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Second Progress Report on Research and Development for TRU Waste Disposal in Japan

— Repository Design, Safety Assessment and Means of Implementation in the Generic Phase —

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Japan Atomic Energy Agency

The Federation of Electric Power Companies of Japan

Second Progress Report on Research and Development for TRU Waste Disposal in Japan

– Repository Design, Safety Assessment and Means of Implementation in the Generic Phase –

Japan Atomic Energy Agency
Tokai-mura, Naka-gun, Ibaraki-ken

The Federation of Electric Power Companies of Japan
Ohte-machi, Chiyoda-ku, Tokyo

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In order to promote the establishment of a regulatory framework and the implementation of TRU waste disposal, the Federation of Electric Power Companies of Japan (FEPC) and the Japan Nuclear Cycle Development Institute (now JAEA) collaborated and published a progress report in Japanese (hereafter TRU-2) in September 2005. The report here is an English version of TRU-2 and has been published to widely inform overseas researchers and engineers of the contents of TRU-2.

In this report, the characteristics of TRU waste generated from the nuclear fuel cycle in Japan and its disposal concept are shown. The design of the TRU waste disposal facility was evaluated and safety assessments were carried out to show that safety could be validated by comparing with regulatory guidelines in overseas performance assessment reports. Alternative technologies were developed to deal with various geological environments and to improve safety margins in addition to evaluating other disposal concepts. Furthermore, optimisation through co-location disposal of TRU waste and high level radioactive waste was investigated, and an example layout of a co-location disposal concept was evaluated. Based on these evaluation results, future issues and outstanding items on research and development for TRU waste disposal are summarised.

Keywords: TRU Waste, Disposal Concept, Safety Assessment, Geological Environment, Alternative Technology, Co-location Disposal

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TRU 廃棄物処分技術検討書
－第 2 次 TRU 廃棄物処分研究開発取りまとめ－
（英語版）

日本原子力研究開発機構
電気事業連合会

（2007 年 1 月 19 日 受理）

TRU 廃棄物処分の事業並びに制度化に資するため，電気事業者等と核燃料サイクル開発機構（現 日本原子力研究開発機構）が協力し，2005 年 9 月に「TRU 廃棄物処分技術検討書（第 2 次 TRU レポート）」を公表した。本報告書は，第 2 次 TRU レポートの内容を広く海外の研究者や技術者に普及するために，英語版として取りまとめたものである。

わが国における核燃料サイクルから発生する TRU 廃棄物の特性及び廃棄物の処分概念について示すとともに，地層処分概念について具体的な処分施設の設計及び安全評価を行い，諸外国の安全基準と比較することにより，その安全性を示した。また，幅広い地質環境や安全裕度を高めるための代替技術や地層処分以外の処分概念の安全評価も実施した。さらに，高レベル放射性廃棄物との併置処分等による処分の合理化について検討を行い，併置処分の具体的なレイアウト評価を行なった。これらの評価結果を基に，TRU 廃棄物処分の実施に向けた展望及び今後の研究開発課題について示した。

本レポートは，日本原子力研究開発機構と電気事業連合会との協力協定に基づいて作成したものである。

日本原子力研究開発機構 バックエンド推進部門：〒319-1195　茨城県那珂郡東海村白方白根 2 番地 4
電気事業連合会：〒100-8118　東京都千代田区大手町 1-9-4　経団連会館ビル

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Executive Summary*

1. Introduction

The reprocessing of spent fuel (SF) from nuclear power plants (NPP) is an essential requirement for maintaining the nuclear fuel cycle. This is especially important in a country such as Japan which lacks energy resources and is dependent on overseas imports to sustain its energy needs. In addition to generating vitrified high level waste (HLW), large volumes of the low-level waste are generated during the operation and dismantling of reprocessing facilities and MOX fuel fabrication facilities containing long-lived radionuclides such as C-14, I-129, Pu-239 and Np-237 (**Figure 1**). This waste is defined as 'TRU-waste' in Japan and broadly equates to long-lived intermediate level waste (ILW) and low level waste (LLW) with significant alpha content.

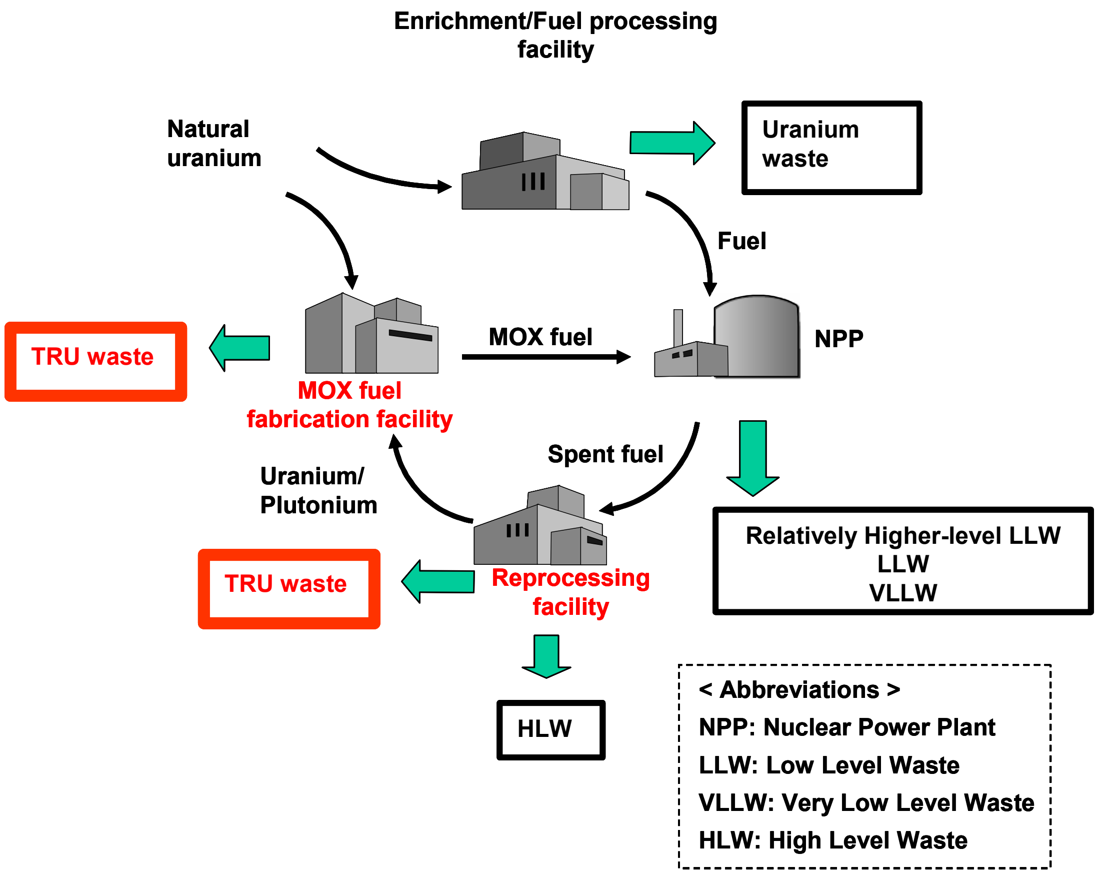

Figure 1. Simplified diagram showing the generation of radioactive waste in Japan (excluding medical, research and industrial wastes).

* You can see the more detailed version of this report in the CD-ROM attached.

Safe geological disposal over the long-term of TRU-waste is clearly a key factor in sustaining the nuclear fuel cycle. In order to establish the nuclear fuel cycle, a safe and optimised disposal methodology is required for TRU-waste. Moreover, several overseas countries have looked into the concept of co-location of TRU-waste at the same site as HLW as an optimisation measure.

To this end, the Federation of Electric Power Companies in Japan (FEPC) and the Japan Atomic Energy Agency (JAEA)[1] have led an investigation looking into the safe and optimum geological disposal of TRU-waste in Japan. The results were summarised in the second progress report (hereafter TRU-2). This report[2] describes the current status of research and development (R&D) of the long-term geological disposal of TRU-waste in Japan. It is not a stand-alone report and is a continuation of an earlier progress report that was published in 2000 (hereafter TRU-1) and produced in parallel with the R&D on the HLW disposal program (**Figure 2**).

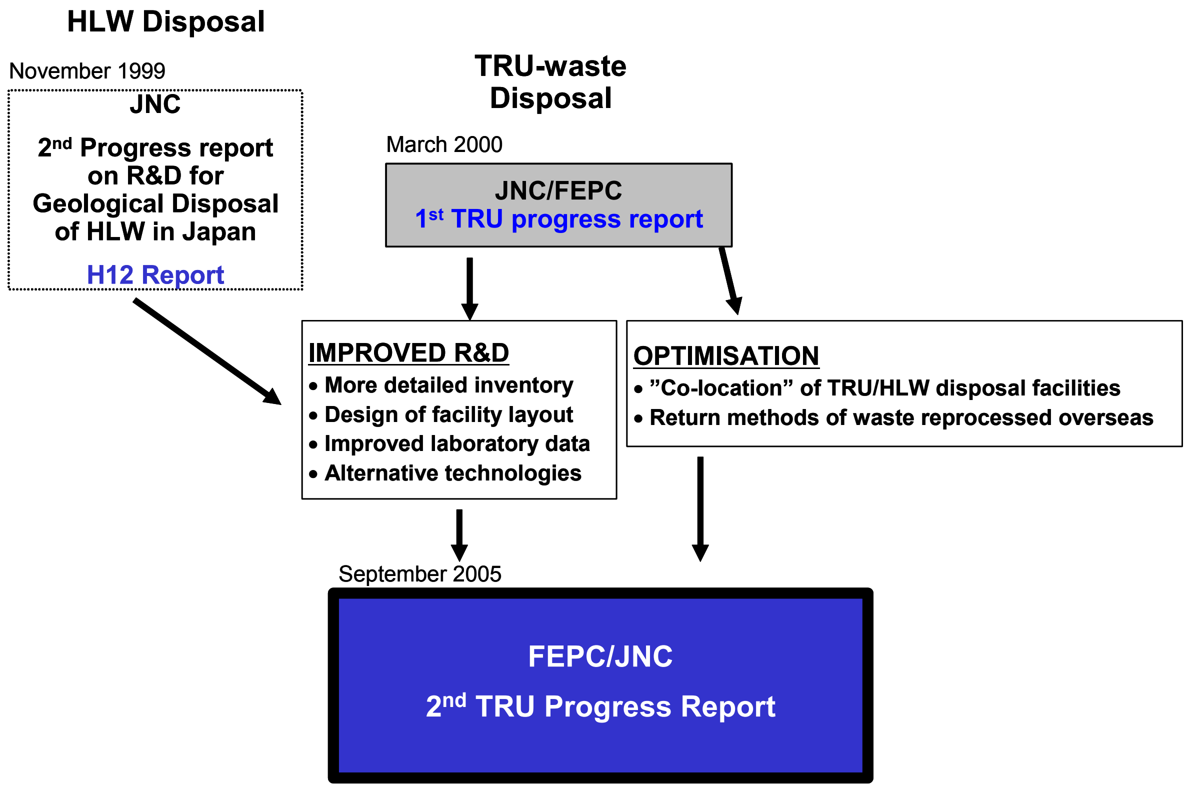

Figure 2. Progress of R&D of TRU-waste disposal in Japan (1999-2005).

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1 The Japan Atomic Energy Agency was formed on 1st October 2005 after the merger between the Japan Nuclear Cycle Development Institute (JNC) and Japan Atomic Energy Research Institute (JAERI).

2 The English version of TRU-2 is an almost direct translation of the original Japanese TRU-2 report published by FEPC and JNC in September 2005. This Executive Summary has been rewritten in order to describe the context of TRU-2 to an international audience.

Additionally, TRU-2 is being used as a technical basis in Japan to develop a programme aimed at the feasible implementation of the geological disposal of TRU-waste including establishment of the necessary institutions. It is envisaged that TRU-2 will promote the establishment of a regulatory framework and an implementation body in Japan to manage this waste form.

In broad terms therefore the TRU-2 report has the following aims:

(1) To summarise the latest results of collaborative R&D carried out by JAEA and FEPC on the geological disposal of TRU-waste;
(2) To promote the establishment of a regulatory framework and an implementation body to manage the disposal of TRU-waste.

The work on TRU-waste disposal is still on-going and at the present time, an organisation for implementing the geological disposal of TRU-waste has yet to be decided.

In this Executive Summary, the overall structure of the TRU-2 is summarised including a brief overview and background of the Japanese HLW and TRU-waste programme, the Japanese definition of TRU-waste, the boundary conditions used in the safety assessments, key results and outstanding future issues. Since JAEA is an R&D organisation, detailed modelling and experimental data are also included in TRU-2.

2. Overview and background of the Japanese HLW and TRU-waste programme (*Chapter 1*)

2.1 Key organisations connected with radioactive waste disposal in Japan

Key organisations related to the generation and disposal of HLW and TRU-waste are shown in **Figure 3**. These can be broadly divided into the public sector and private sector organisations.

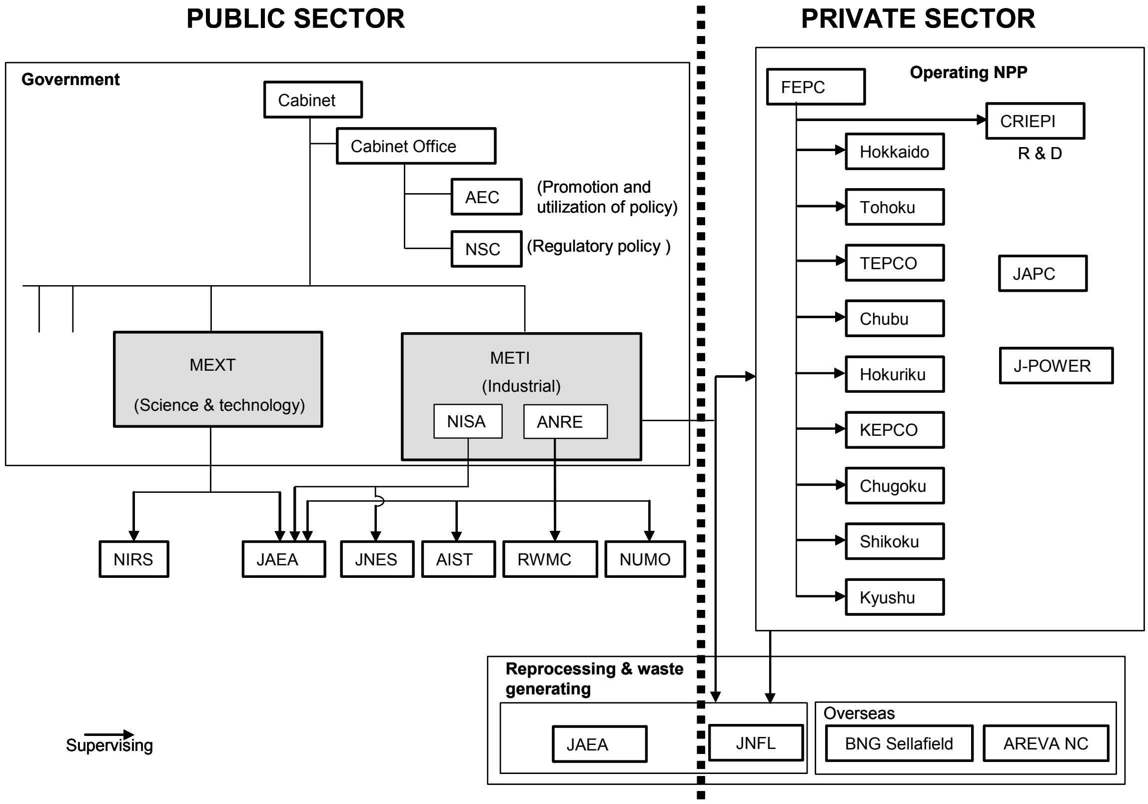

Figure 3. Key organisations that play a role in HLW and/or TRU-waste production and/or disposal in Japan (abbreviations are listed in the Appendix at the end of this Executive Summary). In Japan there are over 50 operating commercial nuclear power plants that produce over 48 GW of electricity.

The Federation of Electric Power Companies of Japan (FEPC) is the trade association for the 10 electric power companies in Japan that supply power to the private and public sectors. **Figure 3** shows 9 electric power companies (Hokkaido, Tohoku, TEPCO, Chubu, Hokuriku, KEPCO, Chugoku, Shikoku and Kyusyu). Not shown is the Okinawa Electric Power Company which does not have any NPPs. FEPC is committed to the promotion and stability of the electric power sector in Japan. Therefore, FEPC has a great responsibility for promoting TRU-waste and HLW disposal. The Central Research Institute of Electric Power Industry (CRIEPI) is a research institute funded by the 9 electric power companies shown in **Figure 3**. CRIEPI is performing R&D for TRU-waste and HLW disposal. The 9 electric power companies and the Japan Atomic Power Company (JAPC) have NPPs. J-POWER is planning to construct an NPP. These companies are generating spent fuel for reprocessing and have therefore a responsibility to promote R&D and to fund disposal of TRU-waste and HLW.

Japan Nuclear Fuel Limited (JNFL) (fuel reprocessing) is now constructing a commercial reprocessing plant which will generate TRU-waste and HLW from the reprocessing of about 800 tU per year. Japan Atomic Energy Agency (JAEA) has a reprocessing pilot plant which reprocesses about 40 tU per year. These organisations are the main producers of TRU-waste and HLW. Also, Japanese electric power companies have used overseas nuclear fuel reprocessing companies (BNG Sellafield, U.K. and AREVA NC, France) for reprocessing spent fuel. The TRU-waste and HLW generated from reprocessing of spent fuel that was originally shipped from Japan to these companies in the U.K. and France will be returned to Japan in future. This waste is termed here as 'returned waste.'

The Nuclear Management Organization of Japan (NUMO) is the implementor for the deep geological disposal of HLW. Currently there is no implementor for the geological disposal for TRU-waste. One of JAEA's key roles among others is to carry out research and develop new technologies for the geological disposal and treatment of radioactive waste. Other research organisations involved in the R&D of the geological disposal of radioactive waste disposal are the Central Research Institute of Electric Power Industry (CRIEPI) and National Institute of Advanced Industrial Science and Technology (AIST). The Radioactive Waste Management Funding and Research Center (RWMC) is responsible for managing funds for the implementation of HLW disposal and for conducting R&D related to the management of LLW, TRU-waste and HLW disposal. The National Institute of Radiological Sciences (NIRS) is responsible for carrying out research in the field of radiology. Japan Nuclear Energy Safety Organization's (JNES) primary role is to ensure nuclear safety but also to carry out its own R&D program. The Nuclear Safety Commission of Japan (NSC) is an independent agency within the Cabinet Office primarily concerned with nuclear safety administration. The Japan Atomic Energy Commission (AEC) was also established within the Cabinet Office, sets out the framework for nuclear energy policy in collaboration with the general public. Much of the R&D conducted in TRU-2 follows the framework and policy promoted by these two Cabinet commissions.

2.2 Geological environment and boundary conditions considered in TRU-2

Japan is a tectonically active country located on or near the boundary of four converging plates in the circum-Pacific orogenic belt as illustrated in **Figure 4**.

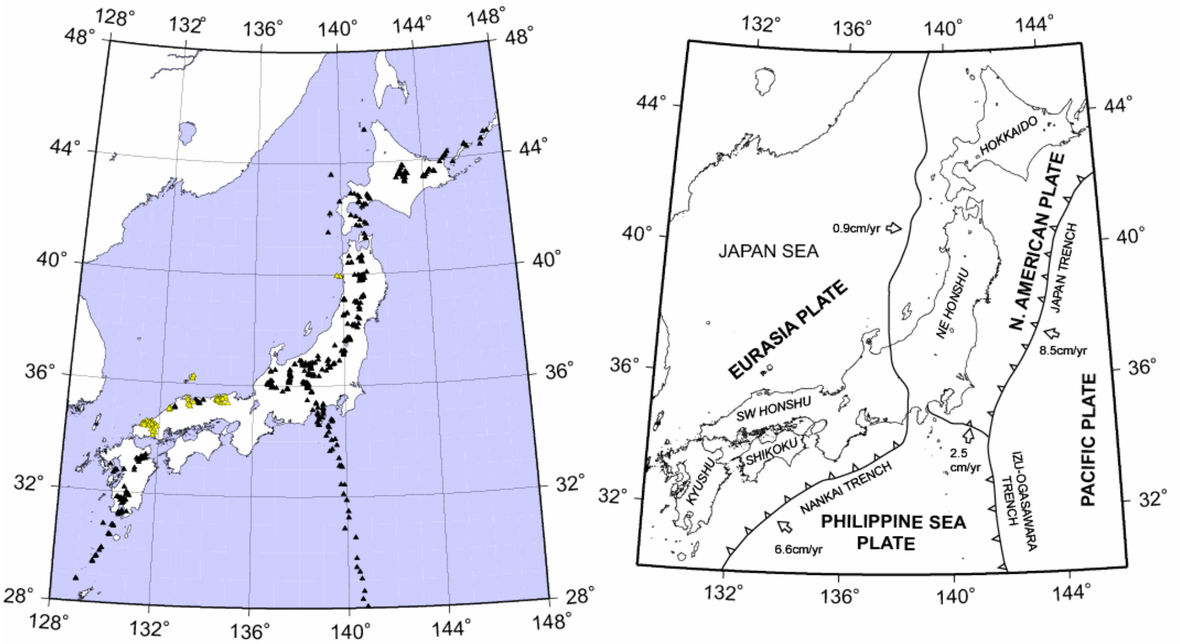

Figure 4. The tectonic setting of Japan. The four main islands that make up Japan are located on or near the boundary of four plates resulting in high levels of volcanic and seismic activity in some areas. Triangles depict locations of Quaternary (< 2 Ma) volcanoes (black: large established multiple eruption types; yellow: smaller, widely distributed single eruption types).

Owing to this arrangement of plates, Japan has higher volcanic and seismic activity compared with many areas of Europe. Japan is affected both by gradual, large-scale phenomena, such as uplift, subsidence and denudation, and sudden localised phenomena, such as volcanic and fault activity. Japan’s rocks can be simplified by distinguishing the older pre-Neogene (> 23 Ma old) basement rocks from overlying Neogene/Quaternary sedimentary and volcanic rocks.

In the report two major rock datasets are considered namely hard crystalline rock (HR) and soft sedimentary rocks (SR). **Table 1** summarises the geological environmental parameters considered in the tunnel stability analyses (Chapter 3) and nuclide migration analyses (Chapters 4 and 6).

Table 1. Boundary conditions used in tunnel stability analyses in TRU-2.
Underlined are reference values used for radionuclide migration analyses.

	A			B	C	D
Geography	Inland			Inland	Coast	Coast
Topographic features	Plain (hills, mountains)*2			Plain (hills, mountains)	Plain	Plain
Lithology	Sedimentary rock			Crystalline rock	Sedimentary rock	Crystalline rock
Groundwater	Fresh			Fresh	Seawater	Seawater
Transmissivity*1 (m^2/s)	10^{-10} (10^{-9}, 10^{-11})			10^{-10} (10^{-9}, 10^{-11})	10^{-10} (10^{-9}, 10^{-11})	10^{-10} (10^{-9}, 10^{-11})
Hydraulic conductivity ($m\ s^{-1}$)	10^{-9} (10^{-8}, 10^{-10})				10^{-9} (10^{-8}, 10^{-10})	
Hydraulic gradient	0.01 (0.05)			0.01 (0.05)	0.01	0.01
Host rock type	SR-C	(SR-B)	(SR-D)	HR	SR-C	HR
Effective porosity (-)	0.3	0.2	0.45	0.02	0.3	0.02
Uniaxial compressive strength (MPa)	15	20	10	115	15	115
Disposal depth (m)	500			1,000	500	500
Biosphere	River water			River water	Seawater	Seawater

*1: Transmissivity is the log-mean value.

*2: Bracket shows variation.

2.3 Official definition of TRU-waste in Japan

In Japan TRU-waste is officially defined as non-HLW waste generated from the operation and dismantling of reprocessing facilities and MOX fuel fabrication facilities containing long-lived radionuclides such as trans-uranium nuclides. It also includes non-HLW returned from BNG Sellafield (formerly part of BNFL) and AREVA NC (formerly COGEMA). **Figure 5** shows the distribution of this waste category on a plot of alpha activity versus beta and gamma activity although this is not to be treated as a formal definition.

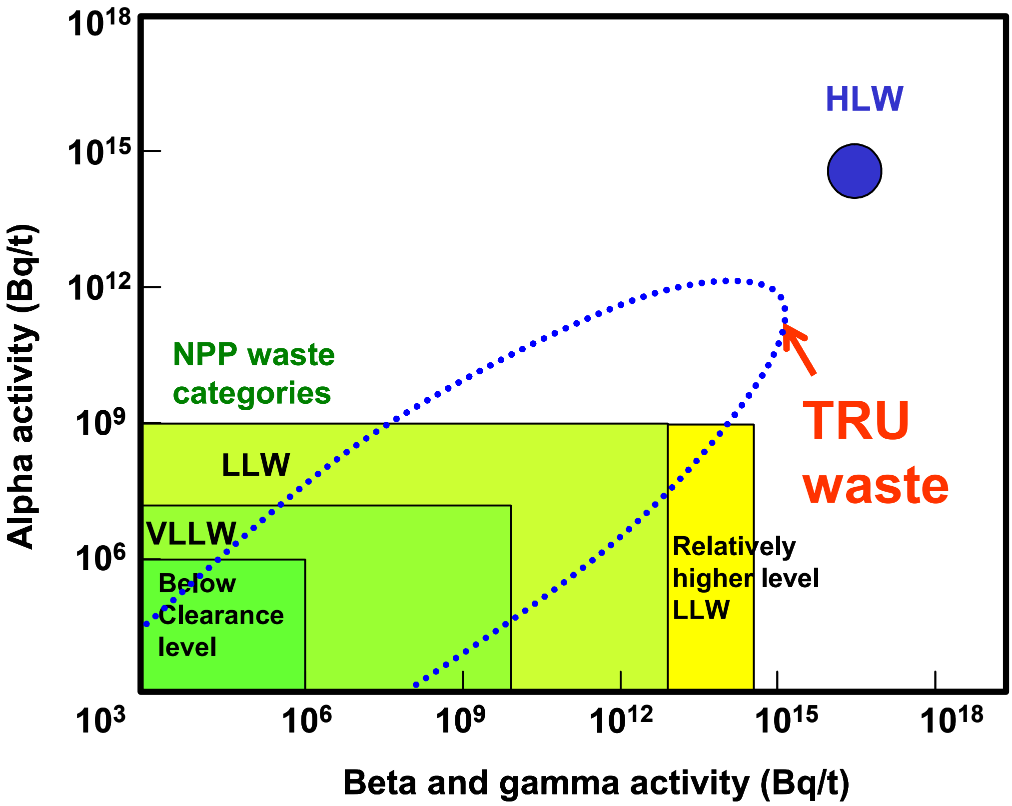

Figure 5. Radionuclide concentration of TRU-waste in Japan and comparison with NPP wastes (green and yellow). Note that VLLW, LLW and relatively higher level LLW refer to waste generated from the decommissioning of NPPs.

2.4 Regulatory guidelines for the geological disposal of TRU-waste

Neither a regulator nor an implementor for TRU-waste have been established in Japan (**Figure 3**). However, the Nuclear Safety Commission of Japan (NSC) published a report indicating that it is possible to dispose of TRU-wastes at various depths depending on the concentration of radionuclides. Many of these disposal concepts are already being used for the disposal of various LLW generated from the decommissioning NPPs in Japan. The disposal concepts considered in the NSC report are as follows:

- Near surface (typically several metres depth) disposal for TRU-waste with the same alpha, beta and gamma activities as VLLW (from decommissioned NPPs);
- Shallow depth disposal (4–9 m) for TRU-waste with the same radionuclide content as LLW (from decommissioned NPPs);
- Intermediate-depth disposal (50–100 m) for TRU-waste with the same radionuclide content as relatively higher level LLW (from decommissioned NPPs);

- Deep geological disposal (greater than 300 m) for TRU-waste with high (greater than all NPP wastes) alpha, beta and gamma activities.

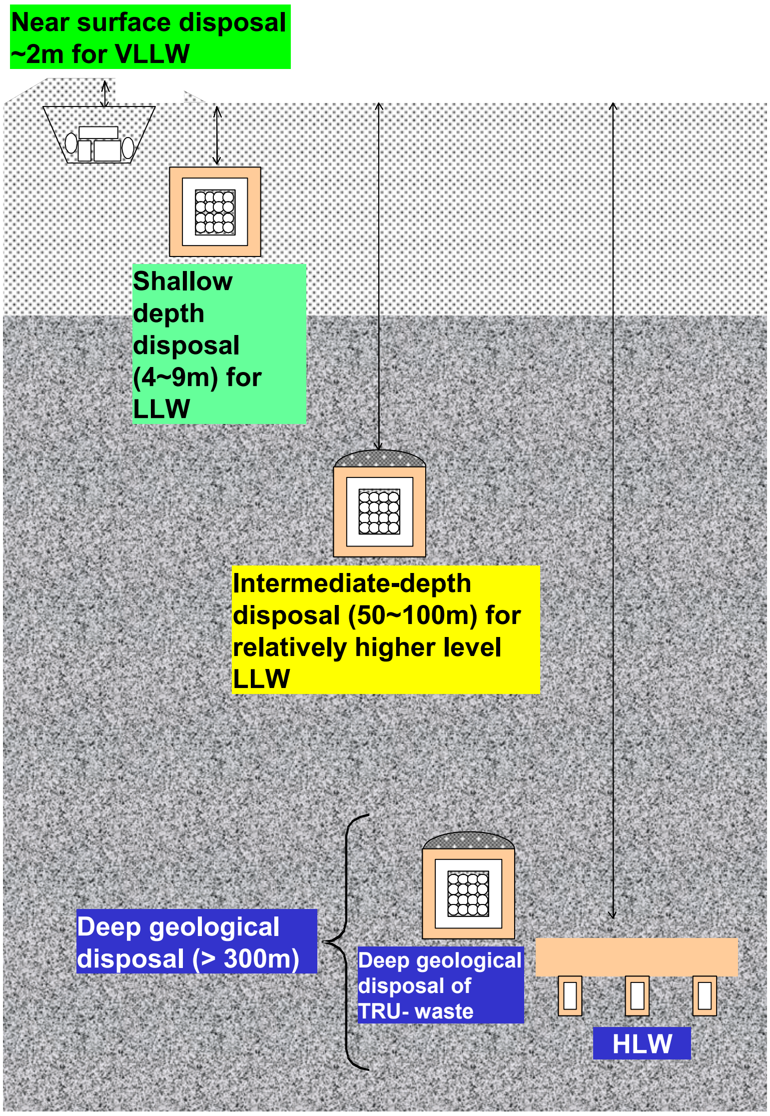

Figure 6. Disposal strategy for VLLW, LLW, HLW and TRU-waste. Deep geological disposal is envisaged for all TRU-waste that contains significant amounts of I-129 and C-14 which can easily migrate in the engineered and natural barriers.

Safety assessments for the deep geological disposal of TRU-waste are covered in Chapter 4. Chapter 5 briefly summarises disposal designs and results of performance assessments on shallow and intermediate-depth disposal systems. This chapter demonstrates that TRU-waste with similar combined alpha activities and beta and gamma activities to VLLW, LLW and relatively higher level LLW from decommissioned NPPs can be disposed of in currently established disposal concepts.

3. Objectives of report

The objectives of TRU-2 can be summarised as follows:

- Build on the R&D of TRU-waste disposal using more realistic boundary conditions and up-to-date databases;
- Describe the progress on Japanese R&D related to TRU-waste disposal;
- Illustrate R&D priorities and focus namely: bentonite-cement interaction models (Chapter 4); methods to reduce effects of nitrates which are particularly voluminous in Japan; introduce a newly developed top-down safety assessment approach (comprehensive sensitivity analysis) (Chapter 4); optimised approaches including co-location disposal with HLW which is new in Japan (Chapter 6), alternative designs to immobilize and confine key radionuclides (Chapter 7);
- Provide a technical basis in order to promote the establishment of a regulatory framework and an implementation body in Japan;
- Highlight outstanding technical and managerial issues and to promote future domestic and international cooperation to help address and solve these issues.

4. Brief outline of waste inventory in Japan (*Chapter 2*)

The volume of TRU-waste generated from the operation and decommissioning of domestic reprocessing and MOX fabrication plants, considering a full operation period, and returned wastes from the overseas reprocessing plants (BNG Sellafield, UK and AREVA, France) up to around 2050 is estimated to be ca 140,000 m^3, assuming application of treatment methods currently planned (**Figure 7**).

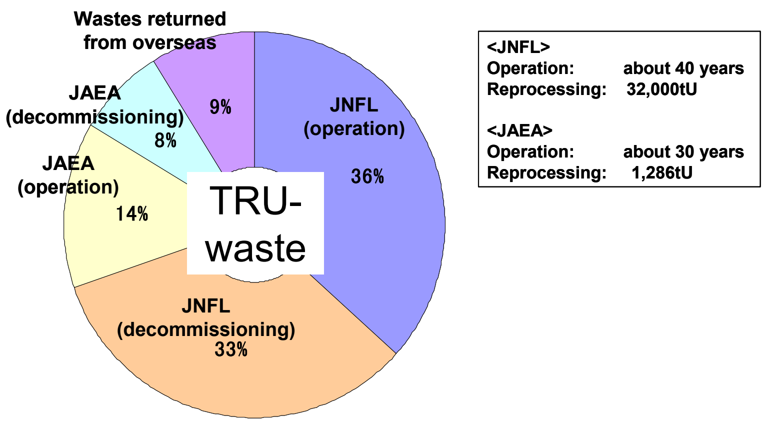

Figure 7. Estimation of TRU-waste generation in Japan.

TRU-2 demonstrated that depending on the alpha, beta and gamma activities in TRU-wastes, 63% would be suitable for near surface disposal (several metres depth), 18% for intermediate-depth disposal (50–100m) and 19% for deep geological disposal (> 300 m). Although the nuclide composition of the LLW originating from NPPs is different to that of TRU-waste, a revised criteria set for specific nuclide concentrations for TRU-waste was formulated for illustrative purposes using the same calculation methods as for the LLW from the NPPs (**Table 2**).

Table 2. Categorisation of TRU-waste in Japan.

Disposal concept	***Volume*, m^3**	***Group***	***Volume*, m^3**
Geological disposal, depth greater than 300 m	26,641	Group 1	318
		Group 2	6,732
		Group 3	6,175
		Group 4	13,416
Intermediate-depth disposal, (50–100 m)	25,205		
Shallow land disposal, (several metres).	88,431		
TOTAL	140,276		

TRU-wastes for geological disposal were grouped into 4 types (**Figure 8**). Group 1 includes weak-sorbing nuclides, such as I-129. Group 2 includes hulls and end-pieces, which generate heat and contain large concentrations of C-14. Group 3 includes chemical substances such as sodium nitrate, which have to be further analysed in terms of impact on radionuclide migration. Group 4 consists of other miscellaneous wastes.

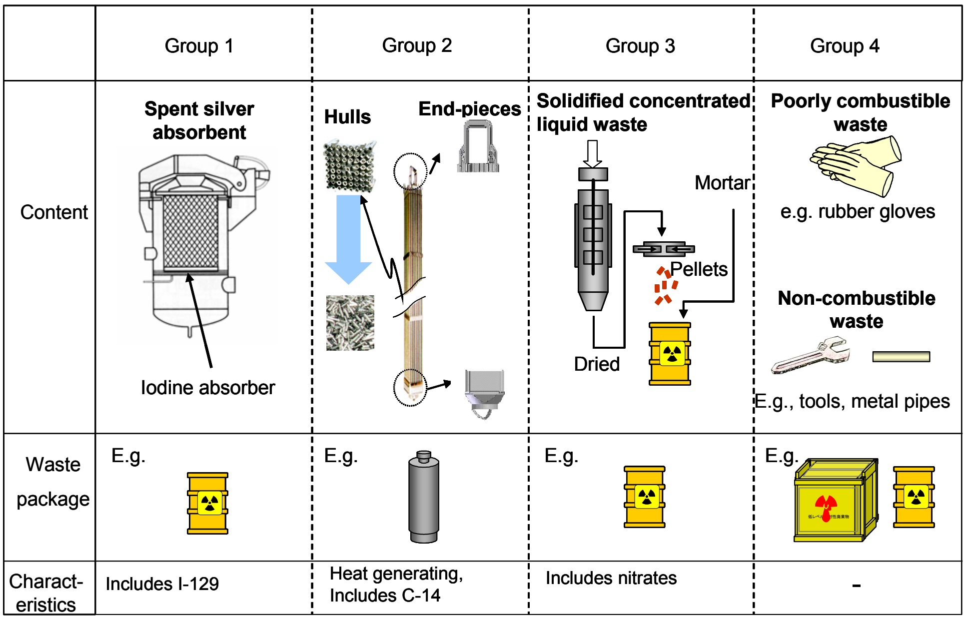

Figure 8. Grouping of TRU-waste for deep geological disposal.

Although all disposal depths are covered in project TRU-2, the report itself has focused mainly on R&D and feasible implementation associated with TRU-wastes destined for deep geological disposal.

5. Outline of key repository designs/layouts in envisaged rock-types (*Chapter 3*)

Since the heat generation is small, TRU-wastes for deep geological disposal can be emplaced together in tunnels with large cross-sections (**Figure 9**).

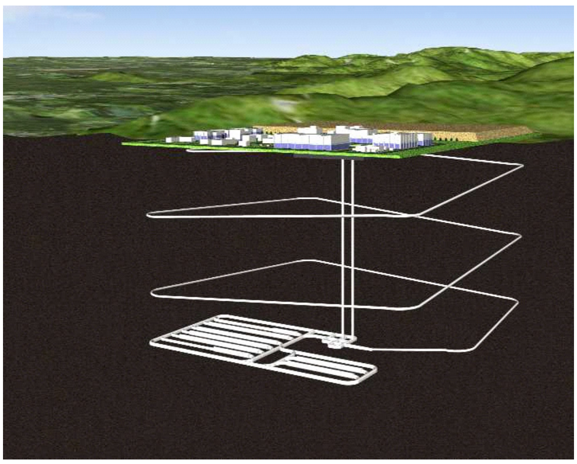

Figure 9. Deep geological repository concept for TRU-waste. Since most wastes do not produce heat, voluminous disposal in large cross-section disposal tunnels is feasible.

However, there is a wide variety of waste materials such as metal, cement, nitrates and organics. For this reason in the basic TRU-waste repository layout, each of the waste groups will be emplaced in separate disposal tunnels. In other words one disposal tunnel or drift will contain waste from one group only (see **Table 2** for associated volumes). Moreover the design specification of each disposal tunnel will depend on the characteristics of the waste group and the surrounding host rock. Since no candidate site exists in Japan yet the generic datasets for soft rocks (SR) (e.g. sedimentary rock) and hard rocks (HR) (e.g. crystalline rocks) were used in numerical analyses to model the performance of the EBS designs. Owing to the larger concentration of highly soluble and low sorbing radionuclides in TRU-waste in Group 1 and Group 2, it was shown that disposal tunnels for these wastes required a buffer consisting of compacted bentonite and sand mixture to maintain a low ground water flow in the repository. On the other hand, disposal tunnels for Group 3 and Group 4 did not require a bentonite buffer.

The effects of thermal stress (originating mainly from Co-60 as gamma heat in Group 2), gas generation and extrusion of buffer material had only a small effect on the mechanical stability of the near-field according to numerical evaluations performed. However, interaction between creep behaviour of the host rock and deformation of the EBS could be considerable depending on rock type. Disposal tunnels with horseshoe-shaped cross-sections and circular cross-sections were shown to be mechanically stable in the hard rock dataset but in soft rock dataset only circular disposal tunnels could be used. An advantage of horseshoe-shaped tunnels is that they allow more efficient and cost effective techniques for the emplacement of buffer and waste packages.

The above results were based on generic environments. When a site is eventually selected it is planned that safety assessments and the design of the TRU-waste repository layout will be carried out iteratively, so that the design can be modified to take into account the specific host rock boundary conditions. This is particularly important when deciding the design of structural support and layout of disposal tunnels for each waste group. For example Group 3 wastes are likely to form a nitrate plume so the disposal tunnels for these wastes need to be located downstream and at a sufficient distance from the disposal tunnels of the other groups; it was shown that a nitrate plume could affect the nuclide migration. With these constraints in mind, several disposal layouts were designed for both hard rock and soft rock datasets. **Figure 10** shows an example layout for a TRU-waste repository in soft rocks (SR).

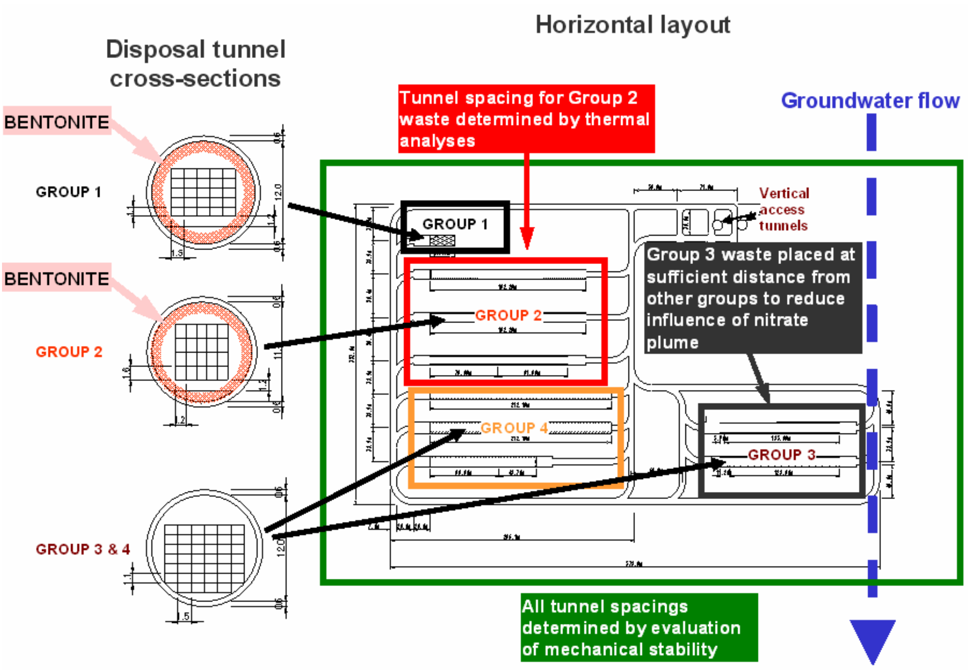

Figure 10. Example layout of TRU-waste disposal facility design in soft rocks (SR).

One of the key concerns in the design of the disposal tunnels for Group 1 and Group 2 wastes was alteration of Na-bentonite to Ca-bentonite which has undesirable swelling properties. Based on the evaluation of the spatial variation in chemical properties in the cement-buffer system it is expected that sufficient amounts of montmorillonite will remain after 100,000 years. However these models showed that although Na montmorillonite is dominant for several 10,000 years, beyond that, Ca montmorillonite dominates. This means that a loss in the impermeability function of the buffer material cannot be ruled out and was taken into account in the safety assessment described below.

Finally detailed planning for construction, operation and closure of a TRU-waste repository in both soft rocks (SR) and hard rocks (HR) are presented and shown to be feasible with current technology.

6. Safety Assessment of TRU-waste (*Chapter 4*)

Since a repository site has not yet been selected and the geological environments in Japan vary widely, in order to demonstrate safety, a conservative disposal analysis that takes into account many types of uncertainty was considered

6.1 Scenario development

In the safety assessment of the deep geological disposal of TRU-waste, important Features, Events and Processes (FEPs) that could potentially affect nuclide migration in the repository environment were investigated, taking into account Japanese geological environments and NEA's international FEP list. Although Japan is a tectonically active country located on or near the boundaries of four converging plates, based on the FEP classification and screening process, FEPs related to volcanism and new fault activity were excluded since it was considered that such natural phenomena could be avoided during site selection. FEPs that could be avoided through engineering measures, were considered to have little influence on the disposal system or to be low probability events. Thus, these were also excluded from the safety assessment calculations.

Scenarios related to safety assessment were constructed from FEPs that were not excluded by screening. The two main scenarios were the groundwater and the isolation failure scenarios (**Figure 11**).

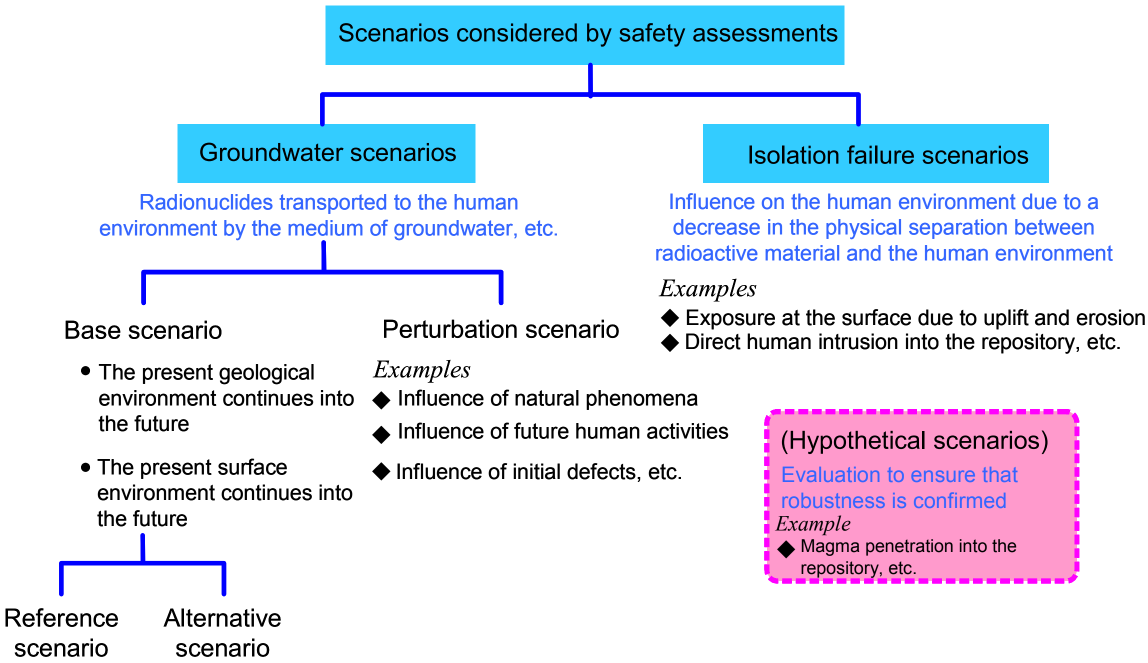

Figure 11. Evaluated scenarios in safety assessment for deep geological disposal of TRU-waste.

In the groundwater scenario, radionuclides may be transported to the biosphere by groundwater. In contrast with HLW, a few radionuclides in TRU-waste (e.g. C-14) may be volatile and a scenario describing the migration of gaseous radionuclides is also classified as one of the groundwater scenarios. In the isolation failure scenario, radionuclides reach the biosphere through a decrease in physical distance between the waste and the biosphere. The groundwater scenarios are further divided into a base scenario, where it is assumed that the present geological conditions and surface environment will continue in the future, and perturbation scenario, where future changes are considered. The base scenario consists of a reference scenario and an alternative scenario.

The reference scenario is based on FEPs connected with initial conditions and FEPs connected with the assumed/specified safety function of the disposal system such as the chemical composition of groundwater, the effects of radiation, the effects of organic materials in waste and the effects of sodium nitrates in Group 3. The list of main FEPs evaluated are shown as follows:

- Chemical composition of groundwater
- Longevity of engineered barrier materials, particularly the cement-bentonite interaction
- High-pH plume effect on host rock
- Hydraulic conditions in the near-field
- Colloid effects
- Effects of natural and artificial organic materials such as bitumen, cellulose, etc.
- Microbial effects
- Radiation effects
- Effect of sodium nitrate
- Impact of gas generation

The alternative scenario is a scenario which includes the uncertainties of evaluations of FEP lists and the geological environment. In the alternative scenario of TRU-2, the following cases were considered including uncertainties of evaluations of each FEP list.

- Effect case of engineered barrier alteration
- Effect case of hydraulic conditions in the near-field (effect of initial oxidizing condition caused by re-saturation period of groundwater)
- Effect case of gas generation (partly including microbe and gaseous radionuclide effect)
- Effect case of colloids (partly including microbe effect)
- Effect case of high-pH plume on host rock
- Effect case of organic material (natural)

6.2 Example FEP evaluations in the base scenario of the groundwater scenario

Here the results of the evaluation of two main FEPs that have some uniqueness to TRU-2 are briefly described. These are (1) longevity of engineered barrier materials, particularly cement-bentonite interaction and (2) effects of sodium nitrates. These two important FEPs have also been the focus of other organizations in Japan. (Results of other FEP evaluations are described in Chapter 4).

(1) Cement-bentonite interactions

It is a well known fact that owing to the large amount of cementitious materials that will be used in a TRU-waste (or I/LLW) repository, interaction between bentonite and hyperalkaline fluids from the cementitious materials can be problematic due to the close proximity of these materials in repository designs. The interaction could cause the alteration of mineralogy and associated change in hydraulic property of bentonite and have a deleterious influence on the function of bentonite as a hydraulic barrier, and may lead to adverse impacts on the long-term safety of the repository. Many studies on such interactions have been carried out in order to establish a bentonite alteration scheme, however, uncertainty in current understanding of the precise alteration scheme, especially mineral paragenetic sequences during alteration, still remains. This is largely attributed to insufficient knowledge about the chemical scheme, thermodynamics and kinetics. Other uncertainties also arise from non-linear relationship between chemical, mechanical and mass-transport events, and in evaluating how the mineralogy and the hydraulic property of bentonite evolves subject to alteration by hyperalkaline fluids. For this reason, multiple scenarios for mineralogical alteration of bentonite were developed and multiple sets of assumptions were employed for numerical simulation, in order to bound the uncertainties in the evaluation of chemical, mineralogical and hydraulic evolution of EBS over the long-term.

The conditions of bentonite buffer in a radionuclide migration analysis were determined on the basis of the following conclusions drawn from analyses of EBS evolution.

- A realistic case: The effectively impermeable characteristics of the bentonite are expected to be maintained for at least 100,000 years. Moreover, because the precipitation of pore-filling secondary minerals occurs near the interface between cementitious materials and bentonite, nuclide migration is significantly prevented in this area. From the results, it is considered that the alteration of the engineered barrier has a positive effect on the radionuclide retention function. However, it is necessary to note that fracture formation and inhomogeneous alteration may damage the retention effect due to pore filling by secondary minerals.

- A conservative case: It is assumed that the pore filling by secondary minerals in the interfacial altered layer will not restrict diffusion because of mechanical instability of altered zone. This means that the initial effective diffusion coefficients of the cementitious material and bentonite will be nearly constant in future. In this case, the impermeable characteristics of the bentonite will be guaranteed for at least 100,000 years since sufficient montmorillonite remains.

- A hypothetical case: The following conditions are considered to have low probabilities: montmorillonite dissolution is promoted by constantly unsaturated conditions because the equilibrium constant for montmorillonite dissolution is larger than that present in the standard database; the dissolution of montmorillonite is promoted since the dissolution rate law for montmorillonite under highly alkaline conditions follows the instantaneous equilibrium model. In these hypothetical cases, the impermeable property of bentonite will be lost after several 1,000 years.

(2) Effects of sodium nitrates

In Japan, the spent fuel from NPPs is reprocessed and U and Pu are recovered by the PUREX method. This method produces spent nitrate salts (mainly $NaNO_3$) which would be brought into a TRU-waste disposal facility (Group 3) if special pre-treatments are not applied. The total amount of nitrate salts to be emplaced in Group 3 disposal tunnels was estimated to be about 3.25×10^6 kg. It was found that nitrates and its reduction product (NH_3) could affect the behaviour of radionuclides. In a radionuclide migration analysis for Group 3 disposal tunnel, an oxidizing condition and formation of ammine complexes were assumed. Moreover NO_3^- might be reduced to N_2 by microbes. However the impact of N_2 gas generation was estimated to be insignificant.

6.3 Radionuclide transport analysis and dose assessment

(1) Base scenario

Based on the results of the scenario analysis and the established initial conditions, nuclide migration analyses were performed with realistic near-field models and databases taking into account the specific design components and phenomena encountered in a TRU-waste disposal system. Migration in the geosphere was the same as that used for HLW in the H-12 report (**Figure 12**).

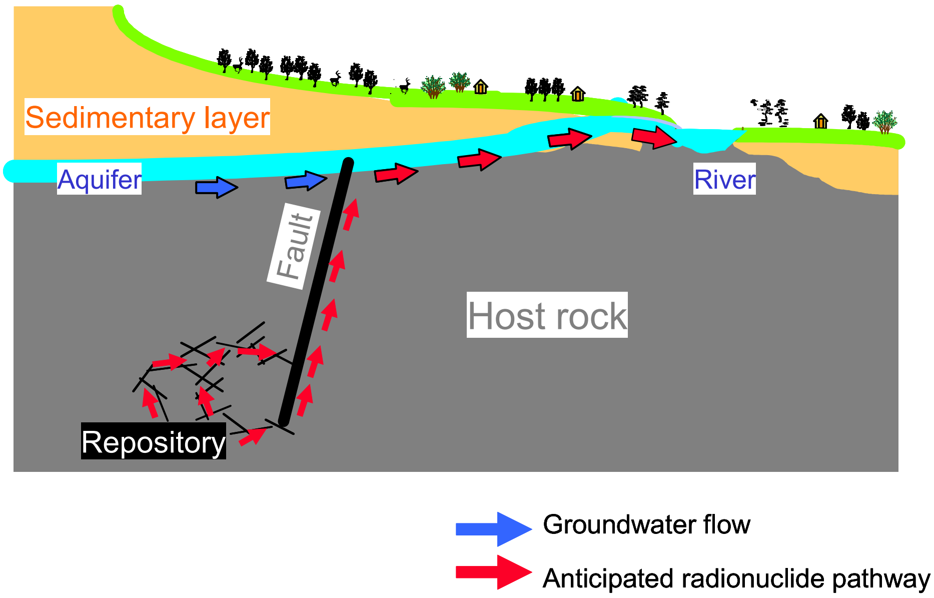

Figure 12. Nuclide transport pathway considered in the Reference Case (same applied to HLW).
A 800m long water conducting fault is assumed to be located 100m away
from the TRU-waste repository and provides a transport path.

➢ **Bottom-up approach (Deterministic consequence calculation)**

In the Reference Case which is the analytical case of the reference scenario, it was assumed that temperature does not exceed 80°C (below which no mineral alteration in cementitious materials is anticipated), cement materials have a pH > 12.5 allowing formation of Ca-type bentonite, re-saturation and radionuclide release is instantaneous, organic material in Group 2 waste affects the EBS and nitrates in Group 3 waste affect both the EBS materials and sorption distribution coefficients of radionuclides. The assumed geological environment is freshwater type groundwater in granite (i.e. hard-rock dataset) with fractures. Dissolution/precipitation, sorption, diffusion and advection dispersion were considered in the nuclide migration analysis in the geosphere. The results of the dose released to the biosphere is shown in **Figures 13 and 14** (the same biosphere methodology used in H-12 was applied).

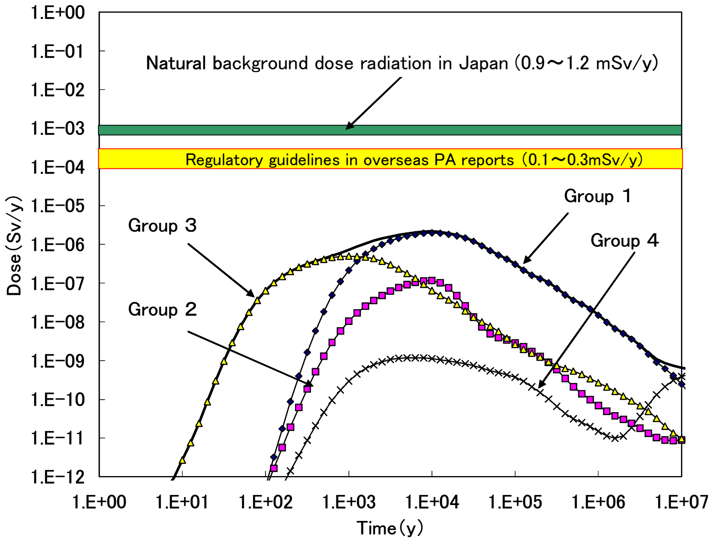

Figure 13. Results of dose assessment for each waste group (Reference Case). Maximum dose is less than natural background dose radiation in Japan and less than regulatory guidelines in overseas PA reports (currently no regulatory guideline in Japan).

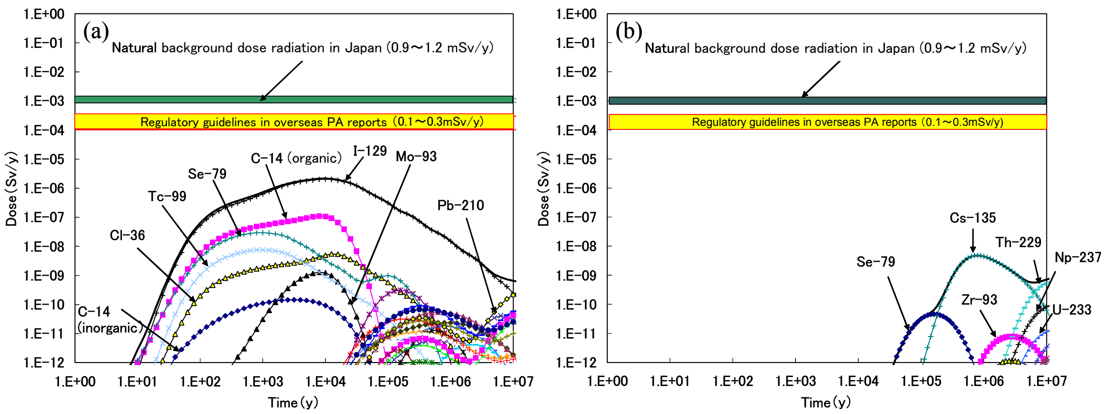

Figure 14. Calculations of dose rate (Reference Case) for (a) TRU-waste and (b) HLW (H-12). For TRU-waste the maximum dose is ca 2 μSv y^{-1} and the dominant radionuclides are I-129 from Group 1 and organic C-14 from Group 2.

I-129 in Group 1 gave the dominant dose but this was much lower than natural background dose radiation in Japan and regulatory guidelines in overseas PA reports. However dose was higher than that obtained from HLW using the same analyses although of course no overpack is used in the disposal concept for TRU-waste.

In the Alternative Case, nuclide migration and dose evaluation were performed considering the uncertainties of each FEPs assessment. The FEPs considered are shown in Section 6.1. In addition to these uncertainties, cases were evaluated incorporating the variation of geological conditions shown in **Table 1**. The results are shown in **Figure 15**.

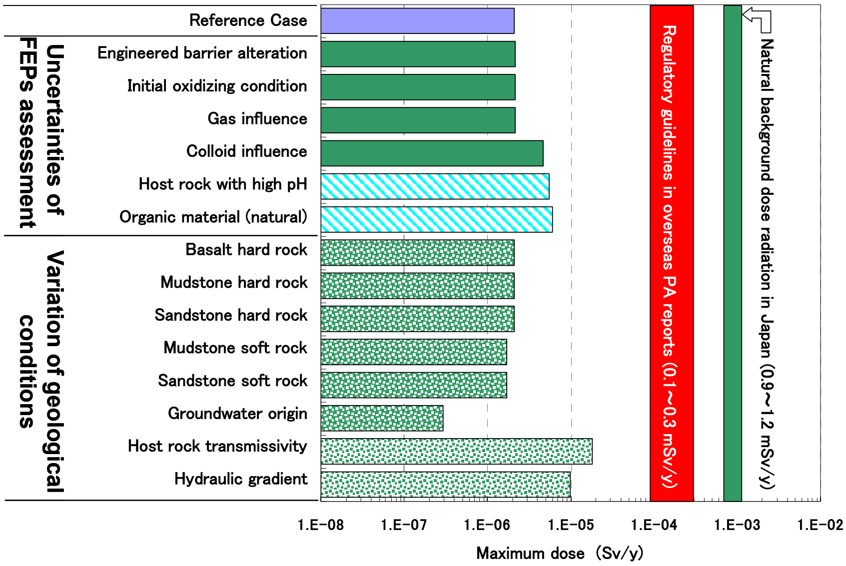

Figure 15. Calculations of maximum dose rate (alternative cases).

As for FEP uncertainty assessment cases, the organic material case shows the highest dose value. However, considering variation of geological conditions, uncertainty of host rock transmissivity has a significant effect on maximum dose in the alternative case. In the TRU-waste repository assessment, weakly-sorbing radionuclides (e.g. I-129 and organic C-14) are dominant, therefore these migrations are strongly affected by hydraulic conditions of the host rock.

➢ **Top-down approach (Comprehensive sensitivity analysis)**

In order to gain confidence in the safety assessments performed, it was necessary to consider the effects of diverse uncertainties in the current generic R&D phase of TRU-waste disposal. These uncertainties could be evaluated using existing deterministic techniques by increasing parameter ranges and the number of parameter combinations, etc. However a comprehensive deterministic evaluation of all uncertainties would result in an unmanageable large number of cases in order to give adequate combinations of uncertainty. To deal with this, some national programs also considered probabilistic approaches to derive a risk estimate for the whole system considering the variation of parameters using probability density functions to model possible parameter variations and the parameter combinations of those in order to complement the adequacy of the deterministic evaluation. However, in addition to such probabilistic estimates on the influence of uncertainty, there is a need in uncertainty analyses to identify the key parameters that have a dominant control on the safety of the system and to extract quantitatively the conditions that would yield a robust system.

To this end, a new top-down assessment approach was developed for TRU-2. This approach, called the comprehensive sensitivity analysis method here, is essentially a statistical approach and was developed to play a new role in the consequence calculation of uncertainty. The overall methodology consists of: (a) a statistical approach used to sample independent parameters randomly and to identify parameters that have a large impact on dose and then to extract threshold values of parameters and/or combinations yielding a 'successful condition' where maximum dose does not exceed a target value (**Figure 16**), (b) a nuclide migration model that as far as possible comprehensively incorporates the various phenomena that occur within the repository.

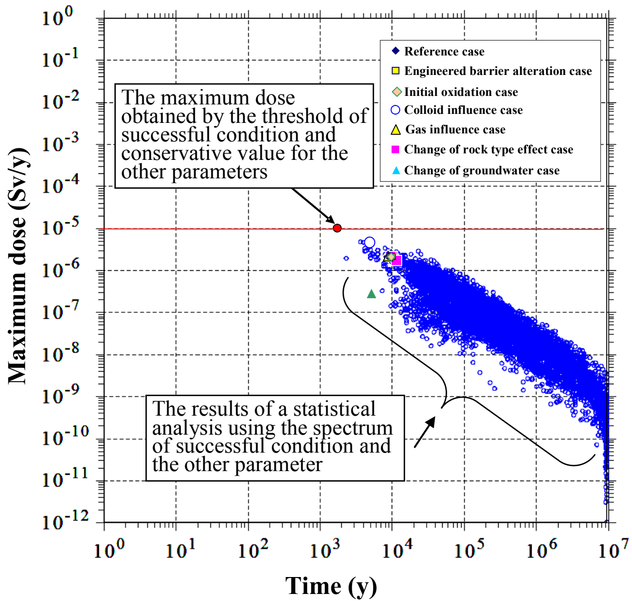

Figure 16. Result of comprehensive sensitivity analysis.

The maximum dose (red circle) obtained from the threshold of the successful condition and conservative values for all other parameters do not exceed the target dose (red line). This result represents the safety of the disposal system would not be compromised in the case where the successful condition is satisfied, even if the uncertainties of all parameters except parameters related to the successful condition are taken into account.

This approach was applied in the safety assessment of the disposal concept considered in TRU-2. It was found that hydraulic parameters significantly affect the maximum dose. If transmissivity, hydraulic gradient, host rock matrix porosity, distance of radionuclide transport, fault length and EBS design parameters were assumed to have reference values intended to be moderately conservative, even if the uncertainties of all other parameters are taken into account, the maximum dose was less than several tens of μSv y^{-1} and safety was not significantly compromised.

Furthermore, it was confirmed that, if a maximum acceptable target dose of 10 μSv y^{-1} is assumed and the successful condition is satisfied, safety is not compromised by the effects of engineered barrier degradation, colloids, gases and initial oxidation. It was also confirmed that the system's safety would not be compromised in the case that the geological environmental conditions were not as favourable as the reference conditions, if improvements in the performance of waste packages were included.

(2) Perturbation scenario

In the perturbation scenario, analytical cases for uplift/erosion, climate/sea-level change, initial defects in EBS components and formation of new migration pathways were evaluated. In many of the cases, the dose did not exceed 10 μSv y^{-1}. In cases such as the climate/sea-level change, which is assumed to imply relatively fast groundwater flow, or the scenario for the formation of a new transport path by well drilling and water sampling, the maximum dose was 100 μSv y^{-1}. However using risk theory, it was shown these are low-frequency events.

(3) Isolation failure scenarios

As an isolation failure scenario, uplift/erosion resulting in the repository approaching the ground surface and the accidental penetration of the repository by drilling were evaluated. The former was smaller than the latter. In the case of penetration by drilling, after dose conversion, the risk was shown to be below 10^{-6}–10^{-5} [y^{-1}] which satisfies the target safety standard in several foreign countries.

7. Alternative technologies for reducing uncertainties (*Chapter 7*)

In the groundwater migration scenario, it was shown that the performance of the TRU-waste repository is highly sensitive to the hydraulic conductivity of the geological environment and sorption distribution coefficients of the key nuclides I-129 and C-14 which are both high soluble. On the other hand, the alkaline alteration of bentonite and long-term effects of nitrates are still controversial issues. In case there is a need to deal with these issues, TRU-2 examined two alternative concepts which are still being developed and not currently integrated into the basic disposal concept:

- Improving safety margins for a wide range of geological environments by developing alternative engineered barrier technologies for immobilizing I-129 (e.g. in quartz) and confining C-14 (e.g. in ultra-low-permeable concrete);
- Minimising uncertainties by developing low-alkaline cement to reduce the alkaline alteration of bentonite and developing nitrate decomposition techniques to reduce the

long-term effects of nitrate/bituminized waste.

In all eight immobilisation techniques were studied for immobilizing I-129 in Group 1 and two kinds of advanced container for confining C-14 in Group 2 were assessed. This research is related to up-grading engineered barrier technology with the prospect of achieving nuclide retention performance for several tens of thousands of years.

It is expected that in future these alternative technologies will contribute to a greatly improved confidence in the geological disposal of TRU-wastes with significant optimized disposal concepts.

8. Co-location disposal with HLW as an optimization measure (*Chapter 6*)

In order to reduce costs and the burden on siting, a concept of co-locating HLW and TRU-waste disposal facilities (**Figure 17**) was examined. Heat generation from HLW, high pH constituents, nitrates and organic material from TRU-waste were identified as the important factors that have been determined as the critical reciprocal influences from HLW and TRU-waste disposal facilities. Knowledge of these influences was summarised and the effect of the separation distance between the two disposal facilities was analyzed. It was shown that these mutual influences could be avoided by establishing a separation distance between the two disposal facilities of several 100 metres. Additionally, to establish the technology of co-location disposal, the layout and engineering measures were evaluated.

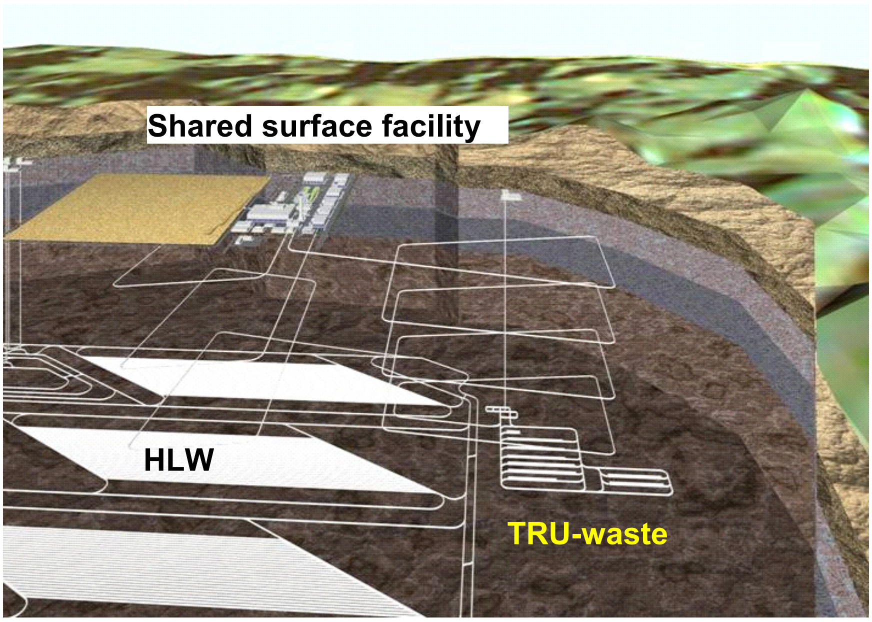

Figure 17. Example concept for co-located HLW and TRU-waste repositories in a single complex.

9. Conclusions (*Chapter 8*)

The main outcomes from project TRU-2 can be summarised as follows:

- I-129 from Group 1 gave the dominant dose in the Reference Case but this was less than regulatory guidelines in overseas PA reports and natural background dose radiation in Japan.
- The results of evaluations of the perturbation/isolation failure scenario analyses, showed risks below 10^{-6}–10^{-5} [y^{-1}], which is the target safety standard used in several foreign countries.
- Much uncertainty surrounds cement-bentonite interactions especially regarding the types of cement used, thermodynamic stabilities/kinetics of bentonite, mineral precipitation/dissolution rates, etc.
- There is also much uncertainty regarding the behaviour of nitrates in the deep geological environment particularly with respect to transitions in geological media, radionuclide solubility in solutions with high concentration of nitrates.
- Uncertainty could be reduced through the development and application of alternative technologies for immobilizing and confining the key radionuclides (I-129 and C-14), development of low-pH cement to reduce the alkaline alteration of bentonite, and development of nitrate decomposition techniques to reduce the long-term effects of nitrate/bituminized waste.
- TRU-2 has demonstrated the feasibility of disposing of TRU-waste at shallow, intermediate and deep geological depths.
- Feasibility could also be improved through the concept of co-location disposal with a HLW disposal facility; a concept that has already been demonstrated in many other countries (e.g. Belgium, France, Germany, Switzerland).

Whilst uncertainties and outstanding issues were identified, these were not considered as insurmountable obstacles for making a safety case.

Appendix

Explanation of abbreviations for key organisations connected to TRU-waste and HLW disposal in Japan and URLs (alphabetical order):

AEC: Japan Atomic Energy Commission, http://aec.jst.go.jp/jicst/NC/eng/index.htm

AIST: National Institute of Advanced Industrial Science and Technology, http://www.aist.go.jp/index_en.html

ANRE: Agency for Natural Resources and Energy, http://www.enecho.meti.go.jp/english/index.htm

AREVA NC (France): formerly COGEMA, http://www.areva-nc.com/

BNG Sellafield (UK): British Nuclear Group Sellafield Ltd. (formerly part of BNFL), http://www.britishnucleargroup.com/

CRIEPI: Central Research Institute of Electric Power Industry, http://criepi.denken.or.jp/en/

FEPC: The Federation of Electric Power Companies of Japan, http://www.fepc.or.jp/english/

JAEA: Japan Atomic Energy Agency, http://www.jaea.go.jp/english/index.shtml

JAPC: The Japan Atomic Power Company, http://www.japc.co.jp/english/index.htm

JNES: Japan Nuclear Energy Safety Organization, http://www.jnes.go.jp/english/index.html

JNFL: Japan Nuclear Fuel Limited, http://www.jnfl.co.jp/english/index.html

J-POWER: http://www.jpower.co.jp/english/index.html

KEPCO: Kansai Electric Power Company, http://www.kepco.co.jp/english/index.html

METI: Ministry of Economy, Trade and Industry, http://www.meti.go.jp/english/index.html

MEXT: Ministry of Education, Culture, Sports, Science and Technology, http://www.mext.go.jp/english/index.htm

NEA: Nuclear Energy Agency, http://www.nea.fr/welcome.html

NIRS: National Institute of Radiological Sciences, http://www.nirs.go.jp/ENG/nirs.htm

NISA: Nuclear and Industrial Safety Agency, http://www.nisa.meti.go.jp/english/index.htm

NSC: Nuclear Safety Commission of Japan, http://www.nsc.go.jp/english/english.htm

NUMO: Nuclear Waste Management Organization of Japan, http://www.numo.or.jp/english/index.html

RWMC: Radioactive Waste Management Funding and Research Center, http://www.rwmc.or.jp/

TEPCO: Tokyo Electric Power Company, http://www.tepco.co.jp/en/index-e.html