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Alternatives for Additional Spent Fuel Storage in South Korea

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As its at-reactor (AR) spent fuel storage pools become saturated, South Korea will have to increase interim storage capacity for spent fuel. This study estimates South Korea's additional spent fuel storage requirements through the year 2030, and then evaluates one measure with the potential for reducing requirements for new away-from reactor (AFR) storage: transshipment of spent fuel between nuclear power plant (NPP) sites. Such transshipment, if implemented, could make a significant contribution to relieving requirements for additional spent fuel storage. If intersite transshipment cannot be implemented due to concerns about transport of spent fuel or for other reasons, on-site dry storage would be the next most cost effective alternative.

INTRODUCTION

All spent nuclear fuel discharged from South Korea's PWRs and CANDU reactors is stored in at-reactor (AR) spent fuel storage pools, with the exception of a small quantity of CANDU spent fuel stored at a dry storage facility.[1] Given that an underground repository for the permanent disposal of spent fuel will not be available for at least three decades,[2] South Korea will have to develop additional interim storage capacity to accommodate the spent fuel as the AR spent fuel stores become saturated. Although there was an early plan for a centralized away-from-reactor (AFR) interim storage facility for the spent fuel,[3] it has been delayed until 2016,[4] due to public opposition in the early 1990s. As a result, much more temporary storage for much longer time periods will be required than was originally anticipated.

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With this background, this study estimates requirements for additional spent fuel storage capacity for spent fuel from PWRs and CANDU reactors in South Korea through the year 2030.[5] Then, it evaluates how these requirements could be reduced by intersite transshipment of spent fuel between NPP sites if such transfer is implemented.

PROJECTION OF TOTAL ELECTRICITY AND NUCLEAR CAPACITY

Future spent fuel generation from PWRs and CANDU reactors will depend on projections of installed nuclear capacity, which in turn will depend on the total electricity generation and on the share of nuclear power for that generation over the period of time being studied. For this study, projections are made out to 2030, the time at which an underground repository for permanent disposal of spent fuel could become available.

Projections of Total Electricity Generation through the Year 2030

Recently, the South Korean government estimated total electricity generation and installed nuclear capacity for the years 1998–2015.[6] In order to estimate total electricity generation for the years 2016–2030, this study uses a logistic curve fitting method[7] to estimate per capita electricity generation for the years 2016–2030. Then, total electricity generation can be calculated by multiplying per capita electricity generation by estimated population.

Table 1 shows total electricity generation, population, and per capita electricity generation in South Korea, which are used as base data in estimating the projections of per capita electricity generation for the years 2016–2030. The year 1995 is assumed as the base year in the projections of per capita electricity generation.

Table 1: Total electricity generation, population and per capita electricity generation in South Korea.*

Year	Total electricity generation (TWh)	Population (million)	Per capita electricity (MWh)
1995	184.7	45.09	4.1
2005	328.6	49.12	6.7
2015	429.7	51.68	8.3

Note: In 2030, South Korea's population will be approximately 52.74 million.
**The Fourth Long-term Power Development Plan (1998–2015)*, MOCIE, South Korea, August 1998 (Korean). *Major Statistics of Korean Economy*, National Statistical Office (NSO), South Korea, September 1997 (Korean). *KOSIS-DB*, NSO, South Korea (Korean).

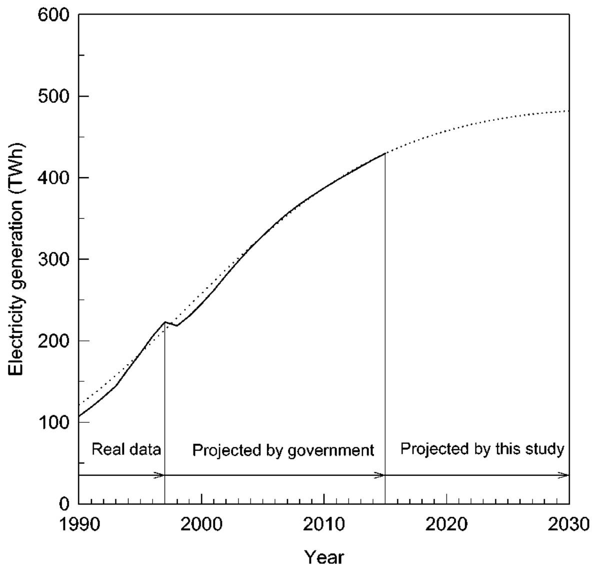

Figure 1: Total electricity generation in South Korea (1990–2030).

The derived asymptote, i.e., E_∞, for the annual per capita electricity generation is 9.3 MWh around the year 2045, about 1 MWh higher than 8.2 MWh of the average per capita electricity of the OECD countries in 1995.[8]

Total electricity generation can then be obtained by multiplying per capita electricity generation by the population projection over the period of time. The derived projections of total electricity generation for the years 2016–2030 are shown in Figure 1. Figure 1 also shows the real historical data up to 1997 and projections by the South Korean government to 2015, plotted as a solid line. Total electricity generation in 2030 is estimated to be approximately 480 TWh.

Projections of Installed Nuclear Capacity through the Year 2030

Projections of nuclear power over the next three decades will be affected by a number of factors, e.g., economic growth, public acceptance, and so on. This study assumes two scenario projections for the years 2016–2030. One is a "reference scenario," based upon the assumption of sustained development of nuclear power. The other is a "low growth scenario," based upon the assumption that no new nuclear power plants are built after 2016.

Table 2: South Korea's long-term nuclear power supply plan.*

Unit	Type	Capacity (MWe)	Operation
Wolsong 3	CANDU	700	1998. 7
Ulchin 3	PWR	1,000	1998. 8
Wolsong 4	CANDU	700	1998. 9
Ulchin 4	PWR	1,000	1999. 12
Yonggwang 5	PWR	1,000	2002. 5
Yonggwang 6	PWR	1,000	2002. 12
Ulchin 5	PWR	1,000	2004. 6
Ulchin 6	PWR	1,000	2005. 6
Unit 1	PWR	1,000	2008. 9
Unit 2	PWR	1,000	2009. 9
Unit 3	PWR	1,000	2009. 9
Unit 4	PWR	1,000	2010. 9
APR1400[a]	Advanced PWR	1,400	2010. 9
APR1400	Advanced PWR	1,400	2011. 9
APR1400	Advanced PWR	1,400	2014. 6
APR1400	Advanced PWR	1,400	2015. 6

[a]Advanced Power Reactor 1400.
**The First Power Supply Plan (2002–2015)*, MOCIE, South Korea, August 2002 (Korean).

For installed nuclear capacity before 2001, real historical data is adopted. For the years 2002–2015, projections by the South Korean government are adopted. This long-term nuclear power supply plan for the years 2002–2015 is given in Table 2.

Reference Scenario

For the reference scenario, projections of the share of nuclear power may be estimated by a similar method used to project per capita electricity generation. The essential assumption is that the nuclear fraction will approach 50% of total electricity consumption asymptotically by 2045. This is shown in Table 3 and Figure 2. In Figure 2, a solid line for the years 2016–2030 shows the projections of installed nuclear capacity for the reference scenario. The installed nuclear capacity will be 32.0 GWe in 2030. The specifics of reactor deployment in the years 2016–2030 are explained in the following.

This study assumes that the specific reactor types deployed in the years 2016–2030 will be based on the long-term nuclear power plan of the South Korean government. According to the 1995 Long-term Power Development Plan[9] and the Comprehensive Nuclear Energy Promotion Plan,[10] PWRs would remain as the main reactor type, with no further deployment of CANDU reactors after completion of four reactors in 1999. The study assumes that PWRs of 1.0 GWe and 1.4 GWe will be mainly deployed for the years 2016–2030, except that a new CANDU reactor of 0.7 GWe will replace a decommissioned CANDU

Table 3: Installed nuclear capacity in South Korea through the year 2030 (reference scenario).

End of year	New PWR (MWe)	New CANDU (MWe)	Decom.[a] PWR (MWe)	Decom. CANDU (MWe)	Cumul.[b] PWR (MWe)	Cumul. CANDU (MWe)	Cumul. total (MWe)
1978	587				587		587
1979					587		587
1980					587		587
1981					587		587
1982					587		587
1983	650	679			1,237	679	1,916
1984					1,237	679	1,916
1985	950				2,187	679	2,866
1986	1,900				4,087	679	4,766
1987	950				5,037	679	5,716
1988	950				5,987	679	6,666
1989	950				6,937	679	7,616
1990					6,937	679	7,616
1991					6,937	679	7,616
1992					6,937	679	7,616
1993					6,937	679	7,616
1994					6,937	679	7,616
1995	1,000				7,937	679	8,616
1996	1,000				8,937	679	9,616
1997		700			8,937	1,379	10,316
1998	1,000	700			9,937	2,079	12,016
1999	1,000	700			10,937	2,779	13,716
2000					10,937	2,779	13,716
2001					10,937	2,779	13,716
2002	2,000				12,937	2,779	15,716
2003					12,937	2,779	15,716
2004	1,000				13,973	2,779	16,716
2005	1,000				14,937	2,779	17,716
2006					14,937	2,779	17,716
2007					14,937	2,779	17,716
2008	1,000				15,937	2,779	18,716
2009	2,000				17,937	2,779	20,716
2010	2,400				20,337	2,779	23,116
2011	1,400				21,737	2,779	24,516
2012					21,737	2,779	24,516
2013				679	21,737	2,100	23,837
2014	1,400				23,137	2,100	25,237
2015	1,400				24,537	2,100	26,637
2016	1,400				25,937	2,100	28,037
2017		700			26,937	2,800	28,737
2018			587		25,350	2,800	28,150
2019	1,000				26,350	2,800	29,150
2020					26,350	2,800	29,150
2021					26,350	2,800	29,150
2022	1,000				27,350	2,800	30,150
2023			650		26,700	2,800	29,500
2024	1,000				27,700	2,800	30,500
2025	1,400		950		28,150	2,800	30,950
2026	2,000		1,900		28,250	2,800	31,050
2027	1,400		950		28,700	2,800	31,500
2028	1,000		950		28,750	2,800	31,550
2029	1,400		950		29,200	2,800	32,000
2030					29,200	2,800	32,000

[a]Decommissioned.
[b]Cumulative.

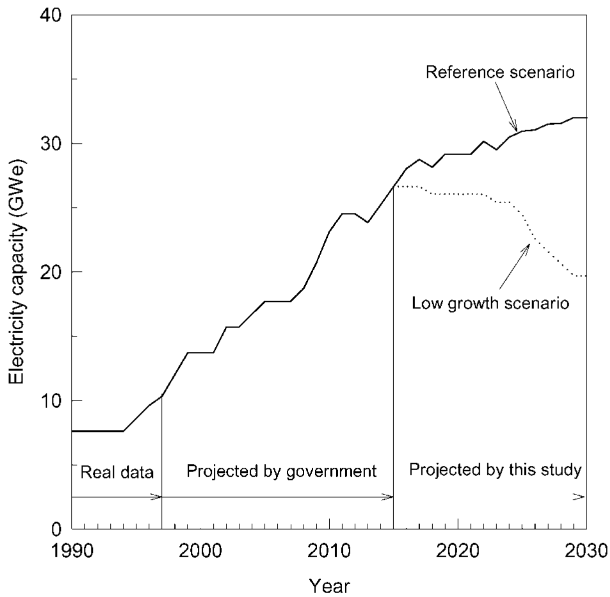

Figure 2: Installed nuclear capacity in South Korea (1990–2030).

reactor in 2017. Then, projections of installed nuclear capacity are adjusted by combination of the deployment of PWRs of 1.0 GWe and 1.4 GWe and a CANDU reactor of 0.7 GWe for the years 2016–2030. The lifetime of all reactors is assumed to be 40 years, although design lifetime of APR1400 is 60 years,[11] except for the first CANDU reactor, which is assumed to be 30 years.[12]

Low Growth Scenario

The low growth scenario assumes that no new reactors will be deployed after 2016. The projection of installed nuclear capacity in the years 2016–2030 for this scenario is shown by the dotted line in Figure 2. The installed nuclear capacity would be 19.7 GWe in 2030.

PROJECTIONS OF SPENT FUEL GENERATION

South Korea's Spent Fuel Inventory

By end of 2001, 5,406 metric tons of initial heavy metal (tHM) of spent fuels had been discharged from PWRs and CANDU reactors, and stored in

Table 4: Inventory of spent fuels in South Korea at end of 2001.*

Kori site (PWR spent fuel, tHM)	Yonggwang site (PWR spent fuel, tHM)	Ulchin site (PWR spent fuel, tHM)	Wolsong site (CANDU spent fuel, tHM)
1,246	819	632	2,709

**2001 Annual Report for Radiation Management in the Nuclear Power Plants in Korea*, Korea Electric Power Corporation (KEPCO), South Korea, 2002 (Korean).

AR spent fuel storage facilities at four NPP sites in South Korea: 2,697 tHM of spent PWR fuels and 2,709 tHM of spent CANDU fuels. Table 4 shows the details of the inventory of spent fuels in South Korea. Currently, there are four NPP sites in South Korea: Kori, Yonggwang, and Ulchin site for PWRs, and Wolsong for CANDU reactors. Figure 3 shows their locations.

Figure 3: NPP sites in South Korea.

Table 5: Characteristics of typical PWR and CANDU fuel assemblies.*

Characteristics	PWR	CANDU
Fuel rod array	17 × 17	N/A
Fuel rods per assembly	264	37
Assembly total weight, kg	657.9	23.6
Uranium per assembly, kg	461.4	18.8
UO_2 per assembly, kg	523.4	21.3

*J. W. Roddy et al., *Physical and Decay Characteristics of Commercial LWR Spent Fuel*, ORNL/TM-9591/V1, October 1985. K. M. Wasywich, *Characteristics of Used CANDU Fuel Relevant to the Canadian Nuclear Fuel Waste Management Program*, AECL-10463, COG-91-340, May 1993.

South Korea's Nuclear Fuel Supply Plan

Projections of spent fuel generation from the reactors largely depend on the nuclear fuel supply plan. According to the current plan, more than 60% of PWRs will be charged with the Vantage 5H (V5H) fuel assembly of Westinghouse for the years 1997–2009, and all PWRs will be charged with the Korean Next Generation (KNG) fuel assembly after year 2010.[13] The V5H fuel assembly has the same fuel rod array structure and contains nearly the same amount of uranium (461.5 kg per assembly)[14] as that for the typical PWR fuel assembly described in Table 5. Average burn-up of spent V5H fuel is anticipated to be 43,000–48,000 MWd/tHM, and that of spent KNG fuel to be 55,000 MWd/tHM.[15] For CANDU reactors, the CANDU Flexible Fuel (CANFLEX) is planned to be loaded from around the year 2005.[16] The CANFLEX fuel, which could use 1.2 weight-percent of enriched uranium, has a much higher burn-up potential than conventional CANDU fuel, approximately 21,600 MWd/tHM.[17] The amount of uranium contained in the CANFLEX fuel (18.6 kg per assembly)[18] is nearly the same as that of the typical CANDU fuel assembly.

Spent Fuel Generation for Reference Scenario

Engineering advances in fuel integrity and improved fuel management techniques likely will result in extended burn-up compared to the current burn-up. Based on the nuclear fuel supply plan, this study assumes two burn-up cases for projections of spent fuel discharges through the year 2030. One is "current burn-up case," based upon the current burn-up levels out to 2030. The other is "extended burn-up case," assuming increased discharged burn-up levels for PWRs and for CANDU reactors from 2010 and 2005, respectively.

Reference Scenario with Current Burn-up Case

Based on the projections of the installed nuclear capacity in Table 3, spent fuel discharges from PWRs and CANDU reactors may be estimated through the year 2030 for the current burn-up case. The historical inventories of spent fuel, given in Table 4, are combined with these projections to provide estimates of cumulative arisings of spent fuel. The estimates assume a once-through nuclear fuel cycle, with no fuel reprocessing.

Average discharged burn-up levels for South Korean commercial spent nuclear fuel in 1996 were around 43,000 MWd/tHM and 7,100 MWd/tHM for spent PWR and CANDU fuel, respectively.[19] The current burn-up case assumes these burn-up figures during the years 1997–2030. Estimation of annual spent fuel discharges is described in the footnote.[20] Currently, average thermal efficiency levels for South Korean commercial spent nuclear fuel are around 34.9% and 33.7% for PWRs and CANDU reactors, respectively.[21] Constant capacity factors of 80% are assumed during the years 1997–2030 for PWRs and CANDU reactors.

Figure 4 shows projections of annual spent fuel generation for the reference scenario with current burn-up. Figure 5 and Table 6 show the projections of spent fuel generation in terms of cumulative inventory. These results include spent fuel discharged from decommissioned reactors. Approximately 43% of the cumulative spent fuel discharged through the year 2030 will be from CANDU reactors, although the electricity capacity of CANDU reactors will be only approximately 8% of total nuclear capacity in 2030.[22]

Scenario with Extended Burn-up

Based on the nuclear fuel supply plan in South Korea, the extended burn-up case assumes that the average burn-up of spent PWR fuel will increase to 55,000 MWd/tHM after 2010, and that of spent CANDU fuel to 21,600 MWd/tHM after 2005. Figure 6 shows projections of annual spent fuel generation for the reference scenario with extended burn-up. Figure 7 and Table 7 show the corresponding projections of cumulative spent fuel generation. The extended burn-up case shows a reduction of cumulative spent PWR fuel by approximately 15% through 2030, compared to the current burn-up case, and of cumulative spent CANDU fuel generation by approximately 47%.

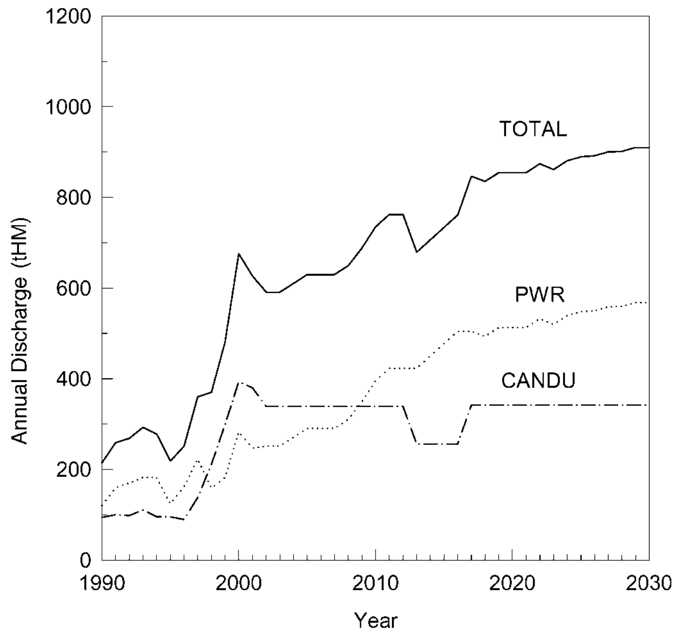

Figure 4: Annual spent fuel generation in South Korea (1990–2030) (reference scenario with current burn-up).

Spent Fuel Generation for Low Growth Scenario

The low growth scenario assumes that there are no new reactors deployed after 2016, except for a new CANDU reactor that replaces a decommissioned one in 2017. Table 8 shows the projections of cumulative spent fuel generation for the low growth scenario with current and extended burn-up. The low growth scenario shows reductions of cumulative spent PWR fuel generation to 2030 of approximately 10% and 9% for current and extended burn-up cases, respectively, compared to the corresponding reference scenario.

PROJECTIONS OF SPENT FUEL STORAGE CAPACITY

Status of At-Reactor (AR) Spent Fuel Storage Capacity

All spent fuel discharged from PWRs and CANDU reactors has been stored in AR spent fuel storage pools, or, for some CANDU spent fuel at a dry storage facility, at the reactor site. Table 9 shows the status of AR spent fuel storage

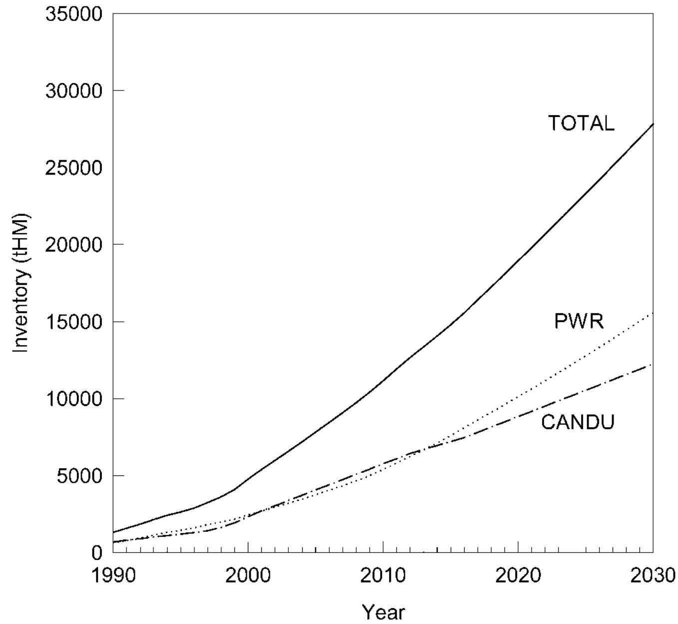

Figure 5: Cumulative inventory of spent fuel generation in South Korea (1990–2030) (reference scenario with current burn-up).

capacities at the four NPP sites in South Korea. The pool capacity of each planned PWR is assumed to be 461 tHM,[23] the same capacity as that of Yonggwang 5 and 6 (Korean Standard Nuclear Power Plants), and that of the new planned CANDU reactor to be 579 tHM.

Additional Spent Fuel Storage Capacity for Reference Scenario

Additional spent fuel storage requirements are then estimated for two cases: (1) no intersite transshipment allowed, and (2) intersite transshipment allowed. In both cases, it is assumed that no spent fuel will be reprocessed or sent out of country in the indicated time period.

Reference Scenario with No Intersite Transshipments

The no intersite transshipment case assumes that spent fuel transfer between sites is not allowed, but that transfer between NPPs at the same site is allowed. A reactor whose pool is full may ship its discharged fuel assemblies to

Table 6: Cumulative spent fuel generation in South Korea (1990–2030) (reference scenario with current burn-up).

Type	By 2010 (tHM)	By 2020 (tHM)	By 2030 (tHM)
PWR	5,400	10,120	15,580
CANDU	5,760	8,830	12,250
Total	*11,160*	*18,950*	*27,830*

another reactor pool that has more capacity. For spent fuel to be discharged from decommissioned reactors, five years are assumed for the movement of all spent fuel from pools to other storage pools at the same site after plant shutdown.[24]

Table 10 shows the years when Kori, Yonggwang, Ulchin, and Wolsong sites are expected to saturate their spent fuel storage capacities for the reference scenario with no intersite transshipment for both burn-up cases. In the extended

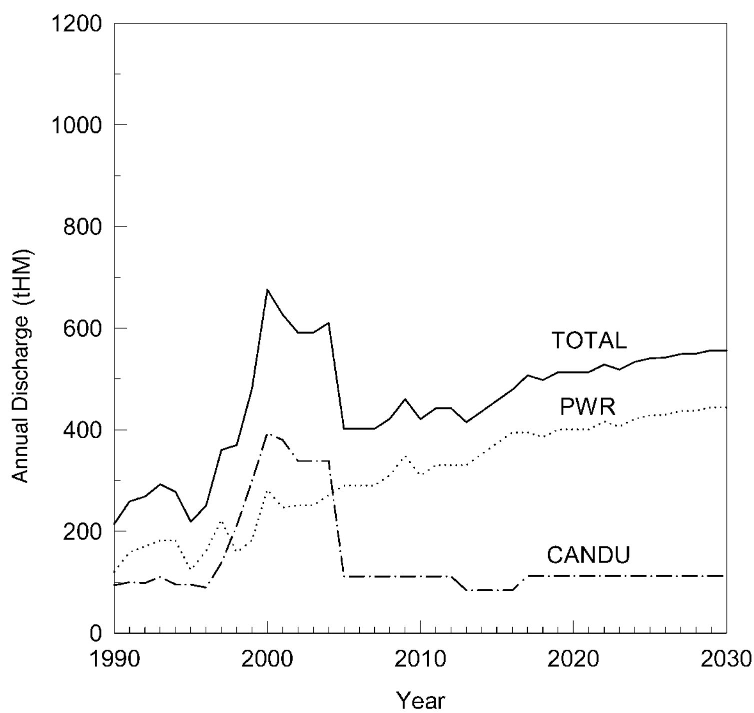

Figure 6: Annual spent fuel generation in South Korea (1990–2030) (reference scenario with extended burn-up).

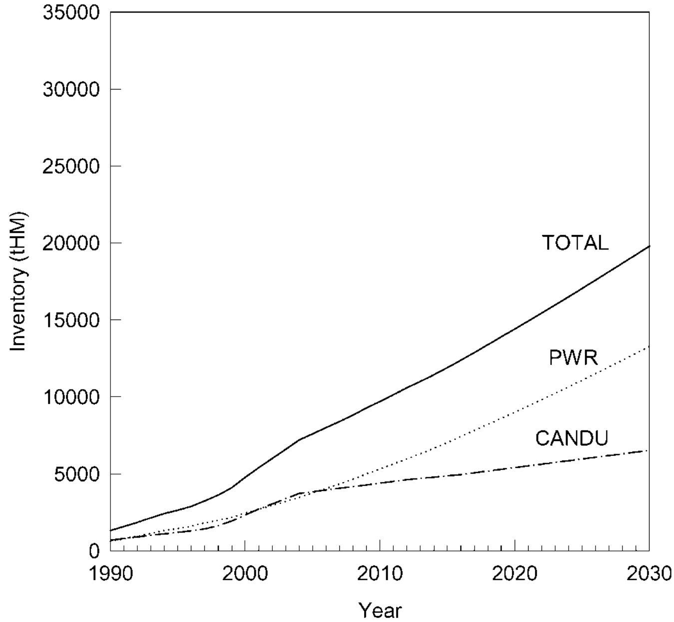

Figure 7: Cumulative inventory of spent fuel generation in South Korea (1990–2030) (reference scenario with extended burn-up).

burn-up case, the saturation times of pool capacities are prolonged by just a few years because of late commencement times of extended burn-up for PWRs and CANDU reactors, compared to the current burn-up case.

Table 11 shows the cumulative additional storage capacity required for the reference scenario with no intersite transshipment for both burn-up cases. The extended burn-up case shows a reduction of additional spent fuel storage capacity requirements of approximately 29% and 67% by 2030 for PWRs and CANDU reactors, respectively, compared to the current burn-up case.

Table 7: Cumulative spent fuel generation in South Korea (1990–2030) (reference scenario with extended burn-up case).

Type	By 2010 (tHM)	By 2020 (tHM)	By 2030 (tHM)
PWR	5,310	9,010	13,270
CANDU	4,400	5,400	6,530
Total	*9,710*	*14,410*	*19,800*

Table 8: Cumulative spent fuel generation in South Korea (1990–2030) (low growth scenario).

Type	By 2010 (tHM)	By 2020 (tHM)	By 2030 (tHM)
Current burn-up case			
PWR	5,400	9,950	14,040
CANDU	5,760	8,490	11,050
Total	*11,160*	*18,440*	*25,100*
Extended burn-up case			
PWR	5,310	8,890	12,070
CANDU	4,400	5,290	6,130
Total	*9,710*	*14,160*	*18,200*

Table 9: Status of AR spent nuclear fuel storage capacity in South Korea.*

Unit	Type	Installed capacity (MWe)	Condition	Management pool capacity (tHM)[a]
Kori-1	PWR	587	In operation	151
Kori-2	PWR	650	In operation	328
Kori-3	PWR	950	In operation	1,189[b]
Kori-4	PWR	950	In operation	652[b]
Yonggwang-1	PWR	950	In operation	652[b]
Yonggwang-2	PWR	950	In operation	652[b]
Yonggwang-3	PWR	1,000	In operation	383[c]
Yonggwang-4	PWR	1,000	In operation	383[c]
Yonggwang-5	PWR	1,000	Under construction	461[c]
Yonggwang-6	PWR	1,000	Under construction	461[c]
Ulchin-1	PWR	950	In operation	744[b]
Ulchin-2	PWR	950	In operation	448[b]
Ulchin-3	PWR	1,000	In operation	383[c]
Ulchin-4	PWR	1,000	Under construction	383[c]
Ulchin-5	PWR	1,000	Planned	461[c]
Ulchin-6	PWR	1,000	Planned	461[c]
Wolsong-1	CANDU	679	In operation	643
Wolsong-2	CANDU	700	In operation	579
Wolsong-3	CANDU	700	In operation	579
Wolsong-4	CANDU	700	Under construction	579 (+1,436)[d]

[a]These values assume that one full core of storage capacity is reserved for emergencies.
[b]Including increased pool capacity by reracking.
[c]Including planned pool capacity increased by reracking,
[d]Dry spent nuclear fuel storage capacity of 1,436 tHM at Wolsong site is in operation.
*Private communication, KNFC, South Korea, December 1998. Private communication, Technology Center for Nuclear Control (TCNC), South Korea, December 1998. *Annual Report*, Korea Atomic Industry Forum (KAIF), South Korea, 1998 (Korean). Private communication, Technology Center for Nuclear Control (TCNC), South Korea, August 2002.

Table 10: Years for NPP sites to saturate their spent fuel storage capacities (reference scenario with no intersite transshipment).

Site	Current burn-up case (Year)	Extended burn-up case (Year)
Kori	2019	2021
Yonggwang	2019	2022
Ulchin	2021	2024
Wolsong	2004	2004
SV	—	—

Reference Scenario with Intersite Transshipments Allowed

The intersite transshipment case assumes that spent fuel transfer is allowed between NPP sites of the same reactor type. Table 12 shows the cumulative additional storage capacity for the reference scenario with intersite transshipment for both burn-up cases. If intersite transshipment is allowed, even for the current burn-up case, no additional spent PWR fuel storage capacity will be needed to the year 2029.

Additional Spent Fuel Storage Capacity for Low Growth Scenario

For the low growth scenario with no intersite transshipment, the pool-saturation times at NPP sites and cumulative additional storage capacity required will be unchanged from those for the reference scenario, as given in Table 10 and Table 11. With intersite transshipment, the pool-saturation times are shortened and the cumulative additional storage capacities are increased, compared to those for the reference scenario, because of no further increase of pool capacity for PWRs after 2016. However, even in this case, there will be no need of additional spent PWR fuel storage capacity by 2023 and by 2027 for the current burn-up case and the extended burn-up case, respectively.

Table 11: Cumulative additional storage capacity required in South Korea (reference scenario with no intersite transshipment).

Type	By 2010 (tHM)	By 2020 (tHM)	By 2030 (tHM)
Current burn-up case			
PWR	0	50	4,100
CANDU	1,950	5,180	8,590
Total	*1,950*	*5,230*	*12,690*
Extended burn-up case			
PWR	0	0	2,930
CANDU	580	1,750	2,870
Total	*580*	*1,750*	*5,800*

Table 12: Cumulative additional storage capacity required in South Korea (reference scenario with intersite transshipment).

Type	By 2010 (tHM)	By 2020 (tHM)	By 2030 (tHM)
Current burn-up case			
PWR	0	0	1,060
CANDU	1,950	5,180	8,590
Total	*1,950*	*5,180*	*9,650*
Extended burn-up case			
PWR	0	0	0
CANDU	580	1,750	2,870
Total	*580*	*1,570*	*2,870*

Note: The year for PWRs sites to saturate their spent fuel storage capacities will be 2030 for the current burn-up case, while there will be no shortage for the extended burn-up case.

ECONOMIC CONSIDERATIONS

Options for Spent Fuel Storage

Through 2015, when pools are saturated, additional spent fuel would be stored on-site in dry-storage facilities. Thereafter, there are six alternative options.

Option 1: Dry storage at NPP sites

Option 1 employs on-site dry storage[25] to provide additional storage capacity for AR spent fuel discharged from PWRs and CANDU reactors.

Option 2: Inter-site transshipment starting in 2016[26]

Option 2 commences intersite transshipment for AR spent fuel discharged from PWRs starting in 2016, while continuing on-site dry storage for fuel discharged from CANDU reactors.

Table 13: Cumulative additional storage capacity required in South Korea (low growth scenario with intersite transshipment).

Type	By 2010 (tHM)	By 2020 (tHM)	By 2030 (tHM)
Current burn-up case			
PWR	0	0	4,140
CANDU	1,950	5,510	8,070
Total	*1,950*	*5,510*	*12,210*
Extended burn-up case			
PWR	0	0	2,170
CANDU	580	2,310	3,150
Total	*580*	*2,310*	*5,320*

Note: PWRs sites will saturate their spent fuel storage capacities by 2023 for the current burn-up case, and 2027 for the extended burn-up case.

Option 3: AFR interim storage facility starting in 2016

Option 3 transports AR spent fuel discharged from PWRs and CANDU reactors to centralized AFR interim storage facility starting in 2016.

Option 4: Overseas storage starting in 2016

Option 4 sends AR spent fuel discharged from PWRs after 2016 overseas for storage until at least 2030,[27] while continuing on-site dry storage for fuel from CANDU reactors.

Option 5: Overseas reprocessing after 2016[28]

Option 5 sends all AR spent fuel discharged from PWRs starting in 2016 overseas to be stored for 10 years, after which period the fuel will be reprocessed and the separated plutonium fabricated into mixed oxide (MOX) fuel. The MOX fuel would then be sent back to South Korea and burned in PWRs. All fuel from CANDU reactors would continue to be stored on-site in dry-storage.

Option 6: Direct Use of spent PWR fuel In CANDU (DUPIC)[29] *fuel cycle after 2016*

Option 6 commences the DUPIC fuel cycle for AR spent fuel discharged from PWRs after 2016. PWR spent fuel that exceeds the feed capacity of DUPIC fuel for CANDU reactors is not processed as DUPIC fuel and is maintained on-site in dry storage.

Cost Analysis

For each option, we consider only the costs incurred in managing spent fuel discharged after the pools are saturated. That is, the cumulative costs shown in Table 15 do not include the costs of pool management, including reracking. Also we do not consider costs for the process for disposal or treatment of the spent fuel subsequent to 2030. Cost estimates for all options are described in terms of undiscounted constant dollars (2001 U.S.$) and discounted net present values (NPV).[30] A 5% and 10% per annum discount rate is used for this purpose. All the evaluations are based on projections of spent fuel generation and additional spent fuel storage capacity for the reference scenario used in this study. The unit price assumptions for the component stages used in this study are summarized in Table 14.

Tables 15 and 16 show a comparison of additional cumulative costs for the six options, described in terms of undiscounted and discounted costs. The total discounted cost is calculated by spreading the constant dollar cash flows consistent with the time schedule, and then discounting these cash flows at 5% and 10% discount rate. All costs are presented in 2001 U.S dollars.

Table 14: Assumed unit prices (2001 U.S.$).

Component	PWR UO_2 fuel	CANDU UO_2 fuel	MOX fuel	DUPIC fuel
Uranium purchase ($/kgU)	33.0[a]	31.7[a]	—	—
Conversion ($/kgU)	8.8[b]	8.2[b]	—	—
Enrichment ($/SWU)	129.7[a]	—	—	—
Fabrication ($/kgHM)	219.8[b]	38.5[a]	1,648.4[b]	613.2–3,000[a]
Transport ($/kgHM)	61.0[c]	15.9[c]	57.9[c]	57.9[c]
Storage ($/kgHM)	142.1[d]	38.5[a]	142.1–184.7[d]	135.7[d]
Reprocessing ($/kgHM)	1,098.9[b]	—	—	—
Overseas transport for PWR UO_2 spent fuel ($/kgHM) = 131.0[e]				
Overseas transport for MOX fresh fuel ($/kgHM) = 261.9[e]				
Overseas transport for VHLW* ($/kgHM of original spent fuel) = 131.0[e]				
Storage for VHLW ($/kgHM of original spent fuel) = 35.5–106.6[d]				

Note: All values in Table 14 are modified values reflecting the GDP deflation of the U.S.[1]
[a]1996 values of prices of uranium purchase, enrichment, fabrication of CANDU UO_2 fuel, fabrication of DUPIC fuel and storage of CANDU spent fuel were 30$/kgU, 118$/SWU, 35$/kgU, 558$/kgHM and 35$/kgHM, respectively.[2] Due to the uncertainty of price of the DUPIC fuel fabrication, 3,000$/kgHM is assumed as maximum range of price.[3]
[b]1996 values of prices of uranium conversion, fabrication of PWR UO_2 fuel, fabrication of MOX fuel and reprocessing were 8$/kgU, 200$/kgU, 1,500$/kgHM and 1,000$/kgHM, respectively.[4]
[c]1991 values of transport prices of PWR spent fuel and CANDU spent fuel were 50$/kgHM and 13$/kgHM, respectively.[5] Transport price of MOX spent fuel and DUPIC spent fuel is assumed to be that of PWR spent fuel.[6]
[d]1989 values of storage prices of PWR spent fuel was 108$/kgHM.[7] Storage price of MOX spent fuel is assumed to be 1 to 1.3 times that of the PWR spent fuel because of its higher heat output.[8] Storage price of the DUPIC spent fuel is assumed to be that of PWR spent fuel.[9] Storage price for vitrified high-level waste (VHLW) is assumed to be 0.25 to 0.75 times that for PWR UO_2 spent fuel originated.[10]
[e]1992 values of overseas transport prices of PWR UO_2 spent fuel, VHLW associated with the same amount of original spent fuel and MOX fresh fuel were 110$/kgHM, 110$/kgHM and 220$/kgHM, respectively.[11]

[1]<http://www.bea.doc.gov/>, U.S. Department of Commerce, Bureau of Economic Analysis.

[2]*Economic Assessment of New Technology of Nuclear Fuel Cycle*, KAERI/RR-1831/97, KAERI, South Korea, June 1998 (Korean).

[3]Private communication, Professor Frank von Hippel, Center for Energy and Environmental Studies, Princeton University, March 1999.

[4]K. A. Williams et al, *A Comparative Assessment of the Economics of Plutonium Disposition Including Comparison with Other Nuclear Fuel Cycles*, U.S. Department of Energy, CONF-970613-1, May 1997.

[5]*The Economics of the Nuclear Fuel Cycle*, OECD/NEA, Paris, 1994.

[6]According to the reference at footnote 7, the same transport cost was used for PWR UO_2 spent fuel and DUPIC spent fuel.

[7]Estimated cost ranges of AR storage costs using metal casks would appear to be $40,000–$50,000 for a PWR assembly, i.e., 87–108$/kgHM, (1989 U.S. $). E. R. Johnson, "Choosing At-Reactor Spent Fuel Storage Technologies," *Proceedings of the International Topical Meeting on High Level Radioactive Waste Management*, Las Vegas, Nevada, April 8–12, 1990, pp. 1030–1036.

[8]Private communication, Harold Feiveson, Center for Energy and Environmental Studies, Princeton University, March 1999. However, the MOX spent fuel is assumed to be stored in the pools of reactors until 2030.

[9]The reference at footnote 7 uses nearly the same (94%) storage cost DUPIC spent fuel as for PWR UO_2 spent fuel.

[10]Private communication, Harold Feiveson, Center for Energy and Environmental Studies, Princeton University, March 1999.

[11]Overseas transportation between Europe and Japan, J. Takagi et al., *Comprehensive Social Impact Assessment of MOX Use in Light Water Reactors*, Citizens' Nuclear Information Center, November 1997.

Table 15: Comparison of additional cumulative costs for options for current burn-up case by 2030 (1998 U.S.$M).

	0% Discount rate			5% Discount rate			10% Discount rate		
Option	**PWR**	**CANDU**	**Total**	**PWR**	**CANDU**	**Total**	**PWR**	**CANDU**	**Total**
Option 1									
Storage on-site	583	331	914	167	156	323	52	85	137
Total (rounded)	*583*	*331*	*914*	*167*	*156*	*323*	*52*	*85*	*137*
Option 2									
Transport (domestic)	186	0	186	56	0	56	18	0	18
Storage on-site	151	331	482	37	156	192	10	85	95
Total	*336*	*331*	*667*	*93*	*156*	*248*	*28*	*85*	*113*
Option 3[a]									
Storage on-site	0	131	131	0	86	86	0	59	59
Transport (domestic)	250	83	333	72	29	101	22	11	33
Storage (AFR)	583	200	783	167	70	237	52	27	78
Total	*834*	*414*	*1,247*	*239*	*184*	*423*	*74*	*96*	*170*
Option 4[b]									
Storage on-site	0	331	331	0	156	156	0	85	85
Transport (Korea –> Europe)	399	0	399	120	0	120	39	0	39
Storage (overseas)	3,043	0	3,043	918	0	918	298	0	298
Total	*3,442*	*331*	*3,773*	*1,038*	*156*	*1,193*	*337*	*85*	*422*
Option 5[c]									
Storage on-site	0	331	331	0	156	156	0	85	85
Transport (Korea –> Europe)	399	0	399	120	0	120	39	0	39
Reprocessing	3,344	0	3,344	1,008	0	1,008	328	0	328
MOX fuel fabrication*[1]	220	0	220	41	0	41	8	0	8
Transport (Europe –> Korea)*[1]	529	0	529	70	0	70	14	0	14
Storage (HLW, on-site)*[2]	324	0	324	57	0	57	11	0	11
Total	*4,816*	*331*	*5,147*	*1,296*	*156*	*1,452*	*400*	*85*	*485*
Option 6[d]									
Storage on-site	229	140	369	57	91	147	15	61	76
Transport (domestic)	152	0	152	53	0	53	20	0	20
DUPIC fuel fabrication (min.)	0	1,126	1,126	0	391	391	0	148	148

(Continued on next page)

Table 15: Comparison of additional cumulative costs for options for current burn-up case by 2030 (1998 U.S. $M). *(Continued)*

Option	0% Discount rate			5% Discount rate			10% Discount rate		
	PWR	CANDU	Total	PWR	CANDU	Total	PWR	CANDU	Total
DUPIC fuel fabrication (max.)	0	7,083	7,083	0	2,460	2,460	0	933	933
Storage (DUPIC spent fuel)	0	331	331	0	112	112	0	41	41
Total (min.)	*381*	*1,597*	*1,978*	*110*	*594*	*704*	*35*	*250*	*285*
Total (max.)	*381*	*7,554*	*7,935*	*110*	*2,663*	*2,773*	*35*	*1,035*	*1,070*

Note: [a]AFR storage cost for spent fuel discharged from PWRs and CANDU reactors is assumed to be the same as that for on-site storage.[1]

[b]This study assumes no return of spent fuel to be sent for overseas storage. A cost of 1,000$/kgHM was assumed for the storage price of the spent fuel.

[c]Overseas storage cost before reprocessing is assumed to be included in the reprocessing cost. Costs related to disposal of recovered uranium, intermediate level waste (ILW) and low level waste (LLW) arising from reprocessing is assumed to be included in the reprocessing cost. Transport cost for the recovered plutonium to MOX fabrication facility is assumed to be included in the MOX fabrication cost. In calculating the MOX fuel fabrication cost, MOX fuel credit was considered.[2]

[d]The DUPIC fuel fabrication facility is assumed to be constructed at the CANDU reactor site, so transport cost for the DUPIC fresh fuel to CANDU reactors is not considered. In calculating the DUPIC fuel fabrication cost, the DUPIC fuel credit was considered.[3] All costs related with the DUPIC fuel cycle are assumed to be included in the cost of CANDU fuel cycle.

*[1]MOX fabrication cost and transport cost from Europe to South Korea include the MOX fabrication cost and transport cost of the MOX fresh fuel and HLW after 2030 until all will be returned.

*[2]A cost of 106.6$/kgHM of original spent fuel was used for the storage price of VHLW. Total additional cumulative cost of Option 5 will be $M 4,715, $M 1,397 and $M 474 for discount rate of 0%, 5% and 10%, respectively, for 35.5$/kgHM of VHLW storage price.

[1]Construction cost for the AFR storage cost for spent fuel would depend on the types of storage, e.g., dry or wet storage. However, if the South Korean government builds the AFR storage facility as a dry type, its construction cost to store the same amount of spent fuel would be similar to the cost of the on-site dry storage.

[2]For simple cost calculation to produce 1 kg of enriched UO_2 fuel, which has a burn-up performance equivalent to the same amount of MOX fuel, no lead time and loss rates from uranium purchase to fabrication of UO_2 fuel are assumed. A 3.7 weight percent (w/o) U-235 enriched UO_2 fuel has a burn-up performance of 43,000 MWd/tHM. In addition, to produce 1 kg of MOX fuel, approximately 6.1 kg of 4 years cooled 43,000 MWd/tHM UO_2 fuel is required. *Plutonium Fuel: An Assessment*, OECD/NEA, 1989. Total cost producing 1kg of enriched UO_2 fuel is the summation of the cost for uranium purchase, conversion, enrichment and fabrication, i.e., $\$33.0 \times 7.5 + \$8.8 \times 7.5 + \$129.7 \times 5.2 + \$219.8 = \$1207.7$. A 7.5 and 5.2 means multiplication constant for required natural uranium and SWU, respectively. Therefore, 1 kg of MOX fuel would have a credit of $1131 to compensate the cost of producing 1 kg of enriched UO_2 fuel.

[3]A 42.3 tHM per annum of the DUPIC fuel is required as a feed fuel for a 0.7 GWe CANDU reactor when the DUPIC fresh fuel is made by 10 years cooled 43,000 MWd/tHM PWR spent fuel. H. Choi et al., "Parametric Analysis of the DUPIC Fuel Cycle," *Proceedings of the 1994 Nuclear Simulation Symposium*, October 12–14, 1994, Pembroke, Ontario, pp. 71–80. A 0.7 GWe CANDU reactor fed with natural uranium fuel requires 85.4 tU per annum. Overall costs for producing 1 kg of natural uranium fuel assumes the summation of the cost for uranium purchase, conversion and CANDU fuel fabrication, i.e., $\$33.0 + \$8.8 + \$38.5 = \$80.3$. Therefore, 1 kg of DUPIC fuel would have a credit of $162.1 ($=\$80.3 \times 85.4/42.3$) to compensate the cost of producing 1 kg of natural uranium fuel.

Table 16: Comparison of additional cumulative costs for options for extended burn-up case by 2030 (1998 U.S. $M).

	0% Discount rate			5% Discount rate			10% Discount rate		
Option	**PWR**	**CANDU**	**Total**	**PWR**	**CANDU**	**Total**	**PWR**	**CANDU**	**Total**
Option 1									
Storage (on-site)	416	111	527	111	51	162	32	27	59
Total (rounded)	*416*	*111*	*527*	*111*	*51*	*162*	*32*	*27*	*59*
Option 2									
Transport (domestic)	179	0	179	48	0	48	14	0	14
Storage (on-site)	0	111	111	0	51	51	0	27	27
Total	*179*	*111*	*289*	*48*	*51*	*99*	*14*	*27*	*41*
Option 3									
Storage (on-site)	0	41	41	0	26	26	0	18	18
Transport (domestic)	179	29	208	48	10	58	14	4	18
Storage (AFR)	416	70	486	111	25	136	32	10	41
Total	*595*	*139*	*734*	*159*	*81*	*220*	*46*	*31*	*77*
Option 4									
Storage (on-site)	0	111	111	0	51	51	0	27	27
Transport (Korea –> Europe)	384	0	384	102	0	102	29	0	29
Storage (overseas)	2,928	0	2,928	782	0	782	224	0	224
Total	*3,312*	*111*	*3,422*	*883*	*51*	*934*	*254*	*27*	*281*
Option 5									
Storage (on-site)	0	111	111	0	51	51	0	27	27
Transport (Korea –> Europe)	384	0	384	102	0	102	29	0	29
Reprocessing	3,218	0	3,218	858	0	858	247	0	247
MOX fuel fabrication	212	0	212	35	0	35	6	0	6
Transport (Europe –> Korea)	509	0	509	79	0	79	14	0	14
Storage (HLW, on-site)	312	0	312	49	0	49	8	0	8
Total	*4,635*	*111*	*4,746*	*1,123*	*51*	*1,147*	*304*	*27*	*331*
Option 6									
Storage (on-site)	62	44	105	15	28	43	4	18	22
Transport (domestic)	152	0	152	53	0	53	20	0	20
DUPIC fuel fabrication (min.)	0	1,126	1,043	0	391	391	0	148	148
DUPIC fuel fabrication (max.)	0	7,083	7,106	0	2,460	2,460	0	935	935
Storage (DUPIC spent fuel)	0	331	331	0	112	112	0	41	41
Total (min.)	*214*	*1,501*	*1,715*	*68*	*531*	*599*	*24*	*207*	*231*
Total (max.)	*214*	*7,458*	*7,672*	*68*	*2,600*	*2,668*	*24*	*994*	*1,018*

Note: This study assumes that the extended burn-up spent fuel released from PWR and CANDU reactors will be stored in pools through 2030.

As indicated by Tables 15 and 16, Option 2 is the least expensive option. In terms of 5% discounted cost, the additional cumulative costs by 2030 for Option 2 are approximately 23% and 41% less than that for Option 1 and Option 3, respectively, for current burn-up case, while approximately 39% and 55% less than that for Option 1 and Option 3, respectively, for extended burn-up case. This reduction is mainly due to the fact that Option 2 allows the maximum existing use of spent fuel storage. The other options are still more expensive, ranging about from 5 to 11 times the cost of Option 2 for current burn-up case, and about from 9 to 27 times the cost of Option 2 for extended burn-up case in terms of 5% discounted cost.

INSTITUTIONAL RESTRICTIONS

Options 2, 3, and 6 call for domestic shipment of spent fuel. For Option 2, the shipment would be 215 tHM per annum for PWR spent fuel from 2016 through 2030. It would be 238 tHM and 166 tHM per annum for PWR spent fuel for Option 3 and Option 6, respectively, for the reference scenario and with current burn-up. For Option 3, further transportation of 347 tHM per annum is needed for CANDU spent fuel for the same time period.

Thus far, only a limited amount of spent fuel has been transported by KAERI, mostly for R&D purposes.[31] Two transshipments have been made between neighboring NPPs at the Kori site. For these purposes, Korean Standard Cask (KSC) series shipping casks have been developed and demonstrated to transport spent fuel safely.[32] Domestic transport of spent fuel is regulated by the Ministry of Science and Technology (MOST), based on the South Korean Atomic Energy Act.[33] The South Korean Atomic Energy Act permits such shipment if utilities can assure adequate safety of spent fuel under safeguards. The past safety record for spent fuel shipment in the U.S. and in other nations shows its feasibility.[34]

Domestic transportation of spent fuel could be provided by road, by rail, or by sea. The last is possible because all South Korean NPP sites are located along the seacoast. Whichever transport is used, the utility will have to provide appropriate measures for shipment of spent fuel, based on routing analysis that considers the overall risk to the public and consultation with affected local jurisdictions.

Options 4 and 5 call for overseas shipment of spent fuel. Such shipment will require consent of the U.S., Canada, and Australia, which are members of the Nuclear Suppliers Group (NSG) and supply uranium to South Korea. The South Korean government has bilateral nuclear cooperation agreements with these states.[35]

Options 5 and 6 call for reprocessing and recycling of PWR spent fuel, and will require the prior consent of the U.S., Canada, and Australia because of the same bilateral nuclear cooperation agreements.[36]

CONCLUSIONS

For the reference scenario and with current burn-up, if intersite transshipment between NPP sites is not allowed, estimated cumulative pool storage capacity will fall short of estimated spent fuel discharges through 2030 by approximately 3,900 MT for PWR spent fuel and 8,200 MT for CANDU spent fuel. The pools will be saturated at current sites between 2006 and 2022. Even with extended burn-up, the pool-saturation times will be delayed only about three years (one-year for the Kori site). If intersite transshipment between NPP sites is allowed, even at current reactor burn-up, there will be no need for additional spent PWR fuel storage capacity until 2027.[37] Economic evaluations for the six options considered in this study shows that intersite transshipment would be the most cost effective solution to the additional spent fuel storage problem in South Korea.

For the low growth scenario, in the case of no acquisition of further capacity of pools after 2016, if intersite transshipment between NPP sites is not allowed, pool-saturation times at NPP sites and cumulative additional storage capacity required will be the same as those for the reference scenario. If intersite transshipment between NPP sites is allowed, even at the low growth scenario, PWR sites will not become saturated until 2023 and 2027 for the current burn-up and extended burn-up cases, respectively.

Intersite transshipment appears the most straightforward and economic way to relieve the burden of additional spent PWR fuel storage requirements before final disposition if domestic transportation of spent fuel is implemented.

If intersite transshipment cannot be implemented due to concerns about transport of spent fuel or for other reasons, on-site dry storage would be the next most cost effective alternative.

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NOTES AND REFERENCES

1. <http://www.most.go.kr/index-new.html> (Subtitle: Nuclear Statistics and General Status) Ministry of Science and Technology (MOST), South Korea (Korean).

2. Commencement of the underground repository is not expected in South Korea by 2030. *White Book of Nuclear Power Generation*, Ministry of Commerce, Industry and Energy (MOCIE), South Korea, July 1998 (Korean).

3. Construction of 3,000 metric tons (MT) of away-from reactor (AFR) spent fuel storage facility by 1997 was planned at the 221st South Korean Atomic Energy Commission (AEC) meeting in December 1988.

4. Centralized AFR interim storage facility for spent fuel that would be in operation in 2016. Type of spent fuel storage, e.g., wet storage or dry storage, will be determined until starting of construction in 2008. 249th South Korean AEC meeting, September 1998.

5. Spent fuel that would be discharged from PWRs of the Korean Peninsular Energy Development Organization (KEDO) program in North Korea is not considered in this study.

6. *The Fourth Long-term Power Development Plan (1998–2015)*, MOCIE, South Korea, August 1998 (Korean).

7. The logistic curve has been used in the estimation of projections of electricity generation and installed nuclear capacity for the world through the year 2025. *Nuclear Energy and Its Fuel Cycle: Prospects to 2025*, OECD/NEA, Paris, 1987. The logistic curve fitting function for per capita electricity generation is specified as follows:

$$E_t = \frac{E_\infty}{1 + e^{-(a_E + b_E T)}},$$

where:

E_t = per capita electricity generation in year t,
E_∞ = an assumed asymptote to which per capita generation tends,
T = the time in years from the base year, and
a_E and b_E = parameters determined by following equation,

$$a_E + b_E T = \log_e \frac{E_t}{E_\infty - E_t}.$$

The derived parameters a_E and b_E are -0.2443 and 0.1177, respectively.

8. *Electricity Information 1996*, International Energy Agency, OECD, 1997.

9. *Long-term Power Development Plan (1995–2010)*, MOCIE, South Korea, December 1995 (Korean).

10. *Comprehensive Nuclear Energy Promotion Plan*, MOST, South Korea, June 1997 (Korean).

11. S. H. Chang et al., "Korea looks beyond the next generation," *Nuclear Engineering International*, vol. 42, no. 511, 1997, pp. 12–16.

12. *The First Power Supply Plan (2002–2015)*, MOCIE, South Korea, August 2002 (Korean).

13. C. S. Rim, "Korean Nuclear Fuel Program," *Journal of Nuclear Science and Technology*, vol. 35, no. 7, July 1998, pp. 467–472.

14. Private communication, Korea Nuclear Fuel Company, Ltd. (KNFC), South Korea, December 1998.

15. Ibid.

16. C. S. Rim, "Korean Nuclear Fuel Program," *Journal of Nuclear Science and Technology*, vol. 35, no. 7, July 1998, pp. 467–472.

17. K. M. Wasywich, *Characteristics of Used CANDU Fuel Relevant to the Canadian Nuclear Fuel Waste Management Program*, AECL-10463, COG-91-340, May 1993.

18. Private communication, Korea Nuclear Fuel Company, Ltd. (KNFC), South Korea, December 1998.

19. Y. E. Lee, M. J. Song, "Expansion of Spent Fuel Interim Storage Capability in Association with Back-End Fuel Cycle Policy in Korea," *Proceedings of the Symposium on Waste Management 97*, Tucson, U.S.A, 1997.

20. The annual spent nuclear fuel discharges is specified as following:

$$SF_t = \frac{NC_t * 365 * CF_t}{TE_t * BU_t},$$

where:

SF_t = annual amount of spent nuclear fuel discharged in year t (tHM),
NC_t = net nuclear capacity in year t (MWe),
CF_t = capacity factor in year t,
TE_t = thermal to electrical efficiency in year t, and
BU_t = average discharge burn-up in year t (MWd/tHM).

International Symposium on Nuclear Fuel Cycle and Reactor Strategy: Adjusting to New Reality, Key Issue Papers, International Atomic Energy Agency (IAEA), Vienna, 1997.

21. *White Book of Nuclear Safety*, Korea Institute of Nuclear Safety (KINS), South Korea, August 1998 (Korean).

22. Decay heat per unit mass from spent CANDU fuel of 7,100 MWd/tHM (cooled several years) is approximately one-tenth that of spent PWR fuel of 43,000 MWd/tHM (see Table 17 in the Appendix). In Table 6, the 12,350 tHM of spent CANDU fuel is equivalent to approximately 1,235 tHM of spent PWR fuel in decay heat generated, approximately 7% of the heat generated in cumulative PWR spent fuel discharges through 2030.

23. However, this pool capacity could have more space if the spent fuel is stored as maximum storage density. Maximum storage density is defined by the maximum ratio of the area of storage cells to the area of pool, approximately 92% in PWR pools. J. Y. Jung, "Status of Onsite Spent Fuel Storage," *Nuclear Industry*, Korea Atomic Industrial Forum, November 1998, pp. 56–75 (Korean). 497.8 cm^2 of pool is required for storage of a PWR spent fuel assembly because the cross section of PWR fuel assembly is 21.4×21.4 cm^2. J. W. Roddy et al., *Physical and Decay Characteristics of Commercial LWR Spent Fuel*, ORNL/TM-9591/V1, October 1985. The maximum number of PWR fuel assemblies per 1 m^2 of pool is 20, corresponding to 9.2 tHM of spent fuel per square meter, considering the mass of 0.4614 tHM per PWR fuel assembly (see Table 6). The pools of Yonggwang 5 and 6 are 902 cm long, 743 cm wide and 1204 cm deep. Private communication, Korea Power Engineering Co., Inc (KOPEC), March 1999. Therefore, each pool of Yonggwang 5 and 6 could accomodate approximately 545 tHM of PWR spent fuel, with one full core storage capacity of 76.3 tHM, reserved for emergencies. Since the spent fuel storage pool is outside of the reactor containment, the size of the pools at future reactors would not be fixed by any other constraints, but economics of spent fuel storage.

24. When a reactor shuts down, there could be two options for the spent fuel, keeping the pools operating or moving all of the spent fuel into other storage facilities. However, at shutdown reactor sites, maintenance of pools following shutdown could lead to a significant cost burden to a utility. Operating one pool following shutdown has been estimated to cost approximately $3.7 million (1989 U.S.$) annually, based on the pool capacity of 595 MTHM. S. R. Rod, *Cost Estimates of Operating Onsite Spent Fuel Pools after Final Reactor Shutdown*, PNL-7778, August 1991. For dry storage, PWR spent fuel must first be cooled in pools for at least five years after it is removed from the reactor. *Disposal and Storage of Spent Nuclear Fuel Finding the Right Balance. A Report to Congress and the Secretary of Energy*, U.S. Department of Commerce, March 1996.

25. Dry storage is considered safer than pool storage. U.S. Nuclear Regulatory Commission, "Waste Confidence Decision Review. 55," Federal Register 38508, September 18, 1990.

26. According to the 249th meeting of the South Korean AEC in September 1998, all spent fuel discharged will be stored at their NPP sites until the commencement of centralized AFR interim storage facility. This is option 3 in this study.

27. British Nuclear Fuels Ltd. (BNFL) has proposed that overseas spent fuel could be stored at the Thermal Oxide Reprocessing Plant (THORP) at Sellafield in northern England for at least a decade, with reprocessing as an option after the end of the storage period. BNFL Inc. "Issues for BNFL's Congressional Staff Tour," August 1995. There are also proposals for overseas storage for spent fuel in Russia and Australia. According to one proposal, spent fuel from South Korea would be sent to Russia for storage with a charge of 700$/kgHM, and possibly ultimate disposal with an additional charge of 1,000$/kgHM. Reprocessing of the spent fuel might be an option for customers to select. *Nuclear Fuel*, February 22, 1999 and March 18, 1999.

28. The Joint Declaration of Denuclearization of the Korean Peninsula in 1991 commits Korea not to possess nuclear fuel reprocessing or enrichment facilities. Y. M. Choi, "Meaning and Organization of International Nuclear Non-Proliferation Regime," *Nuclear Industry*, KAIF, February 1998, pp. 50–56.

29. The basic idea of the DUPIC fuel cycle is to refabricate PWR spent fuel, which still contains approximately two times the fissile-material content of natural uranium

into fuel for heavy water reactors, without separating plutonium. J. Kang, A. Suzuki, "Analysis on DUPIC Fuel Cycle in Aspect of Overall Radioactive Waste Management," *Journal of Nuclear Fuel Cycle & Environment*, vol. 4, no. 1, 1997, pp. 19–27. The extra burn-up of the DUPIC fuel is due to the reactivity increase associated with the removal of some of the fission products, including almost all the cesium, during the DUPIC fuel fabrication process, and the additional reactivity gain resulting from the higher neutronics efficiency of heavy water. C. A. Bollmann et al., *Environmental and Economic Performance of Direct Use of PWR Spent Fuel in CANDU Reactors*, MIT-NFC-TR-014, Massachusetts Institute of Technology, June 1998. PWR spent fuel cooled for 10 years with 43,000 MWd/tHM burn-up produces fresh DUPIC fuel which, when spent, has a burn-up of 16,300 MWd/tHM, while 55,000 MWd/tHM PWR spent fuel gives 12,500 MWd/tHM in DUPIC spent fuel. At 12,500 MWd/tHM, approximately 55 tHM of the DUPIC spent fuel will be discharged annually, which is about 30% more, compared to approximately 42 tHM per annum for 16,300 MWd/tHM. H. Choi et al., "Parametric Analysis of the DUPIC Fuel Cycle," *Proceedings of the 1994 Nuclear Simulation Symposium*, October 12–14, 1994, Pembroke, Ontario, pp. 71–80. Higher burn-up of the PWR spent fuel is less attractive for the DUPIC fuel cycle.

30. (Discounted annual cash disbursement) = (undiscounted value)/(1+(discounted rate))^n, where n = (the year of the expenditure)-2001. The NPV is an appropriate index of costs for comparing competing options because it reflects the time value of money.

31. There have been no urgent needs for a large amount of spent fuel transportation thus far.

32. *International Cooperation at the OECD/NEA on the Geological Disposal of Radioactive Waste*, OECD/NEA, Paris, 1998.

33. See article 86 of the South Korean Atomic Energy Act, article 235 of the Enforcement Decree of the Atomic Energy Act, and article 99 of Enforcement Regulations of the Atomic Energy Act.

34. More than 1,300 MT of spent fuel was transported in the U.S. during 1979–1995, and there were more than 7,000 rail shipments of spent fuel in Britain through 1986. There have been no accidents involving a release of radioactivity. M. Holt, *Transportation of Spent Nuclear Fuel*, Congressional Research Service Report for Congress 97–403, May 29, 1998.

35. The South Korean government has bilateral nuclear cooperation agreements with the U.S., Canada, and Australia in 1972, in 1976, and in 1979, respectively. <http://203.230.61.4/> (Subtitle: Status of nuclear cooperation agreements, MOST, South Korea (Korean). According to the bilateral nuclear cooperation agreements with these nations, transfer of special material, produced through the use of material transferred to South Korea, to the other nations requires prior consent of the governments of those nations. K. S. Lee, "Concept and Major Factors of Nuclear Cooperation Agreement," *Nuclear Industry*, KAIF, February 1998, pp. 57–64 (Korean).

36. Altering in form or content of special material, produced through the use of material or technology transferred to South Korea, requires prior consent of the governments of the nations of origin, i.e. the U.S., Canada and Australia. K. S. Lee, "Concept and Major Factors of Nuclear Cooperation Agreement," *Nuclear Industry*, KAIF, February 1998, pp. 57–64 (Korean).

37. The present South Korean policy for the CANDU spent fuel is that the CANDU spent fuel will be stored in the dry storage at Wolsong site until it is finally disposed of

in the geologic repository. Private communication, Professor C. S. Kang, Department of Nuclear Engineering, Seoul National University, South Korea, April 1999.

38. A. G. Croff, *A User's Manual for the ORIGEN2 Computer Code*, ORNL/TM-7175, July 1980.

APPENDIX

This appendix shows the decay heat, expressed in watts per MTHM, from several types of spent fuel and HLW as a function of cooling time, given in Table 17 and Figure 8. The decay heat was calculated by the ORIGEN2 code.[38]

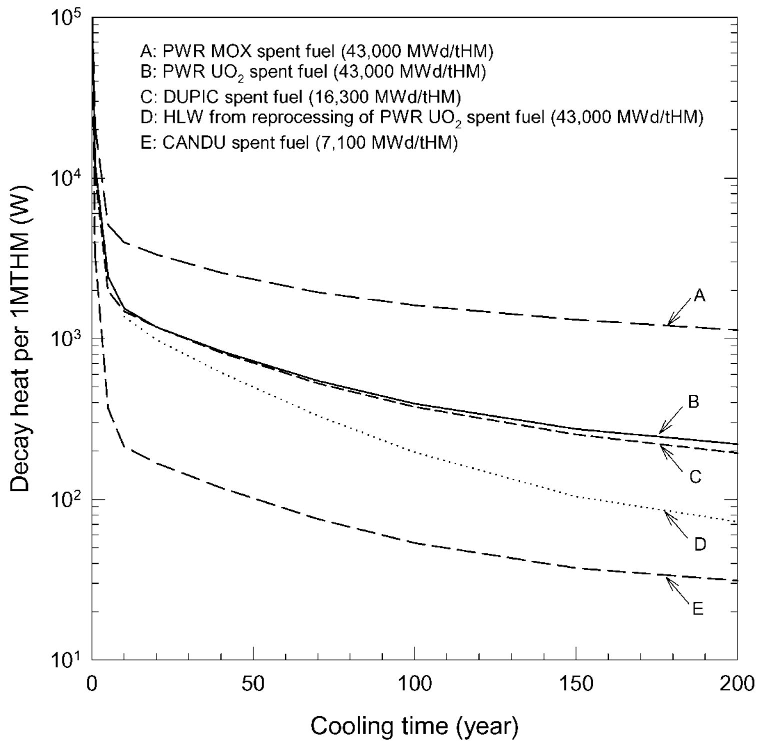

Figure 8: Decay heat from spent fuels and HLW as a function of cooling time.

Table 17: Decay heat from spent fuels and HLW as a function of cooling time.

Item	At discharge (W/tHM)	1-year (W/tHM)	10-year (W/tHM)	100-year (W/tHM)
PWR UO_2 spent fuel[a]				
Actinides	1.22×10^5	8.87×10^2	3.65×10^2	2.73×10^2
Fission products	2.00×10^6	1.16×10^4	1.17×10^3	1.21×10^2
Total	*2.12×10^6*	*1.24×10^4*	*1.54×10^3*	*3.94×10^2*
HLW[b]				
Actinides	N/A	N/A	2.02×10^2	7.52×10^1
Fission products	N/A	N/A	1.16×10^3	1.21×10^2
Total	N/A	N/A	*1.37×10^3*	*1.96×10^2*
PWR MOX spent fuel[c]				
Actinides	1.09×10^5	8.37×10^3	3.06×10^3	1.52×10^3
Fission products	1.88×10^6	1.26×10^4	9.18×10^2	9.25×10^1
Total	*1.99×10^6*	*2.10×10^4*	*3.98×10^3*	*1.61×10^3*
CANDU spent fuel[d]				
Actinides	1.05×10^5	2.63×10^1	2.32×10^1	3.25×10^1
Fission products	1.36×10^6	3.31×10^3	1.90×10^2	2.09×10^1
Total	*1.47×10^5*	*3.33×10^3*	*2.13×10^2*	*5.34×10^1*
DUPIC spent fuel[e]				
Actinides	9.48×10^4	4.02×10^3	6.82×10^2	2.90×10^2
Fission products	1.27×10^6	6.64×10^3	8.02×10^2	8.53×10^1
Total	*1.36×10^6*	*1.07×10^4*	*1.48×10^3*	*3.76×10^2*

[a]With burn-up of 43,000 MWd/tHM.
[b]The HLW is produced as a result of chemically reprocessing 10–year cooled 43,000 MWd/tHM PWR UO_2 spent fuel, containing all of what is in the spent fuel except the volatile elements and 99.5% of the uranium and plutonium.[1]
[c]The MOX fresh fuel is fabricated from plutonium recovered after 10 years cooling of 43,000 MWd/tHM PWR UO_2 spent fuel using depleted uranium.[2]
[d]With burn-up of 7,100 MWd/tHM.
[e]The DUPIC fresh fuel is fabricated from 10 years cooled 43,000 MWd/tHM PWR UO_2 spent fuel, and with a burn-up of 16,300 MWd/tHM when spent.

[1]A. G. Croff et al., *Graphical and Tabular Summaries of Decay Characteristics for Once-Through PWR, LMFBR, and FFTF Fuel Cycle Materials*, ORNL/TM-8061, January 1982.
[2]*Plutonium Fuel: An Assessment*, OECD/NEA, Paris, 1989.