Chapter 15
Radioactive Waste Management After Fukushima Daiichi Accident

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Abstract The categories of radioactive wastes have markedly changed due to the Fukushima Daiichi Nuclear Power Station accident. In addition to the conventional radioactive wastes such as high-level radioactive waste, the designated wastes, the wastes generated by decontamination work such as contaminated soil, the wastes contaminated with radionuclides or nuclear fuel which were generated within the on-site area of the nuclear power station, the spent nuclear fuel and debris, and the contaminated water are now critically required to be taken into account. The technological and legal schemes, by which these radioactive wastes will be appropriately processed and disposed of, must be established as soon as possible. These schemes also have to be widely supported by the public and society. This chapter gives an overview of the concept of radioactive waste management and discusses the problems and challenges to be solved for the management of all types of radioactive wastes and for the sustainable use of nuclear energy in the 21st century.

Keywords Radioactive waste management · Temporary storage · Intermediate storage · Disposal · Contaminated water · Debris · Spent fuel

15.1 Introduction

The Fukushima Daiichi Nuclear Power Station accident of Tokyo Electric Power Company (hereafter, "Fukushima accident") brought about a significant impact and change on the policy of nuclear energy development and use in Japan. Simultaneously, a challenge which has not been assumed scientifically, technologically, and legally before March 11, 2011, namely the processing and disposal

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of radioactive wastes generated by the Fukushima accident, is now becoming evident. All members of the nuclear community in Japan have a responsibility to clearly and concretely illustrate a roadmap of how the processing and disposal of the wastes contaminated with radioactive materials and nuclear fuels, generated by the Fukushima accident, can proceed as a function of time. This is the most critical subject that cannot be bypassed for the restoration and revival of communities and residents who were obliged to evacuate due to the Fukushima accident. Furthermore, this is a primal premise for advancing the safe and steady decommissioning of Units 1–4 of Fukushima Daiichi. Consequently, what we learnt, what we are learning, and what we will learn from the Fukushima accident will be able to be made to be the common property of all human beings in the world.

From now on, it is considered that the concrete plans for processing and disposal will be proposed by the relevant ministries and agencies, and these will be put into action. The purpose of this chapter is to summarize the current legal system for radioactive waste management in Japan after the Fukushima accident and to discuss the practical challenges to be overcome for safe and secure radioactive waste management in the future.

15.2 Legislation for Radioactive Waste Management after Fukushima Daiichi Accident

The waste produced by the use of nuclear fuels such as uranium and plutonium *in* nuclear reactors is regulated by the Law for the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors, and the waste generated by the use of radioisotopes, radiation rays, accelerators, and so on are controlled by the Law Concerning Prevention of Radiation Injury due to Radioisotopes, etc. This is the established legal structure, and the competent authorities have been designated. These laws presume that radioactive waste is generated in a controlled area, and is managed and stored there appropriately.

After the Fukushima accident, in addition to such conventional wastes, waste has been generated that is contaminated with radioactive materials and nuclear fuels produced outside of a controlled area, i.e., nuclear reactors or the nuclear power station of Tokyo Electric Power Company. Consequently, in order to manage the waste generated outside the nuclear power station, the Law on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials by the NPS Accident Associated with the Tohoku District—Off the Pacific Ocean Earthquake that occurred on March 11, 2011 (hereafter, “the Law on Special Measures”) came into force, over which the Ministry of Environment has jurisdiction. Decontamination and processing and disposal of wastes are being conducted under this legal system.

Figure 15.1 shows the flow of processing of waste generated in Fukushima Prefecture by the Fukushima accident, determined by Cabinet decision, based on the Law on Special Measures. Disaster waste is treated by the Law on Special

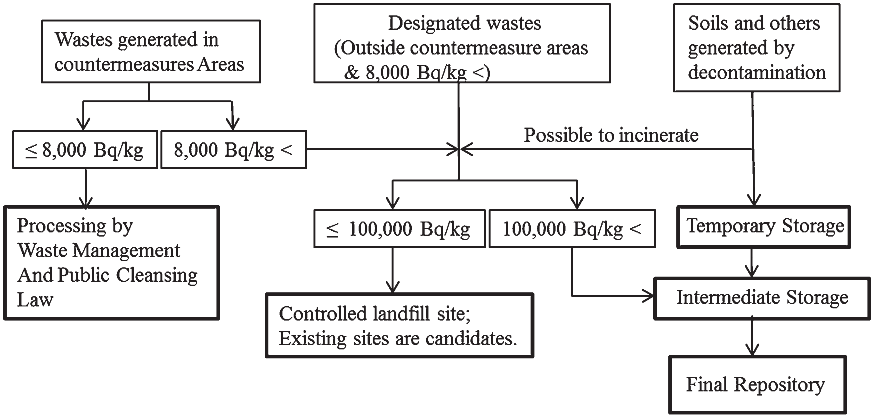

Fig. 15.1 Flow of processing of wastes generated in Fukushima Prefecture by Fukushima accident. Radioactivity level is sum of ^{134}Cs and ^{137}Cs

Measures Concerning Disaster Waste Management after the Great East Japan Earthquake, but the waste of radiation levels higher than 8,000 Bq/kg (sum of ^{134}Cs and ^{137}Cs; hereinafter the same meaning shall apply) is treated in the Law of Special Measures, and hence, it will enter the flow of Fig. 15.1.

The criteria of 8,000 and 100,000 Bq/kg, illustrated in Fig. 15.1, were decided for the following three reasons [1]. First, when waste of 100,000 Bq/kg or less is disposed of in the landfill site which will not be used for residence and will be managed appropriately for a long period, the annual radiation dose rate of the residents around the site after the completion of landfill is estimated to be less than 10 μSv/y. Second, during the operation of controlled landfill sites for waste of 100,000 Bq/kg or less, the annual radiation dose rate of the residents around the site is evaluated to be less than 1 mSv/y, if their residence area is sufficiently far from the boundary of the site. Third, when waste of 8,000 Bq/kg or less is directly transferred to the landfill site, the annual radiation dose rate of workers is expected to be less than 1 mSv/y and the safety of workers is assured.

The waste generated in the countermeasure areas (areas where evacuation orders are ready to be lifted, areas where residents are not permitted to live, and areas where it is expected that the residents will have difficulties in returning for a long time) [2] is classified into two classes: waste of 8,000 Bq/kg or less and waste of over 8,000 Bq/kg. The former will be processed by local municipalities or waste disposers in accordance with the Waste Management and Public Cleansing Law. The latter will be treated as waste equivalent to the designated waste. The waste which is generated outside the countermeasure areas and for which radiation level exceeds 8,000 Bq/kg is labelled as designated waste by the Minister of Environment.

In Fukushima Prefecture, not only a large amount of waste accompanied with decontamination but also highly contaminated waste of over 100,000 Bq/kg is expected to be generated. The contaminated soil and other waste generated from decontamination will be stored in the temporary storage site, and then be transferred to the intermediate storage facility where those will be stored together with waste of over 100,000 Bq/kg. The waste generated outside Fukushima Prefecture is not transferred to the intermediate storage facility. Because waste of over 100,000 Bq/kg is not considered to be generated in prefectures other than Fukushima, the flows which go to the intermediate storage facility in Fig. 15.1 are not assumed for the waste outside Fukushima Prefecture.

Irrespective of location, waste of over 8,000–100,000 Bq/kg or less will be disposed of in a controlled repository/disposal site located in each prefecture. The existing landfill site is considered to be a candidate for this site. When a new controlled repository/disposal site needs to be built, the Japanese Government will select two or more proposed sites within the national lands in each prefecture, and will decide on a site. In addition, the volume of waste will be reduced through incineration, dryness, fusion, and so on, until a controlled repository/disposal site starts operation. A temporary facility will also be built for incinerating the by-products (straw from rice and pastures, etc.) from agriculture or forestry which cannot be incinerated in the existing incineration facility.

The flow through the intermediate storage facility is particular to the waste generated in Fukushima Prefecture. The roadmap of the flow is planned as follows. The waste will be stored in the temporary storage site for approximately 3 years. Each city, town, or village is required to secure its own site within its boundary. In countermeasure areas, the Ministry of Environment will secure the sites in cooperation with local municipalities. By approximately 3 years after starting the formal temporary storage process, transport to the intermediate storage facility will be scheduled to start. The waste stored in the intermediate storage facility will be disposed of in a final repository, which will be constructed and operated outside Fukushima Prefecture. The transport from the intermediate storage facility to the final repository will be scheduled to start within 30 years after the intermediate storage starts.

However, under the current situation, many problems about specific processing and disposal still remain, as mentioned below, and the challenge of site selection for the intermediate storage facility and for controlled landfill has yet to be overcome. As can be seen in opposition movements and protests by the residents of Yaita City, Tochigi Prefecture, and Takahagi City, Ibaraki Prefecture, which were selected as the final landfill site by the Japanese Government, issues such as transparency of the selection procedure, communication with stakeholders, and equity in liability and onus are quite important. Furthermore, the Law on Special Measures decides only the framework on processing, decontamination, and budget. Most procedures and schedules are planned according to the basic policy by Cabinet decision, and specific methodology of landfill is illustrated in the notification from the Ministry of Environment. For the management of waste of over 100,000 Bq/kg, only the abstract requirements for safety of disposal are decided in Enforcement Regulations for the Law on Special Measures.

Management of radioactive waste generated within the Fukushima Daiichi nuclear power station by the accident must be performed primarily by Tokyo

Electric Power Company in accordance with the Law for the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors, but in actuality nothing is decided about processing, reprocessing, storage, and disposal of the waste. Damaged fuel, such as melted fuel, the debris and waste contaminated with radioactive materials, and nuclear fuel generated by the Fukushima accident, are not assumed in the Law for the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors. Thus, revision of the law and/or the preparation of new legal system for the management of these radioactive wastes are critical and essential, and regulation for safety of radioactive waste management is inevitable. At present, solid wastes, such as debris and rubble, are planned to be stored in storage facilities in which the radiation shield and prevention of waste scattering are appropriately implemented. Furthermore, the volume of waste will be reduced and the materials with low radioactivity will be recycled within the Fukushima Daiichi Nuclear Power Station.

In the following three sections, the kinds of waste generated within Fukushima Daiichi Nuclear Power Station and the problems to be solved for safety and security of radioactive waste management are discussed.

15.3 Management of Contaminated Water

To cool fuel debris stably, cooling water is continuously recirculated inside the primary containment vessel. Nevertheless, approximately 400 m^3 of groundwater flows into power station buildings per day, and hence the amount of contaminated water increases daily.

In order to manage the contaminated water, three measures have been implemented [3, 4]: (i) "Remove" sources of contamination, (ii) "Isolate" water from contamination, and (iii) "Prevent leakage" of contaminated water. In order to reduce the risk from contaminated water, some measures have been implemented. For example, the contaminated water has been treated with a multi-nuclide removal equipment (ALPS), the groundwater has been pumped up from sub-drains near nuclear power station buildings, land-side frozen soil impermeable walls have been installed, and the soil has been improved with sodium silicate. Furthermore, some additional measures have been decided. For example, more multi-nuclide removal equipment will be installed, measures to prevent water leakage from tanks will be taken, broader area pavement (surface waterproofing) at the site will be implemented, and the length of contaminated water transfer piping will be reduced. Further detailed measures are illustrated in the Refs. [3, 4].

Also being addressed are the necessity and importance of accelerating the installation of further tanks to the extent possible with combined efforts of the public- and private-sectors, developing measures with high technical difficulties, such as methods to clean up the sea water in the harbor and to remove radioactive materials in the soil, and of making a comprehensive evaluation of all options for tritiated water containing residual risks as soon as possible and consider appropriate measures.

15.4 Management of Radioactive Wastes Generated Within Nuclear Power Station

Figure 15.2 illustrates the kinds of waste contaminated with radioactive materials and nuclear fuels emitted from the damaged nuclear reactors to the atmosphere, groundwater, and soil by the Fukushima accident, and an example of the flow of processing and disposal processes of the radioactive waste. Figure 15.2 roughly consists of three streams of wastes. The two upper streams show the management of wastes generated within Fukushima Daiichi Nuclear Power Station, and the bottom stream represents that generated outside of the Station.

The radioactive waste consists of liquid waste and solid waste. The liquid waste includes the liquid which was initially stored in Mega-Float and the barges and whose radioactivity level is not high, the waste fluid which will be generated from the decontamination processes in future, the zeolite containing waste liquid with high radioactivity level, the sludge with high radioactivity level, and sea water near a sluice gate which the silt fence prevents from diffusing to the open sea, and so on. The radioactive liquid waste will be separated into freshwater components, sea water origin components such as sodium chloride, and solid components through evaporation and condensation, and then the freshwater and sea water origin components will be released into the environment such as the ocean after confirming its safety to discharge into the environment. The radioactive solid waste generated will be classified into waste of which the disposal is judged to be appropriate and waste deemed unsuitable from the viewpoint of current available technologies or existing legal system.

The solid waste includes soil, rubble, and forest in the on-site areas of Fukushima Daiichi Nuclear Power Station. In addition to these, the solid waste also includes the dredged sludge, the soil and rubble on the sea floor, the filters of cesium adsorption facility, and so on. According to its radioactivity level, form, and characteristic, radioactive solid waste is considered to be decontaminated by, for example, washing, blasting, or exfoliation, if necessary. Consequently, waste which does not need to be managed as radioactive waste will be dealt with as industrial waste and suitably processed and disposed of, and waste, of which the safety is confirmed and which is able to be reused, will be recycled. The waste which needs to be managed as radioactive waste will be classified into the waste of which the disposal is judged to be appropriate and the waste to be unsuitable, as described above in the solid waste generated from the liquid waste. The former waste will be reduced in its volume, stored, solidified by appropriate methods and then disposed of. The latter waste, which is judged to be unsuitable for disposal by the current available technologies or in the existing legal system, will be reduced in its volume and stored until the technology development and the new legal system are in place. The adsorption material (ferrosyanide) used in ALPS and the slurry generated in the pre-processing stage of ALPS are examples of such. Hence, it is necessary to develop the technology and prepare the legal system, which include the concept of disposal, the concept of waste form, and the criteria

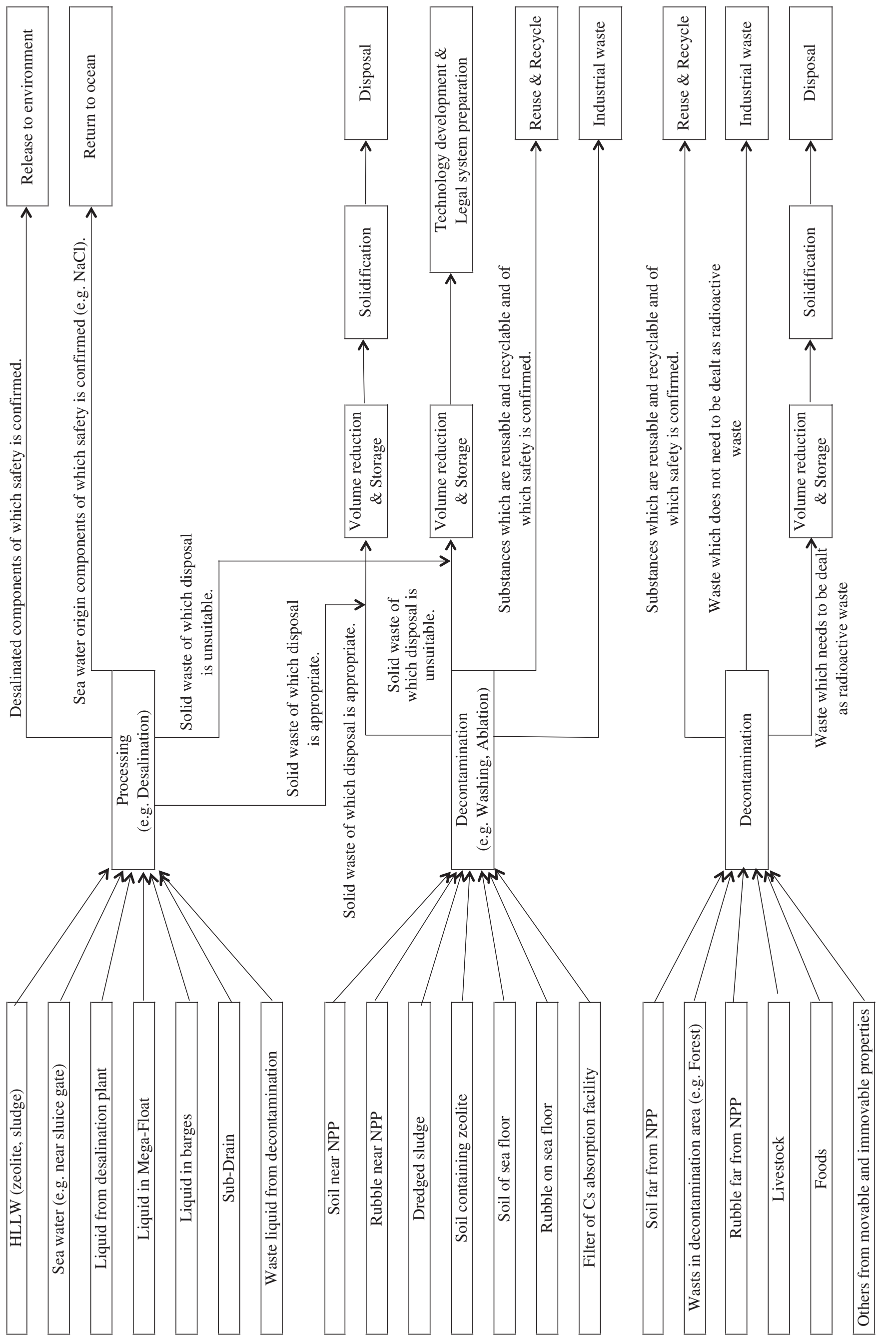

Fig. 15.2 Kinds of waste generated by Fukushima accident and an example of the flow of processing and disposal processes of radioactive waste

of release from the legal control on land use of the repository site and so on, to enable future disposal of this waste through social consensus and agreement.

Furthermore, the kinds and radioactivity levels of waste are widely distributed. For example, incombustible, flame-resistant, and combustible wastes intermingle and most are difficult to separate out from each other. There are wastes containing not only plutonium and/or an anti-scattering agent but also oil and sea water components, and lead, PCB, and asbestos which require special consideration in processing and disposal. It is also necessary to measure their contents in the waste. It is well known that it is difficult to elucidate the physicochemical characteristics of radionuclides in sludge.

In addition to these, there is the problem of the huge quantity of the waste. The processing for efficient reduction of the volume of intermingled waste is indispensable even for temporary storage. The quantity of the sea water components such as sodium chloride is also huge, and these components have to be separated. For example, the sea water components have to be separated from the sludge which is produced in the processing facility of high-level liquid waste, and simultaneously the radionuclides have to be separated from the sea water components. It is also essential and critical to solve the problem of how to reserve the many skilled workers for long-term restoration, considering their radiation exposure management, and so on.

15.5 Management of Nuclear Fuels in Nuclear Reactors and Spent Fuel Pool

Figure 15.3 illustrates an example of management of nuclear fuels in the reactors of Units No.1–3 of Fukushima Daiichi Nuclear Power Station and of spent nuclear fuels in the pools of Units Nos. 1–4.

The spent nuclear fuel in the pools will be classified into non-damaged spent nuclear fuel and damaged fuel. The former will be washed, loaded into canisters, and stored. (The policy on the nuclear fuel cycle in Japan after the Fukushima accident is not discussed in this chapter.) It is not yet clear how to manage the damaged spent fuel concretely and whether the non-damaged spent fuel will be reprocessed. In order to reduce the risk of spent fuel in the pools, the transfer of spent nuclear fuel in the pools to the common pool has started. In Unit No. 4, 726 fuel assemblies (704 spent and 22 new fuels) have been transferred to the common pool as of April 23, 2014, and the transfer of 1,533 fuel assemblies (1,331 spent and 202 new fuels) will be completed around the end of 2014. In Unit No. 3, the removal of large pieces of rubble from the pool is underway. In Unit No. 2, after progress is made in decontamination and shielding within the reactor building, formulation of a concrete plan will be discussed. In Unit No. 1, the construction of a yard to operate large and heavy machines is scheduled, and the demolition of the reactor building cover commenced in the first half of 2014.

Investigation has been performed on the amounts of fuel that were melted down and where the debris is distributed, and the decontamination and the fixation of

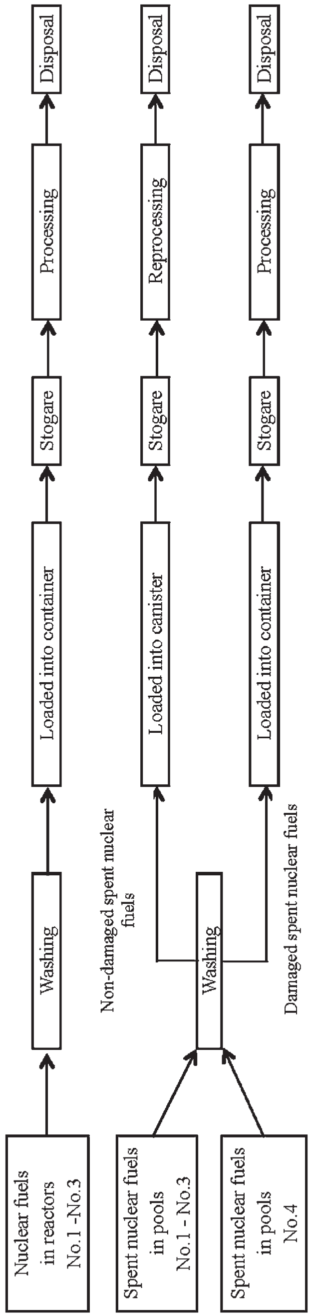

Fig. 15.3 Example of management of nuclear fuel in reactors No. 1–3 and spent nuclear fuel in the pools of No. 1–4

the pressure boundary of the primary containment vessel, as well as examination of physical and chemical characteristics of the debris. Furthermore, management of these nuclear fuels includes resolving the problems of where the nuclear fuels removed from the nuclear reactors are to be stored, who is to implement the final disposal, what the repository site selection procedure is, what the concept of disposal including the nuclear fuel cycle is, and how the legal system is prepared. This will entail the development of the method for processing and disposal of debris/melted nuclear fuel and development of technologies consistent with this method, the development of a specific container, and the development of remote-controlled technologies to locate the leaks of water in reactors and to repair those, as the work of removing the nuclear fuel from the reactors is carried out under the condition in which the reactors are filled with water. In addition to these, it is critical to confirm the soundness of the pressure vessels and containment vessels for a long time (at shortest, until completion of removing all nuclear fuels) because sea water containing salt was boiled in the vessels.

Although some of these steps cannot be taken until the conditions of nuclear fuels are known, we must take steady and appropriate actions one by one.

15.6 Concept of Radioactive Waste Disposal

All nations that have been using nuclear energy have adopted the method of disposal into the underground environments where the radioactive waste is generated. This is because it is most appropriate that the radioactive waste generated in a country is disposed of in its own territory; because currently available technologies, knowledge, and skills can be used in disposal; because the long-term safety assessment of disposal is expected to be performed reasonably; and because the retrievability of radioactive wastes is not technically impossible if it is required.

In Japan, very low-level radioactive waste has been disposed of at approximately 5 m below the ground surface ("landfill disposal" or excavation disposal), and relatively low-level radioactive waste, which is generated in operation and maintenance of nuclear reactors, has been disposed of at approximately 10 m depth from the ground surface ("vault disposal"). For low-level radioactive waste whose level of radioactivity is relatively high, the disposal at depths of 50–100 m ("subsurface disposal") has been considered and will be planned. High-level radioactive wastes are legally mandated to be disposed of at 300 m or more below the ground surface ("geological disposal"). This concept of disposal in Japan is illustrated in Fig. 15.4 [5, 6]. In vault disposal or subsurface disposal, radioactive waste is solidified using cementitious or other materials within a drum or a container specific to the solidification, and the drum or the container is covered by cement or concrete and further covered with material such as clay or mixture of clay and sand through which the groundwater is hard to penetrate and by which cations are easy to be trapped. The barrier of these artifacts is called an artificial barrier, and the safety of disposal is secured by the multi-barrier system which consists of the artificial barrier and the natural barrier which functions in the geosphere and the biosphere. In geological disposal, high-level radioactive liquid waste is mixed with borosilicate glass material and solidified in a stainless steel

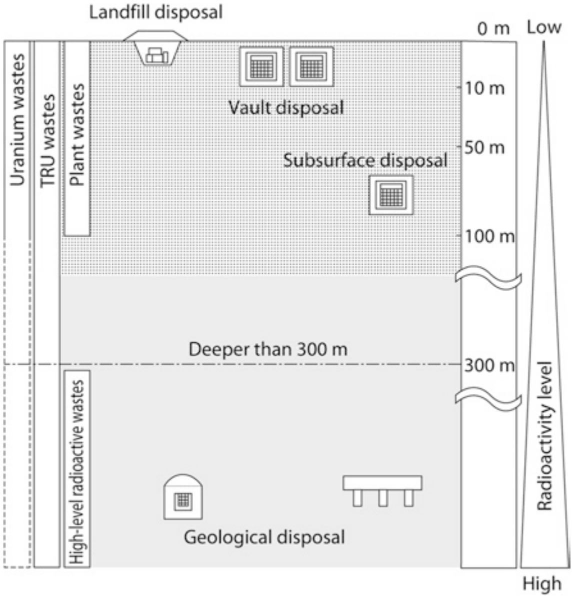

Fig. 15.4 Four types of disposal in Japan [5, 6]

canister (vitrified waste), and inserted into an overpack (e.g., carbon steel). The overpack containing the vitrified waste is transferred to the underground repository, placed in the tunnel and covered with compacted clay materials.

What is described above was the fundamental concept of radioactive waste disposal in Japan before the Fukushima accident. This concept is natural, scientifically reasonable, and technically sound. We mine, for example, iron, copper, or uranium ore, and refine it to use as iron, copper, or uranium. This fact clearly indicates that the deep underground environment has the capability to retain and contain metals over a long period of time in a geological sense (some 10 million years to some 100 million years).

To be accommodated in the disposal system mentioned above, it is expected that the waste contaminated with radioactive materials and the damaged nuclear fuel generated by the Fukushima accident will also be adequately processed, sealed in suitable containers, stored for a certain period, and then disposed of in the repository built in the relevant geological environmental conditions, according to their radioactivity levels. The plan, design, and implementation of the processing of radioactive waste must be optimized for achieving the safety in the final disposal, because the processing may influence the feasibility of disposal options.

Not only the technical and regulatory compatibility with the current system, but also broad support from the public for final disposal of radioactive waste generated by the Fukushima accident must be achieved. It is imperative that the Japanese people share their opinions on this issue with each other. The discussion will inevitably extend to Japan's nuclear future, i.e., whether Japan continues to exploit nuclear energy or phases it out.

15.7 Summary

Many countries, not only Japan, which have been using nuclear energy and have plans to use nuclear energy were forced to rethink the ethical value of use of nuclear energy by Fukushima Daiichi Nuclear Power Plant accident. Considering the final disposal of all nuclear fuels generated by the Fukushima accident, we fully recognize that radioactive waste management is an enterprise which will not be completed within the 21st century. Simultaneously, it goes without saying that the safe and steady management of radioactive waste is the premise for the restoration and revival of communities and residents of Fukushima. In such a situation, the management of various radioactive wastes generated by the Fukushima accident will be expected to proceed steadily and safely under greater coordination among science and technology, politics, and the public and society.

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