WOLSONG LOW- AND INTERMEDIATE-LEVEL RADIOACTIVE WASTE DISPOSAL CENTER: PROGRESS AND CHALLENGES

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In this paper, we discuss the experiences during the preparation of the Wolsong Low- and Intermediate-Level Radioactive Waste Disposal Center. These experiences have importance as a first implementation for the national LILW disposal facility in the Republic of Korea. As for the progress, it relates to the area of selected disposal site, the disposal site characteristics, waste characteristics of the disposal facility, safety assessment, and licensing process. During these experiences, we also discuss the necessity for new organization and change for a radioactive waste management system. Further effort for the safe management of radioactive waste needs to be pursued.

KEYWORDS : Wolsong Low- and Intermediate-Level Radioactive Waste Disposal Center, Site Selection, Site Characteristics, Waste Characteristics, Disposal Facility, Safety Assessment

1. INTRODUCTION

The objectives and associated set of internationally agreed upon principles of radioactive waste management clearly state that radioactive waste has to be dealt with in a manner that protects both human health and the environment, both now and in the future, without imposing undue burden on future generations [1].

Low- and Intermediate-Level Radioactive Waste (LILW) in the Republic of Korea is generated from commercial nuclear power plants (NPPs), research institutes, nuclear fuel manufacturing facilities, and spent radioisotopes (RI).

After the Atomic Energy Act in 1986, the South Korean government has failed nine times to secure a disposal site from 1986 to 2004. A new announcement from the government to change the site selection procedure, in 2005, made Gyeongju city as a candidate site. In January 2007, the Korea Hydro & Nuclear Power Co., Ltd. (KHNP) submitted an application to the national nuclear regulatory authority, the Ministry of Education, Science and Technology (MEST), for the first stage license that would authorize The KHNP to construct and operate the Wolsong LILW Disposal Center. As entrusted by MEST, the Korean nuclear regulatory body (Korea Institute of Nuclear Safety or "KINS"), reviewed the license documents and issued the construction and operation approval in July 2008.

In this paper, we discuss experiences while preparing the Wolsong Low- and Intermediate-Level Radioactive Waste Disposal Center. These experiences have importance as an initial implementation of the national LILW disposal facility in the Republic of Korea.

2. SITE SELECTION

Since the creation of the legal grounds for the implementation of the project by the 1986 revision of the Atomic Energy Act (AEA), the Government of the

Republic of Korea has actively implemented the selection of the sites for radioactive waste disposal facilities. There have been nine failed attempts to secure a disposal site from 1986 to 2004 due to 1) safety concerns about the disposal facility, 2) lack of transparency and fairness during project implementation, and 3) lack of social consensuses among the stakeholders.

In February 2004, the Ministry of Knowledge Economy (MKE) announced new site selection procedures, and MKE/KHNP endeavored in various ways to enhance the acceptance by local residents of disposal facilities. As a result, local residents voluntarily petitioned to host the facilities in ten areas, but site selection ultimately failed due to the absence of preliminary applications by local government heads.

Afterwards, on March 11, 2005, the MKE organized the Site Selection Committee (SSC) in order to guarantee the transparency and fairness of the site selection process. The SSC, consisting of 17 civilian experts from diverse fields, managed and supervised the entire site selection process. In addition, the "Special Act on Support for Areas Hosting Low and Intermediate Level Radioactive Waste Disposal Facilities" was legislated and announced on March 31, 2005 to stipulate support for areas hosting LILW disposal facilities, including special financial support, entry fees, and relocation of the KHNP headquarters. The act also stipulated the following to enhance the democracy and transparency of the selection process: 1) the host area is to be selected through resident voting in accordance with the Referendum Act, 2) the selection plan, site survey results, and selection process are to be implemented openly and transparently, and 3) open forums and discussions are to be held for the local residents.

Accordingly, on June 16, 2005, the MKE announced the candidate site selection method and procedures as well as the support to be provided to the host areas and initiated the process through an announcement regarding LILW disposal facility candidate site selection. Regarding candidate site selection procedures, as depicted in Fig. 1, the local governors applied to host the facilities with consent from local councils. Then, in accordance with the results of the site suitability assessment, the MKE requested local governors to conduct the local referendums in appropriate regions in adherence with the Referendum Act. Local governors proposed and held the referendums. Based on the results of the local referendums, areas with the highest percentage of favorable responses would be selected as the final candidate site.

The local governments that had appropriately applied to host the LILW disposal facility by August 31, 2005 were in the four areas of Gunsan, Gyeongju, Pohang, and Yeongdeok County, and these four local governments conducted referendums. In accordance with the results of the referendums, with the percentage of favorable responses among its residents amounting to 89.5%, Gyeongju was selected and announced as the final candidate site on November 3, 2005; the results of the referendums in the four cities and counties are given in Table 1.

On January 2, 2006, the MKE designated and thereupon announced that the prospective rural development area comprising the entire 49 Bonggil-li, Yangbukmyeon, Gyeongju, North Gyeongsang Province (approximately

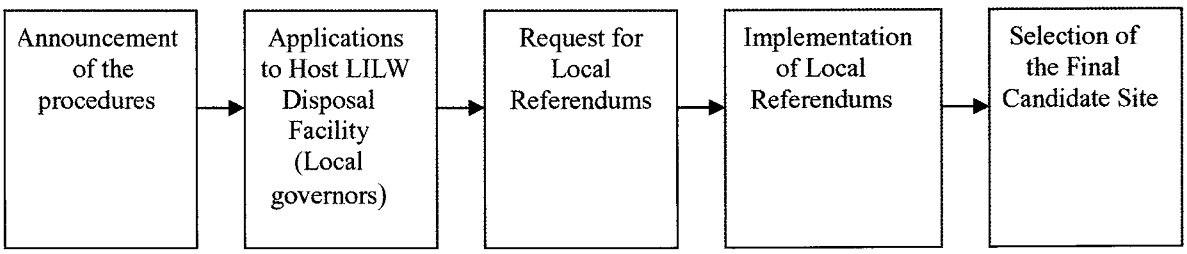

Fig. 1. Site Selection Procedures of the LILW Disposal Facility

Table 1. Results of Referendums for Site Selection (2005)

Classification	Gyeongju	Gunsan	Yeongdeok	Pohang
Number of eligible voters	208,607	196,980	37,536	374,697
Number of actual voters (absentees)	147,636 (70,521)	138,192 (65,336)	30,107 (9,523)	178,586 (63,851)
Voter turnout	70.8%	70.2%	80.2%	47.7%
Percentage of favorite responses	89.5%	84.4%	79.3%	67.5%

2,100,000 m^2) had been selected as the final candidate site for the LILW disposal facility (the MKE Notice No. 2005-133).

3. SITE CHARACTERISTICS

3.1 Basic Information

The Wolsong site is located in the southeastern coastal area of the Korean Peninsula, within the municipality of Gyeong-Ju, about 26.5 km southeast of the city hall. The area, approximately 1.1 km long and 1.8 km wide, is bounded by a national park to the north and the Wolsong NPP to the south. The site area on a local scale consists of the rolling hill topography of EL. 100~250 m with the general eastward slope toward the East Sea. The major streams are mainly extended to the sea and small streams and gullies are more or less developed in a similar pattern.

Based on the detailed geological investigation on the site area of 1km radius, the Wolsong site mainly consists of cretaceous sedimentary rocks and tertiary plutonic rocks and intrusive rocks (See in Fig. 2). The cretaceous sedimentary rocks, which are the predominantly alternating strata of mudstone, siltstone, and sandstones, belong to the Ulsan formation which is correlated to the upper formation of the Gyeongsang sedimentary basin in southeastern of the Republic of Korea. They form a basement in the site and are intruded upon tertiary plutonic and intrusive rocks. The plutonic rocks, which consist of diorite, granodiorite, and biotite granite, belong to early tertiary intrusive rocks (59.8±1.8 Ma).

They are gradually changed from basic to acidic composition away from the boundary of sedimentary rocks; thus it is difficult to delineate a sub-lithological rock boundary. Diorite in fine grains is mainly composed of plagioclase, K-feldspar, biotite, and amphibole. Diorite changes to granodiorite with a decrease in the amount of opaque minerals and an increase in grain size. The major composition of granodiorite is similar to diorite with an increase of quartz and K-feldspar and biotite dominance. The main region in which the silo will be located is mainly composed of granodiorite. A small distribution of biotite granitie was found in the northern part of the site, but wide distribution is recognized to the north up to the Gampo area. Rhyolite is a dominant intrusive rock type in dykes and intrudes Cretaceous sedimentary rocks and Tertiary

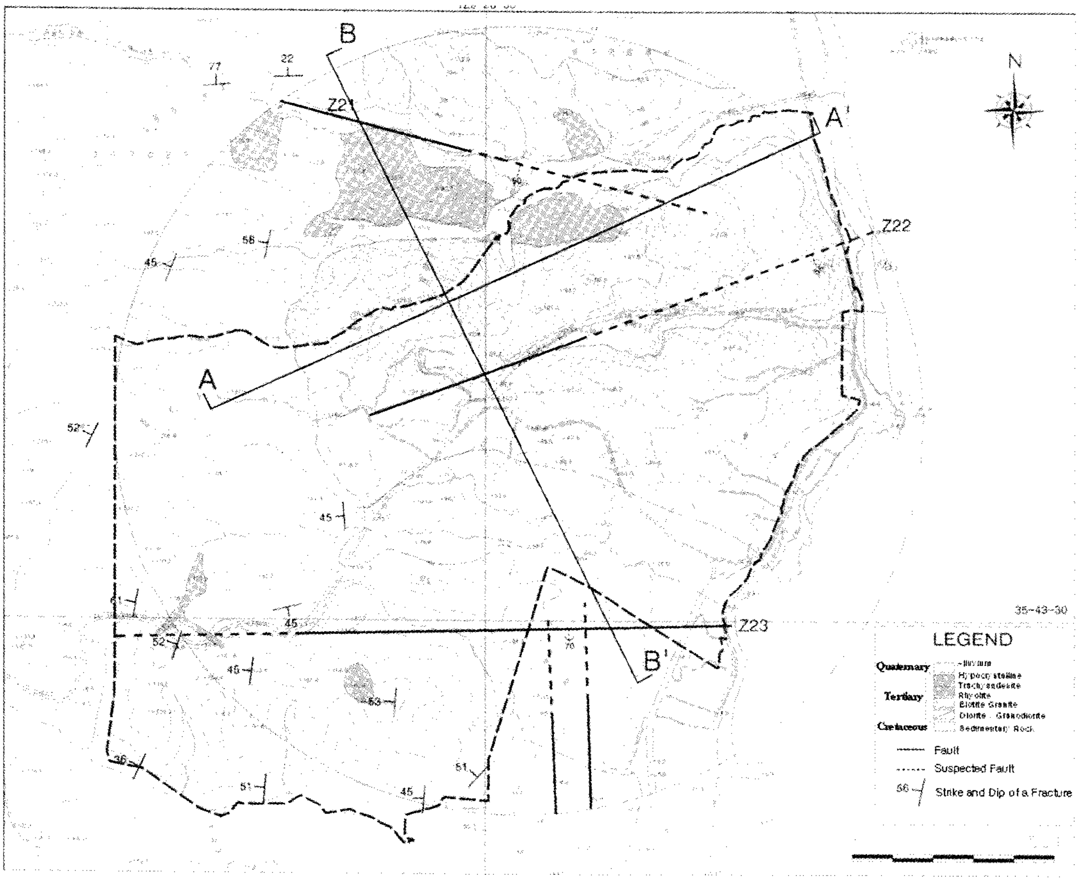

Fig. 2. Geological Map on the Local Scale of the Wolsong Site

granitic rocks. They are distributed as the largest outcrop in the northern area and as dykes in the southern area. Trachytic andesite showing a complex occurrence of shallow intrusive is distributed on a small scale as an intermediate dyke.

The site characterization on the Wolsong site comprised hydrogeological characterization, geochemical characterization, and groundwater flow modeling, which were performed on the basis of the field data collected during the site investigations. The results of the site characterization were used as a basis for its long term performance analysis and the repository layouts as well as information for the construction. It also provided a basis for environmental impact assessment.

3.2 Hydrogeology

The main objectives of hydogeological investigation were to understand the hydrogeological setting and conditions of the site and to provide the input parameters for safety assessment. The hydrogeological characterization of the site was performed from the results of surface based investigations, i.e., geological mapping and analysis, drilling works and hydraulic testing, and geophysical survey and interpretation [2].

The hydrogeological boundary for the groundwater flow system is characterized by topographical ridges and valleys providing the groundwater divide. The North-South (NS) trend of mountain ridge leads the surface water run-off and groundwater to flow easterly toward the East Sea depending on its hydraulic gradient. The hydro-structural model based on the hydrogeological characterization, which is described in the Swedish report [3], consists of one Hydraulic Soil Domain (HSD), three Hydraulic Rock Domains (HRD), and five Hydraulic Conductor Domains (HCD) (See in Fig. 3). The hydrogeological framework and the hydraulic values provided for each hydraulic unit over a relevant scale were used as the baseline for the conceptualization and interpretation of flow modeling.

HSD refers to overburdens and the uppermost fractured rock mass and its thickness ranges from 5 to 20m with a maximum of 24~28m. The hydraulic conductivity is about 2.6~4.5 x 10^{-6} m/s, and the mean bulk porosity is 0.34.

HRD consists of a statistical description of small fracture zones, discrete fractures, and a less permeable rock matrix between the fractures. Three HRDs are primarily defined on the basis of the origin of geological criteria and the major characteristics of fracture orientation

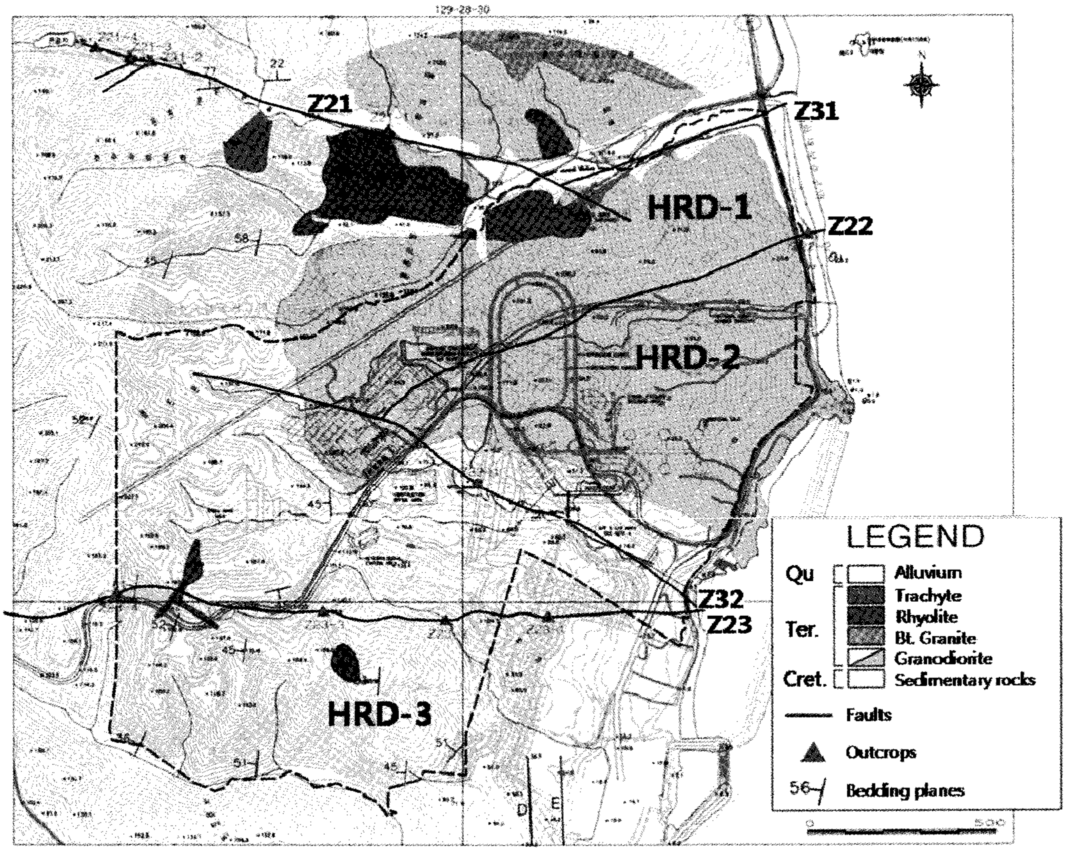

Fig. 3. Hydraulic Rock Domains and Hydraulic Conductor Domains of the Wolsong Site

distribution. The effective hydraulic conductivity of upper regime ($7.7x10^{-8}$ m/s), which is bounded around -120 m depth from ground surface, is more permeable than the lower regime ($6.6x10^{-8}$ m/s). The permeability of the silo regime is $4.5x10^{-8}$ m/s.

HCD includes the deterministic fracture zone of Z21, Z22, Z23, Z31, and Z32 (See in Fig. 3). In the cases where a major fracture zone that is observed in a borehole is inferred to correspond at the surface to a linked lineament, the strike of the zone is assumed to be the trend measured from the surface. The hydraulic conductivity of HCDs is assumed to be about $1x10^{-7}$ m/s.

The current hydrogeological characteristics based on the surface based investigation include some uncertainties resulting from the basic assumption of investigation methods and field data. Therefore, the reassessment of the hydro-structure model and hydraulic properties based on the field data obtained during the construction is necessary for a final hydrogeological characterization.

3.3 Hydrogeochemistry

The hydrogeochemical investigations were carried out to identify the characteristics of the hydrochemistry controlling the groundwater chemical condition at the Wolsong site. For the investigations, 12 boreholes of all monitoring boreholes in the site area were selected, and a total of 46 groundwater samples were collected with depth. In addition, three surface water samples and one seawater sample were collected. For individual water samples, cations and anions were analyzed. The environmental isotopes (O-18, H-2, H-3, C-13, S-34) were also analyzed to trace the origin of water and solutes. The analysis results of O-18 and H-2 showed that the surface water and groundwater originated from precipitation. The tritium concentrations of the groundwater decreased with depth, but high concentrations of tritium indicated that the groundwater was recharged recently. The results of ion and correlation analysis showed that the groundwater types of the site were represented by $Ca-Na-HCO_3$ and $Na-Cl-SO_4$, which was caused by sea spray and water-rock interaction. The high ratio of Na concentration in the groundwater resulted from ion exchanges.

For the redox condition of the groundwater, the values of dissolved oxygen and Eh decreased with depth, indicating that the reducing condition was formed in deeper groundwater. In addition, the high concentration of Fe and Mn showed that the redox condition of the groundwater was controlled by the reduction of Fe and Mn oxides.

Geochemical research on the rocks and minerals of the site was also carried out in order to provide geochemical data for the geochemical modeling and safety assessment. Polarized microscopy, the X-ray diffraction method, chemical analysis for the major and trace elements, scanning electro-microscopy, and stable isotope analysis were applied. The identified fracture-filling minerals from the drill core were montmorillonite, zeolite minerals, chlorite, illite, calcite, and pyrite. Pyrite and laumontite, which are known as the indicating minerals of hydrothermal alteration, were especially widely distributed in the site, indicating that the Wolsong site was affected by mineralization and/or hydrothermal alteration. Sulfur isotope analysis for the pyrite and oxygen-hydrogen stable isotope analysis for the clay minerals indicated that they originated from the magma. Therefore, it is believed that the fracture-filling minerals from the site were affected by the hydrothermal solution as well as the simply water-rock interaction. The hydrochemical and geochemical data of the groundwater and minerals obtained from the Wolsong site were applied to the experimental conditions for a radionuclide migration test for safety assessment of the Wolsong site.

3.4 Groundwater Flow

Numerical simulations for the groundwater flow were carried out to support the input parameters of safety assessment for the Wolsong LILW Disposal Center. Two numerical domains including regional and local scales were prepared in the simulations. The objective of the regional scale model was to select the local model boundaries. Using the results of the regional scale model, the boundary of the local scale was decided. In the local scale modeling, three hydro-geologic units (HSD, HRD, and HCDs in Fig. 3) were used based on the geological investigations. To obtain a hydraulic parameter assigned to each hydro-geologic unit (HRD and HCDs in Fig. 3) except for HSD in Fig. 3, the fracture network modeling work was carried out using a stochastic approach.

As a result, ten different hydraulic conductivity fields were generated which were used as input parameters in the local scale modeling. Concerning the hydraulic conductivity of HSD in Fig. 3, the calibrated values are used on the basis of results of an *in-situ* hydraulic test on the local scale modeling. The numerical simulations for groundwater flow at the Wolsong site were followed in the local scale flow simulations.

3.4.1 First Step: Undisturbed Condition of Groundwater Flow

Based on the results of *in-situ* hydraulic tests such as the observation of the water table and hydraulic tests, the current condition of groundwater flow was analyzed in the local scale domain. In this step, a steady state groundwater simulation was carried out. The result of simulation should be checked by *in-situ* data to calibrate the modeling.

3.4.2 Second Step: Construction of National Road and Disposal Facility

Using the result of the groundwater simulation in the first step, the transient state groundwater simulations were performed under the construction of a national road, operational tunnel, and disposal silo.

3.4.3 Third Step: Prediction of a Recovery of Groundwater Level after Facility Closure

Assuming facility closure, the transient state groundwater flow was simultaneously simulated after the second step of numerical simulation.

3.4.4 Fourth Step: Groundwater Flow System after Facility Closure

The aim of this step is to analyze the groundwater flow after facility closure using the steady state groundwater flow simulation. In this step, the input parameters for the safety assessment of the Wolsong LILW Disposal Center were obtained, such as the groundwater flux through each silo, groundwater flow pathway, and the groundwater flow distance from the silo to the biosphere.

4. WASTE CHARACTERISTICS

4.1 LILW Generation

A rock cavern type disposal facility initially scheduled to dispose of 100,000 waste packages (and ultimately 800,000 waste packages) was conceptualized. The current licensing application for a 100,000 waste package (waste volume of 35,200 m^3) facility has been approved simultaneously for operation and construction. For 100,000 waste packages, the total radioactivity is about 5.63E+15 Bq. The disposal facility consists of six silos, and the capacity of each silo is approximately 16,000 drums.

LILW in the Republic of Korea is generated from commercial NPPs, research institutes, nuclear fuel manufacturing facilities, and spent radioisotopes (RI). The type and quantity of waste packages for each waste producer are summarized in Table 2.

LILWs from the NPP operation of 20 units consist of miscellaneous radioactive solid wastes, concentrates, spent resins, and cartridge filters. Miscellaneous radioactive solid wastes occupy the most quantities among the LILWs generated from the NPP operation. A large portion of miscellaneous radioactive solid wastes are compressed, but non-compressible miscellaneous radioactive solid wastes are kept in 200L drum without waste processing.

Concentrate wastes were solidified with cement material before the installation of concentrate waste drying system (CWDS) in NPPs. After the operation of CWDS, concentrate wastes were solidified with a paraffin matrix. As for spent resin wastes, spent resin wastes were solidified with cement or stored in 200L drums that are shielded with concrete. Cartridge filters are stored in a concrete-lined drum or 320L drum. After the installation of drying using a spent resin drying system (SRDS), spent resin wastes are stored in the high integrity container (HIC) or polyethylene container.

LILWs generated from the research institutes (Korea Atomic Energy Research Institute) are from research reactor operation and decommissioning of the conversion facility. These wastes consist of concentrates, spent resins, cartridge filters, miscellaneous radioactive solid wastes, and decommissioning wastes. The spent resin wastes are solidified with asphalt material, and miscellaneous radioactive solid wastes are mainly solidified with cement materials. The rest of the waste is kept without processing.

LILWs from the nuclear fuel manufacturing facility (Korea Nuclear Fuel) consist of metal, wood, lime deposit, glass, miscellaneous radioactive solid wastes, concrete, composite, etc. These wastes are grinded, compressed, and dried.

Spent radioisotopes (RI) are generated from research institutes, hospitals, and industry. RI wastes consist of unsealed spent sources and sealed spent sources. Unsealed spent sources are grouped into combustibles, incombustibles, cartridge filters, non-compressible sources, organic sources, and inorganic sources. Unsealed sources will be processed in the disposal facility.

4.2 Waste Containers and Disposal Containers

Waste containers are classified with steel drums, concrete containers, HIC, and polyethylene containers. The steel drums are classified with 200L and 320L drums,

Table 2. Type and Quantity of Waste Packages for each Waste Producer

Waste Producers	Quantity (drums)	Type
Commercial nuclear power plants (KHNP)	About 70,000	miscellaneous radioactive solid waste, concentrates, spent resins, cartridge filters
Research institutes (KAERI)	About 16,300	concentrates, spent resins, cartridge filters, miscellaneous radioactive solid waste, decommissioning wastes
Nuclear fuel manufacturing facility (KNF)	About 5,600	metal, wood, lime deposit, glass, miscellaneous radioactive solid waste, concrete, composite, etc
Spent radioisotopes (RI)	About 6,100	unsealed source (Combustibles, incombustibles, cartridge filters, noncompressible, organic, inorganic), sealed source

Table 3. Type and Physical Characteristics of Waste Containers

Type	Form	Size (mm)	Weight (kg)*	Note
200L drum	Steel drum	Ø615 x H884	105~400	All wastes
320L drum	Steel drum	Ø713 x H955	250	All NPPs
Circular concrete	C1, C2	Ø1400 x H1300	6,900	Ulchin 1&2
	C4	Ø1100 x H1300	6,000	Ulchin 1&2
	Kori circular	Ø1060 x H1370	3,500	Kori 1&2
Rectangular concrete	4-Pack	L1460 x W1460 x H1180	6,000	Kori 1&2
Polyethylene	Polyethylene	Ø1194 x H1290	2,000	Kori, Ulchin, Younggwang
HIC	Ferralium	Ø1181 x H1289	2,000	Kori

* including radioactive wastes

Table 4. Disposal Containers for 200L and 320L Drum

Specification	Disposal Containers	
	16-Pack disposal container	9-Pack disposal container
Material	Concrete	Concrete
Size (W × L × H) (m)	2.73 × 2.73 × 1.14	2.4 × 2.4 × 1.21
Max. Weight (container weight) (ton)	18.34 (5.4)	10.81 (4.6)
Density (ton/m^3)	2.5	2.5

and the concrete containers are classified with circular concrete containers and rectangular concrete containers. The type and physical characteristics of containers are summarized in Table 3.

LILWs packed in 200L drums are disposed of in a 16-pack concrete disposal container. The extra compressed 200L drums are packed again in 320L drums. The nine 320L drums are disposed of in a 9-pack concrete disposal container. The physical characteristics of the disposal container for the 200L drums and 320L drums are described in Table 4.

Kori 4-pack waste containers and Kori circular concrete containers are used for the corroded concentrate wastes and spent resin wastes generated from Kori 1&2 NPPs. Circular waste containers such as C1, C2, and C4 are used for packing concentrate wastes, spent resin wastes, and filter wastes generated from Ulchin 1&2 NPPs. Polyethylene containers are used for drying spent resin wastes after the installation of SRDS. The drying spent resin wastes generated from Kori NPPs are packed in ferralium HICs.

5. DISPOSAL FACILITY

5.1 Layout

The facility layout of six disposal silos for the initial 100,000 waste packages is depicted in Fig. 4. The engineered barrier system of the disposal silo consists of waste packages, disposal containers, backfills, and a concrete silo. The conceptual drawing of the post-closure disposal silo is presented in Fig. 5.

5.2 Degradation of Engineered Barrier

The concrete silo has been considered the engineered barrier of the Wolsong LILW Disposal Center. It plays a major role in inhibiting water infiltration into the disposal facility and the release of radionuclides from the disposal facility. However, the permeability of the concrete silo slowly increases because of various degradation mechanisms [4]. After a long period of time, the concrete silo will lose its effectiveness as a barrier against groundwater infiltration and the release of radionuclides.

5.2.1 Concrete Degradation Processes

A number of processes are responsible for concrete degradation in the subsurface environment. Major degradation processes include acid attack, sulfate attack, the corrosion of reinforcement steel induced by chloride attack, calcium hydroxide leaching, alkali-aggregate reaction, and carbonation. Of those processes, sulfate attack, the corrosion of reinforcement steel induced by chloride attack, and calcium hydroxide leaching are reviewed and evaluated because the disposal facility is located below ground surface and is saturated with groundwater.

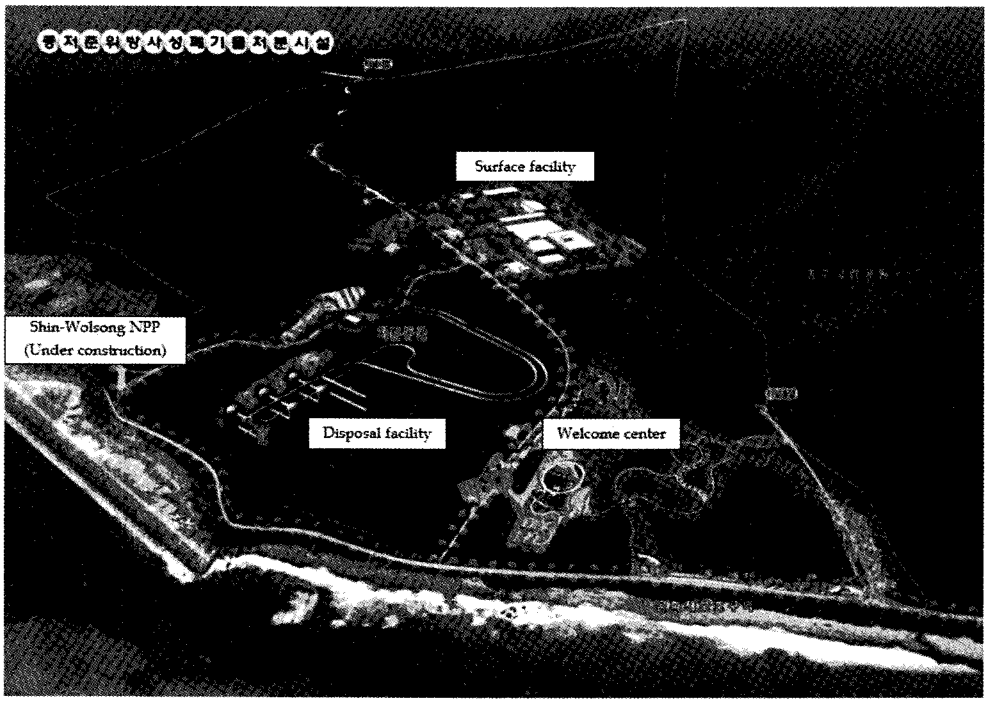

Fig. 4. Layout of the Wolsong LILW Disposal Center

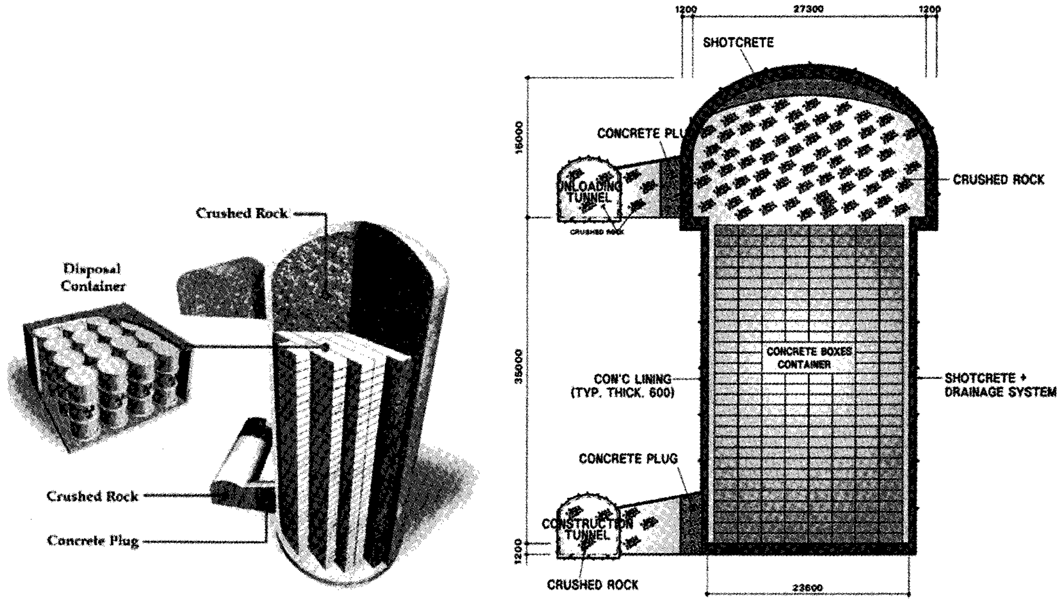

Fig. 5. Concept of Disposal Silos after Closure at the Wolsong LILW Disposal Center

· Sulfate Attack

Sulfate ion penetrates into the surface of the concrete and weakens the concrete wall. The model for sulfate attack was already proposed by Atkinson and Hearne [5]. The degradation rate (R, m/yr) of concrete from sulfate attack is estimated by:

$$R = \frac{EB^2 c_o C_E D_o}{\alpha\gamma(1-\nu)}, \tag{1}$$

where B is the linear strain caused by one mole of sulfate reacted in 1 m^3 (1.8×10^{-6} m^3/mol), c_o is sulfate concentration in water (mol/m^3), C_E is the concentration of the reacted sulfate as ettringite (mol/m^3), D_o is the intrinsic diffusion coefficient (m^2/s), E is Young's modulus (20 GPa), α is the roughness factor for the fracture path (assumed to be 1.0), γ is the fracture surface energy of concrete (10 J/m^2), υ is Poisson's ratio (0.3).

· Calcium Hydroxide Leaching

The leaching of concrete by groundwater removes soluble compounds such as $Ca(OH)_2$ from the hardened concrete. With these compounds removed, the compressive strength of the concrete gradually decreases. A shrinking core model proposed by Atkinson and Hearne [5] is adopted here. The model assumes that the calcium removal from the concrete exterior is rapid compared to the movement of calcium through the concrete. Thus, the transport of calcium in the concrete is controlled by diffusion. The depth into the concrete affected by Ca removal is then given by:

$$X = \left(2D\tau\phi \frac{C_i - C_{gw}}{C_b} t \right)^{1/2}, \qquad (2)$$

where D is the diffusion coefficient of Ca^{2-} ions in concrete (m^2/s), τ is the tortuosity factor (-), ϕ is the porosity (-), C_i is the concentration of Ca^{2+} ions in the pore space (mmol/kg), C_{gw} is the concentration of Ca^{2+} in groundwater (mmol/kg), and C_b is the bulk concentration of Ca^{2+} ions in solid concrete (mmol/kg).

· Corrosion of Reinforcement Steel

When steels corrode, the corrosion products have a larger volume than that of the initial steel. The expansion causes the concrete to crack and simultaneously increase the permeability. The concrete pore water tends to passivate the steel surface due to hyper alkaline condition. The passivated condition must be overcome before corrosion starts. The depassivation process is the result of diffusion of chloride ions, through the concrete, to the surface of the reinforcement steel. The diffusion of chloride ion is described by Fick's second law [6]:

$$C(x,t) = C_i + (C_S - C_i) \cdot erf\left(1 - \frac{x}{2\sqrt{D_{Cl}t}}\right) \qquad (3)$$

where $C(x,t)$ is the chloride concentration at depth x at time t, C_i is the initial chloride concentration (kg/m^3), C_s is the surface chloride content (kg/m^3), D_{Cl} is the apparent Cl diffusion coefficient (m^2/s), and $erf()$ is the error function. In the corrosion evaluation, the corrosion rate of 10^{-5} m/yr is conservatively assumed [7].

5.2.2 Evaluation of Concrete Degradation

Groundwater samples were collected from the disposal site to estimate the amounts of sulfate, chloride, dissolved oxygen (DO), dissolved organic carbon (DOC), pH, and other ions. In the sulfate attack process, the concrete degradation rate is calculated to be 1.03×10^{-3} cm/yr. For the concrete thickness of 60 cm in the disposal silo, this rate is negligible over 5,000 years, and, therefore, sulfate attack is assumed to be negligible for this analysis.

In the model of calcium hydroxide leaching, the Ca concentration in the concrete is calculated to be 15.7 mmol/kg using PHREEQC [8]. After 1,000 yr, the depth of calcium hydroxide leaching is estimated to be approximately 2 cm. Hence, it is concluded that this mechanism is negligible over 5,000 years for the disposal facility. In the evaluation of Eq. (3), it is unveiled that the degradation rate of the concrete silo due to chloride attack is much faster than the rates estimated from sulfate attack and calcium hydroxide leaching. Therefore, the concrete silo will be completely degraded after 1,400 years due to chloride attack on the reinforcement steel with the volume expansion of steel corrosion products creating internal stresses in the concrete silo.

6. SAFETY ASSESSMENT

6.1 Assessment Context

The assessment context provides a framework for the performance of the safety assessment, and it covers the key aspects such as the purpose, stakeholder, regulatory framework, assessment endpoints, assessment philosophy, and time frames. The Korea Hydro & Nuclear Power Co. Ltd. (KHNP) prepared the safety assessment for the licensing application of the Wolsong LILW Disposal Center. In this regard, the safety assessment of the Wolsong LILW Disposal Center can demonstrate that an acceptable level of radiation protection for human health and the environment can be achieved when compared with the nuclear regulatory criteria both now and in the future. Therefore, the target audience to whom the results of safety assessment are presented is the nuclear regulatory authority.

The assessment endpoints of this assessment need to correspond with the Korean regulatory requirements on individual effective dose and the associated risk to members of critical groups. Also, other performance indicators, such as radionuclide fluxes emanating from the disposal facility to the geosphere and from geosphere to the biosphere, can be used to complement those of dose and risk. Radionuclide concentrations at the geosphere-biosphere interface (GBI) can be included in RER and SAR. Approaches to calculate the assessment endpoints were based on a conservative assumption. Site-specific data from field investigation were used whenever possible.

Data values reported from the literature were used instead of those from field investigation when field data were not available. The assessment time for compliance with the performance objectives is specified in the government notice as 1,000 years. Calculations should be carried out to the time of the peak dose or peak risk. If the peak dose or peak risk do not occur during 1,000 years, the KHNP performs a safety assessment up to 1,000,000 years after facility closure. The duration of the active and passive institutional controls was specified by the KHNP. In selecting this period, consideration should be given to the waste characteristics, engineering designs, site characteristics, projected social activities and historical experience of retention of records and information, as specified in the government notice. The KHNP considered the institutional control (active and passive) of the site for a period of 100 years after the end of disposal operations.

6.2 Assessment Scenarios

Various internally consistent scenarios taking into account the evolution of the conditions of the waste disposal system were considered. The scenarios handle future uncertainty directly by describing several possible future paths. Both quantitative analyses and qualitative judgements guide the research. Subject matter experts guide the development of the description of the disposal system and include future projection studies [9].

The generation approach of the post-closure safety assessment scenarios for the Wolsong LILW Disposal Center is summarized by Park [10]. Based on the generation approach of ISAM methodology for scenario development [9], a total of seven post-closure assessment scenarios, including two reference scenarios and five alternative scenarios, were developed. The reference scenarios take into account radionuclide transport processes to both normal groundwater flow and gas-phase transport. The alternative scenarios include variations of the reference scenarios and include human intrusion processes into the disposal system.

6.2.1 Reference Scenarios

To develop the reference scenarios, an original set of plausible lists in the disposal system, or the so-called Features, Events, and Processes (FEPs) [9], were initially screened and reviewed, while considering the planned role of the safety function of the disposal system.

· BS-1 Reference Scenario

In this scenario, the safety functions of the engineered barrier is assumed to function as planned in the design stage. Degradation of the engineered concrete barrier is then assumed. Following this, groundwater in the bedrock starts to infiltrate into the disposal silo. After the groundwater comes into contact with disposed waste packages, and depending on local geochemical conditions of near-field, radionuclide dissolution and/or leaching processes commence. Radionuclides released from the waste matrix then migrate into the near field (disposal container, backfills, and engineered concrete material)

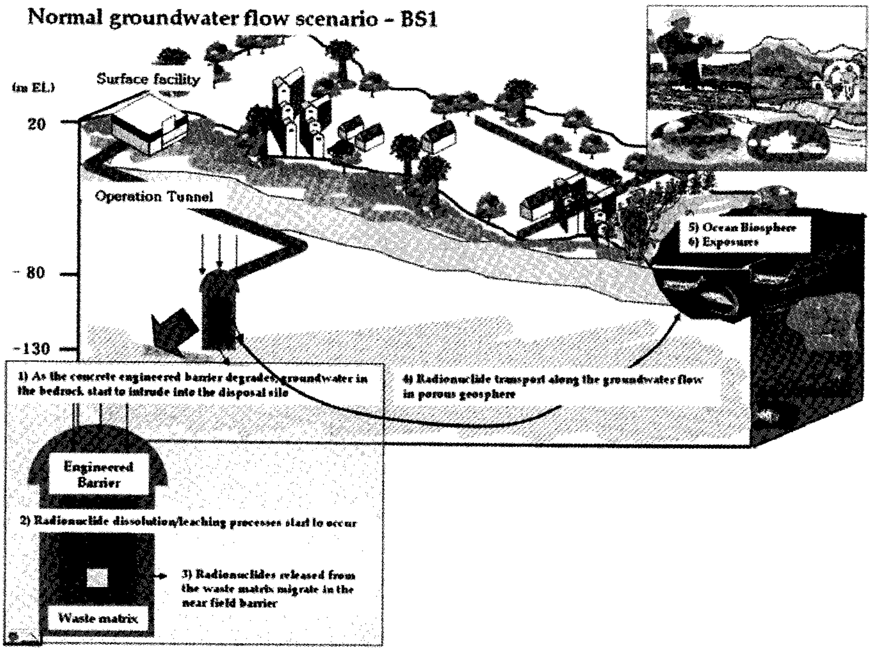

Fig. 6. Concept of the BS-1 Reference Scenario for the Wolsong LILW Disposal Center

via diffusion and/or advection processes. Physical and chemical degradation of the near field barrier was considered in the near field radionuclide transport. Radionuclide transport in a porous medium (the geosphere) is accounted for in the mathematical modeling. Transport processes, such as diffusion, advection, chemical sorption, and radionuclide decay, are considered. Finally, the ocean biosphere is considered in the assessment scenario. Fig. 6 shows the concept of the BS-1 reference scenario.

· BS-2 Reference Scenario

In this scenario, a water-saturated silo is considered. Gas phase C-14, H-3, and other volatile radionuclides generated by chemical and biological reactions were considered. These reactions take place between groundwater and the disposed radioactive waste and include the waste matrix and steel container *et al.* Gas-phase radionuclides are released by both diffusion processes through the barrier system and atmospheric pumping effects due to pressure changes. The dissolution of gas phase material was assumed to be controlled by gas phase solubility and pressure. Radioactive gas released from the near field barrier undergoes transport to the surface biosphere through both the designed gas vent system and geological fractures in the far field. Radiation exposure in the corresponding biosphere from this released gas is then considered.

6.2.2 Alternative Scenarios

Alternative scenarios are developed by varying the conditions of the reference scenarios. A total of 15 alternative scenarios were developed in the initial development stage. After considering the probability, uncertainty, and importance of each of the proposed scenarios, five alternate scenarios, including human intrusion events, were selected.

· ES-1A and ES-1B Alternative Scenarios

The ES-1 assessment scenario considers the premature failure of the engineered barrier due to natural (ES-1A scenario) and artificial (ES-1B scenario) events. The early release of radionuclides from the near-field into the geosphere is considered. Radionuclide exposure in ocean biosphere is also considered. However, the degradation of the concrete barrier is not considered.

· ES-2A and ES-2B Alternative Scenarios

The ES-2 assessment scenario considers the normal release in the near field as in the BS-1 reference scenario. Further considerations include the acceleration of radionuclide transport due to the formation of a preferential flow path in the far-field (ES-2A and ES-2B scenarios). A preferential flow path can be generated via a geological process including seismicity and hydrological/hydrogeological response to geological changes. The degradation of the concrete barrier is considered in the near field. Radionuclide exposure in the ocean biosphere is also considered (as in the BS-1 reference scenario).

· HS-1 Human Intrusion Scenario

The HS-1 scenario considers a human intrusion event into the disposal site due to drilling above the disposal silos. This drilling is considered to take place after the institutional control period and is assumed to be exploratory in nature with the intention of finding natural resources and/or conducting geological investigations. It is also assumed that *a priori* knowledge of the LILW disposal facility is lacking. Through-drilling into the disposal silo and the excavation of radioactive materials during the drilling process are considered. The excavated radioactive materials are assumed to spread out near the surface drilling site. The human (drilling) worker is assumed to receive both external and internal radiation doses.

· HS-2 Human Intrusion Scenario

This scenario is similar to the HS-1 human intrusion scenario. In addition to HS-1, HS-2 considers the activities of local residents, such as living in a house, gardening, farming, etc., in the contaminated biosphere and their associated radiation doses.

· HS-3 Human Intrusion Scenario

Drilling activity intended to develop the groundwater resource by well development is considered in the HS-3 human intrusion scenario, noting that HS-3 is not a direct intrusion into the disposal silo. Radionuclides released from the underground disposal silo are assumed to be extracted by the well-drilling worker to the surface through the well. The well location is assumed, as a reference value, to be 100 m along the radionuclide travel direction (in groundwater flow) away from the silo. Radionuclide transport in the groundwater flow in a porous geosphere is considered.

6.3 Assessment Results

The safety assessment modeling consists of groundwater modeling, radionuclide transport modeling, and biosphere modeling. The three-dimensional

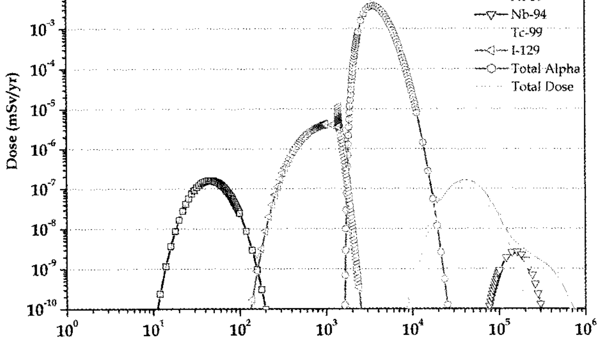

Fig. 7. Result of the Post-closure Safety Assessment for the BS-1 Reference Scenario

groundwater flow modeling discussed in Section 3.4 calculates groundwater travel time and computes a travel path from the individual silo to the corresponding geosphere-biosphere interfaces (GBIs), such as the ocean and the well. The results of the groundwater flow modeling provide essential input parameters for the radionuclide transport-modeling algorithm. The latter is based on a one-dimensional mathematical model. The biosphere model utilizes the radionuclide flux at GBI and calculates the pathway-specific flux-to-dose conversion factors of the radionuclides in the disposal system. In addition, the models themselves must all function simultaneously in a parallel fashion. In Fig. 7, the results of the post-closure safety assessment for BS-1 reference scenario are presented.

To investigate the safe management of LILW, the KHNP developed the first stage safety assessment. Data preparation, processing, and application for the safety assessment were conservatively coordinated. The radiological safety assessment results for all scenarios satisfied the regulatory criteria [11]. During and after the construction phase of the Wolsong LILW Disposal Center, the safety assessment needs to be developed further based on new findings from geological analysis, improved engineering of the barrier system, and new knowledge of waste characteristics.

7. LICENSING

7.1 Regulatory Requirements and Review Process

7.1.1 Regulatory Requirements and Technical Standards

Article 77 of the Atomic Energy Act (AEA) sets forth basic regulatory requirements for the Construction and Operation Permit of the low and intermediate level radioactive waste (LILW) disposal facility as follows:

- Location of a disposal facility and its structure, equipment, and performance shall conform to such standards in such a way that they may not, in any way, impede the prevention of hazards to human bodies, materials, and the general public caused by radioactive materials, etc.
- Construction and operation of disposal facility must not cause any impediments to the prevention of danger or injury to human health and the environment caused by radioactive materials, etc.
- Equipment and manpower prescribed by Article 220-4 of the Enforcement Decree of the AEA must be secured.
- Technical capabilities necessary for construction and operation of disposal facility and related facilities shall be available as per Article 29-2 of the Enforcement Regulation of the AEA.

The Regulations on the Technical Standards for Radiation Safety Control (RSC) and relevant notices issued by the Ministry of Education, Science and Technology (MEST) set forth detailed technical standards on the site, major structures, systems and components (SSCs) important to the safety and performance of the LILW repository and its radiological criteria.

Article 59 of the Regulations on the Technical Standards for RSC prescribes the fundamental siting criteria of the LILW repository and MEST Notice No. 2008-56 (Siting Criteria for the LILW Repository) addresses detailed the technical standards regarding the location of the repository. As for the seismic design, for instance, the repository shall be designed to prevent the failure of the safety-related functions due to earthquakes and shall be established on the basis of the geological conditions, the historical records of earthquake damage, and the current seismic activities of the area around the site. Furthermore, the repository shall be designed in consideration of the effect of natural phenomena other than earthquakes, such as flooding, extreme winds, landslides, sedimentation, and upheavals that can be anticipated through past record reviews and on-site investigations of the area surrounding the site so that the safety-related functions do not fail. In addition, the repository shall be constructed so as to minimize damage to the natural barriers, and the validity of the characteristics of natural barriers assumed at the design stage shall be confirmed through comparison with additional data to be obtained during the excavation and construction period.

Radiological performance objectives for the post-closure period of the LILW repository are set up in terms of the radiological risks for individuals of critical groups in the future. The radiological dose due to normal natural phenomena should not exceed the dose constraint of 0.1 mSv/y. The expected risk due to unpredictable phenomena caused by natural or artificial reasons should be restricted to the risk constraint of 10^{-6} /y or less. When the predicted dose or risk does not reach to its peak within the time-frame of 1,000 years, it must be demonstrated that leakage of radioactive materials into the environment will not increase drastically after the period and that acute radiation risk will not occur to individuals. The operational discharge limits of gaseous and liquid radioactive effluents released to the environment from the LILW disposal facility along with annual dose constraints to the public in the vicinity of the Repository are prescribed in Article 16 of MEST Notice No. 2008-31 (Standards on Radiation Protection, etc.)

Radiological environmental impacts that will be caused by radiation or radioactive materials from construction, operation, closure, and post-closure of the LILW repository must be analyzed and submitted to MEST as a Radiological Environmental Report (RER). Accident analysis for operational phase of the repository should be also conducted and described in the RER. In addition, facility information and the environmental status of neighboring regions should be also provided, and the radiological environmental monitoring programs (REMPs) for the pre-operational phase, operational phase, and post-closure

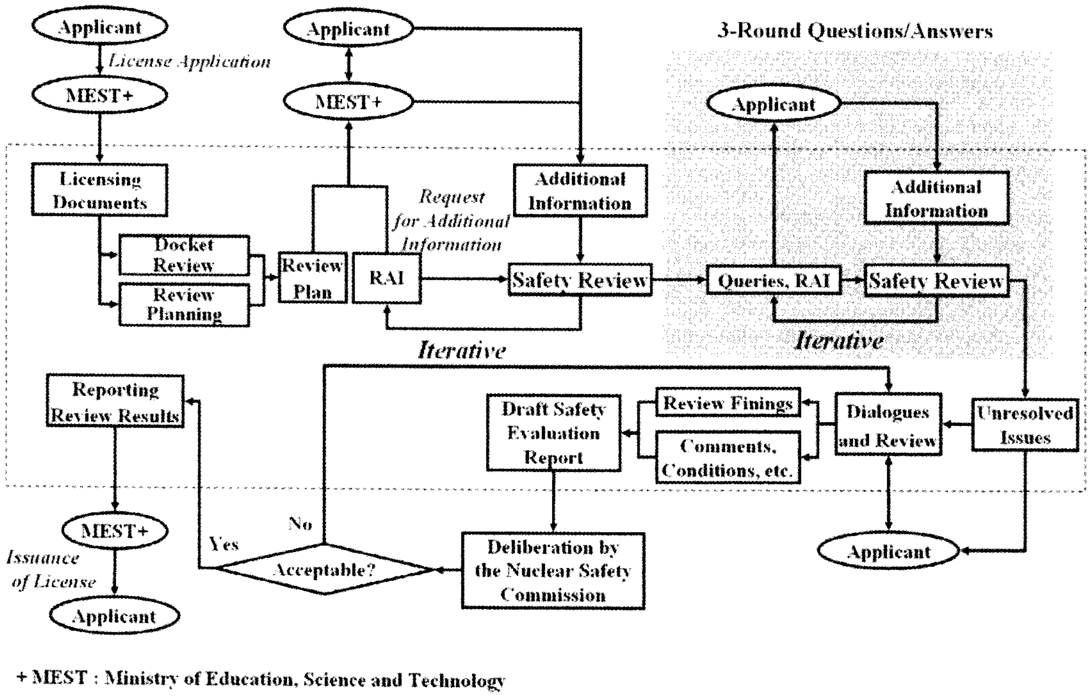

Fig. 8. Safety Review Process for Licensing of the Wolsong LILW Disposal Center

phase should be established, according to MEST Notice No. 2008-28 (Regulation on the Environmental Radiation Survey and Impact Analysis in the Vicinity of Nuclear Facilities).

The Regulations on the Technical Standards for RSC, etc. also set forth basic technical standards on the SSCs important to safety at the LILW repository, such as heating, ventilation, and air conditioning (HVAC), fire protection, monitoring and control, emergency electrical power source, drainage, radiation control, waste treatment systems, etc. More detailed standards on the major SSCs are provided in MEST Notice No. 2008-60 (Criteria for Structure and Equipment of the LILW Repository), and the SSCs important to safety shall be able to maintain normal operational status.

With regard to the QA requirements, a total of 18 QA criteria for the nuclear reactor facilities are also applicable to the LILW disposal facility, as per Article 82 of the Regulations on the Technical Standards for RSC and MEST Notice No. 2008-55 (Quality Assurance Criteria for Radioactive Waste Management Facilities).

7.1.2 Regulatory Review Process

Fig. 8 shows the overall safety review process taken up to the licensing of the LILW Repository, which conforms to the draft recommendations of the Regulatory Review Working Group under the International Atomic Energy Agency (IAEA)-coordinated international research project, the Application of Safety Assessment Methodologies (ASAM).

In the inception phase, before the license application was sent to the Ministry of Education, Science and Technology (MEST), the Korea Institute of Nuclear Safety (KINS) and MEST established an initial plan for the safety review and had dialogues with potential applicants. As requested by MEST, KINS reviewed the draft RER prepared by the applicants for public consultation and then notified the review results to the applicants through MEST for feedback into the revised version of the RER.

The initial safety review was undertaken, just after the KHNP submitted an application form along with ten kinds of license application documents to MEST for the Construction and Operation Permit of the Wolsong LILW Disposal Center on January 15, 2007. KINS officially organized the KINS Review Team (KRT) by recruiting internal technical staff having multidisciplinary expertise and finalized the Regulatory Review Plan including the review strategy, scope, and time schedule of the safety review. The Docket Review was conducted mainly on the completeness of the information in the licensing documents, and issues important to long-term safety were also identified. The applicant was notified through MEST of any identified partial deficiency of information, as well as of the Regulatory Review Plan, and then the license application documents were amended as appropriate throughout the subsequent review process.

The main technical review was conducted through three rounds of questions and answers (Q&As) between KINS and the applicant. The KRT evaluated all relevant technical elements to be verified for determination of whether or not the application met all regulatory requirements and technical standards. During each round of Q&A, the KRT requested for additional information to the applicant, and then the applicant provided amendments of the license application documents and/or supplementary additional information. At the end of each round, resolved issues were closed and unresolved ones were brought to the next round of Q&A for further consideration. In the main review phase, the KRT also collected independent technical perspectives on important issues through consultation with external experts.

In order to improve the public confidence and acceptability for the safety of the first domestic LILW disposal facility to be constructed, an International Review Team (IRT) coordinated by the IAEA conducted an independent peer review of the license application program and activities for the LILW disposal site in October 2007. The external experts' perspectives including the IRT's comments were prudently considered and deemed as appropriate in the KRT's safety review process.

In the completion phase, the KRT wrapped up its review findings and drafted the Safety Evaluation Report (SER), mainly consisting of the KRT's review results on the compliance of the license application with regulatory requirements. The draft review results were submitted to and deliberated by the five sub-committees of the Special Committee on Nuclear Safety under the Nuclear Safety Commission (NSC). KINS submitted the final SER, in which the comments raised by the five sub-committees were appropriately reflected, to MEST. On July 31, 2008, MEST submitted the review results to the NSC for deliberation and finally issued the Permit for Construction and Operation of the Wolsong LILW Disposal Center, based on the NSC's resolution and approval of the review results as submitted.

7.2 Key Technical Issues and Follow-up Action Program

7.2.1 Key Technical Issues

In the main review phase, after completion of three rounds of Q&As, a few Key Technical Issues (KTIs) were brought out and profiled for further intense deliberation. The KTIs which had been taken into consideration throughout the later part of the main review phase can be summarized as follows:

- Groundwater infiltration rate into silos: re-estimation of the groundwater infiltration rate into the concrete silos during the post-closure phase, in combination with justification of the human intrusion scenarios.
- Quality control of geochemical data: reconfirmation of the representativeness of empirically determined site-specific geochemical data (e.g. sorption coefficients, diffusion coefficients, etc.)
- Long-term management of uncertainties in geochemical data.
- Seismic safety and design: verification of the geological structure model and tectonic activity of the site.
- Structural stability of the rock-caverns and silos.

The above KTIs were resolved through regulatory dialogues and requests for more detailed information along with the applicant's amendments to the license application documents reflecting the results of further supplementary site surveys, safety assessments, and design changes, which occurred during the review process.

7.2.2 Follow-up Action Program

A series of items to be developed continuously throughout the life-cycle of the Wolsong LILW Disposal Center had been also derived during the review process and incorporated into the SER as a "Follow-up Action Program (FAP)," which was officially requested by MEST for the applicant to implement as a licensing condition. The action items to be implemented by the Wolsong LILW Disposal Center according to the FAP can be summarized as follows:

- SSCs important to safety: supplementation of the detailed design of instrumentation and control systems, establishment of a detailed fire protection program, etc.
- Operational safety: supplementation of detailed design of effluent monitoring systems, establishment of important operational programs and manuals, etc.
- Site and structural safety: supplementation of detailed information on the performance monitoring systems and programs of structures, experimental results on the durability of the silo, etc.
- Safety assessment and geochemistry: verification of important properties of natural barriers using construction field data, etc.
- Hydrogeology: supplementation of hydrogeological data and relevant models, etc.;
- Geology/hydrogeology: assessment of actual water-proof performance of grouting, etc.;
- Post-closure safety assessment: establishment and development of stepwise comprehensive safety cases, uncertainty management programs, etc.
- Operational safety assessment: further justification of screening and exclusion of potential operational accident scenarios, etc.

Fig. 9 shows the structure and concept of the derivation and implementation of the FAP throughout the review process and the life-cycle of the LILW disposal facility. These follow-up measures should be understood as a general requirement of the continual implementation of the safety assessment over the disposal phases, which correspond well with the technical standard on the periodic renewal of safety assessment prescribed in the MEST Notice for the operation of disposal facilities. Besides such

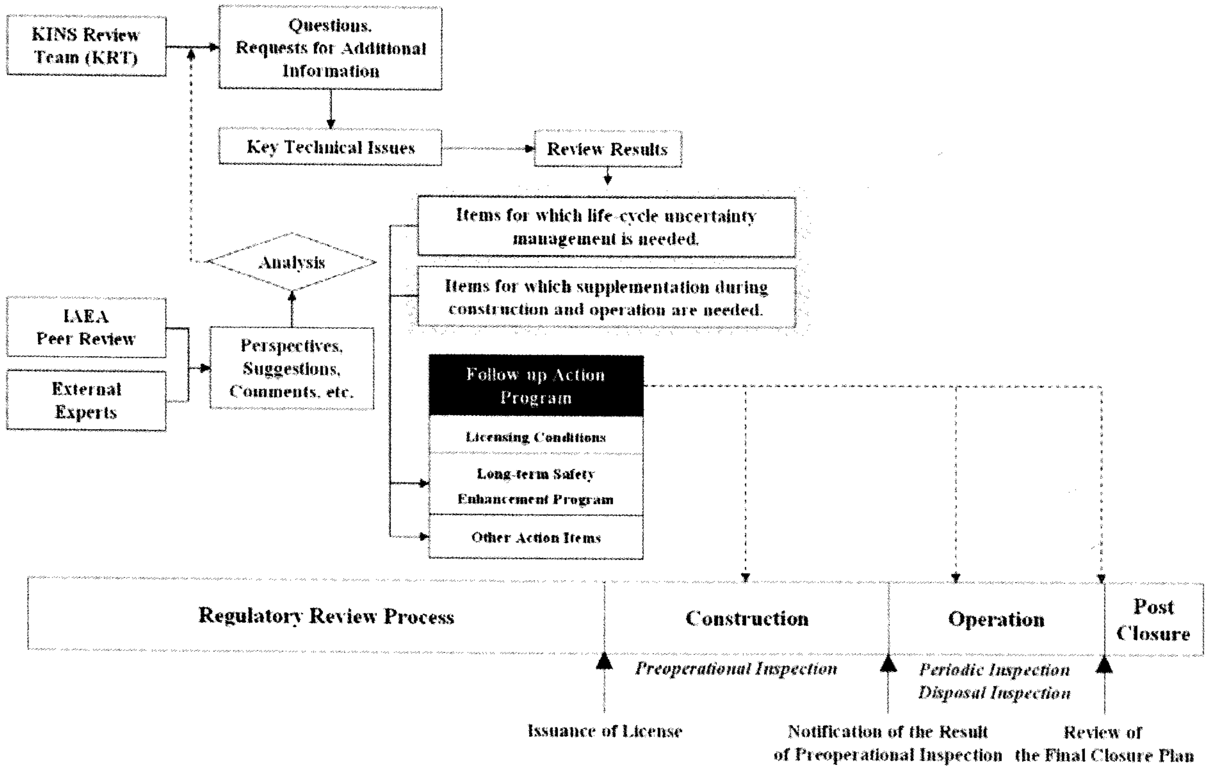

Fig. 9. Framework of Derivation and Implementation of the Follow-up Action Program

an essential ground, the safety assessment has additional significance in that the Wolsong LILW Disposal Center will be gradually expanded into a disposal complex with capacity up to 800,000 waste packages. It is expected that this program will resolve problems with the initial safety assessment and improve the safety of the Wolsong LILW Disposal Center.

8. FURTHER EFFORTS

8.1 New Organization

After obtaining the construction and operation permit from the nuclear regulatory body, construction began on the Wolsong LILW Disposal Center in August 2008 to dispose of 100,000 waste packages.

To meet the international standard of radioactive waste management, a new law on radioactive waste management was promulgated in March 2008 laying the foundation of a new organization named the "Korea Radioactive-Waste Management Corporation (KRMC)" and the "Radioactive Waste Management Fund." The KRMC has a broad spectrum of national missions in radioactive waste management, as follows:

- Transport, storage, treatment(RI), and disposal of LILW,
- Site selection, construction, operation, and monitoring of disposal facilities,
- Research and development (R&D) and technical supports to waste generators,
- Information management, international cooperation, and advertisement in the area of radioactive waste management,
- And finally, operation of the Radioactive Waste Management Fund.

The KRMC undertook the above missions in the beginning of 2009 in order to be the only Korean organization specialized in radioactive waste management. The focus of the KRMC is 1) the safe construction and operation of the Wolsong LILW Disposal Center, 2) the derivation of a social consensus on interim management of spent nuclear fuels, 3) the development of management technology, and 4) the settlement of credibility from the public.

8.2 Change of the Waste Management System

The departure of the Wolsong LILW Disposal Center and the KRMC implies the necessity to change the existing domestic waste management system. Since the complete pathway of the LILW is now established from generation to disposal, the waste management system can proceed naturally to disposal. Until now the regulation has reflected a viewpoint of disposal in predisposal management, but from now on the disposal facility operator should be a practical controller in this stream. This change is very natural in that the acceptance of waste in disposal is judged by the disposal facility operator in terms of its own criteria which specify waste characteristics and, thus, all the previous steps, including pretreatment of waste, treatment, conditioning, storage, and characterization.

Therefore, the disposal facility operator should substantially control all the predisposal steps, and the relevant regulation should focus on the radiation safety while the regulation for waste disposal should be concentrated on the disposal facility. In other words, the legal controls on waste management in terms of disposal will be carried out indirectly through safety inspections of waste disposal on the disposal facility, during which the validity of the operator's predisposal control or the suitability of the waste generators' predisposal management must be proved.

A proper apportionment and mutual assistance is essential between the disposal facility operator, waste generators, and the regulatory institute so that the new system will work well. First of all, the disposal facility operator should establish guidelines on relevant predisposal management and the waste characterization program in relation to disposal, and provide them for waste generators and predisposal managers in a timely manner. Waste generators and predisposal managers should check the existing methods and practices for waste management in terms of the waste acceptance criteria, and adjust them, if necessary, to the repository operator's guidance under close cooperation with the operator.

In addition, the regulatory institute should distinguish the respective scope and content of the regulation, as mentioned above, between the predisposal management and the disposal of waste, and refer to or consult the disposal facility operator about predisposal matters. In short, there is a necessity for close cooperation among the related organizations, particularly for this transition period so that the system can settle down.

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