



High-level radioactive waste disposal in China: update 2010

Ju Wang*

Beijing Research Institute of Uranium Geology, Beijing, 100029, China

Received 11 May 2009; received in revised form 10 October 2009; accepted 20 October 2009

Abstract: For geological disposal of high-level radioactive waste (HLW), the Chinese policy is that the spent nuclear fuel (SNF) should be reprocessed first, followed by vitrification and final disposal. The preliminary repository concept is a shaft-tunnel model, located in saturated zones in granite, while the final waste form for disposal is vitrified high-level radioactive waste. In 2006, the government published a long-term research and development (R&D) plan for geological disposal of high-level radioactive waste. The program consists of three steps: (1) laboratory studies and site selection for a HLW repository (2006–2020); (2) underground in-situ tests (2021–2040); and (3) repository construction (2041–2050) followed by operation. With the support of China Atomic Energy Authority, comprehensive studies are underway and some progresses are made. The site characterization, including deep borehole drilling, has been performed at the most potential Beishan site in Gansu Province, Northwestern China. The data from geological and hydrogeological investigations, in-situ stress and permeability measurements of rock mass are presented in this paper. Engineered barrier studies are concentrated on the Gaomiaozi bentonite. A mock-up facility, which is used to study the thermo-hydro-mechano-chemical (THMC) properties of the bentonite, is under construction. Several projects on mechanical properties of Beishan granite are also underway. The key scientific challenges faced with HLW disposal are also discussed.

Key words: geological disposal; high-level radioactive waste; R&D program; site selection; bentonite

1 Introduction

In 2007, the State Council of China approved the “Medium- to long-term plan for the development of nuclear power plants in China (2006–2020)” [1]. It indicates that the installed capacity of nuclear power plants (NPPs) should reach 40 GW by 2020, while some other NPPs providing a total capacity of 18 GW are under construction. According to the plan, the NPPs should provide 4% of the national capacity of electric power generation. This means that about 30 more nuclear reactors (1 000 MW-grade) need to be constructed before 2020. As a consequence, the total spent nuclear fuel generated from those NPPs during their life time will reach about 83 000 t HM. Those spent nuclear fuel should be stored, reprocessed, vitrified and disposed of safely.

For safe disposal of the HLW generated from the nuclear power plants and other nuclear facilities, the

former Ministry of Nuclear Industry proposed a preliminary long-term program and conducted research for the final disposal of HLW since 1985. In 2006, the first government document for HLW disposal, “R&D Guidelines for geological disposal of high-level radioactive waste”, was jointly published by the China Atomic Energy Authority, the Ministry of Environment Protection and the Ministry of Science and Technology, with the objective to build China’s high-level radioactive waste repository in 2050 [2].

In China, the China Atomic Energy Authority is the government organization in charge of developing plans and projects for HLW disposal. The Ministry of Environment Protection and its affiliated institute, the National Nuclear Safety Administration, are the regulatory bodies. The implementation activities related to radioactive waste disposal are currently managed by China National Nuclear Corporation, while Beijing Research Institute of Uranium Geology is the leading institute for research at the present stage.

It is estimated from the Chinese nuclear power development plan that the spent nuclear fuel accumulated from light water reactors will be 1 000 t by 2010, and 2 000 t by 2015. Later than 2020, about 1 000 t of

Doi: 10.3724/SP.J.1235.2010.00001

*Corresponding author. Tel.+86-10-64960515;E-mail:wangju9818@163.com
Supported by the China Atomic Energy Authority’s Special Program for Radioactive Waste Management and the International Atomic Energy Agency’s Technical Cooperation Project (IAE-TC Project CPR/9/026, CPR/4/024, CPR/3/008)

spent nuclear fuel will be accumulated each year. The spent nuclear fuel from CANDU reactors in Qinshan-III nuclear power plant will also produce about 200 t HM each year.

The spent nuclear fuel from light water reactors should be reprocessed first, followed by vitrification and final geological disposal. The preliminary repository concept is a shaft-tunnel system, located in saturated zones in granite. A pilot reprocessing plant will be put into operation in 2015. A commercial reprocessing plant is planned to be built in 2020 [2].

Over the past few decades, extensive research and development programs related to deep disposal of HLW have been conducted by international nuclear community. The underground research laboratories (URLs) are developed in several countries such as Sweden, Germany, Switzerland, Canada, Belgium and Japan to address the fundamental issues on whether or not a particular rock mass type would be suitable as a repository host rock. Compared with these nuclear nations, the current Chinese HLW disposal program is still at the preliminary stage, and some scientific and technological issues are needed to be further studied.

Recently, the issue of HLW disposal has attracted more attentions from Chinese scientists and government agencies. In 2009, the project “Strategic study of geological disposal of high-level radioactive waste in China”, led by Academicians Ziqiang Pan and Qihu Qian of the Chinese Academy of Engineering, was completed and its final report was published. It urged the government to realize the importance of geological disposal of HLW to the sustainable development of nuclear energy in China. It is also recommended that specific regulations for HLW disposal should be set up, specific fund should be raised, specific R&D facilities should be established, and international cooperations should be encouraged [3].

This paper first reviews the long-term plan for HLW disposal in China and summarizes the main research projects associated with laboratory study and site selection in the 3-step long-term plan for the geological disposal of HLW, and subsequently presents the efforts on conducting a series of studies for investigating site characteristics and analyzing engineered barrier behaviors. Furthermore, the key scientific challenges on the HLW disposal program in China are discussed. The information addressed here

represents the overall framework of this research program and describes some of developments of the program updated to the year of 2010. The aim of the study is to provide some engineering approaches and scientific thoughts for potential use in further research on disposal of HLW in deep rock.

2 Long-term plan for HLW disposal

In 1985, the former Ministry of Nuclear Industry of China proposed a research and development program for the deep geological disposal (DGD) of HLW [4]. The program included four phases: (1) technical preparation phase; (2) geological study phase; (3) in-situ test phase; and (4) repository construction phase. The objective of the program is to build a national geological repository in granite by 2040 that can dispose of vitrified waste, transuranic waste and HLW from decommissioning. Discussions on the long-term strategies were also published in 2004 [5–7].

In 2006, a 3-step long-term plan for the geological disposal of HLW, “R&D guidelines for geological disposal of high-level radioactive waste” (Table 1), was published.

In 2007, the State Council approved the “Medium- to long-term plan for the development of nuclear power plants in China (2006–2020)”, with the decision that “the construction of an underground research laboratory for geological disposal of high-level radioactive waste should be completed before 2020”.

The step 1 is a very important stage for the HLW disposal program. The following R&D projects will be carried out during this step.

(1) Site selection and site characterization: site selection for URL and repository; site characterization and site comparison in Beishan area, Northwestern China; site selection in other areas with granite or clay formations in Western China. The specific projects include studies of regional geological setting, seismic safety, future climate changes, future geological environment changes, geological and hydrogeological features, engineering geological studies, rock mass quality investigation, geophysical survey, borehole drilling and borehole tests. An important project is to review the site investigation results obtained from the 5 pre-selected areas in the past 20 years, especially from the Beishan site in the past 9 years.

Table 1 The 3-step long-term plan for geological disposal of HLW in China.

Step	Period	Milestone
Step 1: laboratory studies and site selection for HLW repository	2006—2020	Preliminary repository sites should be preliminarily selected with preliminary site characterizations completed. A site for an underground research laboratory (URL) is confirmed and its construction is completed. Preliminary technical capabilities in major areas are established through laboratory studies.
Step 2: underground in-Situ tests	2021—2040	Completion of site characterizations and confirmation of the final repository site. Completion of the most in-situ tests in the URL and establishment of technical capability for construction of the repository established. Completion of detailed repository design.
Step 3: repository construction	2041—2050	Completion of the repository construction around 2050. The demonstration for HLW disposal with vitrified HLW.

(2) Engineering studies for URL and repository: detailed engineering design for URL; conceptual repository design; estimation of amount and type of HLW; waste characterization; studies of engineered barrier (canister, buffer and backfill materials); study of stability of underground tunnels; study of the behavior of engineered barriers under coupled thermo-hydro-mechanical conditions; and rock mechanics studies.

(3) Safety assessment: detailed investigation and prediction of waste inventory; studies of safety assessment methodologies; establishment of safety and environment assessment information system; studies of scenario analysis, consequences analysis, modeling, sensitivity and uncertainty; practical safety assessment using the data from the selected site and the proposed repository design; and feedback of safety assessment results.

(4) Radionuclide migration studies: study of the performance of high-level waste, spent nuclear fuel and transuranic waste under repository conditions; study of radionuclide migration in buffer/backfill material, host rock and fractures; preparation of radionuclide migration database and technical standard of vitrified waste; provision of radionuclide migration data for safety assessment; study of speciations of radionuclide in groundwater; study of in-situ radionuclide migration experiments; study of the long-term behavior of spent nuclear fuel, and overpack and canisters.

3 Site selection and site characterization

3.1 Site selection process

Site selection for China's HLW repository started in 1985. The whole sitting process was divided into 4 stages [7–9]: nationwide screening, regional screening, area screening and site confirmation. During the sitting process, the following social-economic factors and natural factors were considered; geological conditions, future natural changes, hydrogeological conditions, geochemical conditions, human activities, construction and engineering conditions, waste transportation, environment protection, land use, social impact, and

public acceptance. Since 1986, the following activities have been conducted for site selection:

(1) Nationwide screening (1985–1986). According to the preliminary sitting criteria, 5 regions were selected as the potential regions: southwestern China region, eastern China region, Inner Mongolia Autonomous Region, southern China region and northwestern China region.

(2) Regional screening (1986–1989). Based on the results from the previous stages, further investigations were conducted, with a result of 21 potential candidate areas. In the northwestern China region, the Beishan area in Gansu Province was considered as the most important area.

(3) Areal screening (since 1990). Since 1990, the major efforts have been concentrated on Beishan area, Gansu Province. Studies include regional crust stability, tectonic evolution, lithological studies, hydrogeological studies and preliminary geophysical survey. Borehole drilling in Beishan area has also been conducted. At the same time, possible host rock types for the repository were also investigated, with the conclusion that the granite is the most suitable host rock for China's repository. In recent years, the possibility of clay formations as host geological media was also proposed.

3.2 Site characterization

Since 1990, the efforts have been concentrated on the Beishan area. Researches include regional geological setting, crust stability, geological characteristics, hydrogeology and methodological studies for site characterization [10, 11].

Within Beishan area, 8 granite intrusions were chosen as candidate sub-areas for a HLW repository. Among them, 3 sub-areas (Jiujiang, Xinchang Xiangyangshan and Yemaquan) were chosen as the three most potential sub-areas.

During 1999–2009, site characterization were conducted at these three sub-areas, with surface geological, hydrogeological and geophysical investigations, drilling of 14 boreholes (BS01–BS14 with 6 deep boreholes and 8 shallow boreholes). A series of

borehole tests, such as pumping tests, injection tests, borehole televiewer and borehole radar surveys, sample-taking and in-situ stress measurement, were conducted. Favorite findings were obtained, which provided important data for evaluating the suitability of Jiujing, Yemaquan and Xinchang sub-areas.

Through the 14 boreholes in the three sub-areas, rock and groundwater samples and subsurface geological environment parameters have been obtained. The suitabilities of the region were evaluated through a series of site characterization methods, and the effectiveness of those methods was proved.

According to China's program, once it is recognized that the Beishan area is suitable, an underground research laboratory will be built there, and more detailed site evaluation, in-situ tests and underground experiments will be conducted. The URL will serve as both a methodological laboratory and a site confirmation tool. Furthermore it might be developed into an actual HLW repository.

The International Atomic Energy Agency assisted China's site characterization program through its technical cooperation projects.

3.3 Geology of Beishan region

The Beishan area is located in Gansu Province, Northwestern China (Fig.1). It is one of the pre-selected areas for China's HLW repository. The topography of the area is characterized by flatter gobi

and small hills with elevations ranging between 1 400 and 2 000 m above the sea level. The height variation is usually several tens of meters. The crust in the area is a block structure, with the crust thickness of 47 to 50 km. The seismic intensity of the area is below than grade VI, and no earthquake with $M_s > 4.75$ was recorded in history. Since Tertiary's Period it is a slowly uplifting area without obvious differential movement, the geological characteristics of the Beishan area show that the crust in the area is stable, and has a great potential for the construction of a HLW repository [12].

The granites in the Jiujing, Xinchang and Yemaquan sub-areas are considered as the potential host rocks for HLW repository. Surface geological mapping and geophysical surveys, and borehole investigation indicated the good integrity of the rock mass in the area.

3.4 Fracture mapping

Fracture investigations of outcrops at Jiujing section in Beishan area were conducted using window statistic method. For each window, the location measured by GPS and outcrop's orientations such as trend (θ) and plunge (δ) were recorded. Fracture parameters, such as location, trace length, dip (α), dip direction (β), aperture and fracture filling, in each window were measured. The fracture orientation was calculated using DIPS developed by Rocscience Inc.. Figure 2 presents the equal area lower hemisphere contours of all the

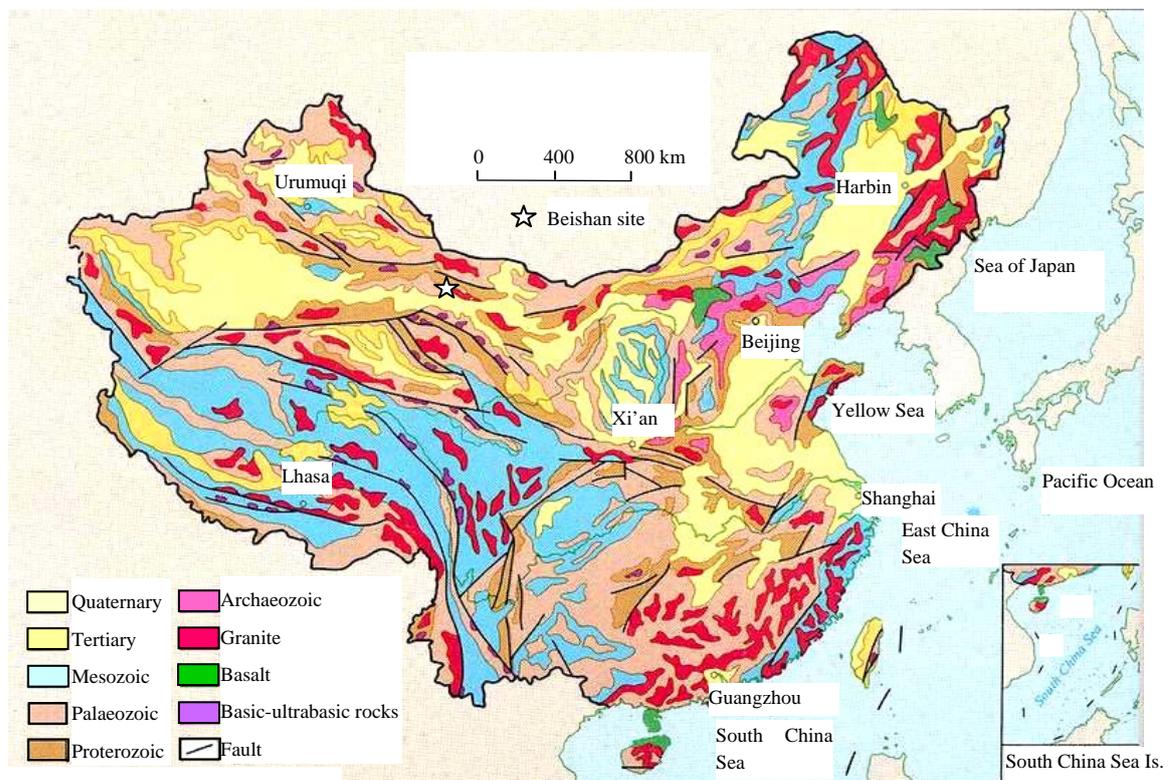


Fig.1 The location of Beishan site in Gansu Province, northwestern China.

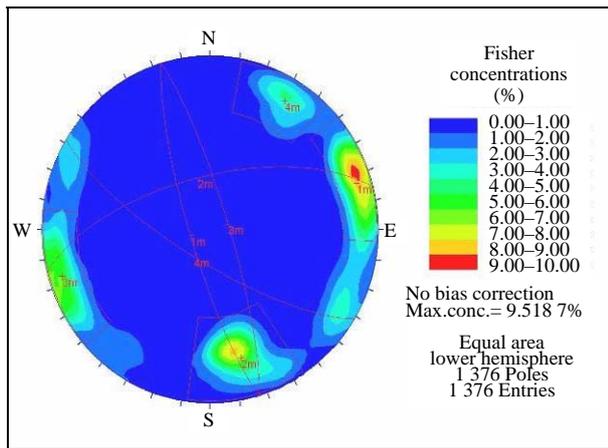


Fig.2 Stereographic contours of fractures around BS03 (equal area lower hemisphere).

fracture mapping results, and four sets of fracture zone in the studied area, with the maximum Fisher concentration of 9.52%. Table 2 gives statistic characteristics of the four fracture sets with the orientations well fitted by Fisher distributions. Set 1 is the prominent set with orientation (dip direction/dip) of 253.2°/80.1°. The statistics of fractures also show that the trace length of each set is fitted by log-normal distribution and distribution of fracture aperture is fitted by inverse exponent function.

3.5 Rock stress

In-situ stresses were measured in Beishan area in 4 deep boreholes (BS01, BS03, BS05, BS06) using hydraulic fracturing method. The results for boreholes BS01 and BS03 have been published [9]. Tables 3 and 4 show the results of hydraulic fracturing measurement at boreholes BS05 and BS06, which are located at Xinchang-Xiangyangshan section in Beishan area.

The stress measurement results show scattering in the stress profiles with depth, but the trend that the stress increases with depth is clear. For both boreholes, the minimum horizontal stress ranges between 4.54 and 12.77 MPa, while the maximum horizontal stress ranges between 6.94 and 19.59 MPa, which belong to a middle stress range. Borehole investigation showed good integrity of rock mass with very few fractures, implying the favorable engineering conditions for the

construction of an underground repository in the area.

Compared with the results from boreholes BS01 and BS03 in Jiujing sub-area, the results obtained from boreholes BS05 and BS06 are very similar without obvious differences.

3.6 Hydrogeology of Beishan region

Beishan area is an arid gobi desert area, with an average annual precipitation of 70 mm, but an annual evaporation of 3 000 mm. More important, there is no yearlong streams and other surface water bodies in the area.

Therefore, Beishan area is also poor in groundwater resources. Pumping tests carried out by local geological teams in the 1980s in the area showed that the outflow rates are less than 50 m³/d in most of wells. The groundwater in Beishan area can be divided into three categories: (1) an upland rocky fissured unit; (2) a valley and depression pore-fissure unit; and (3) a basin pore-fissure unit. The upland rocky fissured unit is the most prevalent one in this area. This type of groundwater occurs in weathered and structural fractures, its recharge is primarily from precipitation infiltration, with discharge mostly through evaporation and lateral outflows into the fractured water-bearing zones, intermountain areas, and valley depressions.

The present water table in the potential site area is 28–46 m below the surface. Chemical analysis shows that the groundwater in Beishan area is of Cl-SO₄-Na type, with pH values ranging between 7–9, while the total dissolved solid (TDS) is larger than 2 g/L. The in-situ water sample from the depth of 440 m in borehole BS03 shows a TDS value of 4.15 mg/L, and a pH value of 7.58, while the dominant ions are Na⁺, Cl⁻ and SO₄²⁻.

3.7 Permeability of rock mass

The permeability study of rock mass was conducted using a “Double Packer Hydraulic Test System”, produced by Golder Associates GmbH. The test system is characterized by packer isolation, pressure monitored above, below and between packers. The system is computer-controlled and can be used to measure hydraulic conductivities less than 10⁻¹³ m/s in

Table 2 Fracture orientation parameters.

Fracture number	Pole orientation		Fracture orientation		Fisher coefficient	Set number
	Trend (°)	Plunge (°)	Dip direction (°)	Dip (°)		
316	73.2	9.9	253.2	80.1	55.2	1
297	166.3	25.2	346.3	64.8	41.5	2
245	252.8	9.0	72.8	81.0	41.0	3
138	31.1	15.4	211.1	74.6	62.2	4

Table 3 Results of hydraulic fracturing stress measurement at borehole BS05.

No.	Depth (m)	Vertical stress, σ_v (MPa)	Minimum horizontal stress, σ_h (MPa)	Maximum horizontal stress, σ_H (MPa)	Direction of maximum horizontal stress
1	114.00	3.02	6.47	11.62	N2°E
2	198.50	5.26	6.26	9.86	N13°W
3	283.50	7.51	8.25	12.36	
4	305.00	8.08	8.08	12.41	N22°W
5	350.50	9.29	6.90	9.64	
6	405.50	10.75	6.95	9.66	
7	446.50	11.83	7.62	10.27	
8	492.50	13.05	10.11	13.94	

Table 4 Results of hydraulic fracturing geostress measurement at borehole BS06.

No.	Depth (m)	Vertical stress, σ_v (MPa)	Minimum horizontal stress, σ_h (MPa)	Maximum horizontal stress, σ_H (MPa)	Direction of maximum horizontal stress
1	113.50	3.01	4.97	7.93	N53°E
2	167.50	4.44	4.54	6.94	
3	207.80	5.51	4.98	7.89	
4	256.50	6.80	5.68	8.50	
5	300.00	7.95	7.50	11.42	
6	341.50	9.05	7.96	11.20	N67°E
7	401.50	10.64	8.79	12.85	
8	449.50	11.91	9.12	12.67	
9	502.50	13.32	9.93	13.89	N52°E
10	552.00	14.63	12.77	19.59	
11	577.00	15.29	9.72	13.27	
12	586.50	15.54	9.97	13.37	

rock and was used in boreholes BS03, BS05 and BS06. Table 5 and Fig.3 show the measured hydraulic conductivity of the rock mass in borehole BS06 at Xinchang sub-area. The data clearly show that most of the borehole sections have extremely low permeability, except in sections between 139.97–150.30, 170.22–180.55 and 210.22–220.55 m. Considering that the in-situ stress magnitude in borehole BS06 is moderate, while the permeability is extremely low, the rock mass around borehole BS06 could be an excellent place the construction of disposal facility and for the permanent isolation of HLW.

4 Progress in engineered barrier studies

4.1 Conceptual design of geological repository

The conceptual design of repositories in different

Table 5 Hydraulic conductivity of rock mass in borehole BS06.

Test	Upper isolation point depth (m)	Lower isolation point depth (m)	Hydraulic conductivity (m/s)
T07	400.22	410.55	2.81×10^{-11}
T08	410.22	420.55	1.49×10^{-11}
T09	420.22	430.55	4.59×10^{-13}
T10	430.22	440.55	4.56×10^{-12}
T11	440.22	450.55	1.05×10^{-12}
T12C	450.22	460.55	5.28×10^{-13}
T13	460.22	470.55	3.97×10^{-14}
T14	470.22	480.55	1.10×10^{-11}
T26	480.22	490.55	1.04×10^{-11}
T25	490.22	500.55	1.31×10^{-12}
T24	500.22	510.55	3.31×10^{-12}
T23	510.22	520.55	1.06×10^{-12}
T22	520.22	530.55	2.36×10^{-14}
T15	530.22	540.55	6.54×10^{-10}
T21	540.22	550.55	7.00×10^{-13}
T20	550.22	560.55	1.47×10^{-11}
T19	560.22	570.55	5.47×10^{-12}
T18	570.22	580.55	2.13×10^{-13}
T17	580.22	590.55	2.11×10^{-13}
T16	590.22	600.55	5.17×10^{-14}

geological formations generally relies on a multi-barrier system, which typically comprises the natural geological barriers provided by the repository host rock and an engineered barrier system. The preliminary conceptual design for China's geological repository in granite is shown schematically in Fig.4. The existence of natural barriers is used for isolation of radionuclides from the biosphere. The engineered barrier system (EBS) includes vitrified waste, waste canisters, buffer materials, backfill and seals. Currently, the Gaomiaozi (GMZ) bentonite is considered as the candidate buffer and backfill material for China's HLW repository [13]. The main functions of EBS components are introduced as follows.

(1) The waste is vitrified to provide a stable waste form that is resistant to leaching and gives slow rates of radio-nuclide release for long-time.

(2) The canister/overpack is designed to facilitate waste handling, emplacement and retrieval, and to provide containment for up to 1 000 years or longer depending on the waste type.

(3) The buffer/backfill is designed to stabilise the repository excavations and the THMC conditions, and to provide low permeability and diffusivities, and long-term retardation.

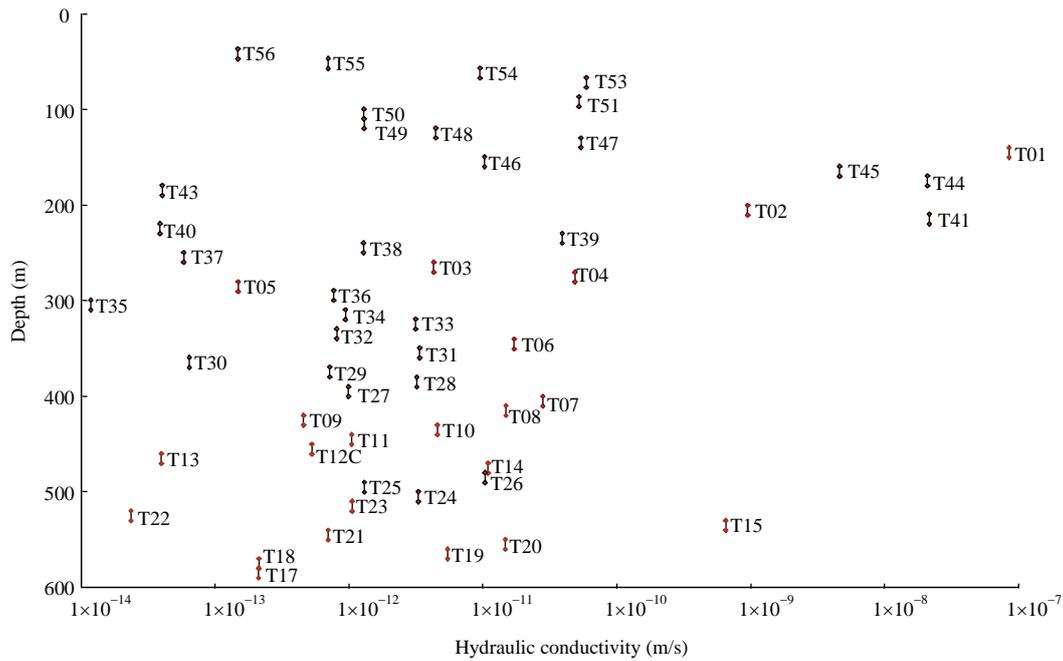


Fig.3 Hydraulic conductivity distribution in borehole BS06.

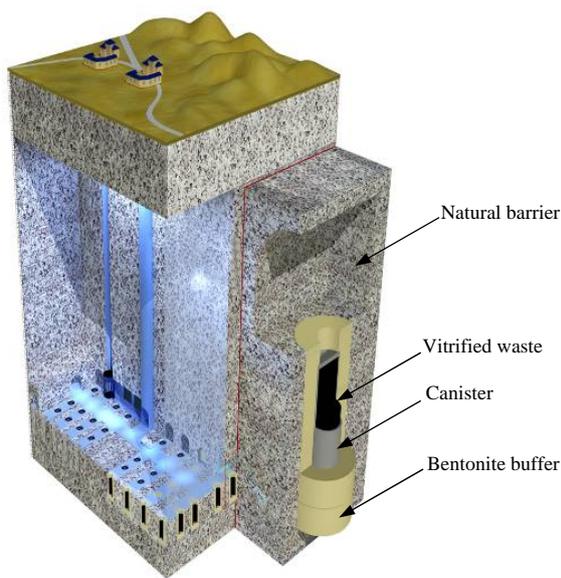


Fig.4 The conceptual model for China's HLW repository in granite.

(4) The other EBS components (e.g. seals, plugs) are designed to prevent releases via drifts and shafts and to prevent access to the repository.

The thermal analysis of disposal hole and the disposal area were conducted by Zhao [14]. The performance assessment study of the total disposal system was conducted by Chen using GoldSim software [15].

4.2 Buffer/backfill

The buffer and backfill are among the main components of EBS for the HLW repository, with the GMZ bentonite selected as the buffer/backfill material after a comprehensive investigation for 84 main bentonite deposits discovered in China.

The GMZ bentonite deposit has a large scale and is located in Inner Mongolia Autonomous Region, 300 km northwest of Beijing, with good transportation conditions. The deposit, with bedded bentonite clay layers, was formed in late Jurassic period. Clay minerals include montmorillonite and quartz, feldspar, cristobalite, etc.. The reserve is about 160×10^6 tons with 120×10^6 tons of Na-bentonite. The major bentonite clay layer of the deposit extends about 8 150 m with thickness ranging from 8.78-20.47 m.

The preliminary study on GMZ bentonite shows that it is characterized by high content of montmorillonite (>70%) and low impurities. Various tests revealed some of other properties of the GMZ bentonite: cation exchange capacity (77.30 mmol/(100 g)); methylene blue exchange capacity (102 mmol/(100 g)); alkali index (1.14). The properties of the compacted bentonite at a dry density 1.8 g/cm^3 are: thermal conductivity (around $1.0 \text{ W/(m} \cdot \text{K)}$ at a water content of 8.6%), hydraulic conductivity ($1 \times 10^{-13} \text{ m/s}$), and swelling pressure (10 MPa, at full saturation). Those figures shown that the GMZ bentonite is a suitable buffer/backfill material.

However, comprehensive studies, including the coupled thermo-hydro-mechanical process of the bentonite, are still needed.

4.3 China-mock-up facility for bentonite study

To study the behavior of the GMZ bentonite under coupled thermo-hydro-mechanical-chemical conditions, a mock-up facility, named China-mock-up, has been designed and will be installed soon in Beijing Research Institute of Uranium Geology. The main objectives of the China-mock-up include: (1) to study the property of GMZ Na-bentonite under coupled THMC conditions; (2) to study the bentonite-canister reaction under coupled THMC conditions; (3) to simulate vertical placement of a waste container; (4) to monitor the behavior of GMZ Na-bentonite barrier at high temperature and specific groundwater from Beishan site; (5) to test the installation method and validity of sensors; and (6) to provide data for future EBS design.

Figure 5 shows the specifications of the China-mock-up: a steel tank, bentonite blocks, a heater and temperature control system, a hydration system, temperature/moisture/stress sensors, gas measurement and collection system and a data acquisition system. The steel tank has an internal diameter of 800 mm and a height of 1 600 mm. The heater, which substitutes a loaded waste canister, is placed inside the bentonite blocks. The highest temperature is designed to be 90 °C. Water flows through the bentonite from its outer surface is to simulate the intake of groundwater. A number of sensors (monitoring the changes in temperature, pressure, displacement and moisture) are placed inside the bentonite barrier. When the experiment is completed, the China-mock-up facility will be dismantled and its fillings (such as metal insertions) will be studied in detail. The test results will reveal the changes of the bentonite properties due to long-term loading with moisture and temperature.

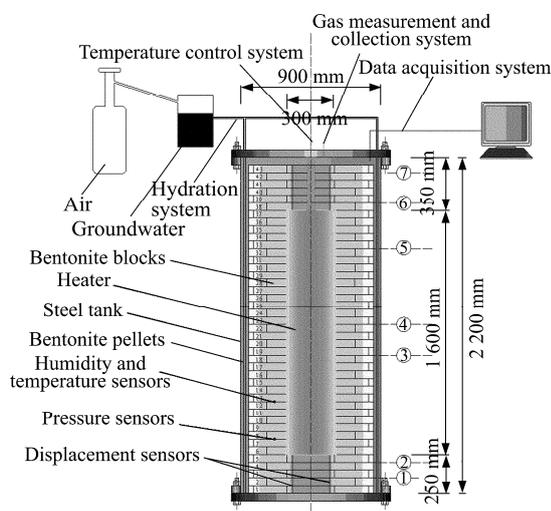


Fig.5 Sketch of the China-mock-up facility.

4.3 Rock mechanics studies of host rock

Rock mechanics studies include: mechanical properties of intact granite rock, excavation disturbed zone, the super-long-term stability of underground tunnels, the behavior of rock mass during coupled THMC processes.

The basic physico-mechanical properties, thermal properties under high temperature and confining pressure of deep intact granite rock from Beishan area were studied.

In Beishan area, the dominant rock types are porphyritic monzonitic granite and tonalite. The intact rock of Beishan area is of high density, low porosity, high strength, low strain and high brittleness. The isotropic extent of deep rock is higher than that of shallow rock. The temperature effects on mechanical properties of the Beishan granite were studied by Liu et al. [16, 17]. The results show that, when the temperature increases to 90 °C, the long-term strength of the monzonitic granite decreases by about 10%, while the strain rate at a steady creep stage increases with the temperature increase. The long-term behaviors of the Beishan granite under constant triaxial loading but under different temperatures and confining pressures were also studied. The results indicate that the effect of temperatures on deformation below 50 °C is not significant. However, when the temperature increases to 90 °C, the crack damage stress (which may be related to the long-term strength of rock) decreases about 10%; the steady state creep strain rate and acoustic emission rate increase; the time to failure at the same stress ratio reduces. The effect of confining pressure on the long-term behavior of granite was also studied. At the same stress ratio, the steady state strain rate and acoustic emission rate increase when the confining pressure decreases. However, the time to fail is shortened when the confining pressure decreases.

SEM in-situ experimental research on Beishan granite under thermo-mechanical coupling condition was conducted. It shows that the critical temperature for cracking is 75 °C. Strength and elastic modulus decrease with increasing temperature. Transition from brittle to ductile was observed with increasing temperature.

5 Key scientific challenges

The safe disposal of HLW/SNF is a scientific and technological challenge, because the fact that HLW/SNF has to be fully and reliably isolated for hundreds of thousand years, even millions of years. The radionuclides, such as Np, Pu, Am, Tc, etc., are highly radioactive, toxic, and with long half-lives. Once those

radionuclides pollute the biosphere near built social environments, it will bring tremendous harm to human society and environments at large.

However, the geological repositories faces a number of key issues, including:

- (1) How to select a suitable site, and to evaluate its suitability;
- (2) How to select engineered barrier materials to effectively isolate HLW/SNF;
- (3) How to design and construct a deep repository;
- (4) How to assess the long-term safety of the disposal system.

To solve the above challenging issues, many large-scale R&D projects have been carried out in the world [18, 19], including: (1) development and testing excavation techniques, e.g. the projects in the Belgian URF and the Finnish Olkiluoto site; (2) studies of excavated damage zone, e.g. the ZEDEX experiment at Äspö, the EDZ experiments at Grimsel Test Site and the Mt.Terri Tunnel in Switzerland; (3) site characterization studies, e.g. full-scale deposition holes research tunnel to Olkiluoto, development of geophysical methods at Grimsel and Stripa underground laboratories; (4) hydrogeological tests, conducted in most of underground research laboratories; (5) in-situ radionuclides migration tests, conducted in most of underground research laboratories; (6) simulation of effects caused by emplacement of radioactive waste, e.g. the TSS project at Asse, FEBEX project at Grimsel, Heater test at Stripa, THM test in Whiteshell, drift-scale heater test in ESF, the international DECOVALEX project [20]; (7) demonstration of engineered barriers system, e.g. RESEAL project in the Belgian URF, FEBEX project at Grimsel, buffer and container testing at Whiteshell, borehole sealing test at Stripa; (8) prototype repository study, e.g. the prototype repository test at Äspö Hard Rock Laboratory, the EU's ESDRED project; and (9) natural analogue and anthropogenic analogue studies, e.g. the Oklo project, the Brazilian Pocos de Caldas project, the Cigar Lake project, the Australian ARAP project, the Lianshangan uranium deposit study in China.

Most of the above R&D projects were carried out in order to deal with the following key scientific challenges: (1) reliable prediction of the evolution of a repository site; (2) characterisation of deep geological environment; (3) behaviour of deep rock mass, groundwater and engineering materials under coupling conditions (intermediate to high temperature, in-situ stress, hydraulic, chemical, biological and radiation process, etc.); (4) geochemical behaviour of transuranic radionuclides with low concentration and its migration

with groundwater; and (5) safety assessment of disposal system.

5.1 Reliable prediction of evolution of a repository site

Because there are a lot of long half-life radionuclides in HLW/SNF, it is required to isolate them in a very long period, as long as $(1-10) \times 10^5$ years from the biosphere. Therefore, reliable prediction of a repository site should be carried out in detail, including the prediction of the geologic stability, regional geologic conditions, regional and local groundwater flow, climate changes, landform, geological hazardous (volcanism, earthquakes, faulting, etc.).

5.2 Characterisation of deep geological environment

The geological repositories are usually located at depth between 300–1 000 m, where the environment is characterized by evolution of temperature, high in-situ stress reducing conditions, groundwater flow, and radiation caused by waste. The understanding of the deep geological environment is key to the safety of a disposal system.

5.3 Behaviour of deep rock mass under coupling conditions

Compared with shallow rock mass, the deep rock mass is characterized by heterogeneity and discontinuities, while the deformation is also discontinuous. Due to the excavation of repositories and radiation, the environment and behaviour of deep rock mass will experience great changes. At present, the behaviours of deep rock mass and geomechanical evolution of the disposal structures under coupling conditions (intermediate to high temperature, stress, and hydraulic, chemical, biological and radiation processes) are scientific frontiers. Many international projects are created to conduct further studies in this area.

5.4 Behaviour of engineering materials under coupling conditions

The engineering materials for repositories include waste forms (such as waste glass), canister (carbon steel, copper, etc.), buffer and backfill materials. These materials play an important role in preventing the intrusion of water and the migration of radionuclide. The behaviours of such materials under coupling conditions (intermediate to high temperature, stress, and hydraulic, chemical, biological and radiation process) are much different from their general behaviours. The long-term evolution of such materials under coupled conditions is also a hot topic in recent R&D programs.

5.5 Geochemical behaviour of transuranic radionuclides with low concentration and its migration

The radionuclide released from repositories will migrate with groundwater and diffuse into rock matrix. The migration behaviours of radionuclide depend on the groundwater flow and complicated geochemical process. At present, we have limited knowledge on the geochemical process of radionuclides such as Np, Pu, Am, Tc. The speciation, complexation, colloids, biological effect of those radionuclides under realistic repository conditions are challenging topics. Some of the radionuclides such as Tc, I and ^3H are difficult to be retarded, so selecting suitable materials is also a challenge.

5.6 Safety assessment of disposal system

The geological disposal system is a complex system, composed of many subsystems (waste forms, canister, buffer material, near-field, far-field, biosphere, groundwater, etc.) which will experience complicated and long-term coupling processes up to hundreds of thousands of years. Therefore, the detailed safety assessment of the system is a difficult challenge to the present computational and technical capabilities.

All of the above issues are cutting-edge scientific challenges and are related to many subjects such as geology, hydrogeology, radiochemistry, rock mechanics, engineering science, material science, mineralogy, thermo-dynamics, nuclear physics, radiation protection and computer science. Only comprehensive and integrated R&D will help the final success of disposal of HLW.

6 Future plan

According to the guidelines approved by the Chinese government, an underground research laboratory should be constructed before 2020, while the construction of a national HLW repository will begin in around 2040.

Before 2020, the following research projects are planned for the HLW disposal program.

(1) Site investigation in Beishan area. More boreholes will be drilled to determine the suitability of the site.

(2) Site selection for HLW repository in Western China. The purpose is to find a second site that can be compared with the Beishan site.

(3) Investigation of clay formation as potential host rocks.

(4) Site selection, feasibility studies and construction for URL.

(5) Conceptual design and detailed engineering design for the URL and geological repository.

(6) Radionuclide migration study. More adsorption and diffusion data on Beishan granite and GMZ bentonite will be obtained.

(7) Safety assessment. Beishan site will be used as a reference site, while the GMZ bentonite is considered as the reference buffer and backfill material.

(8) Fundamental studies on rock mechanics, hydrogeology, geochemistry, radiochemistry, corrosion of metals, numerical modeling, THMC modeling, etc..

7 Conclusions

(1) Realizing the importance of safe disposal of high-level radioactive waste to the sustainable development of nuclear energy and environment protection, the Chinese government has paid higher attention to this issue. A 3-step long-term plan was established to guide R&D for geological disposal of HLW, with major milestones to build an underground research laboratory by 2020 and a national geological repository by 2050. Necessary resources have been arranged for the geological disposal program. Progresses have been made in site selection and characterization, and studied on buffer and backfill materials, radionuclide migration and performance assessment.

(2) Beishan site was selected as the most potential area for China's HLW. Six deep boreholes and eight shallow boreholes were drilled at three sub-areas in Beishan during the period of 2000–2009. The results show that the rock mass is of high integrity, low fracture density, low hydraulic conductivity and moderate in-situ stresses, indicating that the Beishan site has a good potential for the construction of future geological repositories.

(3) A multi-barrier concept was proposed for the preliminary design of geological repository. The GMZ bentonite was selected as the buffer and backfill material. A mock-up facility with objectives to study its properties under coupled THMC conditions is under construction.

(4) The results from rock mechanics studies show that the deep intact rock in Beishan area is of high density, low porosity, high strength, low strain and high brittleness. The long-term properties under high temperature and confining pressure of deep intact granite from Beishan area were studied.

(5) Although progress was made in many aspects, the Chinese HLW disposal task is still facing many social, economic, scientific, technical and engineering challenges. The key scientific challenges include reliable prediction of the evolution of a repository site, characterisation of deep geological environment, behaviour of deep rock mass, groundwater and engineering material under coupled conditions, geochemical behaviour of transuranic radionuclides

with low concentration and its migration with groundwater and safety assessment of the disposal system.

Continuous efforts will be concentrated on Beishan site and comparison with other potential sites, conceptual design of repository, design of underground research laboratory, safety assessment, while other associated laboratory studies will also be conducted in the coming years, for the purpose to build China's underground research laboratory in 2020 and a high-level radioactive waste repository around 2050.

Acknowledgements

The author wishes to thank China Atomic Energy Authority for supporting the geological disposal program. Special thanks should be given to the International Atomic Energy Agency for its support to China's geological disposal program through its technical cooperation projects. The author also wishes to thank his colleagues for their actual execution of the geological disposal projects.

References

- [1] The State Council of China (SCC). The medium- to long-term plan for the development of nuclear power plants in China (2006–2020). Beijing: The State Council of China (SCC), 2007 (in Chinese).
- [2] China Atomic Energy Authority (CAEA), Ministry of Environment Protection, Ministry of Science and Technology. Guidelines for the R&D for geological disposal of high-level radioactive waste in China. Beijing: China Atomic Energy Authority (CAEA), Ministry of Environment Protection, Ministry of Science and Technology, 2006 (in Chinese).
- [3] Pan Ziqiang, Qian Qihu. A strategic study on geological disposal of high-level radioactive waste in China. Beijing: Atomic Energy Press, 2009 (in Chinese).
- [4] Yang Liji. The deep geological disposal program (DGD program). In: Proceedings of Workshop of Geological Disposal of High-level Radioactive Waste. [S. l.]: [s. n.], 1992: 1–8.
- [5] Wang Ju. Discussion on the strategic program for deep geological disposal of high-level radioactive waste in China. Uranium Geology, 2004, 20 (4): 196–204 (in Chinese).
- [6] Zhang Huazhu. Geological disposal of high-level radioactive waste in China: present situation and perspectives. Uranium Geology, 2004, 20 (4): 193–195 (in Chinese).
- [7] Wang Ju, Fan Xianhua, Xu Guoqing, et al. Progress of the deep geological disposal of high-level radioactive waste in China: 1991–2000. Beijing: Atomic Energy Press, 2004 (in Chinese).
- [8] Wang Ju, Xue Weiming, Zheng Hualing, et al. Preliminary site characterization at Beishan, NW China—a potential site for China's high-level radioactive waste repository. In: Witherspoon P A ed. Geological Problems in Radioactive Waste Isolation, the 3rd World Wide Review. Lawrence, USA: Lawrence Berkeley National Laboratory, 2001: 77–84.
- [9] Wang Ju, Su Rui, Chen Weiming, et al. Deep geological disposal of high-level radioactive waste in China. Chinese Journal of Rock Mechanics and Engineering, 2006, 25 (4): 649–658 (in Chinese).
- [10] Wang Ju, Chen Weiming, Su Rui, et al. Site characterization methodology for high level radioactive waste disposal in Beishan. In: Proceedings of international conference on radioactive waste disposal in geological formations. Braunschweig, Germany: Bundesamt für Strahlenschutz (BfS) and Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH, 2007: 232–236.
- [11] Chen Weiming, Wang Ju, Zhao Honggang, et al. Geological characters of Xinchang section in Pre-selected Beishan region for high-level radioactive waste disposal. Chinese Journal of Rock Mechanics and Engineering, 2007, 26 (supp.2): 4 000–4 006 (in Chinese).
- [12] Xu Guoqing, Wang Ju. Study on crust stability of Beishan, Gansu Province, China—the preselected area for China's high-level waste repository. In: Proceedings of the 30th International Geological Congress. Netherlands: VSP Publishing Company, 1996: 25–30.
- [13] Liu Yuemiao. Study on clay-based materials for the repository of high level radioactive waste. Journal of Mineralogy and Petrology, 2003, 23 (4): 42–45 (in Chinese).
- [14] Zhao Honggang. A study of thermal conductivity property and tunnel stability of high level radioactive waste repository—the case of Beishan preselected site, Gansu province, China. PhD Thesis. Beijing: Beijing Research Institute of Uranium Geology, 2009 (in Chinese).
- [15] Chen Weiming. Study of system analysis method for geological repository of high level radioactive waste—taking the Beishan granite site as an example. PhD Thesis. Beijing: Beijing Research Institute of Uranium Geology, 2008 (in Chinese).
- [16] Liu Y M, Wang J, Tham L G, et al. Temperature effects on mechanical properties of the Beishan granite. In: Advances on Coupled Thermo-hydro-mechanical-chemical Processes in Geosystems and Engineering. Beijing: Science Press, 2007: 243–247 (in Chinese).
- [17] Liu Yuemiao, Wang Ju, Tham L G, et al. Basic physical-mechanical properties and time-temperature effect of the deep intact rock from beishan preselected area for high-level radioactive waste disposal, Chinese Journal of Rock Mechanics and Engineering, 2007, 26 (10): 2 034–2 042 (in Chinese).
- [18] Wang Ju. Key scientific challenges in geological disposal of high-level radioactive waste. Engineering Sciences, 2007, (4): 45–50. (in Chinese)
- [19] Kickmaier W, McKingley I. A review of research carried out in European rock laboratories. Nuclear Engineering and Design, 1997, 176 (1): 75–81.
- [20] Tsang C F, Jing L R, Stephansson O, et al. The DECOVALEX III project: a summary of activities and lessons learned. International Journal of Rock Mechanics and Mining Sciences, 2005, 42 (5/6): 593–610.