An Initial Exploration of the Potential for Deep Borehole Disposal of Nuclear Wastes in South Korea[1]

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INTRODUCTION

South Korea's first commercial nuclear power reactor was placed into operation in 1978. Today, the Republic of Korea (ROK) has twenty reactors in operation: 16 pressurized-water reactors (PWRs) with a total electric generating capacity of 15 billion watts (GWe) and 4 CANDU heavy-water reactors (HWRs) with a combined electric-power-generation capacity of 2.8 GWe. An additional 8 PWRs (with a total capacity of 9.6 GWe) are under construction to be put into operation by 2016 and plans have been announced to build 11 additional PWRs (15.4 GWe) by 2030.[2] That will bring South Korea's total nuclear generating capacity up to 43 GWe.

As in other countries with nuclear power plants, South Korea's public has concerns about the management of radioactive waste. As the available space in-reactor storage pools become saturated with irradiated fuel assemblies, spent fuel management has become a hot issue. Korea Hydro and Nuclear Power (KHNP), South Korea's nuclear utility, has asserted that its nuclear power plants will begin to run out of spent-fuel storage capacity in 2016.[3]

At the moment, South Korea's debate regarding "back-end" nuclear fuel cycle issues (spent fuel management) is focused on "pyroprocessing," driven by the Korean Atomic Energy Research Institute (KAERI). This is partially because Japan has established its own spent fuel reprocessing capacity, and because, although a reprocessing plant could not be put into operation by the time that the PWR spent fuel pools begin to fill up, the expectation that the fuel will be reprocessed could provide a justification for establishing central storage for spent fuel near the site where the reprocessing plant would be built. Whether or not it pursues reprocessing, South Korea needs sites to accommodate geological repositories for its spent fuel and/or for the high level wastes (HLW) produced during reprocessing.

The deep borehole disposal concept has been recently receiving global attention due to its potential technical and cost advantages when compared with "normal" geologic disposal. The deep borehole concept involves drilling into crystalline basement rocks to a depth of 3 to 5-km, then placing waste canisters in the bottom 1-2 kilometers of the boreholes and capping the borehole such that the wastes are permanently isolated..

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[1] This study was funded by Nautilus Institute from a grant from the MacArthur Foundation.

[2] National Energy Committee, *The 1st National Energy Basic Plan (2008-2030)*, August 2008 (Korean). Includes 4 PWRs (5.6 GWe) to be brought into operation between 2017 and 2021, Ministry of Knowledge Economy, *The 4th Basic Plan of Long-Term Electricity Supply and Demand (2008 ~ 2022)*, December 2008.

[3] Ki-Chul Park, "Status and Prospect of Spent Fuel Management in South Korea," *Nuclear Industry*, August 2008 (Korean).

This report briefly explores the concept of using deep borehole disposal in South Korea. It begins with a review of international experience to date in evaluating the prospects of deep borehole disposal of nuclear wastes, then provides an initial review of the geologic suitability of the technology for Korea. The paper offers a review of the institutions, laws, and practices related to spent fuel management in the ROK, and offers tentative conclusions as to the applicability of deep borehole disposal for the nation and the Korean Peninsula.

DEEP BOREHOLE DISPOSAL (DBD)

History of DBD

Although US evaluation of DBD began in the 1950s,[4] more recent studies, beginning in the 1990s, have been more significant. A recent MIT study summarized principal earlier studies on DBD as shown in Table 1.[5] A 2003 MIT report recommended that DBD for spent fuel had the potential to significantly reduce risk compared to mined repositories, leading to an on-going project by the joint Sandia National Labs and MIT group to explore DBD as a possible alternative to the (developed but not completed, and recently cancelled) mined repository at Yucca Mountain, in Nevada.[6]

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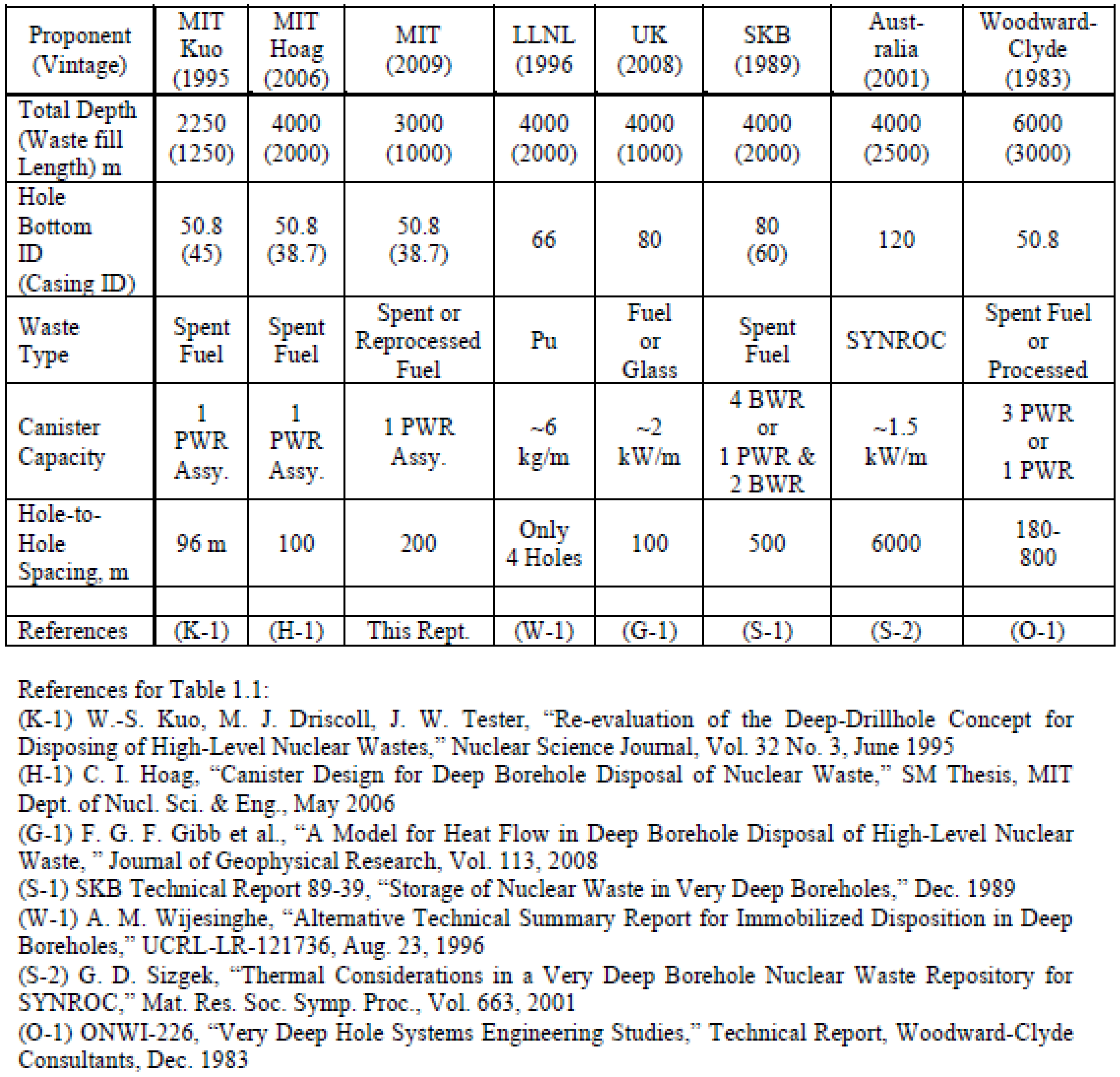
[4] Peter Swift, "Goals for a Deep Borehole Disposal Workshop," SNL-MIT Workshop on Deep Borehole Disposal, Washington, DC, March 15, 2010. Available in www.mkg.se/uploads/SNL_MIT_borehole_workshop_report_final_100507.pdf.

[5] Benyamin Sapiie and Michael J. Driscoll, *A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Wastes: For the MIT Study on The Future of the Nuclear Fuel Cycle*, MIT-NFC-TR-109, August 2009.

[6] Fergus Gibb, "Deep borehole disposal (DBD) methods," *Nuclear Engineering International*, 25 March 2010

Table 1: Summary Comparison of Deep Borehole Concepts



Proponent (Vintage)	MIT Kuo (1995	MIT Hoag (2006)	MIT (2009)	LLNL (1996	UK (2008)	SKB (1989)	Aust-ralia (2001)	Woodward-Clyde (1983)
Total Depth (Waste fill Length) m	2250 (1250)	4000 (2000)	3000 (1000)	4000 (2000)	4000 (1000)	4000 (2000)	4000 (2500)	6000 (3000)
Hole Bottom ID (Casing ID)	50.8 (45)	50.8 (38.7)	50.8 (38.7)	66	80	80 (60)	120	50.8
Waste Type	Spent Fuel	Spent Fuel	Spent or Reprocessed Fuel	Pu	Fuel or Glass	Spent Fuel	SYNROC	Spent Fuel or Processed
Canister Capacity	1 PWR Assy.	1 PWR Assy.	1 PWR Assy.	~6 kg/m	~2 kW/m	4 BWR or 1 PWR & 2 BWR	~1.5 kW/m	3 PWR or 1 PWR
Hole-to-Hole Spacing, m	96 m	100	200	Only 4 Holes	100	500	6000	180-800
References	(K-1)	(H-1)	This Rept.	(W-1)	(G-1)	(S-1)	(S-2)	(O-1)

References for Table 1.1:

(K-1) W.-S. Kuo, M. J. Driscoll, J. W. Tester, "Re-evaluation of the Deep-Drillhole Concept for Disposing of High-Level Nuclear Wastes," Nuclear Science Journal, Vol. 32 No. 3, June 1995

(H-1) C. I. Hoag, "Canister Design for Deep Borehole Disposal of Nuclear Waste," SM Thesis, MIT Dept. of Nucl. Sci. & Eng., May 2006

(G-1) F. G. F. Gibb et al., "A Model for Heat Flow in Deep Borehole Disposal of High-Level Nuclear Waste, " Journal of Geophysical Research, Vol. 113, 2008

(S-1) SKB Technical Report 89-39, "Storage of Nuclear Waste in Very Deep Boreholes," Dec. 1989

(W-1) A. M. Wijesinghe, "Alternative Technical Summary Report for Immobilized Disposition in Deep Boreholes," UCRL-LR-121736, Aug. 23, 1996

(S-2) G. D. Sizgek, "Thermal Considerations in a Very Deep Borehole Nuclear Waste Repository for SYNROC," Mat. Res. Soc. Symp. Proc., Vol. 663, 2001

(O-1) ONWI-226, "Very Deep Hole Systems Engineering Studies," Technical Report, Woodward-Clyde Consultants, Dec. 1983

Concept of DBD

In the DBD concept, a borehole is drilled in crystalline basement rocks to a depth on the order of 5 km. The bottom a 1-2 km of the borehole is used as the waste disposal zone, which might hold 200-400 canisters, as shown in Figures 1 and 2.[7] Figure 1 implies that the region of crystalline basement rocks is hydraulically decoupled from regions of groundwater flow. As shown in Figure 2, one such borehole, for example, could hold about 100-200 tonne heavy-metal (tHM) of pressurized water reactors (PWRs) spent fuel.

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[7] Patrick V. Brady et al., *Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2009-4401, August 2009; N. Chapman and F. Gibb, "A truly final waste management solution," *Radwaste Solutions* 10/4, p.26-37 (2003); Michael J. Driscoll, "A Case for Disposal of Nuclear Waste in Deep Boreholes," SNL-MIT Workshop on Deep Borehole Disposal, Washington, DC, March 15, 2010.

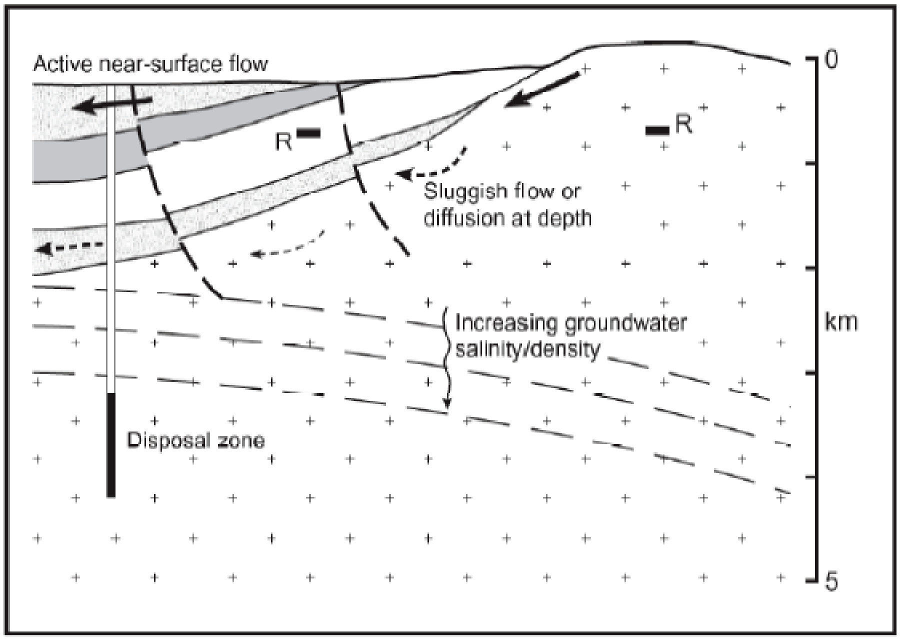

Figure 1: Conceptual Model for Deep Borehole Disposal

DBD would have potential advantages over normal geologic disposal, as it would place waste canisters at greater depths with less dynamic hydro-geological conditions, which increases confidence that eventual impacts on the biosphere by the radioactive waste can be avoided or substantially reduced. Low permeability in the deep crystalline basement rocks and the high salinity in the deep aquifers found there suggest that the chances of interaction of wastes with groundwater should be minimal. Crystalline basement rocks are relatively common at depths of 2 km to 5 km in many countries, leading to wider availability of suitable sites for DBD. In addition to greater safety through better isolation of wastes from the biosphere, greater security against terrorist diversion of wastes disposed of in DBD and better cost-effectiveness would be additional potential benefits.[8]

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[8] Bill W. Arnold et al., "Into the deep," *Nuclear Engineering International*, 25 March 2010; Gibb, F.G.F., Taylor, K.J. and Burakov, B.E. "The 'granite encapsulation' route to the safe disposal of Pu and other actinide," *Journal of Nuclear Materials*, Volume 374 (3), p.364 – 369 (2008). As shown in Figure 2, the waste at the bottom of the borehole would be protected by 3-4 km of clay and concrete plugs and backfill, requiring a major drilling operation to penetrate to where the wastes have been buried, and making it highly unlikely that a terrorist group could access the wastes undetected.

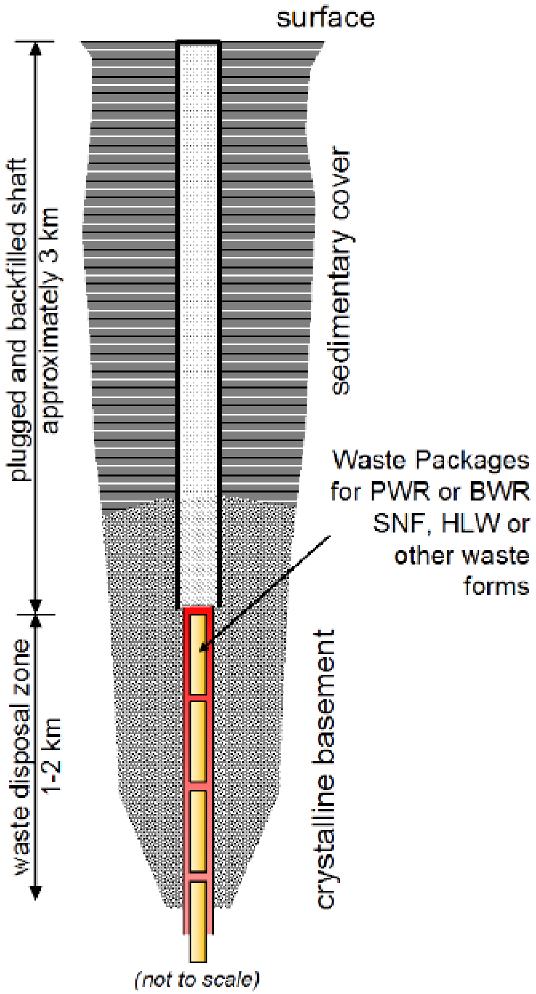

Figure 2: Schematic of Deep Borehole Disposal

Site Selection

Heiken et al. list four factors that define an ideal site for DBD as follows.[9]

- Crystalline rock at the surface or within 1 km of the surface.
- A region that is tectonically stable.
- An area located away from population centers.
- A region not near international borders (i.e. >200 km)

Retrievability

The difficulty of retrieving wastes after final repository closure is one of the contentious issues with respect to DBD. The 2009 MIT report summarizes the main arguments for and against

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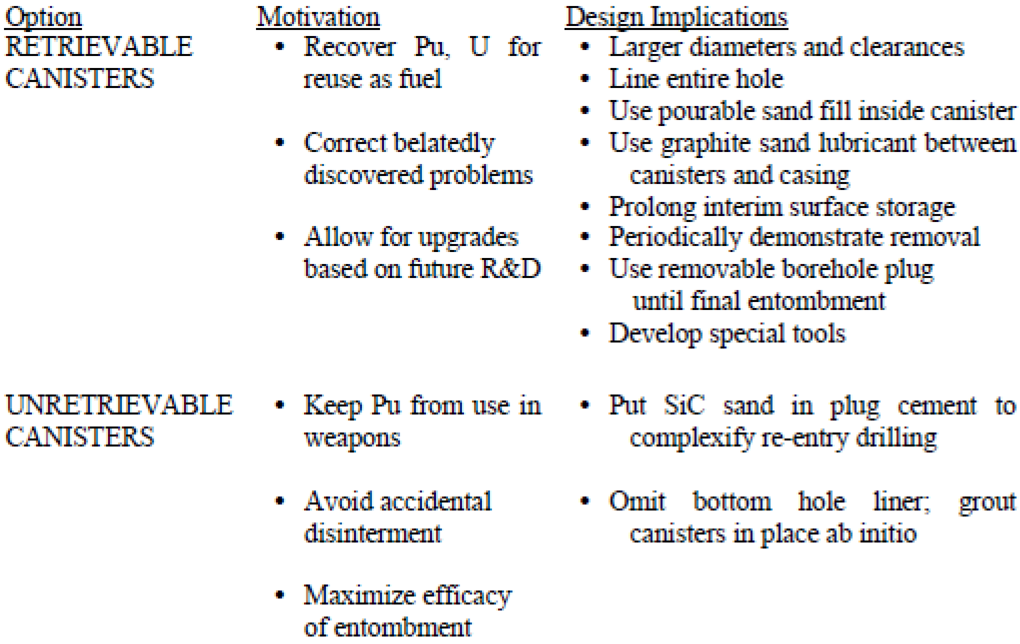
[9] Heiken, G, Woldegabriel, G, Morley, R, Plannerer, H and Rowley, J. *Disposition of excess weapons plutonium in deep boreholes – Site selection handbook*. Report of the Los Alamos National Laboratory, Report LA-13168-MS. 1996.

retrievable variants of DBD, as shown in Table 2, and reaches the conclusion that non-retrievability/permanent disposal is preferred.[10]

Table 2: Nuclear Spent Fuel Emplacement Options and Strategies



Option	Motivation	Design Implications
RETRIEVABLE CANISTERS	• Recover Pu, U for reuse as fuel • Correct belatedly discovered problems • Allow for upgrades based on future R&D	• Larger diameters and clearances • Line entire hole • Use pourable sand fill inside canister • Use graphite sand lubricant between canisters and casing • Prolong interim surface storage • Periodically demonstrate removal • Use removable borehole plug until final entombment • Develop special tools
UNRETRIEVABLE CANISTERS	• Keep Pu from use in weapons • Avoid accidental disinterment • Maximize efficacy of entombment	• Put SiC sand in plug cement to complexify re-entry drilling • Omit bottom hole liner; grout canisters in place ab initio

Borehole Drilling Experience

A 2009 MIT report summarizes borehole drilling experience in the past more recently, as described in Table 3.[11] A 2009 Sandia National Laboratory (US) study estimates a cost of about $20 million for construction of each 5 km-depth borehole, which would require about 110 days to drill, not including emplacement operations, licensing, and other activities. This estimate assumes the use existing drilling technologies.[12]

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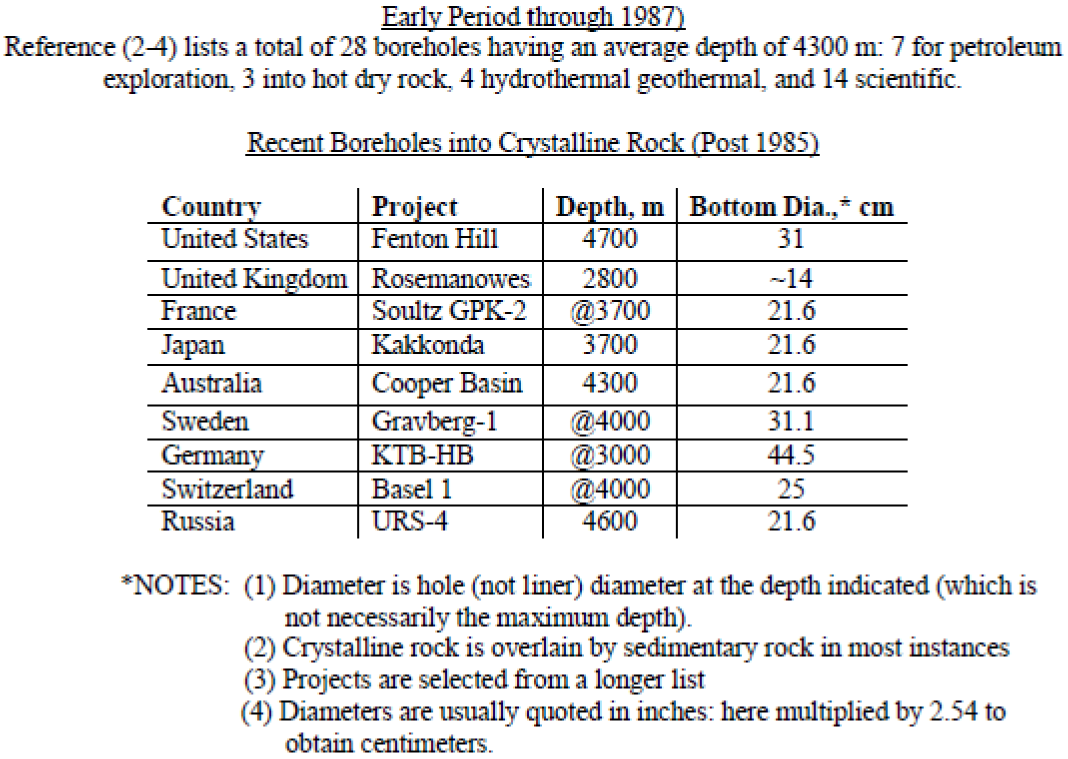
[10] Benyamin Sapiie and Michael J. Driscoll, *A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Wastes: For the MIT Study on The Future of the Nuclear Fuel Cycle*, MIT-NFC-TR-109, August 2009.

[11] Benyamin Sapiie and Michael J. Driscoll, *A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Wastes: For the MIT Study on The Future of the Nuclear Fuel Cycle*, MIT-NFC-TR-109, August 2009.

[12] Patrick V. Brady et al., *Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2009-4401, August 2009.

Table 3: Experience with Deep Boreholes into Crystalline Rock



Early Period through 1987)

Reference (2-4) lists a total of 28 boreholes having an average depth of 4300 m: 7 for petroleum exploration, 3 into hot dry rock, 4 hydrothermal geothermal, and 14 scientific.

Recent Boreholes into Crystalline Rock (Post 1985)

Country	Project	Depth, m	Bottom Dia.,* cm
United States	Fenton Hill	4700	31
United Kingdom	Rosemanowes	2800	~14
France	Soultz GPK-2	@3700	21.6
Japan	Kakkonda	3700	21.6
Australia	Cooper Basin	4300	21.6
Sweden	Gravberg-1	@4000	31.1
Germany	KTB-HB	@3000	44.5
Switzerland	Basel 1	@4000	25
Russia	URS-4	4600	21.6

*NOTES: (1) Diameter is hole (not liner) diameter at the depth indicated (which is not necessarily the maximum depth).
(2) Crystalline rock is overlain by sedimentary rock in most instances
(3) Projects are selected from a longer list
(4) Diameters are usually quoted in inches: here multiplied by 2.54 to obtain centimeters.

SUITABILITY OF THE KOREAN PENINSULA FOR GEOLOGIC DISPOSAL

Appropriate siting of DBD is very important to assure the safety of disposal of spent fuel or HLW. The site used should have characteristics suitable to prevent or retard the potential movement of radionuclides from the disposal system to the biosphere. The natural geologic characteristics of the site play an important role in the disposal concept.[13]

A past study[14] provides the following guidelines on desirable site characteristics of DBD, ideally favoring a combination of:

(1) crystalline rock at the surface or within 1 km of the surface;

(2) a region that is tectonically stable;

(3) an area located away from population centers; and

(4) a region not near international borders.

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[13] IAEA, *Siting of Geological Disposal Facilities: A Safety Guide*, Safety Series No. 111-G-41 (1994).

[14] At an ideal site for DBD, it must be demonstrated that there is no fluid movement from the bottom of the borehole at a depth of 4 kilometers and there will be no significant migration over the next million years. Grant Heiken et al., *Disposition of Excess Weapon Plutonium in Deep Boreholes: Site Selection Handbook*, LA-13168-MS, September 1996.

Geology of the Korean Peninsula

The Korean peninsula is located between the Eurasian continent and the west Pacific mobile belt. More than half of the exposed area of the peninsula consists of Precambrian metamorphic rocks and Paleozoic-Mesozoic plutonic rocks, while sedimentary and volcanic rocks of Paleozoic and Mesozoic era are distributed on those basements accompanied with tectonic movement.[15]

Based on these lithological characteristics, formation stages and continuity of geological history, a division of tectonic provinces on the Korean peninsula is shown in Figure 3.[16]

According to a KAERI study,[17] the massif and fold belts are of primary interest among the tectonic units in Korean peninsula with regard to radioactive waste disposal. Nangnim massif, Kyonggi massif, and Sobaeksan massif are Archean-early Proterozoic massif. Hambuk fold belt and Okchon fold belt are upper Proterozoic-upper Paleozoic fold belt. Kyonggi massif, Sobaeksan massif and Okchon fold belt are located in the southern part of the Korean peninsula.

It is desirable that DBD facilities be located away from population centers. Figure 4 shows population densities in South Korea as of 2005.[18] Combining consideation of the tectonic provinces and the areas of low population density in South Korea provides a rough idea of which areas of the ROK might be suitable sites for DBD.

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[15] C.S.Kim et al., "Lithological Suitability for HLW Repository in Korea," Proceedings of Symposium entitled *Technologies for the Management of Radioactive Waste from Nuclear Power Plants and Back End Nuclear Fuel Cycle Activities*, Taejon, Republic of Korea, 30 August - 3 September 1999.

[16] Ibid.

[17] Ibid.

[18] Modified from "Statistics Korea" (http://atlas.ngii.go.kr/map/territory.jsp?fcode=03)

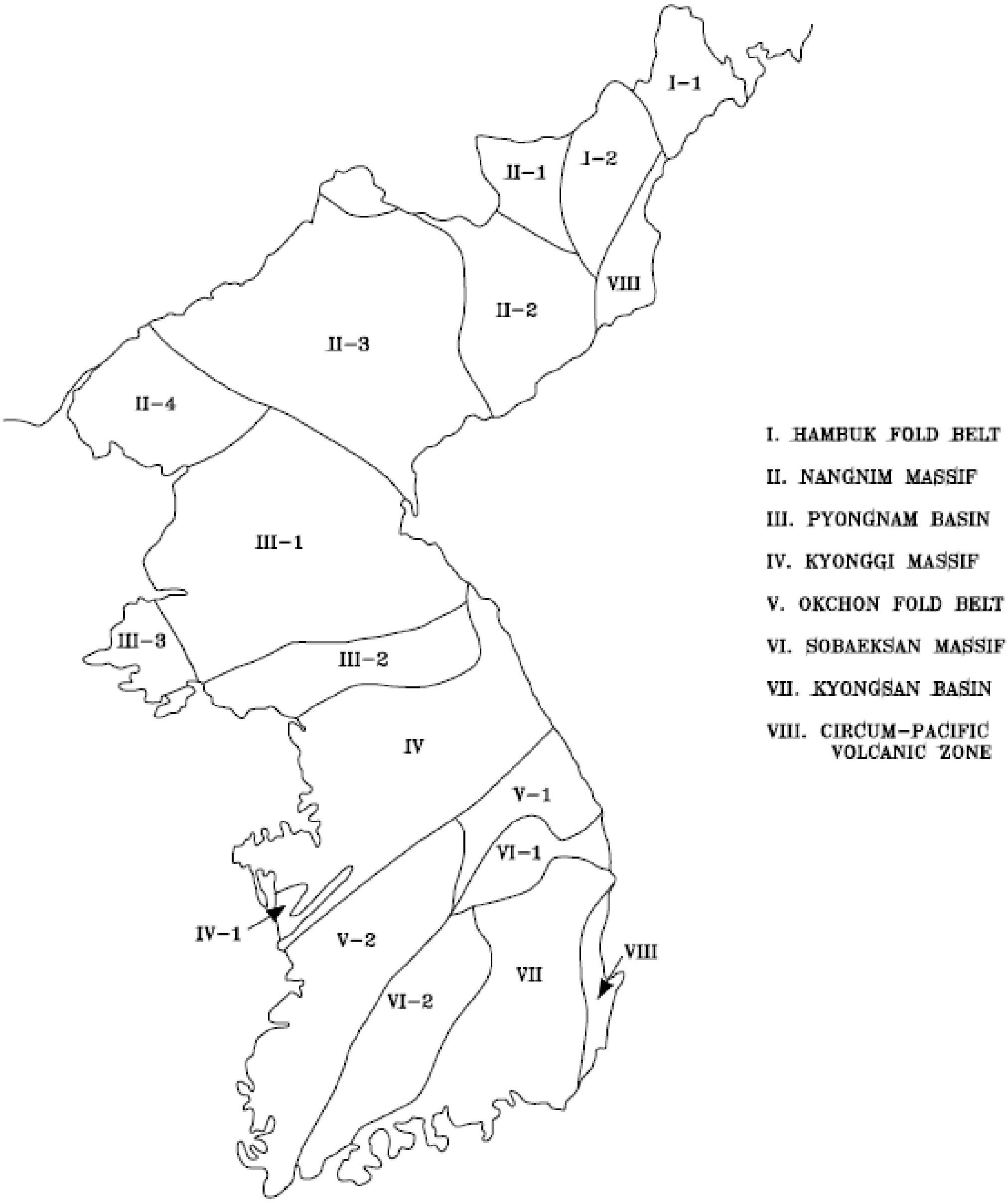

Figure 3: Tectonic Provinces in Korean Peninsula

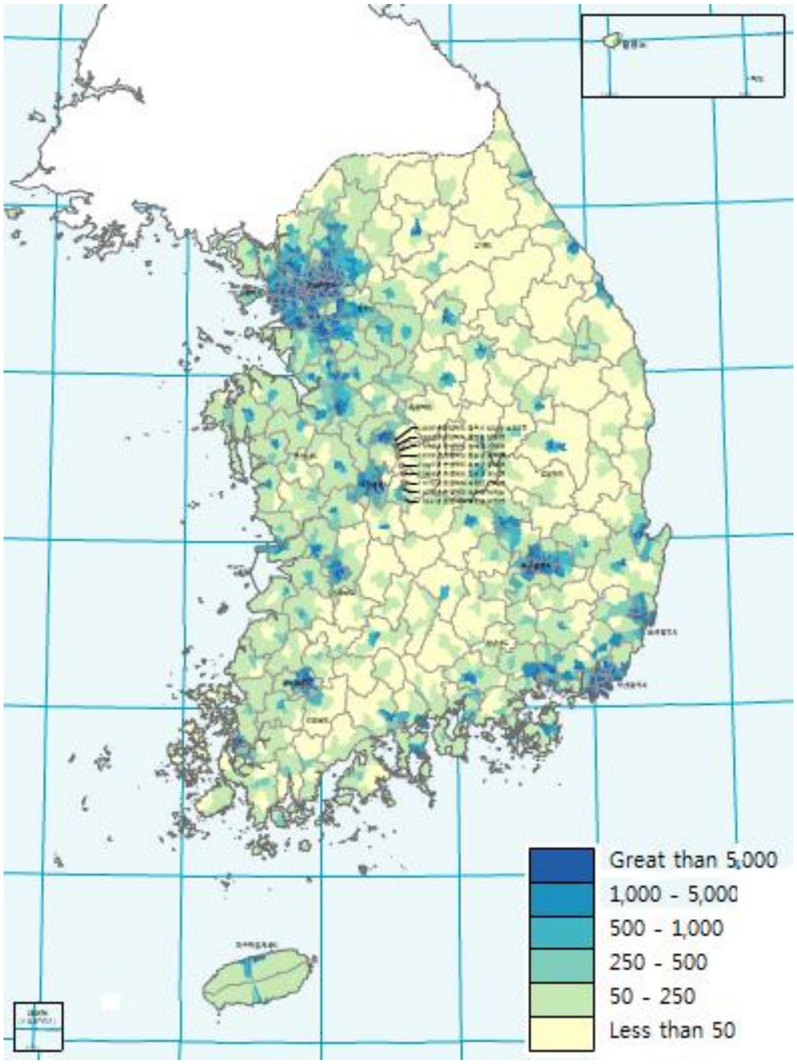

Figure 4: Population Density Map of South Korea in 2005 (Legend: persons per sq. km)

Regional Fractures in South Korea

In South Korea, there are a few large-scale tectonic fractures, while small-scale fractures are evenly distributed throughout the southern peninsula, as shown in Figure 5.[19]

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[19] Ibid.

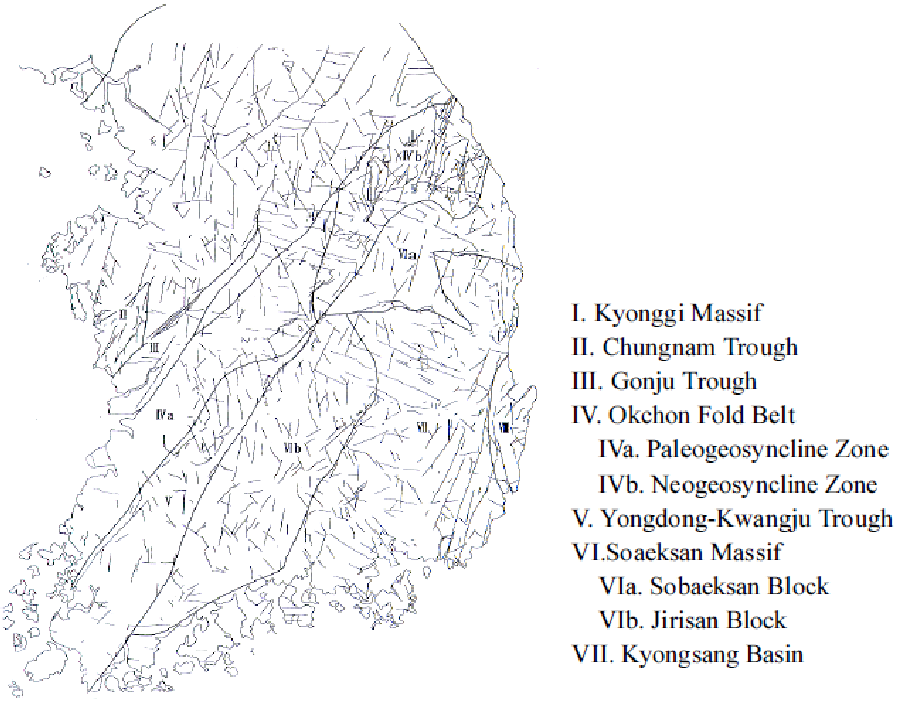

Figure 5: Fracture Map Superimposed on Tectonic Provinces in South Korea

Seismicity

As the Korean peninsula is located in the area where the Eurasian plate contacts with the west Pacific mobile belt, earthquakes in Korea are ascribed to intra-plate seismicity.[20] Table 4 and Figure 6 show historical seismicity records for the Korean peninsula.[21] Even Though low-level earthquake activity has been a historical feature of the Korean peninsula, a large portion of the earthquakes that have occurred have been in the southern part of the peninsula.

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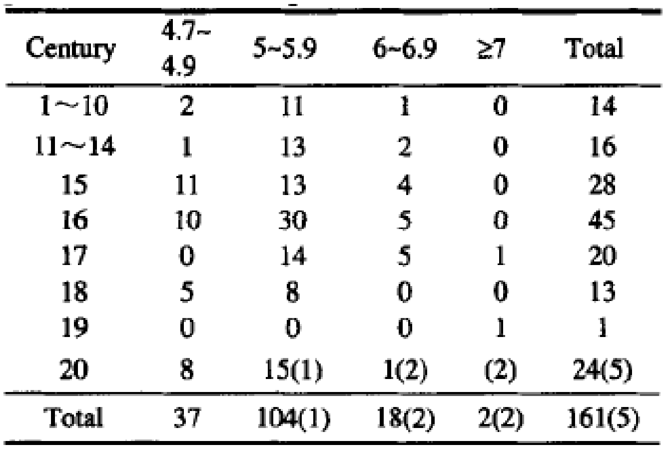
[20] Ibid.

[21] Wenjie Zhai et al., "Research in historical earthquakes in the Korean peninsula and its circumferential regions," *Acta Seismologica Sinica*, Vol.17, No.3, p.366-371, May 2004.

Table 4: Statistics of Magnitude >4.75 Historical Earthquakes on the Korean Peninsula



Century	4.7~ 4.9	5~5.9	6~6.9	≥7	Total
1~10	2	11	1	0	14
11~14	1	13	2	0	16
15	11	13	4	0	28
16	10	30	5	0	45
17	0	14	5	1	20
18	5	8	0	0	13
19	0	0	0	1	1
20	8	15(1)	1(2)	(2)	24(5)
Total	37	104(1)	18(2)	2(2)	161(5)

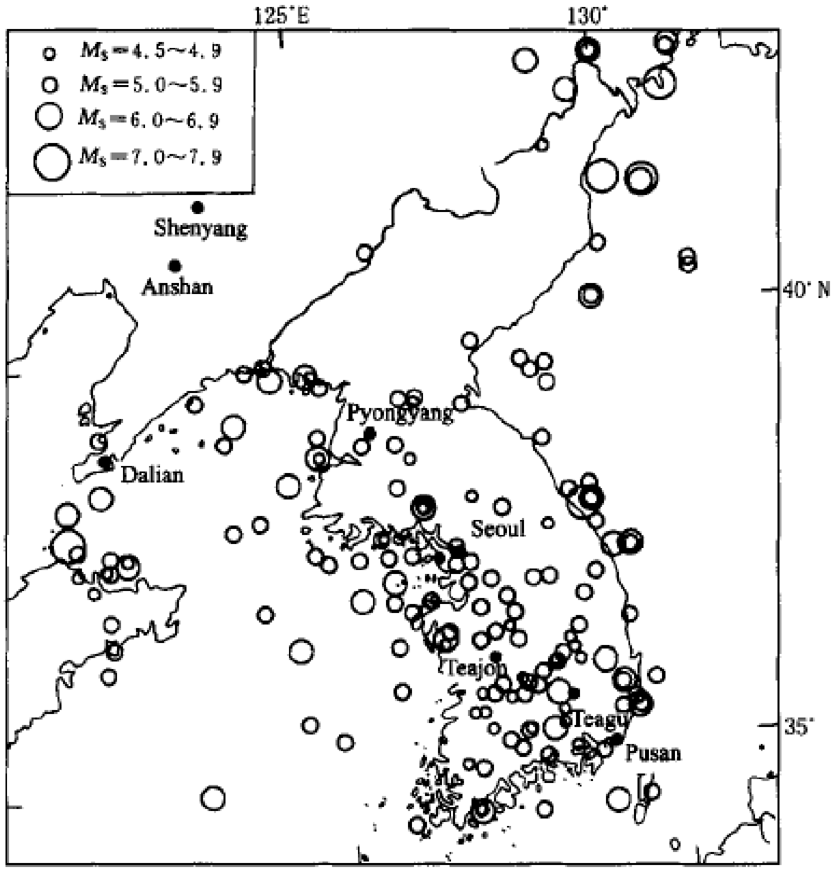


Figure 6: Epicentral Distribution of Historical Earthquakes in the Korean Peninsula

Existing Concept of Spent Fuel Disposal System in South Korea (Mined Repository)

For comparison purpose, this study describes below a concept of a Korean disposal system designed by Korea Atomic Research Institute (KAERI). KAERI's conceptual geologic repository is designed to be located in granite rocks at depth of 500 m, although the real repository site has not been chosen as yet. The layout and other specifics of the repository design are provided in Figure 7 and Table 5.[22] The total capacity of spent fuels disposal in the repository is assumed to be 20,000 tHM of PWR spent fuel and 16,000 tHM of CANDU spent fuel.

According to the KAERI research referenced above, the peak temperature of the bentonite buffer material in which double-walled metal canisters containing spent fuels are buried should be lower than 100 ºC to assure the long term integrity of its physical and chemical properties. With this constraint, the distance between the parallel tunnels in the repository is 40 m, and the minimum distance between two deposition holes for PWR canisters and CANDU canisters are 6 m and 3 m, respectively. These distances are calculated assuming that heat generation is 1,540 W for the PWR canister and 760 W for the CANDU canister, based on spent fuel cooling times of 40 and 30 years, respectively prior to introduction into the repository. This concept of disposal system was designed to be used to evaluate the feasibility of a high-level waste/spent fuel disposal system for the ROK, and to help to formulate data needed to carry out a long-term safety analysis.[23]

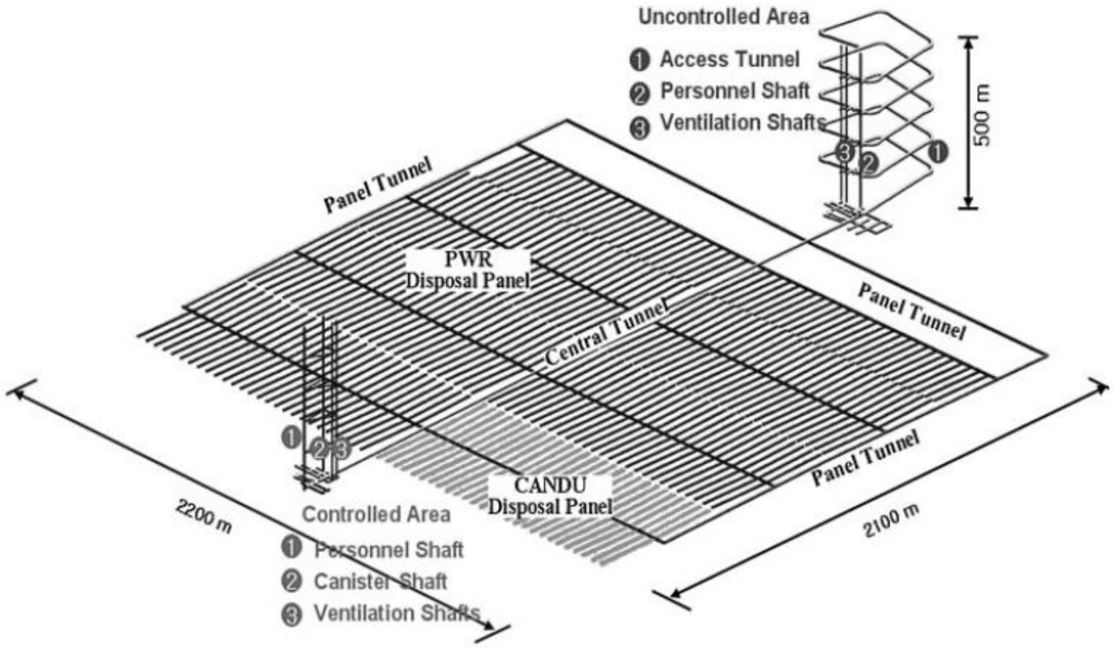


Figure 7: Layout of the Korean Reference Disposal System

Table 5: Length and the Number of Disposal Tunnels

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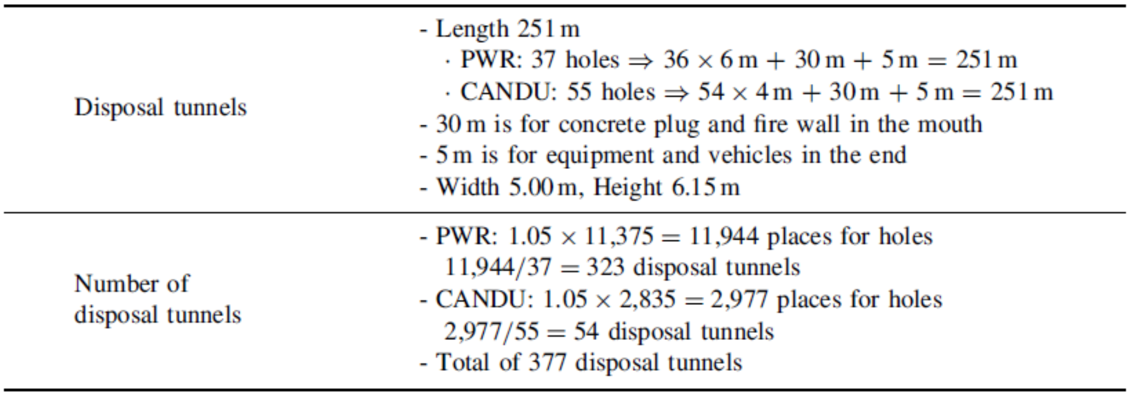
[22] Jongyoul Lee et al., "Concept of a Korean Reference Disposal System for Spent Fuels," *Journal of Nuclear Science and Technology*, Vol.44, No.12, p.1565-1573, 2007. Available as http://www.jstage.jst.go.jp/article/jnst/44/12/1565/_pdf.

[23] Ibid.



Disposal tunnels	- Length 251 m · PWR: 37 holes ⇒ $36 \times 6\,\mathrm{m} + 30\,\mathrm{m} + 5\,\mathrm{m} = 251\,\mathrm{m}$ · CANDU: 55 holes ⇒ $54 \times 4\,\mathrm{m} + 30\,\mathrm{m} + 5\,\mathrm{m} = 251\,\mathrm{m}$ - 30 m is for concrete plug and fire wall in the mouth - 5 m is for equipment and vehicles in the end - Width 5.00 m, Height 6.15 m
Number of disposal tunnels	- PWR: $1.05 \times 11{,}375 = 11{,}944$ places for holes $11{,}944/37 = 323$ disposal tunnels - CANDU: $1.05 \times 2{,}835 = 2{,}977$ places for holes $2{,}977/55 = 54$ disposal tunnels - Total of 377 disposal tunnels

SPENT FUEL MANAGEMENT IN SOUTH KOREA

Institutional Framework in the Radioactive Waste Management

With regard to the governmental organizations concerned with radioactive waste, the main administrative authorities in the ROK are the Ministry of Knowledge Economy (MKE), which supervises the nuclear power program, and the Ministry of Education, Science and Technology (MEST), which is responsible for nuclear safety regulations including the licensing of nuclear facilities. The Atomic Energy Committee (AEC) under the jurisdiction of the Prime Minister is the supreme organization for decision-making on national nuclear policies. The Nuclear Safety Commission (NSC) under the jurisdiction of MEST is responsible for matters concerning the safety of nuclear facilities and radioactive waste management. MEST is also responsible for developing licensing criteria for the construction and operation of radioactive waste disposal facilities, developing technical standards for operational safety measures, and for assuring safe management of radioactive waste at every stage of the site selection, design, construction, operation, closure and post-closure of radioactive waste disposal facilities. MKE also develops and implements management policies regarding radioactive waste treatment, storage and disposal. These policies are prepared by MKE and deliberated by the AEC before implementation.[24]

Legal Framework in the Radioactive Waste Management

Key ROK National laws related to spent fuel and radioactive waste management are the Atomic Energy Act (AEA) and the Radioactive Waste Management Act (RWMA). The AEA provides for matters concerning safety regulations, including permission for construction and operation of radioactive waste disposal facilities. The RWMA, which determines all aspects of managing radioactive waste, was announced on March 28, 2008, and was enacted on March 31, 2010. Based on the RWMA, the Korea Radioactive Waste Management Organization and the Radioactive Waste Management Fund were established. According to the RWMA, KHNP, the utility company, should annually deposit to the Fund the cost of decommissioning of nuclear

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[24] radioactive waste management in Rep. of Korea (http://www.nea.fr/rwm/profiles/Korea%20report%202010%20web.pdf)

power plants, disposal of low and intermediate level waste (LILW), and spent fuel management. Figure 8 shows the financing structure for radioactive waste management in South Korea.[25]

Current Practice in the Management of the Spent Fuel

At its 253rd meeting in 2004, the AEC announced that national policy for spent fuel management would be decided later in consideration of progress of domestic and international technology development, and that spent fuel would be stored at a reactor site by 2016 under KHNP's responsibility.[26] South Korea has not decided whether to directly dispose of or recycle spent fuel. Currently, South Korea has no national plan on geologic disposal of spent fuel or HLW. Therefore there are no regulatory and licensing issues relevant to DBD in South Korea either.

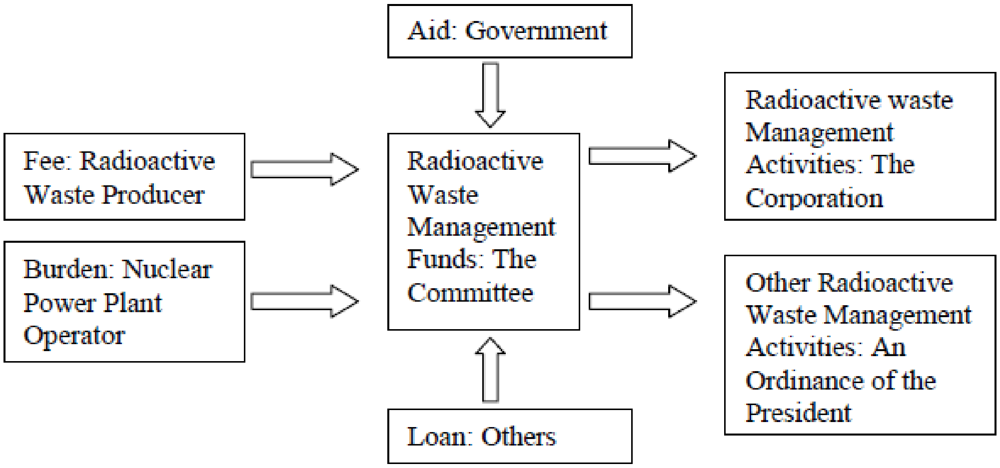

Figure 8: Financing Structure of Radioactive Waste Management in South Korea

Status and Prospect of Nuclear Power in South Korea

As described in the introductory part of this report, currently in South Korea 16 PWRs and 4 HWRs are in operation, with 8 PWR units under construction and due to be completed by 2016, and 11 more PWRs to deployed by 2030. Table 6 shows the generating capacities and expected initial operating dates of South Korea's power reactors through 2021.[27]

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[25] Ibid.

[26] 253rd meeting of Korea AEC in 2004. See, for example, Ministry of Education, Science & Technology, *Korean Third National Report under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, dated October, 2008, and available as www.kins.re.kr/pdf/Korean%20Third%20National%20Report%202008.pdf.

[27] http://www.khnp.co.kr/en/03000100; http://www.khnp.co.kr/en/030100; Ministry of Knowledge Economy, *The 4th Basic Plan of Long-Term Electricity Supply and Demand (2008 ~ 2022)*, December 2008.

Table 6: Current and Planned Nuclear Power Capacity in South Korea through 2021[28]

Site	Unit	Type	Capacity (GWe)	Operation (year.month)	Pool storage capacity (tHM) [a]	Programmed capacity increase from re-racking (tHM)
Kori	Kori-1	PWR	0.587	1978. 4	158.8	
	Kori-2	PWR	0.650	1983. 7	327.6	
	Kori-3	PWR	0.950	1985. 9	270.9	696.4
	Kori-4	PWR	0.950	1986. 4	270.9	697.4
	Shin-Kori-1	PWR	1.000	2010.12	428.7	
	Shin-Kori -2	PWR	1.000	2011.12	428.7	
	Shin-Kori -3	PWR	1.400	2013. 9	625.7	
	Shin-Kori -4	PWR	1.400	2014. 9	625.7	
	Shin-Kori -5	PWR	1.400	2018.12	625.7	
	Shin-Kori -6	PWR	1.400	2019.12	625.7	
	Subtotals		10.737		4388.4	1393.8
Yonggwang	Yonggwang-1	PWR	0.950	1986. 8	270.9	697.4
	Yonggwang-2	PWR	0.950	1987. 6	270.9	186.8
	Yonggwang-3	PWR	1.000	1995. 3	215.4	268.3
	Yonggwang-4	PWR	1.000	1996. 1	215.4	268.3
	Yonggwang-5	PWR	1.000	2002. 5	224.9	
	Yonggwang-6	PWR	1.000	2002.12	224.9	
	Subtotals		5.900		1422.4	1420.8
Ulchin	Ulchin-1	PWR	0.950	1988. 9	144.9	297.7
	Ulchin-2	PWR	0.950	1989. 9	144.9	273.7
	Ulchin-3	PWR	1.000	1998. 8	215.4	352.6
	Ulchin-4	PWR	1.000	1999. 12	215.4	352.6
	Ulchin-5	PWR	1.000	2004. 7	224.9	
	Ulchin-6	PWR	1.000	2005. 4	224.9	
	Shin-Ulchin-1	PWR	1.400	2015. 12	625.7	
	Shin-Ulchin-2	PWR	1.400	2016. 12	625.7	
	Shin-Ulchin-3	PWR	1.400	2020. 6	625.7	
	Shin-Ulchin-4	PWR	1.400	2021. 6	625.7	
	Subtotals		11.500		3673.2	1276.6
Wolsong CANDUs	Wolsung-1	HWR	0.679	1983. 4	842.7	(6,930+ dry-cask storage as of 2009)[29]
	Wolsung-2	HWR	0.700	1997. 7	736.8	
	Wolsung-3	HWR	0.700	1998. 7	736.8	
	Wolsung-4	HWR	0.700	1999. 10	736.8	
	Subtotals		2.779		3053.1	
Wolsung PWRs	Shin-Wolsung-1	PWR	1.000	2012. 3	504.8	
	Shin-Wolsung-2	PWR	1.000	2013. 1	504.8	
	Subtotals		2.000		1009.6	

[a] Pool storage capacity measured in metric tons of original uranium in the fuel (tons heavy metal or tHM). These values do not include the pool capacity for a full reactor core that is held open in case all the fuel in the current reactor core has to be unloaded quickly.

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[28] J.H. Mok et al., *Examination on Amount of Spent Fuel Stored and Verification on Saturation Time of Pool Capacities*, Kookmin University, May 2009 (in Korean).

[29] Jongwon Choi, "R&D Program for Spent Fuel Storage and Disposal," Korea Atomic Energy Research Institute, 27 May 2009.

Status and Prospect of Spent Fuel Generation

As of the end of 2008, 4,866 tons of spent PWR fuel and 6,082 tHM of spent HWR fuel were stored in the spent fuel storage facilities at South Korea's four NPP sites. Table 7 shows the spent fuel inventories at the four sites as of the end of 2008. According to an analysis by the operator, KHNP, the saturation dates for the current storage at the Kori, Yonggwang and Ulchin sites for spent PWR fuel, and at the Wolsong site for spent HWR fuel, will be 2016, 2021, 2018 and 2017 respectively.[30]

Table 7: Inventory of spent fuels in South Korea as of the end of 2008[31]

Kori site (tHM)	Yonggwang site (tHM)	Ulchin site (tHM)	Wolsong site (tHM)
1,768	1,732	1,366	2,912 in pools 3,170 in dry casks

Projections of spent fuel generation depend on the capacity factors of the reactors (that is, what fraction of the time they operate and at what average fraction of their nominal capacities), and the burnup of spent fuel (that is, the number of megawatt-days of heat that can be generated from a kilogram of fuel before it is "spent"). The average discharged burnup level for spent PWR fuel is around 50,000 MWd/tHM in today's reactors.[32] Heavy-water reactors are fueled with natural uranium, and the burnup rate is about 7,100 MWd/tHM. Assuming that all NPPs have thermal efficiencies of 33% and capacity factors of 90 percent, which is reasonably consistent with ROK experience, the projections of cumulative spent fuel generation in South Korea from reactors completed by 2030 are given in Figure 9 for the years 2010 through 2050. This study estimates that approximately 51,000 tons of spent PWR fuel and approximately 20,000 tHM of spent HWR fuel will be generated over the entire lifetimes (that is, until each unit is decommissioned, whether before or after 2050) of the 35 PWR and 4 HWR units that will be deployed by 2030.

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[30] Ki-Chul Park, "Status and Prospect of Spent Fuel Management in South Korea," *Nuclear Industry*, August 2008 (in Korean).

[31] J.H. Mok et al., *op. cit.*

[32] Based on an initial uranium enrichment in fresh PWR fuel of 4.5 percent, J.H. Mok et al., *Examination on Amount of Spent Fuel Stored and Verification on Saturation Time of Pool Capacities*, Kookmin University, May 2009 (Korean); *The Future of Nuclear Power: An Interdisciplinary MIT Study,* MIT, p. 119 (2003).

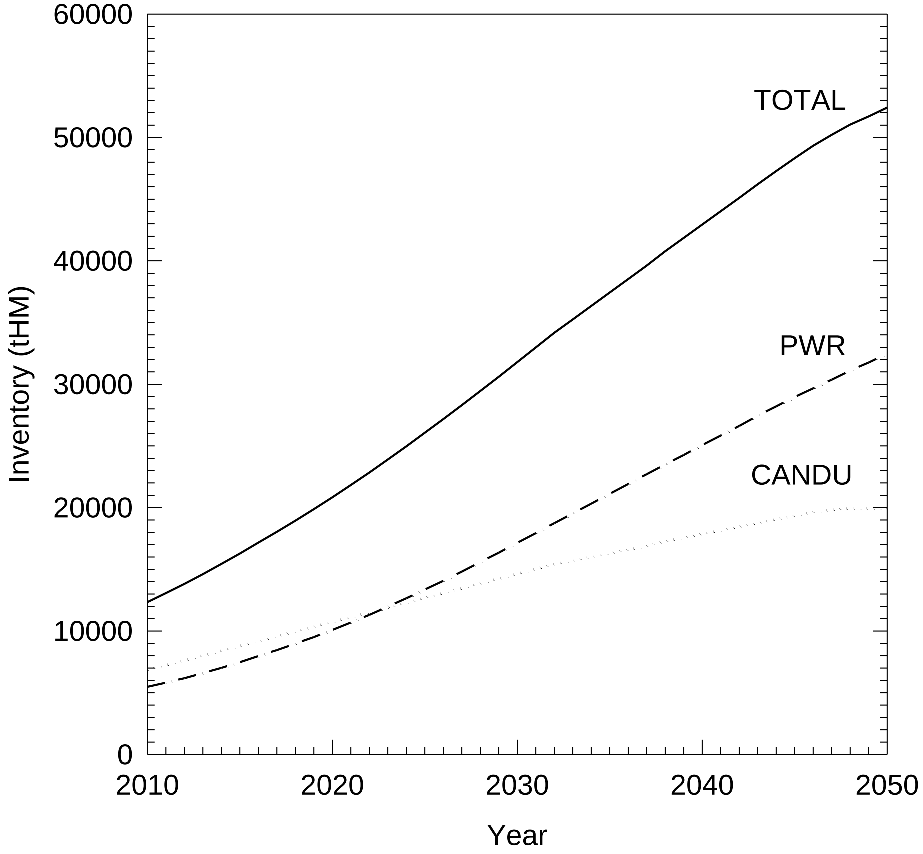

Figure 9: Cumulative Inventory of Spent Fuel Generation in South Korea from Reactors Deployed by 2030[33]

Rough Cost Estimation of DBD Implementation

To estimate what the DBD option might cost as a spent fuel disposal option for South Korea, the author made the assumption that 200-400 canisters containing a total of about 100-200 tHM of spent PWR fuel can be accommodated in a borehole in crystalline basement rocks on the order of 5 km deep with a 1-2 km long waste disposal zone, while one borehole might hold about 1,600-3,200 canisters containing about 32-64 tHM spent HWR fuel, assuming a canister length of 0.6 m.[34]

Table 8 shows the roughly-estimated annual costs of DBD construction through 2050 to accommodate the ROKs spent fuel that has cooled for approximately 30 years to that date. These costs are, based on a cost of about $20 million for construction of each 5 km-depth

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[33] The assumed 60 and 50-year operating lives for PWRs and HWRs, respectively, are based on the 1st National Energy Basic Plan (2008-2030).

[34] Typical HWR fuel, for example, in a CANDU fuel bundle, is about 50 cm in length, 10 cm in diameter, and weighs about 20 kg HM. http://en.wikipedia.org/wiki/Nuclear_fuel#CANDU_fuel.

borehole, as included in the 2009 Sandia National Laboratory study referenced above[35]. The costs shown do not include any additional costs for items such as administration cost, and with no real escalation (or reduction due to learning) in costs assumed. 2030 is assumed to be the start year for borehole disposal. Table 8 shows the amount of spent fuel disposed of annually, as well as the number of boreholes needed to dispose of cooled spent fuels using DBD from 2030 through 2050. Spent fuel disposal by year is based on historical spent fuel quantities removed from ROK reactors through 2008. So, for example, the quantity of PWR fuel shown as being sent to borehole disposal in 2033 is the amount removed from reactor cores in 2003. After 2008, the estimates of annual new spent fuel production implied by Figure 9, plus 30 years, are used to estimate the amount of spent fuel sent to disposal.

Due to the larger volume of spent fuel discharged, the cumulative cost of DBD for CANDU (HWR) spent fuel for 2030 – 2050 is three times greater than that of PWR spent fuel, despite the fact that PWRs produce much more of the ROK's electricity than HWRs. To reduce the cost of DBD, CANDU spent fuel needs to be more densely packed into canisters before it is subjected to deep borehole disposal.

Table 8: The estimated annual cost of DBD construction from 2030 through 2050

Year	PWRs			CANDUs		
	Spent Fuel (tHM)	# of Boreholes	M$	Spent Fuel (tHM)	# of Boreholes	M$
2030	2450	12.3 – 24.5	245.0 – 490.0	2329	36.4 – 72.8	727.8 – 1455.6
2031	247	1.2 – 2.5	24.7 – 49.4	380	5.9 – 11.9	118.8 – 237.5
2032	258	1.3 – 2.6	25.8 – 51.6	390	6.1 – 12.2	121.9 – 243.8
2033	257	1.3 – 2.6	25.7 – 51.4	390	6.1 – 12.2	121.9 – 243.8
2034	185	0.9 – 1.9	18.5 – 37.0	401	6.3 – 12.5	125.3 – 250.6
2035	298	1.5 – 3.0	29.8 – 59.6	390	6.1 – 12.2	121.9 – 243.8
2036	297	1.5 – 3.0	29.7 – 59.4	390	6.1 – 12.2	121.9 – 243.8
2037	336	1.7 – 3.4	33.6 – 67.2	1312	20.5 – 41.0	410.0 – 820.0
2038	538	2.7 – 5.4	53.8 – 107.6	102	1.6 – 3.2	31.9 – 63.8
2039	297	1.5 – 3.0	29.7 – 59.4	390	6.1 – 12.2	121.9 – 243.8
2040	317	1.6 – 3.2	31.7 – 63.4	390	6.1 – 12..2	121.9 – 243.8
2041	338	1.7 – 3.4	33.8 – 67.6	390	6.1 – 12.2	121.9 – 243.8
2042	357	1.8 – 3.6	35.7 – 71.4	390	6.1 – 12.2	121.9 – 243.8
2043	405	2.0 – 4.1	40.5 – 81.0	390	6.1 – 12.2	121.9 – 243.8
2044	432	2.2 – 4.3	43.2 – 86.4	390	6.1 – 12.2	121.9 – 243.8
2045	461	2.3 – 4.6	46.1 – 92.2	390	6.1 – 12.2	121.9 – 243.8
2046	489	2.4 – 4.9	48.9 – 97.8	390	6.1 – 12.2	121.9 – 243.8
2047	488	2.4 – 4.9	48.8 – 97.6	390	6.1 – 12.2	121.9 – 243.8
2048	516	2.6 – 5.2	51.6 – 103.2	390	6.1 – 12.2	121.9 – 243.8
2049	545	2.7 – 5.5	54.5 – 109.0	390	6.1 – 12.2	121.9 – 243.8
2050	572	2.9 – 5.7	57.2 – 114.4	390	6.1 – 12.2	121.9 – 243.8
Total	10,083	50.4 – 100.8	1,008 – 2,017	10,758	168.1 – 336.2	3,362 – 6,724

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[35] Patrick V. Brady et al., *Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2009-4401, August 2009.

Overall, Table 8 shows that the undiscounted cost of disposing of the spent fuel generated in the ROK and sufficiently cooled (30 years) for DBD disposal are in the range of about $4 to $9 billion from 2030 through 2050. Put into perspective, this cost amounts to about $0.001 to $0.002 per kWh of electricity generated in nuclear power plants in the ROK through 2020.

Recent Public Opinion of Local Communities

The author of this report, Jungmin Kang, undertook a week-long research trip to South Korea's four NPPs sites in mid-September 2010. The followings are his key findings from the trip.

- The local people[36] who live near nuclear power plants sites are not aware of the safety superiority of dry cask storage of spent fuel, when compared with pool storage, and are also not aware of the potential safety superiority of deep borehole disposal of spent fuel, compared with normal geologic disposal.
- Local people showed an interest in considering on-site dry cask storage of spent fuel as well as possible in-situ deep borehole disposal if the safety of those options were assured by reliable experts and the local sites are properly compensated financially.
- Educating local people will be very important to achieving on-site dry cask storage of spent fuel as well as possibly in-situ deep borehole disposal in South Korea.

Political and Legal Issues

There would be political implication of implementing DBD of spent fuel in South Korea. The South Korean nuclear fuel cycle community, represented by KAERI, strongly insists on pyroprocessing as its favored alternative for future spent fuel management in the ROK, and would not support any kind of direct disposal of spent fuel in South Korea. Locals living near nuclear facilities, on the other hand, have as their major goal safe geologic disposal of spent fuel and/or HLW.

There are no current legal issues that might affect the practicality of borehole disposal of spent fuel in South Korea, since the current South Korean Atomic Energy Act does not includes any articles relevant to spent fuel disposal.

International Cooperation

A 2010 MIT study recommends research and development of deep borehole disposal for spent fuel and HLW management,[37] based on recent relevant research including a collaborative study done by MIT and Sandia National Laboratories.[38]

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[36] Local people mentioned at this report are representatives of non-governmental organizations based near reactor sites who Jungmin Kang met during his trips in mid-September 2010.

[37] MIT, *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study* (2010). Available as web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle.pdf.

The US – Japan Joint Nuclear Energy Action Plan, a process started in 2007, reached a similar conclusion in its May 2010 report of Phase I of its Waste Management Working Group, as follows:[39]

"… we view the deep borehole disposal approach as a promising extension of geological disposal, with greater siting flexibility and the potential to reduce the already very low risk of long-term radiation exposure to still lower levels without incurring significant additional costs."

Based on the results of these studies, opportunities for cooperation jointly with the US and Japan on DBD would help to spur interest in the South Korean nuclear (scientific and policy) community in DBD evaluation and consideration.

TENTATIVE CONCLUSIONS

Considering its potential safety superiority compared with normal geologic disposal, deep borehole disposal could be an alternative, which could be more acceptable to local communities, for the eventual disposal of spent fuel and/or HLW in South Korea.

Further study needs to be done to identify relevant technical issues, as well as to obtain comprehensive public and local opinions on the deep borehole disposal possibility for the ROK.

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[38] Patrick V. Brady and Michael J. Driscoll, *Deep Borehole Disposal of Nuclear Waste: Report from a Sandia-MIT Workshop on March 15, 2010 in Washington, DC.* Dated May 7, 2010, available as www.mkg.se/uploads/SNL_MIT_borehole_workshop_report_final_100507.pdf.

[39] *Information Basis for Developing Comprehensive Waste Management System – US-Japan Joint Nuclear Energy Action Plan Waste Management Working Group Phase I Report*, FCR&D-USED-2010-000051, Published Jointly as JAEA-Research-2010-015, May 2010. Available as www.ipd.anl.gov/anlpubs/2010/05/67013.pdf.