Estimate of the Potential Amount of Low-Level Waste from the Fukushima Prefecture - 12370

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ABSTRACT

The amount of waste generated by the cleanup of the Fukushima Prefecture (Fukushima-ken) following the releases from the Fukushima Daiichi nuclear power plant accident (March 2011) is dependent on many factors, including:

- Contamination amounts;
- Cleanup levels determined for the radioisotopes contaminating the area;
- Future land use expectations and human exposure scenarios;
- Groundwater contamination considerations;
- Costs and availability of storage areas, and eventually disposal areas for the waste; and
- Decontamination and volume reduction techniques and technologies used.

For the purposes of estimating these waste volumes, Fukushima-ken is segregated into zones of similar contamination level and expected future use. Techniques for selecting the appropriate cleanup methods for each area are shown in a decision tree format. This approach is broadly applied to the 20 km evacuation zone and the total amounts and types of waste are estimated; waste resulting from cleanup efforts outside of the evacuation zone is not considered. Some of the limits of future use and potential zones where residents must be excluded within the prefecture are also described. The size and design of the proposed intermediate storage facility is also discussed and the current situation, cleanup, waste handling, and waste storage issues in Japan are described.

INTRODUCTION

Much of the initial contamination following the accident was blown east of the plant towards the Pacific Ocean. Large amounts of contamination, however, were deposited in areas west/northwest of the plant after a radioactive plume discharge from Unit 2 and subsequent rainfall on the afternoon/evening of March 15 [1]. (Core damage to the Unit 2 fuel is believed to have started on the evening of March 14.) Radioactive Cs-134 and Cs-137 remain as the primary contaminants of concern for external exposures, both within and outside of the evacuation zone.

Cleanup methods and generated wastes will depend on criteria established for future doses to the public. The Japanese government has announced plans to use a range of reference levels to control exposures to the public. Measures will be taken to reduce doses below 20 mSv in areas where annual effective doses are estimated to exceed that value. In areas contaminated at a level where annual doses are currently expected to be 20 mSv or less, the government aims to reduce doses by half within two years, with a long-term goal to reduce annual doses below 1 mSv [2]. Additional measures will be taken to ensure that children do not receive annual exposures in excess of 1 mSv during the time they travel to or attend school [3].

A few estimates regarding the expected waste volumes have been published, and these vary both in scope and method. The International Atomic Energy Agency (IAEA) has estimated that the volume of contaminated material from clean-up of affected areas outside the 20 kilometer restricted area may range from 5 million to 29 million cubic meters. These estimates include soil and other organic material such as fallen leaves and branches [2]. Others have estimated that for 1,110 square kilometers within the no-entry and planned evacuation zones 100 million cubic meters of soil will need to be removed. This estimate assumes that 5 centimeters of topsoil will be uniformly excavated from the area—including uninhabited forested and mountainous regions [4]. In addition, 2.3 million tonnes of contaminated debris (wood, concrete, and metal) from the tsunami has already been collected and will need to be added to the total waste volume [2]. Ultimately, contaminated waste material will include soil, organic material, vehicles, building and road material, and liquids.

A realistic estimate of the level of cleanup needed for various areas will help identify appropriate remediation methods and define waste handling and storage needs. Over-conservatism by treating all contaminated materials identically and all as radioactive waste would put unnecessary burden on the Japanese government and infrastructure. A consistent method for more accurately estimating the amount of waste that will be generated during the cleanup is certainly needed.

METHODS

The IAEA has recommended that the Japanese government focus on remediating areas that would provide the most benefit in terms of reducing doses to the public. Expected land use and selected management options will determine the amount of waste generated using this approach.

Land Use and Estimated Exposures

GIS data on land use in Japan was imported from a database compiled by the Emergency Mapping Team within the Disaster Prevention Research Institute at Kyoto University [5]. Forested areas, farmland, and urban areas were roughly identified within the 20 km evacuation zone. Results of airborne monitoring efforts in May and July 2011 by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) showing air dose rates 1 meter above ground level [6] [7] were overlaid on the map of land use scenarios to provide a rough estimate of expected area dose rates for each land use scenario (see Figure 1). Table I summarizes contamination levels as a function of land use within the 20 km evacuation zone. The total land area within the evacuation zone is approximately 619 km^2.

For the purposes of this analysis, remediation of contaminated waterways is not considered. In addition, each land use area is assumed contaminated to the maximum extent of each dose range (for example, the entire 2.30 km^2 of forested area contaminated in the 0.9-1.8 mSv/year range is assumed contaminated to a level equivalent with an annual dose of 1.8 mSv/year). This will make the waste estimates somewhat conservative.

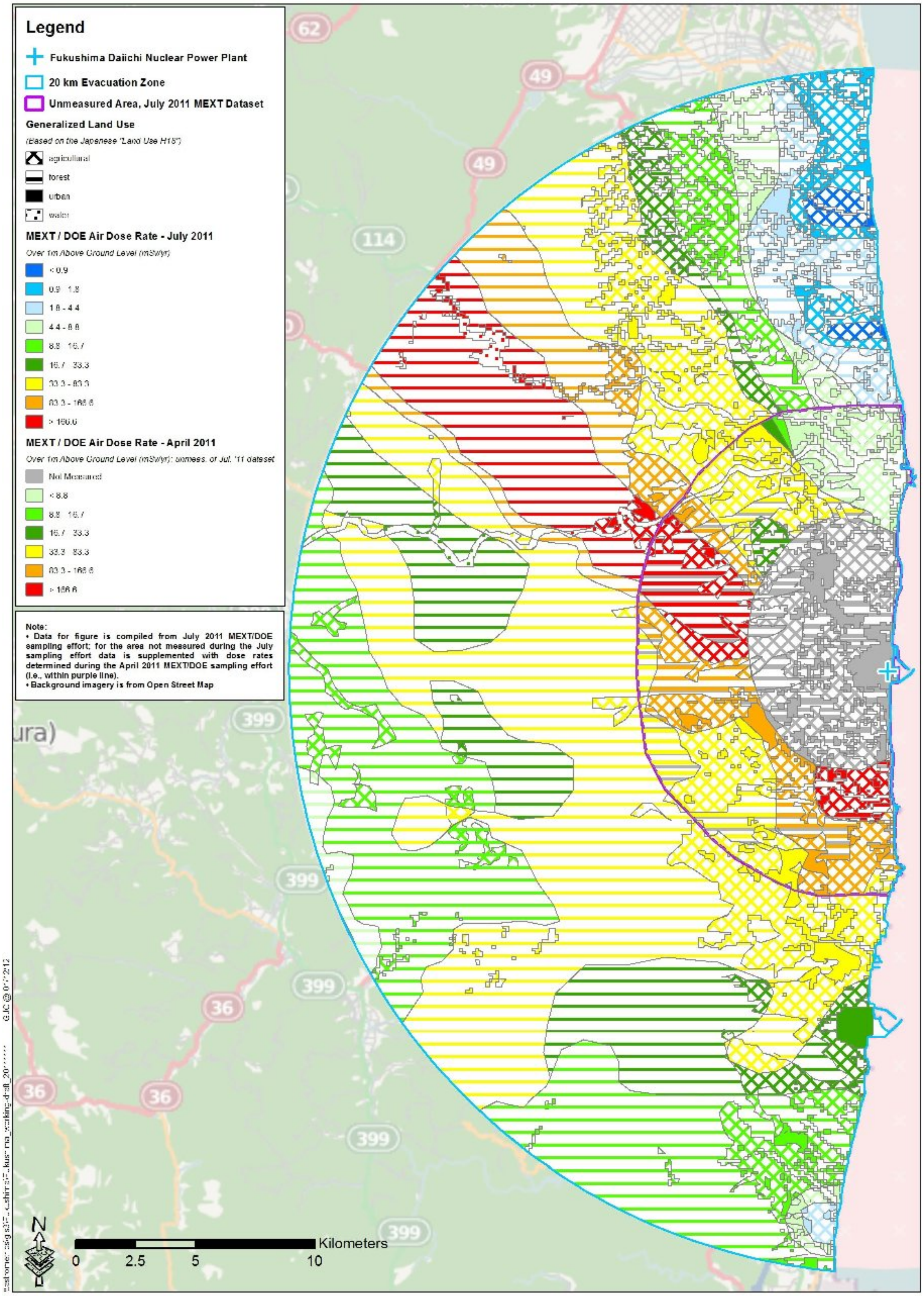

Fig. 1. Land use and aerial dose rates within the 20 km evacuation zone.

Table I. Land Use (km^2) and Expected Annual Dose within the 20 km Evacuation Zone

Expected Annual Dose (mSv)	Forest (km^2)	Urban (km^2)	Agricultural (km^2)	Water (km^2)
Unmeasured	10.44	7.94	14.97	0.39
< 0.9	0.06	0.31	2.91	0.33
0.9-1.8	2.30	2.58	8.58	0.94
1.8-4.4	7.84	3.18	8.93	0.33
4.4-8.8[a]	10.34	3.80	11.8	2.41
8.8-16.7	97.78	3.56	23.73	1.20
16.7-33.3	60.63	2.50	12.23	1.23
33.3-83.3	144.76	9.38	52.07	3.03
83.3-166.6	29.21	3.33	17.14	0.85
> 166.6	43.68	1.73	7.92	2.42
Total Area (km^2)	**407.04**	**38.31**	**160.28**	**13.13**

Remediation Options and Considerations

Excavation and disposal is likely the most effective means (in terms of both cost and decontamination factor) for removing cesium from topsoil. Radiocesium has a low transport coefficient and tends to accumulate within the first few centimeters of topsoil. Removing the first 4 cm of topsoil is assumed to be sufficient to reduce exposure dose rates by 75% [2]. Removing 15 cm of topsoil is assumed to reduce dose rates by as much as 90% [8]. Applying a solidifying agent prior to removing topsoil can slightly enhance the decontamination factor. These broad assumptions do not take into account variances in soil types and composition. Additional considerations for forested areas, farmland, and urban settings are briefly discussed below.

Forests

Remediation options for forested areas include collection of detritus (needles/leaves); peeling bark on existing trees and harvesting existing trees for lumber; and harvesting new growth as the vegetation takes up the cesium. Soil scraping and chemical treatments such as the application of potassium-containing fertilizers can be performed, but these methods should be carefully considered to ensure the benefits of the cleanup effort outweigh potential disruptions to the ecosystem. Alternative measures that are less drastic but effective methods to limit public exposures in forested areas include: managing access to the area, limiting the harvest of food products, restricting firewood collection, and preventing forest fires. Certainly, these methods should also be considered.

The effectiveness of various remediation options will also depend on the type of forest. For example, since many of the broadleaf trees (as opposed to coniferous trees) did not have leaves at the time of the accident, the majority of contamination falling on these types of forests accumulated on the ground and in the detritus [9]. Of Japan's forested area, approximately 53% is coniferous and 47% broadleaf [10].

Agricultural Areas

Remediation of farmland will likely entail removal of existing crops and soil. Additional methods such as application of potassium-containing fertilizers or replacement with clean soil could be

[a] This dataset includes areas measured as "less than 1.0 μSv/hr" (or 8.8 mSv/year) during the April MEXT/DOE sampling effort (reference [6]).

considered to reduce uptake by subsequent plantings and reduce the amount of future crops that must be disposed of as waste. The IAEA also briefly discusses a method by which a thin layer of topsoil in rice paddies is flooded and the suspended soil drained, separating sediments from water. The separated sediments are then disposed of as waste [2]. Because much of the soil in cultivated fields has been previously churned and loosened, the necessary excavation depths will be assumed "doubled" to achieve the same decontamination factors assumed for compacted soil.

Urban Areas

Cleanup in urban areas outside the 20 km evacuation zone has already started, with priority given first to kindergartens and schools, then to community centers and finally to individual residences [2]. A similar prioritization will likely be applied to cleanup efforts within the 20 km zone. Remediation actions that can apply to urban areas include:

- Clearing drains, gutters, and ditches;
- Removing some topsoil and vegetation (grass and shrubs) when necessary;
- Using high pressure hoses to wash surfaces (buildings and/or roads);
- Pruning weeds, trees, and gardens;
- Possibly resurfacing roads.

In highly contaminated areas (primarily the region northwest of the plant), buildings and residences may need to be demolished and roadway surfaces removed for disposal. Remediation options for parks and wooded areas located within urbanized areas will be similar to those for forests. The added potential for public access to parks and woodlands within the urban areas should be considered when evaluating remediation options.

Roads

The remediation of road surfaces within the evacuation zone should be planned to facilitate clean access ways and roads dedicated for waste transport and later remediation. For the purposes of this study, this distinction is not made and all roads are considered to be cleaned.

Decontamination Factors and Waste Estimates

Table II summarizes assumed decontamination factors (DFs) and estimated unit wastes for the remediation options previously discussed. It is assumed that external gamma and beta dose rates from the contaminated surfaces will be reduced by approximately the value of the decontamination factor [11]. These factors and unit wastes are derived primarily from the IAEA final report on remediation [2] and the *Generic Handbook for Assisting in the Management of Contaminated Inhabited Ares in Europe Following a Radiological Emergency* (EURANOS report) [11].

Table II. Assumed Decontamination Factors and Estimated Unit Waste

Remediation Method	DF	Unit Waste
Removal of 4 cm topsoil (general) [2]	4	0.04 m^3/m^2
Removal of 15 cm topsoil (general) [8]	10	0.15 m^3/m^2
Removal of 8 cm topsoil (farmland)	4	0.08 m^3/m^2
Removal of 30 cm topsoil (farmland)	10	0.30 m^3/m^2
Flood soil/separate sediments (farmland) [2]	1.2	1.2E-03 m^3/m^2

Deep ploughing[b] [11]	5	NA
Detritus collection [11]	50	0.5 kg/m^2
Cutting down existing trees [11]	50	10 kg/m^2
Plant/shrub/crop removal[b] [11]	2	2 kg/m^2
Demolition of structures [11]	(100% effective)	70 kg/m^2
High-pressure washing of structures[b] [11]	1.5	20 L/m^2
High-pressure washing of roads[b] [11]	3	20 L/m^2
Surface removal (road planing) and replacement [11]	5	15 kg/m^2 per cm removed

Contamination Deposition

The fraction of cesium deposition on crops, trees, detritus, buildings, and soil was considered for the various land use areas. The number of residential and industrial buildings within urban areas was also estimated for purposes of approximating potential waste volumes. These additional assumptions are summarized in Table III.

Table III. Contamination Deposition in Land Use Areas

Broadleaf forests:	
Deposition on trees	10%
Deposition on detritus	80%
Deposition on soil	10%
Coniferous forests:	
Deposition on trees	25%
Deposition on detritus	25%
Deposition on soil	50%
Agricultural areas:	
Deposition on crops	50%
Deposition on soil	50%
Urban areas:	
Deposition on soil/turf	36%
Deposition on building surfaces	54%
Deposition on forested parks	10%
Number residential buildings[c]	50,000
Avg. size residential buildings	130 m^2
Number office/industrial buildings[c]	25,000
Avg. size office/industrial buildings	566 m^2

Assumptions regarding decontamination factors and deposition were applied to each dose band for the different land use areas to estimate the resultant dose for various remediation options. These values were then used to select an optimized remediation plan in terms of reaching the established cleanup goals and minimizing waste volumes.

[b] For these remediation methods reference [11] assumes a range of DFs if the method is implemented shortly after deposition and before significant rainfall occurs. Given the elapsed time since deposition, the lower end of the DF range is assumed for these calculations.
[c] For waste generation estimates, roughly assumed the number of buildings within each dose band corresponds to the percentage of land area within that band.

RESULTS

Conservative Scenario

In a conservative scenario, waste volumes that would result from decontamination efforts required to meet the current proposed cleanup goals (i.e., remediation to at least 20 mSv/year with a long-term goal to reduce doses below 1 mSv/year) are estimated for the 20 km evacuation zone. All areas were assumed to be remediated within a short period.

Forests

Detritus collection will be paramount for decontamination of forested areas [9]. Simply collecting detritus from all forested areas may reduce estimated annual dose rates by more than 50 percent, and in most cases, below 20 mSv/year. To reach a long-term goal of 1 mSv/year in forested areas, however, will require removal of trees and 4-15 cm of topsoil in areas contaminated above 4.4 mSv/year (about 386 km^2 total). This conservative scenario would generate about:

- 198,300,000 kg detritus waste;
- 3,864,000,000 kg trees waste; and
- 46,066,800 m^3 contaminated soil waste.

Following the forest decontamination and assuming a person spent 100% of his time in this zone, the dose rates under this scenario would range from 2.33-4.66 mSv/year in areas currently contaminated above 83.3 mSv/year. Areas currently contaminated below 83.3 mSv/year would be remediated to below 1 mSv/year under this scenario.

Agricultural Areas

Given the importance of agricultural areas to the livelihood of residents surrounding the plant site, it is likely that the environment ministry will promote fairly extensive remediation to farmland. For all areas, removal of existing crops is a relatively easy and effective method for initially reducing dose rates to some extent. For areas contaminated in the range of 0.9-1.8 mSv/year, additionally removing 8 cm of soil will bring area dose rates below 1 mSv/year. Using only these two methods, however, agricultural areas contaminated above 1.8 mSv/year cannot be remediated to below 1 mSv/year in the near term. Removing 30 cm of soil provides the best additional dose benefit. This scenario would generate about:

- 290,620,000 kg crops waste (assuming crops were removed from all agricultural areas following the accident); and
- 40,832,400 m^3 contaminated soil waste.

Areas originally contaminated above 33.3 mSv/year (about 77 km^2 total) may still provide estimated annual area dose rates above 20 mSv and may need to be set-aside for some time before farming activities can resume. Adding potassium fertilizer to these areas or replacing the removed contaminated soil with clean soil, however, would further reduce cesium uptake by crops. These calculations do not consider additional remediation that may be necessary to achieve contaminant concentrations established as the acceptable threshold for crops (5,000 Bq/kg) by the Japanese government.

Urban Areas

Even though the so-called “urban areas” comprise a much lower fraction of the 20 km evacuation zone than either forested or agricultural areas, remediation of these areas will likely prove the most complicated. Pressure washing alone will likely provide enough cleanup in areas where annual doses are currently expected to be less than 0.9 mSv (although soil cleanup may need to be considered following washing operations). Areas currently contaminated in the range of 0.9-1.8 mSv/year can be reduced to roughly 1 mSv/year by washing structures, clearing detritus, and removing 4 cm of topsoil from yards and parks.

For areas contaminated above 1.8 mSv/year, it could be difficult in the near-term to meet the 1 mSv annual dose goal without demolishing structures. Even in a conservative analysis, however, it is most desirable to avoid demolition whenever possible. The most effective remediation in these areas will come from washing structures, collecting detritus, and removing trees and 15 cm of topsoil from yards and parks. This would meet (or exceed) the 50% by 2013 cleanup goal for areas currently contaminated in the range of 1.8 to 16.7 mSv/year. Areas currently contaminated in the range of 16.7 to 33.3 mSv/year would remain contaminated at about 14 mSv/year under this scenario.

Areas currently contaminated above 33.3 mSv/year would remain contaminated above 20 mSv/year following the above remediation scenario. More extensive decontamination methods and/or some demolition of structures may need to be considered. Assuming structures were razed in these areas, the resulting waste estimates from this conservative urban remediation scenario would be about:

- 1,943,592 m^3 contaminated soil waste;
- 1,503,000 kg detritus waste;
- 27,480,000 kg trees waste; and
- 544,845,210 kg building materials waste.

Roads

Cleanup of road surfaces were not considered in the above estimates. It is likely that pressure-washing or resurfacing alone will be very effective in reducing dose levels on road surfaces and that the amounts of surface scabbling will add little to the total waste volumes. The above results are somewhat conservative since doses from road surfaces are not factored.

Less-Conservative Scenario

Additional methods such as stabilizing contaminants and restricting access to certain areas (referred to as "Institutional Controls" or "ICs" in the U.S.) can be considered for limiting public doses within the 20 km evacuation zone under a less-conservative scenario. Given these methods, a more reasonable estimate can be made for the total waste volumes.

Forests

A much more reasonable approach to forested areas would be to collect detritus from all areas and restrict access to areas contaminated above some established value. Collecting detritus will immediately:

- Reduce dose rates below 1 mSv/year for areas currently contaminated below 4.4 mSv/year;
- Reduce dose rates below 10 mSv/year for all areas currently contaminated in the range of 4.4-33.3 mSv/year;
- Reduce dose rates to about 18 mSv/year in areas contaminated in the range of 33.3-83.3 mSv/year; and
- Reduce dose rates to about 36 mSv/year in areas contaminated in the range of 83.3-166.6 mSv/year.

Inadvertent human intrusion to some of the more highly contaminated areas (after detritus removal) will not likely pose a significant threat to health and safety. Further analysis would be required for areas of forest that are routinely harvested for food products or firewood or selected for temporary or interim waste storage sites. Trees and soil may need to be removed from some forested areas, depending on proximity to occupied areas and the likelihood and consequences of inadvertent human intrusion. At the very least, removing trees and 15 cm of soil from areas currently contaminated over 166.6 mSv/year would generate:

- 436,800,000 kg trees waste; and
- 6,552,000 m^3 soil waste.

Agricultural Areas

In the near-term, estimated annual dose rates in areas contaminated above 1.8 mSv/year could be reduced by more than half by deep ploughing. The dose benefit would be comparable to removing 8 cm of soil, though without the associated waste. Up to 30 cm of soil could be excavated from areas where annual doses are currently estimated above 33.3 mSv/year in order to provide some additional dose benefit. This would significantly reduce the soil waste volume from the conservative scenario (40,832,400 m^3 to 23,139,000 m^3).

Further analysis should be done to ensure that cesium concentrations in the soil in these areas remain below the 5,000 Bq/kg requirement for planting crops [2]. Additional cleanup may be required in the form of excavation, replacement with clean soil, or some form of in-situ or local soil washing method. The extent of additional remediation will be determined by the potential cesium uptake of crops and proximity of inhabitants to the contaminated area.

Urban Areas

The Japanese government is likely to facilitate remediation of the urban areas as much and as soon as possible. It is important that citizens can return to their homes soon and doses to sensitive populations be minimized. Access restrictions may be more difficult to enforce in urban areas, although this might be possible for some parks, depending on their location. The potential dose contribution from contaminated roadways was not considered in this analysis.

For areas currently contaminated in the range of 1.8 to 16.7 mSv/year, removing 4 cm of topsoil and using access restrictions when necessary for parks (i.e., not removing trees or topsoil in park areas) would leave dose rates slightly higher than if 15 cm of topsoil were ubiquitously removed, but would still meet the 50% by 2013 decontamination goal. Replacing removed soil with clean soil would provide some additional dose benefit. Also assuming that most structures in the region currently contaminated in the range of 33.3 to 83.3 mSv/year could be adequately decontaminated by using other surface decontamination methods (e.g., strippable paint/decontamination gels, etc.) would greatly reduce the waste from demolished buildings. Generated wastes under this scenario would be about:

- 1,357,788 m^3 contaminated soil waste;
- 1,503,000 kg detritus waste (no change);
- 16,940,000 kg trees waste; and
- 190,922,214 kg building materials waste.

DISCUSSION

Potential Waste Savings

Significant waste "savings" can be realized by allowing some of the contamination to remain and using institutional controls to control exposures to the public and/or applying additional remediation methods. These savings are highlighted in Table IV for the various proposed land use scenarios.

Table IV. Potential Waste Savings through the use of Institutional Controls

	Conservative Scenario	Less-Conservative Scenario
Forests	• 198,300,000 kg detritus • 3,864,000,000 kg trees • 46,066,800 m^3 soil	• 198,300,000 kg detritus • 436,800,000 kg trees • 6,552,000 m^3 soil waste
Agricultural Areas	• 290,620,000 kg crops • 40,832,400 m^3 soil	• 290,620,000 kg crops • 23,139,000 m^3 soil
Urban Areas	• 1,943,592 m^3 soil • 1,503,000 kg detritus • 27,480,000 kg trees • 544,845,210 kg building materials	• 1,357,788 m^3 soil • 1,503,000 kg detritus • 16,940,000 kg trees • 190,922,214 kg building materials
Totals	• 88,842,792 m^3 soil • 490,423,000 kg detritus/crops • 3,891,480,000 kg trees • 544,845,210 kg building materials	• 31,048,788 m^3 soil • 490,423,000 kg detritus/crops • 453,740,000 kg trees • 190,922,214 kg building materials

Japanese Road Map for Disposal

On October 29, 2011, the Japanese government announced plans for storage and disposal of decontamination wastes. Initially, temporary storage locations will be selected by central and local governments as decontamination efforts begin [12]. Contaminated material that has been removed so far has been buried in near-surface trenches and covered with clean topsoil or collected in bags and covered with plastic sheeting and sandbags [2] (see Figure 2). Most of the new temporary storage areas will be located in government-owned forested regions [13].

Fig. 2. Makeshift yard for contaminated soil within Fukushima-ken [4].

Over the next three years, an intermediate storage facility or facilities will be constructed within Fukushima Prefecture. Wastes stored at the temporary locations will be moved to this interim facility beginning in about January 2015 and stored for up to 30 years. The capacity of the interim storage facility is expected to be between 15- and 29-million m^3; this will depend on the final decontamination plan [14] [2]. The facility will store soil and incineration ash from rubble, rice straw, and cut leaves with radioactivity concentrations of 100,000 Bq/kg or greater [15]. Incineration ash with activity concentrations below 100,000 Bq/kg will be disposed of at municipal landfills. Within 30 years, wastes will be transferred to a final treatment/disposal site. Figure 3 shows a schematic of the proposed interim and final storage sites.

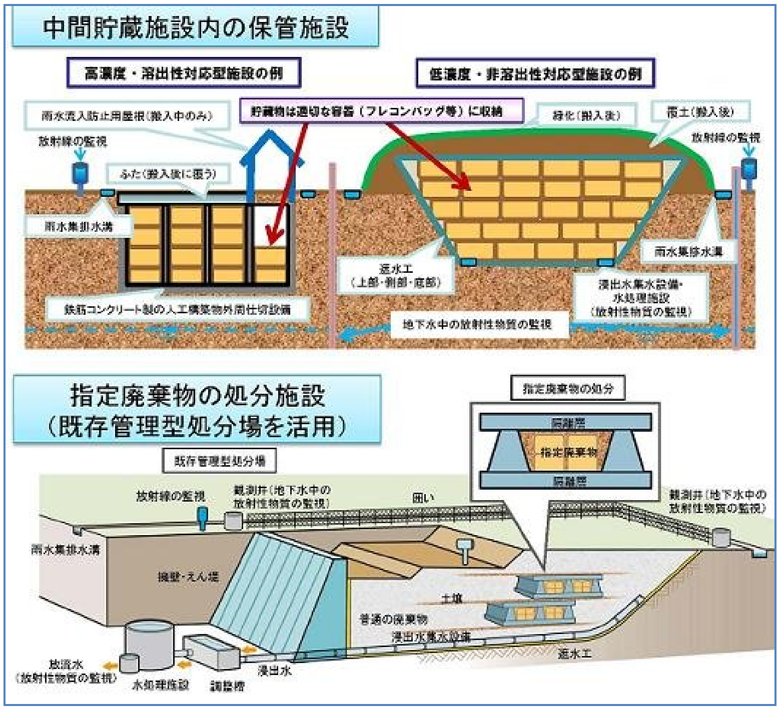

Fig. 3. Proposed interim and final storage sites for contaminated wastes [14].

Some general comments regarding the interim and final storage sites are as follows:

- It is likely, given the long storage period, that both of these repositories would be designed with double liners and leachate collection systems.
- In both cases, it may be advisable to design different cells for the different types of waste. Some cells may also be designed to allow future access so that waste could be retrieved and subjected to some future waste treatment method.

Conclusions

The method for estimating waste amounts outlined above illustrates the large amount of waste that could potentially be generated by remediation of the 20 km evacuation zone (619 km^2 total) if the currently proposed cleanup goals are uniformly applied. The Japanese environment ministry estimated in early October that the 1 mSv/year exposure goal would make the government responsible for decontaminating about 8,000 km^2 within Fukushima-ken and roughly 4,900 km^2 in areas outside the prefecture [16]. The described waste volume estimation method also does not give any consideration to areas with localized hot spots.

Land use and area dose rate estimates for the 20 km evacuation zone indicate there are large areas where doses to the public can be mitigated through methods other than removal and disposal of soil and other wastes. Several additional options for waste reduction can also be considered, including [2]:

- Recycling/reusing or disposing of as municipal waste material that can be unconditionally cleared;
- Establishing additional precautionary (e.g., liners) and monitoring requirements for municipal landfills to dispose of some conditionally-cleared material; and
- Using slightly-contaminated material in construction of reclamations, banks and roads.

Waste estimates for cleanup will continue to evolve as decontamination plans are drafted and finalized.

REFERENCES

[1] Japan Atomic Energy Agency. (2011, June 13). Analysis on the formation process of high dose rate zone in the northwest direction of the Fukushima Daiichi nuclear power plant. Retrieved from http://www.jaea.go.jp/english/jishin/press/press110613.pdf.

[2] International Atomic Energy Agency. (2011, November 15). Final Report of the International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Dai-ichi NPP. Retrieved from http://www.iaea.org.

[3] *World Nuclear News*. (2011, October 14). IAEA urges pragmatic clean-up. Retrieved from http://www.world-nuclear-news.org.

[4] Mori, H. (2011, September 15). Fukushima clean-up may require removal of 100 million cubic meters of soil. *Asahi Shimbun*. Retrieved from http://www.asahi.com.

[5] Emergency Management Team. (2011). [Interactive map illustration of land use in Japan as of April 12, 2011]. *Landuse*. Retrieved from http://www.drs.dpri.kyoto-u.ac.jp/emt/en/.

[6] Ministry of Education, Culture, Sports, Science and Technology. (2011, May 6). Results of Airborne Monitoring Survey by MEXT and the U.S. Department of Energy. Retrieved from http://radioactivity.mext.go.jp/en/monitoring_around_FukushimaNPP_MEXT_DOE_airborne_monitoring/.

[7] Ministry of Education, Culture, Sports, Science and Technology. (2011, July 8). Results of the Third Airborne Monitoring Survey by MEXT. Retrieved from http://radioactivity.mext.go.jp/en/monitoring_around_FukushimaNPP_MEXT_DOE_airborne_monitoring/.

[8] *World Nuclear News*. (2011, October 5). Clean-up in Fukushima. Retrieved from http://www.world-nuclear-news.org.

[9] Okazaki, A. & Sato, H. (2011, September 16). Study: Fallen Leaves Hold Key to Decontamination in Fukushima. *Asahi Shimbun*. Retrieved from http://ajw.asahi.com.

[10] *Japan for Stability Newsletter No. 15* (2003, November). About the Condition of Japanese Forests. Retrieved from http://www.japanfs.org/.

[11] Brown, J., Mortimer, K., Andersson, K., Duranova, T., Mrskova, A., Hänninen, R., Reales, N. (2007). *Generic Handbook for Assisting in the Management of Contaminated Inhabited Areas in Europe Following a Radiological Emergency—Part II: Compendium of Information on Countermeasure Options (EURANOS(CATI)-TN(07)-02*. Oxfordshire, UK:

Health Protection Agency.

[12] Japan Atomic Industrial Forum, Inc. (2011, October 30). Earthquake Report 250. Retrieved from http://www.jaif.or.jp/english/.

[13] Mori, H. (2011, September 30). Government to store radioactive waste in Tokyo, seven prefectures. *Asahi Shimbun.* Retrieved from http://www.asahi.com.

[14] Japanese Ministry of the Environment. (2011, October 29). Roadmap for the Decontamination of Fukushima.

[15] *Asahi Japan Watch*. (2011, October 31). Temporary facility to accept radioactive soil in 2015. *Asahi Shimbun*.Retrieved from http://ajw.asahi.com.

[16] Ishizuka, H. &Harufumi, M. (2011, October 12). Estimated 13,000 square km eligible for decontamination. *Asahi Shimbun*. Retrieved from http://www.asahi.com.

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