Chapter 3 Repository design and engineering technology

3.1 Basic design concept

In this chapter, a design concept is proposed for the engineered barrier system and the disposal facility, taking into account the wide range of geolgical environments in Japan. Examples of engineering specifications for the construction, operation and closure of the disposal facility are also presented. The assessment flow for the engineered barrier system and disposal facility is shown in Figure 3.1-1.

Table 3.1-1 shows the items that are considered in the construction of a disposal facility, taking into account the requirements for ensuring safety (safety factors) which are summarised in Section 1.2. The evaluation of the functioning of the engineered barriers and the disposal facility is based on these requirements.

Based on these requirements, the variations in the geological environment and example specifications for the engineered barriers and the disposal facility, it is shown that the engineered barriers and the disposal facility can be constructed using current technology and/or technology to be developed in the near future. Additionally, the long-term mechanical stability of the near-field is evaluated and the results are presented in the safety assessment in Chapter 4.

Table 3.1-1 Requirements considered in the design of the disposal facility

(i) Design of passive engineered barrier system with multiple safety function
(ii) Design of disposal system for containment, low flow rate, diffusion, dispersion, dilution and retardation
(iii) Design of appropriate infrastructure and layout
(iv) Design to reduce hazardous phenomena and perturbations
(v) Design taking into account the interactions between different barrier components, with the aim of maximizing their complementary effects
(vi) Design to minimise the effects of human intrusion
(vii) Design to ensure safety during operation

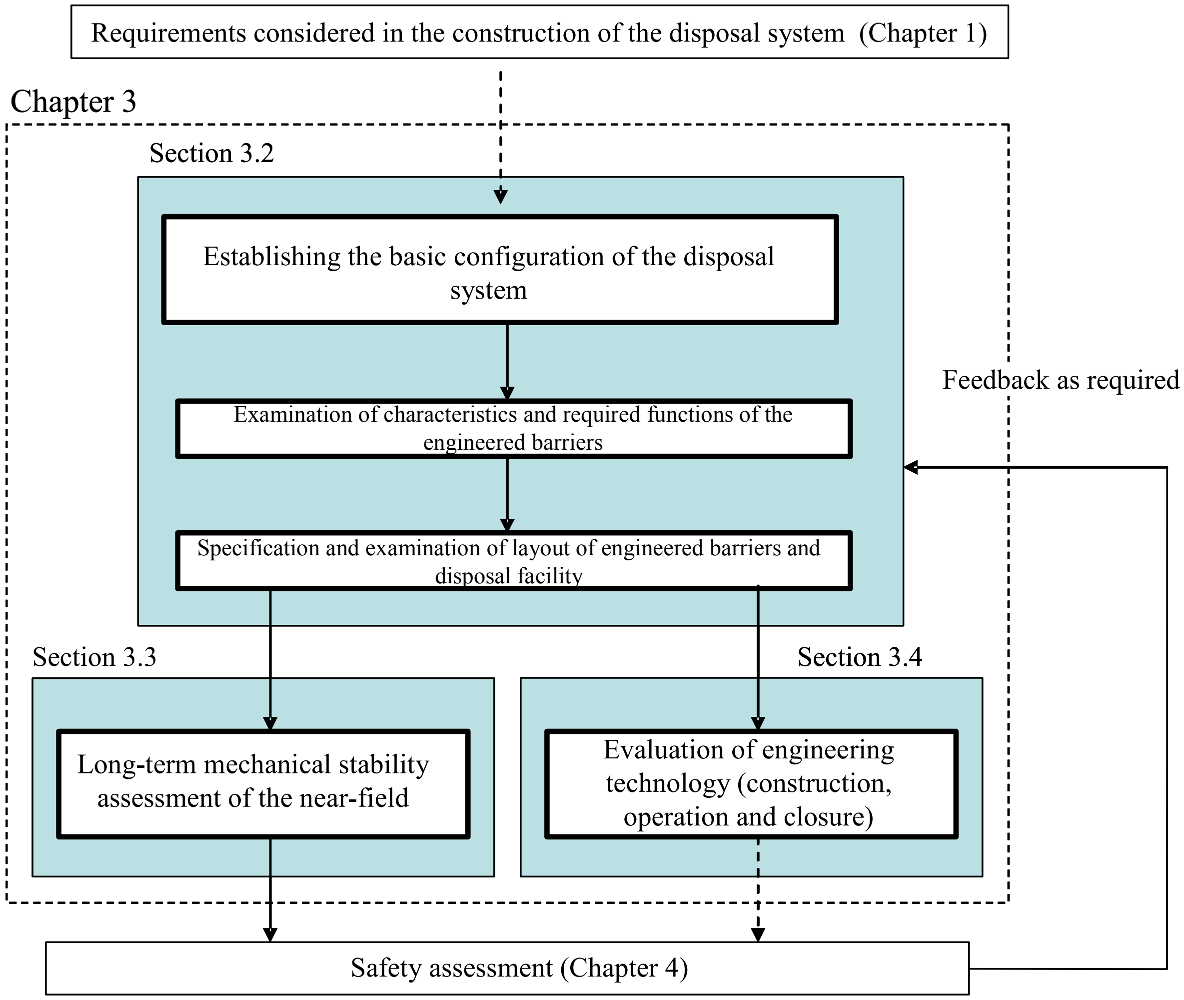


Figure 3.1-1 Assessment flow for the engineered barriers and disposal facility

3.1.1 Basic construction technique for the engineered barriers and the disposal facility

3.1.1.1 Engineered barriers

Given the low heat generation of TRU waste, it is possible to dispose of large waste volumes in disposal facilities with large cavities. Since there is a wide variation in the characteristics of TRU waste (activity of radioactive materials in the waste, physical form, thermal output, etc.), appropriate engineered barrier systems need to be selected taking into account the various groupings of TRU waste.

Firstly, the engineered barriers and their function in the disposal facility are described.

(1) Basic stucture and function of the engineered barriers

The basic concept for the engineered barriers developed from the 1st TRU progress report is shown in Figure 3.1.1.1-1. The functions for each engineered barrier, which should be considered in design, are summarized in Table 3.1.1.1-1. The function of each component of the engineered barrier system is as follows:

(i) Waste form (solidified materials/container/package): To allow efficient emplacement and the prevention of nuclide release during operation. After closure of the disposal facility, since sorption and chemical buffering are expected, investigation of these effects is carried out in this section based on the configured specifications of the engineered barriers. I-129 and C-14 are the most important nulides in the safety assessment of geological disposal of TRU waste and research and development on improved waste forms for these nuclides is described in Chapter 7.

(ii) Filler: This is required to prevent unexpected spreading of contamination during repository operation and to provide additional load support for the waste in the horseshoe-shaped disposal tunnels. Nuclide sorption by cement and other waste materials is expected.

(iii) Structural framework: Necessary for the mechanical stability of the waste and allowing efficient emplacement of the filler and buffer materials. In the case where cement material is used, sorption of nuclides is expected.

(iv) Buffer material: The main function is to restrict the infiltration of groundwater. Additionally, maintaining long-term performance, mechanical support of the waste, structural support and chemical stability are also considered to be important functions.

(v) Backfill: Fills the voids in tunnels used during construction and operation and prevents significant adverse impacts on the multi-barrier system. Additionally, backfilling should be considered as a measure for preventing human intrusion.

(vi) Tunnel support: Necessary for ensuring mechanical stabilitiy of cavities during operations.

(2) Basic configuration for each waste group

In this report, the basic configuration of the engineered barriers is described considering the characteristics of the different waste groups.

The grouping of waste is discussed in Section 2.5.4 and shown in Table 2.5.4-1. Figure 3.1.1.1-1 shows all types of engineered barriers for Group 1 and 2 wastes, which include large concentrations of long-lived nuclides such as I-129 and C-14 that are mobile in groundwater. Since Group 3 and 4 wastes contain lower concentrations of nuclides with long half-lives that are mobile in groundwater, the buffer material illustrated in Figure 3.1.1.1-1 are not used in the engineered barrier system for these groups.

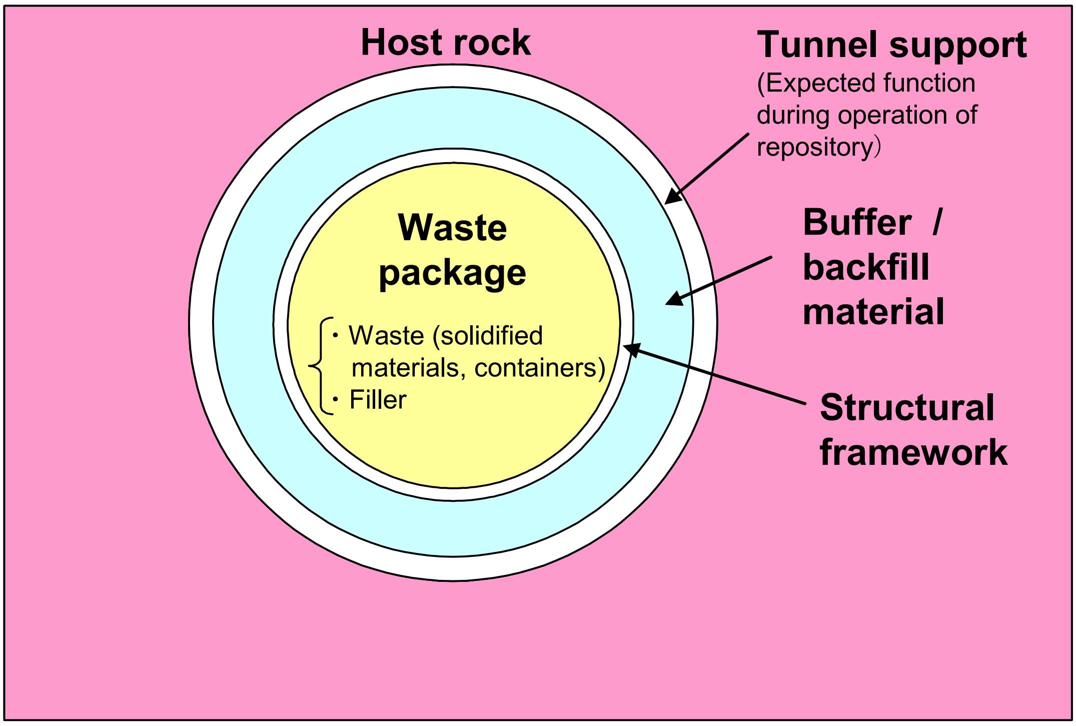


Figure 3.1.1.1-1 Basic concept for the engineered barrier system

Table 3.1.1.1-1 Summary of the main functions of each engineered barrier component

Classi-fication	Safety requirements (Table 3.1-1)		Function	Description of function	Waste		Filler	Structural framework	Buffer material	Backfill material	Support
					Solidified materials	Container package					
During operations	Ensuring safey during operations	(iii), (vii)	Cavity stability	Maintaining shape of access tunnels and prevention of wall surface degradation	—	—	—	—	—	—	●
		(iii), (vii)	Waste emplacement	Fixing waste and allowing filling material construction	—	●	—	●	—	—	—
		(iii), (vii)	Waste strength	High integrity waste form	○	○	●	—	—	—	—
		(iii), (vii)	Restriction of spread of contamination	Prevention of radionuclide release	●	●	●	—	—	—	—
Post-closure	Restriction of leaching and migration	(ii)	Restriction of groundwater movement	Restriction of groundwater infiltration	—	—	○	○	●	○	—
		(ii), (vi)	Restriction of radionuclide leaching	Physical confinement of radionuclides	○	○	○	○	○	—	—
		(ii)		Chemical buffering	○	—	○	○	○	—	—
		(ii)	Sorption of radionuclides	Sorption of radionuclides on engineered barriers	○	—	○	○	○	—	—
		(ii)	Self-sealing property	Filling of voids	—	—	—	—	○	○	—
	Mechanical stability	(i)	Stress buffering property	Buffering of external forces	—	—	—	—	○	○	○
		(i)	Mechanical load-bearing property	Support of the waste/structure by buffer material	—	—	○	—	●	—	—
		(i)	Stability of access tunnel	Mechanical stability of disposal tunnel	—	—	○	○	○	○	○
	Chemical stability	(v)	Reducing chemical alteration	Considering long-term alteration	○	○	○	○	●	—	○
	Others	(iv)	Thermal conduction	Dispersion of waste heat	○	○	○	○	○	○	—
		(iv)	Permeability characteristics	Gas permeability/self-healing	—	○	○	○	○	○	—
		(iv)	Restriction of colloid migration	Colloid filtration	—	—	—	—	○	—	—

● Function considered in the design

○ Function that is not considered in the design, but the effectiveness of which is verified.

3.1.1.2 Disposal facility

The basic concept for a geological repository for TRU waste can be divided into surface and underground facilities. Reception and transport of waste and other materials, construction of the underground facility, operation and closure and overall disposal management are some of the required functions of the surface facility. The underground facility is composed of the access tunnel, main shaft, connecting tunnels and disposal tunnels. The overall functioning of the TRU repository is shown in Figure 3.1.1.2-1.

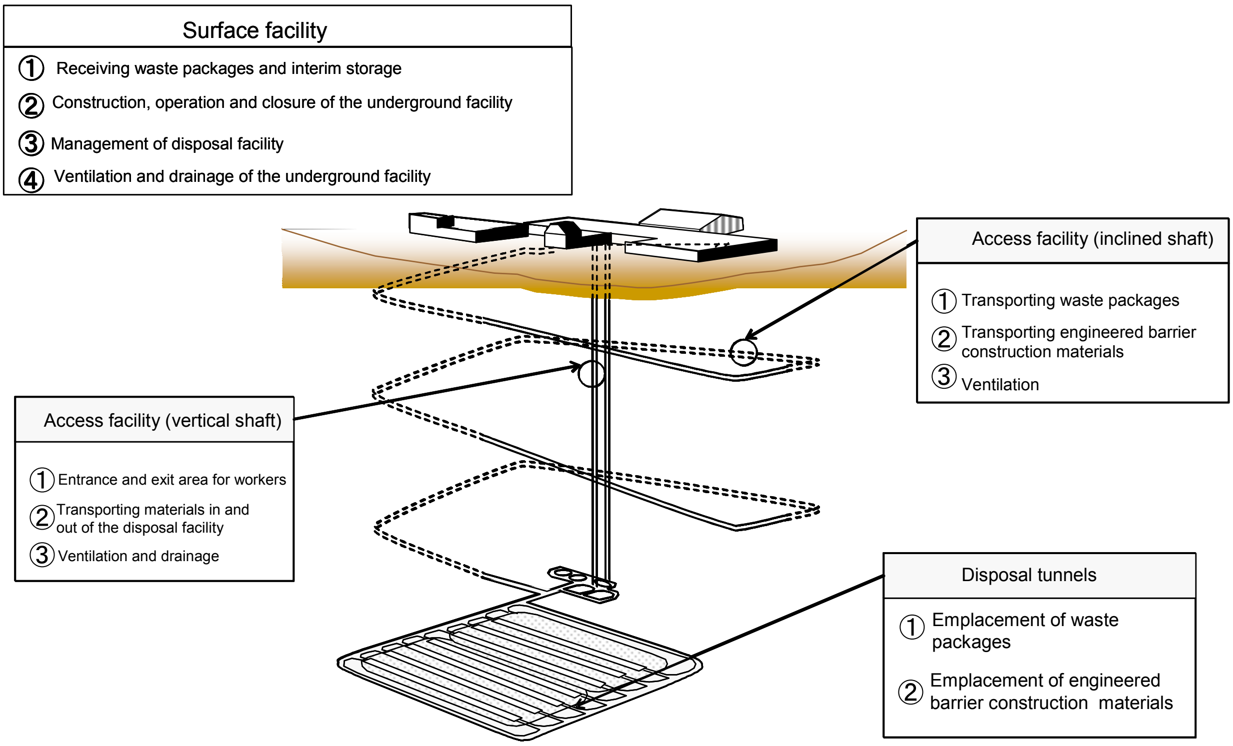


Figure 3.1.1.2-1 Basic concept for the TRU repository

3.1.2 Design conditions

In this section, the waste, the disposal site and the geological environment considered in the design of the disposal system are summarised.

3.1.2.1 Waste

The total volume of waste envisaged for geological disposal is estimated to be 26,640 m^3, which includes domestic TRU waste and low-level waste returned from overseas. The estimate was made by adding together all waste with total alpha particle concentrations above a predefined limit (around 1 GBq/t) and waste with high concentrations of I-129 with beta/gamma nuclides (spent silver absorbent).

3.1.2.2 Disposal site and geological environment conditions

The conditions of the assumed disposal site and geological environment are summarised in Section 1.3.2.1 in Chapter 1. In this report, the repository design is based on the following assumptions regarding disposal site and geological conditions.

Land form: Plain

Host rock properties: Dataset for soft rock (SR-B, SR-C, SR-D)

Dataset for hard rock (HR)

Groundwater: Freshwater type groundwater, Seawater type groundwater

Hydraulic conductivity: 1×10^{-8} m s^{-1}, 1×10^{-9} m s^{-1}, 1×10^{-10} m s^{-1}

Hydraulic gradient: 0.01

Disposal depth: 500 m (soft rock), 1,000 m (hard rock)

3.2 Design of the engineered barriers and the disposal facility

3.2.1 Design of Engineered barriers

3.2.1.1 Design of Waste package

The waste for geological disposal is classified into four types as follows.

(i) 200L drum: 600ϕ × 900H mm

(ii) Canister: 430ϕ × 1,335H mm

(iii) Square packages: 1,500 × 1,500 × 1,100H mm

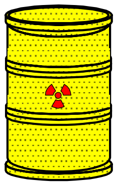
(iv) BNGS 500L drum: 800ϕ × 1,192H mm

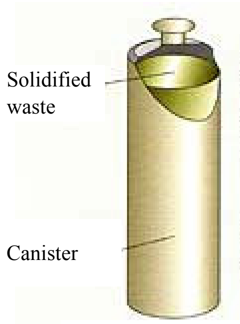
As reported in the 1st TRU progress report, waste drum and canister are packaged from point of efficiency of transportation and emplacement in underground facilities.

For small circular disposal tunnels that do not require any structural support with reinforced concrete, square packages are emplaced directly, each containing four 200L drums weighing less than 1 ton, four canisters or two BNGS 500L drums with the voids filled with cement mortar. In the larger horseshoe-shaped disposal tunnels, 200L drums, BNGS 500 drums and square packages are emplaced directly, with four canisters in each waste package.

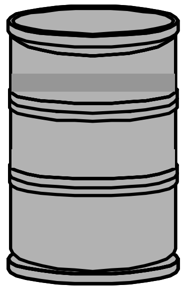
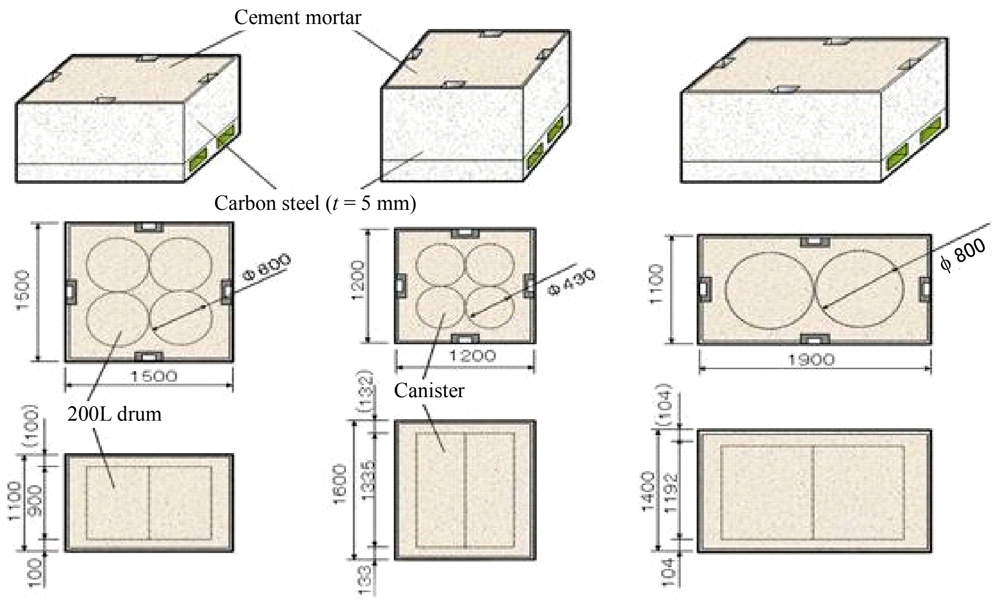
The waste packages shown in Table 3.2.1.1-1 are grouped according to package strength, type of manufacturing and handling properties. The development of alternative packages taking into account the containment function for long-lived nuclides such as C-14 (cf. Chapter 7) is also considered. The details of the development of alternative packages are presented in Appendix 3A.

Table 3.2.1.1-1 Waste package concepts

<table>
<tr>
<td>Waste container</td>
<td>

200L drum



Canister


BNGS 500L drum
</td>
</tr>
<tr>
<td>Waste package</td>
<td>


Waste package A

Waste package B

Waste package C
</td>
</tr>
</table>

3.2.1.2 Buffer material

Bentonite is used as buffer material around the waste package. It functions as an engineered barrier that restricts the migration of radionuclides from the disposal facility.

In this section, the required performance of the buffer material is evaluated based on its properties and specifications.

(1) Required functions of the buffer material

The required functions of the buffer material are shown in Table 3.2.1.2-1. The buffer material is designed to restrict groundwater infiltration and to support the waste/structure of the disposal facility. Additionally, since cementitious materials are used in the engineered barrier system for TRU waste disposal, it is necessary to consider the interaction between buffer materials and cementitious materials.

Table 3.2.1.2-1 Required functions of the buffer material

	Function	Details
Function considered in design	Restriction of groundwater movement	Restrict groundwater flow passing through the disposal facility
	Mechanical stability	Maintain support at a predefined position and prevent significant subsidence on the long term
	Barrier interaction	Consider the interaction with cement materials and maintain the predefined functions on the long term
Function not considered in design but effectiveness of which is verified	Restriction of radionuclide leaching	Confine radionuclides and maintain quality of pore water in disposal tunnel, decreasing the solubility of radionuclides
	Sorption of radionuclides	Sorption of soluble radionuclides and decreasing the radionuclide concentration in pore water
	Self-sealing	Filling pore spaces generated
	Stress buffering	Stress buffering of external forces from surrounding rock
	Stability of disposal tunnel	Maintain stability of disposal tunnels wrt structural changes in the surrounding rock
	Thermal conductivity	Disperse heat from waste in order to maintain temperatures below permitted levels
	Permeability	Prevent significant barrier degradation due to pressure build-up in the disposal facility and the formation of preferred groundwater flow paths by gas percolation
	Restrict colloid migration	Restrict the migration of radio-colloids and infiltration of natural colloids

(2) Required performance of buffer material

The required functions of the buffer material described in (1) are evaluated from the viewpoint of preventing groundwater flow into the disposal facility and the required performance of the buffer material is determined.

a. Restriction of groundwater infiltration

The amount of groundwater infiltration into the disposal facility is calculated using the hydraulic conductivity and the thickness of the buffer material as parameters. Also, the Peclet number can be used to determine whether mass transport is controlled by advection or diffusion. Since it is assumed that the amount of groundwater infiltration into the disposal facility is significantly affected by the direction of groundwater flow relative to the disposal tunnel, cases where the direction of flow is vertical and horizontal to the longitudinal axis of the disposal tunnel are considered. A circular disposal tunnel 12 meters in diameter is assumed. For the calculation of the Peclet number, a typical thickness of buffer material is established and a diffusion coefficient for anionic species set with a small value of 4×10^{-11} m^2/s. The hydraulic conductivity of cementitious material which makes up the the inner part of the buffer material is assumed to be 1×10^{-5} m s^{-1}, taking into account crack generation.

The calculated results for the average Peclet number in the buffer material for the vertical flow case and the horizontal flow case are shown in Figures 3.2.1.2-1 and 3.2.1.2-2, respectively. If the hydraulic conductivity of the buffer material is assumed to be below 1×10^{-10} m s^{-1} in the vertical flow case and below 1×10^{-11} m s^{-1} with increased infiltration into the facility in the case of horizontal flow, the Peclet number is 0.1 or below. If the hydraulic conductivity of the buffer material is assumed to be below 1×10^{-11} m s^{-1} by taking into account the uncertainty of the groundwater flow direction in the disposal tunnel and length of the disposal tunnel, it can be shown that diffusion becomes the dominant mechanism for mass transport through the engineered barrier system.

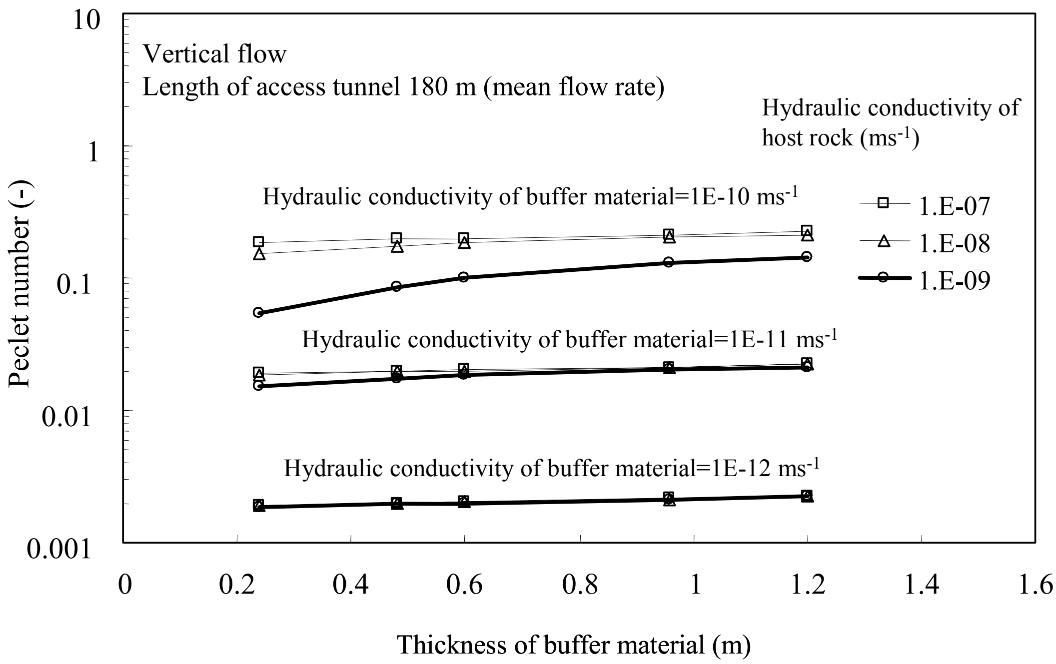


Figure 3.2.1.2-1 Peclet number for buffer material for vertical flow
(mean flow velocity of groundwater)

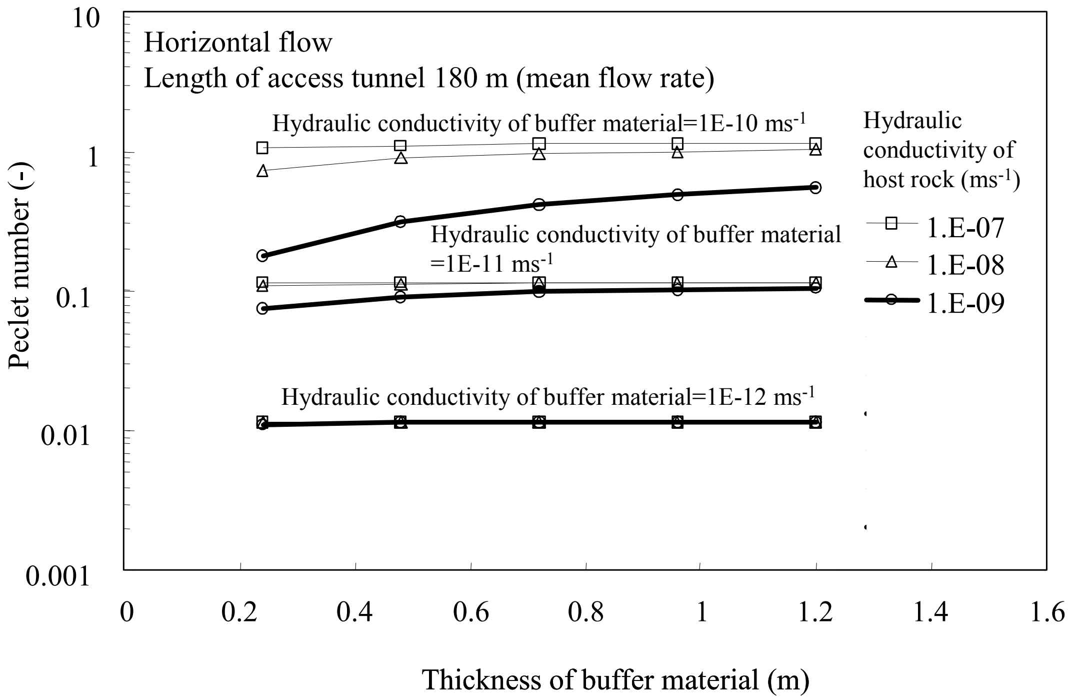


Figure 3.2.1.2-2 Peclet number for buffer material for horizontal flow (mean flow velocity of groundwater)

b. Decreasing nuclide release rates through buffer material diffusion

In this section, the release rate of I-129 in Group 1 waste (the most important nuclide in dose assessments) by steady-state diffusion through the buffer material is calculated using the thickness of the buffer material as a parameter. The effect of buffer material thickness on decreasing release rate is then evaluated.

In the evaluation model, the configuration of the disposal tunnel is considered to be a circular cavity with a diameter of 12 m, with buffer material emplaced concentrically. The inner buffer material is assumed to be a region of complete mixing and nuclide concentration in the pore water is determined from the distribution equilibrium with cementitious material. In the outer buffer material, a zero concentration level was set as a boundary condition, showing the highest release rate from the buffer material estimated by considering a wide range of geological environments. The parameters used in this analysis are shown in Table 3.2.1.2-2. The release rate with steady-state diffusion is calculated from an analytical solution of the cylindrical coordinate system.

The release rates from the near-field that take into account the analytical result based on the thickness of the buffer material are shown in Figure 3.2.1.2-3. Radionuclide release rates decrease as buffer material thickness increases (also shown in the same figure). The release rates from the near-field decrease rapidly with buffer material thicknesses up to 1 m, but decrease only moderately for thicknesses above 1 m. Since the diameter of the disposal tunnel is fixed at 12 m, increasing the thickness of the buffer material will require an increase in repository tunnel length and hence surface area in order to accommodate the same amount of waste. Hence, the small reduction in radionuclide release rate achieved by increasing buffer thickness beyond 1 m will tend to be balanced out by the increase in tunnel wall surface area.

For the case where the diameter of excavated tunnels in the disposal facility is 12 m, since increasing the buffer material thickness beyond 1 m has only a small effect on radionuclide release, the buffer material thickness is set at 1 m in this report.

Table 3.2.1.2-2 Parameter settings used

Parameter	Unit	Set value	Remarks
I-129 inventory	mol	6.06×10^{4}	Summarised in Chapter 2
Volume of Group 1 waste	m^3	318	
Filling rate of waste in disposal tunnel	%	20	Based on filling rate of circular tunnel in first TRU report
Sorption partition coefficient in buffer material	m^3/kg	0.00025	Set based on Section 4.5.2
Density of inner buffer material	Mg/m^3	2.580	
Porosity of inner buffer material	-	0.19	
I-129 concentration in inner buffer material	mol/dm^3	53.5×10^{-3}	Calculated from set condition
Effective diffusion coefficient in buffer material	m^2/s	4×10^{-11}	Set based on Section 4.5.2
Boundary condition of outer buffer material	mol/dm^3	0	Assuming the condition which yields highest release rates

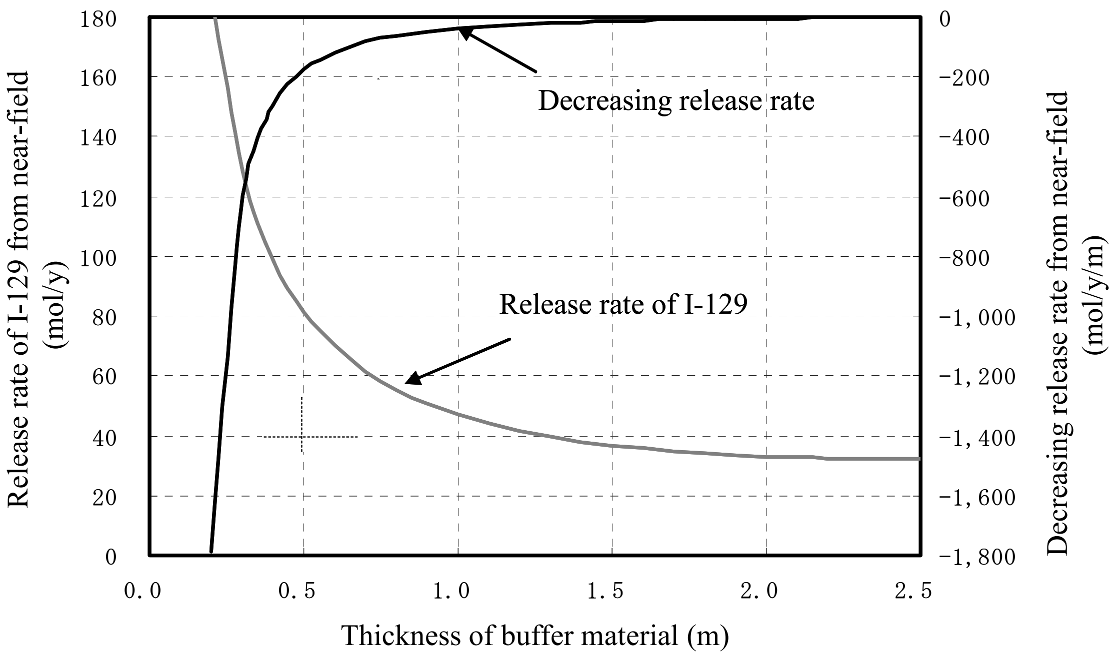


Figure 3.2.1.2-3 Decreasing effect on release rates with increasing thickness of the buffer material

(3) Proposed specifications of buffer material

From paragraphs (1) and (2) above, the specifications of the buffer material are as follows:

- Hydraulic conductivity: below 1×10^{-11} m s^{-1}
- Thickness of buffer material: 1 m

a. Evaluation of hydraulic conductivity

Recent studies have shown that the hydraulic conductivity of the buffer material can be estimated from the effective clay dry density ρ_e (Mg m^{-3}) in equation (1) (e.g. JNC, 2000).

$$\rho_e = \frac{\rho_d(100 - Rs)}{\left(100 - \frac{\rho_d Rs}{\rho_s}\right)} \qquad (1)$$

Where

ρ_d : Dry density of compacted bentonite (Mg m^{-3})

ρ_s : Soil particle density of silica sand (Mg m^{-3})

Rs : Mixing rate of silica sand (%)

A summary of hydraulic conductivities estimated from effective clay dry density by several research institutes is shown in Figure 3.2.1.2-4.

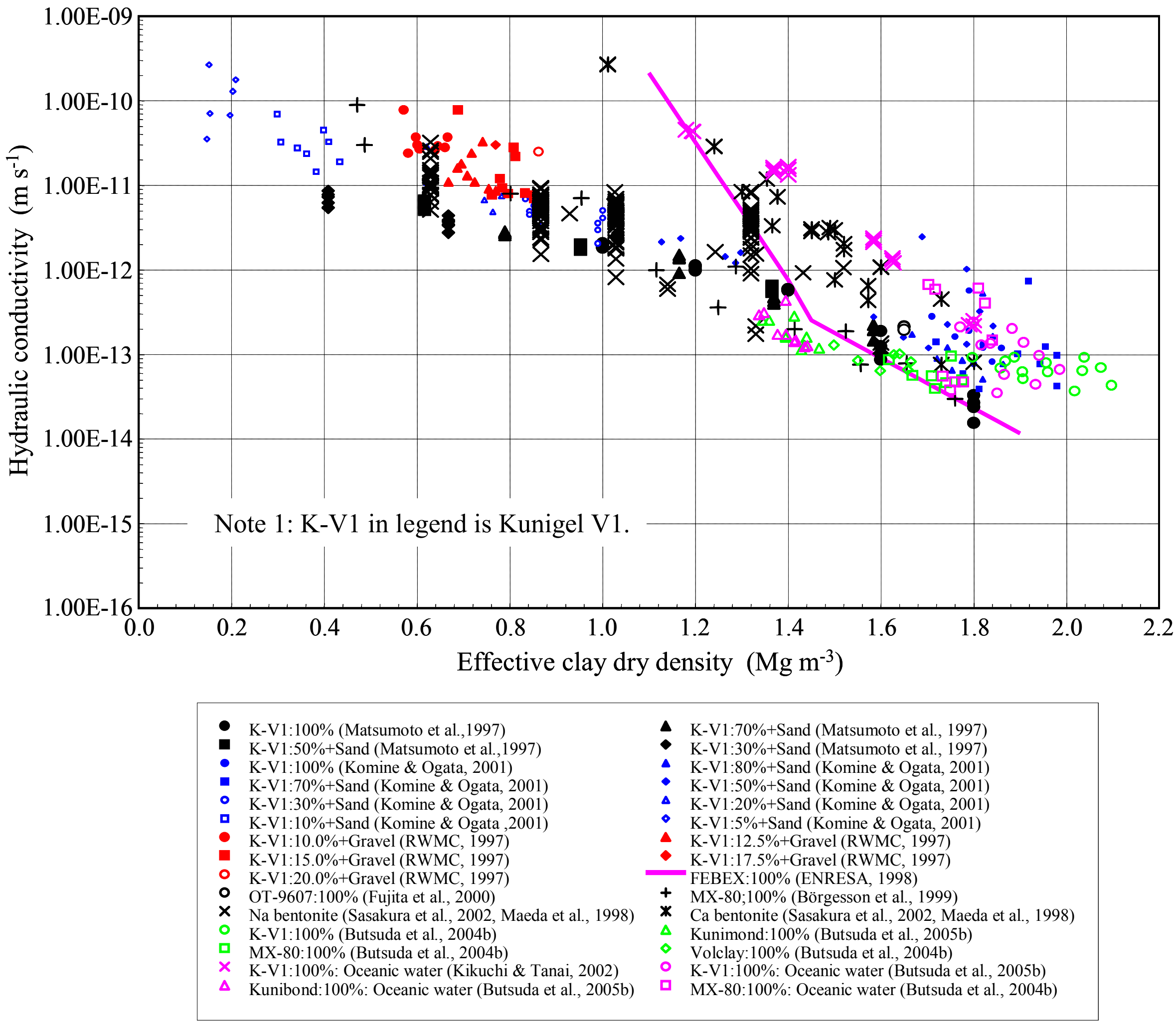


Figure 3.2.1.2-4 Relationship between effective clay dry density and hydraulic conductivity for various types of bentonite

In this Figure, an increasing trend of hydraulic conductivity is shown in the case where bentonite-calcium exchange occurs, forming Ca-bentonite. In the TRU waste disposal facility, since cementitious material will be used in the engineered barriers, the formation of calcium bentonite is assumed and an evaluation based on calcium exchange was performed.

The hydraulic conductivities of Kunigel V1 and Ca-type bentonite (Sasakura et al., 2002) and empirical equations showing the relationship between hydraulic conductivity and effective clay dry density are shown in Figure 3.2.1.2-5. It is revealed in the theoretical model of flow between mineral layers that the variation in exchangeable cations among the montmorillonite layers affects the permeability of bentonite (Komine, 2004). Using the empirical equations in Figure 3.2.1.2-5, it is found that the hydraulic conductivity of Ca bentonite falls below 1×10^{-11} m s^{-1} with an effective clay dry density of 1.34 Mg m^{-3}.

If saline groundwater is assumed, the permeability of bentonite increases because of the electrochemical effect that decreases the thickness of the double diffusion layer. The hydraulic conductivity of Kunigel V1 derived in synthetic saline water is shown in Figure 3.2.1.2-6 (JNC, 2003). It has been reported that saline water has little effect on Ca bentonite with an effective clay dry density above 1.4 Mg/m^3 (Figure 3.2.1.2-5, Butsuda et al., 2004b; Butsuda et al., 2005b; Won-Jin et al., 2002). Although the water resistance of bentonite has yet to be clarified in saline groundwater, the hydraulic conductivity is below 1×10^{-11} m s^{-1} with an effective clay dry density of 1.42 Mg m^{-3} according to the empirical equations in Figure 3.2.1.2-6.

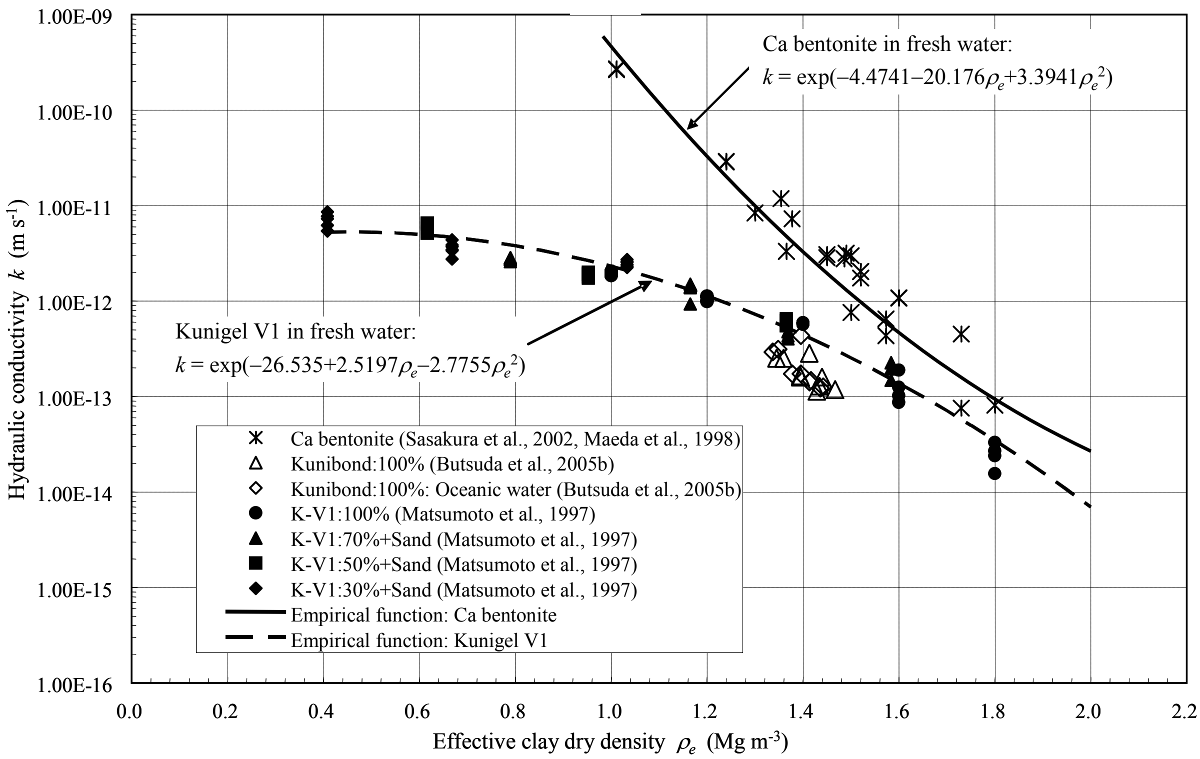


Figure 3.2.1.2-5 Relationship between effective clay dry density and hydraulic conductivity for Ca bentonite

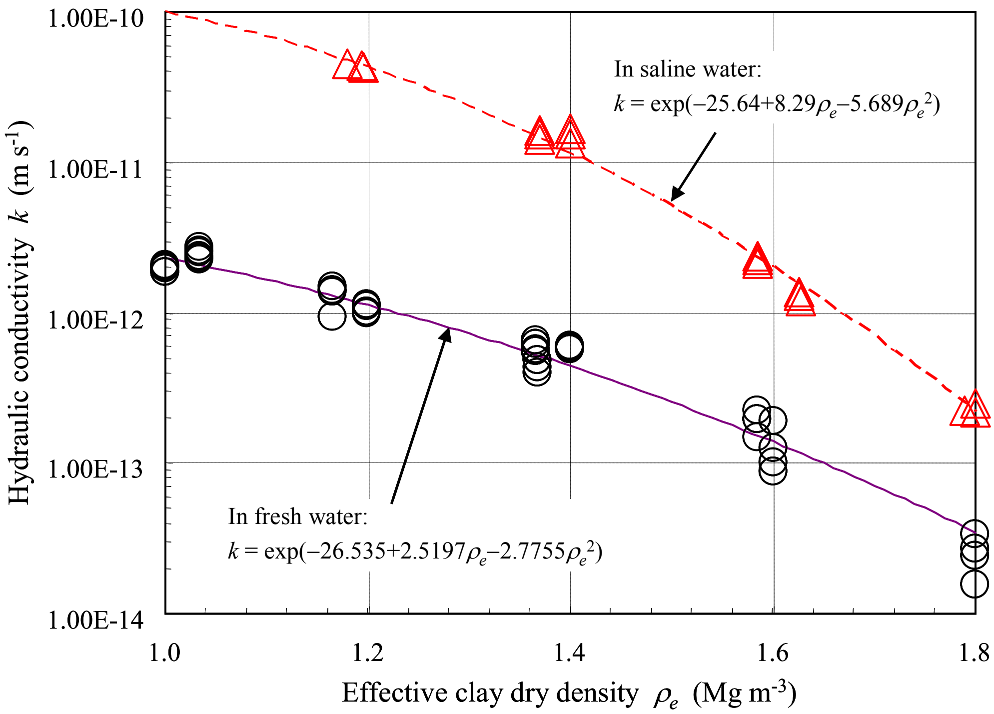


Figure 3.2.1.2-6 Relationship between effective clay dry density and hydraulic conductivity for fresh and saline water

b. Evaluation of the specification for buffer material thickness

Although the thickness of the buffer material was set at 1 m following the evaluation in (2) above, deformation of the bottom buffer material from waste loading, filling materials and structural support also needs to be considered.

Based on an evaluation of long-term deformation in the 1st TRU report, the thickness of the bottom buffer material was set at 1.2 m, allowing for a displacement of -0.2 m at a dry density of 1.6 Mg m^{-3}. The deformation behavior of bentonite on the long-term is evaluated in Section 3.3 below.

c. Example specifications of the buffer material

Taking into account the the evaluation results above, example specifications of buffer material are shown in Table 3.2.1.2-3.

Table 3.2.1.2-3 Example specifications of buffer material

		Bottom	Side	Top
Fresh water	Thickness (m)	1.2	1.0	
	Effective clay dry density (Mg m^{-3})	1.36		
	Dry density (Mg m^{-3})	1.60	1.36	
	Mixing rate of silica sand (%)	30	0	
Saline water	Thickness (m)	1.2	1.0	
	Effective clay dry density (Mg m^{-3})	1.45		
	Dry density (Mg m^{-3})	1.60	1.45	
	Mixing rate of silica sand (%)	20	0	

Note 1: Target value for effective clay dry density in fresh water and saline water is > 1.34 Mg m^{-3} and 1.42 Mg m^{-3}, respectively.

Note 2: Since the dry density of the bottom buffer is required to be > 1.6 Mg m^{-3}, dry density and mixing rate of silica sand of the bottom parts only is shown.

3.2.1.3 Material design of filler

Filler is used to provide structural support during waste emplacement operations by connecting the waste package to structure and is expected to restrict radionuclide migration due to sorption after facility closure. Since cementitious material is stable and has sufficient strength, and is widely used as a construction material in the civil engineering sector, its use is considered for the filler.

(1) Summary of the basic condition

In the disposal facility for TRU waste, cementitious material is used to fill the spaces between the emplaced waste packages. The required functions of the filler include preventing unexpected release of radionuclides and to provide additional load support during operation of the facility. After closure of the disposal facility, the filler is expected to sorb nuclides and retard nuclide migration. However, on the long-term, the functioning of the filler is yet to be established.

The required functions of the filler are summarised in Table 3.2.1.3-1.

Table 3.2.1.3-1 Required functions of the filler

Function		Content
Strength	Short term	Filling of space between waste packages/waste forms and structural support during emplacement operations. As it is not necessary to consider external forces, the regulatory value of 18 - 21 N/mm^2 would be sufficient for filler used in the repository. However, the same value of 30 N/mm^2 as for solidification material (RWMC, 1998) is also set as a target value for the filler here.
Workability	Short term	In order fill the space between waste packages/waste forms and provide support, it is necessary for the filler to have sufficient flow properties to fill narrow spaces between waste packages. Since material separation occurs in the mixture of fillers made of aggregate, there is a possibility that strength will be insufficient in places, hence material segregation resistance is nessesary for the filler.
Thermal properties	Short term	It is desirable to consider the thermal effect from waste packages and to use filling material with high thermal conductivity.
Thermal durability	Short term	Thermal alteration of cement mineralogy is not considered a problem since wastes are emplaced such that the temperature of cementitious material does not exceed 80°C
Chemical (sorption)	Long term	Desired function includes sorption of radionuclides

(2) Filler design

A design concept conforming to each required function in (1) is described as follows:

Strength: The target value of compressive strength of the filler is set at 30 N/mm^2, which is the regulatory value for solidification materials in a repository (RWMC, 1998). Since the hardening rate of the filler might be slower than that of normal concrete (typically 4 weeks), it is preferable for the strength of the filler to last about 13 weeks, which is the strict regulatory time period required for pre-packed concrete to harden (Japan Society of Civil Engineers, 2002).

Fluidity: Since small spaces need to be completely filled, a value that is consistent with the fluidity of grouting mortar for pre-packed concrete (Japan Society of Civil Engineers, 2002) and fluidity required for solidification materials (Japan Society of Civil Engineers, 2002) is selected. In other words, the fluidity should be such that the flow time through a P-type funnel should fall within a JSCE-F521 time range (Japan Society of Civil Engineers, 1999).

Resistance to material segregation: The bleeding ratio should be kept below 3% (below 1% in high strength pre-packed concrete) after 3 hours from the start of the test (Japan Society of Civil Engineers, 2002). If there is the possibility of cavities forming due to bleeding, the composition of the filler should be adjusted to avoid the bleeding.

Thermal conductivity: Aggregates with high thermal conductivity should be selected to prevent an increase in temperature due to the heat generation of the waste. Moreover, the use of an anti-thermogenic admixture (fly ash, silica fine powder for example) is considered for preventing heat generation during hardening of the filler.

Thermal resistance: Since the temperature in the facility is kept below 80°C, alteration of cementitious materials is not anticipated and, where such materials are to be used in the filler, thermal resistance is not considered a problem.

Chemical properties (sorption): Since sorption of radionuclides onto cementitious material is expected, mortar with good sorption properties should be selected as a filler material.

(3) Material composition

Filler material

Filler material required the same properties as for grouting mortar for pre-packed concrete.

Binder (cement and admixture)

The binder used for grouting mortar, fly ash cement or the mixing of OPC and fly ash according to a concrete standard specification document (Japan Society of Civil Engineers, 2002) is selected from the viewpoint of fluidity and thermal control during hardening.

Aggregate

A finer-grained aggregate than that of ordinary concrete should be used in order to improve fluidity and water retention.

Using additives is a way to adjust the fluidity, prolong setting, adjust the resistance to material segregation and adjust the retention time of fluidity of the filler. In selecting an additive, the effect of incorporation of constituents from the engineered barriers should be considered.

3.2.2 Design of the underground facility

The underground facility of the repository is composed of disposal tunnels, a main tunnel, connecting tunnels and access tunnels. The entire underground facility is backfilled after emplacement of the waste.

In this report, feasible configuration and dimensions of the disposal tunnels are established based on the results of a mechanical stability analysis of the disposal tunnel during excavation and/or during an earthquake. The number of waste containers to be emplaced in the disposal tunnel (cross-section) is then established and the distance between disposal tunnels is set based on mechanical and thermal constraints. The layout of the underground facility is evaluated by considering safety during construction, operation and closure of the disposal facility. The assessment flow for the layout of the underground facility is shown in Figure 3.2.2-1.

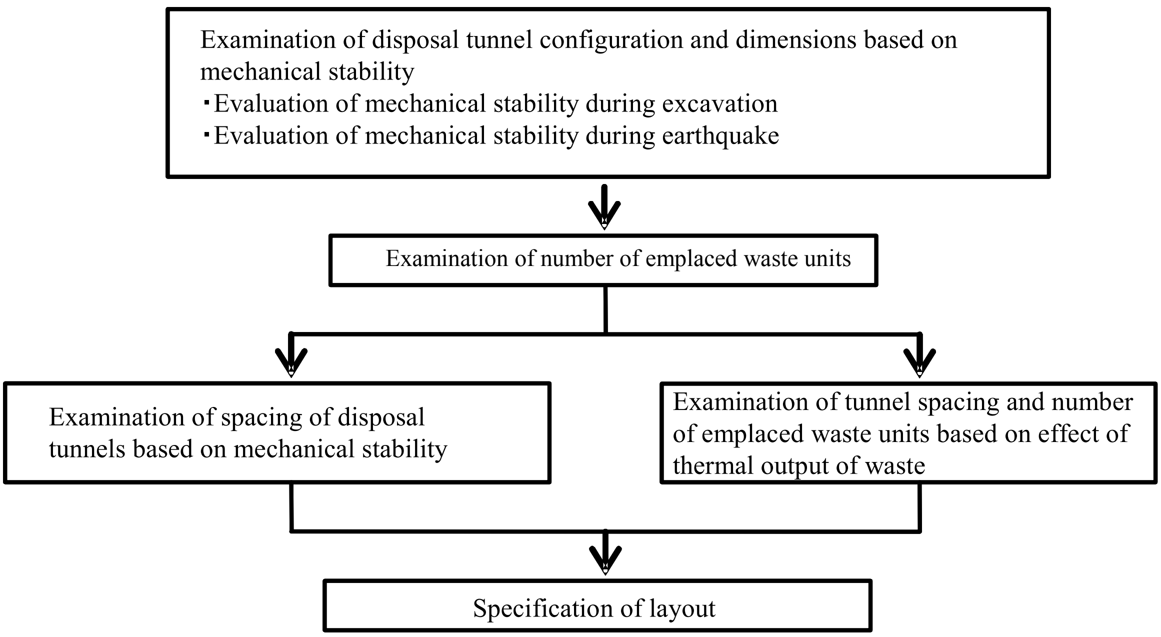


Figure 3.2.2-1 Evaluation process for the layout of the underground facility

In addition to the above, various installations, backfill and plugs are designed to facilitate ease of waste emplacement, etc.

3.2.2.1 Mechanical stability of the disposal tunnel

Since TRU waste has a low heat generation, large amounts of waste can be packed densely in large cavities. The configuration and scale of the disposal tunnel is limited by the mechanical stability of cavities deep underground, as well as by local site charactersitics.

In this report, the configuration and scale of disposal tunnels is evaluated by considering the geological environment of soft and hard rocks as described in Section 1.3

The configuration of the disposal tunnels is based on knowledge obtained from constructing large-scale cavities for underground power plants and emergency underground oil reserves (TRU Coordination Team, 2000)

(1) Evaluation of the configuration and scale of the disposal tunnel

a. Soft rock

Due to a lack of strength in soft rock, a tunnel with a circular cross-section is selected to give maximum mechanical stability under the high pressure conditions of the deep geological environment. The cavity is also supported with concrete and steel.

During excavation, a mechanical stability analysis model developed by CRIEPI (Motojima et al., 1978) was used as this method had already been applied extensively for excavation of large underground cavities for underground power plants and the model parameters of host rock deformation and strength can be easily set.

To evaluate the stability of the disposal tunnel in soft rock, the design and construction guidelines of the New Austrian Tunnelling Method (NATM) (Japan Railway Construction Public Corporation, 1996) were used and a local safety factor of less than 1.2 was determined as being sufficient for excavation diameters within 20% and support stress < 28 MPa.

Table 3.2.2.1-1 shows three soft rock datasets used in the analysis. 9 analytical cases with different combinations of inner tunnel diameter (Table 3.2.2.1-2), target depth and physical properties of the host rock were considered. In this analysis, the initial host rock pressure for the vertical component is estimated from the overburden pressure and the horizontal component is estimated from the lateral pressure coefficient K_0 (= σ_h / σ_v) and depth. In selecting the excavation diameter, 60 cm was assumed for the thickness of support material (thickness of shotcrete + secondary lining).

Table 3.2.2.1-1 Mechanical property values used in the analyses

	SR-B	SR-C	SR-D
Saturated density ρ (Mg m^{-3})	2.35	2.20	1.95
Elastic coefficient E (MPa)	4,000	3,500	2,500
Poisson's ratio ν	0.30	0.30	0.30
Adhesion c (MPa)	4.0	3.0	2.0
Angle of internal friction ϕ (degree)	29	28	27
Tensile strength σ_t (MPa)	2.8	2.1	1.4

Table 3.2.2.1-2 Cases used in analysis

Case	Inner diameter of tunnel	Target depth for inspection	Physical properties of host rock
1	8.0 m (excavation diameter 9.2 m)	500 m	SR-B
2			SR-C
3			SR-D
4	10.0 m (excavation diameter 11.2 m)		SR-B
5			SR-C
6			SR-D
7	12.0 m (excavation diameter 13.2 m)		SR-B
8			SR-C
9			SR-D

The analytical model is shown in Figure 3.2.2.1-1. Analytical steps based on excavation operation stages are shown in Figure 3.2.2.1-2.

In the excavation analysis, the physical property values used assume that primary support is from shotcrete.

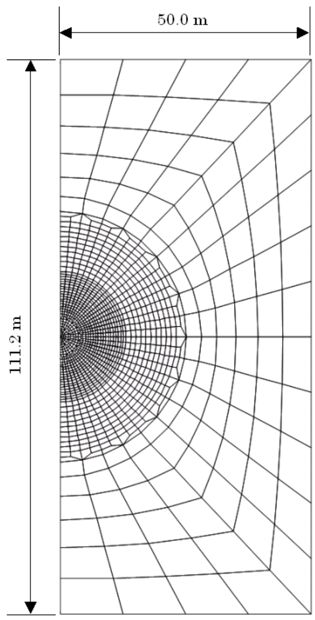


Figure 3.2.2.1-1 Example for analytical model

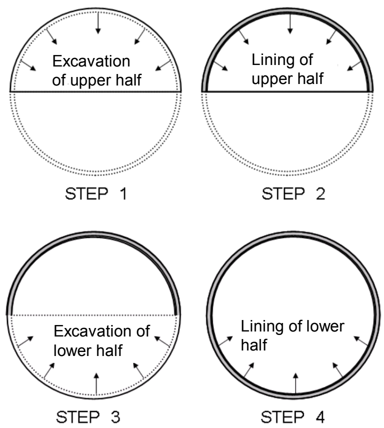
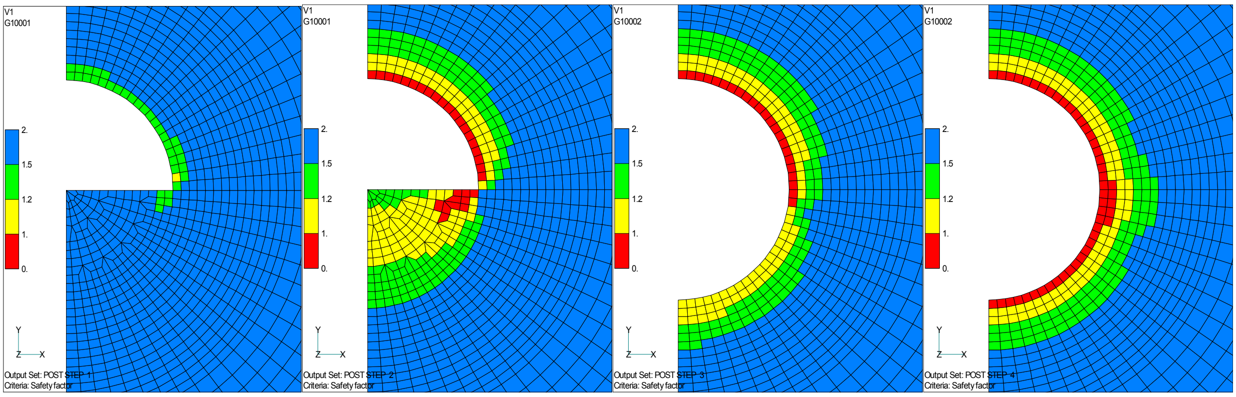


Figure 3.2.2.1-2 Analytical steps

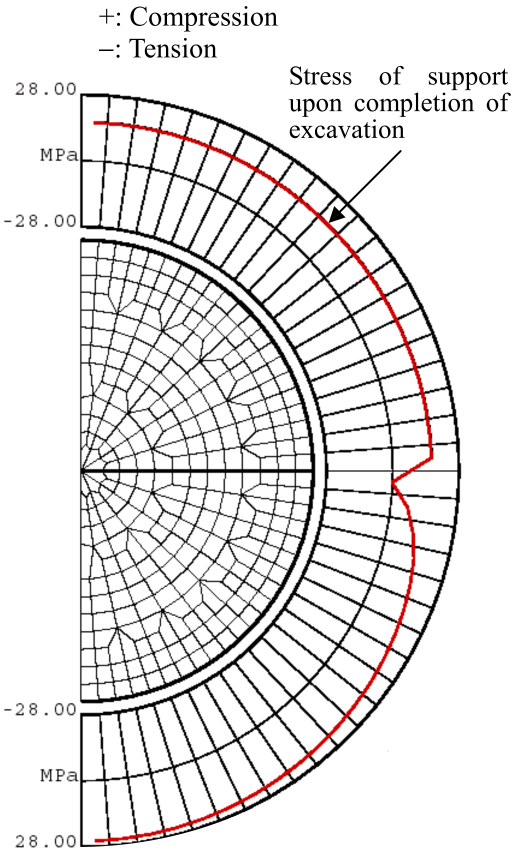
Example distributions of local safety factors of the surrounding host rock of the disposal tunnel and support stress are shown in Figures 3.2.2.1-3 and 3.2.2.1-4, respectively. The corresponding numerical values are shown in Table 3.2.2.1-3.



Excavation of upper half **Support of upper half** **Excavation of lower half** **Support of lower half**

Case 8: Inner diameter of tunnel 12.0 m, dataset SR-C

Figure 3.2.2.1-3 Distribution of local safety factors



Case 8 Inner diameter 12.0 m, SR-C

Figure 3.2.2.1-4 Distribution of support stress

Table 3.2.2.1-3 Summary of analytical result

Case	Inner diameter of access tunnel	Target depth	Host rock	Stability criteria	
				Area with local safety factor is up to 1.2	Stress of support
				Within 20% of excavation diameter	Below 28 MPa
				(m)	(MPa)
1	Inner diameter 8.0 m Excavation diameter 9.2 m	500 m	SR-B	1.0	13.3
2			SR-C	1.5	19.5
3			SR-D	1.5	23.2
4	Inner diameter 10.0 m Excavation diameter 11.2 m		SR-B	1.5	14.9
5			SR-C	2.0	23.0
6			SR-D	2.0	26.5
7	Inner diameter 12.0 m Excavation diameter 13.2 m		SR-B	2.0	16.3
8			SR-C	2.0	25.7
9			SR-D	3.0	30.3

Note1: Indicator value of local safety factor (20% of excavation diameter) is as follows.
ϕ9.2 m × 20% = 1.8 m, ϕ11.2 m × 20% = 2.2m, ϕ13.2 × 20% = 2.6 m

Based on the above analysis results, for the same rock mass increasing the excavation diameter expands regions where the local safety factor is below 1.2 and an increase in support stress is seen. Also, in the case where the excavation diameter is kept the same, the region where the local safety factor is below 1.2 is expanded by a decrease in strength of host rock and an increase in support stress is seen. Based on the stability criteria established in this report, it is shown that stability is assured for all cases except for case 9. Stability appears problematic in case 9 due to target values being exceeded. However, the stability could be assured by changing the excavation steps (e.g. excavating smaller segments at a time).

b. Hard rock

The strength of hard rocks gives more flexibility in constructing tunnels with large cross-sections. As the disposal tunnel for TRU waste is a large underground cavity (several tens of metres in width and height), the existence of fractures might affect its mechanical stability. As shown in the H12 report, the tendency for hard rocks to fracture is higher than that of soft rocks and mechanical stability evaluations therefore take fracturing into account in this report. Cavities with both horseshoe-shaped cross-sections, which allow ease of emplacement operations, and circular cross-sections, providing high mechanical stability, are examined. Support measures are considered necessary for maintaining mechanical stability of disposal tunnels in fractured rocks.

In this report, the MBC analysis model (Yoshida et al., 1996a) was selected as a mechanical stability analysis method for evaluating the effects of fracturing. In the stability analysis of the disposal tunnel, maximum shearing strain is used as one criterion for evaluating stability. Regions with > 0.3% maximum shearing strain around the disposal tunnel were evaluated.

Input physical parameters related to the matrix part of the host rock and fracture charcteristics (e.g. predominant fracture groupings, strike and dip of fracture, fracture interval, length of fracture, friction angle, and relief angle) are listed in Table 3.2.2.1-4. Four cases are analysed with different combinations of tunnel size and configuration, tunnel depth and presence or absence of fractures in the host rock. As with the analysis performed on soft rock, initial ground pressure is estimated.

The analytical model is shown in Figure 3.2.2.1-5. The analytical steps based on excavation steps are shown in Figure 3.2.2.1-6.

Table 3.2.2.1-4 Parameters used in the MBC analysis

Parameter		Input value	Source, etc.
Rock matrix	Elastic modulus	37,000 MPa	Dataset for hard rocks (HR)
	Poisson's ratio	0.25	
Fracture character -istics	Predominant fracture groupings	2 groupings	Based on the results of preliminary analysis
	Predominant direction of fractures	45°	Based on the results of preliminary analysis
	Fracture interval	50 cm	Taken as fracture characteristics in hard rocks in geological environment conditions as described previously
	Fracture length	1.6 m	Assumed from the research report (Ohtsu et al., 2001) on fracture characteristics and modeling in basement rocks in Japan
	Friction angle	35°	Based on the previous case example using MBC analysis (e.g. Yoshida et al., 1996b)
	Inclination angle	10°	

Table 3.2.2.1-5 Cases used in analysis

Case	Configuration/scale of access tunnel	Depth	Presence of fractures
1	Horseshoe-type width 12.0 m, height 18.0 m	1,000 m	None
2			Present
3	Circular type inner diameter 12.0 m		None
4			Present

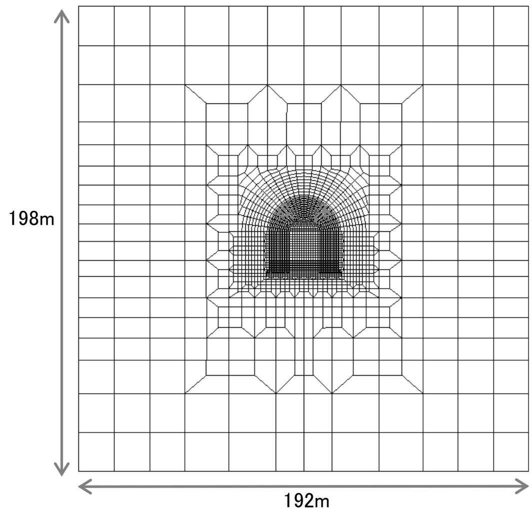


Figure 3.2.2.1-5 Example of analytical model (horseshoe-shape)

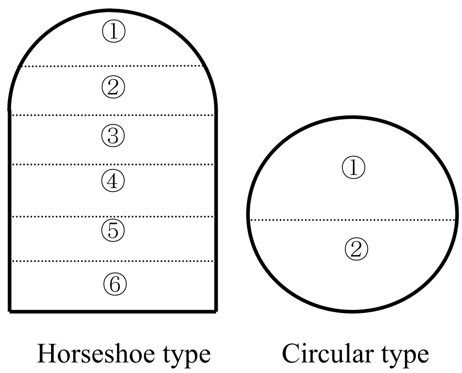


Figure 3.2.2.1-6 Analytical steps

Examples of the distribution of maximum shearing strain in the host rock around the disposal tunnel are shown in Figure 3.2.2.1-7. Case values are shown in Table 3.2.2.1-6.

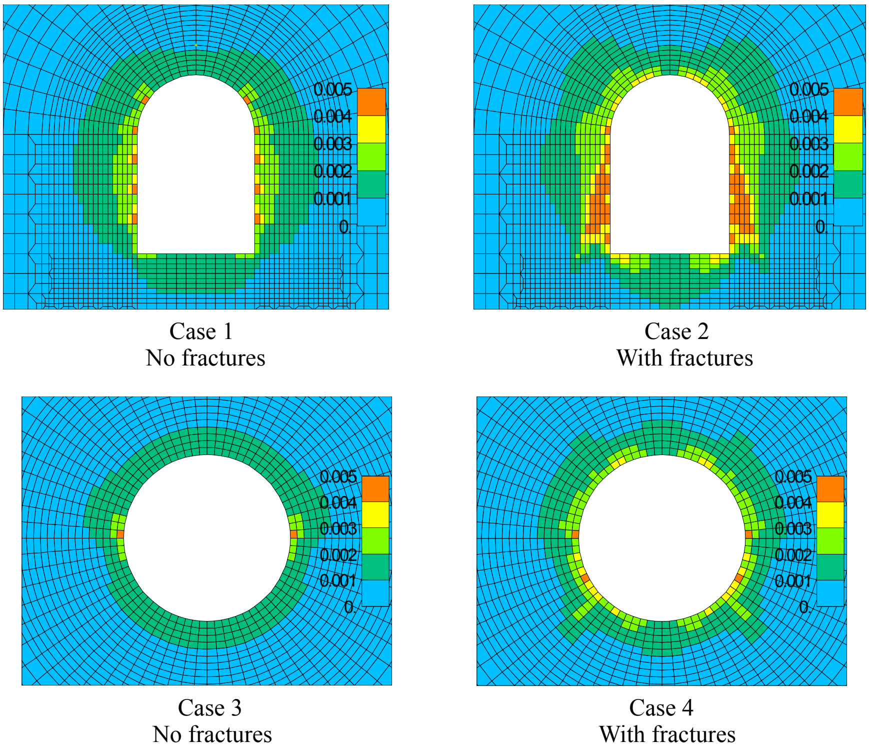


Figure 3.2.2.1-7 Distribution of maximum shearing strain

Table 3.2.2.1-6 Summary of analytical results

Case	Shape and scale of tunnel	Target depth	Presence of fracture	Indicator for local safety coefficient Area with shearing strain is above 0.3% (m)
1	Horseshoe type width 12.0 m, height 18.0 m	1,000 m	None	1.0
2			Present	3.0
3	Circular type inner diameter 12.0 m		None	0.5
4			Present	0.5

It was found that, for the case of horseshoe-shaped tunnels, the presence of fracturing has the effect of increasing regions with maximum shearing strain greater than 0.3%. On the other hand, the presence of fractures does not appear to have much effect in terms of increasing regions with maximum shearing strain > 0.3% in the case of circular tunnels. Also, the distribution of such regions is smaller for tunnels with circular cross-sections than for horseshoe-shaped tunnels; hence the circular cross-section clearly has better mechanical stability.

(2) Quake-resistance assessment of the disposal tunnel

In order ensure safety during construction, operation and closure of the disposal facility, each type of tunnel should be mechanically stable during earthquakes and during excavation.

In this report, an outline assessment of the mechanical stability of the disposal tunnel during earthquake motion is performed using a 2D dynamic finite element analysis (Super FLUSH/2D). This is an analytical method that uses seismic external force (obtained from accelerated time history) as direct input in order to solve equations of motion. El-centro waves which were used for the stability and quake-resistance assessement in the H12 report are taken here as input waves. The analytical model is shown in Figure 3.2.2.1-8 and the seismic velocity structure for the host rock model is shown in Figure 3.2.2.1-9. In this report, an evaluation using the SR-C dataset for a circular tunnel in soft rock is performed and the earthquake-resistance of the disposal tunnel is evaluated considering the local safety factors and support stress as well as mechanical stability. The analytical case is set up using the inner diameter of the tunnel in Table 3.2.2.1-7 as the parameter.

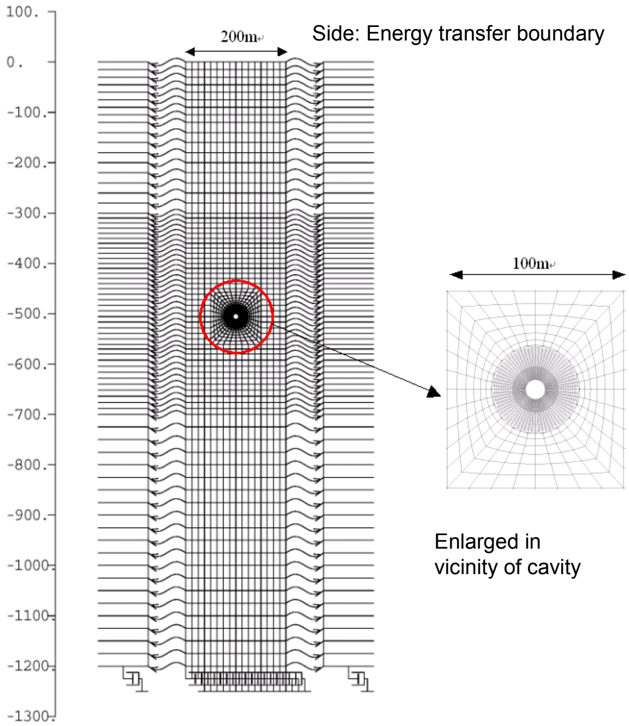


Figure 3.2.2.1-8 Analytical model example

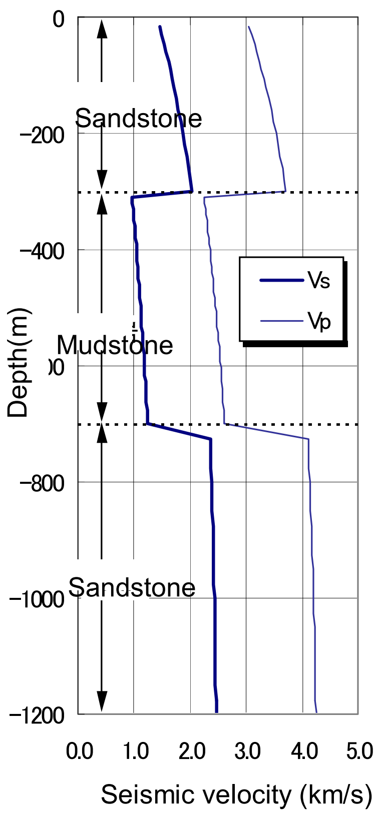
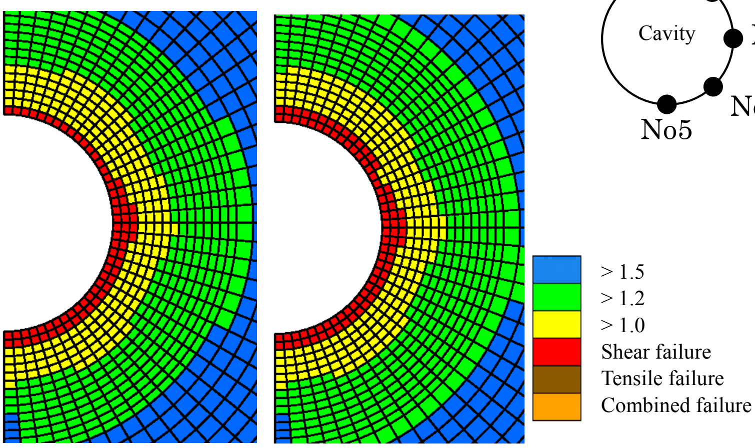


Figure 3.2.2.1-9 Seismic velocity structure in a bedrock model

Table 3.2.2.1-7 List of analytical cases

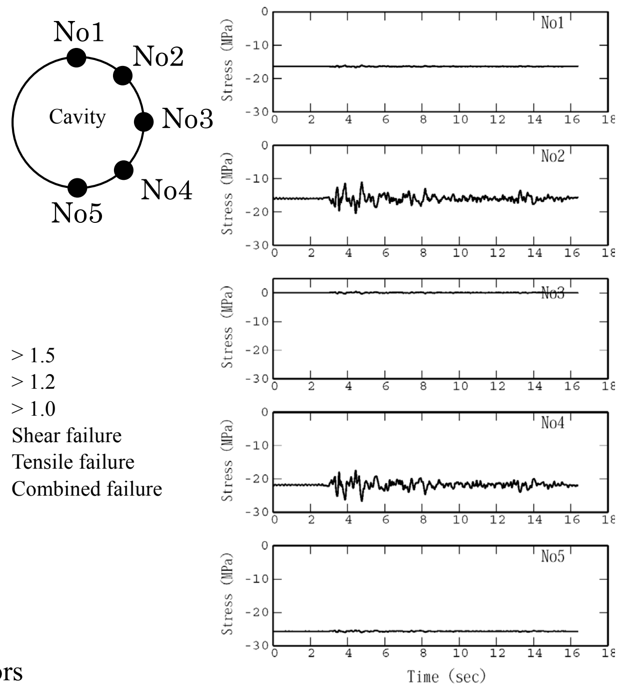
Case	Inner diameter of tunnel	Depth	Physical properties of basement rock
1	8.0 m (excavation diameter 9.2 m)	500 m	SR-C
2	10.0 m (excavation diameter 11.2 m)		
3	12.0 m (excavation diameter 13.2 m)		

An example result of the distribution of the local safety factor and temporal variation of support stress in the disposal tunnel during excavation and during an earthquake are shown in Figures 3.2.2.1-10 and 3.2.2.1-11. The results are summarised in Table 3.2.2.1-8.



Case 3: Inner diameter of tunnel 12.0 m, SR-C

Figure 3.2.2.1-10 Distribution of local safety factors



Case 3: Inner diameter 12.0 m, SR-C

Figure 3.2.2.1-11 Temporal variation of support stress

Table 3.2.2.1-8 Summary of results

Case	Inner diameter	Depth	Host rock	Criteria for local safety factors: Area with local safety factor > 1.2	Criteria for local safety factors: Support stress
				Within 20% of excavation diameter	Below 28 MPa
				(m)	(MPa)
1	8.0 m (excavation diameter 9.2 m)	500 m	SR-C	1.5	21.6
2	10.0 m (excavation diameter 11.2 m)			2.0	25.2
3	12.0 m (excavation diameter 13.2 m)			2.5	28.0

Note 1: Target local safety factors (20% of excavation diameter) as follows.
ϕ9.2 m × 20% = 1.8 m, ϕ11.2 m × 20% = 2.2 m, ϕ13.2 × 20% = 2.6 m

From these results, it is found that the seismic increment is small and the earthquake effect on the disposal tunnel is small. Hence, if the mechanical stability of the disposal tunnel is assured during construction of the disposal facility, its mechanical stability can be assumed to be assured during an earthquake.

(3) Summary

The established configuration and scale of the disposal tunnel for each rock type, based on the evaluation of mechanical stability in (1) and (2), is summarised in Table 3.2.2.1-9.

Table 3.2.2.1-9 Configuration and scale of tunnels in each rock type

Soft rock (500 m)			Hard rock (1,000 m)	
Circular			Horseshoe-shaped	Circular
SR-B	SR-C	SR-D	HR	
ϕ12 m	ϕ12 m	ϕ10 m	W12 × H18 m	ϕ12 m

3.2.2.2 Layout of the underground facility

When evaluating the layout of the underground facility, it is necessary to ensure the mechanical stability of the single/multiple tunnel(s) as shown in Figure 3.2.2. For an engineered barrier that uses cementitious materials, the number of waste packages and tunnel spacing should be established such that a uniform temperature (< 80°C) is maintained in order to prevent cement alteration as this reduces its sorption function. In this section, a mechanical stability of multiple tunnels and the effects of heat generated from the waste on the number of waste packages and tunnel spacing are evaluated. Layout of the underground facility is illustrated taking these considerations into account.

(1) Design of structural framework

In evaluating the number of waste packages, the required thickness of the structure used during waste emplacement needs to be established. In this section, the structural framework for each tunnel type is evaluated.

a. Basic conditions

A required function of the structural framework is to facilitate efficient waste emplacement and filling operations. The required functions of the structural framework are summarised in Table 3.2.2.2-1.

Table 3.2.2.2-1 Desired properties of the structural framework

Function	Explanation
Efficient emplacement of waste packages and filling operations	Ensuring sufficient space for transport and emplacement of waste and filler
Ensuring mechanical stability	Ensuring mechanical stability during emplacement and filling operations

b. Structural framework in the circular disposal tunnel

In the circular disposal tunnel, space for waste emplacement is limited as the structural framwork is rectangular. In order to increase emplacement efficiency per cross-section of waste, thin steel is considered for the structural framework.

The configuration of the steel support is shown in Figure 3.2.2.2-1.

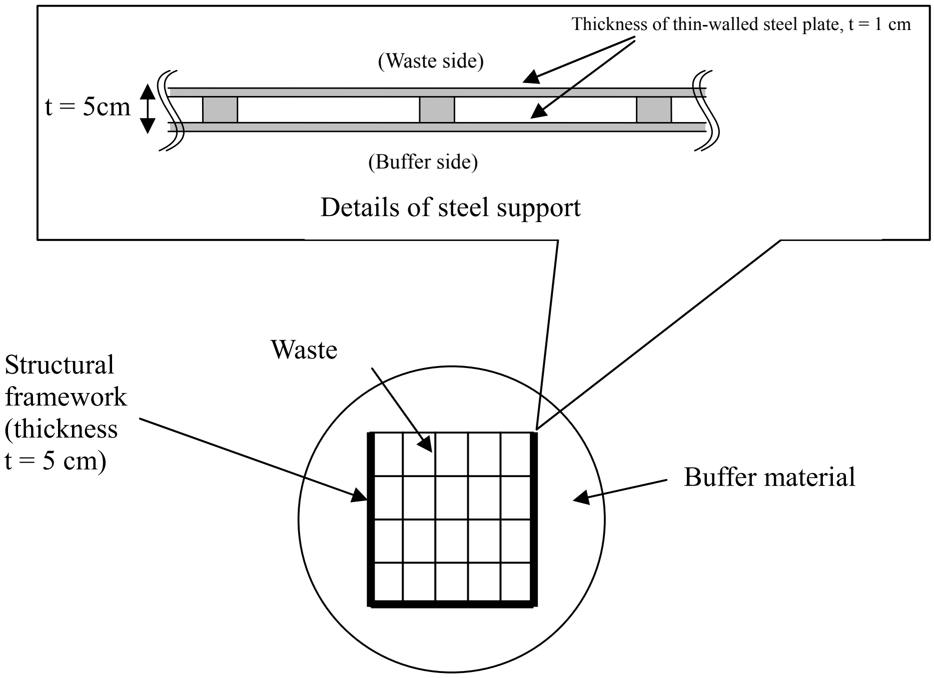


Figure 3.2.2.2-1 Shape of steel structural framework (example)

c. Structural framework in horseshoe-shaped disposal tunnel

In the case of the horseshoe-shaped disposal tunnel, there is sufficient space in the ceiling area (arched section) to set up a crane for lifting and emplacement of waste. In order to provide adequate support, the structural framework is made from reinforced concrete, although, at present, detailed specifications for operations and machinery (forklift, crane) have not yet been decided. The outline configuration of a structural framework made of reinforced concrete is shown in Figure 3.2.2.2-2.

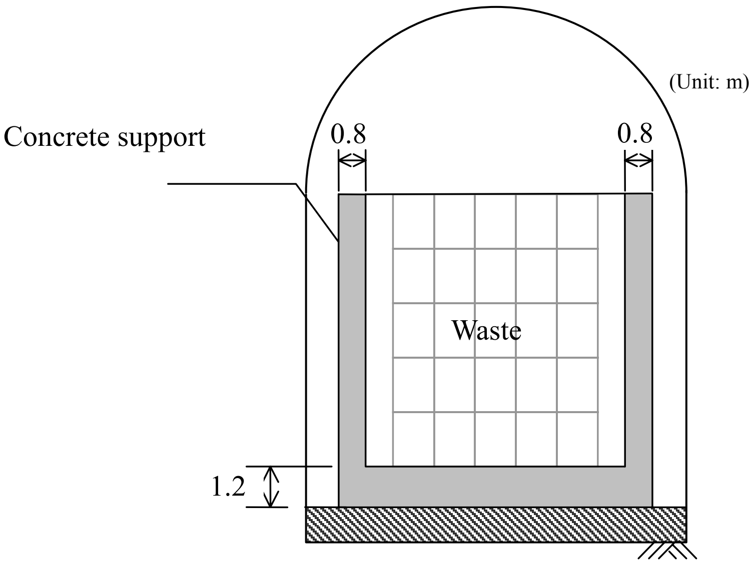


Figure 3.2.2.2-2 Shape of concrete support (example)

(2) Disposal tunnel spacing taking into account the mechanical stability of multiple tunnels

Disposal tunnel spacing (from tunnel centre) is constrained by mechanical stability. In the 1st TRU progress report, disposal tunnel spacing was established from assessments based on the elastic theory.

In this report, the established separation distance of disposal tunnels is 3D (where D is the tunnel diameter) for circular tunnels and 2.5W (W: tunnel width) for horseshoe-shaped tunnels.

(3) Evaluation of the thermal effect of waste

Disposal tunnel spacing for Group 2 waste is primarily controlled by thermal effects.

In the reference case for soft rock and hard rock (soft rock reference case: SR-C rock type, depth 500 m, circular cross-section; hard rock reference case: HR rock type, depth 1,000 m, circular cross-section), a thermal analysis of the modeled cross-section dimension is performed using a non-linear thermal-stess program (ASTEA MACS Ver 3).

a. Upper limit of temperature in disposal tunnel

As described before, the upper limit of temperature in the disposal tunnel is set at 80°C in order to prevent cement material alteration by re-crystallization.

b. Summary of analytical conditions

The physical values used for the thermal analysis are based on the H12 report and the 1st TRU progress report. The values used are shown in Table 3.2.2.2-2.

Table 3.2.2.2-2 Thermophysical properties

Constituents		Density (Mg/m^3)	Thermal conductivity (W/m°C)	Specific heat (J/kg°C)
Host rock	SR-C	2.200	2.20	1,400
	HR	2.670	2.80	1,000
Support*1		2.500	2.56	1,050
Invert		2.350	2.56	1,050
Buffer material*2		1.712	0.78	590
Waste package*3		2.848	3.73	971

*1: Support is reinforced concrete, invert is non-reinforced concrete.
*2: Buffer material is composed of 70% bentonite and 30% sand.
*3: Waste package is composed of concrete and waste canister.

Thermophysical properties used in the analysis of waste heat output are shown in Figure 2.5.2-1.

In the analysis, as in the 1st TRU progress report, the waste package uniformly generates heat in circular disposal tunnels. Since the waste package is a combination of cementitious material, packaging (steel) and

Group 2 waste, 33.7% of the volume of the waste package is considered to be heat-generating. It is considered that the amount of heat output can be managed by selecting different storage duration options of the waste prior to disposal.

The surface temperature and geothermal gradient in the host rock used in the thermal analysis are 15°C and 3°C per 100 m respectively (as in the H12 report).

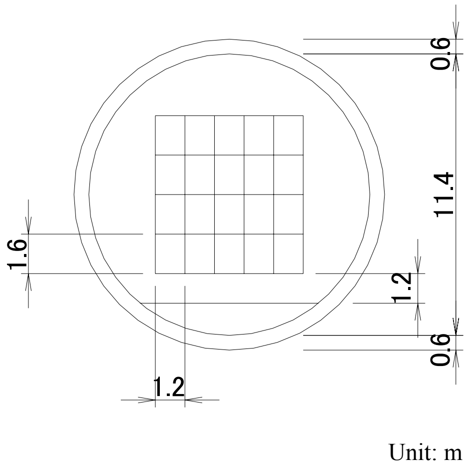
c. Analytical cases

Table 3.2.2.2-3 lists the different cases used in the thermal analysis. A model of disposal tunnels is set up in each case and a thermal analysis is performed using the tunnel separation distance as a parameter. The minimum separation distance necessary to keep the peak temperature below 80°C is estimated in the analysis. The shapes of disposal tunnel cross-sections used in the analysis are shown in Figure 3.2.2.2-3.

Table 3.2.2.2-3 Cases used in the thermal analysis

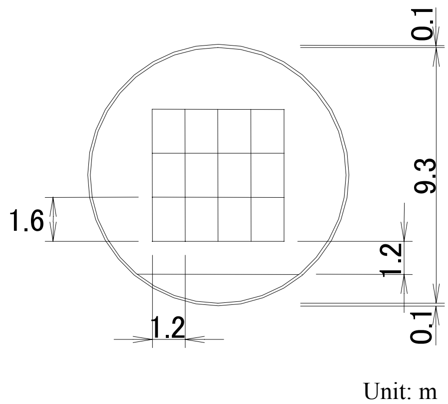
Case	Depth	Rock type	Separation*1	Disposal tunnel shape
1	500 m	SR-C	3D	Circular Inner diameter of tunnel 11.4 m (thickness of support 0.6 m)
2			4D	
3			5D	
4	1,000 m	HR	3D	Circular Inner diameter of tunnel 9.3 m (thickness of support 0.1 m)
5			4D	
6			5D	

*1: D is tunnel excavation diameter.



(ϕ 11.4 m)

(a) Soft rock (SR-C), depth 500 m



(ϕ 9.3 m)

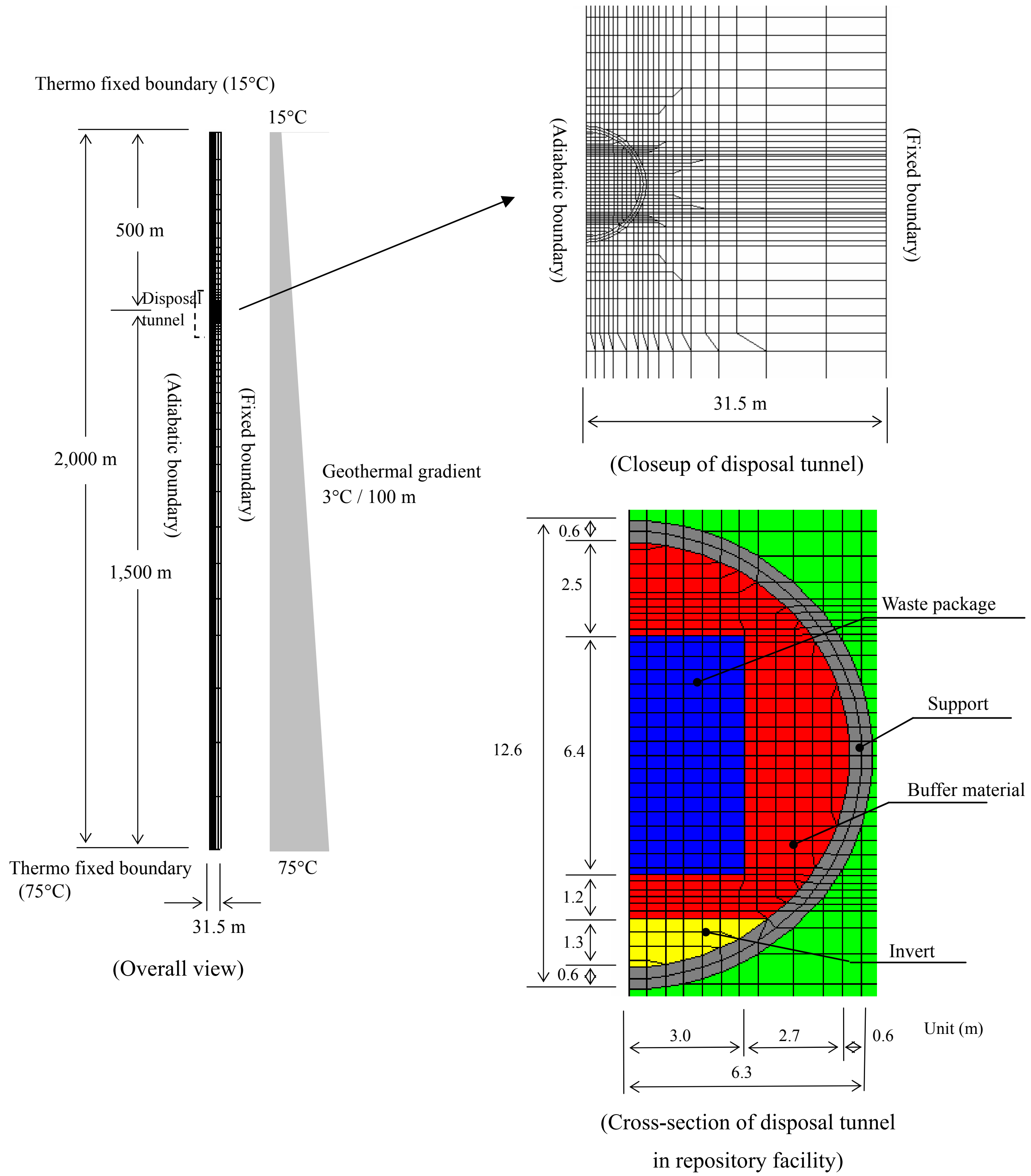
(b) Hard rock (HR), depth 1,000 m

Figure 3.2.2.2-3 Cross-sections of disposal tunnels used in the thermal analysis

d. Thermal analysis model

In the analysis, a two-dimensional model of disposal tunnels for Group 2 (heat-generating) waste is used. A thermal analysis model for multiple tunnels is used since heat generation would be higher than for a single tunnel.

The modelled area is set as follows. The length in the horizontal direction is from the centre of the disposal tunnel to the edge boundary of the model, taken from the separation distance for each case listed in Table 3.2.2.2-3. In the vertical direction, the depth of the disposal tunnel from the surface to the centre of the tunnel is varied according to each case in Table 3.2.2.2-3, and the distance from the tunnel centre to the lower boundary of the model is set at 1,500 m, which is sufficient to prevent boundary effects. A thermal analytical model of multiple tunnels is shown in Figure 3.2.2.2-4.



Soft rock SR-C, ϕ 11.4 m circular cross-section, depth 500 m, separation distance 5D
(D: excavation diameter of tunnel)

Figure 3.2.2.2-4 Example of thermal analysis model

e. Analytical result

The maximum temperature at the centre of waste emplacement area for each analytical case is shown in Table 3.2.2.2-4 and the thermal distribution and thermal output profiles are shown in Table 3.2.2.2-5. The location of each point in the model used to evaluate thermal output profiles is shown in Figure 3.2.2.2-5.

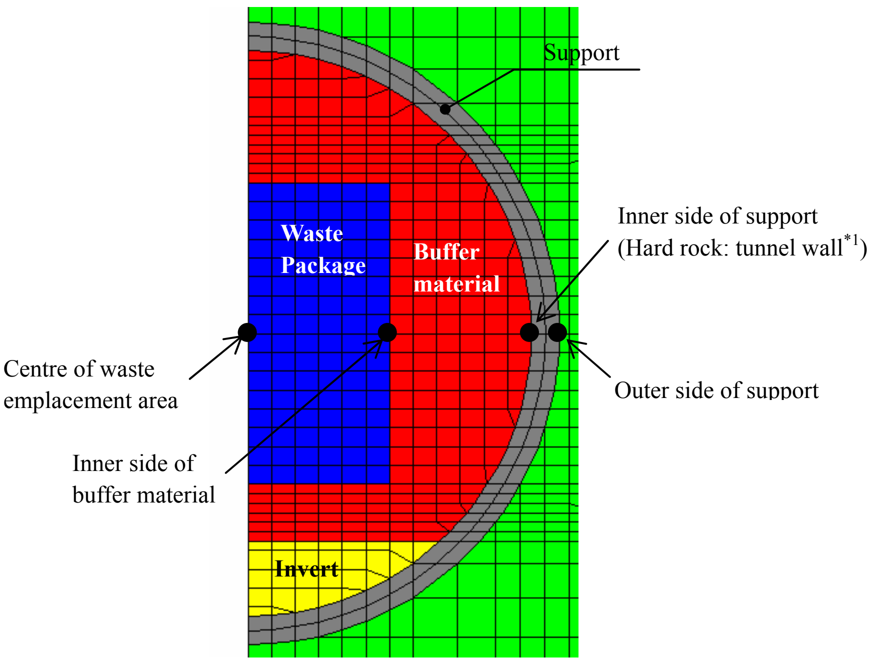
From these analyses, it is found that the maximum temperature in the disposal tunnel does not exceed 80°C if the separation distance is 4D both in soft (SR-C) and hard rock (HR).

Table 3.2.2.2-4 Thermal analysis result for the reference case

Case	Depth	Rock type	Separation distance*1	Disposal tunnel shape	Maximum temperature (°C)*2
1	500 m	SR-C	3D	Circular cross-section Inner diameter of tunnel 11.4 m (support thickness 0.6 m)	81.1
2			4D		79.5
3			5D		79.4
4	1,000 m	HR	3D	Circular cross-section Inner diameter of tunnel 9.3 m (support thickness 0.1 m)	81.2
5			4D		77.5
6			5D		76.7

*1: D equals tunnel excavation diameter.

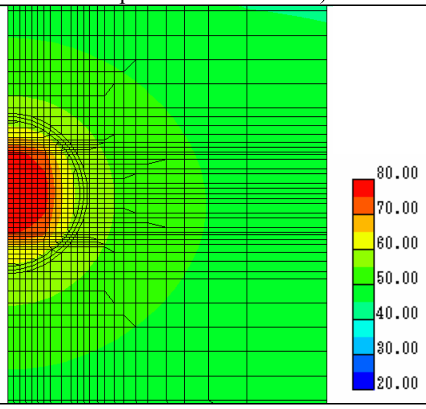
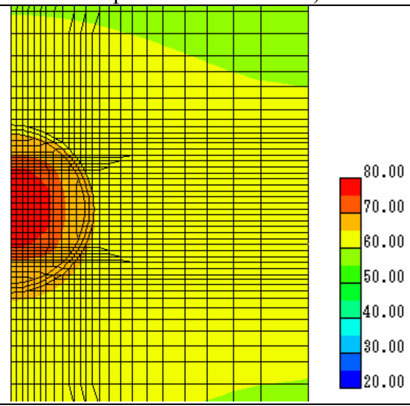
*2: Temperature in table shows maximum temperature at center point of waste emplacement area.



*1: In the case of a circular cross-section in hard rock, shotcrete only is used.

Figure 3.2.2.2-5 Locations of points used in evaluating thermal histories

Table 3.2.2.2-5 Example results of the thermal analysis

<table>
<tr><th></th><th>Soft rock
(SR-C, depth 500 m, circular cross–section,
separation distance 4D)</th><th>Hard rock
(HR, depth 1,000 m, circular cross-section,
separation distance 4D)</th></tr>
<tr><td>Figures showing thermal distribution</td><td>
</td><td>
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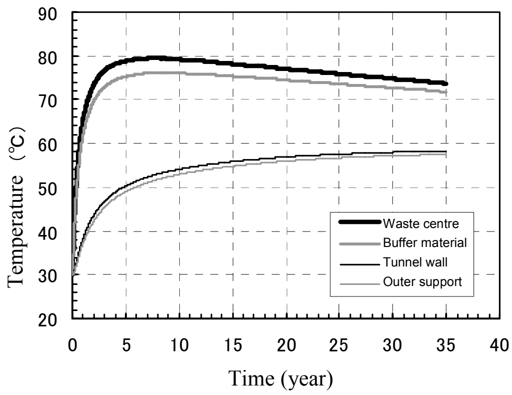
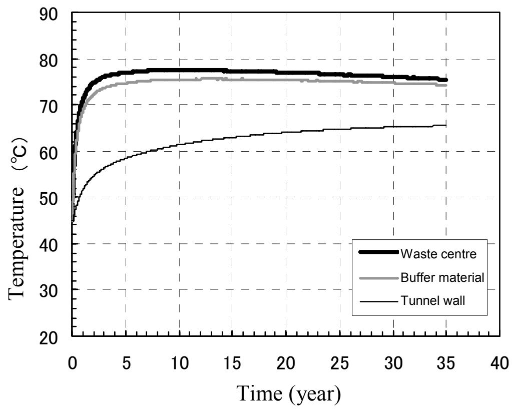
<tr><td>Figures showing thermal output profiles</td><td>
</td><td>
</td></tr>
</table>

(4) Evaluating the number of waste containers to be emplaced

The number of emplaced waste containers is evaluated by considering the following points.

(i) Emplacement of maximum number of waste containers with respect to shape that can be excavated and size of the disposal tunnel.

(ii) Prevention of decrease in nuclide sorption capacity of cement material in the case of Group 2 waste by limiting the number of emplaced waste containers in order to keep the temperature below 80°C.

(iii) Shape and size of the disposal tunnel with respect to the number of emplaced waste containers and required thickness of buffer material estimated in above evaluation.

Taking these factors into account, examples of numbers and arrangement of emplaced waste containers are shown in Figure 3.2.2.2-6.

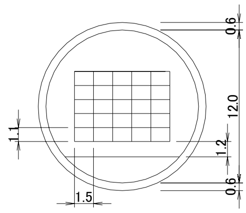
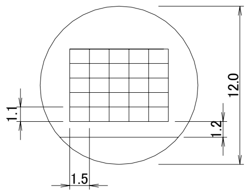
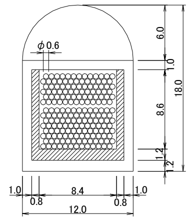
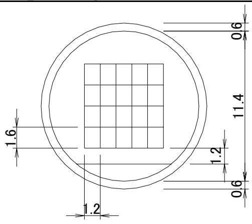
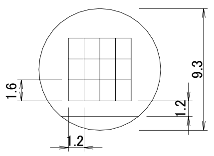
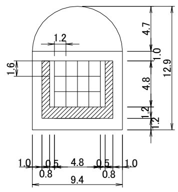
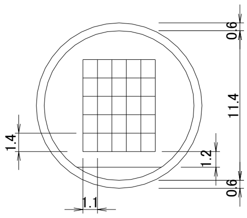
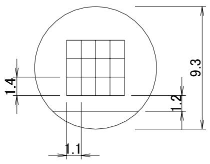
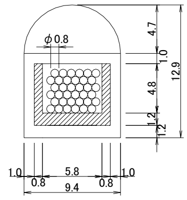
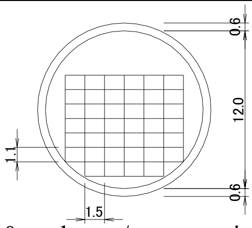
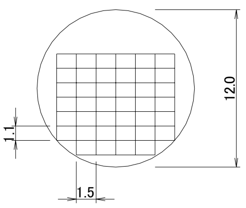
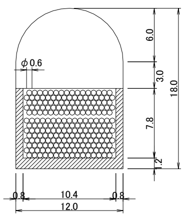
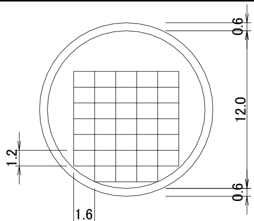
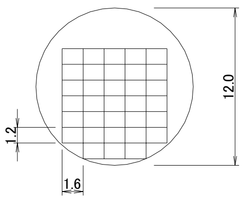
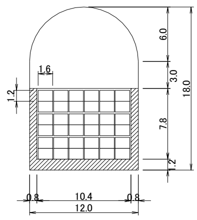
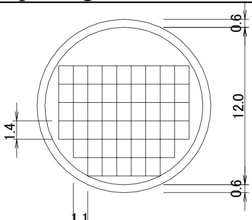
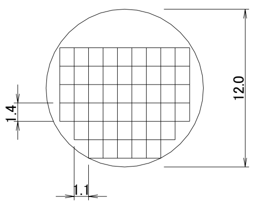
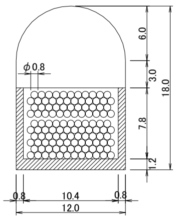
Size of waste container		Circular disposal tunnel		Horseshoe-shaped disposal tunnel
		Soft rock SR-C, depth 500 m	Hard rock HR, depth 1,000 m	Hard rock HR, depth 1,000 m
Group 1	200L Drum: ϕ0.6m × H0.9m Package: 1.5m × 1.5m × H1.1m	 25 packages/cross-section	 25 packages/cross-section	 182 packages/cross-section
Group 2	Canister: ϕ0.43m × H1.335m Package: 1.2m × 1.2m × H1.6m	 20 packages/cross-section	 12 packages/cross-section	 12 packages/cross-section
Group 2	BNGS 500L Drum: ϕ0.8m × H1.192m Package: 1.1m × 1.9m × 1.4m	 25 packages/cross-section	 12 packages/cross-section	 36 packages/cross-section
Group 3 and 4	200L Drum: ϕ0.6m × H0.9m Package: 1.5m × 1.5m × H1.1m	 40 packages/cross section	 40 packages/cross-section	 208 packages/cross-section
Group 3 and 4	Square package: 1.6m × 1.6m × H1.2m	 33 packages/cross- section	 33 packages/cross- section	 36 packages/cross-section
Group 3 and 4	BNGS 500L Drum: ϕ0.8m × H1.192m Package: 1.1m × 1.9m × 1.4m	 48 packages/cross-section	 48 packages/cross-section	 115 packages/cross-section

Figure 3.2.2.2-6 Cross-sections showing number of emplaced waste packages (example)

(5) Summary of underground layout

Considering the results above (1) to (4), the separation distance of the disposal tunnels is selected as shown in Table 3.2.2.2-6.

Table 3.2.2.2-6 Summary of spacing between disposal tunnels

Rock type	Shape	Depth	Waste group	Mechanical constraint	Thermal constraint	Preset spacing of disposal tunnel
Soft rock SR-C	Circular	500 m	1, 3, 4	3D	---	3D
			2	3D	4D	4D
Hard rock HR	Circular	1,000 m	1, 3, 4	3D	---	3D
			2	3D	4D	4D
	Horseshoe		1, 3, 4	2.5W	---	2.5W
			2	2.5W	3W	3W

Note 1: D is excavation diameter of circular disposal tunnel, W is excavation width of horseshoe-shaped disposal tunnel.

The following is considered in the design of the disposal facility layout:

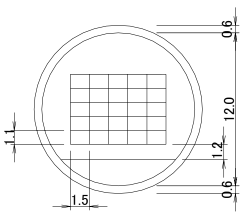
(i) The disposal tunnels for each waste group should be independent of one another.

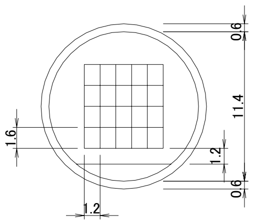
(ii) The waste packages with high doses will be located furthest upstream of groundwater flow so that nuclide migration distances are as long as possible.

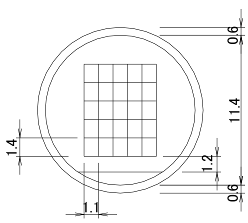
(iii) The disposal tunnels for Group 3 waste packages which contain nitrates are located downstream of groundwater flow or at a sufficient horizontal distance from other disposal tunnels with different waste groups in order to prevent any influence on the engineered barriers and the geosphere.

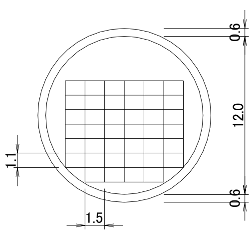
(iv) The access tunnel connecting the underground facility to the surface will be upstream of groundwater flow to prevent it acting as a nuclide transport pathway.

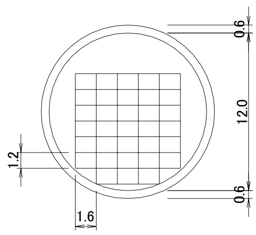
Based on the above criteria, example layouts of the underground facility are shown in Figures 3.2.2.2-7 to 13. In this evaluation, the flow direction of groundwater in the disposal facility is estimated to be constant.

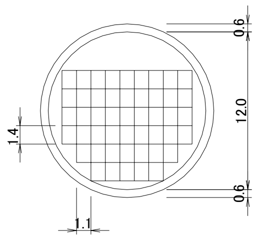
<table>
<tr><td></td><td>Cross-section of diposal tunnel</td></tr>
<tr><td>Group 1</td><td>

Disposal tunnel size inner diameter 12 m
Support thickness 0.6 m
Waste type 200L drum
Waste number 1,589
Waste package size 1500 × 1500 × H1100
Waste package number 398</td></tr>
<tr><td>Grop 2</td><td>

(i) Canister


(ii) BNGS 500L
Disposal tunnel size inner diameter 11.4 m
Support thickness 0.6 m
Waste type (i) Canister (ii) BNGS 500L drum
Waste number (i) 28,800 (ii) 2,070
Waste package size
(i) 1,200 × 1,200 × H1,600 (ii) 1,100 × 1,900 × 1,400
Waste package number (i) 7,200 (ii) 1,035</td></tr>
<tr><td>Group 3 and 4</td><td>

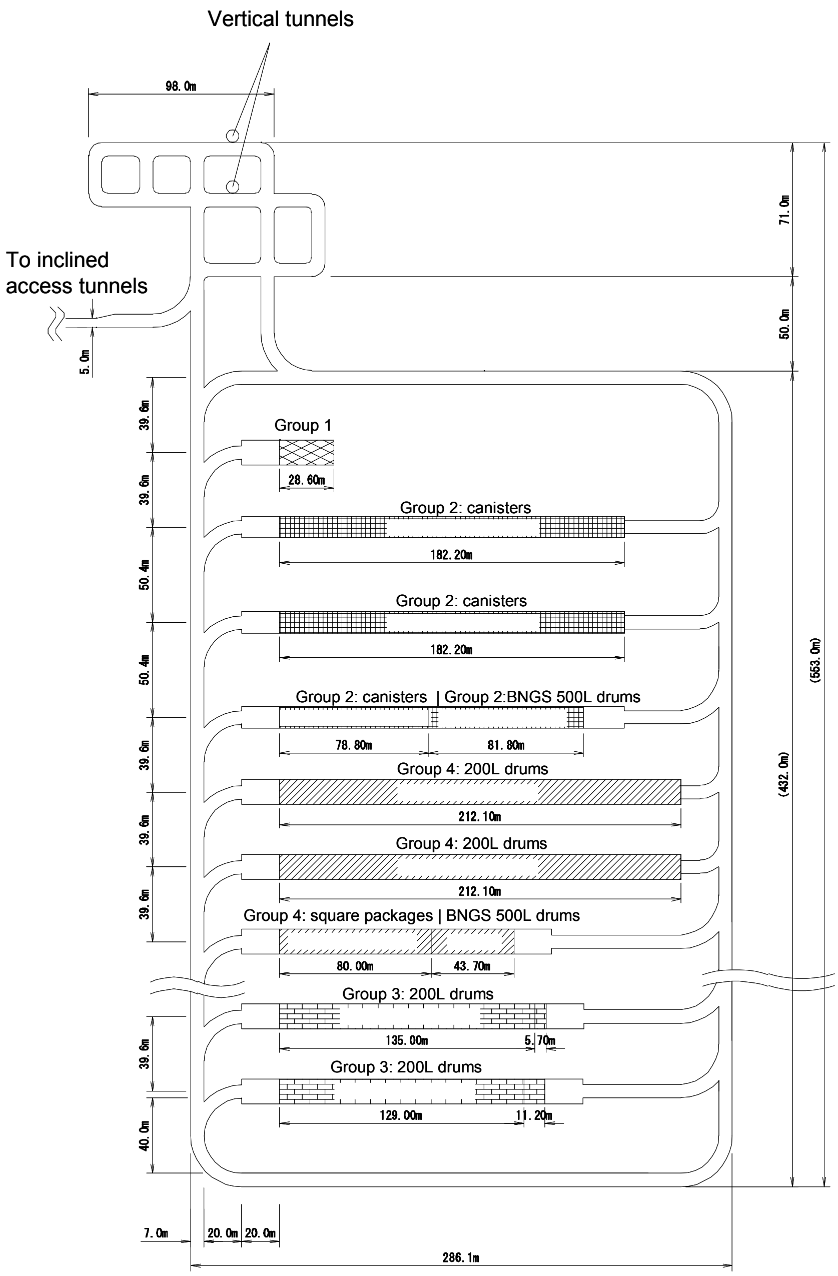
(i) 200L drum


(ii) Square package


(iii) BNGS 500L drum

Disposal tunnel size inner diameter 12 m
Support thickness 0.6 m
Waste type (i) 200L drum (ii) Square package (iii) BNGS 500L drum
Waste number [Group 3] (i) 28,058 (ii) 199 (iii) 250
[Group 4] (i) 45,089 (ii) 1,621 (iii) 2,180
Waste package size (i) 1,500 × 1,500 × H1,100 ((ii) 1,600 × 1,600 × H1,200)
(iii) 1,100 × 1,900 × 1,400
Waste package number [Group 3] (i) 7,015 (ii) 199 (iii) 125
[Group 4] (i) 11,273 (ii) 1,621 (iii) 1,090</td></tr>
</table>

Figure 3.2.2.2-7 Cross-section views of disposal tunnels for soft rock reference case
(SR-C, depth 500 m, circular cross-section)



Note 1: The value in parenthesis does not consider the separation distance for Group 3 waste forms.

Figure 3.2.2.2-8 Example reference case layout in soft rock

(SR-C, depth 500 m, circular cross-section)

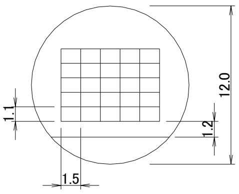
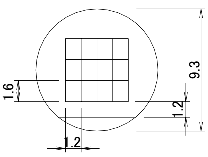
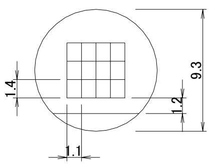
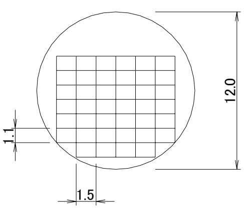
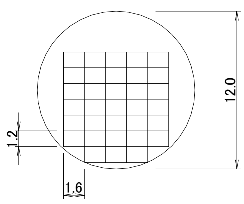
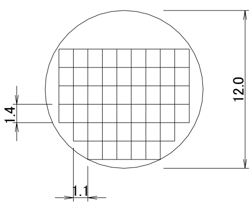
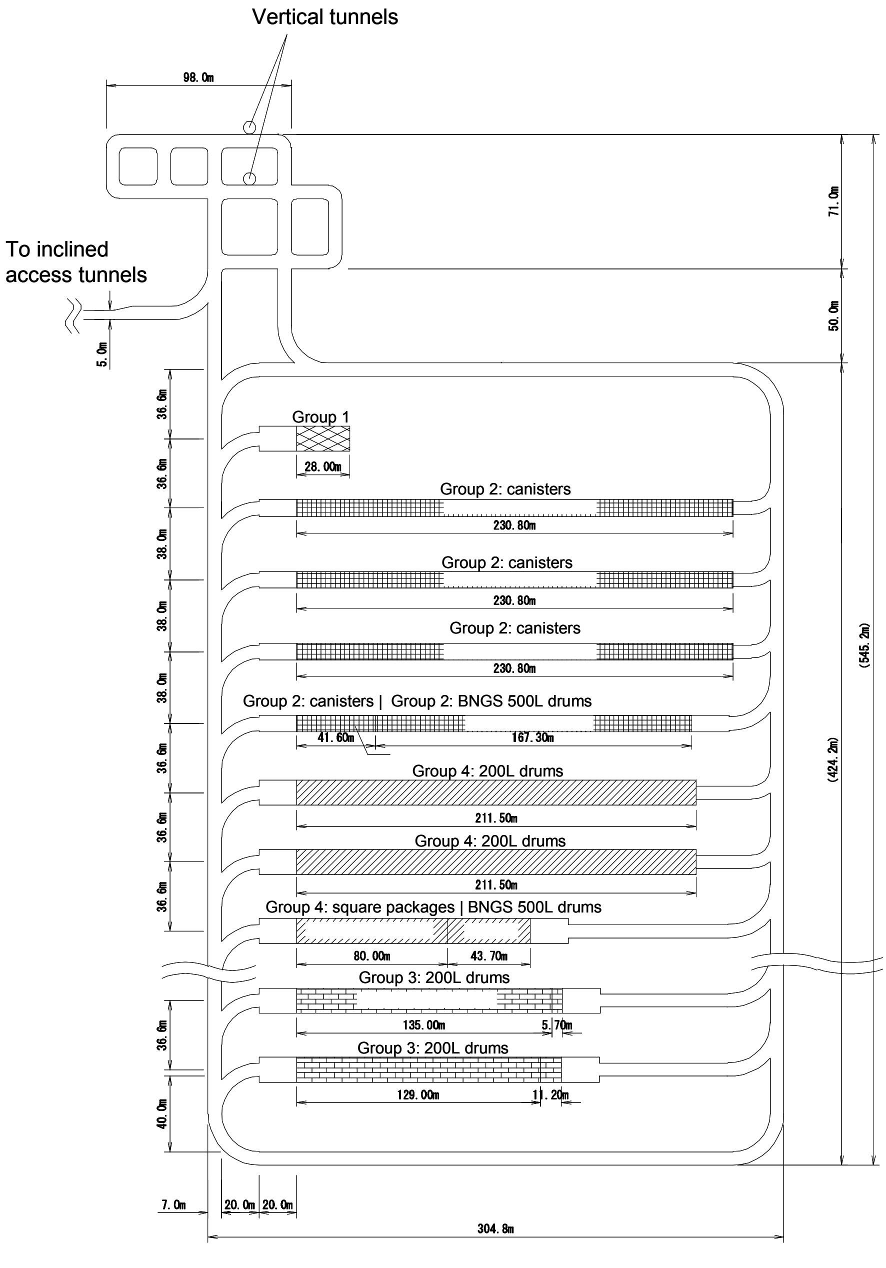
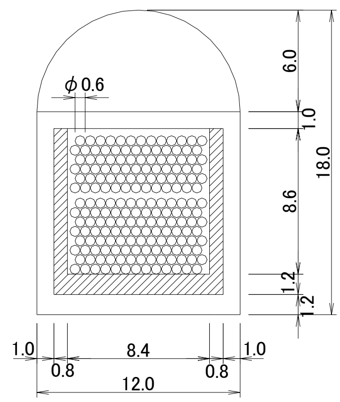
	Disposal tunnel cross-sections	
Group 1		Disposal tunnel size: inner diameter 12 m Support thickness: 0.1 m Waste type: 200L drum Waste number: 1,589 Waste package size: 1,500 × 1,500 × H1,100 Waste package number: 398
Group 2	(i) Canister (ii) BNGS 500L	Disposal tunnel size: inner diameter 9.3 m Support thickness: 0.1 m Waste type: (i) Canister (ii) BNGS 500L drum Waste number: (i) 28,800 (ii) 2,070 Waste package size: (i) 1,200 × 1,200 × H1,600 (ii) 1,100 × 1,900 × 1,400 Waste package number: (i) 7,200 (ii) 1,035
Group 3 and 4	(i) 200L drum (ii) Square package (iii) BNGS 500L drum	Disposal tunnel size: inner diameter 12 m Support thickness: 0.1 m Waste type: (i) 200L drum (ii) Square package (iii) BNGS 500L drum Waste number: [Group 3] (i) 28,058 (ii) 199 (iii) 250 [Group 4] (i) 45,089 (ii) 1,621 (iii) 2,180 Waste package size: (i) 1,500 × 1,500 × H1,100 ((ii) 1,600 × 1,600 × H1,200) (iii) 1,100 × 1,900 × 1,400 Waste package number: [Group 3] (i) 7,015 (ii) 199 (iii) 125 [Group 4] (i) 11,273 (ii) 1,621 (iii) 1,090

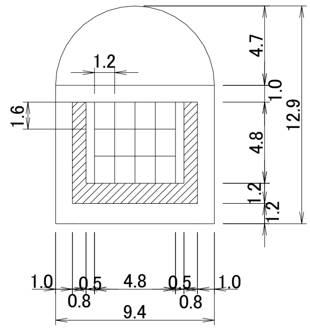
Figure 3.2.2.2-9 Cross-section views of disposal tunnels for the hard rock reference case (HR, depth 1,000 m, circular cross-section)

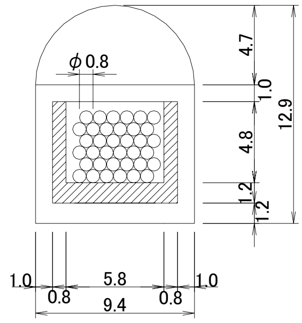


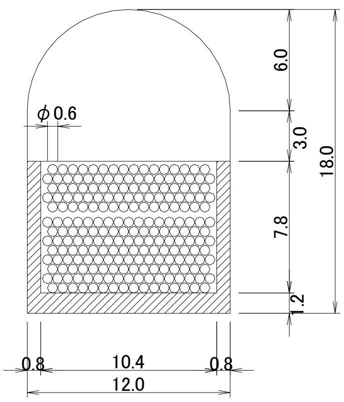
Note 1: The value in parenthesis does not consider the separation distance for Group 3 waste forms.

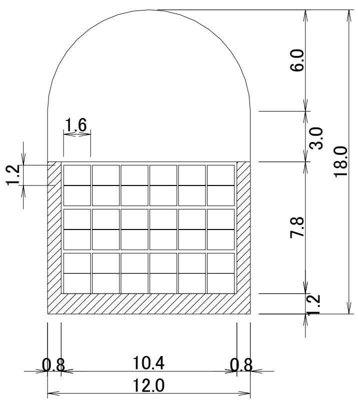
Figure 3.2.2.2-10 Example reference case layout in hard rock
(HR, depth 1,000 m, circular cross-section)

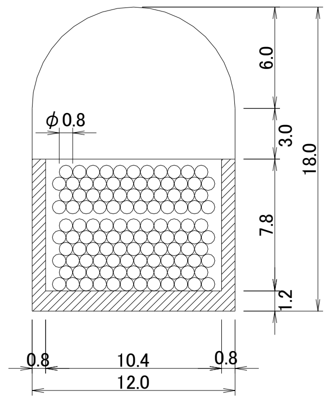
<table>
<tr><td></td><td>Group 1</td><td>Group 2</td></tr>
<tr><td>Disposal tunnel cross-sections</td><td>

Disposal tunnel size
Width 12 m, height 18 m
Waste type 200L drum
Waste number 1,589</td><td>



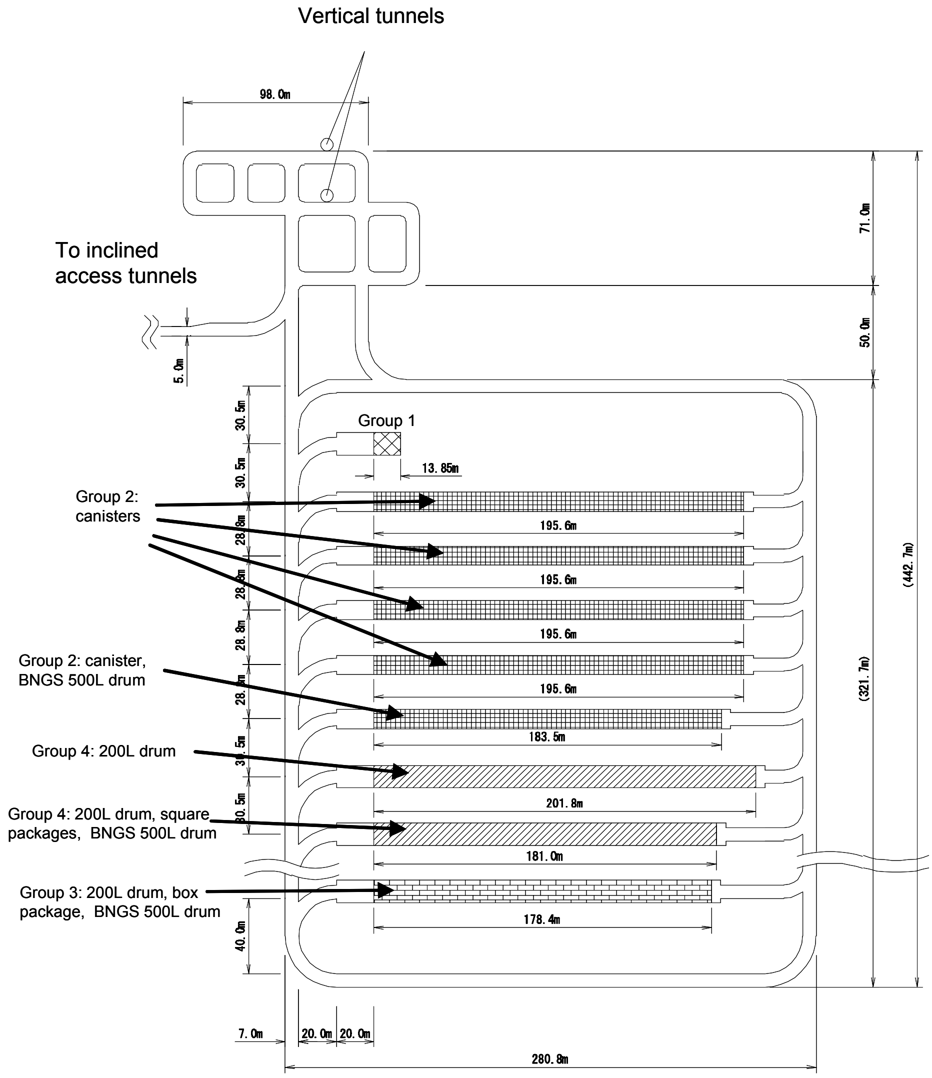
(i) Canister (ii) BNGS 500L drum
Disposal tunnel size width 9.4 m, height 12.9 m
Waste type (i) Canister (ii) BNGS 500L drum
Waste number (i)28,800 (ii) 2,070
Waste package size
(i) 1,200 × 1,200 × H1,600 (ii) BNGS 500L drum (φ800 × H1,192)
Waste package number (i) 7,200 (ii) –</td></tr>
<tr><td></td><td colspan="2">Group 3 and 4</td></tr>
<tr><td>Disposal tunnel cross-sections</td><td colspan="2">





(i) 200L drum (ii) Square package (iii) BNGS 500L drum
Disposal tunnel size width 12 m, height 18 m
Waste type (i) 200L drum (ii) Square package (1,600 × 1,600 × H1,200)
(iii) BNGS 500L drum (φ800 × H1,192)
Waste number [Group 3] (i) 28,058 (ii) 199 (iii) 250
[Group 4] (i) 45,089 (ii) 1,621 (iii) 2,180</td></tr>
</table>

Figure 3.2.2.2-11 Cross-section of horseshoe-shaped disposal tunnel in hard rock
(HR, depth 1,000 m)



Note 1: The value in parenthesis does not consider the separation distance for Group 3 waste forms.

Figure 3.2.2.2-12 Example layout of horseshoe-shaped disposal tunnels in hard rock (HR, depth 1,000 m)

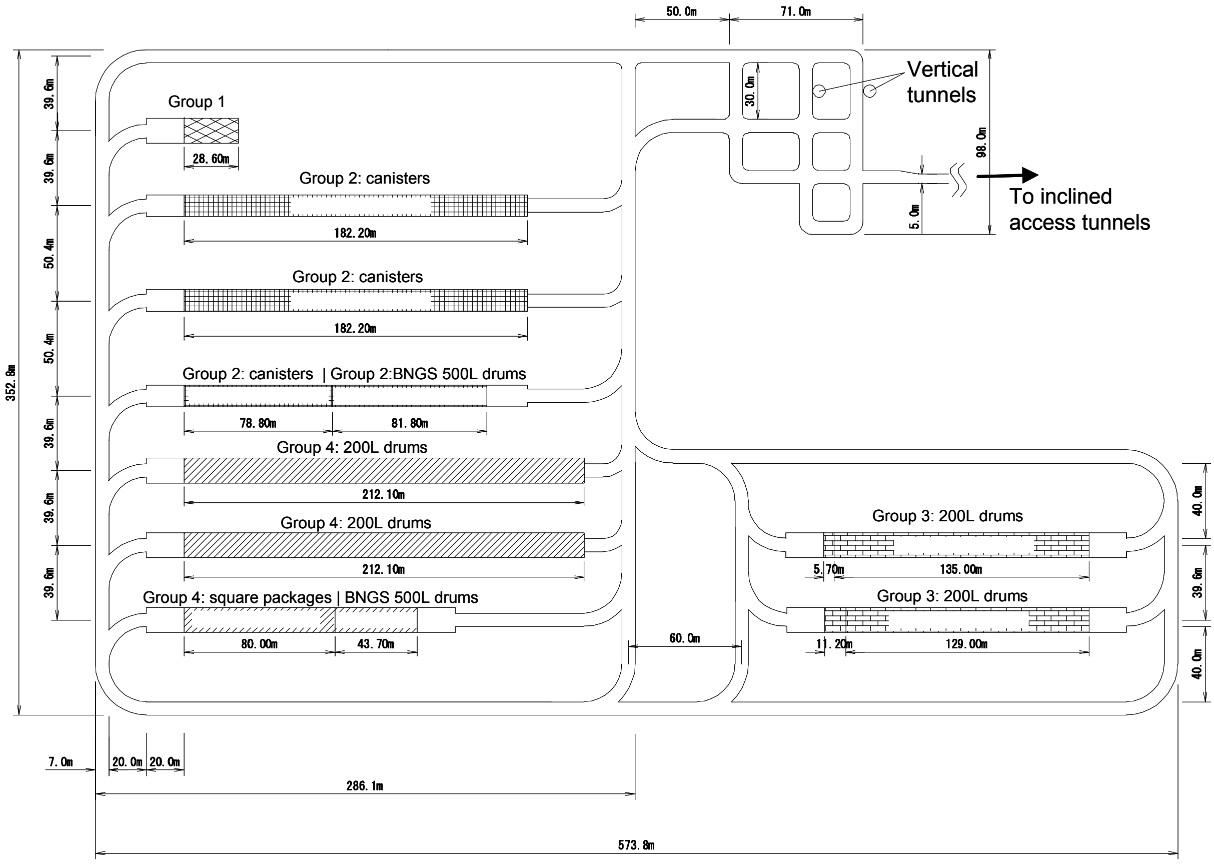


Figure 3.2.2.2-13 Example layout in soft rock with Group 3 waste arranged parrallel to groundwater flow (SR-C, depth 500 m, circular cross-section)

3.2.2.3 Design of backfill and plugs

The long-term safety of a repository could be compromised if tunnels excavated for disposal operations are left open, unfilled, or no treatment of the excavation disturbed zone (EDZ) for a long time period. Detrimental effects include the potential for the tunnels to act as transport pathways for radionuclides and reduced mechnical stability of unfilled tunnels due to prolonged rock pressure. Moreover, the possibility of human intrusion needs to be considered if tunnels directly connected to surface are left open (JNC, 2000). For these reasons, every tunnel will be backfilled before closure of the disposal facility.

The backfill material and locations of plugs are selected so that they function effectively as a multi-barrier system against nuclide migration. In particular, preventing the formation of dominant nuclide migration pathways and degradation of the performance of the engineered barriers after closure of the disposal facility are concerns that need to be addressed. It is considered that dominant nuclide migration pathways may form due to connectivity through the EDZ and cavities resulting from deterioration of tunnel support. In addition to backfilling tunnels with low permeability material, watertight plugs are necessary to segment connected nuclide migration pathways in the EDZ, etc. Another concern is the decrease in average density of buffer material, as this can compromise the perfomance of the engineered barriers. In order to prevent movement or flow of the buffer material, plugs with mechanically stable properties are used and backfilling is carried out so that no voids remain. The functions of the backfill and plugs in the disposal facility for TRU waste are shown in Figure 3.2.2.3-1.

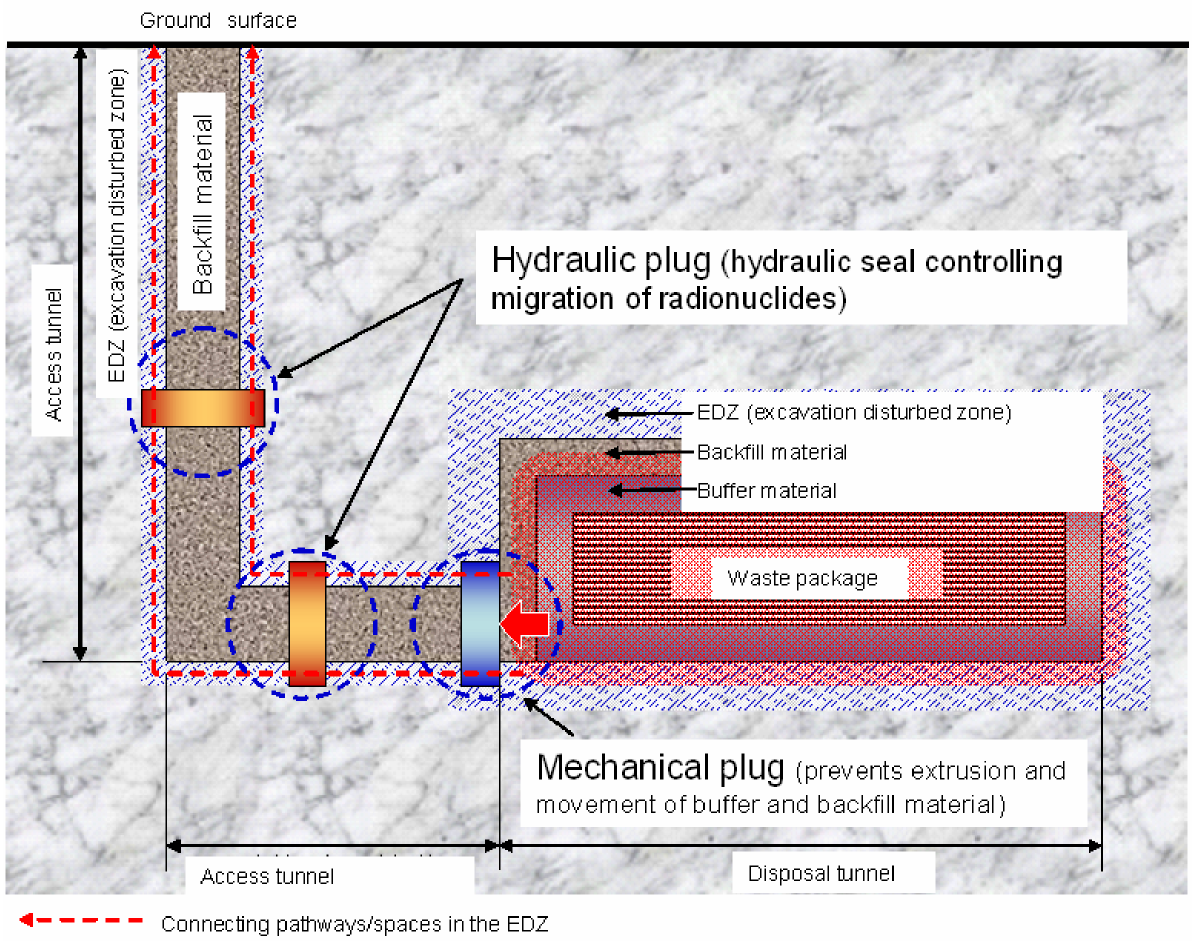


Figure 3.2.2.3-1 Function of backfill and plugs in a disposal facility for TRU waste

(1) Design of backfill material

After closure of the disposal facility, backfill material prevents degradation of the performance of the engineered barriers and formation of preferential nuclide transport pathways. The choice of backfill material is thus an important issue. In regions where dominant nuclide pathways may form, the use of material with low permeability and self-sealing properties is desirable. Moreover, for backfill material in disposal tunnels, it is necessary to consider the effects from the engineered barriers. Bentonite is considered to be the most suitable material for backfilling access tunnels, connecting tunnels and disposal tunnels with Group 1 and Group 2 wastes. Cementitious material, which can be used efficiently and economically, is considered most suitable for backfilling disposal tunnels for Group 3 and 4 wastes since low permeability and self-sealing properties are not required and there is no concern regarding bentonite alteration. Candidate backfill materials for each part of the disposal facility are summarized in Table 3.2.2.3-1.

Table 3.2.2.3-1 Candidate backfill materials for the disposal facility

Location		Required functions and/or concerns	Main candidate material
Access tunnel		Low permeability, self-sealing	Bentonite
Connecting tunnel		Low permeability, self-sealing	Bentonite
Main shaft		Low permeability, self-sealing	Bentonite
Disposal tunnels	Group 1, 2	Low permeability, self-sealing, interaction with engineered barriers	Bentonite
	Group 3, 4	Interaction with engineered barriers	Cementitious material

Bentonite used as backfill material should have a low permeability, preventing the formation of dominant nuclide transport pathways, and should be compatible with the surrounding host rock. Table 3.2.2.3-2 shows example specifications of bentonite backfill material based on the designs in Section 3.2.1.2. For cementitious backfill materials, normal concrete can be used.

Table 3.2.2.3-2 Example specifications for bentonite backfill material

Item	Specification
Hydraulic conductivity ($m\ s^{-1}$)	Below 1.0×10^{-10} $m\ s^{-1}$ (same hydraulic characteristics as host rock)
Effective clay dry density (Mg/m^3)	Above 1.2 Mg/m^3
Example material specification	(i) Mixture of bentonite-silica sand (1:1) - Dry density above 1.65 Mg/m^3 (ii) Coarse bentonite (Kunigel V1 crushed ore rock) - Dry density above 1.2 Mg/m^3

(2) Design of the plug

There are two types of plug: a hydraulic plug designed to segment dominant nuclide flowpaths created by the EDZ and a mechanical plug designed to prevent material movement and outflow by swelling of buffer materials. The hydraulic plug must have low permeability and self-sealing properties. Since it is necessary to segregate dominant nuclide migration pathways, it is considered that the plug design in this report has the same properties as the buffer material. An example specification of the hydraulic plug is shown in Table 3.2.2.3-3.

Concrete is used to construct the mechanical plug as it is considered sufficient for withstanding the pressure generated by the swelling of the buffer material (several MPa).

Table 3.2.2.3-3 Example specifications of the hydraulic plug

Parameter	Specification
Hydraulic conductivity ($m\ s^{-1}$)	Below 1.0×10^{-11} $m\ s^{-1}$ (same hydraulic characteristics as buffer)
Effective clay dry density (Mg/m^3)	Above 1.45 Mg/m^3
Example material specification	(i) Mixture of bentonite and silica sand (7:3) - Dry density above 1.60 Mg/m^3 (ii) Granular bentonite (Kunigel V1) - Dry density above 1.45 Mg/m^3

(3) Closure concept for the disposal facility

Examples of closure concepts for circular and horseshoe-shaped disposal tunnels are shown in Figures 3.2.2.3-2 and 3.2.2.3-3 respectively.

It is considered that the system can be rationalized by using optimum combinations of backfill and plugs. For example, it is possible to ease the specifications of the backfill material by optimizing the arrangement and specifications of the hydraulic plug (Takeuchi et al., 2004).

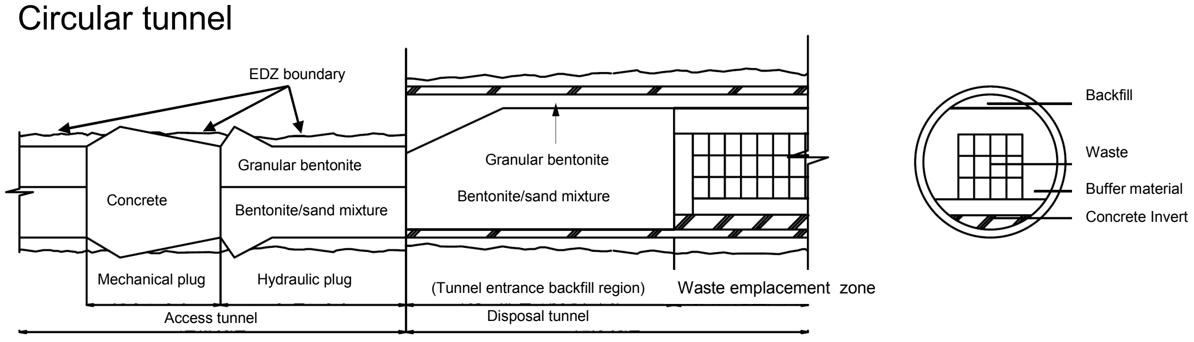


Figure 3.2.2.3-2 Closure concept for circular disposal tunnel

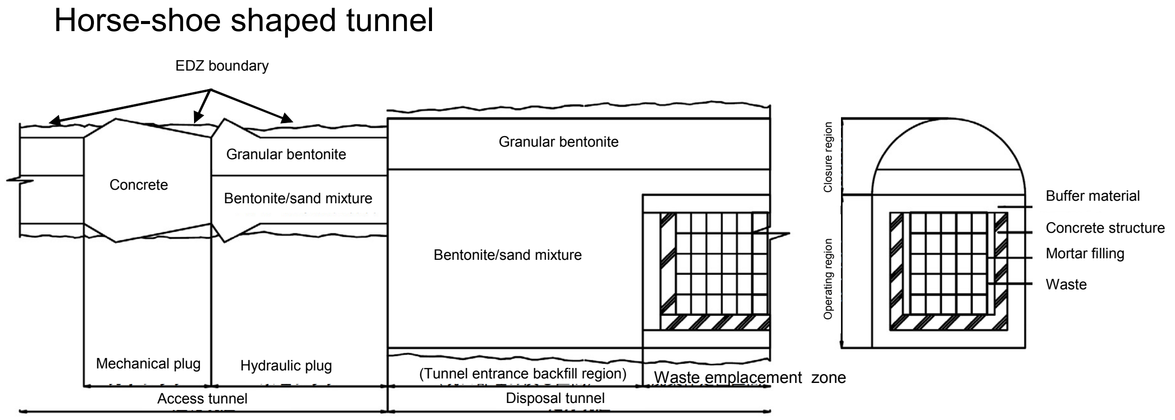


Figure 3.2.2.3-3 Closure concept for horseshoe-shaped disposal tunnel

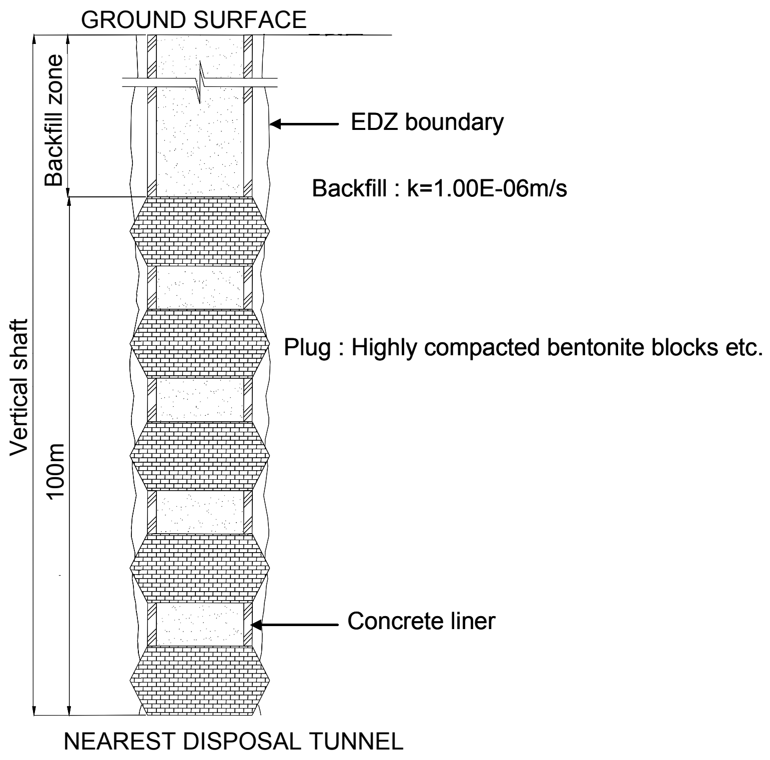


Figure 3.2.2.3-4 Closure concept for access tunnel

3.3 Long-term mechanical stability of the near-field

It is considered that creep affects the stress state of both the engineered barriers and the host rock surrounding the disposal tunnels. As described in Section 4.4.2, if alteration occurs to the engineered barriers, it is considered that stress will change due to a change in swelling pressure and decrease in the rigidity of the engineered barriers. A change in the stress can also affect the dimensions and shape of the engineered barriers.

In this section, the long-term stress state in the near-field after closure of the disposal tunnels is evaluated. Also, the shape of the engineered barriers considered in the safety assessment is evaluated. In particular, the thickness of the buffer material used as a pre-condition in the nuclide migration analysis is evaluated over the long-term. Phenomena which may affect the mechanical stability of the enginnered barriers and the surrounding host rock are identified and the effect(s) of each phenomenon is evaluated.

3.3.1 Long-term mechanical behavior in the near-field

3.3.1.1 Factors affecting long-term mechanical behaviour

As shown in Section 3.2, cementitious materials, bentonite and steel are used in the filler, support, buffer materials, backfill materials and waste forms emplaced in the disposal tunnels. The stress in the near-field varies according to different effects of the host rock and the engineered barriers. Variation in stress can also result from events associated with construction and closure of the repository. Although gradual changes in mechanical stability result from excavation, construction of the engineered barriers and effects of closure, based on safety assessment preconditions (specifications such as the shape of disposal tunnels, engineered barriers, etc.), it is considered that mechanical behaviour prior to closure is assured by design, construction, operation and closure technologies. Hence, the factors affecting the mechanical behavior in the post-closure phase are considered in this section.

Since environmental factors depend on the geological environment of the disposal facility, restored values (i.e. initial values prior to excavation) of the water level, ground pressure (creep) and chemistry of infiltrating groundwater are considered among the factors that might affect the post-closure mechanical behaviour. Moreover, the thermal output of the waste, leaching of waste components, metal corrosion (gas generation, volume swelling), dissolution of cementitious material in groundwater, viscous deformation of buffer material, buffer material swelling and extrusion of buffer material are considered as long-term factors related to the performance of the engineered barriers.

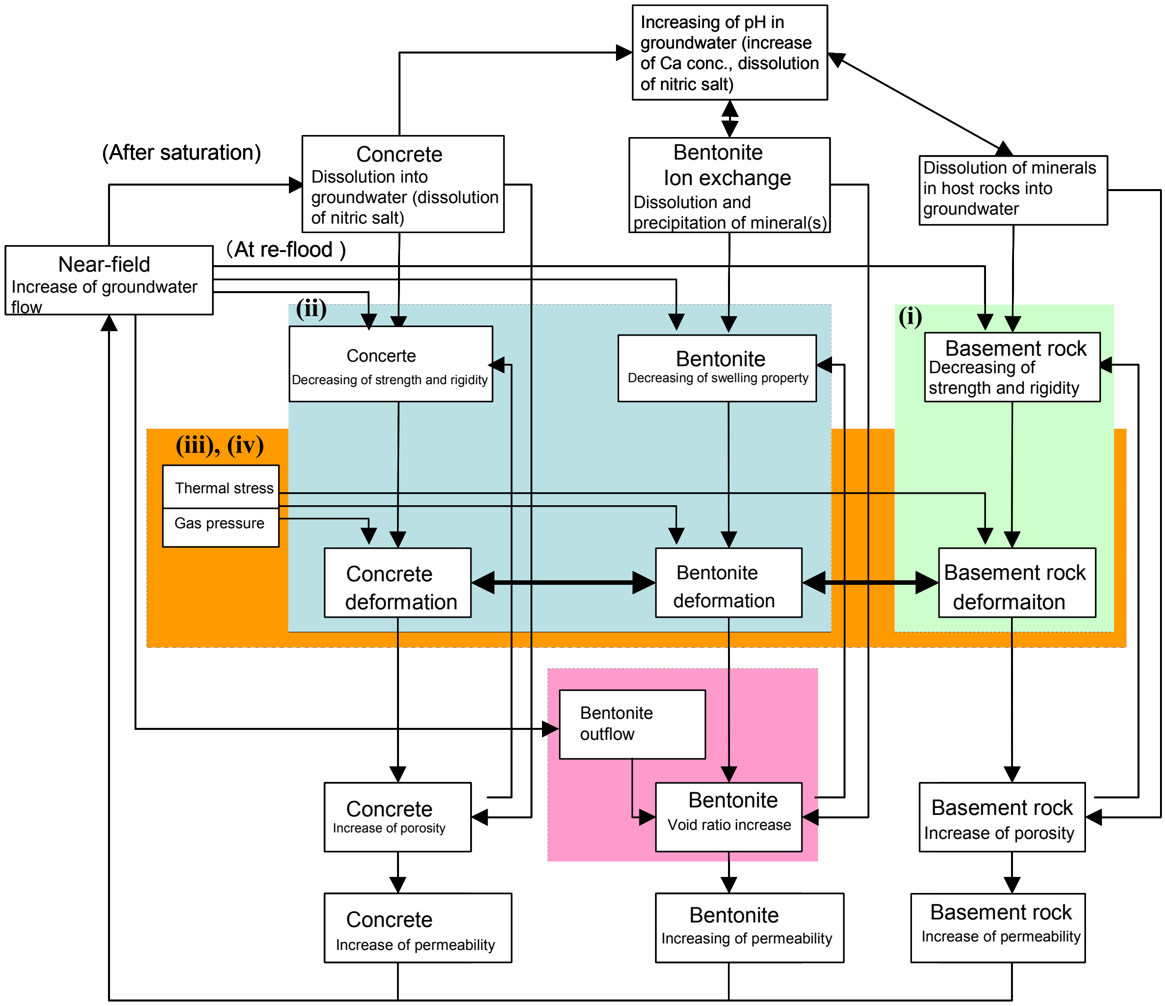


Figure 3.3-1 Process influence diagram

3.3.1.2 Evaluation method for long-term mechanical behaviour

In evaluating the long-term mechanical behaviour in the near-field, variations in the occurrence and duration, as well as the interactions, of the factors above are considered. Significant phenomena and their interactions are shown in the influence diagram in Figure 3.3-1. The influence diagram is also applicable to disposal tunnels for Group 3 and 4 wastes by excluding bentonite.

The stress state of the host rock and the engineered barriers reaches equilibrium by action-counteraction, so the behaviour of both the host rock and the engineered barriers should be considered in order to evaluate the long-term mechanical behaviour of the near-field. However, as the geological environment cannot be defined yet, the lack of information on host rock deformation and deformation of the engineered barriers is quite large and only assessments of single processes are carried out. Since the effects of deformation due to thermal stress, deformation due to gas pressure and bentonite extrusion are considered to be insignificant, they are assessed separately. However, in the event that these effects are found to be significant they should be assessed together with the first two. The stress change induced by corrosion expansion of metal in cementitious materials in waste and supports, etc. is bufferred by the cementitious materials softening due to leaching over the long-term so it is excluded from the evaluation. Also, the stress change in buffer material induced by corrosion of the steel supports is excluded from the evaluation because these are thin plates. After closure, resaturation causes an increase in the swelling capacity of bentonite as water content increases and significant deformation occurs. Since the buffer material takes only several hundreds of years to become fully saturated, this is used in the evaluation.

The effect of mechanical stability on the engineered barriers and surrounding host rock is assessed for each of the five preceding items. The assessment method for each phenomenon is described below. The appropriate model is applied for the respective phenomenon in the analytical assessment. The modelling of the phenomenon for analytical assessment is shown in Table 3.3-1.

(i) Long-term creep deformation of host rock

Rock creep in various geological environments is evaluated by combing the present analytical result. The effects of the change in mechanical properties of the engineered barriers are considered by a sensitivity analysis using the characteristics of the tunnel wall as a parameter.

(ii) Changes in the mechanical function of the engineered barriers and swelling pressure of buffer material

For the diposal tunnels for Group 1 and 2 wastes, the deformation of the engineered barriers as a result of swelling of the buffer material is evaluated by numerical analysis considering the change with time in the mechanical function of the engineered barriers. The host rock is not modelled because the mechanical influence on surrounding rock of swelling pressure from the engineered barriers is assumed to be small. In evaluating the influence on the engineered barriers of creep deformation of the host rock, forced displacement of the tunnel wall is considered.

(iii) Effect of thermal stress due to heat output from waste

For the temperature increase generated by heat output from Group 2 wastes, mechanical effects induced by thermal stress of the engineered barriers and the surrounding rock are evaluated based on existing analytical results.

(iv) Effect of increase in pore pressure due to gas generation

For the increase in pore pressure due to gas generation, the mechanical influence on the surrounding rock is evaluated based on existing analytical results.

(v) Effect of extrusion of buffer material

For disposal tunnels with Group 1 and 2 wastes, the possibility of extrusion of buffer material through fractures is evaluated based on the existing test and analytical results.

Table 3.3-1 Modelling of phenomena for analytical evaluation

	(i) Long-term creep deformation of host rock	**(ii)** Changes in the mechanical function of the engineered barriers and swelling pressure of buffer material	**(iii)** Effect of thermal stress	**(iv)** Effect of increase in pore pressure	**(v)** Effect of extrusion of buffer material
Phenomenon to be evaluated	Creep deformation of host rocks	Swelling/compressive deformation of buffer, volume contraction of cementitious materials	Effect of mechanical stability from thermal stress	Effect of mechanical stability from gas pressure	Intrusion into crack of buffer
Disposal tunnel	Group 1 – 4	Group 1, 2	Group 2	Group 1 – 4	Group 1, 2
Evaluated parameter	Amount of creep displacement of tunnel wall	Deformation amount of each barrier member (thickness of buffer etc.), stress condition	Amount of deformation of host rocks	Stress condition of host rocks	Density change of buffer
Method of analysis	Finite element method	Finite element method	Finite element method	Finite element method	(Simple calculation)
Analytical dimension	2-dimensional plane strain	2-dimensional plane strain	2-dimensional plane strain	2-dimensional plane strain	–
Model structure Host rock	Non-linear viscoplastic member	–	Elastic member	Elasto-plastic member	–
Buffer material	Elastic member	Elasto-plastic body (revised version of Sekiguchi-Ohta model)	Elastic member	–	Calculated minimum densities based on inflow velocity experiments
Cement material*1	Elastic member	Non-linear elastic member (strain-softening and re-distribution of stress after yield)	Elastic member	–	–
Remarks	Exclude time-variable mechanical feature of engineered barrier (performance of sensitivity analysis)	Modelling creep deformation as forced displacement Consideration of time-variable mechanical functions of engineered barrier Exclude the effect of (iii) – (v)	Examination of cross-sections in 1st TRU report Exclude deformation from other effects and variable mechanical feature in engineered barrier	Examination of cross-section in 1st TRU report Exclude deformation from other effects	Examination of cross sections (vertical emplacement) in H12 report Exclude deformation and variable mechanical features in engineered barrier

*1: Shows materials constrained by mortar characteristics (waste package, filler) and concrete materials (invert, support, reinforced concrete structural framework).

3.3.2 Evaluation of long-term mechanical stability in the near-field
3.3.2.1 Long-term creep deformation of the host rock
(1) Analytical conditions

Constitutive equations of creep deformation of the host rock based on a non-linear visco-elastic model (Okubo et al., 1987) are applied in an analysis carried out by a two-dimensional finite element method (plane strain). Second or third stage creep and creep determine the appropriate equations, however there are several ways in which stress-strain relationships can be modelled including elastic, non-linear elastic and elasto-plastic (The Japanese Geotechnical Society, 2003).

Here, an analytical system is modelled based on the design of the tunnel cross-section. As described in the preceding paragraphs, the design of the disposal facility itself depends on the geological environment (mechanical properties, disposal depth, etc.) and the characteristics of the emplaced waste as discussed in Section 3.2.2.2. A circular tunnel with an excavated diameter of 12.6-13.2 m is selected for disposal in soft rock (SR-C dataset, 500 m) and a circular tunnel with an excavated diameter of 9.3-12.0 m and/or a horseshoe-shaped tunnel with an excavated width of 9.4-12.0 m (excavated height 12.9-18.0 m) for disposal in hard rock (HR dataset, 1,000 m). In this section, in order to understand the amount of creep deformation of the host rock in different geological environments, analytical cases are established using the disposal tunnel shape (excavated diameter) and mechanical characteristics of the host rock (depth) as parameters. Moreover, changes to the mechanical properties of the engineered barriers depend on long-term alterations as described Section 3.3.2.2(1). In order to understand to what extent creep deformation affects the engineered barriers, the engineered barrier system is modelled as an elastic body and analytical cases are established using the elastic modulus as the main parameter.

The attributes used in the analysis are estimated in the same way as in the 1st TRU progress report (Aoyagi et al., 2001) and 17 analytical cases are derived by combining the results from this report.. The excavated diameter, host rock characteristics and the elastic modulus of the engineered barrier system are shown in Table 3.3-2. Analytical cases 12-16 are taken from the 1st TRU progress report.

Table 3.3-2 Analytical cases

No.	Tunnel configuration (excavated diameter)	Host rock property, disposal depth*1	Elastic modulus of the engineered barriers*2
1	Circular (D 13.2 m)	SR-C, 500 m	0 MPa
2			3 MPa
3			100 MPa
4			3 – 3,000 MPa*3
5		SR-B, 500 m	3 MPa
6		SR-D, 500 m	
7		HR, 1,000 m	
8	Circular (D 12.5 m)	SR-C, 500 m	0 MPa
9			3 MPa
10			100 MPa
11	Circular (D 12.0 m)	SR-C, 500 m	3 MPa
12	Circular (D 11.2 m)	SR-B, 500 m	0 MPa
13			1 MPa
14			3 – 32,300 MPa*4
15			10 MPa
16			100 MPa
17	Horseshoe (W 12 m, H 18 m)	HR, 1,000 m	3 MPa

*1: Rock properties and lateral pressure coefficients K_0 are from the dataset in the H12 report. Parameter m and n_0 of the Ohkubo model is m = 20 and n_0 = 30 for hard rock (HR) and m = 5 and n_0 = 20 is for soft rock (SR), respectively.

*2: A uniform model is applied to the engineered barriers except for Cases 4, 14. Poisson's ratio of 0.4 which is equal to the value for buffer material is used.

*3: Case 4 is modeled by dividing into emplacement of waste (mortar), buffer material and support components. It is assumed that each part has the same amount of degradation and the elastic modulus and Poisson's ratio are (1,000 MPa, 0.2), (3 MPa, 0.4) and (3,000 MPa, 0.2), respectively.

*4: Case 14 is modelled by dividing into emplacement of waste (mortar), buffer material and support components. It is assumed that emplacement of waste and buffer material are unaltered and that support degrades by the same amount as the buffer material. Elastic modulus and Poisson's ratio are (32,300 MPa, 0.184), (3 MPa, 0.4) and (3 MPa, 0.2), respectively.

(2) Analytical results

For case 2, the time profile of creep displacement of the central apex of the tunnel up to 1 million years and a cross-section of tunnel deformation after 1 million years are shown in Figure 3.3-2. Creep displacement between 100,000 and 1,000,000 years was less than the displacement up to 100,000 years. Moreover, the creep displacement of the tunnel wall is highest at the central apex. These trends are found in all analytical cases. The creep displacement after 1,000,000 years in the central apex of the tunnel is shown in Figure 3.3-3. It is revealed that creep deformation depends significantly on the elastic modulus and physical properties of the host rock surrounding the engineered barriers. For example, for the entire engineered barrier system with an elastic modulus set to that of saturated buffer material (3 MPa), depending on the mechanical properties of the host rock (HR, SR-B, SR-C, SR-D datasets) the amount of creep deformation ranges from 0 – 30 cm. However, if the elastic modulus is set to 100 MPa, which is about 1/100 to that of mortar, the amount of creep deformation is about 2 cm in the case of SR-B and SR-C datasets. On the other hand, comparing the result of cases with equal elastic modulus of the host rock and physical properties of the engineered barriers, the variation in creep deformation slightly depends on the excavated diameter and varies no more than several cm for a diameter ranging from 11.2 – 13.2 m.

(3) Long-term creep of the host rock

In a disposal tunnel constructed in soft rock, support (shotcrete and secondary lining) 60 cm thick is applied to the tunnel wall. As an initial condition, the elastic modulus of the support is set to around. 30,000 MPa. 3,000 MPa of the elastic modulus is maintained even if the calcium in (except for aggregate) is completely leached as presented in Section 3.3.2.2(1)e. Hence, estimated creep deformation in host rocks with SR-B and SR-C datasets is no more than several cm after 100,000-1,000,000 years. Considering uncertainty in host rock properties such as heterogeneity, excavation effects and alkaline alteration, it is considered that even larger deformation might occur locally. However, in the disposal tunnel in hard rock, creep deformation is considered to be negligible after 100,000 – 1,000,000 years.

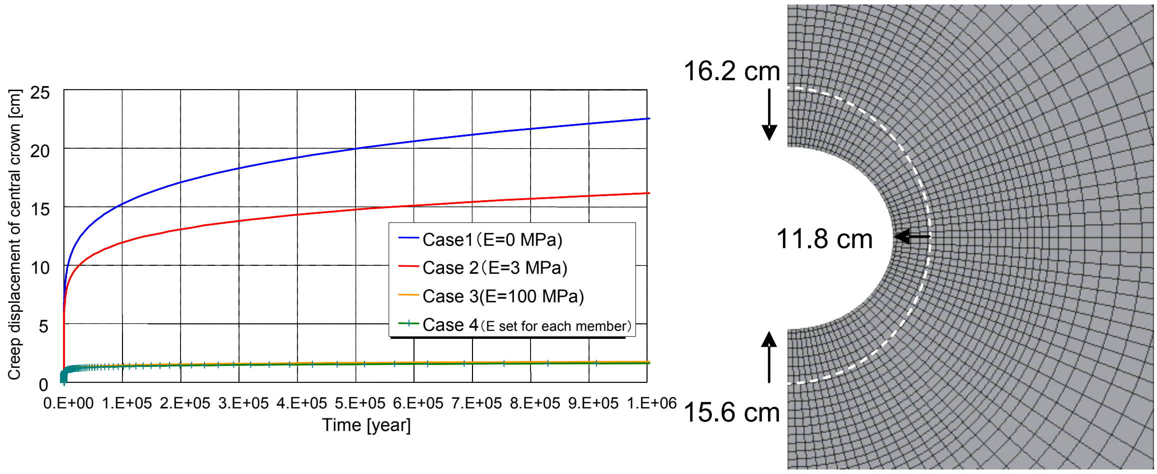
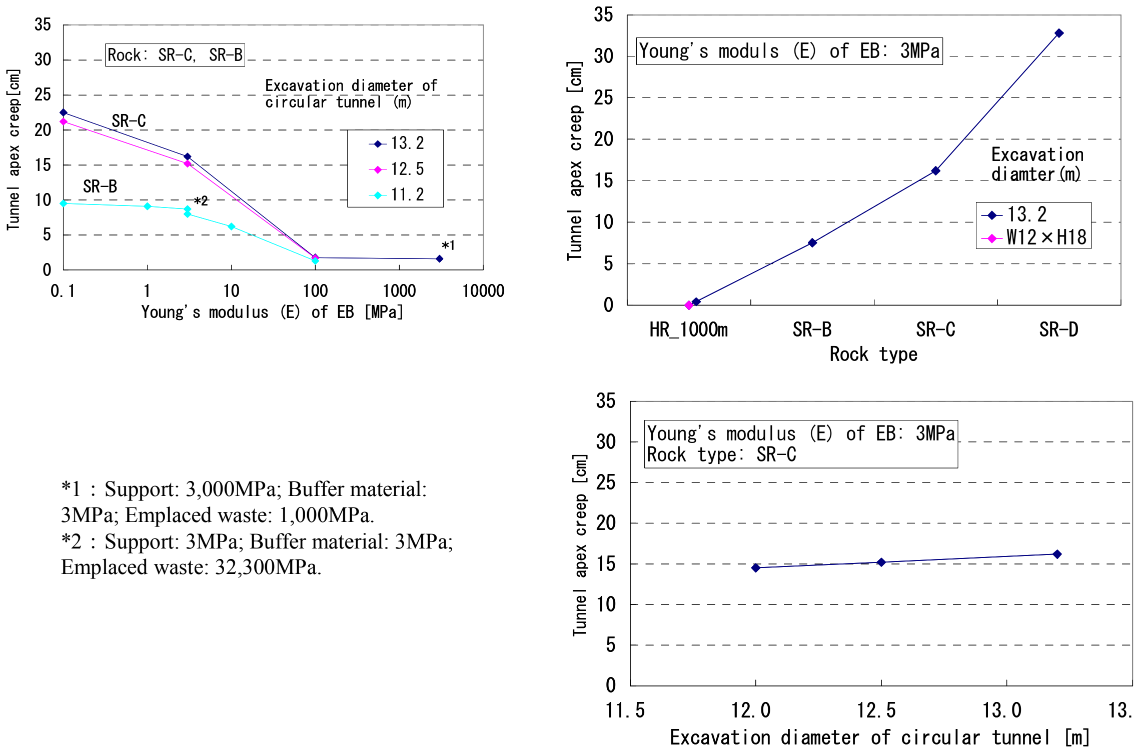


Figure 3.3-2 Result of creep deformation analysis (Case 2)



*1 : Support: 3,000MPa; Buffer material: 3MPa; Emplaced waste: 1,000MPa.
*2 : Support: 3MPa; Buffer material: 3MPa; Emplaced waste: 32,300MPa.

Figure 3.3-3 Creep displacement in the central apex after 1 million years

(Summarised from the viewpoint of the sensitivity of the elastic coefficient of engineered barriers, host rock features and excavation diameter. The result shows 0.1 MPa when the elastic coefficient of engineered barriers is 0 MPa.)

3.3.2.2 Changes in engineered barrier properties and effects of swelling pressure of the buffer material

(1) Analytical condition

a. Analytical flow

The long-term deformation behaviour of the engineered barriers after saturation depends on variations in mechanical properties, which in turn depend on variations in chemical properties. Hence, the long-term deformation behaviour is evaluated using a stepwise approach. The analytical flow of the code "MACBECE" used for the evaluation (Sasakura et al., 2004; Okutsu et al, 2005) is shown in Figure 3.3-4. The chemical property in each analytical step is preconditioned and the deformation increment for each step is calculated using a mechanical property that depends on some chemical property. Here, if the mass transport characteristics are considered to have changed significantly due to increased deformation, the spatial distribution of the chemical property in the next step is revised.

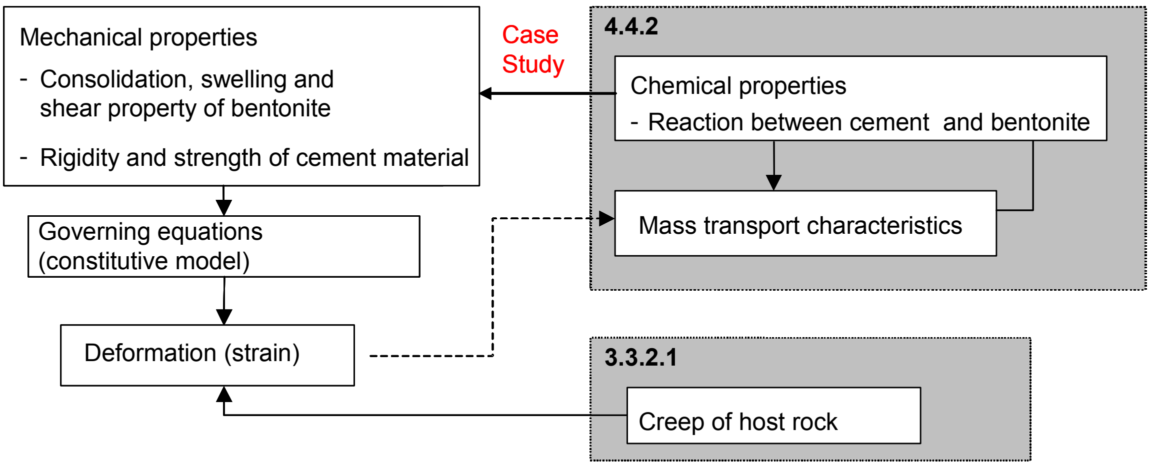


Figure 3.3-4 Analytical flow

b. Analytical system

An evaluation is carried out using the disposal tunnel for Group 1 waste in soft rock (internal diameter 12.0 m, excavated diameter 13.2 m) with buffer material. The analytical cross-section is modelled from the cross-section design. The initial waste emplacement location is set 20 cm lower in order to take into account rapid subsidence from the loading weight of the waste after emplacement (density is assumed to be unchanged at this time). The engineered barrier system is modeled based on an example specification shown in Table 3.3-3.

Table 3.3-3 Model of the engineered barriers (for Group 1 waste in soft rock)

EBS member	Specification for analysis	Remarks
Emplaced waste form (waste, filling material, structural framework)	Mortar (W/C = 55%, aggregate 54 vol%)	See Appendix 3B
Buffer material	Bentonite mixed with silica sand (dry density 1.6 Mg/m^3, mixing ratio of silica sand 30 wt%)	Based on example specification of bottom part
Invert Secondary lining, shotcrete	Concrete (W/C = 45%, aggregate 67 vol%)	See Appendix 3B

c. Analytical case

Based on the evaluation of the spatial variation in chemical properties in the cement-buffer system, it is thought that sufficient amounts of montmorillonite will remain after 100,000 years; Na montmorillonite is dominant for several 10,000 years and then alters to Ca montmorillonite after several 1,000 years. This means that a loss in the impermeability function of the buffer material cannot be ruled out (see Section. 4.4.2). In this section, 4 cases (i – iv) are established as analytical cases in order to evaluate the occurrence and degree of influence of each factor or process that controls the amount of deformation. Indicators of chemical evolution are described in e and f of this section. The evolution of chemical properties is shown in Table 3.3-4. The rate of change of processes is kept constant until the final condition and divided. Of the 4 cases, two are analysed as follows: (a) the case where rock creep can be ignored in hard rock and (b) the case where rock creep cannot be ignored in soft rock. If the creep deformation of the host rock is ignored, the tunnel wall is fixed, whereas if creep deformation is not ignored a maximum creep deformation of 16 cm (Figure 3.3-2) is considered. For the support in case (b), the initial stress is considered to be generated during excavation (Figure 3.2.2.1-4).

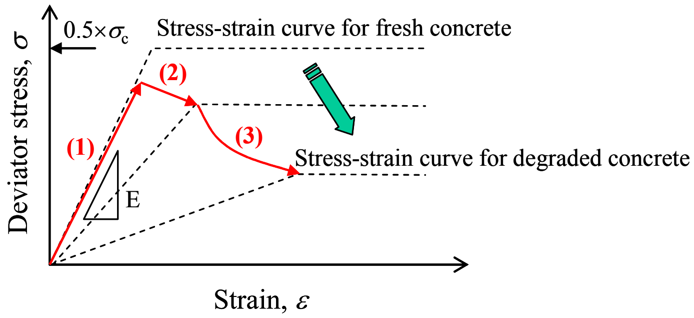
Table 3.3-4 Evolution of chemical properties up to final step

No.	Emplaced waste		Buffer material	Invert Support
	Center	1 m from boundary of buffer		
i	No change	25% of original amount of calcium*1 is leached	No change*2	100% of original amount of calcium*6 is leached
ii	No change	25% of original amount of calcium*1 is leached	ESP of bentonite only is lowered from 0.85 to 0.15 *3	100% of original amount of calcium*6 is leached
iii	No change	25% of original amount of calcium*1 is leached	Smectite partial density only is decreased from 0.92 Mg/m^3 to 0.55 Mg/m^3 *4	100% of original amount of calcium*6 is leached
iv	No change	25% of original amount of calcium*1 is leached	Equivalent ionic concentration of groundwater only is increased from 0 eq/dm^3 to 1 eq/dm^3 *5	100% of original amount of calcium*6 is leached

*1: Equals to Ca content existing as ($Ca(OH)_2$) in mortar (see Appendix 3B).
*2: Condition of original buffer: porosity is 0.40, smectite partial density 0.92 Mg/m^3 and the Exchangeable Sodium Percentage (ESP) 0.85. The equivalent ionic concentration is 0 eq/dm^3 which is effectively treated as distilled water.
*3: Assumed to be Ca type. ESP = 0.85 is natural Kunigel V1 and ESP = 0.15 is equivalent to Ca type Kunigel V1.
*4: Assumed that 50% of smectite in bentonite is altered to non-swelling minerals. True density of altered minerals is assumed to be the same value, and the porosity of silica sand mixture does not change. Cation exchange is not considered.
*5: Assumed that the equivalent ion concentration increases due to infiltration of seawater type groundwater or leachate from cement materials.
Cation exchange of bentonite and the alteration of smectite are not considered.
*6: Equals to the total calcium content existing as hydrate like $Ca(OH)_2$ and C-S-H in concrete (see Appendix 3B).

d. Analytical model

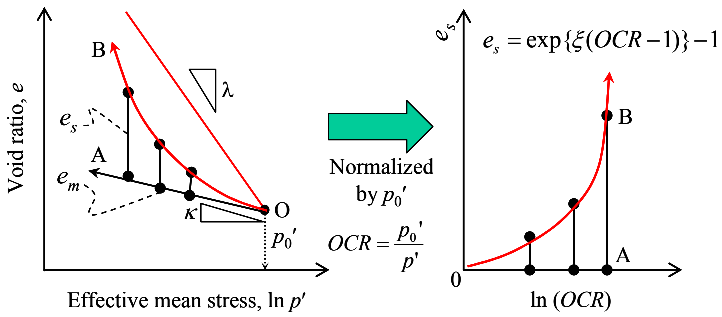
Cement material (mortar, concrete) is deformed by swelling pressure and ground pressure as stiffness and strength decrease (Figure 3.3-5). A non-linear elastic model (Motojima et al., 1981) is applied for constitutive equations which can be used to fit the behavior of strain-softening. As the swelling capability of bentonite material is reduced, the balance between swelling pressure and ground pressure is used to show the deformation of bentonite materials. An expanded model (Sasakura et al., 2004) which focuses on swelling properties is used based on the constitutive equations (Sekiguchi and Ohta, 1977; Iizuka and Ohta, 1987) for common clay (proposed by Sekiguchi and Ohta) (Figure 3.3-6). In the initial step soon after saturation, pressure due to constraints of swelling deformation (equilibrium swelling pressure) works isotropically and, in the following steps, a decrease in the equilibrium swelling pressure by alteration is taken into account as a negative external force (Okutsu et al., 2005).



Deformation due to load and initial swelling pressure (1).

Deformation due to decrease in stiffness and strength (2, 3), which is calculated as stress does not exceed strength when strength decreases below stress.

Figure 3.3-5 Concept of deformation behaviour of cement material



Common clay swells along O–A (κ constant) while bentonite swells along O–B (κ increasing).
In order to make the model widely applicable, OCR, which expresses difference of e_s between void ratio and that given at the initial gradient κ_0, is introduced.

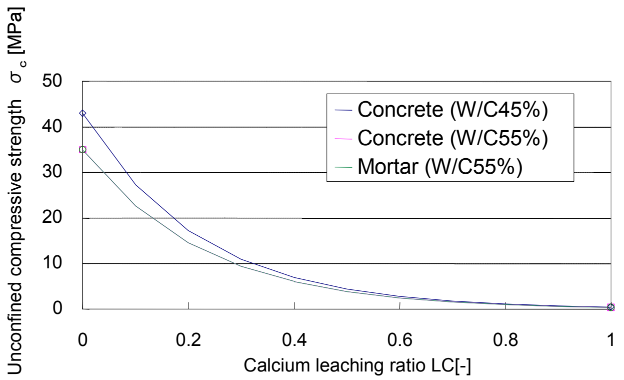
Figure 3.3-6 Concept of swelling behaviour of bentonite materials

Since the evolution of the spatial variation in chemical properties and forced displacement in the tunnel wall is not established as a function of time, the time relationship of creep deformation of cement material and viscous behavior of bentonite are not considered. Care is needed if plastic deformation is significantly affected in this analysis.

e. Mechanical properties of cement material

The increase in void through leaching of cementitious components and the processes that decrease strength and rigidity are revealed from flow tests with distilled water in cement paste and mortar. In the actual disposal environment, the possibility of void filling by precipitation of Si ions in leachate from bentonite and Mg ions in saline groundwater is considered. However, the change in strength due to void filling is uncertain. It is considered that the decrease in strength and stiffness depends on the leaching ratio of Ca (LC). In this section, the shear strength of mortar and concrete is set to 1/2 of the uniaxial compressive strength and the variation in the uniaxial compressive strength is set as equal to the rate of change in strength of cement paste with equal W/C.

A relational function (Architectural Institute of Japan, 1999) is used for concrete and a regression function estimated from experimental results (Yasuda et al., 2002) is used for mortar (Toida et al., 2005; Okutsu et al., 2005). The uniaxial compressive strength and elastic modulus of emplaced waste forms (mortar, W/C = 55%) and invert and support (concrete, W/C = 45%) versus the leaching ratio of Ca (LC) are shown in Figure 3.3-7. Poisson's ratio during pre-yield is estimated as 0.2 assuming that there is no significant change due to leaching and that elasticity is within a valid range (Japan Society of Civil Engineers, 2002b). Poisson's ratio is estimated as 0.45 post-yield since maximum stress increases by 80% (Japan Concrete Institute, 1996). Although unit volume weight can vary with degree of leaching, in actual fact it is found to be constant because porosity does not vary significantly (see Section 4.4.2).



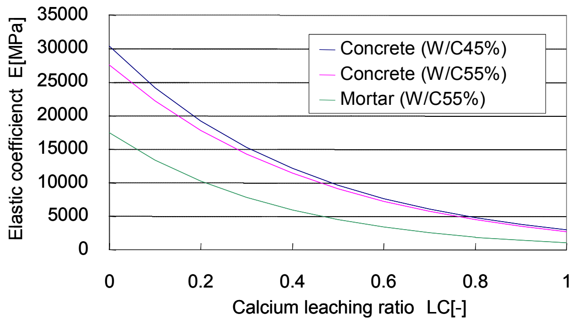


Figure 3.3-7 Variation in mechanical properties of mortar and concrete (Left figure shows variation in uniaxial compressive strength and right figure shows variation in elastic modulus)
(The green curve for mortar overlapped on the pink one for concrete (W/C55%) in the left figure.)

f. Mechanical properties of bentonite material

Changes in consolidation/swelling properties and shearing properties of bentonite caused by its own alteration and groundwater conditions can be induced in the laboratory with Ca-converted bentonite-silica sand and varying mixes of bentonite-silica sand in different solutions. The variation in cation exchange capacity is revealed using the exchangeable sodium percentage (ESP) in cations of bentonite obtained from experimental results (Okutsu et al., 2005). Changes due to smectite dissolution are determined from porosity in bentonite-silica (θ) and the smectite partial density (ρ_{sme}). The change in salt concentration in groundwater is obtained from equivalent ionic concentration (C_i) in groundwater. Since the effect on the compression index and critical state parameter of chemical alteration could not be clarified, both are kept constant and an empirical equation where swelling index and swelling pressure vary according to the chemical evolution index is applied. The indicators for density here indicate that chemical alteration and the density change due to deformation of the same material can be treated in constitutive equations as variation of void ratio so that there are no influences on the properties. Moreover, in the design of the specifications of buffer material, since the smectite inclusion ratio in bentonite has a small effect on mechanical properties, effective clay dry density is specified. However, in order to handle smectite dissolution, the smectite partial density is used.

Assuming the swelling index depends on the chemical evolution index, the plots in Figure 3.3-8 represent swelling behaviour of buffer material (sand-mixed Kunigel VI, mixing ratio 30 wt%) during unloading. The variation in equilibrium swelling pressure of buffer material depends on the chemical evolution index of each case and is shown in Figure 3.3-9.

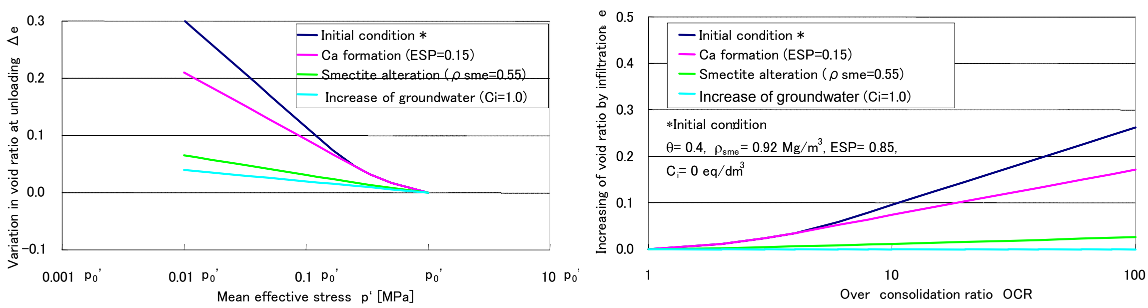


Figure 3.3-8 Swelling behaviour of buffer material during unloading

(Shows swelling behavior of 0.01 p_0' from pre-compacted load p_0'. Here, OCR = p_0'/p'.)

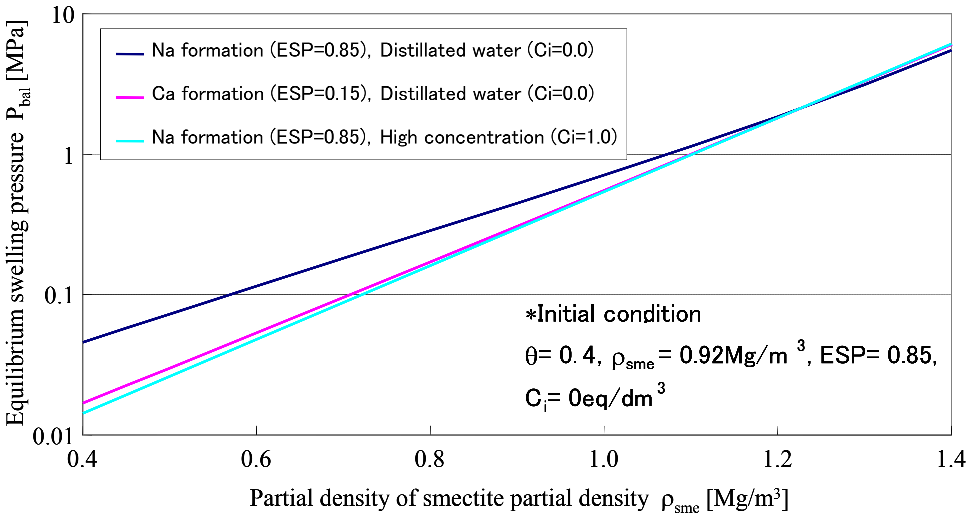


Figure 3.3-9 Variation in equilibrium swelling pressure of buffer

(2) Analytical result

The displacements in the final steps of case (ii-a) and case (ii-b) are shown in Figure 3.3-10. In case (ii-a), since the elastic modulus is set to a high value of 1,000 MPa up until the final step, displacement inside of the tunnel is no more than 1 mm. As no tensile stress is generated, buffer material will not fragment. The same results were obtained in cases (i-a), case (iii-a) and case (iv-a).

In case (ii-b), the entire disposal tunnel is deformed towards the center since a maximum displacement of 16 cm to the tunnel wall from external force is considered. Comparing emplaced waste forms and buffer materials, it is found that larger deformation occurs in buffer material with a low elastic modulus. Relative displacement of the boundary of buffer material (the thickness of the buffer material) is compressed by about 10 cm at the edges and the minimum thickness of the buffer material is about 95 cm in the bottom center of the tunnel. These results are also observed in cases (i-b), case (iii-b) and case (iv-b).

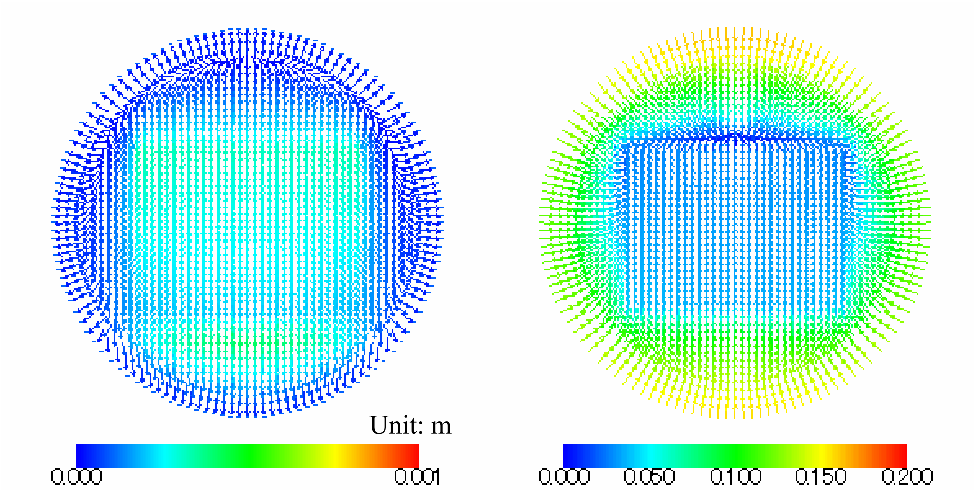


Figure 3.3-10 Deformation contours

(Left figure shows the result of ii-a, right figure shows the result of ii-b.

The arrows correspond to the displacement direction.)

(3) Effects of deformation of the engineered barriers

The amount of deformation of the engineered barriers after saturation is analyzed using a finite element method, assuming that buffer material doesn't intrude into cement material (see Section 3.3.2.5). In host rocks where creep deformation can be ignored, deformation inside of the tunnel by swelling pressure of the buffer material is insignificant and the buffer material seems to be stable. On the other hand, buffer material is compacted and its thickness decreased by up to 5 cm under compression, generated by a 16 cm deformation of the host rock. For host rock with a strength equivalent to that of SR-C, creep deformation is estimated to be only several cm and the decrease in the thickness of the buffer material is even smaller. Although conservative values are not used in the initial condition (e.g. 20 cm deformation), it is very unlikely that the thickness of the buffer material will decrease below 1.0 m. Under high compression, the effect of mass transport might be balanced out even for a decrease in thickness of about 5 cm, if the effects of the chemical properties described in the preceding paragraphs are small.

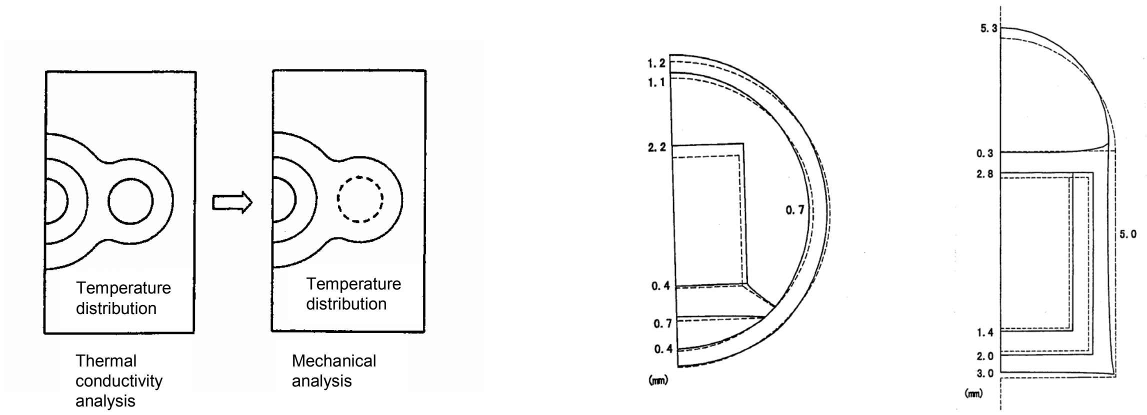
3.3.2.3 Influences of thermal stress due to thermal output of the waste

a. Temperature conditions in the disposal facility

In disposal tunnels for Group 2 waste, the temperature in the near-field increases due to the thermal output of the waste. According to a heat conduction analysis in multiple disposal tunnels in soft rock, it is estimated that the maximum temperature at the center of the waste increases up to 80°C after 8 years. It is also estimated that the temperature of the tunnel wall reaches 52°C after 8 years, with a maximum temperature of 58°C reached after 35 years. In the disposal tunnel in hard rock, it is estimated that the maximum temperature of the center of the waste reaches 78°C after 15 years. The temperature of tunnel wall reaches 62°C after 15 years, and a maximum temperature of 66°C is reached after 35 years (see Section 3.2.2.2 (3)).

b. Effect of thermal stress

The effect of thermal stress on mechanical stability was evaluated by carrying out a 2D FEM analysis (plane strain) using the elastic analytical model in the 1st TRU progress report. The temperature condition is based on the temperature distribution obtained from a heat transfer analysis of multiple tunnels and the temperature of the host rock in multiple tunnels is assumed to be constant in order to apply a thermal stress analysis to a single tunnel (cf. Figure 3.3-11). From the thermal stress analysis, it is found that the waste and structural framework expand isotropically and their maximal deformation is estimated to be about 5 mm for crystalline rock under the condition where the temperature of waste and tunnel wall reaches a maximum after 15 years. The maximum deformation in sedimentary rock is less than 2 mm and does not significantly affect the stability of the disposal facility (cf. Figure 3.3-11). The temperature of the host rock reaches a maximum after 30 years and remains the same after 15 years. Hence, the effect on mechanical stability of the host rock is estimated to be small.



(a) Set-up for temperature distribution (b) Deformation by thermal stress

Figure 3.3-11 Thermal stress analysis (TRU Coordination Team, 2000)

c. Summary

The temperature distribution at maximum temperature is similar to the analytical result in the 1st TRU progress report. The deformation of the host rock caused by temperature stress generated by the thermal output of waste is estimated to be several mm and suggests that the effect on mechanical stability is small.

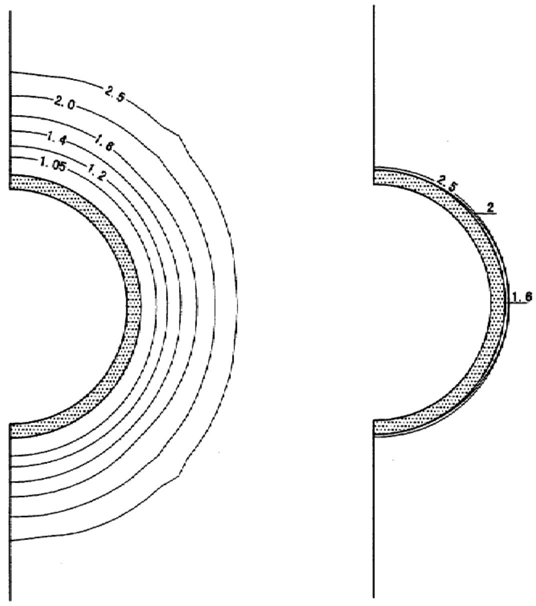
3.3.2.4 Effects of increasing pore pressure due to gas generation

a. Gas pressure generated in the repository

Both the waste and the engineered barriers generate gas through the biodegradation and radiolysis of organic material, which could potentially increase pore pressure in the disposal facility. Based on a gas migration analysis, pore pressure in the facility is highest in tunnels with buffer material and increases to a maximum of about 11.3 MPa at 1,000 m depth in hard rock and about 6.5 MPa at 500 m depth in soft rock (cf. Section 4.4.10).

b. Effect of gas pressure

The effect of increasing pore pressure on mechanical stability is evaluated by a 2D FEM analysis (plane strain) using an elasto-plastic analysis model in the 1st TRU progress report (TRU Coordination Team, 2000). In this analytical evaluation, the stress and deformation are calculated for a circular tunnel with an 11.2 m excavated diameter and a maximum inner pressure of 12 MPa. It is found that, since the local safety factor in host rock near the cavity is increased (cf. Figure 3.3-12), the inner pressure acts against the stress release from excavation and hence improves the mechanical stability of the host rock.



At excavation

At loading of the maximum pore pressure due to gas generation

Figure 3.3-12 Local safety factor in sedimentary rocks surrounding disposal tunnels for Group 2 waste (TRU Coordination Team, 2000)

c. Summary

The maximum pore pressure in disposal tunnels in this report is estimated to be smaller than in the 1st TRU progress report. While the strength of host rock is lower than in the 1st TRU progress report, the effect of increased pore pressure with gas generation on mechanical stability is estimated to be small.

3.3.2.5 Effect of extrusion of buffer material

Swelling of the buffer material is due to hydration. If there are any cracks in the secondary lining or in the shotcrete, pressure generated by swelling of the buffer material can result in its intrusion into the cracks and, eventually, extrusion into the host rock. If the density decreases due to extrusion of the buffer material, the mechanical stability in the near-field might be affected as the mechanical properties change. Moreover, if bentonite grains entering fractures are eroded by groundwater flow, colloids might be formed. The formation of colloids is evaluated in Section 4.4.5 and density decrease through crack intrusion is evaluated in this section.

From an investigation of bentonite intrusion into a single planar fracture in distilled water with no flow, it is found that fracture displacement by intrusion of Na bentonite is proportional to the square root of time and the intrusion velocity depends on the fracture aperture width and amounts of incorporated bentonite (JNC, 2000).When synthetic seawater is used instead of distilled water, it is found that fracture intrusion is controlled due to an increase in ionic strength (Matsumoto and Tanai, 2004, 2005). This result implies that swelling pressure in synthetic seawater is smaller than that in distilled water. The average density of bentonite intruded into artificial fractures is estimated using non-destructive techniques such as X-ray CT (Matsumoto and Tanai, 2003, 2004, 2005).

The density decrease in buffer material is estimated from the intrusion velocity of buffer material into a fracture and average density of intruded bentonite. As an example, when fracture width is set to 0.5 mm and fracture frequency set to ca. 7.5/m, the buffer density is found to decrease by about 0.02 Mg/m^3 (decrease ratio of density: ca. 1.4%) after 1 million years (Matsumoto and Tanai, 2003). For the same values of width and frequency of cracks in concrete used for buffer material emplacement, it is considered that the density decrease due to intrusion is small. If bentonite alteration is considered, such as conversion to Ca bentonite or dissolution of smectite, intrusion velocity into fractures is reduced and the density reduction is smaller since the swelling pressure of altered bentonite is less than or equal to that of Na bentonite (Figure 3.3-9).

3.3.3 Summary

Several phenomena which affect mechanical stability are evaluated and summarised. The results are as follows:

- The displacement of the tunnel wall due to creep of the host rock is negligible even after 100,000 – 1,000,000 years in HR. The displacement is several centimeters after 100,000 – 1,000,000 years with SR-B and SR-C datasets. If other uncertainties in the host rock are taken into account, such as heterogeneity, excavation effects and alkaline alteration, the displacement might increase locally.

- Deformation of the engineered barriers after saturation depends strongly on the displacement of the tunnel wall. If the displacement of the tunnel wall is small, the deformation inside of the tunnel wall due to swelling pressure is negligible and the buffer material is considered to be stable. 16 cm of deformation to the tunnel wall is required in order to decrease the thickness of buffer material by 10%. Although deformation of the host rock might occur locally, since the density of the buffer material increases due to compaction material migration is negligible.
- The deformation of the host rock by thermal stress is estimated as several millimeters and its effect on mechanical stability is considered to be small.
- Increased pore pressure due to gas generation effects acts against the stress release caused by tunnel excavation and thus improves the mechanical stability of the host rock.
- The density decrease due to buffer material intrusion into cracks in concrete is estimated to be 1.4% after 1 million years for a crack frequency of 7.5/m and aperture width of 0.5 mm. Moreover, if a decrease in swelling pressure due to alteration is considered, it is estimated that the density decrease would be even smaller and the effect on mechanical stability due to extrusion of the buffer material is not expected to be significant.

The effects of thermal stress, gas generation and leaching of buffer material on the mechanical stability of the near-field are small. However, interaction between creep behavior of the host rock and deformation of the engineered barriers could be considerable. In this case, the mechanical stability could be evaluated by modeling each component separately for a host rock with a strength similar to SR-C.

Based on the evaluation in this report, it is considered that mechanical stability can be maintained for a long time in the geological environments considered.

3.3.4 Future tasks

In this evaluation, it is shown that the deformation of the cross-sections of disposal tunnels is constrained in the range of geological environments considered. In order to design a rational engineered barrier system and to ensure mechanical stability over the long-term, it is necessary to develop techniques for reducing the inherent uncertainties and quantifying the tolerance over the long-term. In order to address these requirements, the following technical tasks should be considered.

- In evaluating coupled deformation of the host rock and the engineered barrier system, since knowledge of the properties of host rocks is limited, a simplified evaluation technique is applied here. However, a new method that takes into account the host rock creep behaviour and its effect on the engineered barriers and effects of chemical alternation processes should be developed and applied.

- Concerning the limited conditions used in laboratory experiments to investigate the relationship between alteration and mechanical properties of the engineered barrier system, more comprehensive, upgraded datasets are needed to better understand error uncertainties and safety margins.
- Verification tests with 2D models of tunnel shapes (circular, horseshoe-shape, etc.) are necessary to improve on initial conditions (prior to re-saturation) used in current laboratory tests of individual components of the engineer barrier system.
- Verification is required of the methods used in this report to estimate effects on the mechanical stability of the engineered barrier system and host rock of corrosion expansion of steel and a subsequent increase in void pressure in tunnels.
- A wider range of widths and frequencies of cracks in concrete need to be included in evaluations of density decrease caused by extrusion of buffer material.
- Upgraded datasets of host rock properties and models for evaluating the behaviour of host rocks need to be made more applicable to specific geological environments.

In order to improve reliability, continual revision of evaluation models using data obtained during construction and operation also needs to be considered.

3.4 Construction, operation and closure of the disposal facility

3.4.1 Structure of the disposal facility

3.4.1.1 Components of the disposal facility (surface and underground facilities)

(1) Concept

The TRU waste disposal facility is divided into surface and underground components as follows.

- TRU waste disposal facility
  - Surface facility
  - Underground facility
    - Access tunnels
    - Main tunnel
    - Connecting tunnels
    - Disposal tunnels
    - Bottom hole facility (at base of access tunnel(s))

(2) Surface facility

The main functions of the surface facility are receiving and transporting wastes and materials and providing infrastructure for the construction, operation and closure of the underground facility. The following buildings/facilities are required:

(i) Receiving/inspecting waste

(ii) Central control

(iii) Manufacturing of waste package

(iv) Material Storage

(v) Manufacturing of equipment and transporters

(vi) Manufacturing of the engineered barriers (buffer, backfill and filling materials)

(vii) Access to shaft building

(viii) Ventilation

(ix) Drainage

(x) Electricity supply, etc.

(3) Underground facility

The underground facility comprises access tunnels, main tunnels, connecting tunnels, disposal tunnels and the bottom hole facility. The purpose of each of these components is as follows.

(i) Access tunnels: Tunnels for connecting the surface and underground facilities. Access tunnels are classified into vertical and inclined tunnels.

(ii) Main tunnel: Access tunnel-connecting tunnel for the disposal area

(iii) Connecting tunnel: Disposal tunnel-connecting tunnel for main tunnel

(iv) Disposal tunnel: Emplacement tunnel for waste and engineered barriers (filling, buffer and backfill materials)

(v) Bottom hole facility: Main control room, material storage and space for underground research facility

As shown in Section 3.2.2.2, the shape of the disposal tunnel cross-section is constrained by the mechanical properties of the host rock. The two types of tunnel (circular and horseshoe-shaped) considered in this report are shown in Figures 3.2.2.2-7 to 3.2.2.2-13. Since the appropriate disposal/emplacement technique depends on the shape of the disposal tunnel, both circular and horseshoe-shaped tunnels are evaluated in this section. The basic layout for each disposal tunnel type considered in this report is shown in Figures 3.2.2.2-7, -8, -11 and -12.

3.4.1.2 Schedule for geological disposal of TRU waste

Details from a report published by a sub-committee of METI on the cost of the disposal facility (ANRE, 2004), including the schedule for geological disposal of TRU waste, are introduced here (cf. Figure 3.4.1.2-1):

(i) Site selection following the procedure outlined in the report of METI on appropriate and systematic approaches for the disposal of high-level radioactive waste in March 1999 (METI, 1999), to be initiated in 2035.

(ii) Operation of reprocessing and MOX fuel fabrication facilities, generation of decommissioing waste and return of low-level waste from overseas over a period of 25 years, with completion of disposal operations envisaged for 2060.

(iii) After completion of disposal operations, decommissioning of the surface facility and closure of the underground facility, followed by a continuous monitoring period of 300 years.

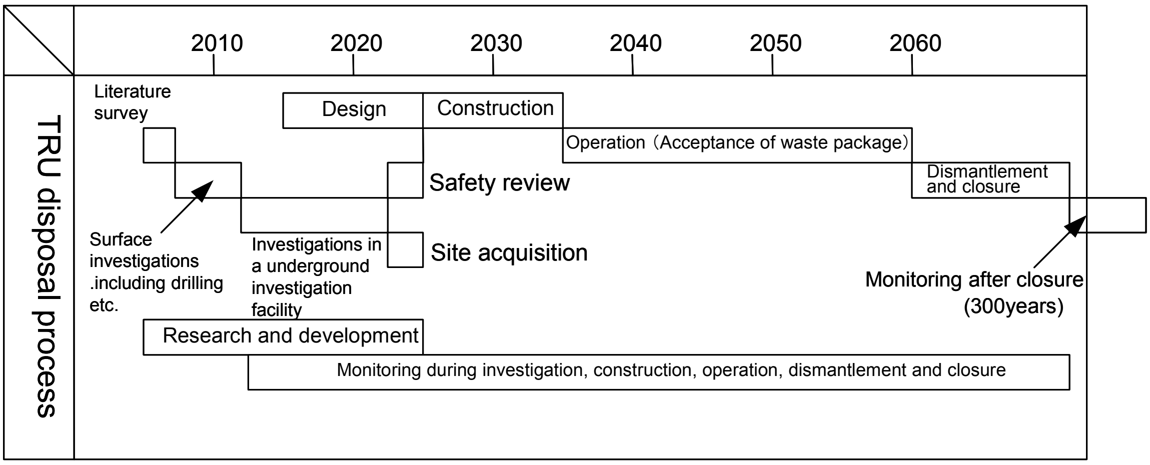


Figure 3.4.1.2-1 Disposal schedule for TRU waste (tentative)

Repository construction, operation and closure techniques are described below.

3.4.2 Construction

3.4.2.1 Surface facility

(1) Main facility

The surface facility includes (a) a facility for receiving and inspecting waste, (b) a facility for manufacturing buffer material and (c) a facility for manufacturing waste packages. In this section, the framework and specifications of these components are summarized.

a. Facility for accepting and inspecting waste

This facility has various functions, (i) receiving and interim storage of transportation cask loading TRU waste, (ii) inspecting the waste, (iii) shipping of transportation casks, (iv) incorporating waste into waste packages, mortar filling and curing, (v) interim storage of waste packages.

The design of the transportation cask and the required shielding depends on the radioactivity and surface radiation dose of the waste.

Most TRU waste for geological disposal has high radionuclide concentrations. For this reason, they should be transported in casks. Four types of cask are used: 200L drum, canister, BNGS 500L drum and square package.

Waste with relatively low nuclide concentrations, such as spent silver absorbent, can be transported in a container for loading 8 waste drums.

The size and equipment of the facility for receiving and inspecting the waste depend on the volume of waste to be received and the type of inspections required. In this report, based on the above transportation method of waste, the size of the facility and the apparatus required for handling and treating waste are discussed. The main required items are shown in Table 3.4.2.1-1.

- The interim storage area for transportation casks has to be large enough to handle one full shipment.
- The required interim storage area for inspected waste is calculated taking into account the buffer capacity based on the maximum loading number of waste for one full shipment.
- An estimated 3 weeks storage is required for curing of waste packages after filling with mortar.

Table 3.4.2.1-1 Main equipment in facility for receiving and inspecting waste

Component	Equipment
Handling facility for transportation casks and containers	Crane for transportation cask, cask sling, cask transfer car, shielding door of examination room, shielding door of removal room, inspection apparatus for inner gas of cask, sample changer, container sling
Handling facility for waste packages	Crane for waste removal, crane for temporary storage of waste, transport carrier for waste, conveyor for waste (for waste package), regimen conveyor for mortar filling waste, crane for removal and temporary placement of waste, lifting machine for waste, lifting machine for storage of empty package, transfer equipment for waste, equipment for mortar filling.
Ancillary facility	Equipment for ventilation and air-conditioning, electrical equipment, equipment for operation control, equipment for data management, equipment for liquid waste treatment

b. Manufacturing facility for buffer material

The manufacturing facility for buffer material is evaluated assuming that buffer material blocks will be used. The manufacturing process and the main equipment in this facility are shown in Table 3.4.2.1-2.

Table 3.4.2.1-2 Processing and manufacturing techniques

Main process	Candidate technique	Outline of technique	Main elements
a. Receiving and storing buffer material	Silo storage	Normally used for storing fine-grained particles and granular material such as livestock feed. Materials are poured in from above and are removed below. If the silo is made of metal, the storage function varies with light and humidity. It is necessary to check for bridge phenomena which occur when stored materials are removed.	Silo storage techniques
	Bag storage	Storage in flexible bags/ease of storage and transport of powdered and flaky material. Sometimes used for long-term storage, however easily affected by environment during storage.	Filling bags, etc.
	Transport method for fine particles	Transport of fine particles/Transport technique includes using a conveyor belt, blowing in air, etc.	Transport techniques for fine particles
b. Measuring buffer material	Device for weighing heavy materials	Techniques for measuring mass: This technique is for measurement of mass and is divided into electromagnetic type and load cell type. The former has high accuracy and is for small sizes and the latter is for large sizes. Both types are possible for measuring buffer material.	Measuring weight of heavy materials
	Device for measuring volume	Technique for measuring volume of material with fine particles/Several methods can be used such as measuring rotation speed of screw feeder and measuring supply speed and vibration of conveyor belt, etc.	Measuring volume
c. Mixing of buffer material	Batch-type mixer	Related mixing techniques/a general method where material is inserted into a long tube and mixed using gravity, or mixed with a blade. The former is able to mix well, but is designed only for small amounts of material. The latter is suitable for large amounts of material, but heterogeneous mixing may occur due to limited movement. Rotation tube type mixing technique/mixture and removal of material controlled by varying rotation axis of tube. Mainly used for mixing concrete.	Batch-type mixer system
	Continuous mixer	Continuous mixing system/in this method, materials are inserted into a tube and mixing occurs during movement of materials. Mixing finishes after the materials reach the end of tube and are ejected.	Continuous mixer system
d. Buffer compaction	Static pressure	Static pressure system/uniaxial, biaxial and triaxial compression methods. Uniaxial and biaxial are commonly used. Triaxial method is occasionally used for super high pressure compression. After compression, some stress still remains in mold. Dimensions may change after removal from mold because of the effect of residual stress.	Static pressure method Material injection method Removal method
			Compression quality management
	CIP (cold isotropic pressure)	Material is filled into a rubber mold and is dipped in a pressure container. With this technique it is possible to make large complex structures. A high density and homogeneous product can be made. After molding, a machining process is necessary.	Material filling technique (hopper, vibrator)
			Pressure fabrication technique (CIP)
			Pressure technique (Turnery technique, dry system)
e. Screening of buffer	Optical type measurer	Measurement technique using an optical type counter/this technique is for distance measurement using a laser and distance and conditioning measurement using an image data processing technique. Can measure shape, but it is not possible to measure mass. In water, light reduction is large.	Optical transmission system Optical reception system Counter unit operation system Data transmission system
			Image data processing technique
	Ultrasonic type measurer	Ultrasonic technique for distance measurement/this technique is for distance measurement using ultrasonic sound. In the air, the accuracy and measurable area of this technique are higher than using a laser.	Ultrasonic transmission system Ultrasonic reception system Ultrasonic process system
	Contact-type measurer	Contact-type measuring technique/Length is measured though extension of probe needle.	Contact-type measuring system Data processing of contact-type measuring system
f. Storage of buffer	Storage with ventilation	Storage with ventilation/prevents alteration of material through ventilation.	Storage technique
	Storage with wrapping	Storage with wrapping/this storage technique blocks air from target material by wrapping.	Storage technique
g. Loading of buffer materials	Vacuum grabbing system	Vacuum grabbing system/ object is held using a vacuum pad. Useful for holding and moving material that is not porous and does not have any holding points (same method used for holding car windshields).	Vacuum grabbing system
	Pallet system	Pallet storage/this technique creates empty space by setting a pallet under the package. Material is transported by insertion of fork into empty space.	Pallet type loading system
	Mechanical grabbing system	Mechanical grabbing technique/transport by clutching material with a mechanical clamp. Same technique as for moving gravel, scrap, lumber, etc. In some machinery, clamps can be exchanged with shovel parts. Some machinery can be fixed with a crane.	Mechanical grabbing system

c. Manufacturing facility for waste packages

This facility is for manufacturing waste packages (200L drum, BNGS 500L drum and canister) and for storage.

The required function of the manufacturing facility is as follows.

(i) Temporary storage of material

(ii) Manufacturing of waste package

(iii) ID numbering

(iv) Temporary storage of manufactured waste packages

(v) Collection of data for quality management

(vi) Temporary storage of material and maintenance of environment

The manufacturing process and management of waste packages is shown in Table 3.4.2.1-3.

Table 3.4.2.1-3 Management and manufacturing processes

Manufacturing process	Work description	Main equipment	Checked items
Receiving and temporary storage of construction materials	Receiving and temporary storage of construction materials		- Number - Size and materials
Assembly of EBS	Bending, welding	- Press machine - Welding machine	- Welding control - Size measurement - Weight measurement
Surface preparation	Painting, drying etc.	- Blast machine - Painting machine	- Process grade - Number of painting
ID Numbering	ID Numbering	Numbering machine	Response to ID
Temporary storage	Temporary storage of waste package		Environmental monitoring (temperature, moisture)

3.4.2.2 Underground facility

(1) Concept for the underground facility

The underground facility is composed of the access tunnel, main tunnel, connecting tunnel, disposal facility and bottom shaft facility. The concept for each component is shown as follows.

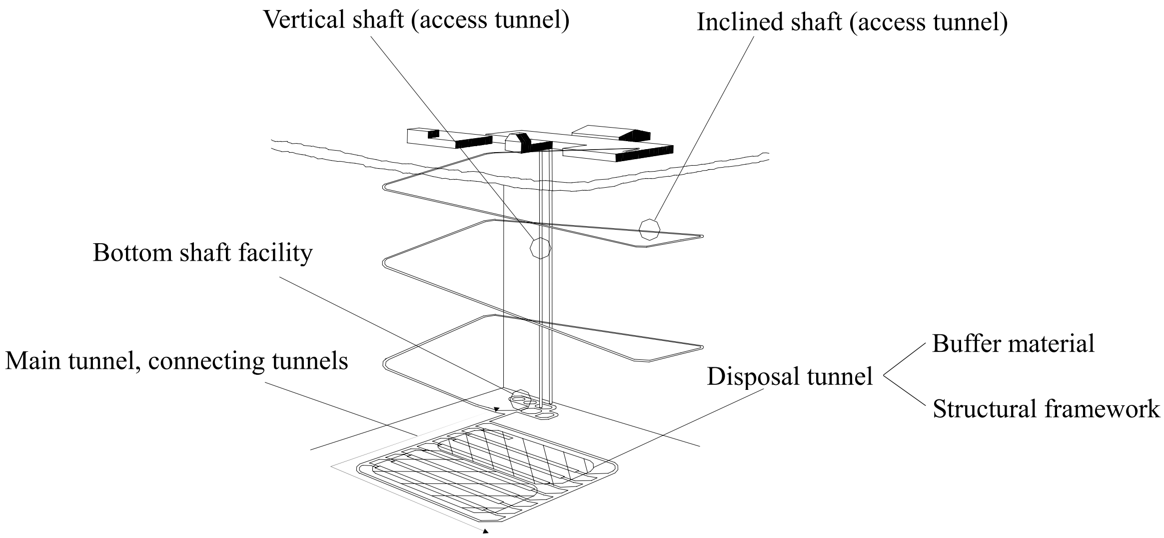


Figure 3.4.2.2-1 Concept for underground facility

The buffer material (bottom part and side part, if necessary) and structural framework is constructed in the disposal tunnel as one construction step. Evaluations of construction techniques for each tunnel type, buffer material and structural framework is summarised as follows.

(2) Construction of the vertical shaft

a. Specifications of the vertical shaft

The vertical shaft functions as an access tunnel connecting the surface facility to the underground facility. It is used for transporting workers and materials and for removing excavated rock during construction of the underground facility. It is also used for transporting materials, ventilation and drainage during operation.

Although a lift is used for transporting materials and workers, capsule transportation using air pressure is being evaluated as a candidate technique (Okutsu et al., 2004). An example design of the cross-section of a vertical shaft is shown in Figure 3.4.2.2-2.

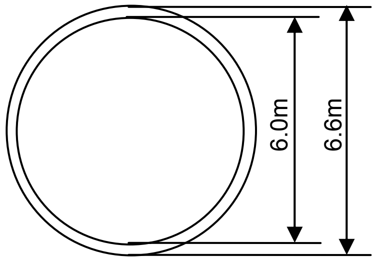


Figure 3.4.2.2-2 Cross-section of a vertical shaft

b. Evaluation of construction methodology

A method for excavating to great depths is required for constructing the vertical shaft of a TRU disposal facility. The construction method is limited to vertical excavation from the surface. The following excavation methods for the vertical shaft are considered.

(i) Tunneling by full face blasting
- Short step method
- Long step method
- Semi long step method
- Rock bolt/spraying method

(ii) Machine excavation method
- Full face tunneling method

The short step method of construction is considered to be most appropriate in hard and soft rocks as it as been used widely and the construction of support and lining is possible at an early stage after excavation. Moreover, it does not depend strongly on the ground conditions and has a high safety record. However, controlled blasting is required (e.g. with smooth plastic) in order to loosen the surrounding rocks.

(3) Construction of the inclined shaft

a. Specification of the inclined shaft

The inclined shaft serves as an access tunnel connecting the surface facility and underground facility and has various uses, including transportation of waste and materials for the engineered barriers. The inclination of the shaft is set to a maximum of 10%. However, the inclination depends on the adopted transportation method in the tunnels (e.g. free orbit type, rail type, rack-and-pinion type). An example cross-section design of an inclined shaft is shown in Figure 3.4.2.2-3.

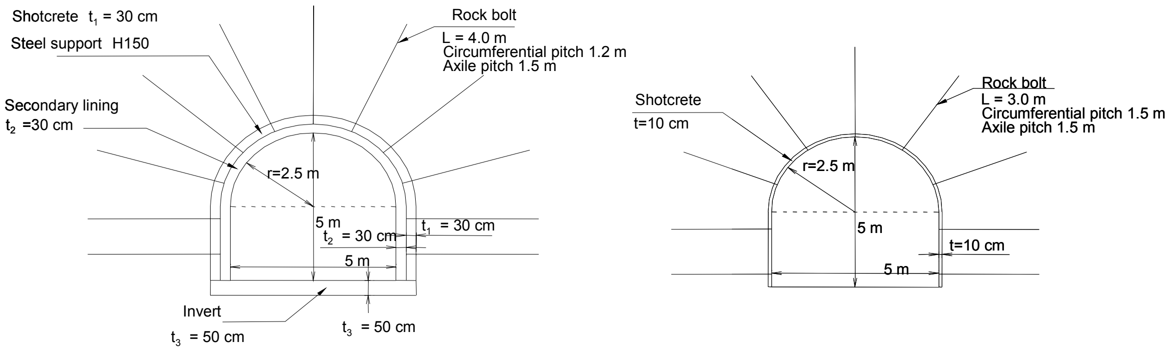


Figure 3.4.2.2-3 Cross-section of inclined shaft
(left: soft rock, depth 500 m, right: hard rock, depth 1,000 m)

b. Evaluation of the construction methodology

Excavation using explosives and machine excavation, e.g. with a partial cutting machine, are used. For excavation in hard rock where the unconfined compressive strength is above 100 MPa, controlled blasting such as smooth blasting is considered to be appropriate. The NATM construction method which uses rock bolts and shotcrete is considered appropriate for support and tunnel lining. If the host rock is of good quality, no support will be used. However, shotcrete is needed at least from the viewpoint of safety assurance during construction.

For soft rocks with unconfined compressive strength above 20 MPa, machine excavation using e.g. a road header is considered. For support and lining, the NATM construction method will be used with suitable amounts of lining concrete as required for the facility.

(4) Construction of main and connecting tunnels and bottom shaft facility

a. Specification of main and connecting tunnels

The main and connecting tunnels are horizontal tunnels connecting the access tunnel and disposal tunnels. The basic use is same as the inclined shaft. The design of the cross-section of the main and connecting tunnels is shown in Figure3.4.2.2-4.

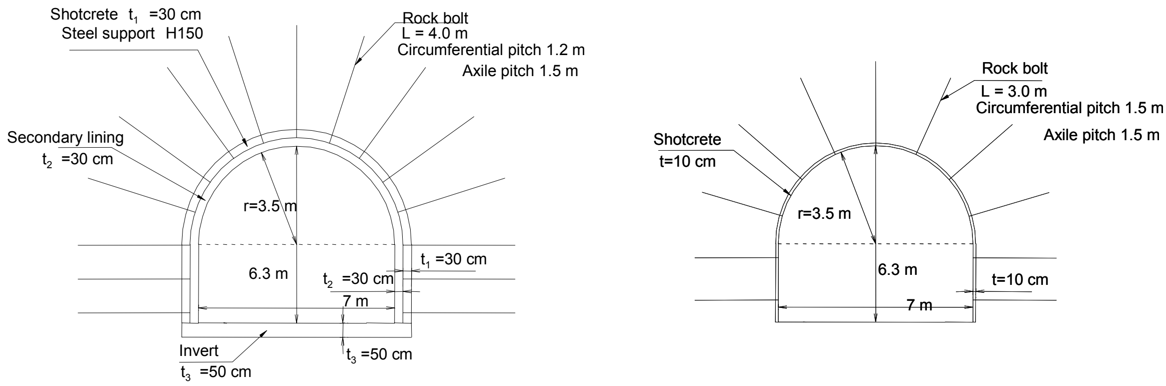


Figure 3.4.2.2-4 Cross-section of main tunnel and connecting tunnel
(left: soft rock, depth 500 m, right: hard rock, depth 1,000 m)

b. Evaluation of construction method

In hard rocks with unconfined compressive strength above 100 MPa, controlled blasting such as smooth blasting is considered appropriate. For the support and lining, the NATM construction method using rock bolts and shotcrete is considered appropriate.

In soft rocks with unconfined compressive strength above 20 MPa, machine excavation using e.g. a road header is considered appropriate. For support and lining, the NATM construction method will be used, with appropriate amounts of lining concrete as required for the facility.

(5) Construction of disposal tunnels

a. Specification of disposal tunnels

Two types of disposal tunnels will be used and their cross-sections are shown in Figure 3.2.2.2. The circular disposal tunnel will be used in soft rock and both circular and horseshoe-shaped tunnels according to the crack frequency in hard rock. Example designs of disposal tunnels are shown in Figure 3.4.2.2-5 and 6. The specification of support for each tunnel is based on existing construction techniques.

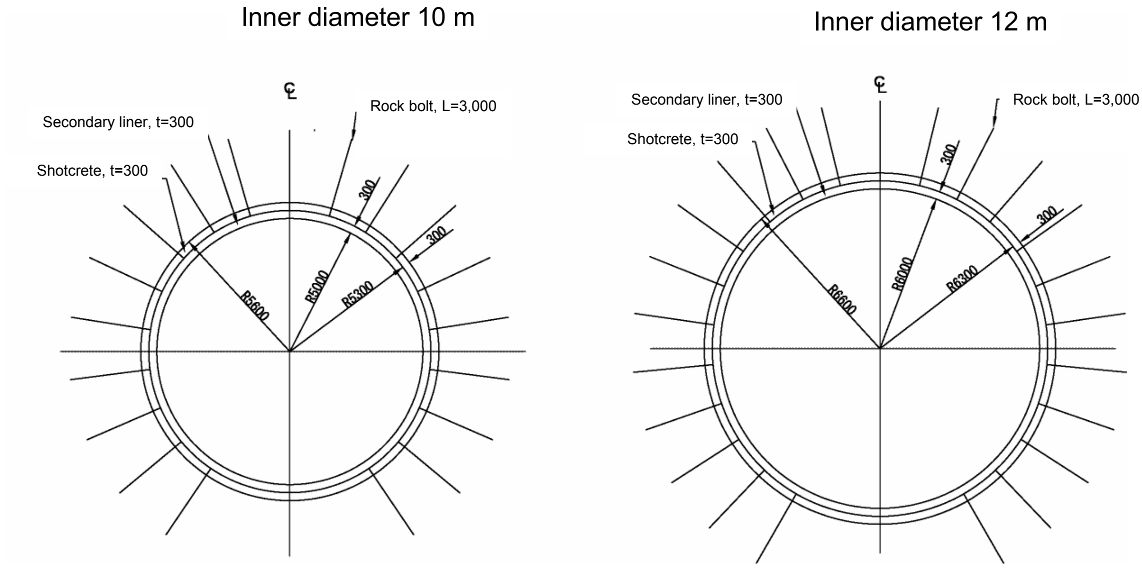


Figure 3.4.2.2-5 Cross-section of a circular disposal tunnel in soft rock

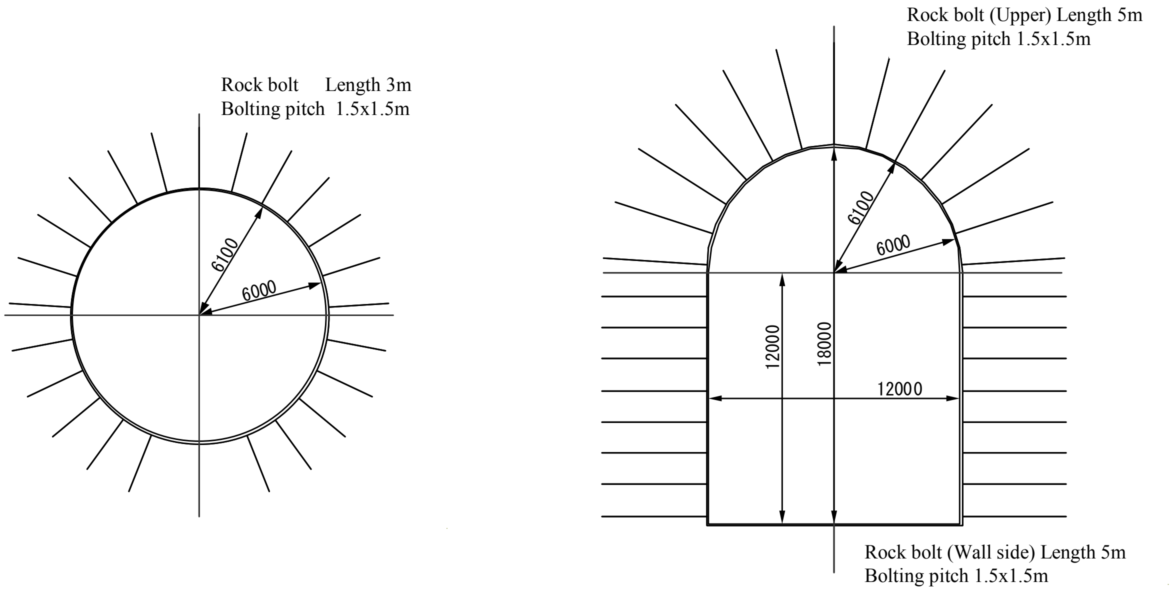


Figure 3.4.2.2-6 Cross-section of circular and horseshoe-shaped disposal tunnels in hard rock

b. Evaluation of construction methodology

The excavation method for circular disposal tunnels is the same as that for the main tunnel.

For horseshoe-shaped disposal tunnel, large amounts of excavated material are generated and this has to be taken into account in the excavation process. In Figure 3.4.2.2-7, the concept for the excavation process for this type of disposal tunnel is shown. Essentially, upper and lower connecting tunnels are constructed at the both ends of the disposal tunnel and excavated material is transported away from the lower connecting tunnel. Excavation is carried out in the following order:

(i) Upper and lower connecting tunnels are excavated.

(ii) After excavation of the top part of the disposal tunnel, support and lining is constructed if necessary.

(iii) A vertical connecting hole for moving excavated material from the top of the disposal tunnel to the lower part is excavated.

(iv) The disposal tunnel is partially excavated in layers (bench cut) from top to bottom.

(v) The excavated material is dropped into the lower connecting tunnel via a connecting hole. After the loading onto a lorry, the excavated material is transported to the surface.

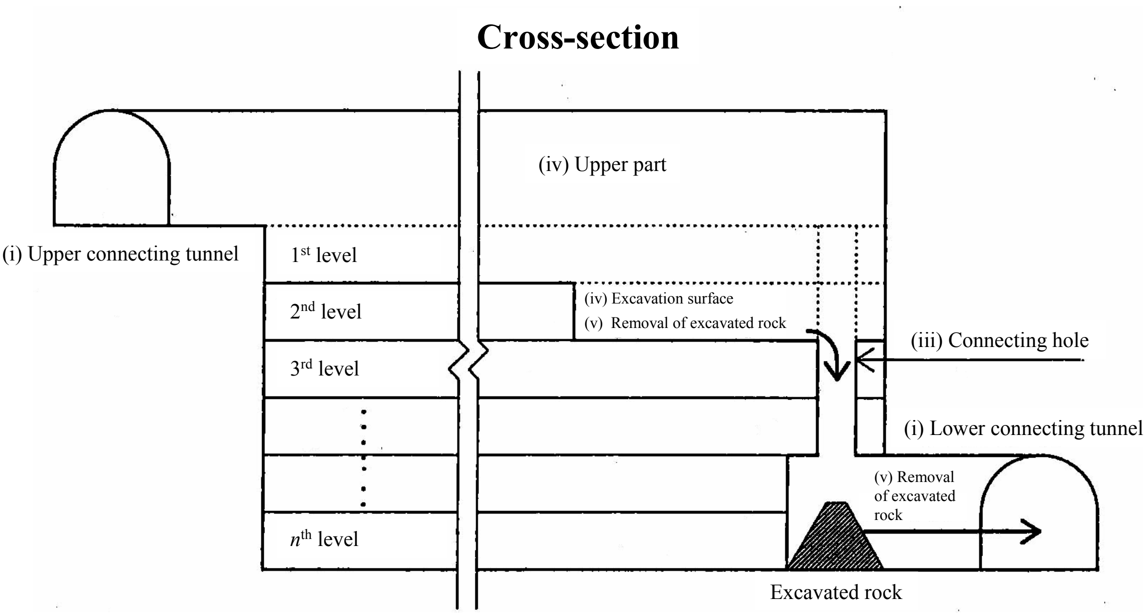


Figure 3.4.2.2-7 Concept for the excavation process of large disposal tunnels

(6) Construction of the buffer material

a. Construction methods and scope of application

The construction methods for the buffer material can be divided into in situ compaction methods and block emplacement methods, as described in the H12 report. The in situ compaction method is further subdivided into impact, vibration and compression methods. Moreover, if the target density is low, other methods such as spraying with compressed air and natural drop are also appropriate. The construction methods for the buffer material are summarized in Tables 3.4.2.2-1 and 3.4.2.2-2-5.

Table 3.4.2.2-1 Emplacement techniques of buffer material

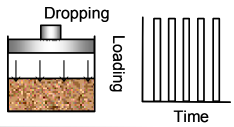
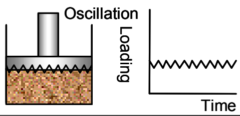
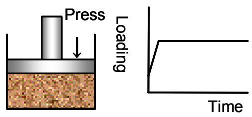
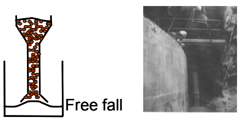
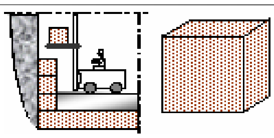
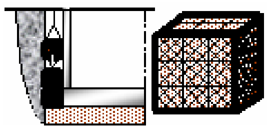
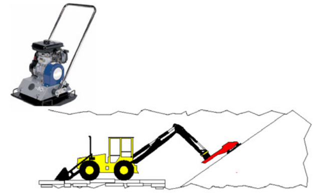
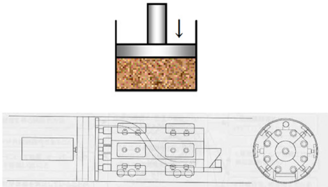
	Concept	Principle	Equipment
In-situ method			
Percussive method		Buffer material compacted by dropping or acceleration of heavy load. (possible to produce 0.05 Ec of impact energy)	Ram dropping, rammer, air hammer, hydraulic accumulator
Vibration method		Buffer material is compressed by vibrating plate	Plate compactor, vibratory roller, hydraulic vibro
Compression method		Buffer material is compacted by weight	Steel ring roller, macadam roller, hydraulic compression machine
Shotcrete method		Materials are sprayed on using compressed air	Dry-type and wet-type spraying such as ARIBA
Dropping method		Granular bentonite dropped from a shute	Bucket and chute
Block method			
Emplacement of large blocks		Emplacement of large blocks by fork-lift	Fork-lift, vacuum contact
Pre-assembly method		Small sized blocks stacked from above.	Fork-lift, crane
Emplacing small blocks by hand		Small blocks emplaced one at a time by hand.	

Table 3.4.2.2-2 In situ buffer emplacement techniques (1/4)

	Rammer type			Vibratory type	
Technique	1 Falling weight	2 Rammer	3 Air/hydraulic rammer	1 Vibratory plate compactor	2 Large vibratory plate method
Photograph					
Overview	Buffer material compacted by weight dropped from a fixed height. Degree of compaction of buffer material is controlled by adjusting mass of weight, height dropped and number of times dropped.	Buffer material compacted using small multi-purpose rammers. Strong compaction possible with high vibration frequencies (500-600 vpm).	Buffer material compacted by vibrating metal parts (1000 vpm). Machinery normally used for breaking up concrete or rock can be modified for this technique. Remote control is possible.	Plate fixed to hydraulic vibrator. This technique is used in earth moving but compaction energy is low. Has already been modified experimentally at SKB for compacting backfill material.	Use of large scale hydraulic vibrator. Large vibration energy possible but vibration width is narrow and bentonite grains likely to be crushed by percussion.
Demonstration of technique	20-30% silica-sand mixture compacted to 1.75 Mg/m^3 in a full scale test pit (1.7 m in diameter).	Technique demonstrated in in-situ experiments. Crushed natural bentonite compacted to > 1.6 Mg/m^3.	1.6 Mg/m^3 density achieved with an air rammer used for breaking up concrete. If hydraulic hammer is used, high compaction energy can be achieved.	Natural bentonite can be compacted to about 1.2-1.3 Mg/m^3 with this technique so it can be used in preliminary, first stage compaction of buffer material.	Dry density of 1.4 Mg/m^3 demonstrated for 30% silica-sand mixture under experimental conditions in a laboratory.
Issues/ future studies	Mechanical shock to surrounding structures and host rock during in-situ compaction. Difficulty in developing automatic compactors.	Difficult to manufacture on large scale. Difficult to increase size of rammer	Verification of design of specialized machinery. Examination of surrounding mechanical shock, residual load, etc.	Compaction demonstrated but compaction energy is small.	Compared with the falling weight and static pressing techniques compaction energy is low. Specialized machinery needs to be developed
Tunnel emplacement application/ feasibility — Bottom	(X) Inadequate for compacting large surface areas.	(X) Inadequate for compacting large surface areas.	(F) Development of special machinery for compacting large areas	(X) Difficult to compact material to required density of 1.6 Mg/m^3.	(X) Difficult to compact material to required density of 1.6 Mg/m^3.
Side	(F) Compaction quality.	(F) Considered to be a supplementary method (e.g. compaction in narrow spaces).	(O) Shown to be feasible under experimental conditions.	(F) Appropriate for compacting pellet fillings.	(F) Development of specialized machinery required.
Top	(X) Inadequate for compacting large surface areas.	(X) Not suitable for compacting large areas.	(F) Feasibility in narrow top part needs to be demonstrated.	(F) Appropriate for compacting pellet fillings.	(F) Development of specialized machinery required.

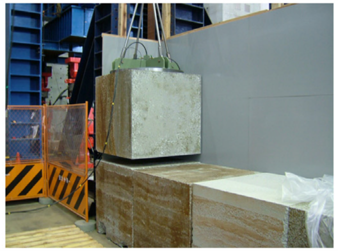
Legend O：Appropriate method. F：Possible method. X：Inappropriate method.

Table 3.4.2.2-3 In situ buffer emplacement techniques (2/4)

	Vibratory	Compression type	Shotcrete type	Free falling type	
Technique	3. Vibratory roller	1. Static press	1. Concrete spraying technique	1. Crushed natural ore	2. High density pellet filling
Photograph / Figure					
Overview	Compaction with a vibratory roller. Degree of compaction can be easily changed (1 to 5 times) by interchanging drums with different weights and adjusting drum oscillation.	Compaction using a non-vibratory roller/press. However, energy is low and not appropriate for buffer material. A uniaxial press has been suggested for use in tunnels for high-level waste.	Wet and dry processes can be used. The former involves spraying material through a nozzle under high pressure and adjusting water content. In the latter, water content is increased at the end of the nozzle. Quality control problematic with both processes.	Natural ore dropped through a chute. Easiest and cheapest method. Has been used in SFR silo in Sweden.	Bentonite pellets that can be compacted to a high density (about 1.6 Mg/m^3) using simple compaction techniques without need for vibration.
Feasibility or demonstration of technique	1.6 Mg/m^3 density (2.13 m in width and 5.74 m in length) achieved with natural bentonite in tests using an 11.3 ton vibratory roller.	2 MPa pressure required to compact buffer material to a density of 1.6 Mg/m^3. However, problematic to generate such high pressure on-site.	Under experimental conditions 1.07-1.33 Mg/m^3 density has been achieved using the wet process on the walls of a tunnel. 1.3 Mg/m^3 has been achieved with the dry process.	Side parts in SFR filled by free falling method. Target dry density of 0.95 Mg/m^3 exceeded. In Japan, dry density > 1.29 Mg/m^3 published by RWMC using natural ore crushed to < 20 mm.	Pellets can be made with a density up to 2.25 Mg/m^3. By mixing with different grain sizes, very high density buffer material is possible.
Issues/ future studies	Due to the size of the vibratory rollers, large spaces are need for operation. Smaller accessories need to be developed for co-use.	Currently a suggested technique only and many developments still required.	Problem with nozzle blockage. Difficult to control water content with dry process. After spraying, problematic to control density.	Maximum density about 1.3 Mg/m3. Possible material disintegration. Degradation from heat dispersion before groundwater infiltration.	Material breakup by dropping possible. Cost assessment of high-density pellets required. Degradation from heat dispersion before groundwater infiltration.
Tunnel application/ emplacement feasibility — Bottom	(O) Demonstrated in tests.	(X) Counter-force not feasible.	(X) Problematic to achieve target density of 1.6 Mg/m^3.	(X) Problematic to achieve target density of 1.6 Mg/m^3.	(X) Problem with support strength.
Side	(F) Tests needed to demonstrate required density.	(F) Design and verification of appliance required	(F) Basic tests needed to measure density.	(F) Basic tests needed to measure density.	(O) Problem with heat transfer; manufacturing possible.
Top	(F) Smaller accessories need to be developed.	(X) Counter-force not feasible	(F) Basic tests needed to measure density.	(F) Basic tests needed to measure density.	(O) Problem with heat transfer; manufacturing possible.

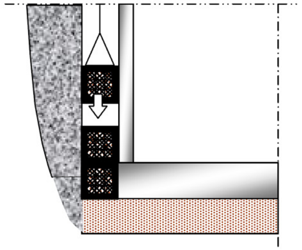
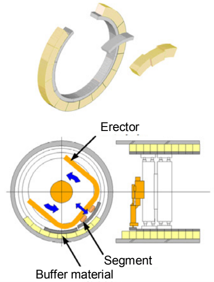
Legend O: Appropriate method. F: Possible method. X: Inappropriate method.

Table 3.4.2.2-4 In situ buffer emplacement techniques (3/4)

		Large block type			
Technique		1. Forklift (Push-pull forklift)	2. Forklift (Clamp forklift)	3. Crane (Mechanical grasping method)	4. Crane (Vacuum grasp method)
Photograph / Figure					
Overview		Block placed on plate and transported to predefined location and then plate is pulled out. Sufficient density required for enduring resulting frictional force as plate is pulled out. 1 cm spacing occurs at furthest side.	Blocks are clamped with two panels either side, then lifted and emplaced in position using a forklift. About 10 cm spacing between blocks remains after emplacement.	Blocks are grasped mechanically with two panels on either side then lifted and emplaced in position using a crane. Practical for narrow spaces. About 10 cm spacing between blocks remains after emplacement.	Blocks are lifted and emplaced using a vacuum grasping method. Can only be used with high-density bentonite and grasp surface must be smooth. No spacing between blocks after emplacement.
Feasibility or demonstration of technique		Tests carried out using a 1 m^3 block with a dry density of 1.6 Mg/m^3 demonstrated the feasibility of this emplacement technique.	Tests carried out using a 1 m^3 block with a dry density of 1.6 Mg/m^3 demonstrated the feasibility of this emplacement technique.	Specialized hardware has already been designed and manufactured. Tests carried out using a 1 m^3 block with a dry density of 1.6 Mg/m^3 demonstrated the feasibility of this emplacement technique.	Demonstrated in tests that 1 m^3 blocks could be grasped if dry density is about 1.8 Mg/m^3.
Issues/ future studies		Possible frictional damage.	Blocks need to be shifted to remove spaces after emplacement.	Blocks need to be shifted to remove spaces after emplacement. Lifting/emplacement/sliding work needs demonstration of feasibility. Hoist required for overhead crane.	Measures to prevent blocks from dropping need to be designed and verified. Hoist required for overhead crane.
Tunnel emplacement application/ feasibility	Bottom	(F) Practical but damage during emplacement should be checked.	(O) Emplacement practical.	(F) Lower efficiency compared with forklift.	(F) Improved reliability required.
	Sides	(F) Practical but damage during emplacement should be checked.	(O) Practical if emplaced before construction of support structure.	(O) Very practical if it is possible to slide the blocks.	(F) Improved reliability required.
	Top	(F) Practical but damage during emplacement should be checked.	(O) Emplacement practical.	(F) Lower efficiency compared with forklift.	(F) Improved reliability required.

Legend O: Appropriate method. F: Possible method. X: Inappropriate method.

Table 3.4.2.2-5 In situ buffer emplacement techniques (4/4)

		Pre-assembly method	Shield method	Small block type
Technique		1. Rack method	1. Erector method (large block)	1. Packing by hand
Photograph / Figure				
Overview		Pre-assembled blocks stacked with a rack. This approach is more efficient and accurate than stacking by hand.	Buffer material blocks are emplaced using an erector that is set up in a tunnel with a circular cross-section.	This approach is labour intensive but appropriate for narrow spaces or when other techniques would be problematic.
Feasibility or demonstration of technique		Idea currently under consideration only but is expected to be a feasible emplacement technique owing to its simplicity.	Idea currently under consideration only but is expected to be appropriate for emplacement in a tunnel with a circular cross-section.	This technique was verified through sealing tests on a bentonite plug carried out by AECL. However emplacement efficiency is low.
Issues/ future studies		Concern over physical and chemical effects as well as nuclide migration effects in each component of the engineered barriers. Containers used for suspending the blocks will need to be removed.	Strength of buffer material needs to be established. Verification of design and performance required.	Labor intensive
Tunnel emplacement application/ feasibility	Bottom	(X) Inferior to in-situ compaction techniques.	(F) High efficiency envisaged but verification of performance required.	(X) Inferior to in-situ compaction techniques.
	Sides	(F) Problem with making adequate performance assessment in the case where guide rails are not removed.		(F) Candidate technique for narrow spaces.
	Top	(X) Inferior to in-situ compaction techniques.		(X) Inferior to in-situ compaction techniques. Appropriate for narrow parts.

Legend O:Appropriate method. F:Possible method. X:Inappropriate method.

b. Scope of application of each construction method

In Table 3.4.2.2-6, various construction techniques for buffer material are shown. Since the construction method depends on the compaction properties of the buffer material, knowledge from construction tests for each material is summarized. In the table, the solid line refers to the range of dry density and dashed lines show effective clay dry density. At the bottom of the table, the hydraulic conductivities of Kunigel V1 (estimated from effective clay dry density) in freshwater type groundwater and seawater type groundwater and after conversion to Ca type bentonite are shown.

Based on the results of construction tests, a combination of in situ compaction methods and choice of materials are used to set appropriate hydraulic conductivities as follows.

(i) Hydraulic conductivity below 10^{-11} m s^{-1} in fresh groundwater (target effective clay dry density > 0.5 Mg/m^3)

- The buffer material can be manufactured to a certain density using all methods.
- Gravity mixing of material without adjusting moisture is considered as a candidate method since it is the easiest.

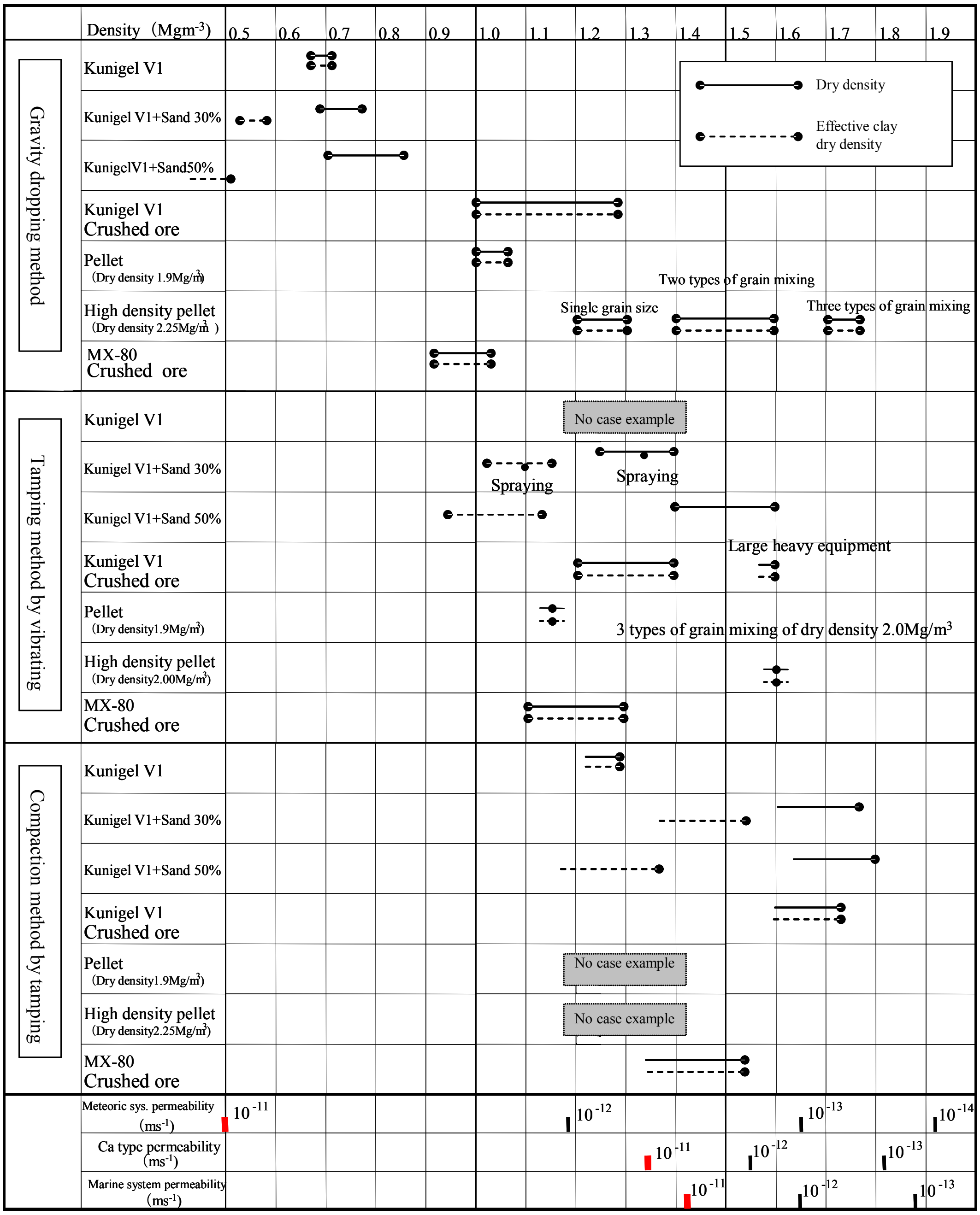
(ii) Hydraulic conductivity below 10^{-11} m s^{-1} on the formation of Ca type (target effective clay dry density > 1.34 Mg/m^3)

- Gravitational mixing: By adjusting grain size, the effective clay dry density is set to approximately 1.34 Mg/m^3 using Kunigel crushed ore. Gravitational mixing is also applicable for high density pellets (dry density 2.25 Mg/m^3) with different grain sizes.
- Vibro-compaction: The crushed ore of Kunigel is compressed by vibrating at 50 Hz. Three types of high-density pellet with 2.0 Mg/m^3 dry density can be mixed and compressed by vibration.
- Impact compaction: The target dry density is achieved by using appropriate material (mixed with silica sand, crushed ore of Kunigel or MX), except for Kunigel V1.

(iii) Hydraulic conductivity below 10^{-11} m s^{-1} in seawater type groundwater (target effective clay dry density > 1.42 Mg/m^3).

- Gravitational mixing: Several types of high density pellet (dry density 2.25 Mg/m^3) are mixed with the same Ca type bentonite and gravitational mixing is considered to be applicable.
- Vibro-compaction: Kunigel principal ore, which can be used to adjust the moisture content, can be compressed by large heavy machinery. Three types of high density pellet with 2.0 Mg/m^3 dry density are mixed and compressed by vibration.
- Impact compaction: Target density is achieved by mixing 30% of silica sand, crushed ore of Kunigel or MX to adjust the moisture content.

Table 3.4.2.2-6 Relationship between construction method of buffer material and attained density/hydraulic conductivity



References

(JNC, 2000)
(JNC, 2003)
(Maeda et al., 1998)
(RWMC, 2002)
(RWMC, 2004)
(RWMC, 2005b)
(Wada et al., 2002)
(Wada et al., 2004)

c. Emplacement methods for buffer material

Based on the applicable scope of each emplacement method and the required performance of each part of the buffer, examples of feasible emplacement methods in circular and horseshoe-shaped disposal tunnels are shown in Figures 3.4.2.2-8 and -9. Optimized emplacement and the required specifications of the buffer material are evaluated taking into account the planned tunnel shape which can be feasibly excavated.

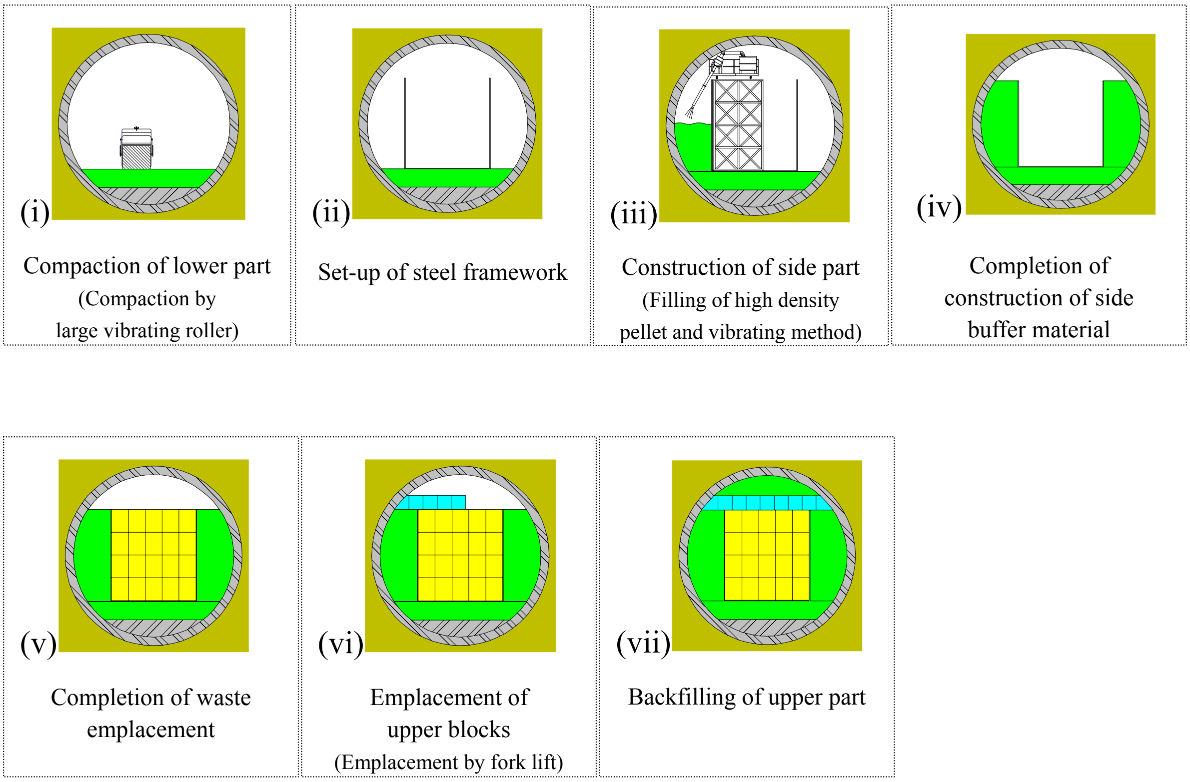


Figure 3.4.2.2-8 Construction of buffer material in the circular disposal tunnel

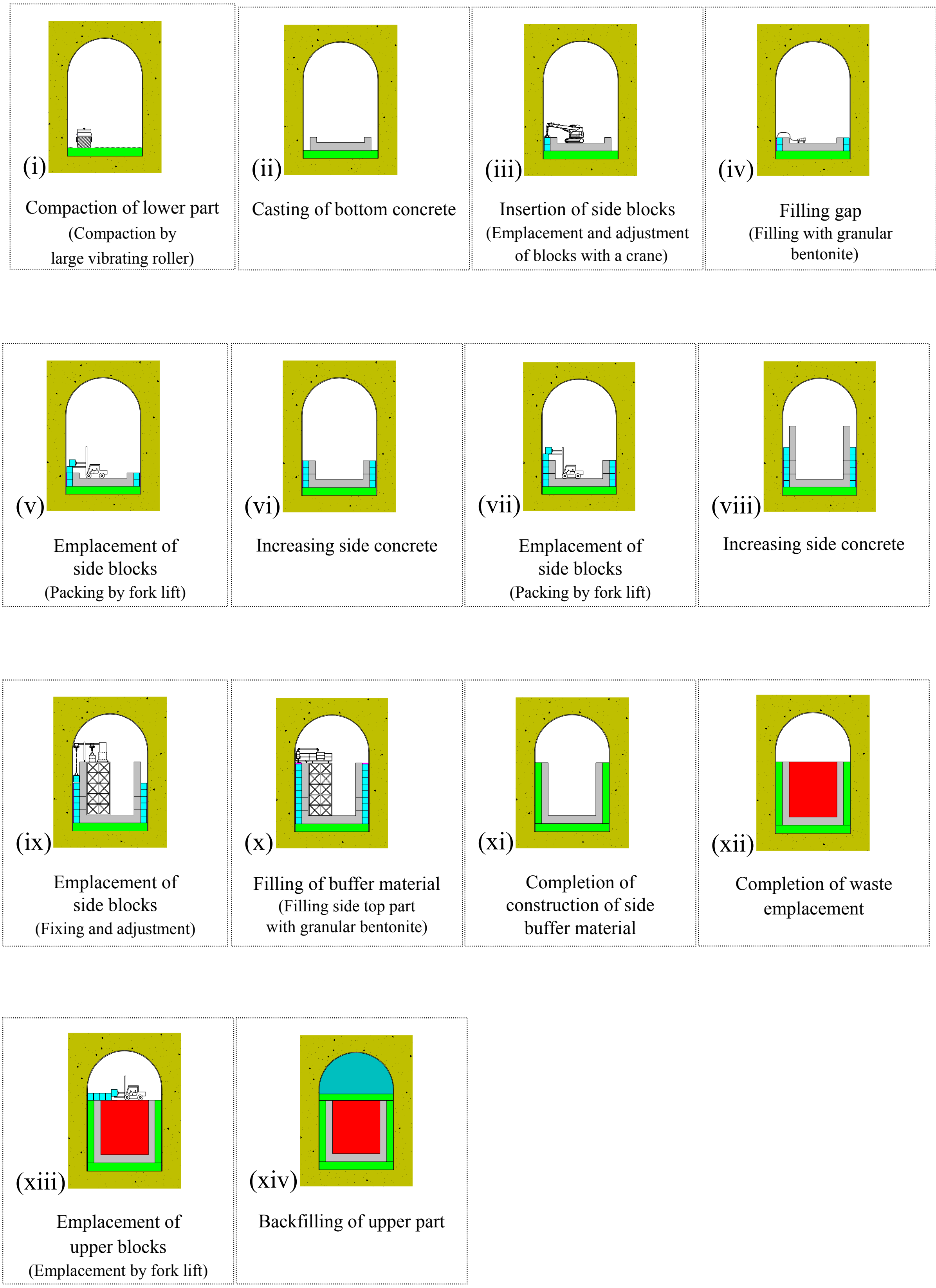


Figure 3.4.2.2-9 Construction of buffer material in horseshoe-shaped disposal tunnel

(7) Construction of the structural framework

a. Construction

The steel structural framework in the circular disposal tunnel is made by welding steel plates. It is envisaged that the sidewall is jointed to U-shaped deck slabs.

For the structural framework made of reinforced concrete in horseshoe-shaped disposal tunnels, the standard method is considered; re-bar arrangement and concrete casting is performed in-situ. In the case where buffer material is required (Groups 1 and 2), concrete to support workers and construction machines is constructed on the bottom buffer material. Sheets are used to prevent water from the concrete contacting and swelling the bentonite.

The concept for the structural framework in each rock type and for each waste grouping is shown in Figures 3.4.2.2-10 to 3.4.2.2-12.

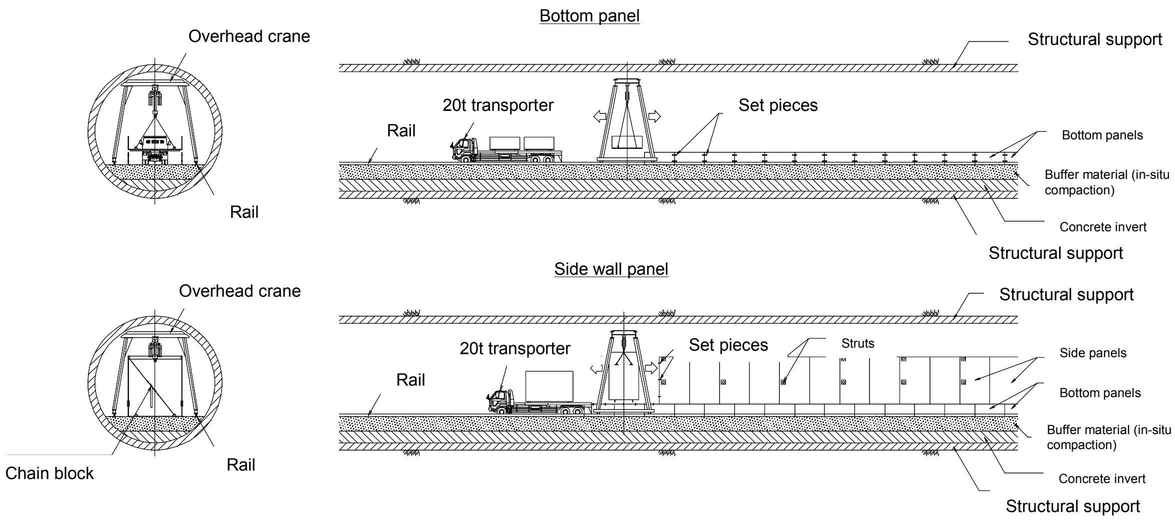


Figure 3.4.2.2-10 Construction of steel structural framework (circular disposal tunnel, Groups 1 and 2)

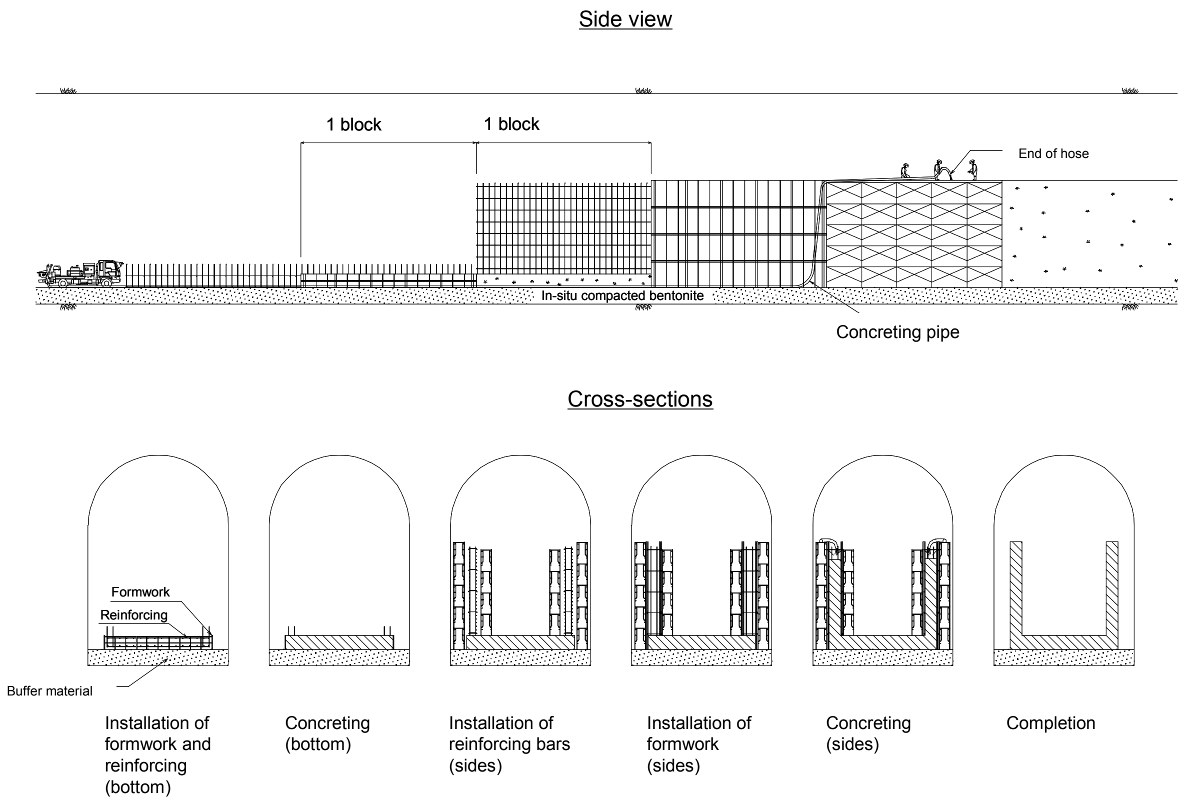


Figure 3.4.2.2-11 Construction of reinforced concrete structural framework (horseshoe-shaped disposal tunnel, Groups 1 and 2)

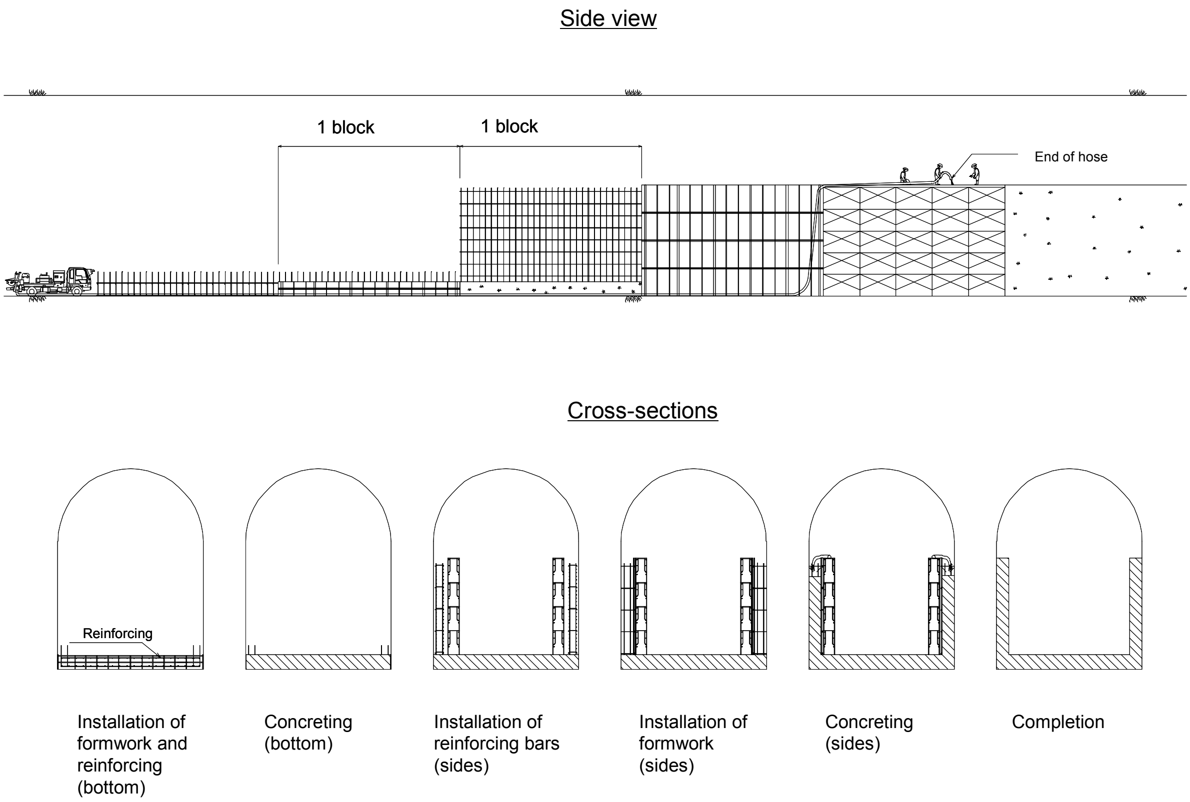


Figure 3.4.2.2-12 Construction of reinforced concrete structural framework (horseshoe-shaped disposal tunnel, Groups 3 and 4)

b. Other construction methods

(a) Simultaneous construction of buffer material and structural framework

An optimised approach in the construction of the circular disposal tunnel is for the bottom buffer material and deck slab of the structural framework to be constructed simultaneously and for the sidewall to be constructed simultaneously with the bottom buffer material. The invert is used not only for transportation during construction of the bottom buffer material, but is also used to move construction material for the structural framework. Hence, the structural framework is constructed without excess loading on the bottom buffer material and prevents it from being damaged.

Through simultaneous construction of the side buffer material and the structural framework, workspace during construction of the buffer material is increased, which aids operations. The functioning of the side buffer material is improved by using large buffer material blocks. The emplacement of the side buffer material is performed in the direction of the tunnel axis. Alternatively, the emplacement of the side buffer material is performed from the upper part of the sidewall, and lowered into the deck slab of the structural framework.

The structural framework block, which is welded and joined onto the invert, is emplaced on the upper part of the lower buffer material. Through this process, thermal effects during welding are decreased and the working environment is improved, thereby increasing the quality of the structural framework.

(b) Use of pre-cast structure

Pre-casting of the structural framework is considered in order to prevent adverse effects to the buffer material during construction of reinforced concrete. It is possible to construct high quality material since pre-cast material is manufactured in the surface facility.

The bottom pre-cast material manufactured in the surface facility is transported to the disposal tunnel and set up on the bottom buffer material. The dimensions of each block are limited to sizes that can be handled during transportation. It is desirable that the deck slab part is not divided in the direction parallel to the cross-section in the case where cementation is used to join pre-cast material.

(c) Cast-in-situ concrete

Concrete is casted directly onto the bottom buffer material when the effect of free water in the concrete is small due to the low permeability of the buffer material.

(d) Use of steel structural framework

There is little need to use steel in the structural framework in horseshoe-shaped disposal tunnels with large cross-sections. However, the cubic content of the structural framework might be decreased by using steel material instead of reinforced cement, allowing the cross-sectional area of the disposal tunnel to be reduced.

By decreasing of the amount of cement, the effect on the buffer material as described in Section 4.4.2.2 might be decreased. However, as described in Section 4.4.10.2, gas generation will increase since the amount of metal is increased.

3.4.3 Operation

3.4.3.1 Evaluation of general operations

In this section, the procedures for reception of waste and disposal operations are described.

(1) Summary of boundary condition

The boundary conditions for the operation of TRU disposal facility are as follows:

(i) Operating conditions

- Operating period: 25 years
- Annual operating days: 200
- Operating hours: 7 hours/day (effective operating hours)

(ii) Number of waste packages, type of packages for transfer and group classification

The number and type of waste packages for geological disposal are shown in Figures 3.2.2.2-7 and 11.

(iii) Basic flow

The basic flow of operations is shown in Figure 3.4.3.1-1. This includes several processes such as receiving transported waste packages, emplacement in disposal tunnels of the underground facility and the construction of filling and buffer material.

(iv) Waste packages for disposal

The form of waste packages for emplacement is shown in Table 3.2.1.1-1. In horseshoe-shaped disposal tunnels, only canisters of Group 2 waste are emplaced (4 waste units/package). In the circular disposal tunnel, every waste package type except for square packages is used (4 wastes/package).

(v) Radiation controlled zone

Based on legislation relating to regulation of nuclear source materials, nuclear wastes and nuclear reactors (Nuclear Reactor Regulation Law), radiation protection measures must be established for workers in the radiation controlled zone.

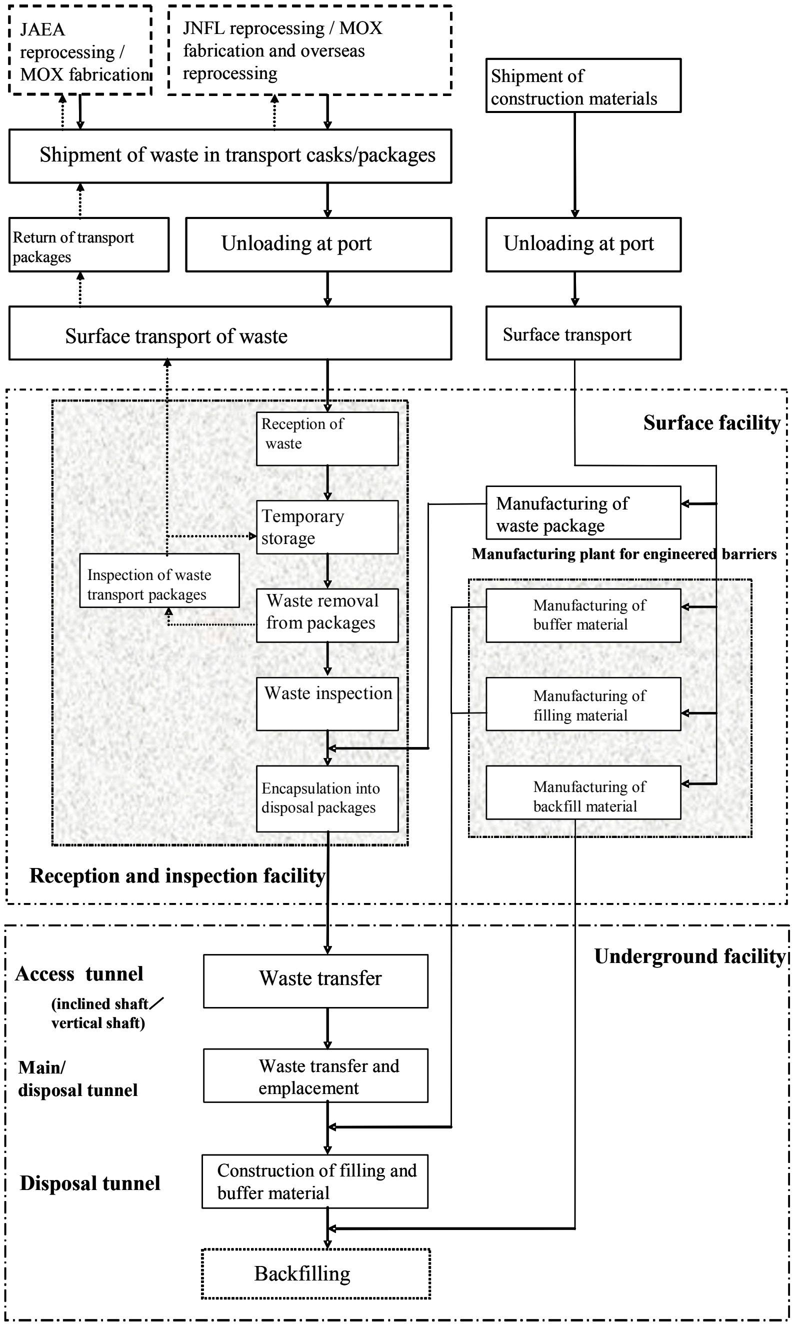


Figure 3.4.3.1-1 Basic flow of TRU waste disposal

(2) Evaluation of the flow of waste material

Figures 3.4.3.1-2 and 3.4.3.1-3 illustrate the material flow process from reception of waste casks and containers in the surface facility to emplacement of waste and construction of filling material and buffer material in the underground facility.

In the surface facility, casks and containers are inspected before waste is unloaded and also inspected. After interim storage, waste (except for square packages and 200L drums that are emplaced in horseshoe-shaped disposal tunnels) is placed in waste packages. After curing by cement mortar filling, a surface contamination test is performed. After that, the waste is transported to the underground facility through the access facility.

In the underground facility, waste is transferred close to the disposal tunnel, emplaced and then the filling material and buffer material are installed.

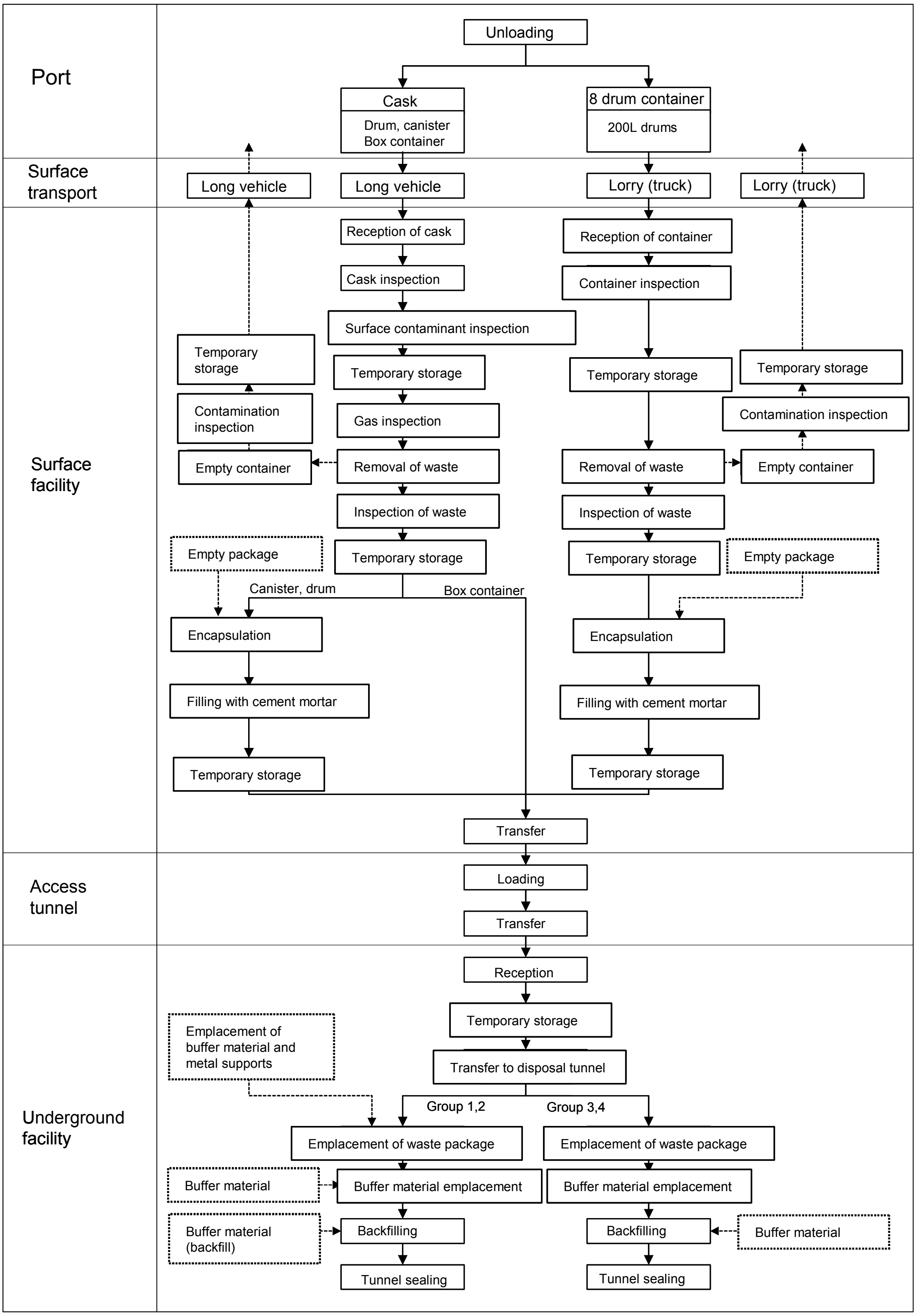


Figure 3.4.3.1-2 Flow for waste emplacement in circular disposal tunnels and construction of filling material and buffer material

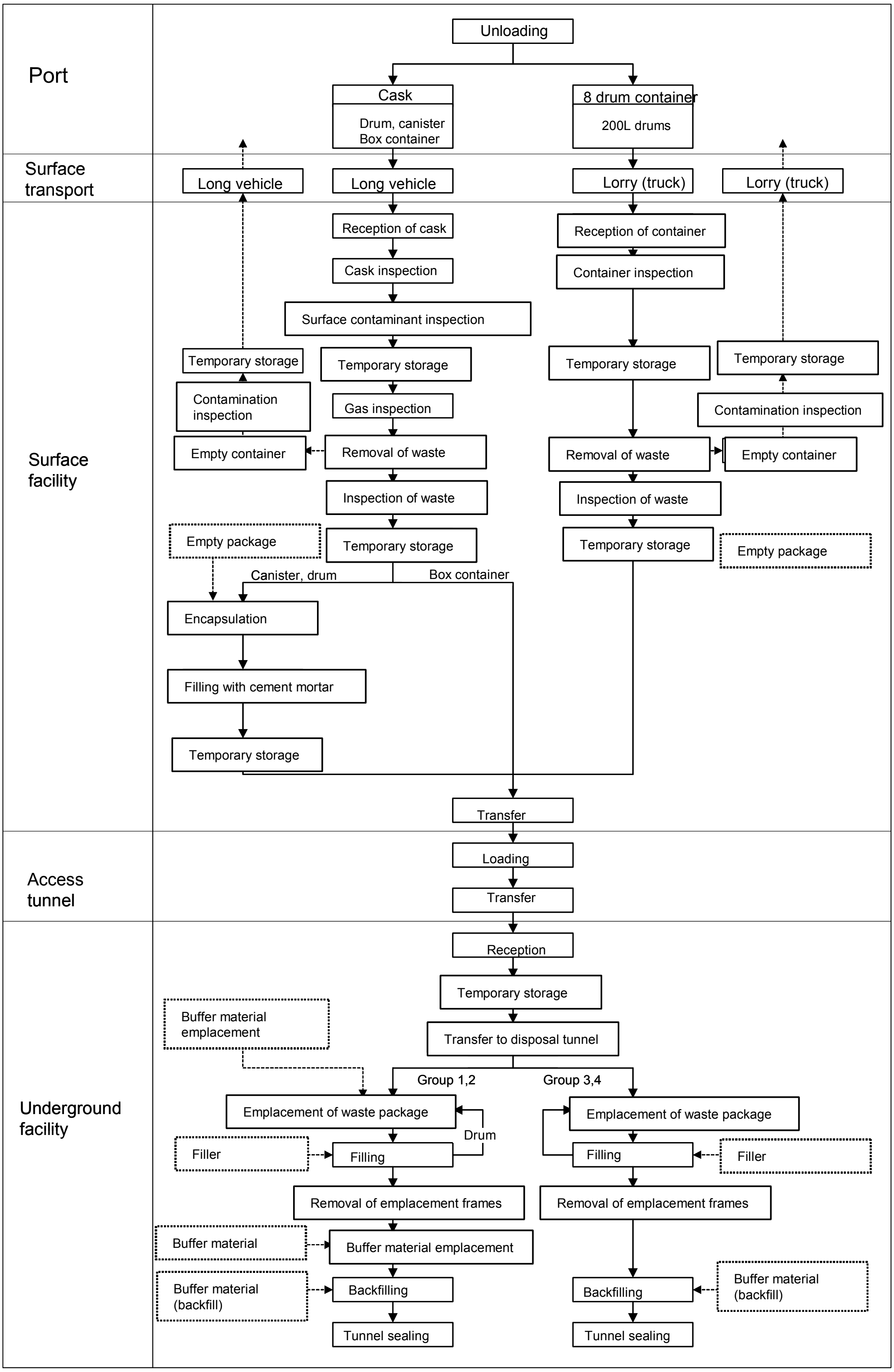


Figure 3.4.3.1-3 Flow for waste emplacement in horseshoe-shaped disposal tunnels and construction of filling material and buffer material

(3) Operations management

a. Operation concept

The concept for operation and maintenance of the TRU waste disposal facility is described below.

① Operations management and monitoring of each part of the facility and radiation monitoring and data management are performed in the central control facility.

② Since the waste has a high dose rate, the handling of waste, buffer material and filling material in the reception and inspection facility and underground facility is performed remotely; maintenance and inspection are also performed remotely.

③ The access tunnel is regarded as a non-controlled zone since waste is stored in shielded packages and it is safe for workers to drive the transfer trailers.

④ The areas except for ② and ③ where waste is not handled are non-controlled areas and the same operations management methods as those used in general industry are sufficient.

Table 3.4.3.1-1 Operation concept for the TRU waste repository

Area		Operation type	Activity
(1) Surface facility			
① Waste reception / inspection facility		Remote	① Waste reception / inspection and transportation ② Waste encapsulation and inspection of surface contamination
② Other facilities		Direct	① Each operation performed in non-controlled areas
(2) Underground facility			
① Access tunnel	Inclined	Direct	① Transportation of waste, filling material and buffer material
	Vertical		① Entrance of workers ② Transportation of general material
② Main and connecting tunnel		Remote	① Transport of waste, filling material and buffer material
③ Disposal tunnel		Remote	① Transport and emplacement of waste ② Transport and construction of filling material and buffer material
④ Lower shaft facility		Remote	① Temporary storage, transport of waste

b. Concept for controlled area

According to regulations on dose limits (Ordinance No. 187 of the Ministry of International Trade and Industry), the area which exceeds the following conditions is regarded as a radiation controlled zone and radiation control is a statutory requirement to provide appropriate radiation protection for workers.

- External radiation dose: 1.3 mSv/3 months → 2.6 μSv/h (500 hours/3 months)
- Concentration of radioisotopes in air: average concentration for 3 months is 1/10 of the Japanese safety limit.
- Surface contamination density: 1/10 of surface contamination density limit

(a) Possibility of contamination

The radiation controlled zone is divided into 2 areas, one in which only external exposure is considered (secondary controlled zone) and one in which both external and internal exposure are considered (primary controlled zone). In the waste management part of the surface facility, since contaminated areas and areas with high dose rates from waste may exist, appropriate controlled zones should be set up as required. In other facilities where waste is not handled, there is no need to set up a controlled zone.

It is shown from surface contamination tests that there is no dose from waste in the surface facility (acceptance of waste and screening facility) and that air-tightness is ensured. Hence, it is considered that no contamination in the underground facility will occur. From these considerations, a secondary controlled area is sufficient for operations in the underground facility.

(b) Exposure to radioactivity (external)

Since the concentration of radioactive materials in TRU waste has a wide range, the surface radiation dose also has a wide range. For this reason, the amount of shielding depends on the level of surface radiation dose. The surface radiation dose is limited to 2 mSv/h based on transportation regulations and dose rate is limited to below 0.1 mSv/h at 1 m. Moreover, the access tunnel is treated as a non-controlled zone since there is no possibility of ordinary contamination.

Since waste is exposed during transfer and emplacement in the underground facility, the area is regarded as a secondary controlled zone. The basic concept for radiation control in the TRU waste repository is summarized in Table 3.4.3.1-2. In the ventilation tunnel and the effluent treatment facility, continuous monitoring is performed and, if the ventilation and drainage exceed management criteria, a predefined response is carried out.

Table 3.4.3.1-2 Basic concept for radiation control

Facility and equipment	Classification	Contamination check	Monitoring
(1) Surface facility			
① Waste reception and inspection facility	Primary controlled zone	○	○
② Ventilation facility	Non-controlled	–	○
③ Effluent treatment facility	Non-controlled	–	○
④ Other surface facilities	Non-controlled	–	
(2) Underground facility			
① Access tunnel	Non-controlled	–	–
② Main tunnel	Secondary controlled area	–	○
③ Connecting tunnel	Secondary controlled area	–	○
④ Disposal tunnel	Secondary controlled area	–	○

Based on the above evaluation, the concept for operations management in the TRU waste repository is shown in Figure 3.4.3.1-4.

Surface facility

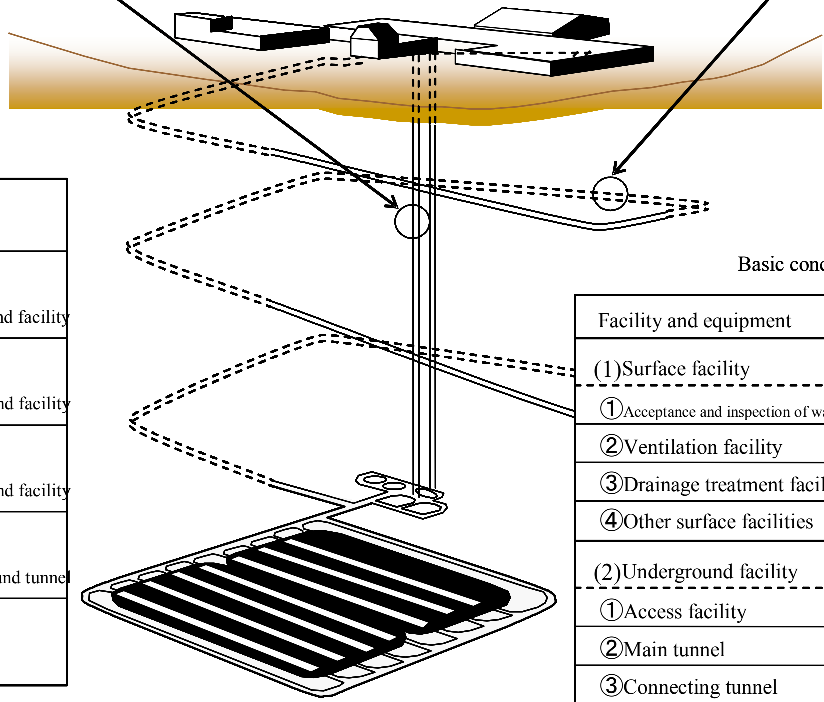
① Acceptance and temporary storage
② Support of construction, operation and closure of underground facility
③ Management of repository
④ Ventilation and drainage treatment from underground facility

Access tunnel (Vertical shaft)

① Entrance area for workers
② Carrying in and out of material
③ Ventilation and drainage

Access tunnel (inclined shaft)

① Transport of waste
② Transport of engineered barriers
③ Ventilation



Transport and ventilation route for waste

Target	Main route
Waste	Acceptance and inspection facility →Access facility (inclined shaft)→underground facility
Material for engineered barriers	Engineered barrier manufacturing facility →Access facility (vertical shaft) →underground facility
Material	Material storage →Access facility (vertical shaft) →underground facility
Workers	Central controlled facility → Access facility (vertical shaft) →underground tunnel
Ventilation (2 systems)	①Air supply (vertical shaft) →underground facility →Discharge air (vertical shaft) ②Air supply (inclined shaft) →discharge air (inclined shaft)

Basic concept for radiation control

Facility and equipment	Classification	Contamination check	Monitoring
(1)Surface facility			
①Acceptance and inspection of waste	1st controlled area	○	○
②Ventilation facility	Non-controlled area	—	○
③Drainage treatment facility	Non-controlled area	—	○
④Other surface facilities	Non-controlled area	—	
(2)Underground facility			
①Access facility	Non-controlled area	—	—
②Main tunnel	2nd controlled area	—	○
③Connecting tunnel	2nd controlled area	—	○
④Disposal tunnel	2nd controlled area	—	○

Operations management in TRU waste repository

Figure 3.4.3.1-4 Operations management for a TRU waste repository

3.4.3.2 Transport and emplacement of waste

(1) Equipment for transporting waste

a. Preconditions

(a) Handling number

The number of waste units that can be handled per day based on the limitations of each process is shown as below.

(i) Drums : 20/day

(ii) Waste package : 5/day

(iii) Square package : 4/day

The number of waste units that can be handled in each disposal tunnel is shown in Table 3.4.3-2-1.

Table 3.4.3.2-1 Number of handled waste units

Waste group	Amount of waste		Circular disposal tunnel		Horseshoe shaped disposal tunnel	
	Form	per year	Type	per year	Form	per year
1	200L drum ϕ600 × H900	64	Package □1,500 × H1,100	16	200L Drum ϕ600 × H900	64
2	Canister ϕ430 × H1,335	1,152	Package □1,200 × H1,600	288	Package □1,200 × H1,600	288
	BNGS 500L drum ϕ800 × H1,192	84	Package 1,100 × 1,900 × 1,400	42	BNGS 500L drum ϕ800 × H1,192	84
3	200L drum ϕ600 × H900	1126	Package □1,500 × H1,100	282	200L drum ϕ600 × H900	1,126
	Square package □1,600 × H1,200	9	Square package □1,600 × H1,200	9	Square package □1,600 × H1,200	9
	BNGS 500L drum ϕ800 × H1,192	10	Package 1,100 × 1,900 × 1,400	5	BNGS 500L drum ϕ800 × H1,192	10
4	200L drum ϕ600 × H900	1,817	Package □1,500 × H1,100	455	200L drum ϕ600 × H900	1,817
	Square package □1,600 × H1,200	69	Square package □1,600 × H1,200	69	Square package □1,600 × H1,200	69
	BNGS 500L drum ϕ800 × H1,192	88	Package 1,100 × 1,900 × 1,400	44	BNGS 500L drum ϕ800 × H1,192	88

(b) Materials to be transported

Material for transportation and its weight are shown below. The thickness of shielding is assumed to be the same as that in 1st TRU progress report:

(i) Canister : 300 mm

(ii) 200L drum : 200 mm

(iii) Square package : 200 mm

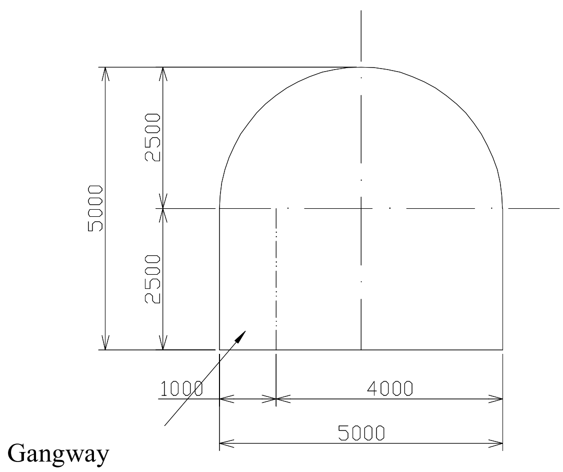
Table 3.4.3.2-2 Material for transportation and weight

Transported material			Weight (t)			Total amount (t)	
Group	Form	Shielding size/ dimensions	Waste	Package	Shielding package	Circular disposal tunnel	Horseshoe-shaped disposal tunnel
1	200L drum	□ 2,200×H1,550	0.36 – 0.43×4	6.0 – 6.3	33.5	39.4 – 39.7	34.9 – 35.2
2	Canister	□ 2,100×H2,250	0.7 – 0.85×4	7.0 – 7.6	52.4	59.4 – 60.0	59.4 – 60.0
	BNGS 500L drum	2,800×2,000×H2,050	1.51 – 1.56×2	7.9 – 8.0	58.7	66.7 – 66.8	61.7 – 61.8
3	200L drum	□ 2,200×H1,550	0.28 – 0.43×4	5.7 – 6.3	33.5	39.1 – 39.7	34.6 – 35.2
	Square package	□ 2,300×H1,650	8.1×1	8.1	36.9	45.0	45.0
	BNGS 500L drum	2,800×2,000×H2,050	1.12×1	7.2	58.7	65.9	60.9
4	200L drum	□ 2,200×H1,550	0.43 – 0.88×4	6.3 – 8.0	33.5	39.7 – 41.5	35.2 – 37.0
	Square package	□ 2,300×H1,650	8.26 – 21.3×1	8.3 – 21.3	36.9	45.1 – 58.2	45.1 – 58.2
	BNGS 500L drum	2,800×2,000×H2,050	1.15 – 1.2×2	7.2 – 7.3	58.7	65.9 – 66.0	61.0 – 61.1

The drum waste in the horseshoe-shaped disposal tunnel consists of 2 drums loaded in 1 pallet.

(c) Shape of inclined shaft

The inclined shaft has a horseshoe-shaped cross-section, 5 m in width and 5 m in height. An access path 1 m wide is provided for workers. In the corner of the tunnel, an access road is provided for trailer passage.



Maximum gradient: 10%

Travel distance: ca. 5,000 m (depth 500 m: one way), ca. 10,000 m (depth 1,000 m: one way)

Radius of corner part: 30 m

Others: space is prepared every 100 m so as to allow passage for incoming trailers

Figure 3.4.3.2-1 Shape of inclined shaft

(d) Shape of main tunnel

The main tunnel has a horseshoe-shaped cross-section, 7 m in width and 6.3 m in height.

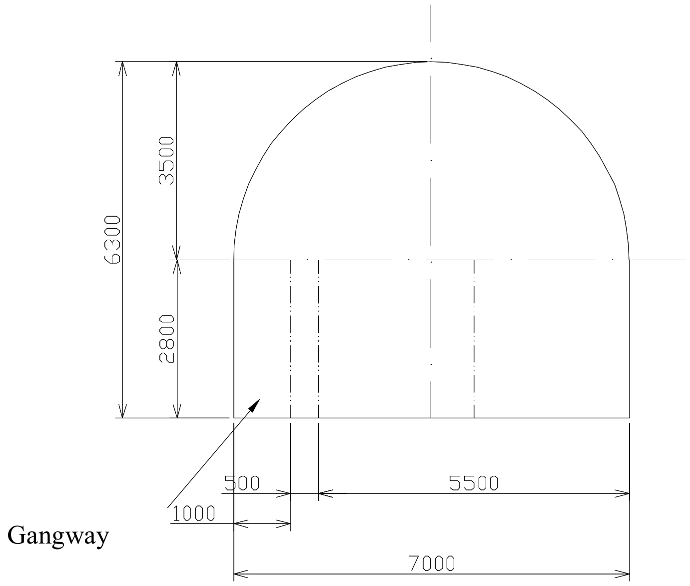


Figure 3.4.3.2-2 Shape of the main tunnel

b. Transportation of waste

An example of waste transportation and equipment is shown in Table 3.4.3.2-3.

Table 3.4.3.2-3 Example of waste transportation

Process name	Transportation in access tunnel			
Content	Waste loaded in the surface facility is transported to the bottom shaft facility.			
Required amount	Drums: 20/day Waste package: 5/day Square package: 4/day			
Required function	Transport: Optimisation of waste transport Shielding: Since the access tunnel is a non-controlled zone, it is necessary for shielding to meet the regulatory dose rate limit			
Site and equipment selection	Item for evaluation		Tire method	Orbit type
			Hydraulic transporter	Electric transporter
	Transporting function	Inclination: 10%	Moveable	Apt type
		Distance 5,000 m (10,000 m) × 2	Transportation is possible	
		Access tunnel Size W 5m × H 5m	Transportation is possible	
		Corner R30 m	Transportation is possible	
		Loading weight 62.2 t	Transportation is possible	
		Amount	1 package	
		Number of times	5	
		Running speed	10 km/h	Down: 10 km/h Up: 5 km/h
	Shield-ing function	Thickness of shielding	200 mm – 300 mm	
		Shielding material	Carbon steel	
		Weight of shielding	ca. 33.6 t – 52.7 t	
	Safety		- Engine idle-down function in an emergency - ITV monitoring - Braking distance: ca. 10 m	- Infrared radiation sensor - Bumper switch - Emergency stop function - Braking distance: ca. 30 m
	Additional equipment		- Concrete pavement	- Orbit facility - Vehicle maintenance
	Evaluation		- Reliable method in nuclear reactors. - Ventilation equipment necessary.	- Large amount of equipment and electricity supply needed for orbit type. - Running speed in upward direction is slow.

(2) Waste emplacement

Emplacement of waste is evaluated separately since the operating methods and structure of the engineered barriers are different in circular and horseshoe-shaped disposal tunnels.

a. Circular disposal tunnel

(a) Preconditions

a) Waste forms

The waste forms to be handled are shown in Table 3.4.3.2-4.

Table 3.4.3.2-4 Waste forms in circular disposal tunnel

Handling material		Size (mm)	Disposal number		Weight (t)	
Group	Form		Per year	Total amount	Min	Max
1	Waste package	□ 1,500 × H1,100	16	398	6.0	6.3
2	Waste package	□ 1,200 × H1,600	288	7,200	7.0	7.6
	Waste package	1,100 × 1,900 × 1,400	42	1,035	7.9	8.0
3	Waste package	□ 1,500 × H1,100	282	7,015	5.7	6.3
	Square package	□ 1,600 × H1,200	9	199	8.1	
	Waste package	1,100 × 1,900 × 1,400	5	125	7.2	
4	Waste package	□ 1,500 × H1,100	455	11,273	6.3	8.0
	Square package	□ 1,600 × H1,200	69	1,621	8.3	21.3
	Waste package	1,100 × 1,900 × 1,400	44	1,090	7.2	7.3

The waste form is considered in the design of shielding in the access tunnel. In the underground facility, it is considered that the road surface for transfer is almost horizontal and has sufficient space for handling equipment.

Taking into account the largest waste package (square package) and maximum thickness (300 mm), the estimated weight of transporting material is as follows:

Weight of shielding: 80.2 t   Shielding + maximum weight of waste: 92.0 t

b) Underground facility

The ground plan of the underground facility is shown in Figure 3.2.2.2-8. The conditions of underground facility are as follows:

(i) The main tunnel is horseshoe-shaped, 7 m in width and 6.3 m in height.

(ii) The main tunnel is designed for one-way movement (anticlockwise direction relative to disposal tunnels).

(iii) The length of the main tunnel is estimated to be about 1,500 m.

(iv) The minimum radius at the corner is 20 m (sufficient space for operating equipment)

The cross-section of emplaced waste for each group is shown in Figure 3.2.2.2-7.

(b) Waste emplacement in a circular disposal tunnel

An example of waste emplacement and equipment for a circular disposal tunnel is shown in Tables 3.4.3.2-5 and 6.

Table 3.4.3.2-5 Transportation of waste to a disposal tunnel and required equipment (circular disposal tunnel)

Process	Transfer to disposal tunnel			
Content	Process for transferring waste to the emplacement zone in disposal tunnels by passing through the main tunnel.			
Required amount in facility	Waste package: 5/day Square package: 4/day			
Required function	Shielding: The equipment in the main tunnel needs sufficient shielding to satisfy the regulatory dose safety limit Waste transfer: Optimised transfer of waste is necessary. Remote control: A remote control system is necessary because of the high levels of radiation.			
Site and equipment selection	Item for evaluation		Tire method Hydraulic transporter	Orbit method Electric transporter
	Transporting capability	Inclination: drainage slope	Transportation is possible	
		Distance	1,500 m/movement for at least 5 orbits	
		Main tunnel W7 × H6.3 m	Single rail	Dual rail
		Corner R20 m	Single rail	Dual rail
		Loading weight 92 t	Loadable	
		Transported amount	1 package	
		Number of times for transporting	6 times	
		Running speed	10 km/h	
	Remote controlled capability	Operation method	Remote controlled	
		Operability	Adequate technology required for accurate remote control in narrow space of disposal tunnel	Stable movement
	Shielding capability	Thickness of shielding material	300 mm	
		Material type of shielding material	Carbon steel	
		Weight of shielding material	80.2 t	
		Access direction	Access from the side is possible because of the structure of loading equipment	
	Safety		- Engine-idling down device in case of emergency - ITV monitoring - Braking distance: ca. 10 m	- Infrared radiation sensor - Bumper switch - Emergency stop function - Braking distance: ca. 25 m
	Additional equipment		- Concrete pavement	- Orbit facility - Vehicle maintenance
	Evaluation		- Two rails considered taking into account congestion of underground transporters	- Applicable

Table 3.4.3.2-6 Example waste emplacement method (circular disposal tunnel)

<table>
<tr><td>Process</td><td colspan="4">Loading and unloading of waste, transporting to emplacement zone, emplacement of waste</td></tr>
<tr><td>Work content</td><td colspan="4">Loading and unloading of waste: Process for loading and unloading of waste from main tunnels into emplacement zone.
Transport to emplacement zone: Transport of waste to emplacement zone.
Emplacement of waste: Process for loading of waste into an emplacement zone.</td></tr>
<tr><td>Required amount in facility</td><td colspan="4">Waste package: 5/day Square package: 4/day</td></tr>
<tr><td>Required function</td><td colspan="4">Gripping: Gripping waste packages and square packages
Transporting: Safe transportation of waste
Remote control: The remote control system is necessary because of high levels of radioactivity.</td></tr>
<tr><td rowspan="14">Site and equipment selection</td><td colspan="2">Evaluation item</td><td>Forklift</td><td>Crane</td></tr>
<tr><td rowspan="2">Gripping capability</td><td>Gripping material</td><td colspan="2">- Gripping tool for waste package and square package is necessary.</td></tr>
<tr><td>Gripping method</td><td>- Lifting from underside</td><td>- Since side of waste cannot be accessed, difficult to attach waste</td></tr>
<tr><td rowspan="4">Transporting capability</td><td>Waste weight 5.6 – 11.8 t</td><td colspan="2">Transportation is possible</td></tr>
<tr><td>Transporting speed</td><td>10 km/h (167 m/min)</td><td>5 m/min</td></tr>
<tr><td>Transport distance</td><td>Sufficient amount</td><td>Area for crane rails</td></tr>
<tr><td>Disposal tunnel size ϕ10 m</td><td colspan="2">Handling is possible.</td></tr>
<tr><td rowspan="2">Re mote controlling</td><td>Operation method</td><td>Radio-controlled type</td><td>Wired/wireless type</td></tr>
<tr><td>Operability</td><td colspan="2">- From the experience from general industry and nuclear reactors, there is no problem in operability.</td></tr>
<tr><td colspan="2">Safety</td><td colspan="2">- ITV monitoring capability
- Overload protection</td></tr>
<tr><td colspan="2">Additional equipment</td><td colspan="2">None</td></tr>
<tr><td colspan="2">Evaluation</td><td>- Appropriate for unloading, transportation and emplacement.</td><td>- Unloading of waste is difficult because crane cannot access from side.
- Another facility for transportation and emplacement is necessary.</td></tr>
</table>

b. Horseshoe-shaped disposal tunnel

(a) Preconditions

a) Waste forms to be handled

The waste forms to be handled are shown in Table 3.4.3.2-7.

Table 3.4.3.2-7 Waste forms in horseshoe-shaped disposal tunnel

Waste forms		Size (mm)	Amount		Weight (t)	
Group	Form		Annual	Total amount	Min	Max
1	200L drum	ϕ600 × H900	64	1,589	0.36	0.43
2	Waste package	□ 1,200 × H1,600	288	7,200	7.0	7.6
	BNGS 500L drum	ϕ800 × H1,192	84	2,070	1.51	1.56
3	200L drum	ϕ600 × H900	1,126	28,058	0.28	0.43
	Square package	□ 1,600 × H1,200	9	199	8.1	
	BNGS 500L drum	ϕ800 × H1,192	10	250	1.12	
4	200L drum	ϕ600 × H900	1,817	45,089	0.43	0.88
	Square package	□ 1,600 × H1,200	69	1,621	8.26	21.3
	BNGS 500L drum	ϕ800 × H1,192	88	2,180	1.15	1.2

b) Underground facility

The plan view of the underground facility is shown in Figure 3.2.2.2-12. The preconditions for the underground facility are as follows:

(i) The main tunnel has a horseshoe-shaped cross-section, 7 m wide and 6.3 m high

(ii) Movement is possible in both directions

(iii) The length of main tunnel is about 1,200 m.

(iv) The minimum radius of the corner part is 20 m.

In the circular disposal tunnel, waste transporters can only move in one direction. In the horseshoe-shaped disposal tunnel, 2 loops are constructed in the left main tunnel in Figure 3.2.2.2-12 and the waste transporter is adapted for movement in both directions between the bottom shaft facility and disposal tunnels. This is done to avoid the inclined part in the main tunnel (except for the left main tunnel).

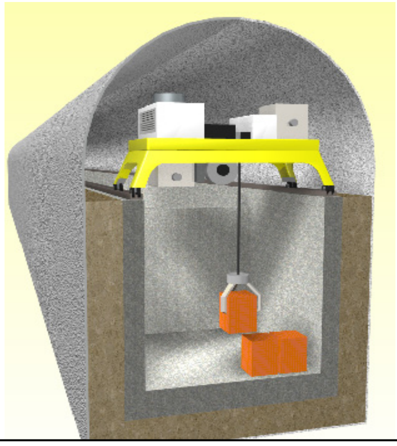
(b) Waste emplacement in horseshoe-shaped disposal tunnels

Transfer to the disposal tunnel is the same as for the circular disposal tunnel. An evaluation of waste emplacement and equipment is shown in Table 3.4.3.2-8.

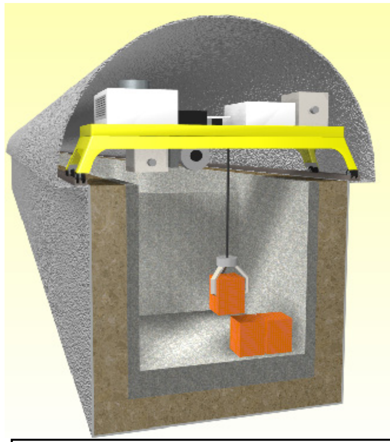
Table 3.4.3.2-8 Example waste emplacement method (horseshoe-shaped disposal tunnel)

Process	Waste emplacement
Content	Process for loading waste into given site
Required amount in facility	Drums: 19/day Waste package: 5/day Square package: 4/day
Required function	Transport: Safe transport of waste is necessary. Gripping: Gripping of drums, waste packages and square packages is necessary. Remote control: The remote control system is necessary because of the presence of material with high levels of radiation.
Selection of equipment	Crane for emplacement of waste.
Evaluation issues	- Establishment of safety guidelines for waste emplacement

As an alternative, the host rock is used as a foundation for the crane. The crane is set up at the same height as the upper part of the tunnel vertical wall. Sufficient space in the roof area of the tunnel is excavated to ensure smooth transport and emplacement operations.



Case where structural framework is used as crane foundation



Case where host rock is used as crane foundation

Figure 3.4.3.2-3 Use of host rock as crane foundation

If the host rock is used as a crane foundation instead of the structural framework, the thickness and strength of the structural framework can be reduced since it only needs to support the side buffer material during waste emplacement and to form a mould for filling material.

(3) Construction of filling material

a. Circular disposal tunnel

(a) Precondition

Group 3 and 4 wastes require the construction of filling material.

Material is transferred to the disposal tunnels from the bottom shaft facility and filling operations are performed at waste emplacement sites. The cement filling material has suitable fluidity for filling small voids and for shotcrete for the upper sides of the disposal tunnel.

(b) Construction of filling material in circular disposal tunnels

An example of the construction method for filling material in a circular disposal tunnel is presented below.

(i) Loading of partition panels

As with buffer material, partition panels are loaded onto an electric forklift truck. The partition panels form a framework during the emplacement of filling material.

(ii) Transfer of partition panels to disposal tunnels

Transfer using orbital electric locomotive (same as for other materials) and unloading in the disposal tunnel.

(iii) Emplacement of partition panels

Electric forklift truck is used for emplacement of partition panels.

(iv) Loading of mortar

Mortar is loaded using a pump.

(v) Transfer of mortar to disposal tunnel

Transferred using an orbital electric locomotive. Special trailer is used with cement filling hopper and concrete pump.

(vi) Refilling

Hopper device in the disposal tunnel is refilled with mortar from the surface using a pump.

(vii) Mortar filling

Spaces between waste packages are filled using a trailer with a pump. Additionally, a spraying method using compressed air is used for filling the upper part of the disposal tunnel. Shotcrete has been used extensively in the construction of large underground cavities.

b. Horseshoe-shaped disposal tunnel

(a) Precondition

Filling of spaces between the structural framework and waste is required for Group 1 – 4 wastes in horseshoe-shaped disposal tunnels. The underground transport of the mortar from the interim storage area at the surface to the disposal area is described below.

- Transfer to the underground from the surface: same as for material removed during tunnel excavation and construction
- Transfer to disposal area: same as for the case of the circular disposal tunnel

(b) Mortar filling in horseshoe-shaped disposal tunnel

An example of mortar filling in a horseshoe-shaped disposal tunnel is shown in Table 3.4.3.2-9. A high pressure pumping system is used instead of a crane because mortar filling is performed at the same time as waste emplacement.

Table 3.4.3.2-9 Example of mortar filling method

Process	Mortar filling			
Content	The mortar is filled into the structural framework.			
Required amount in facility	5 m^3/day (maximum)			
Required function	Transfer: Transfer of filling material should be performed safely. Filling: Filling material fills voids Remote control: Since the filling operation is performed in a radioactive environment, remote control is necessary.			
Site and equipment selection	Evaluation item		Pneumatic transport by pump	Batch type
	Filling function	Filling method	Pneumatic transportation by pump	Batch type injection using crane for emplacement.
		Concurrent with waste emplacement	Possible	Not possible with crane
	Transport function	Transporting of mortar (5 m^3/day)	Pneumatic pump possible	Batch type possible
	Safety		- ITV monitoring capability - Overload protection	
	Additional equipment		None	Crane for waste emplacement
	Evaluation		Applicable	Poor operating efficiency because performed concurrently with emplacement of waste.

(4) General processes and operations

All operations in the circular repository tunnel are shown below. Waste transported by vehicle into the disposal tunnel is emplaced using an electric forklift.

For Group 1 and 2 wastes, since buffer material is already emplaced at the bottom and side surfaces of the disposal tunnel, buffer material only needs to be emplaced in the upper space of the disposal tunnel.

Waste emplacement and construction method of buffer material in the circular disposal tunnel

Process (i): Emplacement of buffer material in the bottom and side of the disposal tunnel
Process (ii): Transfer by special trailer
Process (iii): Emplacement of waste by forklift
Process (iv): Emplacement of buffer material in the upper space of the disposal tunnel
{ (i) → ((ii)→(iii)→(iv)) → ((ii)→(iii)→(iv)) → ... → ((ii)→(iii)→(iv)) }

For Group 3 and 4 wastes, a concrete invert is emplaced in the bottom part of the disposal tunnel, and mortar is filled in after waste emplacement at constant intervals. This process is repeated and each disposal tunnel is closed.

The operating method in the horseshoe-shaped disposal tunnel is described below.

The waste which is transported to the disposal tunnel using transfer trailers is emplaced using a crane. Mortar is infilled after a predetermined number of waste packages for each disposal pit (space which is surrounded by side wall and partitioning walls of structural framework) have been emplaced. This process is repeated and when waste emplacement and mortar filling is complete in all disposal pits of the disposal tunnel, buffer material (in the case of Group 1 and 2 wastes) is filled into voids after removal of the overhead crane in the upper part of the tunnel. Finally, the upper part is backfilled using a bentonite–sand mixture with. For Group 3 and 4 wastes, no buffer material is used and the upper part of the disposal tunnel is backfilled with mortar. This is summarised as follows:

Waste emplacement and construction of buffer material in horseshoe-shaped disposal tunnel.

Process (i): Transportation of waste by special trailer
Process (ii): Emplacement of waste by crane
Process (iii): Filling of mortar into disposal pit
Process (iv): Removal of crane and construction of buffer material in the upper space of the disposal tunnel
{ ((i)→(ii)→(iii)) → ((i)→(ii)→(iii)) → ... → ((i)→(ii)→(iii)) → (iv) }

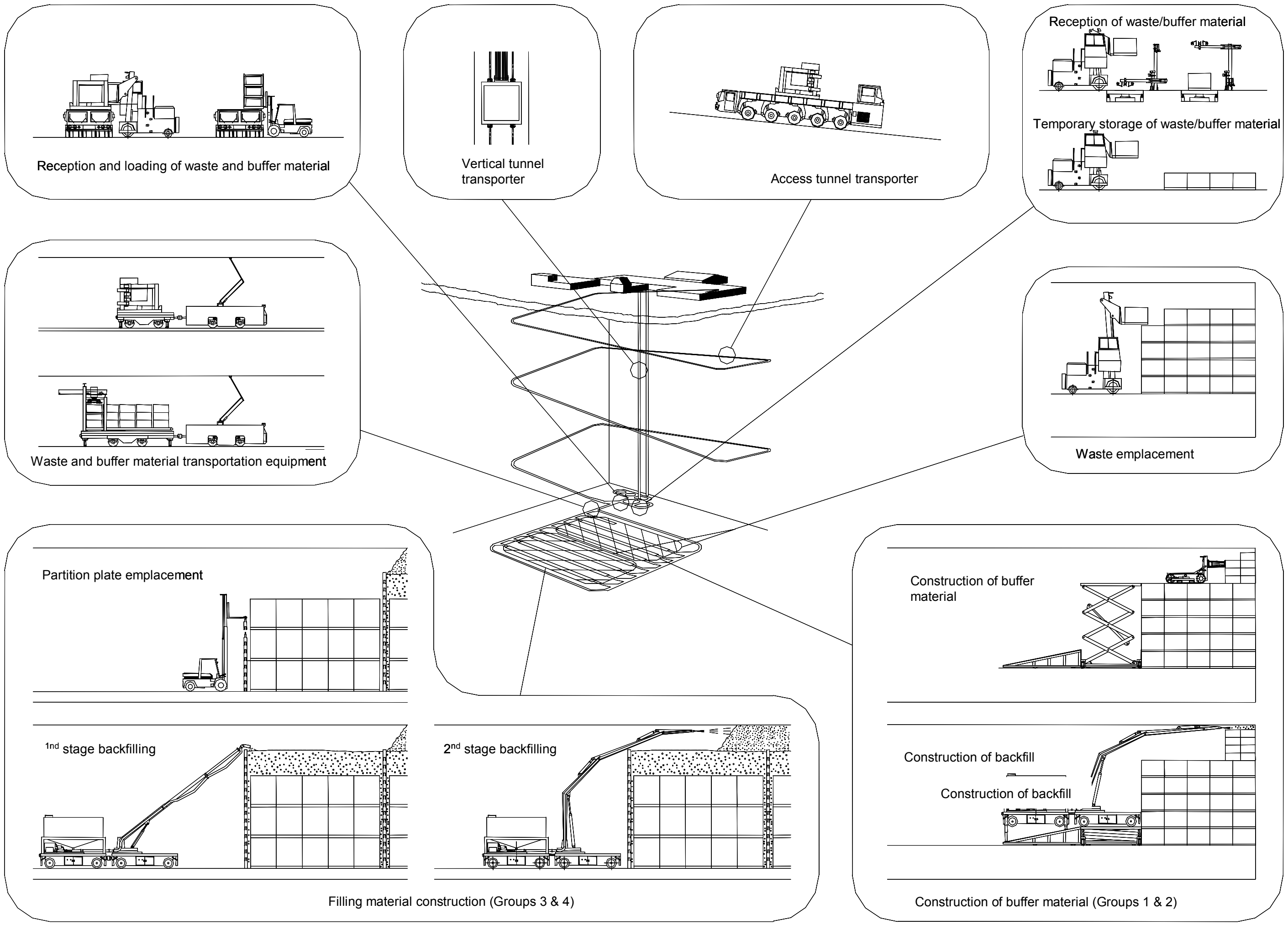


Figure 3.4.3.2-4 Overall view of handling equipment for underground facility (circular disposal tunnel)

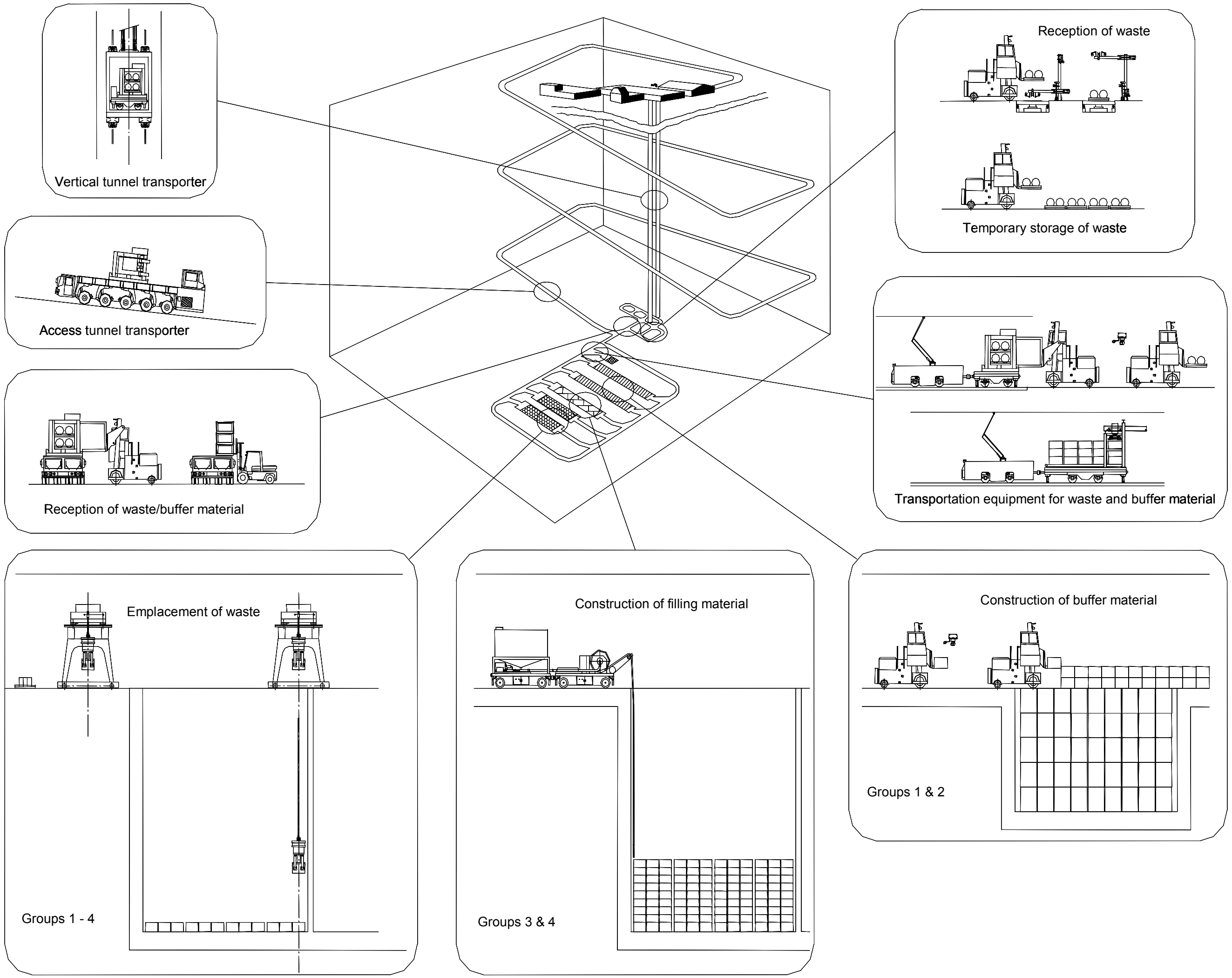


Figure 3.4.3.2-5 Overall view of handling equipment for underground facility (horseshoe-shaped disposal tunnel)

3.4.4 Closure

The specifications of the backfill material and plugs are described in Section 3.2.2.3. In this section, one example construction technique is presented.

3.4.4.1 Construction of backfill material

The major candidate materials for the backfill summarized in Section 3.2.2.3 are shown in Table 3.4.4.1-1. They are essentially divided into bentonite and cementitious materials.

Table 3.4.4.1-1 Backfill materials and location

Location		Main candidate material
Disposal tunnel	Groups 1 and 2	Bentonite material
	Groups 3 and 4	Cement material
Main and connecting tunnels		Bentonite material
Access tunnel	Vertical and inclined shaft	Bentonite material

(1) Backfilling with bentonite

The list of construction methods using bentonite materials is shown in Table 3.4.4.1-2. The tunnel is backfilled using a combination of these methods, depending on space constraints.

Table 3.4.4.1-2 Backfilling methods with bentonite

Construction method	Construction concept
Spraying	**(Construction method)** Material is transported by a cement mixer and then injected into a spraying machine. Bentonite is sprayed into place. The rebound after spraying depends on the condition of material and pneumatic transport strength is considered. Hence, estimation of required construction density is important. **(Applicable parts)** All parts. **(Problems)** Since powdered dust is generated during blowing, the working environment is worse than for other construction methods. Material and quality management is also difficult.
In situ compaction	**(Construction method)** The material which is transported by the cement mixer is scooped out by a dozer and is compacted using a vibrating roller. Construction efficiency is good. Density depends on the capability of the compaction machine. **(Applicable parts)** Mainly used in lower part of tunnel. **(Problems)** Since large machinery is required, the construction area is limited.
Blocks	**(Construction method)** Blocks transported by vehicle are emplaced at a given location using a block emplacement vehicle. **(Applicable parts)** Used for all parts except at edge along the wall **(Problems)** Although quality management of block material is ensured, filling of spaces by spraying of powdered bentonite between blocks and between blocks and host rock is required.

a. Backfill in the upper part of the disposal tunnel

In the upper part of the disposal tunnel, in situ compaction and block emplacement is difficult so filling with crushed bentonite ore is considered appropriate. It has been shown that high quality filling can be achieved using a screw feeder (RWMC, 2004).

If the shielding of radiation from the waste is difficult, remote handling is required during construction. Examples of construction methods in a circular disposal tunnels (Group 2) and horseshoe-shaped tunnels (Groups 1 and 2) are shown in Figures 3.4.4.1-1 and 3.4.4.1-2.

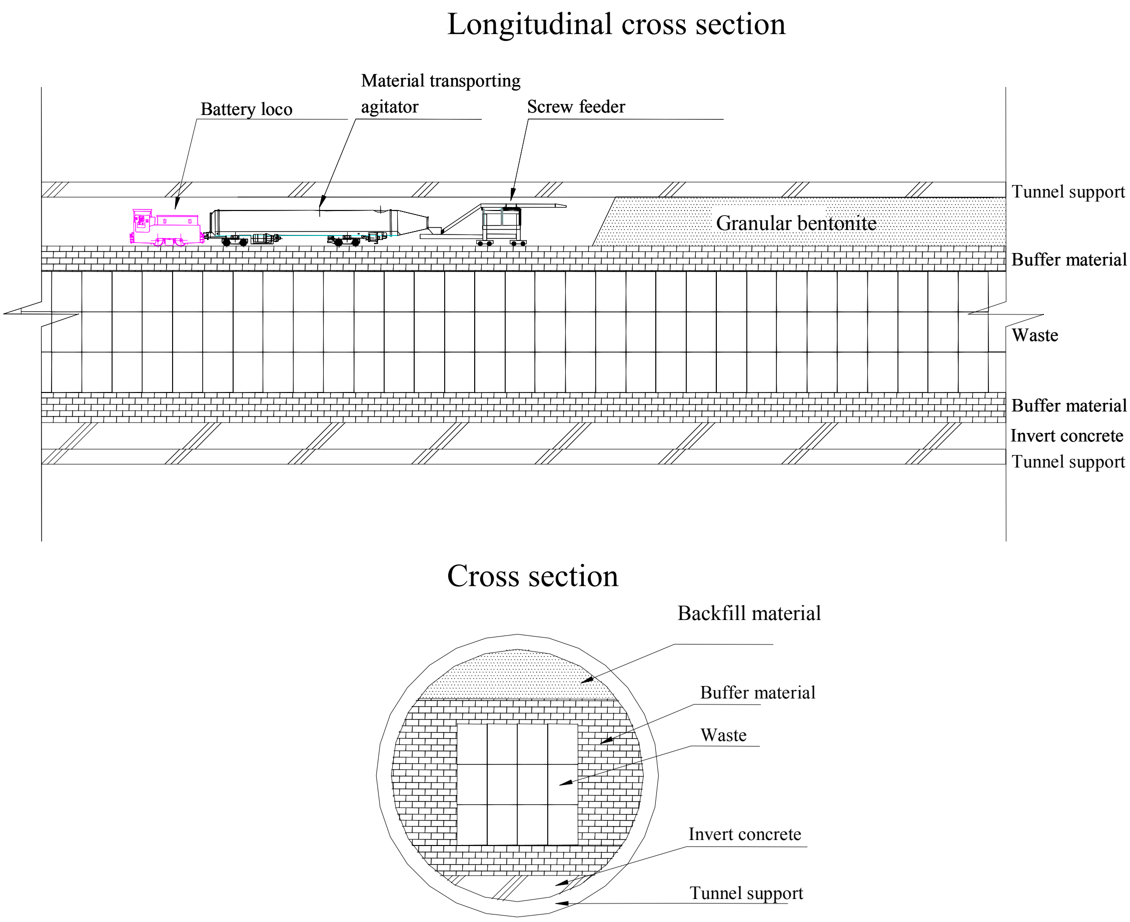


Figure 3.4.4.1-1 Example of construction of backfill in the upper part of a disposal tunnel (circular disposal tunnel)

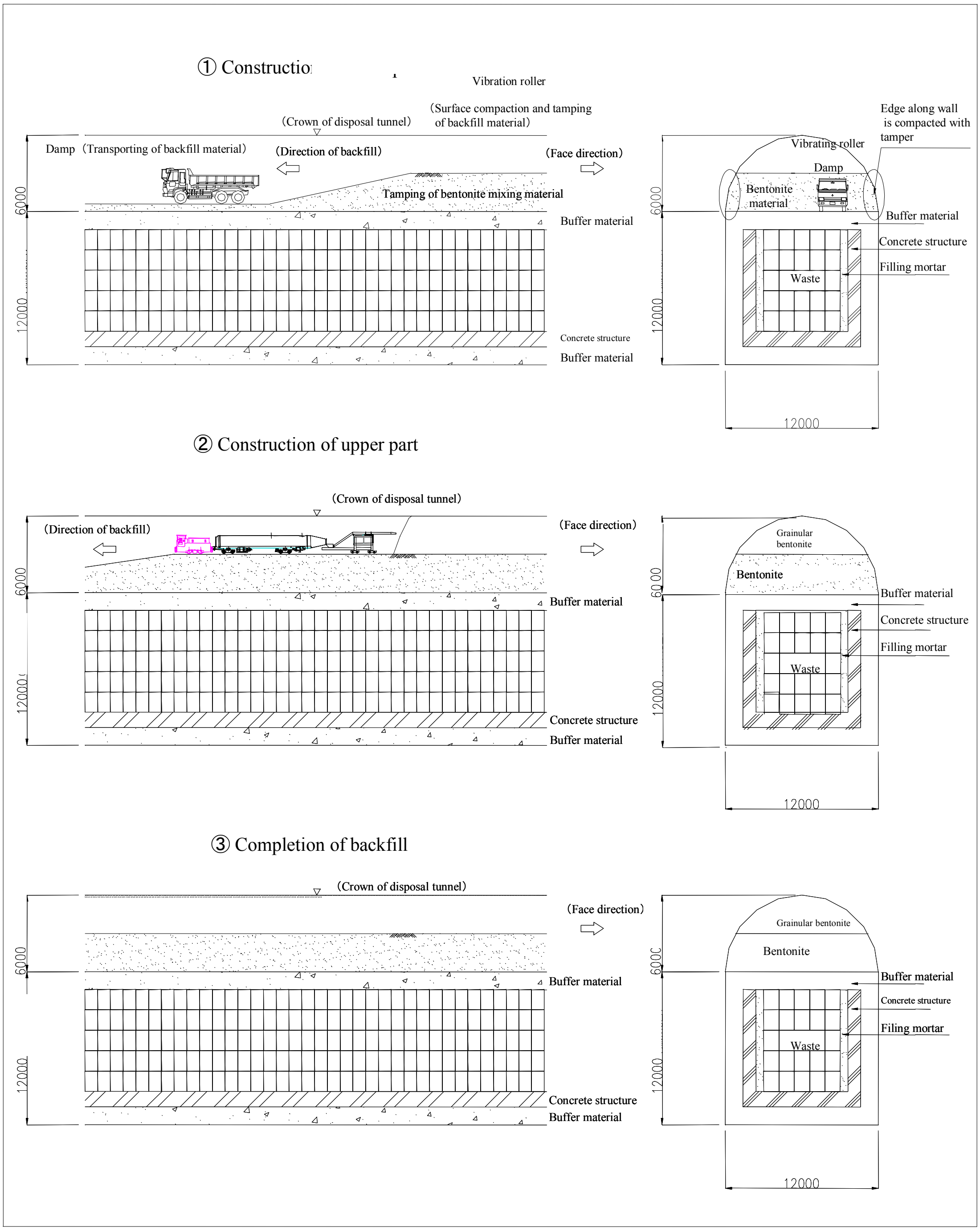


Figure 3.4.4.1-2 Example of construction of backfill in the upper part of a disposal tunnel (horseshoe-shaped disposal tunnel)

b. Backfilling of main approaching and connecting tunnels

Backfilling of the main and connecting tunnels is considered to be same as that of the upper part of the disposal tunnel. The backfill for the main approaching and connecting tunnel is summarized in Table 3.4.4.1-3.

Table 3.4.4.1-3 Appropriate backfilling methods for the main shaft and connecting tunnel

Part	Applicable construction method
Narrow upper part	Spraying
General upper part	Spraying Blocks
Lower part	Spraying In situ compaction Blocks

c. Backfilling of access tunnels

The backfilling method for the inclined access tunnel is the same as that for the main and connecting tunnel. For the backfilling of the vertical shaft, the compaction method is considered to be the easiest.

3.4.4.2 Construction of plugs

Plugs are classified into hydraulic and mechanical plugs.

Hydraulic plugs are made of bentonite with the same low permeability as that of the buffer material used in the disposal tunnel. Bentonite used for hydraulic plugs is constructed in the same way as other bentonite structures, as shown in Figures 3.4.2.2-2 to 3.4.2.2-5.

Since segmenting of the EDZ is an important function of the hydraulic plug, removal of the damaged zone at the point where the hydraulic plug will be constructed and grouting with bentonite material are required.

For the mechanical plugs designed to prevent material movement and outflow such as buffer material and backfill material, concrete is a candidate material since it is mechanically strong and has been used extensively in the construction industry.

3.4.4.3 Grouting

The primary function of grouting is to form a temporary waterproof layer and to help reduction of the hydraulic conductivity in the EDZ over the long-term. Bentonite material is considered appropriate for the latter purpose. For grout injection, a round pipe system and double tube method are considered as appropriate methods used extensively in mountain tunnels (TRU Coordination Team, 2000).

3.4.5 Management of the disposal facility

The aim of geological disposal is to isolate waste from the biosphere through deep burial and to prevent adverse impacts on humans. In the planned geological disposal concept for high-level waste, it is shown that the geological repository does not require further human intervention after closure (JNC, 2000). Although a specific evaluation of the management of the TRU repository has not yet been performed, it is necessary to consider consistency with high-level waste regarding the basic concept and management strategy. Management of the HLW repository as presented in the H12 report is described below.

(i) Quality management for design and construction procedures.
(ii) Monitoring of the geological environment in the surrounding area of the engineered barriers and the repository.
(iii) Other management activities (monitoring of the surrounding environment, safety monitoring during operation)

(i) Quality management during design and construction is performed in order to ensure the required functioning of each component. During research and development, data acquisition and technological development are pursued. (ii) involves monitoring the near-field and is performed in order to ensure the required performance of the engineered barriers and the surrounding geosphere. (iii) is performed to ensure safety in the surrounding area of the repository and continues until closure of the facility. The main information and measurements are the same as for high-level waste and are shown in Table 3.4.5-1 (JNC, 2000).

While human intervention is not planned in the design of the repository after closure, the possibility of retrieval of the waste has recently been discussed both domestically and internationally. It is necessary to summarize the concept for TRU waste disposal taking into account the current trend regarding this possibility. These are regarded as future issues and it is necessary to evaluate them in order to ensure consistency in TRU waste disposal.

Table 3.4.5-1 Main measurements/information during stepwise construction of the repository (example of high-level waste disposal) (continued on next page)

		Investigation of site characteristics	Construction step	Operation step: Emplacement of buffer material and waste	Operation step: Backfilling of repository tunnels and main tunnel	Closure step: Backfilling of connecting tunnel, access tunnel and boreholes and dismantling of surface facilities	Post-closure
Quality management of design and construction	Quality of design	**Design quality of engineered barriers** -Thermal stress of buffer material -Evaluation of erosion of overpack, etc.					-Limitation of land usage -Markers -Fences -Records
			Behavior of surrounding basement rock near cavities -Displacement of inner space	**Behavior of surrounding basement rock near cavities** -Displacement of inner space		**Behavior of surrounding basement rock near cavities** -Displacement of inner space	
			Integrity of support -Stress of support	**Integrity of support** -Stress of support		**Soundness of support** -Stress degree of support	
	Quality of construction	**Quality management and technology for construction** -Base values for management -Inspection frequency					
			Construction of tunnels -Quality of support -Manufactured material, etc.				
			Construction of grout -Injection control -Management of whole site	**Construction of grout** -Injection control -Management of whole site			
				Construction of engineered barriers -Quality of buffer material -Emplacement of buffer material			
					Backfilling of tunnels -Quality of backfill material -Construction of backfill	**Backfilling of tunnels** -Quality of backfill material -Construction of backfill	
					Plug construction -Quality of plug -Construction of plug, etc.	**Plug construction** -Quality of plug -Construction of plug, etc.	

Monitoring of geological environment	**Hydrological features** -Groundwater level -Pore pressure, etc.	**Hydrological features** -Groundwater level -Pore pressure, etc.	**Hydrological features** -Groundwater level -Pore pressure, etc.	**Hydrological features** -Groundwater level -Pore pressure, etc.	
	Geochemical features -pH -Eh, etc.	**Geochemical features** -pH -Eh, etc.	**Geochemical features** -pH -Eh, etc.	**Geochemical features** -pH -Eh, etc.	
	Geological features -Ground temperature -Earthquakes, etc.	**Geological features** -Ground temperature -Earthquakes, etc.	**Geological features** -Ground temperature -Earthquakes, etc.	**Geological features** -Ground temperature -Earthquakes, etc.	
Monitoring of surrounding environment of disposal site	-Quality of surface water -Radiation environment, etc.	-Quality of surface water -Radiation environment, etc.	-Quality of surface water -Radiation environment, etc.	-Quality of surface water -Radiation environment, etc.	
Management for operation	**Non-radiological safety** -Temperature, moisture -Gas -Dust, etc.	**Non-radiological safety** -Temperature, moisture -Gas -Dust, etc.	**Non-radiological safety** -Temperature, moisture -Gas -Dust, etc.	**Non-radiological safety** -Temperature, moisture -Gas -Dust, etc.	
			Radiological safety -Radiation in work environment	**Radiological safety** -Radiation in work environment	

(JNC, 2000)

3.5 Summary

In this Chapter, specifications were presented for the design concept of the repository and the engineered barriers that take into account the wide range of geological environments in Japan. Based on these specifications, an optimised design for the repository was considered. The specific technologies required for construction, operation and closure of the repository were evaluated. The areas considered were as follows:

- Basic design concept
- Design of the engineered barriers and repository
- Long-term mechanical stability in the near-field
- Construction, operation and closure of the repository

<u>Basic design concept</u>

The components required in the disposal system were established by considering the “Requirements for ensuring safety (safety factors)” in Section 1.2. Also, the required functions of the engineered barriers and repository were evaluated and a basic configuration for the engineered barrier system and repository facility were summarized.

<u>Design of the engineered barriers and repository</u>

Designs for waste packages, buffer material and filling material in the engineered barriers were considered. The required performance was established based on the required function of each member of the engineered barrier system. Design specifications for bentonite were established, which take into account its degradation as a result of conversion to Ca type bentonite and/or change to seawater type groundwater conditions.

In the design of the underground facility, the shape of the disposal tunnels, the size and the separation distance between tunnels were set considering, for example, mechanical and thermal constraints. The layout of the underground facility was then established. In the evaluation of the mechanical stability of the disposal tunnels, a mechanical stability assessment during excavation and/or an earthquake was performed.

In the layout of the underground facility, waste grouping, mechanical stability of the tunnels and influences of heat from the waste were considered. Layouts in each rock type were presented, in addition to an example layout that takes into account the effects from nitrates included in Group 3 waste.

Long-term mechanical stability in the near-field

The phenomena that affect the mechanical stability of the near-field were summarized and the effect of each was evaluated. Since temperature stress, gas formation and leaching of buffer material have only a small effect on the mechanical stability of the near-field, the overall mechanical properties of the near-field could be assessed by evaluating each effect individually. Although it was revealed that the interaction between deformation of the host rock and the engineered barriers is significant, the mechanical stability of the near-field could be assessed through individual evaluations of the host rock and EBS if the host rock has the strength of SR-C. From these evaluations, the mechanical stability of the near-field is assured over the long term under the geological conditions assumed in this report.

Evaluation of repository construction, operation and closure

It is considered that the engineered barriers and the repository can be constructed using current technology and technology that will be developed in the near future. The necessary technology for construction, operation and closure was examined. The disposal concept was broadly divided into layouts with circular type disposal tunnels and layouts with horseshoe-shaped disposal tunnels. Optimized disposal technologies for each were proposed.

The latest knowledge and data were reflected in the evaluation above and technical reliability was improved on from the 1st TRU progress report. This report not only improves on reliability through evaluation of larger and broader datasets, but also presents quite different design and performance concepts for the engineered barrier under a variety of geological conditions to that in the 1st TRU progress report. A stepwise approach was developed in the design of the disposal system. It was found through various evaluations that the design concept responded well under different geological conditions. Understanding disposal technology was essential in this project and will become more important in the near future.

There is a need to review the optimization of the engineered barrier and repository design with further progress of science and technology and detailed refinement of waste inventories. The contents of this report are regarded as providing a basis for this work.

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