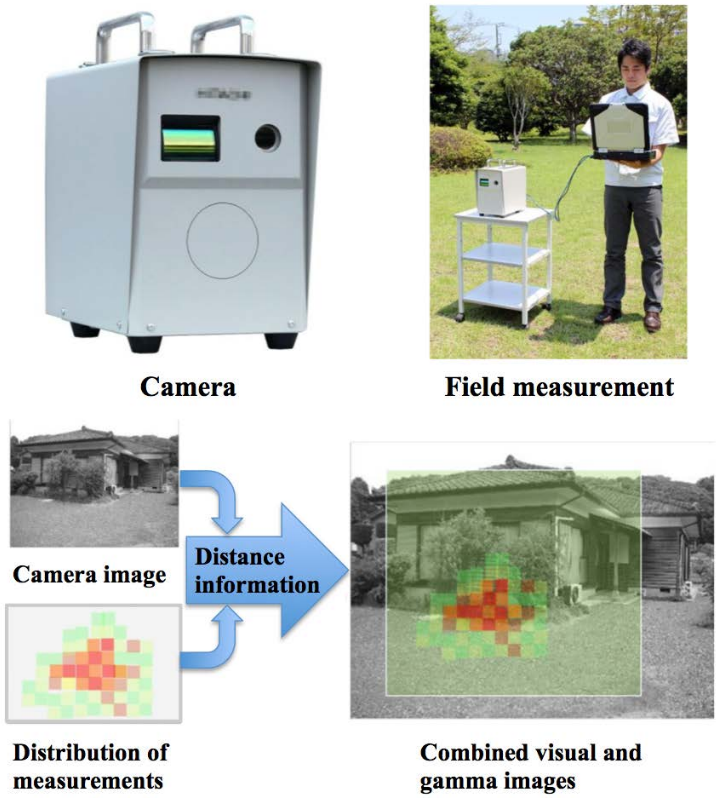

Figure 2-6. Example of Gamma Camera Applications in Japan (recreated from MOE, 2013b)

Mitsubishi demonstrated a gamma camera to image Cs-137 contamination in a parking lot and on a house in the Fukushima area both before and after decontamination (Matsuura et al., 2014). The tests identified a 20 μSv/h hot-spot in a parking lot after a 30 minute count time under a 1.5 μSv/h air dose (background) one meter from the camera and another hot-spot of 30 μSv/h at a distance of 10 m from the camera.

Additionally, technology developed by Chiyoda Technology Corporation[6] presented at the recent 2015 symposium on radiological issues associated with the revitalization of Fukushima highlighted the use of a lightweight Compton gamma camera for monitoring surface contamination during decontamination efforts. Such techniques permit both the identification of contamination and a measure of decontamination progress. Compton gamma cameras are being developed at several US DOE sites to support DOE, DHS and IAEA search capabilities (LLNL, 2014b). Such cameras should be made more widely available in response to wide-area radiological events, allowing remediation workers to locate contamination and monitor the progress of decontamination.

In areas affected by the Fukushima Dai-ichi NPP release, the Japanese government has deployed airborne dose rate equipment with large visual displays in urban areas such as Fukushima City and on

[6] http://www.c-technol.co.jp/eng, accessed June, 2016

freeways to inform the public (Figure 2-7). Similar detectors would provide useful information and public confidence in response to a U.S. radiological event.

Figure 2-7. Airborne Dose Rate Meters in Urban Areas (left) and on Freeways in the Evacuation Zone (right) in Japan

2.2 Decontamination

Decontamination technologies can be divided among the substrates to be remediated. In a wide-area release such as that observed from the Fukushima Dai-ichi NPP release, there exists a wide range of surfaces, from porous to nonporous, man-made to natural, and urban to rural. In many cases, the different types of surfaces co-exist, for example, vegetation at the side of an asphalt road, or farm buildings on agricultural land. However, it is possible to utilize several decontamination techniques to address each of the surfaces. MOE developed and revised "Decontamination Guidelines" (MOE, 2013b) using experience and knowledge gained, lessons learned and new technologies acquired from the decontamination pilot tests and ongoing remediation practices to assist the municipalities to develop their remediation approaches. The most commonly used decontamination methods such as debris removal, high-pressure washing and surface removal are suitable to large areas and aim to efficiently reduce the external radioactivity and the radiation dose rates in the living environment. Although decontamination can involve mainly low level technologies to wash surfaces and remove contaminated materials, efforts are taken to reduce the costs, the time required and the volume of waste produced.

A collaboration between MOE, JAEA and local governments has performed significant public outreach, including holding town-hall meetings, lectures and demonstrations to aid public understanding of radioactivity, survey techniques, dose, decontamination and waste. One example of such outreach is the *Decontamination Information Plaza*, a dedicated facility in downtown Fukushima City.[7]

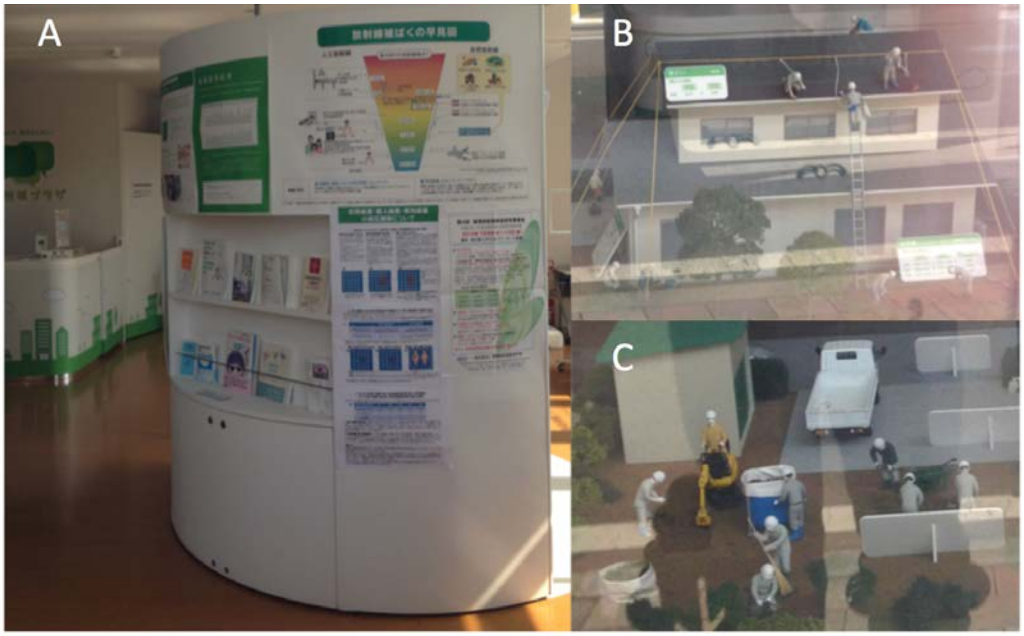

Figure 2-8. Displays Demonstrating Radiation and Residential Decontamination at the Fukushima City Decontamination Information Plaza

The “plaza” is a large storefront-type facility that includes displays (e.g., Figure 2-8), reading material, interactive videos and example equipment. Such displays are vital in improving public understanding, particularly as it relates to their health (A), land and property decontamination strategies, such as high-pressure washing (B) and top-soil removal decontamination strategies (C).

Prior to carrying out large-scale regional decontamination efforts, JAEA used a Decontamination Pilot Project (DPP) as a test bed for new approaches and technologies, evaluating the effectiveness of different techniques and options, and providing the technical guidelines for optimization towards the decontamination goals. In general, the remediation technologies and approaches used for each contaminated site were selected based on the site characterization and radiological monitoring data. For sites with relatively high contamination levels, the primary goal was to reduce dose rates to the maximum extent possible. Therefore, technologies that can effectively reduce dose rates had higher priority. However, for sites with relatively low dose rates, the emphasis was minimization of the waste volume generated during remediation. In those cases, technologies that generate less or no waste were preferred. Further, the selection of technology and approaches was based on the type of site. JAEA grouped technologies and approaches used in the DPP by specific type of target site, and the performance of each technology was evaluated based on the following major quality criteria (JAEA, 2015a):

1. Speed of implementation: the goal was to allow people to return to their normal lifestyle as quickly as possible.

[7] Additional information available at https://josen.env.go.jp/en/pdf/decontamination_information_plaza.pdf?0930, accessed June, 2016.

2. Efficiency in terms of minimizing waste volume generated during decontamination, avoiding re-contamination and reducing repeated efforts.
3. Effectiveness in terms of decontamination factor (DF) and reduction of dose rate.

For each technology and site type, detailed evaluations were performed including decontamination speed (one person-day); waste type and the volume generated; volume of water used, method of waste water collection and additional treatment; decontamination factor and gamma dose rate reduction, the remediation cost and information on how to tailor the technology to specific site conditions were provided in Appendix A in JAEA, 2015a. Table 2.4 lists some of the most common technologies used to remove radioactivity from different surfaces in the DPP.

Table 2.4. Common Decontamination Techniques used to Remove Radioactive Material from Surfaces (reproduced from JAEA, 2015a; IAEA, 2014)

Decontaminated item	Decontamination technique used
Forest	Pruning, thinning, trimming, removal of humus layer of surface soil by mechanical digger
Agricultural land, gardens and other grounds	Topsoil stripping, mowing grass, collection of clippings, pruning, replacing turf, plowing
Roofs and outer walls	High-pressure washing, washing, brushing, wiping, stripping agent
Parking lots and other paved surfaces	Washing, high-pressure washing, surface removal (shot blasting, grit blasting, etc.)
School athletic grounds etc. (dirt)	Surface dirt removal
Roads (asphalt paved surfaces)	Washing, high-pressure washing, shaving off

The key characteristics of technologies used and evaluated for forests, agricultural land, residential buildings, roads and public areas are summarized below. Many of the techniques could easily be implemented in the U.S. in response to a wide area radiological event.

2.2.1 Forests

Forests have a very high uptake capacity (~80 to 90%) for contaminants, and radiocesium is initially intercepted by the foliage and over time is transported to the surface as leaf litter (JAEA, 2015a). The distribution of radioactivity in forest areas depends on the type of trees present. Deciduous trees lose their leaves seasonally, and associated activity is deposited on the forest floor creating periods of greater downward transfer. Evergreen trees lose their leaves gradually or not at all, so downward transfer is typically less than for deciduous trees. The removal of litter and humus layers (either manually or by mechanical digging) was the primary decontamination approach for the forest floor. However, it is unclear if removal of such material promotes resuspension or runoff. Further reduction of radioactivity can be achieved by removal of topsoil and trimming lower branches of evergreen trees at the expense of increased costs and time required. Table 2.5 compares key factors of the technologies (reproduced from JAEA, 2015a) and the decontamination results. Example images showing the collection of leaf litter and humus and pruning back foliage are shown in Figure 2-9 (MOE, 2013b).

Table 2.5. Comparison of Technologies for Forest Decontamination (JAEA, 2015a)

Decontamination Technology		**Removal of Litter and Humus Manually or by Mechanical Digging (Flat Ground)**	**Removal of Litter and Humus Manually or by Mechanical Digging (Slopes)**	**Removal of Litter, Humus and Topsoil by Mechanical Digging (Flat Ground)**	**Trees**	
					High Pressure Washing Trunk	**Branch Pruning (Lower Trunk)**
Distribution of radioactivity in evergreen forest (September 2011)[A]		44 – 84%			Trunks: 1 – 3%	Branches and leaves: 14 – 53%
Percentage dose reduction[B] (at 1 cm)		60 – 80%	60– 80%	60 – 80%	~ 30%	5 – 30%
Volume of decontamination waste generated (L/m^2)		20-90	20-90	100-200	< 1,000 per tree	270 (non-compacted waste volume)
Secondary contamination		N/A	N/A	N/A	Water infiltration to soil	Foliage from branches to forest floor
Effects on surrounding environments		Possibility of causing erosion on slopes				
Decontamination speed (one person day)		50 m^2	30 m^2	40 m^2	8 trees	40 m^2
Direct implementation cost Japanese Yen (JPY)/m^2 for area > 1,000 m^2)		530	760	890	3,390	580
Overall evaluation	Deciduous forests	Highly effective	Highly effective	Effective	Limited effect	not applicable
	Evergreen forests	Highly effective	Highly effective	Effective	Limited effect	Effective

For branch pruning of trees, the dose rate was measured at a height 1 m above the ground; for other techniques, the dose rate was measured at a height of 1 cm from the ground. The techniques are climate- and season-dependent.

A: Approximately half of the radioactivity was found to be contained in the trees, mainly on the branches and leaves. Branch trimming was confined to the lower parts of trees.

B: Percentage dose reductions were calculated using the values measured before and after decontamination. In most cases, branch pruning was carried out simultaneously with forest floor cleanup (e.g., litter removal), therefore dose reduction was a composite of multiple methods and could not be separately estimated.

Figure 2-9. Example Forest Decontamination (MOE, 2013b)

2.2.2 Agricultural Land

The goal of remediation of agricultural land is (to the extent possible) to allow returning farmers to grow and sell crops and produce without safety concerns from consumers. Studies of Cs-134 and Cs-137 depth profiling suggest that the contamination penetrates mostly within the upper 5 cm of undisturbed soil and up to 20 cm of plowed soil. To decontaminate agricultural land, the vegetation surface was first removed, then various approaches were applied to reduce the dose rates of the contaminated soil. In some cases, a fixative or solidification agent was applied (e.g., inorganic magnesium-based or cement-based sprays) to facilitate thin-layer stripping of the soil. During periods of freezing weather, no additional fixation is needed. Table 2.6 lists the decontamination technologies used and their evaluated results. Examples of agricultural land remediation are shown in Figure 2-10, first mowing (left) and plowing (right) to remove vegetation and dilute contamination below the topsoil surface.

Figure 2-10. Example Remediation of Agricultural Land [8]

[8] http://josen.env.go.jp/en/framework/pdf/decontamination_guidelines_2nd.pdf, accessed June, 2016

Table 2.6. Comparison of Technologies for Agricultural Land Decontamination (recreated from JAEA, 2015a)

Decontamination Technology	Thin Layer Soil Stripping/ Mowing (Manual or Mechanical Hammer Knife)	Mechanical Digger (Stripping Thickness 5 cm)	Application of Solidification Agent and Collection by Mechanical Digger	Reversal Tillage (Tractor and Plowing) (~ 25-50 cm)	Interchanging Topsoil with Subsoil (Mechanical Digger) (~ 45 cm)
Dose rate reduction (at 1 m)	~ 70%	65 - 95%	~ 40-70%	65 - 80%	~ 65%
Volume of removed soil	Actual volume to be removed	Actual volume to be removed and overbreak[A]	Actual volume to be removed and overbreak[A]	-	-
Secondary contamination	-	-	-	-	-
Area decontaminated (m^2/person day)	70	90	50	1100	100
Application conditions	Effective for thin stripping Flat ground only Cannot use when ground is frozen	Must have sufficient load bearing capacity Cannot strip to a depth of less than 5 cm	Must have sufficient load bearing capacity; Cannot use when standing water is present or ground is frozen; 1 week required for solidification	For low level contaminated soil	For low level contaminated soil
Direct implementation cost JPY/m^2 (area > 1000 m^2)	690	560	880	33	310
Overall evaluation	Effective	Effective	Moderately effective[B]	Effective	Highly effective

A: The *overbreak* is the excess soil removed around the area that was decontaminated, due to the precision of machine operation.
B: The time required for both application of the solidification agent and meeting the correct soil conditions reduces the overall evaluation of this technique.

2.2.3 Residential Buildings

Major remediation efforts have been applied to residential structures, particularly external surfaces including roofs and supporting walls. The decontamination was implemented in a top-down manner to prevent recontamination of lower surfaces. Prior to roof decontamination, leaves and debris were removed from rainwater gutters and drainage systems, which were identified as potential hot-spots.

The decontamination methods ranged from simple washing, wiping and scrubbing, to novel technology such as a surface-stripping agent (e.g., K-Pack), and the methods were tested side-by-side on the same surface. The results were very dependent on building materials. The stripping agents are not suitable for remediation of large area in terms of efficiency and effectiveness. The surrounding environment of residential buildings such as gardens and dirt roads were decontaminated using technologies similar to the technologies used to treat forests and agricultural lands. Figure 2-11 shows example decontamination of external residential surfaces, including roof cleaning with high-pressure water (top left), gutter wiping (bottom left), high-pressure drain pipe (down-spout) cleaning (top right) and topsoil removal (bottom right).

Figure 2-11. Example Residential External Decontamination Activities [9]

Tables 2.7 and 2.8 summarize some of the decontamination techniques used and results of evaluation studies for different types of roofing materials.

[9] http://josen.env.go.jp/en/framework/pdf/decontamination_guidelines_2nd.pdf, accessed June, 2016 and http://josen.env.go.jp/en/work_report/20120709.html, accessed June, 2016

Table 2.7. Comparison of Technology for Decontamination of Residential Roofs (recreated from JAEA, 2015a)

Technology Information		High-Pressure Water Jet	Brushing	Wiping	Stripping Agent
Count rate reduction	Iron (baked finish)	N/A	~ 10%		
	Iron (spray finish)	N/A	~ 30%	~ 5%	15 -18%
	Clay	N/A	~ 50%	70%	30%
	Cement	~ 30%	~ 5%	0 - 3%	30%
	Slate	10%	0%	25%	35%
Decontamination waste generated		Negligible		Small (waste cloths)	Small (stripping agent)
Secondary contamination		Spray contaminates surrounding surfaces	Almost no secondary contamination occurs as water is collected	N/A	
Area decontaminated (per person day)		> 20 m^2	20 m^2	< 20 m^2	10 m^2
Application conditions		Topsoil stripping will be required in the surrounding area. Water may potentially infiltrate through gaps between roof tiles.	Collection and treatment of wash water	Wash water treatment	Requires 24 hours after application before removal can begin.
Direct implementation cost JPY/m^2 (area > 1000 m^2)		1,230	1,090	1,100	N/A
Overall evaluation		Moderately effective: Application speed is high, but secondary contamination occurs that requires treatment.	Effective		Moderately effective: Area decontaminated is not large and takes time.

Table 2.8. Comparison of Technology for Cleaning Concrete for Roofs, Floors and Walls (recreated from JAEA, 2015a)

Decontamination Method	Dust Collection Sander (Concrete)	Ultra-High-Pressure Water Jet (150-240 MPa)	High-Pressure Water Jet (10-50 MPa)	Shot Blasting
Count rate reduction	60 – 80%	~ 80%	20 – 70%	~ 90%
	(Depends on number of applications)	(Depends on pressure)		(Depends on shot density)
Decontamination waste generated (L/m^2)	Concrete debris ~ 1	Concrete debris ~ 3	Sludge 0.02 - 0.04	Concrete debris ~ 3
Secondary contamination	None. Blast material collected via suction.	As almost all wash water is collected, virtually no secondary contamination occurs.		Dust is collected via suction but some fine material may be lost.
Area decontaminated (m^2 / person day)	10	80	50	170
Application condition	Inefficient for use on large areas. Surface must be dry.	Not applicable for areas such as corners where access is limited. Can't use for vertical surfaces.	Should be applied carefully to prevent scattering	No corners or narrow sections. Difficult to apply to vertical surfaces. Surface must be dry.
Direct implementation cost JPY/m^2 (area > 1,000 m^2)	1,940	1,150	960	480
Overall evaluation	Effective	Effective	Effective	Effective

MPa: megaPascals

Inside residential buildings, accumulated dose is largely from contamination deposited on surfaces outside the house, including the ground next to the house and the roof. The walls do provide some shielding to external sources (IAEA, 2015b). Dust inside the residence typically contributed a small fraction of the dose (IAEA, 2015b), largely associated with entrained and resuspended soil from outside and resuspended dust from nearby trees and vegetation. The dust inside the residence can be kept to a minimum by regular cleaning. Once inside, contamination was enriched in small particles (< 53 microns), but was also associated to a lesser extent with fibrous materials and soluble fractions of dust (U.S. EPA, 2015). Regular cleaning can reduce indoor contamination, but in Japan it is common for homeowners to open windows to promote air flow, particularly in homes without air conditioning. Such actions are likely to cause additional migration of contamination into the house from surrounding areas such as soil and vegetation.

Table 2.9 details demonstrated technical performance, cost and waste generation for a variety of residential decontamination techniques used in Japan (JAEA, 2015a).

Table 2.9. Technical Performance and Waste Generation for Example Residential Decontamination Techniques (JAEA, 2015a)

Surface	Technique	Area Decontaminated (m^2, 1 person day)	Waste Type and Volume	Collection Type and Rate	Decon Factor; Gamma Dose Rate Reduction	Direct Implementation Cost (Yen/m^2; \$/ft^2)[a] for Areas > 1000 m^2
Roof (clay tile, iron)	Surface brushing and washing	20	Sludge and solids; Depends on purification process; ~ 6 mL sludge, 60 g solids per liter of water treated	Buckets and tanks; 100%	2; 50% (clay)/ 1.1 – 1.5; 10 – 30 % (iron)	1,090; 0.80
Gutters	Removal of debris and wiping	25 (linear meters)	Litter, soil; Depends on age of house and when gutters last cleaned; ~ 1 m^3 / house	Bucket; 100%	1.4 – 10; 30 – 90%	1,100; 0.81
Gutters	Debris removal followed by high-pressure water	20 (linear meters)	Litter, sludge; Depends on age of house and when gutters last cleaned; ~ 1 m^3 / house	Vacuum; 100%	~2.5; ~60%	1,230; 0.91
Walls	Dry brushing	130	N/A	N/A	1.3 – 1.4; 20 – 30%	100; 0.07
Concrete Walls	High pressure wash	50	Sludge; depends on location, water collection and treatment methods	Vacuum; 100%	1.3 – 3.3; 20 – 70%	960;0.71
Garden	Soil removal (manual and mechanical)	70	Vegetation, soil; 20 – 40 L/m^2, stripping @ 2-3 cm depth	N/A	1.1 – 10; 10 – 90%	590; 0.44
Garden	Gravel bed stripping (manual and mini-mechanical digger)	30	Gravel, soil; 20 – 40 L/m^2, stripping @ 2-3 cm depth	N/A	1.3 – 6.7; 20 – 85%	820; 0.61
Garden	Pebble washing with high pressure water	20	Sludge, water; depends on location, water collection and treatment methods	Tanks; 90%	2.5 – 20; 60 – 95%	930; 0.69
Garden	Mowing and turf stripping	15	Turf; 20 – 50 L/m^2, stripping @ 2-5 cm depth	N/A	~5; ~80%	1,500; 1.11
Garden	Tree pruning and removal of root soil	30	Vegetation, soil; ~ 30 L/m^2	N/A	1 – 1.3; 0 – 20%	740; 0.55
Paved areas	High pressure wash	15	Sludge; 0.2 L/m^2	Vacuum suction; ~100%	1.4 – 5.0; 30 – 80%	1,320; 0.97
Flat concrete	Dust collection abrasion sander	10 (small areas only)	Dust, 1L/m^2	Separate vacuum	2.5 – 5; 60 – 80%	1,940; 1.43

[a] Internal Revenue Service's 2015 Average Exchange Rates for Converting Foreign Currencies into U.S. Dollars (125.911 Yen per Dollar) was used for conversion.

2.2.4 Roads and Vehicles

Decontamination of vehicles has not been evaluated and presents a significant gap, particularly considering the number of vehicles left in the evacuated zone, and the vehicles that travel through contaminated areas such as the Jõban Expressway in Japan. As discussed in Section 2.1.2 with respect to the JAEA radiation detection vehicle, traditional car washing techniques did not remove all exterior contamination. This failure to remove all exterior contamination was also demonstrated at a 2015 joint EPA/DHS demonstration event hosted at Battelle in Columbus, Ohio. Low-tech washing methods such as garden hose or pressure washer failed to remove all surrogate contamination from a vehicle (U.S. EPA, 2016). Addition of decontamination foams such as Environment Canada's UDF foam additive may aid removal of contamination. Furthermore, the interior of vehicles may contain contamination, as will key components of the air intake, so both engine and cabin air filters should be replaced frequently to remove contamination remaining in the air intake and any additional contamination deposited from the environment while driving.

Cs-134 and Cs-137 activity in the Fukushima area (and the corresponding dose rates) were relatively low on roads and paved areas (e.g., parking lots) as a result of natural self-cleaning processes (rain, falling on roads divided contamination between porous road surfaces and runoff into drainage channels) which are also dependent on the time since deposition, weathering and traffic volume since deposition.

In addition to road surfaces, other road infrastructure such as roadside gutters and drains must also be decontaminated. Typically in Japan, runoff from cleaning roads and houses was diverted to roadside gutters and drains, where it was ultimately trapped and removed. Given the large surface areas associated with roadways, collection and removal of contaminated runoff (both during natural precipitation events and decontamination efforts) must be considered. Vacuum removal of debris in gutters and drains can be performed using a vacuum tanker or by mechanical digger, depending on the gutter size. JAEA (2015a) conclude that 28 meters of gutter or drain can be treated per person day, resulting in approximately 100 to 200 liters per m^2 (L/m^2) of sludge and vegetation, a decontamination factor of 1 to 10 and a gamma dose rate reduction of between 30 and 90%, at a cost of 1080 Japanese Yen per square meter (0.80 $ per ft^2).

Figures 2-12 and 2-13 show the decontamination flow diagrams for paved and unpaved roads, respectively (MOE, 2013b). An initial decision was made to decontaminate only roads near residential areas to reduce dose contributions to people living in the surrounding residential areas.

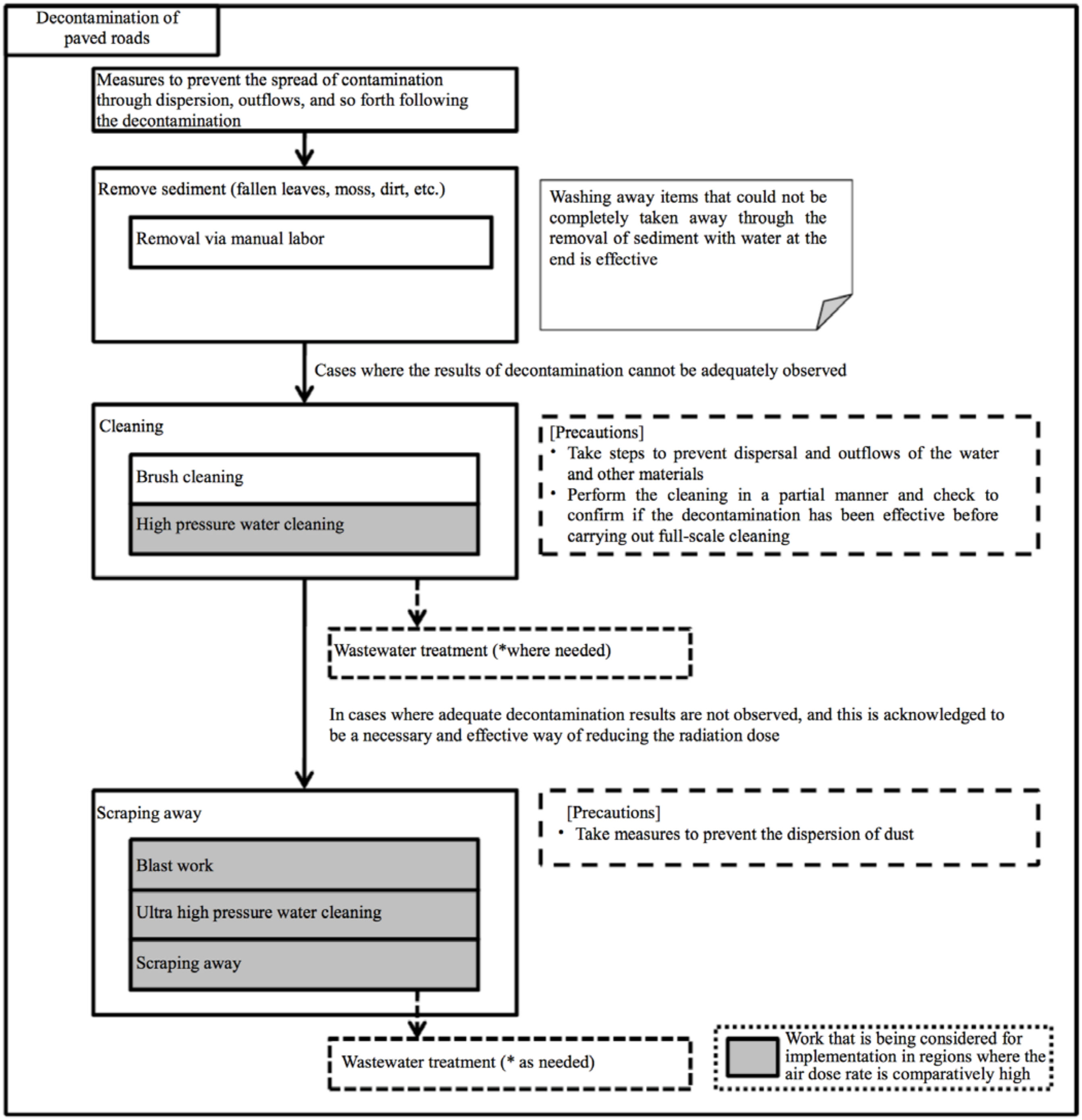

Figure 2-12. Flow Diagram for Decontamination of Paved Roads (MOE, 2013b)

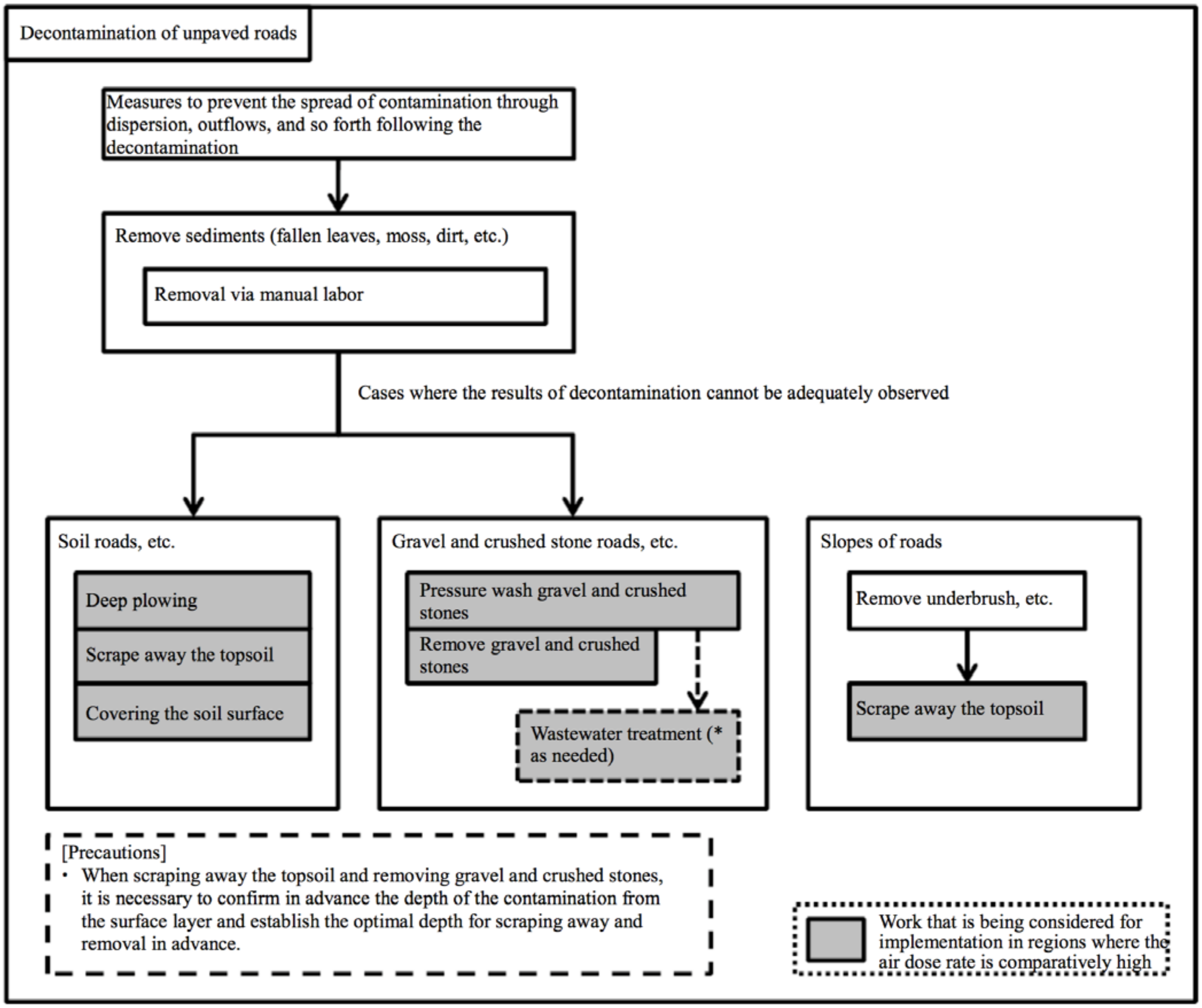

Figure 2-13. Flow Diagram for Decontamination of Unpaved Roads (MOE, 2013b)

Depth profile studies of contaminant migration into porous road surfaces indicated that much of the radio-cesium was concentrated within the top 2 mm, possibly up to 4 mm for some porous asphalt roads. Penetrations were much greater on damaged roads. Where low levels of contamination existed close to the road surface, manual or vehicle-based high-pressure washing was used, in some cases followed by mechanical decontamination with rotating brushes. Runoff water from decontamination efforts was collected and pumped into vehicular-based tanks requiring additional treatment. For road surfaces that exhibited higher levels of contamination and deeper penetration, destructive erosion technologies such as shot-blasting, surface planing/shaving and asphalt removal were employed. Since asphalt and concrete surfaces respond differently to the different techniques, tests were evaluated by JAEA and data are summarized in Table 2.10 (recreated from information in JAEA, 2015a).

Table 2.10. Comparison of Technologies for Cleaning Asphalt Roads (recreated from JAEA, 2015a)

Decontamination Method	Water-Jet Vehicle[A]	High-Pressure Water Jet[A] (10–20 MPa)	Ultra-High Pressure Water [A] (240 MPa)	Shot Blasting[B]	Surface Stripping[C]
Secondary contamination	As almost all wash water is collected, virtually no secondary contamination occurs.			Dust is collected via suction but some fine material may be lost.	
Application conditions	Best for smooth surfaces that are not distorted or damaged.	Best for smooth surfaces that are not distorted or damaged. Roadside drain lids can also be washed		Best for smooth surfaces that are not distorted or damaged. Dry surface	
Area decontaminated (m^2 per person day)	1,000	50	80	170	145
Direct implementation cost (JPY/m^2) for area > 1,000 m^2	150	960	1,150	480	390
Overall evaluation	Count rate reduction depends on the pressure. Effectiveness largely depends on road surface conditions and depth of Cs penetration.	Effectiveness largely depends on road surface conditions and depth of Cs penetration.	Count rate reduction depends on the pressure. Highly effective but causes damage and therefore should only be used on highly contaminated roads.	Count rate reduction depends on the blasting density. Highly effective but causes damage and therefore should be used only on highly contaminated roads.	Highly effective but causes damage and therefore should be used only on highly contaminated roads.

[A]These vehicles were equipped with water collection devices to minimize secondary contamination.
MPa = megaPascals.

[B]These vehicles had a collection system for blast materials and therefore secondary contamination was minimal. The little secondary contamination that was produced was manually collected after blasting was completed.

[C]Secondary contamination was minimal as above.

[D] The uneven condition and/or cracks in roads may reduce decontamination effectiveness.

Figure 2-14 shows example techniques demonstrated in Japan for decontamination of roads (JAEA, 2015a), including: (A) street sweeping, (B) ride-on sweeping, (C) water-jet vehicle, (D) manual high-pressure water washing, (E) hydro-blast ultra-high pressure water washing, (F) dry-ice blasting, (G) sand-blasting, (H) medium-scale shot-blasting, (I) large-scale shot-blasting, (J) asphalt planing/shaving, (K) mechanical digger asphalt removal, and (L) topsoil removal from unpaved road or soft-shoulder. Corresponding data for each technology are presented in Table 2.11.

Figure 2-14. Example Road Decontamination Techniques (recreated from JAEA, 2015a)

Table 2.11. Technical Performance and Waste Generation for Example Road Decontamination Techniques (JAEA, 2015a)

Figure 2-12 Panel	Technique	Area Decontaminated (m^2, one person day)	Waste Volume Generated (L/m^2)	Waste Type	Collection Type and Rate	Decon Factor; Gamma Dose Rate Reduction	Direct Implementation Cost (Yen/m^2; $\$/ft^2$)[a] for Areas > 1000 m^2
A	Street sweeping	3,500	1 – 1.5	Soil, road dust, vegetation	N/A	1 – 2; 0 – 45%	10; 0.01
B	Ride-on sweeping	1,750					20; 0.01
C	Water-jet vehicle	1,000	30 – 40	Sludge	Vehicle 50 – 70%	1 – 3; 0 – 70%	150; 0.11
D	Manual high-pressure water washing	50			Vacuum 100%	1 – 3; 0 – 65%	960; 0.71
E	Hydro-blast ultra-high pressure water washing	80	3	Road dust, water	Vacuum absorption 100%	2 – 15; 40 – 95	1,150; 0.85
F	Dry-ice blasting	70	2	Road dust	N/A	2.5 – 10; 60 – 90%	1,310; 0.97
G	Sand-blasting	5	20	Road dust, sand			4,190; 3.09
H	Medium-scale shot-blasting (iron balls)	170 – 270	3	Concrete, asphalt dust, iron shot		~10; ~90%	570; 0.12
I	Large-scale shot-blasting (iron balls)	170		Road dust, iron balls		3 – 23; 60 – 95%	480; 0.35
J	Asphalt planing/shaving	150	8 (@5 mm thickness)	Asphalt		22; 95	390; 0.29
K	Mechanical digger asphalt removal	26	150			3 – 10; 70 – 90%	1,620; 1.20
L	Top-soil removal from unpaved road or soft-shoulder	90	20 – 50	Gravel, soil		1 – 13; 30 – 95%	560; 0.41

[a] Internal Revenue Service's 2015 Average Exchange Rates for Converting Foreign Currencies into U.S. Dollars (125.911 Yen per Dollar) was used for conversion.

A major freeway in Japan is the Jõban Expressway, connecting the two major cities of Tokyo and Mito, and including the Prefectures of Ibaraki, Iwaki and Fukushima. The expressway passes through areas of elevated dose rates and comes within four miles of the Fukushima Dai-ichi NPP. An example of high-pressure water washing of the Jõban Expressway using a spin-jet is shown in Figure 2-15.

Figure 2-15. Spin-Jet Decontamination of the Jõban Expressway (recreated from MOE)[10]

High-pressure water cleaning technologies have been tested and proven to be one of the most highly effective techniques for large area decontamination. The higher the pressure, the higher the decontamination factors obtained. However, one major drawback of high-pressure washing is that it generates large volumes of waste water. The demonstration projects proposed by several companies (Fukushima Komatsu Forklift Co. Ltd.; Muramoto Corporation; Todenkogyo Co. Ltd. [MOE, 2012] and Shimizu Corporation [MOE, 2013a]) provide an on-site waste water treatment technology to their ultrahigh- and high- pressure mobile units to re-use/recycle water, thereby reducing the volume of generated waste water during decontamination. Some of the vendors also integrate other technologies such as a remote handled robot that can perform high-risk operations (Muramoto Corporation) or a 3-dimensional (3-D) decontamination function feature applicable to either horizontal or vertical surfaces.

There have also been some efforts to reduce the volume of solid wastes generated from decontamination of roads and sediments in water areas (MOE, 2013a). The technologies demonstrate removal of only a minimum layer of the surface to minimize waste volumes while achieving a desirable decontamination factor (DF). For example, NIPPO Corporation (MOE, 2013a) has developed a special bit for thin-layer (5 mm) cutting on road surfaces, demonstrating a high DF, minimizing waste volumes and preserving surface properties that enable road restoration without repaving. A remote-controlled scraping machine for high-slope soil decontamination was demonstrated by Fukasawa Co. Ltd. (MOE, 2013a) to reduce radiation exposure to workers and for use in high radiation areas. Additionally, Taisei Corporation (MOE, 2013a) decontaminated the sediment surface in water areas by either thin-layer dredging or thin-layer capping the surface.

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[10] http://josen.env.go.jp/en/work_report/20130301.html, accessed June, 2016

2.2.5 Playgrounds, Schools and Swimming Pools

Special attention and high priority has been assigned to the decontamination of playgrounds and swimming pools due to the concerns of potential dose exposure to children. Depending on the type of playground surfaces, contaminant penetration ranged from depths of 5 to 12 centimeters (cm), with the majority in the upper 5 cm layer. For soil or grass playgrounds, the decontamination methods used were the same as those used for agricultural land. Example images from decontamination of schoolyards using soil grading (top left), artificial turf infill material (top right), and play-structures (bottom) are shown in Figure 2-16 (MOE, 2013b). For swimming pools, the contamination present in the water was collected on absorbents placed in the pool, which then settled on the bottom of the pool and were removed by a combination of vacuum, sweeping and shoveling before being sent to temporary storage facilities. The pool surfaces then were brushed and washed by high-pressure water jets. Additional JAEA guidance on cleaning contaminated swimming pools can be found in JAEA (2011b). Technical data on performance and waste generation for such decontamination methods are summarized in Table 2.12 (JAEA, 2015a).

Figure 2-16. Example Decontamination of Outdoor School Areas and Playgrounds (recreated from MOE, 2013b)

Table 2.12. Technical Performance and Waste Generation for Examples of Park, School Field and Swimming Pool Decontamination Techniques (JAEA, 2015a)

Surface	Technique	Area Decontaminated (m^2, per day)	Waste Volume Generated (l/m^2)	Waste Type	Collection Type and Rate	Decon Factor; Gamma Dose Rate Reduction	Direct Implementation Cost (Yen/m^2; \$/ft^2) for Areas > 1000 m^2
Artificial Turf	Vacuum filling material	2600 (nine men, two machines)	10 – 20 @ 5 mm thickness	Artificial turf infill	N/A	2.5 – 2.9 60 – 65%	150; 0.11
Turf	Thin-layer topsoil stripping (hammer knife mower and sweeper)	65	20 @ 2 cm depth	Soil	N/A	~10 ~90%	710; 0.52
Turf	Thin-layer topsoil stripping (vibrating rollers, road stripping vehicle and collection)	175	20 – 50 @ 2-5 cm depth	Soil	N/A	5 – 10 80 – 90%	360; 0.27
Turf	Thin-layer topsoil stripping (vibrating rollers, motor-grader and collection)	160	20 – 50 @ 2-5 cm depth	Soil, grass	N/A	10 ~90%	290; 0.21
Turf	Topsoil-subsoil substitution (mechanical digger, stripping subsoil, backfill topsoil, backfill subsoil)	150	None Excavate top 10cm, strip to 20 cm, backfill with first 10 cm, then with 20 cm	N/A	N/A	5 – 6.7 80 – 85%	230; 0.17
Turf	Turf stripping (large turf stripping machine)	180	20 – 50 @ 2-5 cm depth	N/A	N/A	1.8 ~45%	470; 0.35
Swimming Pool	Water removal, sludge removal, high pressure water washing, brushing	45	1	Sludge and water	Vacuum suction 100%	2.5 – 10.0 60 – 90%	800,000; 590.28

[a] Internal Revenue Service's 2015 Average Exchange Rates for Converting Foreign Currencies into U.S. Dollars (125.911 Yen per Dollar) was used for conversion.

2.3 Waste Treatment

Significant volumes of waste continue to be generated during the wide-area remediation efforts following the Fukushima Dai-ichi NPP release. Currently in the Fukushima Prefecture, waste is separated based on originating location, generation method, waste type and specific activity. The location in which the waste was generated is divided between that generated in the SDA and ICSA. The generating method is divided between remediation activities, demolition of houses damaged during the earthquake, and waste generated during cleaning of houses in the evacuated zone. The waste type is distinguished to best disposition without incompatibility and with volume reduction in mind, specifically combustible, non-combustible and soil. The specific activity is characterized between less than 8 kBq/kg, less than 100 kBq/kg and above 100 kBq/kg. The term “specified waste” is used to classify waste from within the SDA consisting of debris from the tsunami, disaster-hit house demolition, and house cleaning in long-term evacuation areas above 8 kBq/kg. Soil and waste from decontamination work is termed “decontamination waste”. The process for determining the disposition of waste generated in the Fukushima Prefecture is shown in Figure 2-17 (IAEA, 2015b). Similarly, the flow chart for the disposition of wastes generated in other Prefectures and the SDA is shown in Figures 2-18 and 2-19, respectively (IAEA, 2015b).

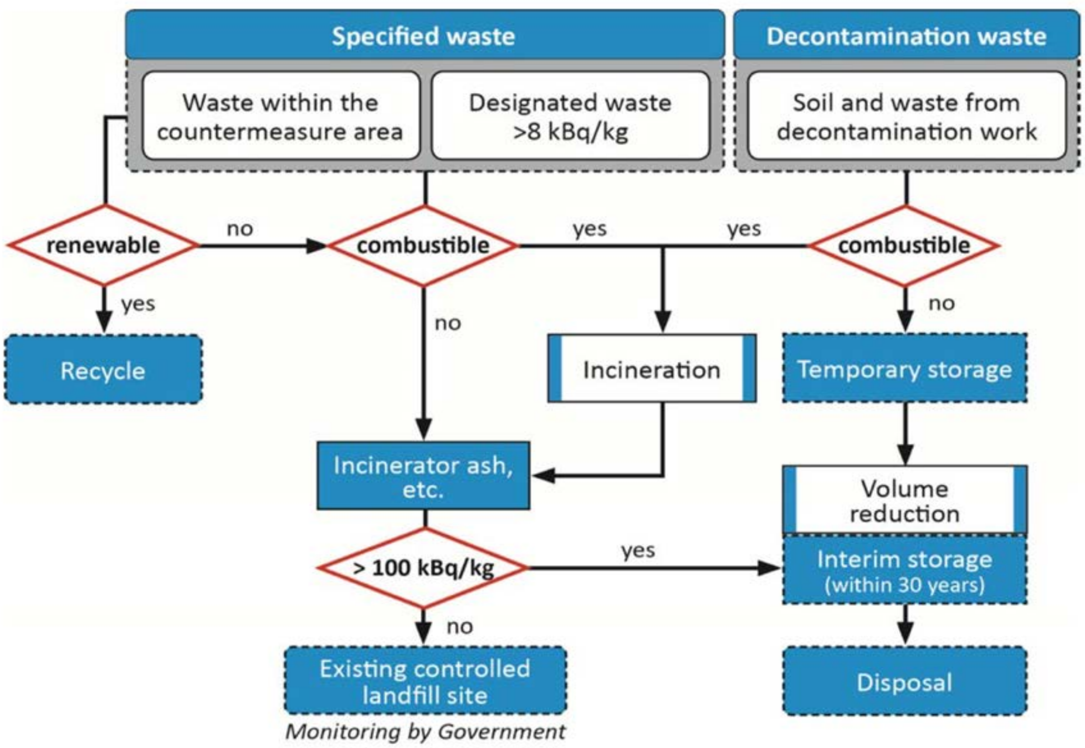

Figure 2-17. Process of Waste Segregation and Treatment in the Fukushima Prefecture (IAEA, 2015b)

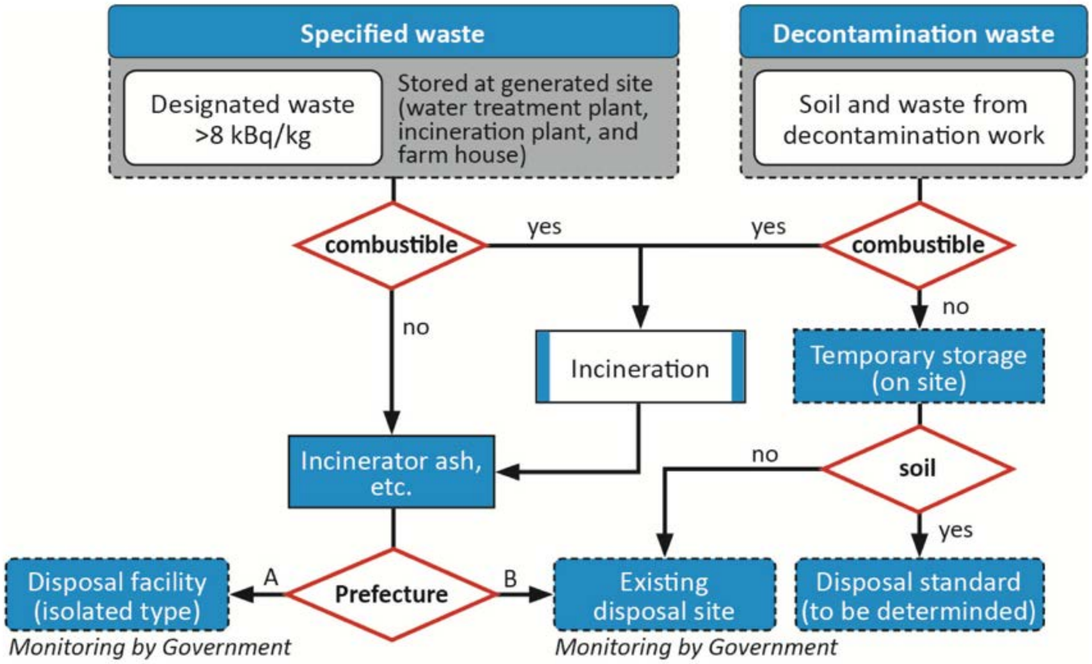

Figure 2-18. Process of Waste Segregation and Treatment in the Other Prefectures (IAEA, 2015b)

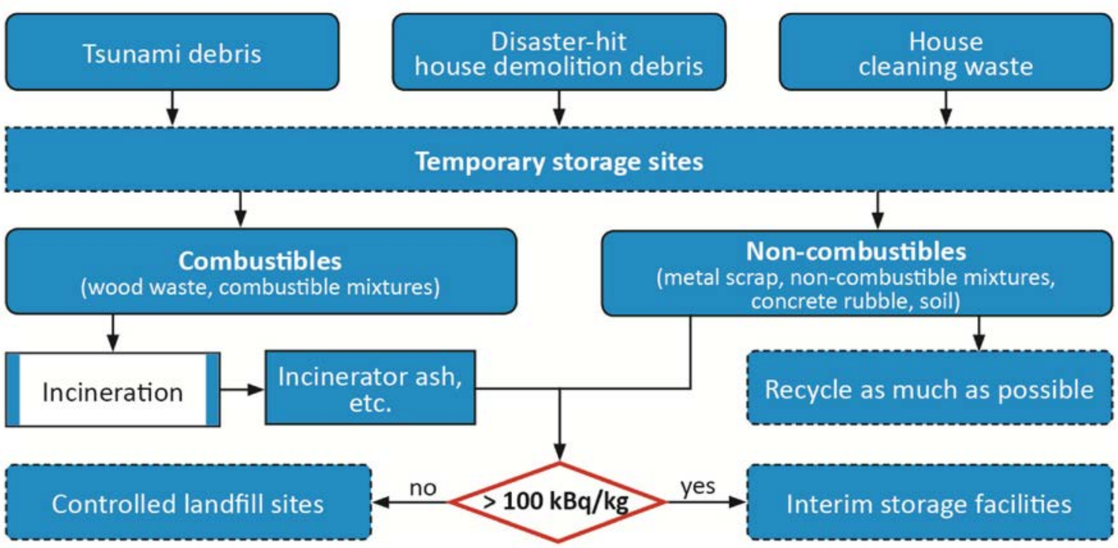

Figure 2-19. Process of Waste Segregation and Treatment in the SDA (IAEA, 2015b)

In the Fukushima Prefecture, waste is initially stored at the point of generation and is then moved to a local temporary storage site. The intent is to construct three interim storage locations, capable of storing the waste from each temporary site for up to 30 years and providing waste minimization capabilities and allowing Cs-137 to decay by one half-life before a final disposal site is constructed.

By December 2014, a total of 157,416 tons of designated waste > 8 kBq/kg had been generated (IAEA, 2015b).

Liquid waste generated from the decontamination of surfaces is treated using selective ion exchange as well as sorption on zeolites (IAEA, 2015b). While removing cesium contamination, the process creates additional solid waste requiring subsequent disposal.

By far the largest fraction of waste from outside the Fukushima Dai-ichi NPP fence is soil and vegetation removed from contaminated land. Vegetation is trimmed and the top six inches of soil is removed using excavators and transported to staging and containment areas using trucks (Figure 2-20).

Figure 2-20. Excavation of Topsoil and Vegetation

Figure 2-21 shows soil and vegetation being placed in impermeable bags (A), sealed and labeled (B) and subsequently stored in a temporary satellite location on top of an impermeable layer and surrounded by a channel to prevent interaction with the groundwater (C). The spray-painted label on the waste bag in panel B identifies the contents as “shielding”, i.e., lower activity waste placed on the outside of the pile to shield higher activity waste stored deeper in the pile.

Figure 2-21. Contaminated Soil and Vegetation Waste Containment

Figure 2-22 shows one example of the more than 700 satellite storage locations, with over one thousand waste bags stored on each side of the road (circled in red). Eventually, waste stored at the satellite storage locations will be sent to a waste treatment and minimization facility located in or near a future interim disposal facility, with a capacity of 15 to 28 million m^3 and occupying an estimated area of 3 to 5 km^2.

Figure 2-22. A Panoramic View of an Example Satellite Waste Storage Location in Iitate

The volume of waste generated from decontamination depends on several factors, including:

- Material type
- Volume reduction processes
- Decision to decontaminate versus dispose
- Material being decontaminated
- Decontamination method used
- Efficacy of decontamination and the number of cycles

The volume of waste and the contaminant leachability greatly impact the selection (type and location) of both the interim storage facility and the disposal site. The volumes of contaminated waste generated and subsequent waste management during the DPP were important consideration factors in the decontamination technology selection processes, specifically regarding efforts to optimize the overall remediation efficiency. For example, the high-pressure water jet technology used in the DPP generated large volumes of wastewater and subsequently presented a challenge for waste treatment techniques. Therefore, use of "dry" decontamination technologies such as dry-stripping of paint combined with High-Efficiency Particulate Arrestance (HEPA) filtration, shot blasting, dry ice blasting, or otherwise minimizing use of fluids by increasing efficiency (e.g., high-pressure jet with recirculating water, or the use of surfactants, microbubbles and ozonation) was preferred. For solid wastes, volume reduction is implemented wherever practical. The reduction in vegetation and soil waste generated from decontamination efforts continues to be a focus of techniques and technologies evaluated by MOE and JAEA, particularly where incineration, thermal decomposition and heat drying are primary technologies. Table 2.13 lists technologies used for treatments of various types of wastes. A number of soil decontamination treatments were tested on the laboratory scale, including:

- High temperature (1,300 °C) Cs extraction;
- Washing to remove fine clay particles;
- Milling and washing to remove fines, with or without additional heat treatment at 700 °C;
- Cavitation jet and microbubble separation processes; organic acid extraction; and
- Separation based on activity levels.

However, these treatments are costly and have not yet been tested on an industrial scale (JAEA, 2015a).

Table 2.13. Technologies used for Waste Treatments

Type of Material		Typical Examples	Treatment Options	Treatment Results	Direct Implementation Cost[a]
Non-combustible decontamination wastes	Liquid waste	Swimming pool water, sludge from decontamination washing	Various combinations of filtration, ion-specific sorption, precipitation and coagulation of suspended material with radioactivity. Discharge the supernatants.	Before treatment: 290 – 33,100 Bq/kg; after treatment: below limit of detection (4 Bq/kg), DF> 100	6,000 JPY/m^3; 1.35 $/$ft^3$
	Organic (soil)	Topsoil, forest soil, mineral soil, agricultural soil and gutter sediment	Scanning technique to separate higher from lower radioactivity materials.	Dispose of higher radioactivity materials and return lower ones to the field.	--
	Inorganic (residential paving, etc.)	Stones and gravel	Load these wastes into large flexible bags, label and then transport to a temporary storage location.	--	--
	Inorganic (materials from surface stripping)	Blasting materials, peelable strippers			
	Inorganic (asphalt)	Road surface, pavements			
	Inorganic (secondary wastes)	Plastic sheets, filters (masks and water treatment filters)			
Combustible decontamination wastes	Organic (vegetation)	Grass (turf grass, moss, weeds, etc.). Timber, branches and leaves (bamboo, pruned branches, etc.)	Significant volume reduction by mechanical shredding / chipping. Further volume reduction via incineration.	Volume reduction rate by incineration ~ 95%	--
		Soil and sand mixed with roots	Rotary drier (Minamisoma), low-temperature incineration, 250 – 400 ºC	Volume reduction rates of ~ 70-90%	--
	Other flammable wastes generated as a result of decontamination work	Tyvek® packaging, waste cloth, etc.	Incineration	--	--

[a] Internal Revenue Service's 2015 Average Exchange Rates for Converting Foreign Currencies into U.S. Dollars (125.911 Yen per Dollar) was used for conversion.

A flow diagram for the treatment of waste waters resulting from decontamination of roofs, guttering and roads is shown in Figure 2-23. Since cesium binds to soil particulates and other materials, it is important to separate solids from the water itself before discharging. This propensity also serves as a method of separation.

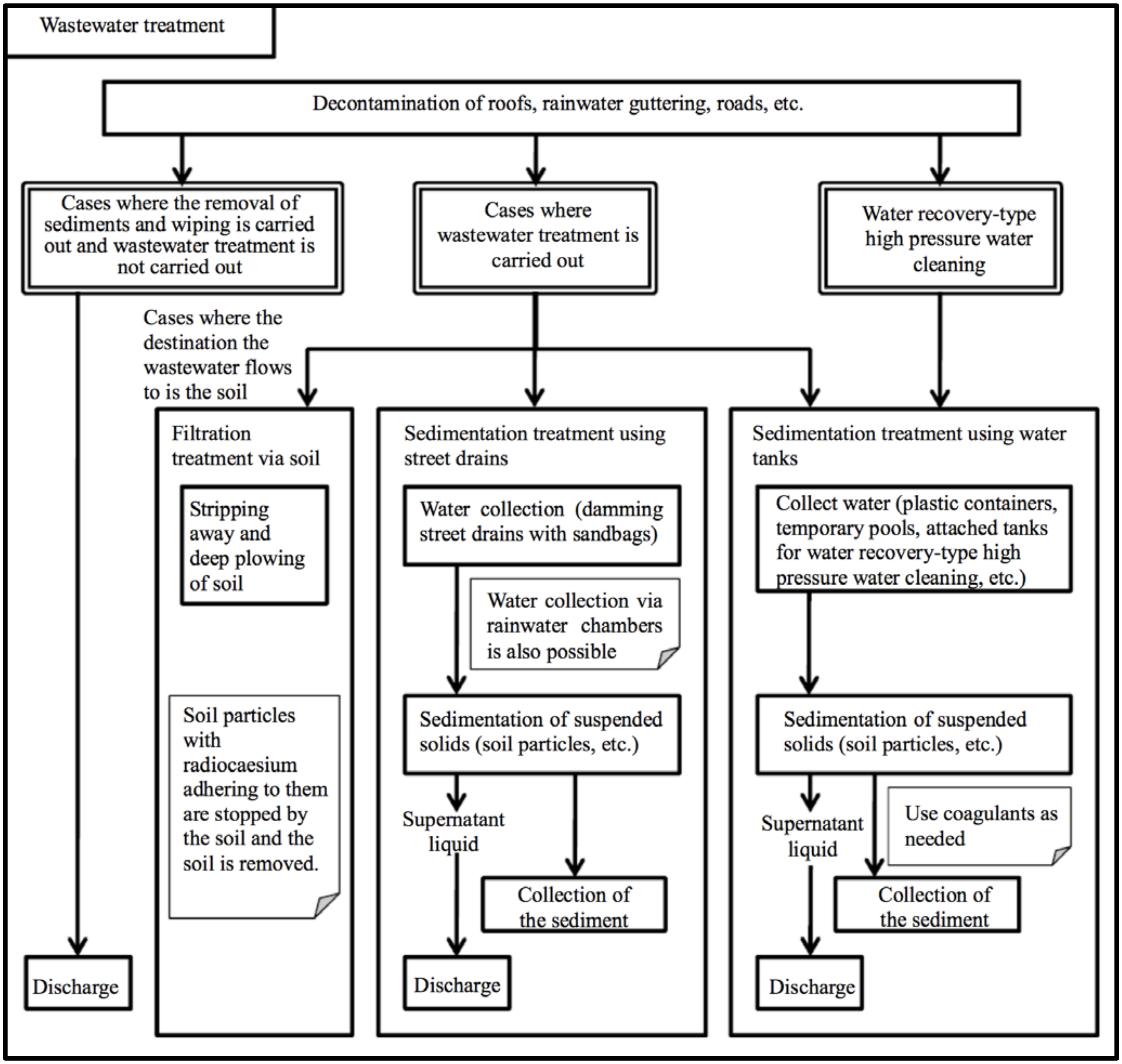

Figure 2-23. Flow Diagram for Wastewater Treatment (MOE, 2013b)

During the period from 2011 to 2014, the MOE decontamination technique demonstration program selected a total of 58 waste management techniques for verification prior to their field applications. The vast majority of techniques selected in this program involved waste using volume reduction and radioactivity stabilization in waste forms prior to transporting waste to storage facilities.

For organic wastes, an approximate volume reduction rate of 95% was achieved by incineration and thermal decomposition. The fly ash generated in the processes was decontaminated using water washing to remove soluble Cs-137. Some demonstration projects also used an integrated waste treatment and decontamination technology to produce ethanol as fuel for decontamination machines. In other projects, the decontaminated fermentation byproducts were retained to be used as fertilizer, also aiding the reduction of organic waste volume. Soil sorting methods have also been employed to reduce the volume of contaminated soils. Such methods included separation of fine particles from coarse uncontaminated soil, and separation of organic debris by washing (with water or chemicals) to remove water-soluble contamination. Table 2.14 summarizes the waste treatment technologies selected in the MOE demonstration program during 2011 to 2014 (MOE, 2012; 2013a; 2014a; 2014b).

Table 2.14. Summary of Waste Treatment Technologies Selected in MOE Demonstration Program (2011-2014)

Objects	Techniques	Features	Organization
Organics	Biomass power generation and production of ethanol	Pyrolytic gasification and carbonization, and utilization of the generated gases	Tekken Corporation
Organics		Production of ethanol (using grasses and woods)	Contig-I Inc.
Organics		Phytoremediation and production and gasification power generation of ethanol (using polysaccharide plants)	Japan Groundwork Association
Organics	Biomass power generation	Thermal decomposition (carbonization and gasification), and combustion of the charcoal	Konoike Construction Co. Ltd.
Organics	Volume reduction by carbonization	Carbonization (transportable type)	Yamaguchi Seisakusho Co. Ltd.
Organics		Superheated steam carbonization.	Shirakawaido Boring Inc.
Organics	Incineration	Mobile in-furnace air-cooling incinerator and volume reduction.	Shinseigiken Engineering Co. Ltd.
Organics	Volume reduction and removed soil and wastes	Demonstration of the Bio-coke technology for volume reduction and stabilization of contaminated organic matter, and verification of transport efficiency improvement, safety and economic efficiency by volume reduction	Chugai Ro Co., Ltd.
Organics	Shredding, suction and recovery	Laborsaving for greenery decontamination using shredding and suction.	Fukushima Komatsu Forklift Co., Ltd.
Organics	Drying and shredding	Drying, shredding and segmented gate for mixture of plant and soil.	Obayashi Corporation
Organics	Volume reduction	Incineration (low temperature incineration)	Tohoku University
Organics		Low-temperature pyrolysis and biofuel.	Toonokosan Corporation

Objects	Techniques	Features	Organization
Organics	Washing	Water washing and measurement of surface contamination density.	NEONITE Co. Ltd.
Organics	Cleaning	Grinding cleaning	Aizudoken Corporation
Organics		Water cleaning and compression molding	Toonokosan Corporation
Incineration ash		Leaching of Cesium from fly ash and adsorption of cesium with Prussian blue	Koriyama Chip Industry Co. Ltd.
Incineration ash	Washing	Saving wastewater load using high efficiency washing.	Fujita Corporation
Incineration ash	Washing and magnetic separation	Recovery of Cs using magnetic nanoparticle coated with absorbent after washing.	Taisei Corporation
Incineration ash	Solidification (Superfluid method)	Solidification and volume reduction of incineration ash using solidification agent and external vibration. Solidification (Superfluid method)	Hazama Corporation
Incineration ash	Solidification /non-leachability	Compound synthetic resin solidification.	E&E Techno Service Co. Ltd.
Incineration ash		Granulation, solidification and washing.	Obayashi Corporation
Incineration ash	Melting	Melted slag and volume reduction.	Kobe Steel Co. Ltd.
Soil	Segmented gate system	Automated wet segmented gate, scrubbing cleaning (wet system) and treatment of concentrated residues.	Shimizu Corporation
Soil		Mixed air jet pump, swirl segmented gate system (wet system)	Maezawa Industries, Inc.
Soil		Mixed air pump, Sieve-based segmented gate (wet type)	Radioactive Waste Management and Nuclear Facility Decommissioning Technique Center
Soil		Grinding and segmented gate (dry system) and surface grinding (dry system)	Fuji Furukawa Engineering & Construction Co. Ltd.
Soil	Fluoride salt	Cs elution using fluoride salt at normal temperature and pressures.	Swing Corporation
Soil	Vacuum pressure	Dewatering and solidification using cement and vacuum pressure.	Maeda Corporation
Soil	Volume reduction and removed soil and wastes	Demonstration of classifying and washing the contaminated soil by movable system on the truck, and the validation for reusing the cleansed soil	HITACHI KIKAI Co.
Soil sorting	Transportation, temporary storage and interim storage of removed materials	Demonstration test of the Contaminated Soil Sorting Unit for radioactive	AREVA NC Japan Projects Co., Ltd.

Objects	Techniques	Features	Organization
Bottom sediment	Segmented gate system	Segmented gate system for bottom sediments	Aomi Construction Co., Ltd.
Bottom sediment	Coagulation sedimentation	Coagulation sedimentation (Fast)	Mitsubishi Kakoki Kaisha Ltd.
Bottom sediment	Dredging/segmented gate	Dredging system and centrifuge segmented gate (wet system)	Toyo Construction Co. Ltd.
Sewage sludge	Incineration	Water glass solidification and ferric ferrocyanide	Tokyo Institute of Technology
Sludge	Volume reduction and removed soil and wastes	Demonstration test for reduction of radiological exposure using a cloth traveling filter press	ISHIGAKI Company, LTD
Waste treatment	Waste treatment	Multifunctional fill	Asahi-Kasei Geotechnologies Co. Ltd.
Water		Adsorption of Cs ion and filtration using functional carbide	GAIA Institute of Environmental Technology Inc.
Construction method	Transportation, temporary storage and interim storage of removed materials	Effective construction method for low permeability layer of radioactive storage facility by simply crushing in-situ excavated soil	Taisei Corporation
Transportation		Demonstration of mass transportation management system using Dedicated Short Range Communications (DSRC) to transport the removed soils in Fukushima prefecture	Hanshin Expressway Company Limited
Breaking of flexible container bags		Technology demonstration of non-contact, high efficiency and energy conserving Water-Jet-Cutter for breaking flexible container with low level radioactive materials in interim storage facility	SHIMIZU Corporation
Bag breaking and polluted water processing		Demonstration of the container-bag unloading and breaking system requiring no worker and cleanup technology for polluted water in container bags	Obayashi Corporation
Concrete debris	Utilization	Reducing dose rates of contaminated concrete debris by crushing and using as coarse aggregates for structural concrete	Toda Corporation
Concrete debris	Grinding/segmented gate	Moisture solidification & abrasion segmented gate (dry system)	Takasago Thermal Engineering Co. Ltd.

MOE has a plan to construct the interim storage facility (ISF) in Okuma and Futaba town in Fukushima Prefecture.[11] MOE is currently working to obtain land acquisition from individual land owners. MOE assesses approximately 22 million (M) m^3 of radioactive wastes to be transported, treated, and stored in the ISF. The radioactive wastes consist of 10 Mm^3 soil with radioactivity less than 8000 Bq/kg, 10 Mm^3 soil with 8000-100,000 Bq/kg, 10,000 m^3 soil with higher than 100,000 Bq/kg, 1.55 Mm^3 of incineration ash, and 20,000 m^3 of other wastes with higher than 100,000 Bq/kg from the temporary storage sites across Fukushima Prefecture. The ISF will consist of several facilities including waste separation, soil waste storage, volume reduction (incineration), and high level (more than 100,000 Bq/kg) waste storage. For safe and secure waste transportation, MOE conducted a pilot transportation project from March 2015 for a year. This project transported approximately 1000 m^3 of decontamination soil from municipal temporary storage sites to the future ISF site. The project used a total of 45,382 m^2 of stock yards in towns of Okuma and Futaba. The used tucks are a total of 7,529 and each truck was screened for radioactivity. All trucks passed the screening standard of 13,000 cpm. The pilot project results showed that transportation route, traffic peak hour, local traffic volume, and road repairs should be considered prior to the full scale transportation.

In the U.S. a software exists, developed for the Yucca Mountain Project for disposal of nuclear waste canisters from U.S. nuclear reactor fleet, to determine such factors as transportation route, populations affected, radiological consequences and risks to workers, by-standers and residents. RADTRAN was developed and maintained by Sandia National Laboratories (Weiner et al., 2014) and is being extended into DOE Nuclear Energy's Nuclear Storage and Transportation Planning Project. The software may be applicable to address logistical and risk calculations for the transport of decontamination waste from impacted towns and Prefectures to temporary, interim and final storage/disposal locations in Japan.

3. Conclusions and Recommendations

A significant lesson learned from nuclear (as well as chemical and biological) incidents is that prior preparation, testing of technologies and development of guidance aids recovery. Having a toolbox of technologies to deploy and criteria to make decisions on appropriate technologies for surfaces and areas provide decision-makers with valuable insight when comparing the trade-offs of efficacy, speed, cost, risk to workers and waste generation. What is abundantly clear in Japan is the magnitude of the recovery effort, including the time and resources needed, the impact on residents and the volume of waste that is being generated from decontamination activities.

After reviewing technologies implemented since the Fukushima Dai-ichi nuclear power plant release in Japan in 2011, it is evident that *both* traditional, well-proven and newly developed techniques are available for surveying from the air and ground, decontamination of a wide variety of surfaces, and waste treatment and volume reduction.

Sensitivity and portability improvements in detection technology allow real-time mapping of contamination. These improvements are largely driven by DOE and DHS needs to detect radiological material, and application in Japan is providing additional improvements. Deployment on UAVs would

[11] http://josen.env.go.jp/en/pdf/progressseet_progress_on_cleanup_efforts.pdf last accessed June 2016

improve the capabilities for challenging environments that preclude the use of larger aircraft, vehicles or hand-held detectors.

Deployment of PSF on vehicles has been demonstrated by JAEA. However, the design should be improved so that the vehicle speed (which is currently 1 mph) can be increased to more practical speeds such as 10-30 mph. Additionally, deployment of PSF on vehicles capable of either marking, stabilizing or remediating contamination *in situ* would be a significant benefit.

Public outreach and real-time monitoring with displays accessible to the public are also key aspects of the response. In Japan, the Decontamination Plaza provides public education on radiation, risk and decontamination methods, making residents aware of what they can expect to experience. Similarly, urban air monitoring and freeway signs provide information on local conditions. Both education and real-time information can significantly improve public trust and cooperation. Deployment of “crowd-sourced” detectors such as KURAMA-II provide a network of real-time information. Such networks can be extended to include a variety of vehicles, from buses and taxis, to delivery and utility trucks.

Organizing decontamination techniques by area (e.g., forest, or residential) and subsequently by surface type provides the basis for a plan. Many decontamination methods were reviewed in preparing this report, which highlights key technologies fielded in Japan. Methods that utilize widely available technologies with ease of use allow rapid deployment with minimal training. In Japan, rather than relying on radiation workers to perform decontamination activities, the work is being performed by contractors who receive training in radiation protection, allowing wide-area remediation to begin quickly and continue over long periods. A range of techniques, from minimally destructive (such as pressure washing and vacuuming), partially destructive (e.g., concrete or asphalt shaving, shot-blasting), to completely destructive (e.g., excavation) provides to be effective in remediating contamination. Opportunities exist to improve such widely available technologies. Application of filtration systems to mowers, or applying fixatives prior to mowing or sod removal can reduce the potential for resuspension while remediating lawns and wild-grass areas. Similarly, applying efficient filters to street-sweeping and vacuum trucks will reduce re-aerosolization, as will application of water or agglomeration agents prior to collection.

Ultimately, one of the greatest factors in wide-area remediation is waste. Typically, the larger the waste volume is, the higher the cost. Determining responsibilities for waste generation, staging, minimization and disposition is equally important as determining limits and methods for treatment. In Japan, this was divided between Federal and Municipal Governments. Differences in U.S. branches of government (Federal, State and Local) as well as social and cultural differences between the U.S. and Japan may result in different processes and expectations.

Many waste treatment technologies continue to be developed and tested in Japan, from incineration of organic waste to segmented gate separation of soils. Technologies are also being developed for automated surveying, moving and opening storage/transportation bags, which is vital considering the volume of waste. Transportation logistics from one site to another, from the site of generation to the temporary storage location, to the interim storage location and to the ultimate internment location must be considered. This must include the route, the associated activity and the risk to residents near the route. Software exists, developed for the Yucca Mountain Project in the U.S., to determine such factors, and is being extended as part of DOE’s Office of Nuclear Energy Storage and Transportation Planning

Project. Such software (RADTRAN) should be considered to evaluate transportation routes for radiological waste from wide area remediation.

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