Engineering Aspects for Landfilling Radioactively Contaminated Wastes Derived from the Fukushima Daiichi Nuclear Power Plant Accident

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Abstract

Wastes contaminated with radiocesium released from the accident of the Fukushima Daiichi Nuclear Power Plant are classified as low-concentration wastes with 8,000 Bq/kg or lower, and high-concentration wastes exceeding 8,000 Bq/kg. The former is called “specified municipal solid waste” or “specified industrial waste,” and the latter, “designated waste.” This paper introduces off-site management, such as landfilling; characteristics of these wastes; and the legal framework for their management. In their management, the key characteristics of these wastes are high leachability of radiocesium from incineration fly ash from specified municipal solid wastes, and low leachability from bottom ash and sewage sludge ash. The radiocesium leachability of cement-solidified designated waste decreases with increasing unconfined compression strength. The significant engineering aspects of landfilling are as follows: soil can inhibit migration of radiocesium in landfill sites, capping over a layer of the radioactively contaminated waste is an effective method of containing radiocesium in landfill sites, and no barrier layer should be installed beneath the waste layer to control migration of radiocesium. Installation of such a barrier would result in production of highly concentrated leachate.

Key words: containment, contaminated waste, landfill, legal framework, radioactively, radiocesium

1. Introduction

The Fukushima Daiichi Nuclear Power Plant accident, a consequence of the Great East Japan Earthquake of March 11, 2011, released radioactive substances into the atmosphere. These substances advected, diffused and were deposited onto ground surfaces in eastern Japan. This fallout contaminated all above-ground structures and objects, such as roads, residential buildings, parks and trees (Fig. 1; NIES, 2012). Waste and sewage treatment plants are facilities in the downstream part of material cycles, where chemical substances are concentrated through incineration and condensation. As a result of the accident, radioactivity concentrations in incineration ash increased. Radioactive substance concentration in ash, however, did not become a major topic of concern for a month or two after the accident, since people initially focused on only the air dose rate caused by the fallout. In May of 2011, the authorities revealed the high radioactivity concentration of sewage sludge and its incineration ash produced by sewage treatment plants located within Fukushima Prefecture. A notification entitled “A View on the Provisional Handling of By-products Generated from the Service Water and Sewage Treatment Processes, in Which Radioactive Substances Have Been Detected” (Nuclear Emergency Response Headquarters, 2011) was issued on June 16. This notification indicated aspects to consider in the transportation and storage of by-products, and it established 8,000 Bq/kg as the threshold radioactivity concentration for landfilling, with restrictions on the land-use of closed landfill sites. In the statement “Policy on the Landfill of Disaster Wastes in Fukushima Prefecture” issued on June 23, the Ministry of the Environment (MOE) established the landfill standard for radioactivity concentration as 8,000 Bq/kg — which became the maximum permitted concentration for landfilling at controlled-type industrial waste (IW) and municipal solid waste (MSW) landfill sites for all other wastes as well as by-products from service water and sewage treatment plants (MOE, 2011a). At this point in time, it was considered appropriate to store wastes temporarily if their radioactivity concentration exceeded 8,000 Bq/kg. The earliest records on the concentration of MSW incineration ash and fly ash — those from July
2011 — indicated that the concentration exceeded 8,000 Bq/kg even in the southern part of the Kanto region, such as Tokyo.

The aim of this paper is to introduce management of off-site radioactively contaminated waste derived from the accident. We are not concerned here with removed soil and on-site radioactively contaminated waste, even though the huge amount of removed soil being produced at present and treatment of on-site waste are significant issues.

2. Landfill Standards for Radioactively Contaminated Wastes

2.1 Establishment of 8,000 Bq/kg Concentration as the Standard

Landfill standards for wastes contaminated by radioactive substances generated by the accident (hereinafter referred to as “radioactively contaminated wastes”) were established considering the safety of the treatment of landfill wastes and by-products as indicated by the Nuclear Safety Commission on June 3, 2011. The aforementioned notification (Nuclear Emergency Response Headquarters, 2011), and the MOE statement (MOE, 2011a) as well as “The Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District-Off the Pacific Ocean Earthquake that Occurred on March 11, 2011” (hereinafter referred to as “the Act on Special Measures”; Law No. 110 of 2011) also followed this guideline. Specifically,

- The radioactive substances of interest are Cs-134 and Cs-137.
- The annual radiation dose to local residents as a result of waste treatment processes, including landfilling work, must not exceed 1 mSv.
- Every precaution must be taken so that the annual radiation dose to workers as a result of waste treatment processes does not exceed 1 mSv.
- Precautions based on scientifically sound scenario assumptions must be taken after the completion of treatment and landfill works so that the “rough standard,” which limits the annual radiation dose to local residents to 0.010 mSv or lower (or to 0.300 mSv or lower after accounting for fluctuating factors), must be adhered to.
- Verifications must be made to ensure that the concentration of materials disposed and drainage from treatment facilities remain below the limits indicated by the “Notification on Dosage Equivalent Limits on the Basis of the Ministerial Notification on Commercial Power Reactors” (March 21, 2011; Notification No. 187 of the Ministry of Economy, Trade and Industry).
These guidelines indicate that the concentration standard of 8,000 Bq/kg was determined by considering additional exposure doses to workers and local residents. According to the MOE, at a landfill radioactivity concentration of 8,000 Bq/kg (8 Bq/g), the annual additional exposure dose to workers should be 0.78 mSv. Furthermore, if incineration ash with a radioactivity concentration of 3,000 Bq/kg is used as landfill on land to be used as a closed landfill site and if people reside on such land without covering the ground with soil, the additional annual exposure dose to children would be 0.93 mSv, which exceeds the rough standard of 0.010 mSv. However, if the ground is covered with soil and closed landfill sites are transformed into parks, then the annual dose would be much lower (0.00048 mSv).

The Safety Assessment Investigative Commission of the MOE evaluated a scenario in which internal exposure occurred from the oral ingestion of groundwater contaminated by radioactive cesium (Cs-134 and Cs-137) leaking from a landfill site (MOE, 2011b). The additional exposure dose following the oral ingestion of well water extracted from such groundwater was found to be extremely low. The most dangerous scenario was that of an adult orally ingesting farm crops grown using such groundwater, wherein the annual exposure dose would reach 0.010 mSv when incineration ash at a concentration of 46,000 Bq/kg was landfilled — more than five times the established landfill standard (8,000 Bq/kg) — and its leachate leaked. Scenario assessments involving the use of groundwater generally tend to be more on the safe side than those of external exposure doses such as landfill work. There are two primary reasons for this: (a) soil has extremely high radioactive cesium adsorption capacity and (b) groundwater flow dilutes the radioactivity concentration.

2.2 Concentration Standards for Discharge Water

No concentration standards have been specified for radioactive substances in discharge water (final effluent) from landfills. The monitoring process for discharge water is described in the implementing regulations of the Act on Special Measures (Ministerial Ordinance of the MOE No. 33, dated December 14, 2011) and the MOE guidelines (MOE, 2013). The standards themselves, however, are specified only for the concentration limits of public waters surrounding landfill sites. Therefore, monitoring of the discharge water can be interpreted as an early-warning safety mechanism to ensure that the dose in public waters is below the concentration limits. Methods of calculating concentration limits are outlined in the guidelines provided in the Public Notification of the Ministry of Economy, Trade and Industry No. 187 (March 21, 2011). The guidelines only describe the concentration limit of two radioactive nuclides, Cs-134 and Cs-137, the accident-generated radioactive substances.

\[
\frac{\text{Cs-134}}{60(\text{Bq/L})} + \frac{\text{Cs-137}}{90(\text{Bq/L})} \leq 1
\]

The limit of 8,000 Bq/kg as the landfill standard was derived through numerous scenario assessments, including those on external exposure of workers and local residents and internal exposure after leakage. Not considered, however, was whether the radioactivity concentration in the discharge water from landfill sites would be below the limit. The safety assessment scenario did not account for the installation of a barrier system (i.e., the installation of geomembrane sheets or a compacted clay liner) underneath control-type IW and MSW landfill sites. For a conservative assessment, all the leachate and radioactive cesium were assumed to transfer into the groundwater. In practice, however, barrier systems and leachate collection pipes are installed so that the leachate does not transfer to the groundwater, and the collected leachate is treated and discharged without any sorption into the soil and dilution into the groundwater; this prevents radioactive cesium from entering the groundwater at high concentrations. In other words, the concentration limit may not be satisfied even if the landfill standard is satisfied according to the scenario assessments. It is therefore important to understand and assess the following factors and additional measures for landfilling: the leaching characteristics of radioactive cesium in radioactively contaminated wastes, especially incineration fly ash; the adsorption capacity and other characteristics of the intermediate soil cover; the presence of existing waste below the landfill layer of radioactively contaminated wastes; the characteristics of the impermeable final soil cover (capping system); the landfilling method; the behavior of radioactive cesium within landfill sites; and appropriate landfill management. Moreover, landfill work must be a part of land preparation even though radioactively contaminated wastes are landfilled.

2.3 Classification of Radioactively Contaminated Wastes

Radioactively contaminated wastes are classified in terms of MSW or IW status, decontamination actions, regions and concentrations (Fig. 2). MSWs, IWs and decontamination wastes with radioactive cesium concentrations of 8,000 Bq/kg or lower are referred to as “specified MSWs” or “specified IWs.” Wastes with radioactivity concentrations exceeding 8,000 Bq/kg are classified as “designated wastes.” Wastes from inside the management area — special decontamination area in Fukushima Prefecture — are referred to as “contaminated wastes within management area” and are classified as “specified wastes.” Wastes within the management area with concentrations of 8,000 Bq/kg or lower are termed “standards-compliant specified wastes.” Designated wastes are classified as a part of specified wastes, for which the national government is responsible for treating. By contrast, the local government is responsible for treating specified MSWs and IWs. The classification is complex because the entities responsible for treatment must be clarified. Irrespective of the treatment entity, the additional measures for landflling have been set with
8,000 Bq/kg as a threshold concentration.

2.4 Landfill Standards for Specified MSWs and IWs

Structural standards are detailed in the Enforcement Regulation for the Act on Special Measures as well as the waste-related guidelines. Figure 3 represents the structural standards for specified MSWs and IWs (controlled-type) with concentrations of 8,000 Bq/kg or lower. An approximately 50-cm-thick soil layer must be installed where specified MSWs or IWs are to be landfill. This soil layer is designed to adsorb the radioactive cesium leaching from the wastes and prevent its migration to the leachate treatment facility. Sufficient compaction of the existing waste layer or the installation of a geotextile layer is recommended to inhibit the differential settlement of specified MSWs or IWs, but the regulation contains no related details.

To ensure that all leachate from the specified MSWs or IWs will pass through the lower soil layer, even when the unsaturated flow is lateral due to suction, the lower soil layer should be extended in the horizontal direction by approximately 3 m outside the area where the specified MSWs or IWs are landfill. Because lateral flow is generally assumed to spread at an approximately 45 degree angle, if the landfill height for each layer of specified MSWs or IWs is 3 m, the lateral extension would be approximately 3 m, whereas if the landfill height is 1.5 m, then the extension would be approximately 1.5 m. Landfills must be located away from any slope face to prevent radioactive cesium-containing leachate from passing through the light-blocking nonwoven fabric or drainage pipes, which are usually present on the slope faces of landfill sites. Prolonging the travel time of the radioactive cesium within the landfill site is an effective method of containment because it decreases radioactive concentration through radiation attenuation and adsorption (which helps retard the migration).

For landfilling contaminated fly ash, an impermeable soil cover (i.e., capping system) must be installed after landfilling as a final or intermediate cover system (depending on the height of the landfill) in order to prevent rainwater infiltration. Furthermore, using recycled crushed stones and crushed concrete debris atop the impermeable soil cover as a horizontal drainage layer is an effective method to prevent the infiltration, but this is not described in the related guidelines. At the top of the impermeable soil cover, a gradient of approximately 5 percent is required to ensure that a drainage gradient of at least 2 percent can be secured even when differential settlement occurs to a certain extent. For the lateral soil cover in the direction of the slope face as well as in the direction of the gas...
Figure 3  Landfill standards for specified MSWs and IWs.
Methods are all considered to produce the same results, designated wastes do not contact water. The following principle of these landfill standards is that the landfilled wastes are solidified with cement and the surroundings are covered with an impermeable soil layer; the designated wastes are solidified with cement in a highly durable container made of steel-reinforced concrete; the designated wastes that have been solidified with cement landfill in closed-type landfill sites whose roof and walls prevent rainwater infiltration. The soil layer beneath the designated wastes for adsorbing radioactive cesium must be installed in the same manner as the landfill standards of specified MSWs and IWs.

Designated wastes with radioactivity concentrations exceeding 100,000 Bq/kg must be landfilled in a site equivalent to isolated-type landfills. However, a new isolated-type IW landfill site had to be constructed because no isolated-type landfills were constructed after the revision of the Waste Disposal Law in 1998. The time required to select suitable land for a new landfill site usually exceeds 10 years, irrespective of the involvement of accident-derived radioactive substances. When contaminated fly ash is landfilled in an isolated-type landfill, the waste is not solidified. Thus, measures must be taken to prevent the corrosion (rusting) of steel-reinforced concrete wall by salts eluted from the fly ash. Furthermore, if the fly ash contains large quantities of calcium chloride, it would deliquesce by absorbing moisture. Therefore, quality control of the fly ash, landfill method, corrosion-prevention method, and maintenance are all factors that must be considered. In addition to covering wastes with steel-reinforced concrete, a final soil covering (capping) using bentonite material is planned in order to prevent the infiltration of rainwater, protect the underlying layers and reduce skyshine. The design and installation of such a capping system are issues for future consideration. Inspection galleries at the landfill site are to be filled with bentonite material after the first inspection period has expired. Because we have no experience in filling bentonite without compaction by heavy machinery, the quality

![Fig. 4 Landfill standards for designated wastes.](image-url)
control of bentonite, the filling method and the construction quality inspection system are also expected to be major concerns.

3. Characteristics of Radioactively Contaminated Wastes

3.1 Leaching Characteristics

Various tests were conducted to characterize the leaching of radioactive cesium from radioactively contaminated wastes. The radioactively contaminated wastes were subjected to an agitated leaching test at a liquid-solid ratio of 10 for 6 hours at 200 rpm without sample size reduction (i.e., “as is” sample) in accordance with JIS K0058-1 as indicated in MOE Notification No. 3 (January 13, 2012). This method was adopted because the wastes that must be solidified are high in radiation and are highly leachable. This method is adopted even for powdery wastes in order to maintain equity of the leaching test method.

Table 1 lists the leaching test results for representative contaminated wastes (NIES, 2012). These data indicate MSWs and IWs, not including decontamination waste and its ash. For bottom ash and sewage sludge incineration ash, leaching rates are indicated for stable cesium because that of radioactive cesium was less than the detectable threshold. One of the objectives of the treatment is to insolubilize heavy metals within the fly ash. The leaching rates for untreated fly ash comprising soluble salts as well as that for cement—and/or chelating—treated fly ash were within 60 to 90 percent. These results indicate that the leaching rate for radioactive cesium does not change after treatment for heavy-metal insolubilization. Fly ash solidified with cement was compressed during curing and was found to have an unconfined compressive strength of at least 0.98 MPa. The leaching rate of solidified fly ash decreased to 10 to 15 percent, but the powdery fly ash had a high leaching rate. Many types of incineration ash, including bottom and fly ash, were subject to the leaching test, and the leaching rates of all fly ashes were comparable. The leaching rate of fly ash was found to be very high irrespective of its treatment status, whereas those of bottom ash and sewage sludge incineration ash were low. When the leaching period was beyond six hours, the leaching rate of the fly ash was 100 percent, whereas those of bottom ash and sewage sludge incineration ash were stable (Ishimori et al., 2013).

The leaching rates are crucial knowledge for the operation and management of landfill sites, and external exposure of workers and local residents must be managed according to the radiation concentration of the wastes. Assuming that the leaching rate from fly ash with a concentration of 1,000 Bq/kg is 90 percent and that from bottom ash with a concentration of 45,000 Bq/kg is 2 percent, the leaching load of both ashes to the leachate treatment facility would be equivalent (i.e., 90 Bq/L in both cases). In addition, the leachate concentrations of radioactively contaminated inert-type wastes could not be detected (<10–15 Bq/L) in tens of samples. Thus, it can be concluded that there are no inert-type wastes containing easily water-soluble radioactive cesium.

3.2 Cement Solidification

Cement solidification is the treatment required when landfilling designated wastes with a radioactive concentration of 100,000 Bq/kg and lower at MSW and controlled-type IW landfill sites. Solidification is performed according to MOE Notification No. 14 by adding at least 150 kg/m³ of cement. In addition, the unconfined compressive strength must be at least 0.98 MPa. This solidification method is the same as that specified in an earlier detoxication measure for metals, namely the “Standards for Solidification of Waste Materials Including Metals” of Environmental Agency Notification No. 5 (March 14, 1977). Solidification with cement is aimed at restraining the leaching of radioactive cesium and is effective at significantly delaying the leaching rate even in the presence of water. Cement itself cannot immobilize radioactive cesium; nevertheless, cement solidification reduces porosity and hydraulic conductivity, which strongly reduces the migration of radioactive cesium because its diffusion coefficient in solids is lower than that in liquids. This effect strengthens with decrease in porosity. The properties of fly ash, however, are not constant, and its strength depends on the composition ratios of ZnO, PbO, and SO₃ as well as the atmospheric temperature. Nishikawa et al. (2012) reported that solidified fly ash occasionally does not achieve the prescribed strength within 14 curing days at a water-cement ratio of 0.8 and 500 kg/m³ added cement. Designated wastes are of many types, including weeds, sticks mixed with soil and disaster-astes; therefore, solidification methods have to be demonstratively developed.

Leaching of radioactive cesium from solidified wastes is a diffusion phenomenon within solids; even if the leaching rate is only 10 percent during a standard six-hour leaching test, the rate would increase sharply when leaching continues over several weeks. Moreover, the specimen dimensions affect the leaching rates. Actual solidified wastes are designed to be large cubes of size 1 m, with surface area per 1 m² being approximately 6 m². The leaching specimens were approximately 5 cm

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**Table 1** JIS K0058-1 leaching test results of representative radioactively contaminated wastes.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Radioactive Cs leaching rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW: incineration bottom ash</td>
<td>1.6*</td>
</tr>
<tr>
<td>MSW: untreated fly ash</td>
<td>64.1–89.1</td>
</tr>
<tr>
<td>Cement-treated fly ash</td>
<td>62.5–86.3</td>
</tr>
<tr>
<td>Solidified fly ash with cement</td>
<td>13.1</td>
</tr>
<tr>
<td>Bottom ash–fly ash (4:1) mixture</td>
<td>27.1</td>
</tr>
<tr>
<td>Sewage sludge incineration fly ash</td>
<td>0.9*</td>
</tr>
</tbody>
</table>

*Leaching rate of stable cesium is calculated since that of radioactive cesium is less than the lower detection threshold.
in size, meaning that the actual leaching cannot be evaluated solely using the JIS K0058-1 leaching test. In addition, since long-term leaching behaviors vary because of surface deterioration or expansion of solidified waste, the leaching test results must be presented as leaching flux per unit surface area. Landfilling is the final disposal of designated wastes, not temporary or intermediate storage; thus, it is crucial to evaluate the total amount of radioactive cesium that is expected to leach over a long period, and subsequently the leaching rate. The long-term leaching rate should accordingly be appropriately controlled through solidification in order to prevent its negative effects on the environment in the future.

4. Engineering Performance Standards for Each Material

4.1 Required Performance of Lower Soil Layer

Four characteristics, namely adsorptivity of radioactive cesium, water permeability, workability and deformability, of the lower soil layer, and characteristics such as waste scattering, bad odor and pest outbreaks of the intermediate soil covering must be evaluated.

- Adsorption must be adequately high to prevent the leakage of radioactive cesium and to capture radioactive cesium within the landfill area. Radioactive cesium, like potassium, can be adsorbed by hexagonal holes in silica sheets containing clay minerals. The adsorption ability of clay-rich soils is expected to be high. Adsorption ability is typically evaluated as the distribution coefficient (mL/g), which is derived through batch-type adsorption tests. Radioactive cesium has high adsorptivity to soils under natural groundwater condition, but potassium and stable cesium in water are adsorption inhibitors. Because fly-ash-leached liquid contains several thousands of milligrams per liter of potassium and because its electrical conductivity generally exceeds several thousands of millisiemens per meter, the adsorption ability of soil in landfill sites is not as high as is usually reported. Ishimori et al. (2012) reported that the distribution coefficient of soil in leachate is one hundredth that in pure water.

- The lower soil layer serves as an adsorption layer; therefore, its performance cannot be evaluated unless water permeates through it. Water permeability is therefore a desired characteristic, and a hydraulic conductivity of at least approximately two times that of the waste layer is desirable. The distribution coefficient of decomposed granite produced in Ibaraki prefecture is 16 mL/g, and its hydraulic conductivity is $10^{-3}$ cm/s, whereas those of Saitama soil is 31 mL/g and $10^{-5}$ cm/s, respectively (Ishimori et al., 2012). This means that while the soil has sufficient adsorption ability, it is unsuitable for use as the lower soil layer because of its low permeability.

- Merely the presence of soil is not adequate; it must be workable. This is because all areas in the lower soil layer must exhibit high adsorption ability. What must be used for compaction control are soil, artificial materials and soil mixtures with adequate hydraulic conductivity and suitable radioactive cesium adsorption capacities (a distribution coefficient of at least 10 mL/g in leachate is desired).

- Soil must be installed with sufficient thickness to ensure its performance as the adsorption layer even under differential settlement. Swellable materials should not be used as they are impermeable. Therefore, appropriate management measures must be enacted to ensure that the leached liquid would still pass through the soil layer and be transported to the water treatment facility even if uneven settling has occurred. Installing geotextiles such as geogrids and geonets beneath the lower soil layer may be efficient in preventing deformation of the existing waste layers.

4.2 Required Performance of Water-impermeable Soil Cover

The impermeable soil cover (i.e., the capping system) is the final soil cover or the intermediate soil cover placed atop landfilled wastes with high leachability of radioactive cesium. Four performance measures—rainwater impermeability, radiation shieldability, workability and deformability—must be evaluated for this soil cover.

- Impermeability can be ensured by reducing the hydraulic conductivity and by placing a drainage layer in the upper section of the impermeable capping. A gradient of approximately 5 percent is necessary considering the differential settlement of landfilled waste layers. In addition, a gas-extraction layer must be installed beneath the impermeable capping layer because landfill gases will be produced even if only incineration ash is landfilled. Regarding the long-term durability of the capping system, Japanese authorities do not have enough experience to construct such a capping system as there are no firm regulations on such capping systems in Japan.

- Shieldability depends on the density and thickness of the impermeable soil cover layer. An ordinarily-compact ed soil layer with thickness of 50 cm can shield 90 percent of the radiation from radioactive cesium.

- Workability of the soil cover differs from that of the bottom liner in that the former is installed on the upper section of the landfilled waste layers. Thus, the reaction force of compaction, deformation of landfilled waste, differential settlement, and landslides must all be focused on during implementation.

- The impermeable soil cover must be deformable because differential settlement is inevitable. This is because the soil cover must be installed on the upper section of radioactively contaminated waste layers, atop existing waste layers. Swellable clay, such as bentonite or geosynthetic clay liner, is a suitable material. Geotextiles may be effective in reducing differential settlement.
Apart from the aforementioned four characteristics, additional scenarios require attention, such as when the existing waste layers contain sludge or perishable waste materials, when a large amount of gas is discharged to the treatment plant from the draining pipes (fume stacks), and when temperatures of the waste material layers are high. In these cases, additional measures, such as installing an exhaust layer underneath the water-impermeable layer in order to remove the gas, must be implemented.

5. Future Issues and Outlook

Factors such as the capacity of the intermediate soil cover to adsorb radioactive cesium, installation of an impermeable soil cover or rainwater drainage layer, preventing the accumulation of perched water, slope stability, and leaching controls must be accounted for in the landfilling of radioactively contaminated wastes. Landfill management must take into consideration not only the leachate quality but also external exposure and land use restrictions.

The lower soil layer must have adequate adsorption ability and water permeability; thus, compaction control and appropriate material selection are essential. Because there are no standard methods for calculating the distribution coefficient, a measure of adsorption ability, it is difficult to adopt either batch-type or column-type adsorption tests. Moreover, properties of the solvent in the adsorption test must be accounted for since adsorption ability decreases due to such factors as the concentration of potassium being higher in fly ash leachate than in seawater.

No methods are available to determine the required performance standards of an impermeable soil cover; these need to be experimentally determined to ensure adequate long-term performance. The final soil cover required at hazardous waste landfill sites (e.g., subtitle C landfill sites in the US) comprises double impermeable layers, a protective layer, a drainage layer and a gas-extraction layer. Japan has no landfills with such soil covers, making it difficult to clarify whether such structures might be effective under the meteorological conditions in Japan. Thus, experimental and demonstrational tests will be vital for obtaining related data.

Sites where radioactively contaminated wastes have been landfilled have restrictions on land use as well as on land-use change. The annual radiation exposure dose can be controlled to sufficiently low levels, even should people live at these sites, if a soil cover of an appropriate thickness is installed. Land-use changes can be managed the same way as for landfill sites where wastes containing asbestos are landfilled. Appropriate landfill management is essential for all lower soil layers, the soil covers and land use. Structural stability to prevent differential settlement and landslides as well as appropriate containment of heavy metals and radioactive cesium must be ensured. Landfill sites have aspects of social infrastructure as well as those of land-resource creation. After the construction of a landfill site, it may be possible that engineering perspectives have not been sufficiently implemented during landfilling. Although investigating the engineering parameters of waste layers that have already been landfilled can be difficult, compaction and permeability controls of waste layers can nevertheless be performed for land use even if radioactively contaminated wastes are landfilled. Thus, long-term planning, such as anticipating the use of landfill sites after tens of years, and long-term landfill management are imperative.

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MOE ( Ministry of the Environment) (2011c) Policy on Treatment Methods for Incineration Ash That Exceeds 8,000 Bq/kg and up to 100,000 Bq/kg, August 31. (in Japanese)


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