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《Technical Note》

Technology Assessment of the Repository Alternatives to Establish a Reference HLW Disposal Concept

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Abstract

As disposal packaging concepts of spent fuels generated from the domestic NPP, two types, one is to package PWR and CANDU spent fuels in different containers and the other is to package them together, were proposed. The configuration of the containers and the layout of underground repository, such as the container spacing and the deposition tunnel spacing, were developed. The layout of underground repository satisfies the thermal constraint of the bentonite buffer surrounding disposal container, which should be lower than 100℃ in order to keep the physical and chemical properties of bentonite. From the spent fuel packaging concepts and container emplacement methods, seven options were developed. With a typical pair-wise comparison methods, AHP, the most promising disposal concept was selected based on the technology point of view.

Key Words : high level waste (HLW) disposal concept, repository system

1. Introduction

The United States started recently commission-ing WIPP (Waste Isolation Pilot Plant), which has been prepared to dispose TRU (TRansUranic) waste in the 600m deep rock salt layer since the middle of seventies. TRU waste is clearly different from HLW (high-level waste) generating decay heat. However, both wastes contain long-lived elements with high radiotoxicity, which is a principal factor affecting the long-term disposal safety. Because of that, the operation at WIPP could be considered as the first trial for practical operation of deep geological repository in the world. The U.S. is also preparing a deep geological repository for spent fuel and HLW at Yucca Mountain in Nevada for commissioning in 2010[1]. Other countries such as Sweden, Finland, Germany and Canada have already established or developed their own disposal concepts with regards to their peculiar geo-environmental conditions and waste characteristics since the middle of seventies or early eighties[2]. While, Korea has just started a R&D program for HLW disposal technology development since 1997. The main purpose of this program is to establish a reference HLW repository system by 2006. The disposal concept being conceived in this program is to encapsulate the spent fuel in corrosion resistant containers. The spent fuel packages are then to be disposed in a mined underground facility located at about 500m below surface in a crystalline rock mass. No site for the underground repository has been specified in Korea, but a generic site with granitic rock is considered for this study. The waste packages are placed in the boreholes drilled in the floor or in the wall of deposition tunnels. Many of different alternatives concerning the emplacement patterns of the container, waste packaging methods as well as the distance between deposition holes and tunnels, are available. From these feasible options, it is necessary to choose a reference disposal concept, which is the most promising from the aspect of technology, long-term safety and cost. In this study, the reference concept was selected based only on the technology assessment of the proposed options because of the lack of relevant information for the safety and cost assessments. Further research including safety and cost will be carried out in the future.

In this study, two types of packaging options were proposed with consideration of the characteristics of spent PWR and CANDU fuels generated from the domestic nuclear power plants. The emplacement methods and the repository layout options, which are to sketch how the containers can be configured in the underground repository, were then proposed. The repository layouts are based on the results of the thermal calculations, which were designed to determine whether the deposition holes and/or tunnels spacing satisfy the thermo-mechanical safety constraints or not. From the packaging concepts, the emplacement methods, and repository layout options, seven different disposal alternatives were developed. In order to select one or two most promising option(s), a typical pair-wise comparison method, the analytical hierarchy process (AHP) method[3], was used. The comparison of each alternative was done with regard to the construction and operation technology. For construction technology, construction method, safety, site availability and environmental impact for each alternative were considered as the comparison criteria. For operation technology, waste encapsulation, transportation/ handling, deposition and buffering, backfilling and sealing technology including the operation safety and retrievability were included.

2. Basic Concerning for Disposal Alternatives

In this study, spent fuel, which is more conservative than HLW at the point of radioactivity and residual heat, was considered as the waste form to be disposed of. For developing alternative disposal concepts as well as for preparing the fundamental disposal method of the waste, the following items were focused in this study.

- Container material and packaging methods: It is required to decide the optimum packaging method with consideration of the types and characteristics of the spent fuel from the nuclear power plants in Korea. In this study, only intact spent fuel is assumed to be disposed of.
- Emplacement of container: From the literature review of deep geological disposal concepts of several countries, it was found that the vertical or horizontal emplacement method was usually considered. Thus both emplacement methods were considered in this study.
- Deposition tunnel configuration: Several deposition tunnel configurations were developed based on the thermal criteria, which forces that the temperature in bentonite buffer around the container should be lower than 100°C in order

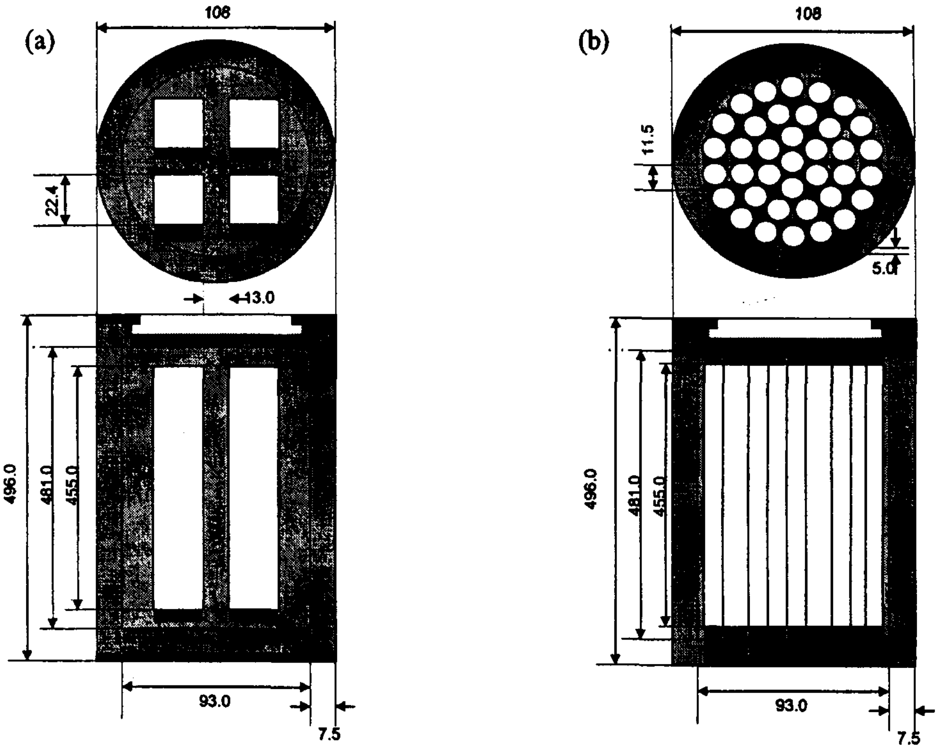
not to lose the physical and chemical properties of bentonite. The deposition tunnel spaces and deposition borehole intervals for the alternatives were determined from the thermal analysis.

3. Disposal Alternatives

3.1. Basic Assumptions

Basic assumptions include disposal capacity and the functional and technical criteria, which are needed in developing feasible packaging methods and underground repository concepts with concerning the characteristics of the reference spent fuel[4]. This information might be changed in parts in the future due to new scientific information or adjustments of waste management policies or strategies. The following basic assumptions were proposed for this study:

- Repository capacity : 36,000 tHM
  - Spent PWR fuel : 20,000 tHM (45,500 assemblies, based at 0.44 tHM/assembly)
  - Spent CANDU fuel : 16,000 tHM (842,100 bundles, based at 0.019 tHM/bundle)
- Decay heat (40 years cooling) : PWR 385 watt/assembly, CANDU 2.28 watt/bundle
- Spent fuel packaging criteria :
  - Temperature of spent fuel cladding in the container<200℃ (in air), which is to protect long-term integrity of spent fuel by preventing UO_2 oxidation, oxidation film on fuel clad, and etc. under the underground repository conditions.
  - Surface temperature of the disposal container <100℃, which is to keep the desired functions of the bentonite buffer as physical and chemical barrier.
  - Dose rate on the surface of the container <500 mGy/hr, which is to prevent significant radiolysis of surroundings of near-field.
  - Nuclear criticality, $K_{eff} \leq 0.95$
- Operation period of repository: 50 years for which a repository should be subject to monitored retrievable operation to retrieve spent fuel from the underground repository, when the national disposal safety regulation or strategy or philosophy would be changed. In the cases of mistakes, equipment failure or other incidents at the container emplacement or later, the container may be forced to be recovered to correct the errors.
- Depth of underground repository: 500m.
- One ramp and several shafts connect surface and sub-surface facilities. The ramp is used for the transportation of the containers and the heavy parts for construction and operation. The shafts are for ventilation, drainage, utilities provision and the transportation of excavation wastes.
- The access and deposition tunnels are constructed by conventional drill and blasting. The vertical and horizontal deposition holes for the final emplacement of the waste packages are prepared by blind boring and raise boring methods, respectively.
- The waste packages are vertically handled in the encapsulation processes and then horizontally loaded on the transportation vehicle.
- As soon as the waste package is emplaced in the deposition hole, the empty space surrounding the disposal container in the deposition hole is filled with compacted bentonite buffer material. After the designed monitored-retrieval operation, all access and deposition tunnels are backfilled with the mixture of crushed rock and bentonite.
- In order to protect the operators from radiation, the disposal container is handled in a shielded flask during the whole transportation and emplacement processes.
- The repository operation and construction works are concurrently conducted.



(a)

- ❖ Canister Outer shell : Copper or Ni-Alloy
- ❖ Cast Insert (Fuel region) : Carbon steel
- ❖ Capacity : 4 PWR Spent Fuel Assemblies
- ❖ 11,375 containers
- ❖ Residual Heat in Canister : 1,540 Watt
- ❖ Total Volume : 4,513 m³
- ❖ Surface : 19 m²
- ❖ Total Weight : 32,963kg
  - ☞Fuel wt. : 2,660 kg
  - ☞Cast Insert : 19,189kg
  - ☞Container wt. : 11,114 kg (copper)
    9,885 kg (Ni-alloy)

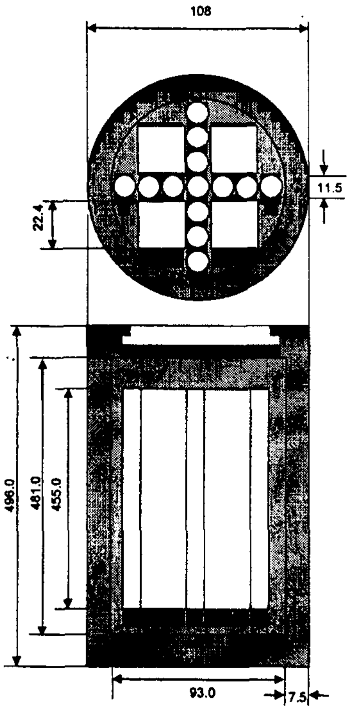
(b)

- ❖ Canister Outer shell : Copper or Ni-Alloy
- ❖ Cast Insert (Fuel region) : Carbon steel
- ❖ Capacity : 333 Bundles (37 tubes x 9 stacks)
- ❖ 2,529 canisters
- ❖ Residual Heat in Canister : 760 Watt
- ❖ Total Volume : 4,513 m³
- ❖ Surface : 19 m²
- ❖ Total Weight : 34,967kg
  - ☞Fuel wt. : 8,325 kg
  - ☞Cast Insert : 15,528kg
  - ☞Outer-shell wt. : 11,114 kg (copper)
    9,885 kg (Ni-alloy)

Fig. 1. Schematic Diagram of Separated-Packaging Disposal Container for Spent PWR (a) and CANDU (b) Fuels

3.2. Spent Fuel Packaging Concept for Disposal Container

Two different packaging concepts are available in consideration of the characteristics of spent PWR and CANDU fuels from the nuclear power plants in Korea. Figure 1 shows the separated-packaging concept in which spent PWR and CANDU fuels are loaded in different containers. Figure 2 shows the co-packaging container, which can accommodate spent PWR and CANDU fuels together. The overall sizes and material types of the containers for the two concepts are exactly same independent of the encapsulation process and disposal concepts. Inside of the container is consisted of square tubes for spent PWR fuel and circular tubes for spent CANDU fuel. For the complete isolation of the waste from the environment for a long time, high nickel alloy (Alloy22) and cast iron were chosen as the reference materials for the outside and inside shells of the container. In the case of copper for



- ❖ Canister Outer shell : Copper or Ni-Alloy
- ❖ Cast Insert (Fuel region) : Carbon steel
- ❖ Capacity : 4 PWRs + 13x9 CANDUs
- ❖ 7,198containers + 4177PWR containers
- ❖ Residual Heat in Container : 1,807 Watt
- ❖ Total Volume : 4,513 m³
- ❖ Surface : 19 m²
- ❖ Total Weight : 33,305kg
  - ☞Fuel wt. : 5,585 kg
  - ☞Cast Insert : 16,606kg
  - ☞Outer-shell wt. : 11,114 kg (copper)
    9,885 kg (Ni-alloy)

Fig. 2. Schematic Diagram of Co-Packaging Disposal Container for Spent PWR and CANDU Fuels

the outer shell material, the life time is expected from several hundred and thousand years to several million years under the normal disposal conditions, but the cost will be increased significantly and will be important part of the overall disposal cost [5]. The outside nickel alloy wall thickness of the reference container is about 7.5 cm and the space between the inside baskets and spent fuel will be filled with cast iron insert. The evaluation of the mechanical/structural stability as well as the expected lifetime for the presumed structure and materials of the reference container will be carried out in the future in consideration of the required performance of the container and technical availability. Also quantitative cost analysis for different material types will be carried out.

The followings list some important features of the proposed container concepts for developing repository system alternatives.

1) In the case of separated-packaging concept, 11,375 containers for spent PWR fuel and 2,529 containers for spent CANDU fuel are required to dispose the spent fuel of 36,000tHM. According to the co-packaging concept, 11,375 containers for loading spent PWR and CANDU fuels together.
2) Engineering data for the comparison of the packaging concepts are as following:
   - Shape, size, weight, material, and etc. : Figure 1 to 3
   - Capacity of the container :
     - Separated-packaging : 4 spent PWR fuel assemblies in a PWR container and 333 spent CANDU fuel bundles in a CANDU container
     - Co-packaging : 4 PWR fuel assemblies and 72 CANDU fuel bundles
   - Container filling method and filling material: Cast iron insert fills the whole container except the space for square/circular tubes, in which spent fuel will be loaded.
3) Defect rate of the containers during the manufacturing processes of the container and the encapsulation processes is 10^{-3}. The containers defected before the final emplacement will not be disposed and the disposed containers are assumed not to be damaged by the surrounding environment during its lifetime.
4) Even though the containers are designed and

manufactured for being intact against possible accidents of small height drop during transportation and handling, the possibility of defect on the container to be handled is considered and determined from the transportation system from the surface facility to the final disposition location, the number of containers, the weight and size of container, and the number of hoisting, lifting, and tilting.

3.3. Underground Repository Concept

As described earlier, vertical and horizontal emplacement methods were considered as the emplacement methods of the separated-packaged container as well as the co-packaged container in underground repository. Table 1 shows how the separated- or co-packaged containers are emplaced and configured in the 7 alternative disposal concepts (4 alternatives for vertical emplacement and 3 alternatives for horizontal emplacements).

3.3.1. VAT (Vertical Emplacement of PWR or CANDU Container in Alternative Tunnels) Concept

General

In the VAT concept, the separated-packaging containers for spent PWR fuel and for spent CANDU fuel are vertically emplaced into the boreholes drilled along the center of the floor of the deposition tunnels. Deposition tunnels for the PWR fuel containers and for the CANDU fuel containers are located alternatively. The tunnel space and borehole interval for the PWR fuel deposition were determined from thermal analysis as 40 m and 6 m, respectively. With the tunnel space and deposition hole interval, the maximum temperature on the container surface was calculated as 93℃ (6.4 watt/m^2). Because of the lower decay heat generation from CANDU fuel, the deposition hole interval was determined as 3 m. In this concept, the required sub-surface area to accommodate 11,375 PWR fuel containers and 2,529 CANDU fuel containers was estimated to be around 2,192m × 1,824 m (3,998,208m^2).

Constructional Concerns

- Configuration of the deposition tunnels and boreholes
  - Length of a deposition tunnel: 250m, in which 12 m at the entrance and 10 m at the end of the tunnel are left without boreholes as a buffer zone.
  - Cross-sectional size of deposition tunnel : 4m (width) × 6m (height)
  - Size of the vertical deposition hole : 210 cm (diameter) × 796 cm (length)
  - Number of boreholes for PWR fuel deposition in a tunnel: 39 boreholes for emplacing 38 containers and 1 extra borehole. Therefore, the total number of PWR fuel deposition tunnels and boreholes in the repository are 300 and 11,700, respectively.
  - Number of boreholes for CANDU fuel deposition in a tunnel : 77 boreholes for emplacing 76 containers and 1 extra hole. The total number of boreholes in the repository is 2,618.
  - Total excavation volume of deposition tunnels and deposition holes : 2,305,633 m^3, in which ramp/shafts and access/transportation tunnels are excluded because those are the same for all alternatives.

Operation Concerns

- Transportation and handling of containers
  - Number of containers : 11,375 PWR fuel containers and 2,529 CANDU fuel containers.
  - The container is horizontally loaded on the

Table 1. Repository Alternatives with Respect to the Emplacement Methods of Waste Packages

Item	Case	Emplacement Method	Arrangements due to thermal load	Disposal Density[3]
Vertical Emplacement	VAT	Each separate-packaged PWR or CANDU fuel container is vertically emplaced in alternative deposition tunnels.	• Borehole Spacing : 6 m • Tunnel Spacing : 40 m • Container Surface Temp.: 93℃	9.0
	VSA	Each separate-packaged PWR or CANDU fuel container is vertically emplaced in separated deposition areas.	• Refer to note 1)	9.0
	VCop	Co-packaged PWR/CANDU fuel container is vertically emplaced.	• Borehole Spacing :10 m • Tunnel Spacing: 40 m • Container Surface Temp.: 93℃	9.0
	VAT-SPDC	For PWR fuel deposition tunnel, one container is vertically emplaced in one borehole and for CANDU fuel deposition tunnel two canisters in one hole.	• Borehole Spacing : 6 m • Tunnel Spacing : 40 m • Container Surface Temp.: 96℃	6.1
Horizontal Emplacement	HAT	Each separate-packaged PWR or CANDU fuel container is horizontally emplaced in alternative deposition tunnels.	• Borehole Spacing : 6 m • Tunnel Spacing : 40 m • Container Surface Temp.: 94℃	8.5
	HSA	Each separate-packaged PWR or CANDU fuel container is horizontally emplaced in separated deposition areas.	• Refer to Note 2)	9.3
	HCop	Co-packaged PWR/CANDU fuel container is horizontally emplaced.	• Borehole Spacing : 6 m • Tunnel Spacing : 40 m • Container Surface Temp.: 93℃	8.8

Note : 1) PWR fuel deposition area :
- Container spacing : 6 m
- Deposition tunnel spacing : 40 m
- Container surface temperature : 93℃

CANDU fuel deposition area :
- Container Spacing : 3 m
- Deposition tunnel spacing : 40 m
- Container surface temperature : 87℃

2) PWR fuel deposition area :
- Container spacing : 6 m
- Deposition tunnel spacing : 40 m
- Container surface temperature : 97℃

CANDU fuel deposition area :
- Container Spacing : 6 m
- Deposition tunnel spacing : 20 m
- Container surface temperature : 86℃

3) Disposal density = (total amount of spent fuel to be disposed of, kg of heavy metal)/(required area to accommodate all waste containers in accordance with the given alternatives, m^2)

vehicle after encapsutation process and then unloaded with rotating from horizontal position to vertical for the emplacement into deposition hole.

- Because PWR and CANDU fuel containers are emplaced in alternative tunnels, extra work for

Table 2. Hierarchic Structure of the Evaluation Criteria for Comparing 7 Repository Alternatives

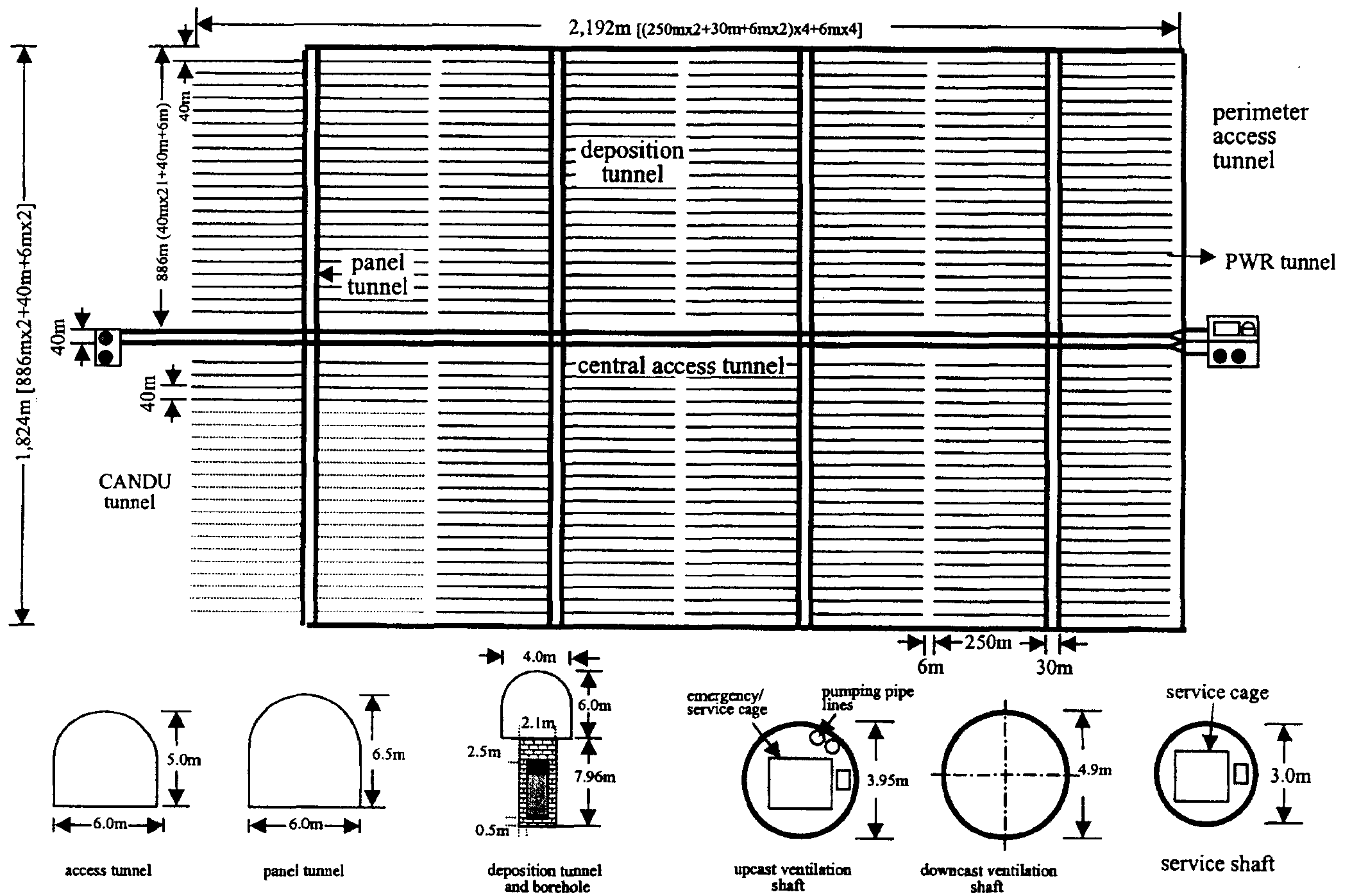
Level L0	Level L1	Level L2	Level L3	Factors to be compared	Alternatives
Technology (1.0)	Construction (0.407)	Site Availability (0.103)	⇒		VAT VSA VAT-SPDC HAT HSA Vcop Hcop
		Construction Method (0.145)	Excavation Method (0.044)	V/H/SPDC	
			Rock Support (0.025)	V/H	
			Ground Water Control (0.041)	V/H	
			Adjustability (0.035)	V/H/SPDC	
		Constructional Safety (0.081)	⇒	V/H/SPDC	
		Environmental Impact(0.078)	Excavation Waste (0.038)	⇒	
			Emissions (0.040)	V/H	
	Operation (0.593)	Encapsulation (0.089)	⇒	S/Co	
		Transport & Handling(0.081)	⇒	V+S/H+S/ V+Co/H+Co	
		Deposition & Buffering(0.0130)	⇒	V/H/SPDC	
		Backfilling & Sealing(0.104)	⇒	V/H	
		Radiation Protection(0.0807)	⇒	V+S/H+S/ V+Co/H+Co	
		Retrievability (0.102)	Several Container Retrieval (0.038)	V/H/SPDC	
			Partial Retrieval (0.040)	⇒	
			Whole Retrieval (0.024)	V/H/SPDC	

• Note :

- V : Vertical emplacement mode, H : Horizontal emplacement mode
- S : Separated-packaging container, Co : Co-packaging container
- V+S : Vertical emplacement of Separated-packaging container
- H+S : Horizontal emplacement of Separated packaging container
- V+Co : Vertical emplacement of Co-Packaging container
- H+Co : Horizontal emplacement of Co-Packaging container
- Values in the parentheses of the criteria are the average importance of the criteria

confirming that the container is to be emplaced in which deposition tunnel is required.

- Deposition of the container and buffering : Maximum height of possible drop during deposition is about 8m.



Deposition tunnel/borehole(PWR)	1,993,811
" (CANDU)	311,821
Panel tunnels	512,722
Shafts	28,519
Access tunnel	263,776
Total	***3,110,649***

No. of deposition tunnel (PWR)	300
No. of deposition tunnel(CANDU	34
No. of canister(PWR)	11,375
No. of canisters(CANDU)	2,529
Vol. for Buffering (m^3)	322,641
Vol. for backfill(dep. tunnel, m^3)	1,860,646

Fig. 3. Schematic Diagram of the VSA Repository Concept(Borehole Spacing : 6m for the PWR fuel and 3m for the CANDU fuel; funnel spacing: 40m)

3.3.2. VSA (Vertical Emplacement of PWR or CANDU Container in Separated Deposition Areas) Concept

Generals

In the VSA concept, the separated-packaging containers for spent PWR fuel and for spent CANDU fuel are vertically emplaced into the drilled-boreholes as described in the VAT concept. The different feature is that deposition tunnels for the PWR fuel containers and for the CANDU fuel containers are located in separated areas. From thermal analysis, the deposition tunnel space for both fuels was determined to be 40 m, while the borehole intervals for spent PWR and CANDU fuels deposition were determined as 6 m and 3 m, respectively. With the tunnel space and borehole interval, the maximum temperature on the PWR fuel container surface was calculated as 96℃ (6.4 watt/m^2), while 87℃ (6.3 watt/m^2) on the CANDU fuel container surface. In this concept, the required sub-surface area was estimated to be around 2,192m × 1,824 m (3,998,208 m^2).

Constructional Concerns

- Configuration of deposition tunnels and deposition holes
  - Length of a deposition tunnel : 250m tunnel, in which 13 m at the entrance and 12 m at the end of the tunnel are left without boreholes as a buffer zone.
  - Cross-sectional size of deposition tunnel : Same as the VAT concept
  - Size of the vertical deposition hole : Same as the VAT concept
  - Number of boreholes for PWR fuel deposition in a tunnel : 39 boreholes for emplacing 38 containers and 1 extra borehole. Therefore the total number of deposition tunnels and boreholes for PWR fuel deposition in the repository are 300 and 11,700, respectively.
  - Number of boreholes for CANDU fuel deposition in a tunnel : 77 boreholes for emplacing 76 containers and 1 extra hole. Therefore total number of CANDU fuel deposition tunnels and boreholes in the repository are 34 and 2,618, respectively.
- Total excavation volume of deposition tunnels and deposition holes : 2,305,633 m^3, in which ramp/shafts and access/transportation tunnels are excluded .

Operational Concerns : The overall operation process is similar to the VAT concept. In this concept, process to confirm that the container from surface is to be transported to spent PWR or CANDU fuel deposition area is required.

3.3.3. VAT-SPDC (Vertical Emplacement of PWR or Double CANDU Containers in Alternative Tunnels) Concept

General

In the VAT-SPDC concept, the basic emplacement patterns of separated-packaging containers for spent PWR and CANDU fuels are the same as mentioned in the VAT concept. The only difference is that two CANDU fuel containers are emplaced into one borehole in the CANDU fuel deposition tunnel. This concept was based upon the fact that the heat generation from spent CANDU fuel is approximately a half of that from spent PWR fuel. In this concept, the required sub-surface area was estimated to be around 2,192m × 1,824 m (3,998,208 m^2).

Constructional Concerns

- Configuration of deposition tunnels and deposition holes
  - Length of a deposition tunnel : 250m tunnel, in which 12 m at the entrance and 10 m at the end of the tunnel are left without boreholes as a buffer zone.

- Cross-sectional size of deposition tunnel : Same as the VAT concept
- Number of deposition holes in a PWR fuel deposition tunnel : 39 boreholes for emplacing 38 containers and 1 extra borehole. Therefore the total number of PWR fuel deposition tunnels and boreholes in the repository are 300 and 11,700, respectively.
- Number of boreholes in a CANDU fuel deposition tunnel : 39 boreholes for emplacing 76 (38×2) containers and 1 extra hole. Therefore, the total number of CANDU fuel deposition tunnels and boreholes are 34 and 1,326, respectively.
- Total excavation volume of deposition tunnels and deposition holes : 2,245,221m^3, in which ramp/shafts and access/transportation tunnels are excluded.

Operational Concerns : The overall operation processes are similar to the VAT concept. In this concept, the maximum height of possible drop during deposition is about 13.5 m.

3.3.4. VCop (Vertical Emplacement of a Co-Package) Concept

General

In the VCop concept, the co-packaged containers for spent PWR and CANDU fuels are emplaced in the vertical boreholes drilled along with the centerline in the floor of the deposition tunnels. The deposition tunnel space and borehole interval were determined from thermal analysis as 40 m and 10 m, respectively. With the tunnel space and deposition hole interval, the maximum temperature on the container surface was calculated as 96℃ (4.5 watt/m^2). In this concept, the sub-surface area required to accommodate 11,375 containers was estimated to be around 2,740 m×2,144 m (5,874,560 m^2).

Constructional Concerns

- Configuration of deposition tunnels and deposition holes
  - Length of a deposition tunnel : 250m tunnel, in which 12 m at the entrance and 8 m at the end of the tunnel are left without borehole excavation as a buffer zone.
  - Cross-sectional size of deposition tunnel : Same as the VAT concept
  - Size of the vertical deposition hole : Same as the VAT concept
  - Number of deposition holes in a PWR deposition tunnel : 24 for emplacing 23 containers and 1 extra borehole. The total number of PWR deposition tunnels and boreholes are 495 and 11,880, respectively.
- Total excavation volume of deposition tunnels and deposition holes : 3,085,079 m^3, in which ramp/shafts and access/transportation tunnels are excluded.

3.3.5. HAT (Horizontal Emplacement of PWR or CANDU Container in Alternative Tunnels) Concept

General

In the HAT concept, the basic repository layout and overall configuration of the separated-packaging containers for spent PWR and CANDU fuels are the same as mentioned in the VAT concept. The only difference is that all containers are horizontally emplaced in deposition holes that are horizontally drilled by raise boring method. The deposition hole space and the container interval were determined from thermal analysis as 40 m and 6 m, respectively. With the deposition hole space and container interval, the maximum temperature on the PWR fuel container surface was calculated as 94℃ (4.8 watt/m^2). In this concept, 11,375 PWR fuel containers and 2,529 CANDU fuel containers should be accomodated in the underground repository and the required sub-surface area was estimated to be around 2,063m × 2,068 m (4,266,284 m^2).

Constructional Concerns

- Configuration of deposition tunnels and deposition holes
  - Size of a horizontal deposition hole : 2.1 m (diameter) x 250 m (length) tunnel, in which 14 m at the entrance and 14 m at the end of the tunnel will be left without containers as a buffer zone.
  - Number of containers in a PWR fuel deposition tunnel : 37 containers with 6 m interval.
  - Number of deposition holes : 308 holes for the PWR fuel and 69 holes for the CANDU fuel
  - Total excavation volume of tunnels and deposition holes : 326,445 m3, in which ramp/shafts and access/transportation tunnels are excluded.

Operational Concerns : The overall operation processes are similar to the VAT concept. In the underground repository, the container horizontally loaded on the transportation vehicle is moved to the entrance of the horizontal deposition hole and then pushed into the deposition hole. Thus the operation processes are different from the vertical emplacement mode and the possibility of drop during deposition is much lower than vertical emplacement concepts.

3.3.6. HSA (Horizontal emplacement of PWR or CANDU container in Separated deposition Areas) Concept

General

In the HSA concept, the basic repository layout and the overall configuration of the separated-packaging containers for both fuels are the same as described in the VSA concept, except for the horizontal emplacement of the containers in the horizontally drilled-deposition holes. The deposition hole spacing and the container interval for the PWR fuel were determined from thermal analysis as 40 m and 6 m, respectively. In the case of spent CANDU fuel, the deposition hole spacing and the container interval were determined as 20 m and 6m. With the hole space and container interval, the maximum surface temperature of the PWR fuel container was calculated as 97°C (6.4 watt/m^2). In this concept, the required sub-surface area was estimated to be around 2,063m × 1,868 m (3,853,684 m^2).

Constructional Concerns

- Configuration of deposition tunnels and deposition holes
  - Length of a deposition tunnel : 250m tunnel, in which 14 m at the entrance and 14 m at the end of the tunnel will be left without containers as a buffer zone. And the cross-sectional area is the same as the HAT concept.
  - Number of containers in a PWR fuel deposition hole : 37 containers with 6 m interval.
  - Number of deposition holes : 308 holes for PWR fuel and 69 holes for CANDU fuel
  - Total excavation volume of tunnels and deposition holes : 326,445 m^3, in which ramp/shafts and access/transportation tunnels are excluded.

Operational Concerns : Same as the HAT concept

3.3.7. HCop (Horizontal Emplacement of Co-Packaging Containers) Concept

General

In the HCop concept, the co-packaging

Table 3. Ranking and Scores of the Alternatives on the Level of L0 and L1

Alternatives	Technology		Construction		Operation	
	Score	Rank	Score	Rank	Score	Rank
VAT	0.9037	2	0.3426	4	0.5611	2
VSA	0.9126	1	0.3426	4	0.5700	1
VAT-SPDC	0.8088	5	0.3080	6	0.5008	3
HAT	0.8472	4	0.3747	3	0.4725	6
HSA	0.8628	3	0.3864	1	0.4764	5
Vcop	0.8040	7	0.3074	7	0.4965	4
Hcop	0.8056	6	0.3796	2	0.4259	7

containers of the PWR and CANDU fuels are emplaced in horizontal deposition holes. The deposition hole space and container interval were determined from thermal analysis as 60 m and 7 m, respectively. With the hole space and container interval, the maximum temperature on the container surface was calculated as 98.5℃ (4.3 watt/m^2). In this concept, the required sub-surface area was estimated to be around 2,063m × 1,988 m (4,101,244 m^2).

Constructional Concerns

- Configuration of deposition tunnels and deposition holes
  - Length of a deposition tunnel : 250 m tunnel, in which 13 m at the entrance as well as at the end of the tunnel will be left without containers as a buffer zone. And the cross-sectional area is the asme as the HAT concept.
  - Number of containers in a PWR deposition hole : 32 containers with 7 m interval.
  - Number of deposition holes for co-packaging containers : 356
- Total excavation volume of tunnels and deposition holes: 308,261 m^3, in which ramp/shafts and access/transportation tunnels are excluded because those are the same for all alternative concepts.

Operational Concerns : Similar to the VCop concept except horizontal emplacement.

4. Comparison of the Disposal Alternatives

4.1. Evaluation Method

In order to compare and rank seven repository alternatives defined in the previous section, the Analytic Hierarchy Process (AHP) method developed by Saaty[3] was applied. AHP is a multi-criteria decision tool that uses hierarchic structure to represent a decision problem. It identifies priorities for the alternatives based on decision-maker' s judgments throughout the system. On the system, not only quantitative criteria but also qualitative ones can be used. Specifically, the selection of the AHP method was based on the following characteristics of the problems of ranking repository alternatives. First, it is a multi-criteria decision problem, since there are several criteria to be compared simultaneously. Second, the comparison criteria possess hierarchic characteristics and higher level criteria are composed of several lower level ones. Third, the process entails subjective ranking in that almost all comparisons have to be based on expert' s judgment. These characteristics, plus the fact that

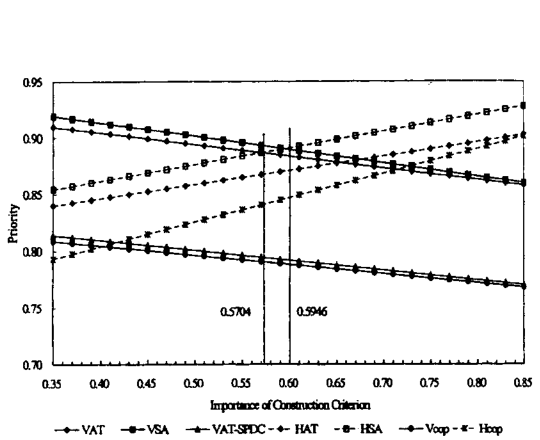


Fig. 4. Effects of the Importance of Construction and Operation Criteria on the Ranking of the Repository Alternatives

the AHP is an well established and proven method and that there are several computer softwares available for the evaluation led to the selection of the method.

The main steps of applying the AHP are 1) hierarchically structuring the problem and 2) making pair-wise comparisons of criteria and alternatives on those criteria. The first step is to structure the problem in the form of a hierarchy with the ultimate goal at the top and with one or more levels of criteria below. The structure would be expanded with the branches going down until one reaches the different alternatives to be compared at the bottom. The sub-level of the hierarchy can be anything describing the problem such as different scenarios and actors. What to be recommended in structuring is that the participants in the ranking process are involved in the early design of the hierarchic structure.

An important feature of the AHP is that all comparisons between criteria and between alternatives are made pair-wise. In this way it is possible to give correct judgments even in the case where lots of criteria are involved and intangible ones are included. This advantage, however, may be diluted in a problem of quite a few criteria and alternatives since the number of pair-wise comparisons to be required would put a burden on the respondents.

4.2. Evaluation Criteria

Based on the literature survey of the several countries' repository alternative system studies [7-10] and the consensus of the researchers who are involved in the HLW disposal technology development program in KAERI (Korea Atomic Energy Research Institute), the hierarchic structure of the evaluation criteria was prepared as listed in Table 2. On the level 1 (L1), Technology, the highest level as the final goal, is separated into Construction and Operation. Construction is again separated into 4 sub-criteria on the level 2 (L2) and Operation into 6 sub-criteria. Some criteria on the L2 are more classified into lower sub-criteria on the level 3 (L3).

Site Availability criterion concerning the disposal density is to evaluate which alternative could accommodate greater amount of waste in the unit sub-surface area. Excavation Method assesses the currently available excavation technologies to construct the underground repository. Here, the deposition tunnels were assumed to be constructed by conventional drill and blasting technique and the vertical deposition boreholes by blind boring, and the horizontal holes by raise boring. Rock Support deals with the easiness, technical maturity, and working condition of the supporting work needed to reinforce the underground space. Ground Water Control includes grouting, drainage, and sealing of the tunnels. Adjustability is to evaluate how the alternative has the ability to avoid unfavorable geological conditions during constructing. Environmental Impact is to evaluate which alternative has less environmental impacts caused by the excavation waste, dust, gas, water, vibration, and noise from the construction.

Encapsulation, Transportation & Handling, Deposition & Buffering, and Backfilling & Sealing are to evaluate the easiness, technical maturity, or working condition during the disposal container preparation and transportation to the underground facilities, deposition, buffering, backfilling, and sealing. Several Container Retrieval assesses the technology to retrieve the damaged containers or to correct the mistakes or errors during emplacement operation. Partial and Whole Retrieval deal with the retrieval of PWR fuel containers only or the complete retrieval of the containers emplaced in the repository during the monitored-retrieval operation period or after the final closure of the repository.

As an example, Figure 3 shows the schematic diagram of the VSA concept as defined in the previous section, which provides the required sub-surface disposal area, the volume of the excavation waste, the basic information for the repository layout such as the deposition tunnel and hole spacing and numbers, etc. Based on this information, the proposed seven alternatives are compared with respect to the evaluation criteria mentioned above.

4.3. Comparison and Evaluation

On the lowest leveled-evaluation criteria in Table 2, all alternatives are not necessarily evaluated with all corresponding criteria. On some criteria by which the alternatives are not distinguished well, only the representative common feature of the alternatives was taken into account in the comparison. In the case of Rock Support on L3, for example, this criterion discriminates only between the vertical and horizontal emplacement methods of seven alternatives. In the cases of Site Availability, Excavation Waste, and Partial Retrieval, there are some differences between the alternatives and thus all alternatives were evaluated on the assigned criteria. The distinguishing factors to be compared are shown in Table 2.

In this comparison and evaluation, 14 experts on different areas such as underground excavation, geoenvironment, nuclear engineering, and repository system were participated. Most of them have involved on various projects related to radioactive waste disposal for the last 10 years and thus they are thought to be the most familiar group to the HLW disposal technology. Among the 14 participants, 5 participants used pair-wise comparison, while others used direct comparison of the SMART(Simple Multi-Attribute Rating Technique) method[6].

Among the final evaluation by the 14 experts, 10 experts gave the highest score to the VAS concept, while the other 4 experts chose the HSA concept as the best disposal concept. From the average of the final score of all evaluation, it was possible to determine the preferred concepts as order of VSA, VAT, HSA, and VCop. However, it is not easy to consider this result as the final, because the investigation of each evaluation shows that one or two experts' scores for the evaluation criteria are too far from the average. Therefore, the maximum and minimum scores of each detail evaluation criteria were filtered out and then the average of the scores was used to derive the final result.

5. Results and Discussion

Values in the parentheses listed in Table 2 mean the importance level of each evaluation criterion. On the level 2 (L2), the most important criterion was Construction Method, and Deposition & Buffering, Backfilling & Sealing, Site Availability, Retrievability, and Encapsulation are followed.

Table 3 shows the final scores and ranking of the repository alternatives on the level L1, Construction and Operation, and on the level L0, technology. The HSA concept was ranked as the best alternative on the construction point of view, while the VSA concept was ranked as the best on the operation point of view. The overall results show that the VSA and VAT concepts were ranked as the first and second alternatives and the HSA and HAT concepts were 3rd and 4th alternatives. Since the alternatives adapting horizontal emplacement method are advantageous on construction point of view, it is expected that the scores of the HSA and HAT concepts would increase as the importance of construction increases.

Currently, the ratio of the importance of Construction and Operation is about 0.4 : 0.6. Figure 4 shows the possibility of ranking change of the alternatives with variation of the ratio. If the importance of construction is over 0.5704, the HSA concept will be better than the VAT. If it is over 0.5946, the HSA concept could be chosen as the best alternative. Since the best alternative is strongly dependent on the importance of construction, it is necessary to carry detail analysis of the results. Actually, the experts considered the importance of construction as a range of 0.17 to 0.7, which includes the critical point of ranking change. The average of importance of construction is 0.41 and the standard deviation (σ) is 0.15. Thus, the VSA concept is still the best alternative in the range of $\pm 1\sigma$, but not sure in the range of $\pm 2\sigma$. Even after filtering the minimum and maximum, there is ranking variation in the $\pm 2\sigma$ range, because the average is 0.41 and the standard deviation is 0.12. Future work is required to confirm the influence of importance of construction on the ranking of the alternatives. Compared to the strong influence of construction on the results, other parameters did not show a significant influence on the ranking of the alternatives. The reliability as well as the acceptability of the evaluation results could be assured as followings:

- Are the experts selected well? As commented earlier, the 14 experts have involved on various projects for the radioactive waste disposal technology development program for the last decade and can be considered as a reliable expert group for the evaluation of the alternative concepts. Also, it was possible to reduce the influence of non-expert' s opinion by filtering the minimum and maximum scores for each evaluation item.
- Is the hierarchic structure of evaluation criteria for the AHP application correct? Since the hierarchic structure of evaluation criteria was determined from the discussion between the experts on different areas, it can be assumed to be reliable. The most controversial item was retrievability. In the stage of the development of evaluation criteria, several experts did not agreed on including retrievability as an evaluation item. From the sensitivity analysis without retrievability, it could be proved that the influence of retrievability on the final ranking is not significant. Since other evaluation criteria also did not influence on the final ranking, the influence of unreliable evaluation criteria on the results is not significant. The possibility of excluding important evaluation criteria is low, because extensive literature review was carried out in the early stage of this study and tried to include all important evaluation items in the hierarchic structure.
- Is the result stable with minor variation of inputs? The results can be classified into two parts, the importance of evaluation criteria and the alternative score on the evaluation criteria. As discussed earlier, the importance of evaluation criteria is only sensitive to the result on L1 level but not sensitive to the other levels and thus stable with the variation. It is required to confirm the ranking of the alternatives with

respect to the sub-evaluation criteria, because the final score of the alternative is more influenced by the ranking than by the score. Therefore, it is more necessary to analyze the ranking of sub-evaluation criteria than the sensitivity analysis of the score. Experts participated in the ranking process reviewed the final results and concluded that the ranking reflected the current status of knowledge correctly.

- Are the final results possible to explain? The final ranking varies with the variation of the importance of L1 level. As already discussed, this is from the fact that some alternatives are better on construction point of view, while others possess advantages on operation.

6. Conclusions

In order to select the most promising concept from the proposed seven alternatives for a deep geological HLW repository system, 14 experts compared all alternatives and the results were analyzed systematically using the AHP method. From the study, it was possible to derive some meaningful results and the following conclusions could be drawn:

1. On the operation technology point of view, the vertical emplacement method is better than the horizontal and the VSA and VAT concepts were ranked as the best and the second best concepts, respectively.
2. On the construction technology point of view, the horizontal emplacement method is advantageous and the HSA and HCop concepts were ranked as the best and the second best concepts, respectively.
3. The ranking of the repository alternatives can be changed with the variation of the importance of Construction criterion. In the sensitivity analysis, the variation of the importance of Construction showed that the ranking of the VSA concept, the VAT, and the HSA could be changed in the range of the evaluation.
4. Variation of importance values below L1 level did not change the ranking of the alternatives.

From the study, vertical emplacement of separated-packaging containers in separated areas named as the VSA concept was suggested as the reference disposal concept. Horizontal emplacement of separated-packaging containers in separated areas (the HSA concept) can be considered as an possible alternative for the reference disposal concept.

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