JNC'S RESEARCH AND DEVELOPMENT TO ENHANCE THE CONFIDENCE OF GEOLOGICAL DISPOSAL TECHNOLOGY OF HLW: STUDY IN THE PHASE OF SURFACE-BASED INVESTIGATION OF TWO URLS OF JAPAN

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ABSTRACT

JNC has promoted the research and development on disposal technology to contribute to the implementation and safety regulation in the implementation phase. The field of the R&D covers geological environment, engineering of geological disposal and performance assessment. As to the two underground laboratories (URLs), surface-based investigations have been carried out and the constructions of both have already started. On the basis of these investigations, geologic environmental models have been developed from geological, hydrogeological, geochemical and mechanical aspects. The study on natural phenomena such as volcanism and faulting has been conducted. In the above ground research facilities, the development of advanced models, databases for the long-term evolution of the near-field and engineering technologies has been carried out. These studies focus on development of databases for the engineered barrier system (EBS), long-term coupled processes occurring in the near-field, demonstration of engineering technologies and the applicability of specific EBS design techniques to the URL environment. In terms of safety assessment methodologies, development of relevant databases and advanced safety assessment models and techniques has been carried out. Taking into account the results from studies of the deep geological environment, long-term research/assessment models have been refined through improved mechanistic understanding of individual processes such as radionuclide migration. Documentation of the studies conducted in the surface-based investigation phase at the URLs is envisaged for 2005.

INTRODUCTION

Japan Nuclear Cycle Development Institute (JNC) and its predecessor - the Power Reactor and Nuclear Fuel Development Corporation (PNC) - conducted comprehensive research and development on geological disposal of HLW and prepared the second progress report (referred to as H12 1) which documents R&D achievements up to that time. The "Law on Final Disposal of Specified Radioactive Waste" came into force in June 2000; it takes into account the technical achievements documented in the H12 report. According to the government program, repository operation will start in the 2030s. Pursuant to the new Law, the Nuclear Waste Management Organization of Japan (NUMO), with responsibility for implementing geological disposal of high-level waste (HLW), was established in October 2000 and the program moved into the implementation phase. This paper describes the progress of JNC's R&D activities in this phase.

JNC's R&D PROGRAM IN THE IMPLEMENTATION PHASE

In accordance with the new framework specified by the Atomic Energy Commission of Japan (AEC) 2, JNC continues to be responsible for R&D activities aimed at enhancing the reliability of disposal technologies and establishing safety assessment methodologies and associated databases 345. JNC has thus actively promoted R&D aimed at contributing to the implementation of disposal and to the content of the safety regulations formulated by the Nuclear Safety Commission of Japan (NSC).

In the JNC's program the fields of research and development on geological disposal technology are classified into three, i.e. studies of the geological environment, engineering development of the geological disposal system and repository performance assessment (PA). These R&D program are being executed with two main goals, i.e. (1) applicability of disposal technologies to the actual geological environment and (2) understanding the long-term behavior of the geological disposal system.

JNC has conducted the R&D studies with above-ground research facilities mainly in the Engineering-scale Test and Research Facility (ENTRY) and the Quantitative Assessment Radionuclide Migration Experimental Facility" (QUALITY) at Tokai, Ibaraki Prefecture. These studies are linked with the geological/hydrological/geochemical/mechanical data obtained from the URLs program. The ENTRY was designed for performing a series of relatively large-scale and non-radioactive experiments and to assess the performance of the multibarrier system 67. In this facility, JNC has conducted R&D on scenario development, model development & validation and data acquisition for chemical, hydrological, mass transport and thermo-hydro-mechanical-chemical (THMC) coupled processes which are assumed to occur under geological disposal conditions. PA studies of the multibarrier system supported by an extensive computer analysis have also been carried out in the ENTRY with the use of both mechanistic and assessment models and the databases developed from laboratory experiment, in-situ experiments and geological environment studies. The QUALITY was designed to obtain basic data concerning the chemical properties and migration behavior of radionuclides under geological disposal conditions 8. This facility has atmospheric-controlled chambers to simulate the chemical conditions of the deep underground environment. It also has high-resolution analytical equipments for analyzing rocks and measuring radionuclide tracers in solutions, etc.

JNC has also promoted the program of two URLs 91011: one at Mizunami city in Gifu prefecture in crystalline rock with fresh groundwater and the other at Horonobe town in Hokkaido in sedimentary rock with saline groundwater with a view to confirming the reliability of investigation and assessment techniques for geological environment. These URLs are classified as purpose-built (generic) URLs and thus are distinct from on-site (site-specific) URLs, which may be constructed at potential waste disposal sites. Figure 1 shows the locations of JNC's R&D facilities for geological disposal technology research.

Investigations of the geological environment at the URL sites will be conducted in a stepwise manner in three phases planned over a period of 20 years. Investigations from the surface (Phase 1) will be followed by excavation of shafts and drifts (Phase 2) and, finally, detailed investigations in the underground facility (Phase 3). In each phase, information on the geological environment will be collected, evaluated and verified and the volume of data will increase as the program moves forward. The investigation and evaluation methodologies used will be iteratively improved and integrated as necessary and the applicability of engineering technologies for the design and

construction of an underground facility will be verified. The results of R&D in each phase will be documented as progress reports to be provided for the corresponding phase of disposal program from the viewpoints of implementation and safety regulation. The results for the phase-1 are planned to be documented in 2005. The annual progress of the R&D in phase-1 has been published as annual reports 171819.

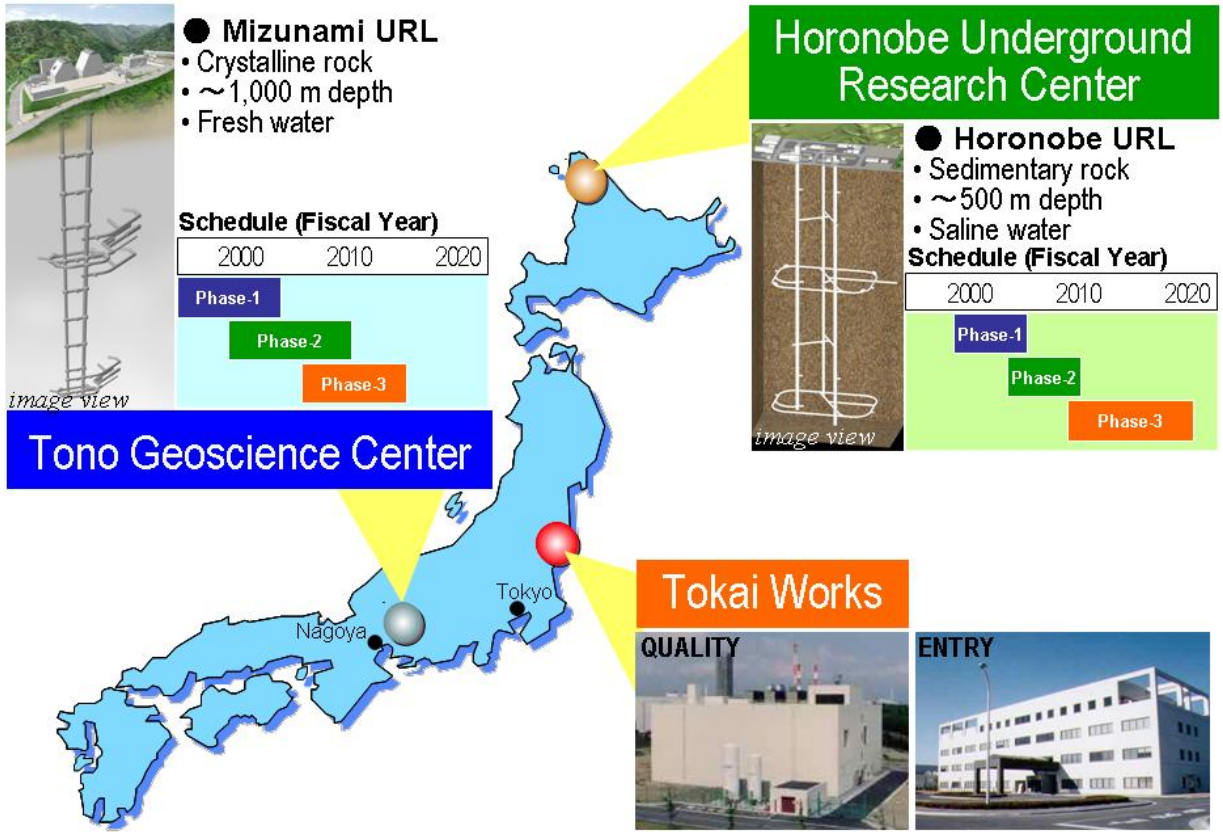

Fig. 1. JNC's R&D facilities for HLW disposal

RESULTS FROM THE SURFACE-BASED INVESTIGATION PHASE (PHASE 1) IN THE URLS

JNC's surface-based investigations include seismic and electromagnetic surveys on a scale of several tens of km^2 and boreholes to depths of 500 to 1000 m in the Tono (around the Mizunami URL site) and Horonobe URL areas. Based on these investigations, models of the geological environment have been developed taking into account geological, hydrogeological, geochemical and mechanical aspects.

Case studies have been conducted to investigate and model natural phenomena such as volcanism and faulting in terms of their effect on the long-term stability of geological environment in Japan. The nationwide databases documented in the H12 reports have been extended and improved. Uranium deposits in the Tono area have also been studied as a natural analogue for uranium migration, as a basis for research on the long-term stability of the geological environment.

Mizunami URL Project (MIU Project)

The MIU project commenced in 1996. Initial research activities were carried out at the Shobasama

site owned by JNC. In January 2002, the site for the URL facilities was relocated to the MIU construction site, located on land owned by Mizunami City approximately 2 km southeast of the Shobasama site. Initial investigations at the Shobasama site included literature surveys and surface-based investigations, including geophysical surveys and deep borehole investigations (4 boreholes), with models of the geological environment being constructed and groundwater flow simulations carried out 12. Following relocation of the site, the surface-based investigations at the MIU construction site began in March 2002 13. So far, the work carried out includes geophysical surveys (reflection seismic and vertical seismic profiling) and investigations in 4 new shallow boreholes (100 m to 200 m depth). A new deep borehole project (1,300 m depth) began in March 2003 at the MIU site 14. It is planned to complete the Phase 1 surface-based investigations at the beginning of 2005.

Construction of the Mizunami URL began in July 2002. The MIU site has an area of approximately 7.5 ha. According to the current design, the Mizunami URL will consist of two 1,000 m deep shafts, namely the main shaft (ø 6.5 m) and the ventilation shaft (ø 4.5 m). There will be two main experimental stages: the bottom stage at a depth of 1,000 m and the middle stage at a depth of approximately 500 m. In addition, sub-stages consisting of horizontal galleries will be constructed every 100 m to connect the two shafts. Shaft excavation commenced in July 2003 and, as of October 2004, entrance structures to the shafts had been constructed and shafts had been excavated to a depth of 50 m. Construction of the Mizunami URL is expected to be completed around 2010.

Geology of the Mizunami Area

The geology of the research area consists mainly of Cretaceous granitic rocks (Toki Granite) and Miocene (Mizunami Group) and Pliocene (Seto Group) sedimentary rocks. The E-W-striking Tsukiyoshi Fault crosscuts the Toki Granite and the Mizunami Group. Uranium mineralization occurs in the basal part of the Mizunami Group. The Mizunami Group unconformably overlies the Toki Granite. The Mizunami Group has been divided into four formations and shows evidence of several marine transgressions. The Seto Group consists mainly of gravels of pre-Tertiary rock. The Tsukiyoshi Fault, with a southerly dip of 60 to 70° and a reverse displacement of about 30 m, consists of a cataclastic zone ranging in thickness from 10 to 20 m; it is bordered by an associated fracture zone around 100 m thick on each side.

Current Status of Investigations

At the MIU site, lineament analyses, geological mapping, reflection seismic surveying, existing (DH-2) and new shallow borehole (MSB-1, 2, 3 and 4) investigations and a new deep borehole (MIZ-1) project were carried out up to October 2004. Crosshole tomography between MIZ-1 and DH-2 and vertical seismic profiling (VSP) in MIZ-1 were completed by the end of 2004. Improvement of the geological model is ongoing based on input from the above investigations. The current geological model is shown in Fig. 2.

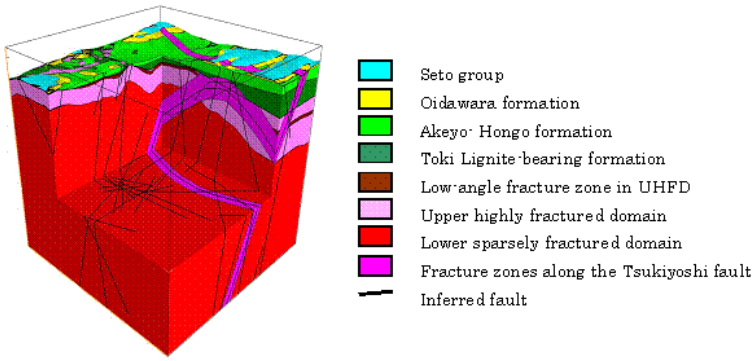

Fig. 2. Geological model based on the results of the Mizunami borehole investigations

Data on the hydraulic conductivities of the Toki Granite obtained from hydraulic tests are shown in Fig. 3. Fig. 3(a) shows hydraulic conductivity profiles from 11 boreholes drilled for the Regional Hydrogeological Study (RHS) project 15. These indicate that conductivity decreases with depth and that a possible boundary is present at around 400 m depth; this is consistent with the boundary between an Upper Highly Fractured Domain (UHFD) and a Lower Sparsely Fractured Domain (LSFD) defined from the geological information. The mean hydraulic conductivity in the UHFD is in the order of 10^{-8} m/s, while in the LSFD the value is in the order of 10^{-9} m/s (Fig. 3(b)). One of the main aspects of characterizing the hydrogeological environment in fractured crystalline rock is to evaluate the hydraulic properties of faults and fracture zones.

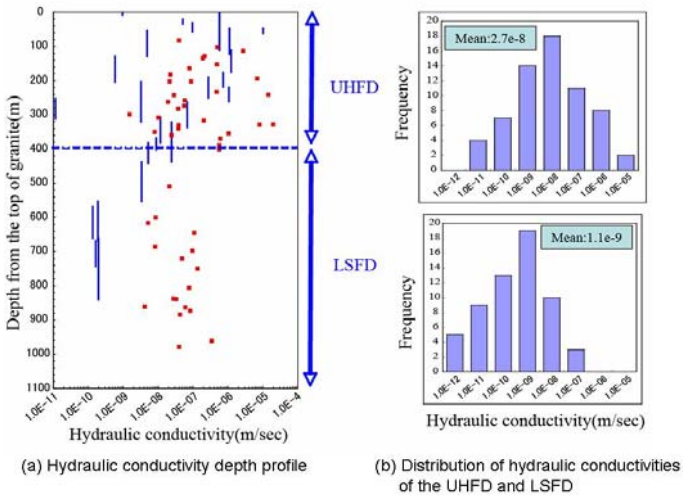

Fig. 3. Hydraulic conductivities of the Toki Granite

Groundwater in and around the MIU construction site was classified into a Na-Ca-HCO3 type in the upper sedimentary rocks (mainly the Akeyo and Hongo Formations) and a Na-(Ca)-Cl type in deeper, older sedimentary rocks (Toki lignite-bearing Formation) and the granite. The Na-Ca-HCO3 groundwater includes considerable amounts of silica and sulphate due to the weathering of the surface zone. In granitic groundwater, the trend of gradually increasing Cl concentration with depth changes at about 400 m below sea level (mbsl). The rapid increase in Cl concentration at depths greater than 400 mbsl may be indicative of relatively slow groundwater flow conditions compared to flow at levels shallower than 400 mbsl. The hydrogeochemical

conditions around the MIU site are controlled to some extent by the geological structure.

Physical and mechanical tests were performed on core samples from the DH-2 borehole (500 m depth) drilled near the MIU site. Investigations are also ongoing in the MIZ-1 borehole. These include a full range of physical and mechanical tests (effective porosity measurements, elastic wave velocity measurements, unconfined compressive tests, confined compressive tests, etc.), in-situ stress measurements (hydraulic fracturing tests) and additional laboratory tests on cores, such as AE (Acoustic Emission), DSCA (Differential Strain Curve Analysis), etc. Fig. 4 shows a comparison of laboratory tests on core samples from the MIZ-1 borehole (~500 m) and the DH-2 borehole (~500 m). Anisotropic deformability of core specimens is investigated using the DSCA method.

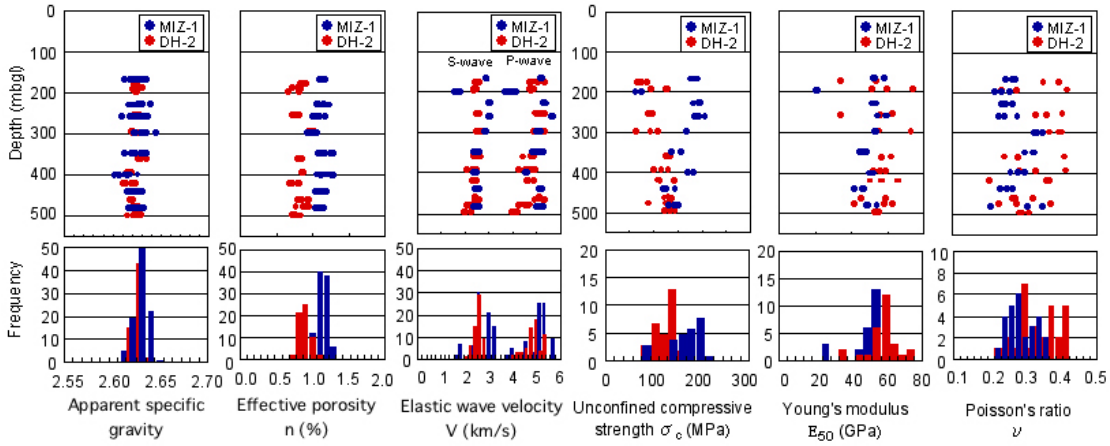

Fig. 4. Physical/mechanical properties of core samples from the MIZ-1 & DH-2 boreholes

The results of the above investigations, observations and analyses will be reflected in the final geological and hydrogeological model constructed during the surface-based investigation phase.

Horonobe URL Project

In the Horonobe URL Project, surface-based investigations have been ongoing since 2001 16. Along with the regional investigations, an area for intensive site investigations (URL area) was identified. The land for construction of the facility (URL site) was then acquired within the URL area and site preparation began in July 2003. The investigations provided a wealth of data which improved understanding of the geological environment in the area. The main investigation methods included helicopter-borne electromagnetic, magnetic and gamma spectrometry surveys, ground geophysical surveys (magnetotelluric methods (MT/AMT) in 2001, 2003, reflection seismic survey in 2002), geological mapping, shallow borehole investigations (including methane measurements), observation of precipitation, evapotranspiration and run-off (river flux) and deep borehole investigations.

The URL site has an area of approximately 19.1 ha. According to the present conceptual design, the Horonobe URL will consist of two 500 m deep access shafts (ø 6.5 m), a ventilation shaft (ø 4.5 m) and two experimental stages, the bottom stage at 500 m and the middle stage at 250 m depth. Shaft excavation will start in 2005. In the area, methane is generally dissolved in the groundwater and it is therefore very important to excavate shafts and drifts safely under conditions with methane gas inflow. Construction of the Horonobe URL is expected to be completed around 2010.

Geology of the Horonobe Area

The geology of the Horonobe area consists of Neogene sedimentary sequences (in ascending order: Souya coal-bearing Formation, Masuhoro Formation, Wakkanai Formation, Koetoi Formation and Yuchi Formation); these are underlain by igneous and Palaeogene to Cretaceous sedimentary basement. There are several faults (the Omagari Fault and Nukanan fault zone) in the area of interest. The Wakkanai and Koetoi Formations, which are Neogene argillaceous sedimentary formations, have been selected as the host geology for the URL. The Omagari Fault was active until the early Quaternary and is thought to have a maximum vertical displacement of over 1,000 m. Present fault activity is thought to have shifted to the western side of the Omagari Fault. This region is located in an oil/gas field and associated exploration work, including deep borehole investigations, has been conducted.

Current Status of Investigations

The total number of deep boreholes drilled by the end of March 2004 was 8 (depths between 470 m and 720 m). Hydraulic monitoring systems have been installed in the existing deep boreholes and are preparing to start recording baseline hydrogeological and hydrogeochemical conditions before the start of URL construction. In addition, seismic and electromagnetic active monitoring systems, called ACROSS (Accurately Controlled Routinely Operated Signal System), have been developed. As the last activity of the surface-based investigations, 3 borehole projects and a detailed reflection seismic survey are presently ongoing. The seismic survey is expected to provide a clearer image of the Omagari Fault.

The host argillaceous formations consist of porous diatomaceous mudstones. The Koetoi Formation in particular has a maximum porosity of around 60 %. The even more compacted mudstone of the Wakkanai Formation has a porosity of 30 to 40 %. The mudstones in this area also have fairly frequent fractures, which seem to be an effect of the Omagari Fault. The mudstones are classified as soft rock. For instance, the mudstone of the Koetoi Formation has an average unconfined compressive strength of about 5 MPa. On the other hand, that of the Wakkanai Formation varies from less than 10 MPa to more than 30 MPa and the average is around 15 MPa. Some of the variation is possibly due to the heterogeneous nature of the formation (Fig. 5).

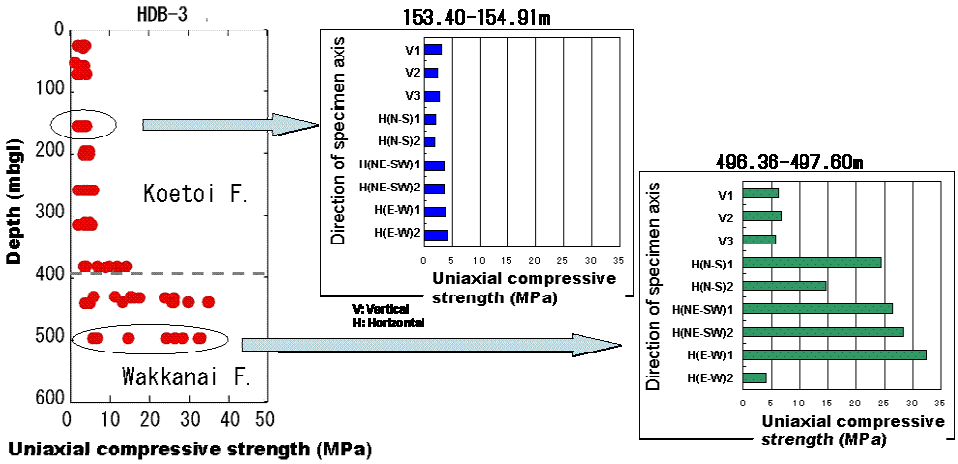

Fig. 5. Anisotropy of rock mechanical properties

The hydraulic conductivity of the mudstone measured in in-hole hydraulic tests is less than 10^{-7} m/s, with the exception of some data obtained from fracture zones in the Wakkanai Formation in shallower sections. The vertical distribution of hydraulic conductivity shows a depth-dependence, particularly for fracture zones of the Wakkanai Formation (Fig. 6). Overpressure was observed in a deeper section of the Wakkanai Formation in a borehole drilled in the south of the area.

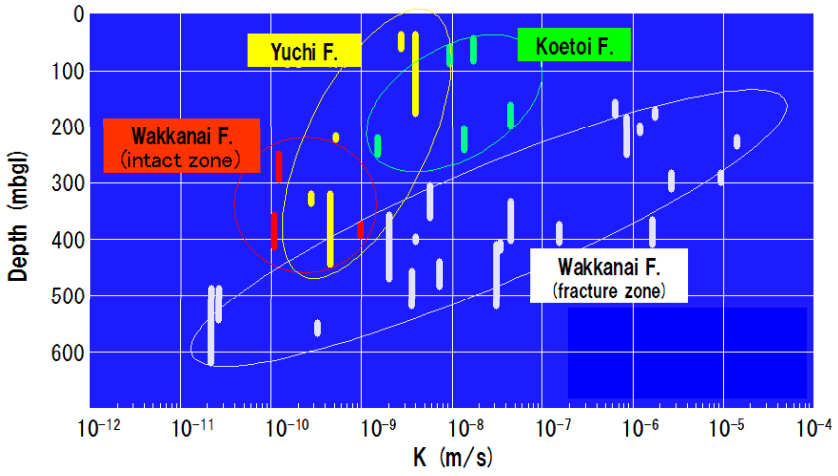

Fig. 6. Depth profile for hydraulic conductivity measured in in-hole hydraulic tests

Groundwater samples are collected from packed-off sections in the boreholes and by squeezing of drill-cores. Groundwater can be classified into three types, namely deep Na-Cl saline water, very shallow meteoric fresh water and a mixture of these two. The salinity of the deep saline water appears to be inversely proportional to the degree of diagenesis of the host rock. Despite such differences in total salinity, the oxygen and hydrogen isotopic data for all saline waters are much the same. The oxygen and hydrogen isotopic data also support the mixing of the deep saline water and shallow fresh water. Methane is generally found dissolved in groundwater.

After 4 years of investigations, the understanding of the geological environment of the area has advanced considerably. One important task still to be performed is to synthesize the data to provide a comprehensive, multidisciplinary explanation (model) of the geological environment. Also, in-situ experiments are planned to improve understanding of the near-field system and the applicability of disposal technologies. The former consists of experiments on THMC behavior, creep behavior, gas migration, overpack corrosion, cement effects and solute transport; the latter deals with transport and emplacement of the engineered barriers, performance of low-alkaline concrete and sealing of shafts and tunnels.

ENGINEERING OF THE REPOSITORY SYSTEM AND PERFORMANCE ASSESSMENT

Improving the Reliability of Disposal Technologies

Development of advanced models and databases for the long-term evolution of the near-field and for the demonstration of engineering technologies has been carried out using the ENTRY facility and the URL at Horonobe. The studies are focused on development of databases for the engineered barrier system (EBS), long-term coupled processes occurring in the near-field, demonstration of engineering technologies and assessment of the applicability of the EBS design techniques to the

URL.

Development of databases for the EBS

Existing databases on the corrosion of candidate overpack materials, including corrosion mechanisms and long-term corrosion rates, have been extended and refined to confirm the reliability of the containment lifetimes of the materials concerned. The databases for buffer materials also have been further developed to increase the reliability of buffer material design. In addition, it is necessary to develop the knowledge, assessment techniques and databases required for establishing the technical standards applied to ensure the performance of the EBS.

The corrosion lifetime of the carbon steel overpack has been refined based on experimental data, taking into consideration a wide range of geological environmental conditions in Japan. Based on immersion tests of carbon steel in the buffer material performed under anaerobic conditions, corrosion rates of about 0.2 - 2 μm/y have been determined 2. These corrosion rates are roughly consistent with the long-term average corrosion rates determined for archaeological iron artifacts which had been buried in soil for several hundred years 21. This confirms that the corrosion rate of 10 μm/y used in the lifetime assessment by JNC 1 was sufficiently conservative compared with realistic corrosion rates.

The effects of the high-pH plume resulting from use of cementitious materials and of corrosion products (Fe_3O_4) on the long-term corrosion rate of the carbon steel overpack have been studied in detail and are found not to be significant 2223.

Regarding the fundamental characteristics of the buffer material, several experiments have been carried out to study the influence of saline groundwater on the hydraulic, swelling and mechanical properties. It was found that hydraulic conductivity increases with increasing temperature and a correlation between effective clay density and intrinsic permeability was determined. Fundamental characteristics of the buffer material acquired by the end of 2003 were compiled and developed into a database 24.

Studies on long-term, coupled processes occurring in the near-field

The models and databases on long-term EBS behavior, including deformation and degradation, have been refined to increase the reliability of EBS performance. A typical study involves developing numerical experimental techniques for predicting long-term THMC coupled processes. These studies provide the technical basis for more realistic repository design and associated PA.

To develop a model for extrusion of buffer material into fractures under saline groundwater conditions, extrusion experiments for bentonite with artificial seawater have been conducted (Fig. 7). Based on these experiments, the extrusion behavior of the buffer material is found to depend on the dry density of the bentonite, the mixing ratio with silica sand, fracture width and flow velocity in the fractures. The data for bentonite density distribution along the fracture, which can be used for validation of the extrusion model, have been obtained by X-ray computed tomography (X-ray CT) 25.

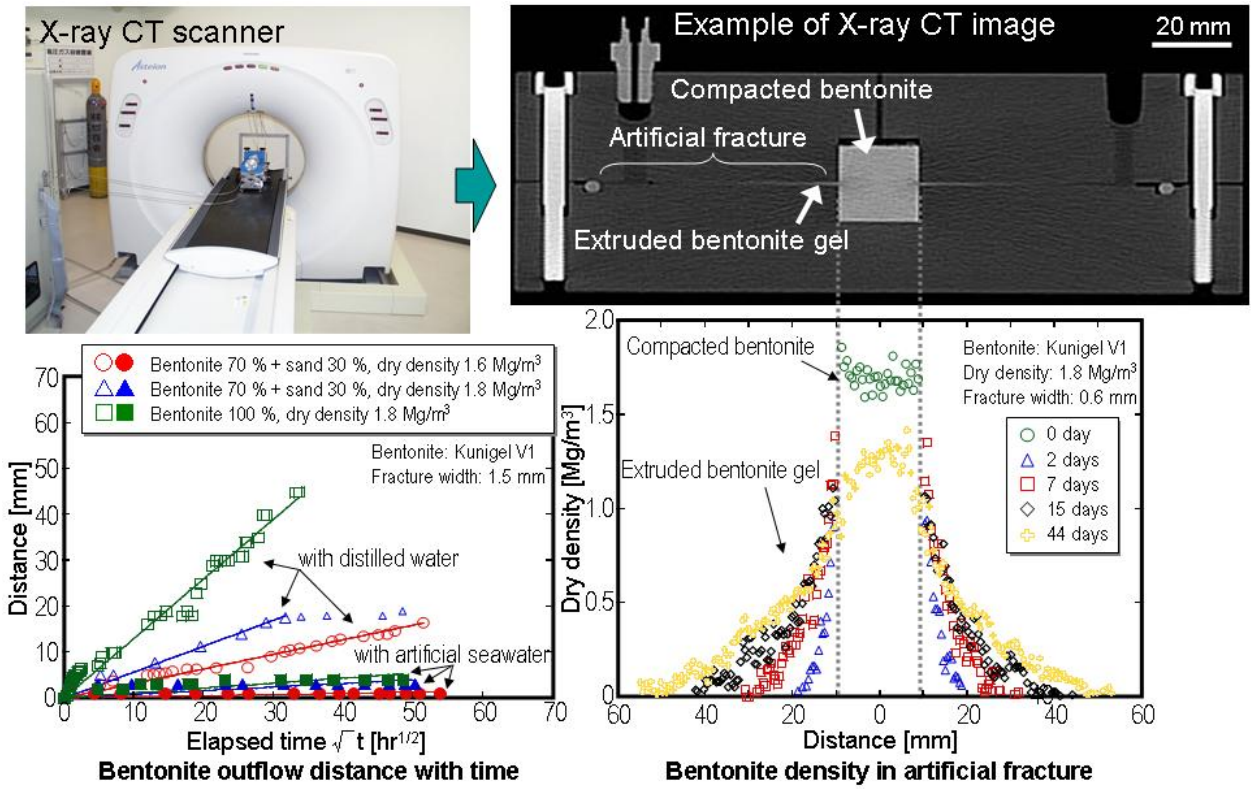

Fig. 7. Experimental results of the bentonite extrusion study

Work has also been initiated on a numerical experiment on coupled THMC processes in the near-field, with the aim of predicting long-term evolution. The main objective of such experiments is to provide confidence in PA by pre-closure monitoring and to predict the near-field behavior for long-term PA by including the near-field chemical evolution. These approaches reduce the gap between laboratory and in-situ experiments and associated PA and will consequently increase confidence in PA results. The THMC model has undergone preliminary verification through the DECOVALEX Project (International co-operative project for the DEvelopment of COupled models and their VALidation against EXperiments in nuclear waste isolation) 26. With an advanced model taking account of THMC processes, preliminary numerical experiments were conducted for the EBS design adopted in the H12 project; it was found that the results are in agreement with those of H12 27.

To understand perturbation effects on the EBS, studies focusing on mechanical effects of fault movement on the EBS and gas migration through the buffer material have been carried out. Regarding the mechanical effects on the EBS, medium-scale tests and simulation analyses have been conducted to study mechanisms for mitigation of the stress caused by fault movement and subsequent effects on the integrity and stability of the EBS. Based on the results, if rock displacement corresponding to "C-class" fault movement is less than 80 % of the buffer thickness, it appears that the mechanical integrity of the overpack is not significantly affected. To understand the effects of gas migration through the buffer material, relevant tests were carried out to clarify gas migration behavior in the buffer material under saline groundwater conditions and to develop an appropriate model. The experiments showed that the breakthrough pressure of hydrogen gas for

saturated compacted bentonite is almost the same as the swelling pressure. Data on bentonite density re-distribution caused by gas migration, which can be used for model validation, are currently being obtained by X-ray CT.

To evaluate the long-term stability of the EBS components, natural analog studies have been conducted on long-term corrosion or degradation of natural volcanic glass, archeological metals and natural bentonite. As natural analogs for the carbon steel overpack, corrosion depths of archaeological iron artifacts buried in soil were analyzed using X-ray CT 21. The samples, which were buried for 130 to 1200 years, include nails, small knives, swords, axe heads, arrowheads, vessels and gas pipes. The soil and groundwater sampled with the artifacts were also analyzed and the correlation between corrosion behavior and environment conditions was studied. As a result, it was found that the average corrosion rates of the samples, which were buried in a slightly oxidizing to reducing environment, were 0.3-0.9 μm/y and hence that those used for overpack lifetime prediction by JNC 1 were conservative.

Demonstration of Engineering Technologies

The reliability of engineering technologies as they affect the performance of the repository system has been improved by conducting performance tests on tunnel seals in a foreign URL and by development of low-alkaline cement for the mechanical support of tunnels in soft rock.

As a candidate for low-alkaline cement, a high fly-ash content silica fume cement (HFSC) has been developed to prevent (or reduce) alteration of bentonite, localized corrosion of the iron overpack and alteration of rock due to the effects of hyperalkaline solutions generated from cementitious materials used for mechanical support of tunnels in soft rock. To demonstrate the application of the HFSC for tunnel construction, experiments such as shotcreting tests, compressive strength tests, measurements of decrease in pH and corrosion tests of re-bars have been carried out. The experiments indicated that the HFSC satisfies constructability requirements as a shotcreting material and demonstrates the necessary compressive strength for use in conventional tunnel construction. It has also been found that measures against corrosion should be taken, since steel bars in the HFSC tend to corrode more readily compared with those in ordinary cement materials.

Confirmation of Applicability of EBS Design Techniques to the URL

It is planned to demonstrate EBS design techniques within the framework of the JNC URL projects. It is necessary to examine the applicability of key EBS design techniques to the actual geological environment and to provide guidelines for data acquisition from the viewpoint of the EBS design. To achieve these objectives, design and experimental studies on the EBS have been conducted under the conditions of the geological environment at Horonobe. Based on these activities, a flowchart for EBS design has been developed and mechanical stability analyses of the tunnels have been conducted to select the relevant depth for a reasonable design of the EBS without a requirement for mechanical support 28.

Development of Advanced Safety Assessment Methods

To establish reliable safety assessment methodologies, it is necessary to develop relevant databases, advanced safety assessment models and supporting system understanding. Taking into

account the results of research on the deep geological environment, long-term research/assessment models have been refined through improved mechanistic understanding of individual processes such as radionuclide migration, taking into consideration the long-term evolution of the near-field environment.

Establishment of databases for nuclide migration

Based on the data obtained to date, JNC developed a thermodynamic database (JNC-TDB) 29 and a sorption database (JNC-SDB) 3031 for the safety assessment in the H12 reports 1. The applicability of the JNC-TDB for performing realistic analyses has also been analyzed in recent studies 32. To improve the database, it has been necessary to obtain reliable data for safety-relevant elements in alkaline solutions and saline water systems and to standardize data acquisition methods, particularly for sorption coefficients. Therefore, studies on the migration behavior of Se, Cs and tetravalent actinides (especially Np(IV)), which are considered to be important for the safety assessment, have been performed under reducing conditions in alkaline solutions and/or saline water systems.

For the determination of thermodynamic data, the solubility of Se and Np was studied under reducing conditions. The measured equilibrium constant between Se(cr) and SeO_3^{2-} at zero ionic strength ($K_{SeO3}^0 = [SeO_3^{2-}][H^+]^6[e^-]^4$) was slightly larger than that in the JNC-TDB 33. The solubility product of NpO_2(am) ($K_{sp}^0 = [Np^{4+}][OH^-]^4$) was obtained as shown in Table I 34. The equilibrium constant at zero ionic strength between NpO_2(am) and $Np(CO_3)_2(OH)_2^{2-}$ ($K_{122}^0 = [Np(CO_3)_2(OH)_2^{2-}]/[HCO_3^-]^2$) was slightly larger than that in the JNC-TDB and that between NpO_2(am) and $NpCO_3(OH)_4^{2-}$ ($K_{114}^0 = [NpCO_3(OH)_4^{2-}]/[CO_3^{2-}]$) was determined 35.

Table I. Solubility Product (K_{sp}) of NpO_2(am)

Ionic strength ($mol.dm^{-3}$)	log K_{sp}	Ref.
0.03 0	-53.3 ± 0.3 -54.5 ± 0.3	36
0.1 0	-54.4 ± 0.4 -56.4 ± 0.4	37
1.0 0	-53.1 ± 0.3 -56.2 ± 0.3	34

The distribution coefficient (Kd) of Cs and Np on various solids were investigated in sorption studies. It was suggested that sorption of Cs onto sedimentary rocks, including not only commercially available samples 38 but also samples from Horonobe drill-cores 39, was predominantly onto potassium-dominated sorption sites, e.g. illite. The Kd of Np(IV, V) for smectite decreased with increasing total carbonate concentration and the sorption of hydrolysis species and carbonate complexes of Np was preliminary investigated 4041. Furthermore, JNC has participated in the OECD/NEA Sorption Project and some sorption data of interest were analyzed using a combined model of ion-exchange and surface complexation 42.

A diffusion database (DDB) for rock has also been developed, in which diffusion coefficients published from 1980 to 1998 are summarized for crystalline and sedimentary rocks 43. In the

experimental study, the diffusion behavior of Se and Np was investigated. It was found that the apparent diffusivity (Da) of Se in compacted bentonite under reducing conditions was lower than that under oxidizing conditions, and increased with increasing silica sand content and temperature 44. Corrosion in compacted bentonite and its effect on diffusion of Np was also studied, with and without carbon steel, under reducing conditions. It was found that the corrosion of carbon steel created strongly reducing conditions which keep most Np in the low oxidation state, Np(IV), which has lower solubility and mobility than Np(V) 45.

Since August 2003, the JNC-TDB and JNC-SDB can be accessed through JNC's website 46. Related TDBs from the OECD/NEA TDB Project 47 are also available for a range of geochemical calculation codes 46.

Development of Advanced Safety Assessment Models

In order to enhance confidence in PA, JNC is investing considerable effort in understanding key phenomena and developing more realistic models, including hydrology, mass transport, groundwater and porewater evolution, colloid transport, effects of organic substances, biosphere assessment methodologies and methodologies for evaluating the impact of natural phenomena on system performance. These developments require understanding of relevant phenomena based on the experiments conducted in the ENTRY facility and the URLs, as well as on international collaborative research.

JNC has been studying two typical rock types, namely crystalline and Tertiary soft sedimentary rock, in modeling studies of groundwater flow and mass transport. For crystalline rock, a site-scale study using a nested model (a coupled discrete fracture network (DFN) and continuum model) is being conducted to accommodate surface-based investigations at the MIU construction site 48. A block-scale study (approx. 100 m) using a DFN model has been conducted for Äspö Hard Rock Laboratory data. Laboratory experiments on flow and transport in a single fracture 4950 and a fracture intersection are being conducted to study important processes and heterogeneity on the block scale. Diffusivities and porosities of fault gouge within fractures were obtained using the X-ray absorption imaging method 51 and high diffusivities of gouge indicate that this material could play an important role for PA and tracer experiments. Fracture intersections showed an elevated transmissivity 52. For Tertiary soft sedimentary rock, both regional and block scales have been studied. Modeling studies aimed at understanding the anomalous heads at Horonobe 53, density-driven groundwater flow and development of the sedimentary basin model to estimate heterogeneous sedimentary structures are being carried out on a regional scale in the Horonobe Project 54. Laboratory experiments on the effects of fractures using core and rock blocks are being carried out on the block scale 55; fractures in the Wakkanai Formation seem to control flow and transport even in soft sedimentary rocks.

Models of groundwater evolution 56 and of porewater chemistry in compacted bentonite have been developed. Direct pH measurements and experiments in highly compacted bentonite were carried out in the laboratory. Key thermodynamic data for geochemical elements and kinetic data for mineral dissolution have also been developed and compiled for geochemical modeling of groundwater evolution and porewater chemistry. Kinetic data are also compiled for mineral dissolution under high-pH conditions.

Experimental and theoretical studies have also been performed in order to develop a model of colloid-facilitated radionuclide transport and the effects of natural organic substances on

radionuclide migration. Sorption kinetics of radionuclides onto colloids and colloid filtration onto fractures were investigated and found to be important (Fig. 8) 57.

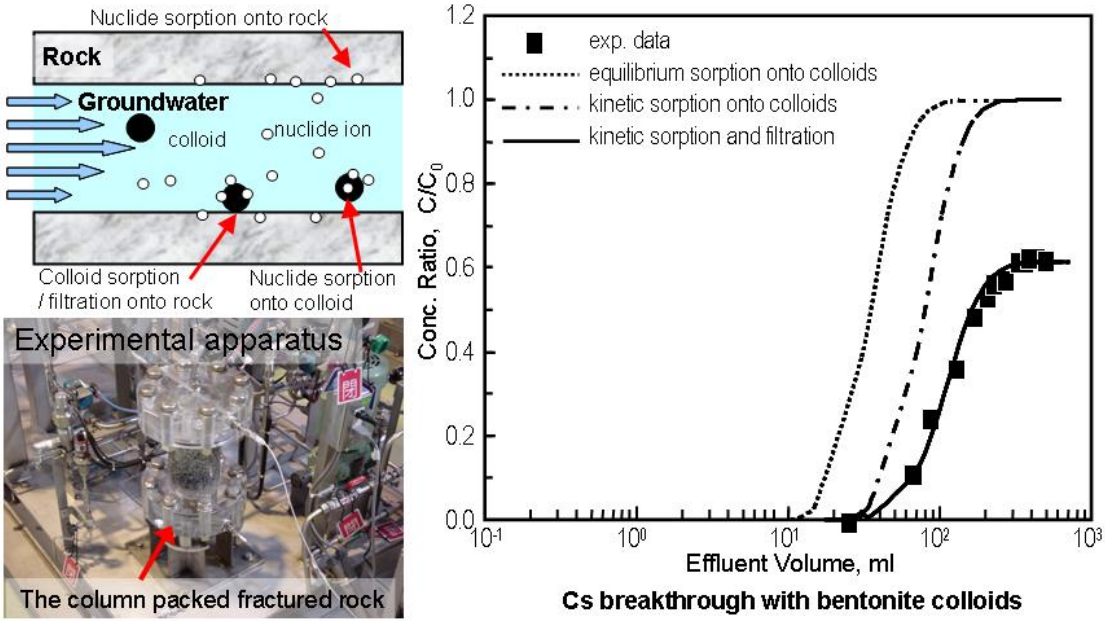

Fig. 8. Experimental and numerical results for solute transport with colloids in fractured rock

A batch method was applied to the sorption and desorption experiments of Cs and Np(IV, V) onto bentonite colloid to obtain distribution coefficients (Kd) and information on the reversibility of sorption 5859. It was found that at least the first 20 % of sorbed Cs was sorbed reversibly. JNC also participated in the Colloid and Radionuclide Retardation (CRR) experiment carried out in fractured crystalline rock at the Grimsel Test Site (Switzerland), as part of an international collaboration study from 1998 to 2003. Complexation behavior of Np(IV) with humic acid was investigated using a batch method and it was found that the solubility of Np(IV) increased with increasing concentration of humic acid. The apparent stability constant of Np(IV) complexation with humic acid was provisionally determined 60.

Improvement of biosphere models for evaluating radionuclide migration and radiological impacts on human beings has been carried out based on a "reference biosphere" concept as part of the international research projects BIOMOVS II (Biospheric Model Validation Study) and BIOMAS (Biosphere Modeling and Assessment). The methodology for setting the geosphere-biosphere interface (GBI) has been studied and an approach for identifying key biosphere model parameters and availability of these data through sensitivity analysis has been developed 61. Regarding complementary safety indicators, literature data for Japan have been collected and made available to the Co-ordinated Research Program organized by the IAEA.

To evaluate the potential impact of natural phenomena (volcanic activity, fault movement, uplift/erosion and climatic/sea-level change) on system performance, conservative scenarios, models and parameters have been used and a series of illustrative calculations have been carried out. To improve the assessment of the potential impact of natural phenomena on system performance, studies on the occurrence modes of natural phenomena and related impact patterns on system performance have been conducted systematically, taking into account results from case studies in Japan and scientific opinions of experts.

Establishment of Advanced Safety Assessment Methods

It is necessary to develop advanced safety assessment techniques, such as uncertainty analysis, scenario analysis and systematic information management.

Scenarios describing the possible behavior of the disposal system have been constructed by considering features, events and processes (FEPs) in a systematic manner to provide a framework for safety assessment. Construction of a matrix consisting of features and processes/events has been carried out to investigate the influences between them in the development of scenario analysis. This method will clarify the understanding of the scenario construction procedure and will be integrated into a modified framework for scenario analysis methodology.

Analyses of data and model uncertainty have been performed using the software package "GoldSim". Monte Carlo simulations, taking into account data uncertainty, confirmed the conservativeness and sufficiency of the data uncertainty analysis applied in the H12 total system performance analysis 162. Based on these simulations, a series of sensitivity analyses using multivariate analysis methods have been carried out and the parameters with a strong influence on total dose, such as transmissivity, were examined quantitatively. For model uncertainty, the focus has been on radionuclide transport in an excavation disturbed zone (EDZ). A new two-dimensional transport model through the EBS and EDZ has been developed. It was found that the maximum release rates of Cs-135 and Pu-239 in the EDZ calculated using the two-dimensional EBS/EDZ model were one and three orders of magnitude lower, respectively, than those derived from the one-dimensional EBS model. A possible retardation effect within the EDZ was thus indicated, although this effect was ignored in the H12 report 63.

JNC has developed the "JNC Geological Disposal Technical Information Integration System (JGIS)", which aims to facilitate integration and sharing of technical information between the areas of site investigation, repository design and safety assessment 64. JGIS is an archive system for technical information, in which a relational database is constructed to store information in the form of a flowchart which systematically represents the information structure, in line with the structure of research activities.

Confirmation of Applicability of Safety Assessment Methods to the URL

It is planned to compile and integrate the results of investigations conducted as part of individual R&D projects, based on the knowledge and information obtained in the URLs and other research facilities. It is also proposed to make rough evaluations of safety assessment techniques and to provide guidelines for surveying the geological environment.

The aim of studying the applicability of safety assessment methodologies is to evaluate the relevance of safety assessment models, related models and methodologies for the actual geological environment. JNC has been conducting field investigations in connection with the Mizunami and Horonobe URL Projects and has applied flow models and methodologies developed for crystalline and sedimentary rocks to the URLs. In addition, hydraulic properties such as hydraulic conductivity, porosity and dispersivity measured for drill-core samples have been compared with the results of field tests.

FUTURE PLANS

The construction of the URLs will be continued with the goal of their completion around 2010. The results will be documented as progressive reports in 2005 on the basis of the phase-1 investigation of the URLs and are intended to contribute to the preliminary investigation of candidate sites by NUMO and the preparation of safety regulations by the NSC.

CONCLUSIONS

The results of studies carried out since publication of the H12 reports in 1999 and up to 2003 have been documented for individual subjects as annual reports; these will form the basis for the Phase 1 reports to be prepared in 2005. As part of these results, data on nuclide migration obtained in the QUALITY facility, etc. were compiled as databases that are open to the public. The study on geological environment such as the URL program has progressed successfully.

REFERENCES

1. Japan Nuclear Cycle Development Institute (JNC), 2000. H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan: Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan. JNC Technical Report, JNC TN1400 2000-001-004.
2. Atomic Energy Commission of Japan (AEC), 2000. Long-Term Program for Development and Utilization of Nuclear Energy.
3. T. Kawata, S. Yamasaki, K. Shimizu and M. Shiotsuki, 2001. A New Scope of JNC's R&D Programme to Support Implementing Phase of Japanese HLW Disposal Programme. Proceedings of the International Conference on Back-End of the Fuel Cycle: From Research to Solutions (GLOBAL 2001). September 9-13, 2001, Paris, France, (CD-ROM).
4. Y. Nakagami, 2002. Waste Management Program in JNC and its Contribution to National Program. Proceedings of the 13th Pacific Basin Nuclear Conference (PBNC 2002), October 21-25, 2002, Shenzhen, China, p. 174.
5. M. Shiotsuki, T. Ishimaru, H. Igarashi, K. Shimizu, K. Ishiguro, H. Ishikawa, S. Takeda and S. Yamasaki, 2003. JNC's R&D on HLW Disposal to Enhance Technical Reliability and Confidence in the Implementation Phase, Proceedings of the 10th International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, USA, pp. 1025-1032.
6. Yamato, S. Masuda and H. Sakuma, 1992. The high level radioactive waste management program in Japan. Proceedings of the 3rd International High-Level Radioactive Waste Management Conference, April 12-16, 1992, Las Vegas, Nevada, USA, pp. 41-48.
7. M. Uchida, M. Yui and T. Kanno, 1997. ENTRY-2 Project - Contribution of Engineering Scale Laboratory Experiments to Performance Assessment of Geological Disposal. Proceedings of the International Conference on Future Nuclear Systems (Global '97), October 5-10, 1997, Yokohama, Japan, pp. 934-939.
8. H. Igarashi, K. Kawamura, K. Yamada, M. Yui and J. Ohuchi, 2000. Start of radioactive test in the "Quantitative Assessment Radionuclide Experimental Facility" (QUALITY) for fundamental studies on nuclide migration behavior in a deep geological environment.

Proceedings of Waste Management 2000 Symposium, February 27-March 2, 2000 Tucson, Arizona, USA.

9. N. Shigeta, S. Takeda, M. Matsui and S. Yamasaki, 2003. Underground Research Laboratories for Crystalline Rock and Sedimentary Rock in Japan. Proceedings of Waste Management 2003 Conference, February 23-27, 2003 Tucson, Arizona, USA, (CD-ROM).
10. T. Sato, S. Mikake, M. Sakamaki, K. Aoki, S. Yamasaki, N. Shigeta and S. Takeda, 2003. Underground Research Laboratories in Japan - What are the important factors for facilities design. Proceedings of the 9th International Conference on Environmental Remediation and Radioactive Waste Management (ICEM'03), September 21-25, 2003, Oxford, UK, ICEM03-4736.
11. S. Yamasaki, 2004. Underground Research Laboratory Program of Japan; Its Technical and Social Aspects. Abstracts of the 14th Pacific Basin Nuclear Conference (PBNC 2004), March 21-25, 2004, Honolulu, Hawaii, USA, pp. 166-167.
12. JNC, 2001. Mizunami Underground Research Laboratory Project: Results from 1996-1999 (revised edition). JNC Technical Report, JNC TN7400 2003-004.
13. JNC, 2002. Master Plan of the Mizunami Underground Research Laboratory Project. JNC Technical Report, JNC TN7410 2003-001.
14. K. Nakano, K. Amano, S. Takeuchi, K. Ikeda, H. Saegusa, K. Hama, N. Kumazaki, T. Iwatsuki, S. Yabuuchi and T. Sato, 2003. Working Program for MIZ-1 Borehole Investigations. JNC Technical Report, JNC TN7400 2002-008.
15. JNC, 2000. Regional Hydrogeological Study Project Results from 1992-1999 (Revised edition). JNC Technical Report, JNC TN7400 2003-007.
16. J. Goto and K. Hama, 2003. Horonobe Underground Research Laboratory Project: Plans for Surface-based Investigations (Phase 1) (Translated Document). JNC Technical Report, JNC TN5510 2003-002.
17. JNC, 2002. Annual Report of Research and Development on HLW Geological Disposal in 2001. JNC Technical Report, JNC TN1400 2002-003 (in Japanese).
18. JNC, 2003. Annual Report of Research and Development on HLW Geological Disposal in 2002. JNC Technical Report, JNC TN1400 2003-004 (in Japanese).
19. JNC, 2004. Annual Report of Research and Development on HLW Geological Disposal in 2003. JNC Technical Report, JNC TN1400 2004-007 (in Japanese).
20. N. Taniguchi, M. Kawasaki, S. Kawakami and M. Kubota, 2004. Corrosion Behaviour of Carbon Steel in Contact with Bentonite under Anaerobic Condition. Presented at European Corrosion Conference (EUROCORR 2004). September 12-16, 2004, Nice, France.
21. H. Yoshikawa, K. Ueno, T. Honda, S. Yamaguchi and M. Yui, 2003. Analysis of the Excavated Archaeological Iron Using Xray-CT. Proceedings of the 9th International Conference on Environmental Remediation and Radioactive Waste Management (ICEM'03), September 21-25, 2003, Oxford, UK, ICEM03-4776.
22. N. Taniguchi, M. Kawasaki, S. Kawakami and H. Suzuki, 2003. Propagation Behavior of Localized Corrosion of Carbon Steel in Alkaline Groundwater Environment, Proceedings of

the 13th Asian-Pacific Corrosion Control Conference, H-06.

23. N. Taniguchi, 2003. Effect of Magnetite as a Corrosion Product on the Corrosion of Carbon Steel Overpack, Prediction of Long Term Corrosion Behaviour in Nuclear Waste Systems, European Federation Corrosion Publications, Number 36, pp. 424-438.
24. H. Kikuchi and K. Tanai, 2003. Basic characteristics data base for buffer material (Set of Data). JNC Technical Report, JNC TN8450 2003-010 (in Japanese).
25. K. Matsumoto and K. Tanai, 2004. Extrusion and Erosion of Bentonite Buffer, JNC Technical Report, JNC TN8400 2003-035 (in Japanese).
26. http://www.decovalex.com
27. Neyama, A. Ito, M. Chijimatsu, Y. Ishihara, T. Hishiya, M. Yui, Y. Sugita and S. Kawakami, 2003. Prototype Code Development for Numerical Experiments on the Coupled Thermo-Hydro-Mechanical and Chemical Processes in the Near-Field of a High-Level Radioactive Waste Repository. Proceedings of the International Conference on Coupled T-H-M-C Processes in Geosystems (GeoProc2003), October13-15, 2003, Stockholm, Sweden, Part 1, pp. 358-363.
28. Y. Kurihara, M. Yui, K. Tanai, S. Kawakami, Y. Sugita, N. Taniguchi, T. Hirai, T. Ogawa, S. Aoyagi, H. Matsui, M. Nakayama and A. Fujishima, 2004. Design Studies on the Engineered Barrier System and on the In-Situ Experiments under the Condition of Geological Environment in Horonobe. JNC Technical Report, JNC TN8400 2004-006 (in Japanese).
29. M. Yui, J. Azuma and M. Shibata, 1999. JNC Thermodynamic Database for Performance Assessment of High-Level Radioactive Waste Disposal System. JNC Technical Report, JNC TN8400 99-070 (in Japanese).
30. T. Shibutani, M. Shibata and T. Suyama, 1999. Sorption Database of Radionuclides on Bentonite and Rocks. JNC Technical Report, JNC TN8400 99-050 (in Japanese).
31. T. Suyama and H. Sasamoto, 2004. A renewal of the JNC-Sorption Database (JNC-SDB). Addition of Literature Data Published from 1998 to 2003. JNC Technical Report, JNC TN8410 2003-018 (in Japanese).
32. M. Yui, D. Rai and M. Shibata, 2003. Applicability of the Thermodynamic Database of Radioactive Elements Developed for the Japanese Performance Assessment of a HLW Repository, Journal of Nuclear Science and Technology, Vol. 40, No.5, pp. 356-362.
33. Kitamura, M. Shibata and H. Kitao, 2004. Solubility Measurement of Iron-Selenium Compounds under Reducing Conditions. Materials Research Society Symposium Proceedings, 807, pp. 609-614.
34. K. Fujiwara and Y. Kohara, 2004. Solubility Product of Tetravalent Neptunium in the Reducing Condition. Presented at "The Fourth International Symposium on Advanced Science Research - Advances in Heavy Elements Microbiology Research (ASR2004)-." November, 2004, Tokai, Ibaraki, Japan.
35. Kitamura and Y. Kohara, 2004. Carbonate Complexation of Neptunium(IV) in Highly Basic Solutions, Radiochimica Acta, Vol. 92, pp. 583-588.
36. D. Rai, J. L. Swanson and J. L. Ryan. 1987. Solubility of $NpO_2 \cdot xH_2O$(am) in the presence

of Cu(I)/Cu(II) redox buffer. Radiochimica Acta, 42, pp. 35-41.

37. V. Neck, J. I. Kim, B. S. Seidel, C. M. Marquardt, K. Dardenne, M. P. Jensen and W. Hauser, 2001. A spectroscopic study of the hydrolysis, colloid formation and solubility of Np(IV). Radiochimica Acta, 89, pp. 439-446.
38. Kitamura, T. Tomura, M. Nakayama and H. Sato, 2004. Effect of Competitive Ions on Distribution Coefficient of Cesium onto Sedimentary Rocks. Presented at "2004 Spring Meeting of Atomic Energy Society of Japan", March, 2004, Okayama, Japan (in Japanese).
39. X. Xia, M. Shibata, A. Kitamura and G. Kamei, 2004. Model Development on Radionuclide Sorption in a Sedimentary Rock/Groundwater System (1): Effect Factor on Cesium Sorption onto a Sedimentary Rock under Saline Groundwater Condition. Presented at "2004 Spring Meeting of Atomic Energy Society of Japan", March, 2004, Okayama, Japan.
40. Kitamura, T. Tomura and T. Shibutani, 2002. Sorption Behavior of Neptunium onto Smectite under Reducing Conditions in Carbonate Media. Proceedings of the International Symposium NUCEF2001, October and November, 2001, Tokai, Ibaraki, Japan, JAERI-Conf 2002-004, pp. 659-666.
41. Kitamura and T. Tomura, 2003. Sorption Behavior of Neptunium onto Smectite under Reducing Conditions in Carbonate Media. JNC Technical Report, JNC TN8400 2003-025 (in Japanese).
42. T. Jintoku, M. Shibata, Y. Yoshida and T. Suyama, 2003. Sorption Modeling Study in the OECD/NEA Sorption Project. JNC Technical Report, JNC Technical Review, No. 21, 65-77 (in Japanese).
43. H. Sato, 1999. Diffusivity Database (DDB) for Major Rocks: Database for the Second Progress Report. JNC Technical Report, JNC TN8400 99-065.
44. H. Sato and S. Miyamoto, 2004. Diffusion Behavior of Selenite and Hydroselenide in Compacted Bentonite. Applied Clay Science, in press.
45. X. Xia, K. Idemitsu, T. Arima, Y. Inagaki, T. Ishidera, S. Kurosawa, K. Iijima and H. Sato, 2004. Corrosion of Carbon Steel in Compacted Bentonite and its Effect on Neptunium Diffusion under Reducing Condition. Applied Clay Science, in press.
46. JNC, 2003. JNC Thermodynamic and JNC Sorption Database. http://migrationdb.jnc.go.jp/.
47. R. Guillaumont, T. Fanghänel, J. Fuger, I. Grenthe, V. Neck, D. A. Palmer and M. H. Rand, 2003. Update on the Chemical Thermodynamics of Uranium, Neptunium, Plutonium, Americium and Technetium. North-Holland, Amsterdam.
48. Sawada, H. Saegusa and Y. Ijiri, 2004. Uncertainty Evaluation of Groundwater Flow by Multiple Modeling Approach at Mizunami Underground Research Laboratory Project, Japan. Proceedings of the 2nd International Symposium on Dynamics of Fluids in Fractured Rock, pp.232-236.
49. R. Saito, Y. Ohnishi, S. Nishiyama, T. Yano, A. Sawada and A. Takebe, 2004. Study on Hydraulic and Transport Characteristics of Rock Fracture using Lattice Gas Automaton. the 3rd Asian Rock Mechanics Symposium 2004, Japanese Committee for Rock Mechanics, Kyoto Japan, in preparation.

50. H. Sato and A. Takebe, 2004. Improvement to the tracer test method and application to the 10cm scale single Fracture Experiment. Proceedings of the 59th Japan Society of Civil Engineers Annual Meeting, CS1-014.

51. S.J. Altman, M. Uchida, V.C. Tidwell, C.M. Boney, and B.P. Chambers, 2004. Use of X-ray absorption imaging to examine the heterogeneous nature of diffusion in fractured crystalline rocks. Jour. Contaminant Hydrology Vol.69, Nos.1-2, pp.1-26.

52. K. Tetsu, A. Sawada and M. Uchida, 2003. An Evaluation of Hydraulic Permeability along the Fracture Intersection. Proceedings of the 58th Japan Society of Civil Engineers Annual Meeting, CS7-069.

53. K. Ito, K. Karasaki, K. Hatanaka and M. Uchida, 2004. Hydrogeological Characterization of Sedimentary Rocks with Numerical Inversion using Vertical Hydraulic Head Distribution – An Application to Horonobe Site –. Journal of Japan Society of Engineering Geology, Vol. 45, No.3, pp.125-134.

54. Hara and M. Uchida, 2004. Evaluating heterogeneity in mudstones based on geological process at Horonobe, Japan. Abstracts of the 66th European Association of Geoscientists & Engineers Conference and Exhibition, Paris, France, H007.

55. K. Hatanaka, M. Uchida, M. Shimo, H. Yamamoto and S. Kumamoto, 2004. Experimental Study for Evaluating Hydraulic and Transport Properties of Fractured Sedimentary Rocks. Presented at "2004 Spring Meeting of Atomic Energy Society of Japan", March, 2004, Okayama, Japan.

56. M. Yui, H. Sasamoto and R. Arthur, 2004. Geostatistical and Geochemical Classification of Groundwaters Considered in Safety Assessment of a Deep Geologic Repository for High-Level Radioactive Wastes in Japan. Geochemical Journal, Vol. 38, No. 1, pp. 33-42.

57. S. Kurosawa, M. Ibaraki, S. Ueta, M. Yui and H. Yoshikawa, 2004. Effects of Kinetic Radionuclide Sorption onto Colloids for Radionuclide Transport in Fractured Rock Experimental and Numerical Studies, Trans. At. Energy Soc. Japan, Vol. 3, No. 3, pp. 249-256 (in Japanese).

58. K. Iijima, T. Masuda and T. Tomura, 2004. Sorption Behavior of Cesium onto Bentonite Colloid. JNC Technical Review, No. 23, 51-61 (in Japanese).

59. T. Masuda, K. Iijima and T. Tomura, 2004. Sorption of Neptunium on Bentonite Colloids. Presented at "2004 Spring Meeting of the Atomic Energy Society of Japan", March, 2004, Okayama, Japan (in Japanese).

60. K. Iijima, S. Tobitsuka and Y. Kohara, 2004. Complexation Behavior of Np(IV) and Humic Acid. JNC TN 8400 2004-005 (in Japanese).

61. T. Kato, Y. Suzuki, H. Makino and M. Uchida, 2003. Biosphere Assessment for High-level Radioactive Waste Disposal: Modelling Experiences and Discussion on Key Parameters by Sensitivity Analysis in JNC. International Symposium on Radioecology and Environmental Dosimetry, Abstracts.

62. K. Wakasugi, E.K. Webb, H. Makino, Y. Ishihara, Y. Ijiri, A. Sawada, T. Baba, K. Ishiguro and H. Umeki, 2000. A Trial of Probabilistic Simulation for Reference Case in the Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan.

PSAM5 Vol.4, pp.1469-1475.

63. K. Wakasugi, H. Makino and S, Koo, 2004. Study on Retardation Effects in the Excavation Disturbed Zone Using a Two-Dimensional Radionuclide Migration Model. 2004 GoldSim International User Conference.

64. M. Uchida, H. Makino, K. Wakasugi and K. Shibata, 2003. Development of JNC Geologic Disposal Technical Information System – An approach to integrate and share technical information among safety assessment, repository design and site investigation. OECD/NEA Amigo project, First Workshop on building confidence using multiple lines of evidence, June 3-5, 2003, Yverdon-les-Bains, Switzerland.