Spent Fuel Management in South Korea: The Illogic of Pyroprocessing[#]

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Background

South Korea has nuclear-power reactors at four sites (Figure 1) with a combined generating capacity of about 18,000 Megawatts (18-GWe), an additional 10 GWe under construction[1] and announced plans to build an additional 15 GWe by 2030.[2] That would bring South Korea's total nuclear generating capacity to 43 GWe – almost equal to Japan's nuclear-generating capacity today.

Figure 1. **Locations of South Korea's nuclear power plants.[3]**

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[1] Korea Hydro and Nuclear Power Company, http://www.khnp.co.kr/en/030100.

[2] National Energy Committee, *The 1st National Energy Basic Plan (2008-2030)*, August 2008 (Korean). Includes four 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] Map from presentation by Prof. Jooho Whang, Kyung Hee University, South Korea, "Discussions on Spent Nuclear Fuel in Korea," 27 May 2009.

South Korea's nuclear utility, Korea Hydro and Nuclear Power (KHNP) has stated that the spent-fuel pools at some of its power reactors will be full in 2016.[4] In theory, the older spent fuel in the pools could be shifted to dry cask storage, as is standard practice at U.S. nuclear power plants. In practice, however, local communities in South Korea are likely to resist the addition of spent fuel storage capacity at the reactor sites.

In January 2009, South Korea's Ministry of Knowledge and Economy established the Korea Radioactive Waste Management Corporation and launched a public consensus process to formulate a national policy on spent fuel management.[5] Six months later, in July 2009, however, the Blue House (South Korea's equivalent of the U.S. White House) halted the process because the government did not feel adequately prepared.[6]

In Japan, a similar situation led Japan's nuclear utilities to first ship spent fuel to Europe for reprocessing and then to build a domestic spent fuel reprocessing plant.[7] Although any country with nuclear-power plants requires a geological repository, whether it reprocesses or not, a reprocessing plant provides a central interim location to which spent fuel can be shipped from the reactor sites.

Since Japan's reprocessing plant does not have the capacity to reprocess spent fuel at the same rate at which it is discharged from Japan's power reactors, of central dry-storage capacity for five thousand tons[8] of spent fuel is being built in Mutsu near the Rokkasho reprocessing plant. In 1993, five hundred tons of interim dry-cask storage capacity was authorized to be built at the Fukushima I reactor site. In both cases, however, commitments were received by the local authorities that the spent fuel would be reprocessed in a second reprocessing plant if and when one is built. in the expectation that the fuel would be shipped to the second reprocessing.[9] Given the delay in building the second reprocessing plant, which was originally scheduled to operation in 2010, however, and delays in full-scale operation of Rokkasho, it is likely that interim storage capacity will be required. In March 2009, Chubu Electric Power proposed to construct a 700-ton dry cask storage facility at its Hamaoka nuclear power plant where the utility plans to build a new reactor to replace two old reactors. It is not yet clear whether the local government will accept such a storage facility.[10]

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

[5] "Establishing Korea Radioactive Waste Management Corporation (KRMC)," MKE Press Release, 31 December 2008 (in Korean).

[6] The public consensus process was stopped after the chairman of the committee for public consensus had been tentatively selected. On 6 Aug. 2009, the South Korean government announced that a legal framework would be required and expert opinion would have to be solicited before the launch of the public consensus process. The relevant authorities are therefore preparing an experts' consensus process, personal communication, Professor Jooho Whang, Kyung Hee University, 21 October 2009. See also "Why delay the public consensus process of spent fuel," *Dong-a Ilbo* [*East Asia Daily*] 13 August 2009 (Korean).

[7] Tadahiro Katsuta and Tatsujiro Suzuki, *Japan's Spent Fuel and Plutonium Management Challenges* (International Panel on Fissile Materials, 2006, available at www.fissilematerials.org.

[8] Spent fuel is ordinarily measured by the original tonnage (metric) of uranium that it contained. Thus this weight does not include the weight of the oxygen in the uranium oxide or the fuel's zirconium alloy cladding.

[9] Masafumi Takubo, "Wake Up, Stop Dreaming: Reassessing Japan's Processing Program," *Nonproliferation Review,* Vol. 15.1, March 2008.

[10] Personal communications, Tatsujiro Suzuki and Masafumi Takubo, 1 November 2009.

Reprocessing also provides a country with a nuclear-weapon option. Although Japan has been a model with regard to its compliance with the Nonproliferation Treaty, the governments of Japan's neighbors – especially China and South Korea – regard it as a latent nuclear-weapon state. The nuclear-weapon programs of France and India were both built on reprocessing programs that were initially nominally civilian. The upsurge of demands from opposition parties following North Korea's nuclear test in May 2009 that South Korea have "nuclear sovereignty" -- i.e. the right to enrich uranium and reprocess nuclear fuel like Japan -- suggests an interest in a nuclear-weapon option in some sectors of South Korea's polity.[11]

South Korea's Atomic Energy Research Institute (KAERI), with support from South Korea's Ministry of Education, Science and Technology, urges that the spent fuel from South Korea's pressurized water reactor (PWRs) be reprocessed using pyroprocessing technology in which the elements in the fuel would be separated electrochemically after being dissolved in molten salt. KAERI also proposes that South Korea build liquid-sodium-cooled fast-neutron reactors. The plutonium and other transuranic elements[12] recovered from PWR fuel then would be recycled repeatedly through the fast-neutron reactor cores until they were completely fissioned.

This is, in fact, the same vision promoted by the G.W. Bush Administration's Department of Energy (DOE) for the management of U.S. spent fuel.[13] Under the Bush Administration, KAERI conducted joint research on pyroprocessing in collaboration with the DOE's nuclear-energy laboratories.

KAERI has had a modest spent-fuel reprocessing R&D program ever since the early 1970s, when South Korea briefly pursued nuclear weapons after President Nixon proposed that the United States' Asian allies take primary responsibility for their own defense.[14] Since 1997, KAERI has been doing R&D related to pyroprocessing. About 10 percent of KAERI's 1100 employees work on pyroprocessing.[15]

The 1974 U.S.-South Korea Agreement on Cooperation on Atomic Energy requires U.S. agreement if "any irradiated fuel elements containing fuel material received from the United

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[11] Lee Jong-Heon, "South Koreans call for nuclear sovereignty," UPI, June 15, 2009; Jungmin Kang, "The North Korean nuclear test: Seoul goes on the defensive," *Bulletin of the Atomic Scientists*, June 12, 2009 (http://www.thebulletin.org/web-edition/features/the-north-korean-nuclear-test-seoul-goes-the-defensive); Mark Hibbs, "US might permit offshore reprocessing but not return of South Korean plutonium, *Nuclear Fuel,* 21 September 2009, p. 8.

[12] The other long-lived transuranic elements that are produced in significant quantity by neutron capture in a reactor are neptunium, americium and curium. Twenty years after discharge, in light-water-reactor spent fuel with a burnup of 53 MWt-days/kgU, plutonium constitutes 82.4% of the total transuranic mix by weight, americium 10.7%, neptunium 6.6%, and curium 0.4%, Jungmin Kang and Frank von Hippel, "Limited Proliferation-Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-water Reactor Spent Fuel," *Science and Global Security* Vol. 13 (2005) p. 169, Table 1.

[13] U.S. Department of Energy, *Report to Congress on Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research,* 2003.

[14] Jungmin Kang and H.A. Feiveson, "South Korea's Shifting and Controversial Interest in Spent Fuel Reprocessing," *Nonproliferation Review*, Spring 2001.

[15] In 2007 fiscal year, the budget of the Ministry of Education, Science and Technology (MEST) for total nuclear energy R&D – virtually all of which went to KAERI – was approximately $170 million ($1 equaled 1,242 Korean Won on 1 September 2009) of which approximately $22 million went for research on the nuclear fuel cycle, *Atomic Energy White Paper*, MEST, December 2008.

States of America [is to be] altered in form or content".[16] As a matter of policy, the ROK requests U.S. agreement to such activities even if U.S.-origin material is not involved.[17] The Agreement of Cooperation will expire in 2014, however. South Korea's Ministry of Foreign Affairs and Trade hopes to negotiate a new Agreement of Cooperation that will give South Korea prior consent to pursue spent-fuel pyroprocessing, similar to that given in the 1988 U.S. Agreement of Nuclear Cooperation with Japan.

KAERI has not yet carried out any processing of irradiated fuel in its pyroprocessing R&D program[18] but has requested U.S. permission to do so. It has constructed an Advanced Spent Fuel Conditioning Processing Facility (ACPF) capable of converting the uranium and transuranic elements in 20-kilogram batches of spent PWR fuel from oxide to metal form. No chemical separation would occur at this stage but the high temperatures involved would drive off the volatile element cesium-137, which generates most of the gamma-radiation field around spent fuel that is more than a decade old.[20] This would make it much easier to separate the plutonium.

KAERI hoped to receive permission from the U.S. to begin its experiments with irradiated fuel by the end of 2009. Since India used civilian plutonium for its 1974 nuclear test, however, the U.S. Government has generally opposed reprocessing outside of the weapon states. Indeed, during the Carter Administration, the U.S. attempted to persuade Japan, the only non-weapon state that still reprocesses today, not to reprocess. The U.S. gave up its opposition only after Japan's Prime Minister Fukuda publically called the right to reprocess "a life or death issue for Japan," [21]

Although plutonium recovered from light-water-reactor fuel is not weapon grade, it is weapon-usable.[22] A single 1-GWe pressurized-water nuclear power plant discharges about 200 kilograms of plutonium in its spent fuel annually -- enough, if separated, for 25 Nagasaki-type nuclear bombs.[23] If South Korea goes ahead with pyroprocessing, it could have critical implications for the future of the nonproliferation regime. Although the current confrontation over Iran's

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[16] "Agreement for Cooperation Between the Government of the Republic of Korea and the Government of the United States of America Concerning Civil Uses of Atomic Energy," effective since June 16, 1974, Article VIII. F.

[17] "South Korea's Shifting and Controversial Interest in Spent Fuel Reprocessing," *op. cit*.

[18] In March 2000, KAERI processed some spent PWR fuel into fuel pellets for heavy-water reactors with mechanical and thermal processing – i.e. no chemical separations – in its now discontinued DUPIC program, "The Status and Prospect of DUPIC Fuel Technology," *Nuclear Engineering And Technology*, Vol.38 No.4 June 2006, p. 359.

[20] Hansoo Lee, "The Korean Strategy in Nuclear Fuel Cycle," KAERI, 25 May 2009.

[21] Charles S. Costello III, "Nuclear Nonproliferation: A Hidden but Contentious Issue in US-Japan Relations During the Carter Administration (1977-1981)" *Asia-Pacific Perspectives,* May 2003, p. 1.

[22] "At the lowest level of sophistication, a potential proliferating state or subnational group using designs and technologies no more sophisticated than those used in first-generation nuclear weapons could build a nuclear weapon from reactor-grade plutonium that would have an assured, reliable yield of one or a few kilotons (and a probable yield significantly higher than that). At the other end of the spectrum, advanced nuclear weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium having reliable explosive yields, weight and other characteristics comparable to those of weapons made from weapons-grade plutonium." *Nonproliferation and arms control assessment of weapons-usable fissile material storage and excess plutonium disposition alternatives* (U.S. Department of Energy, DOE/NN-0007, 1997), pp. 38–39.

[23] The IAEA assumes that 8 kilograms of plutonium is sufficient for a first-generation nuclear weapon, *IAEA Safeguards Glossary, 2001 Edition,* p. 23.

enrichment program has focused attention on the proliferation of enrichment plants, reprocessing is even more dangerous. Civilian enrichment plants are designed to produce low-enriched uranium (LEU) to fuel nuclear power plants. LEU is not directly weapon useable but separated plutonium is – as is the mixture of plutonium with the minor transuranic produced by pyroprocessing.[24]

When Presidents Ford and Carter reversed the positions of previous administrations and decided to forego reprocessing at home and discourage it abroad, Belgium, Germany, Italy and Taiwan had pilot reprocessing plants.[25] Argentina was building a plant.[26] And France and Germany were contracting to sell reprocessing plants to South Korea and Brazil respectively.[27] Many of these plants were originally launched out of interest in acquiring at least a nuclear-weapon option. Today, Japan is the only non-weapon state with an operating reprocessing plant. This is in part due to the fact that reprocessing is costly and unnecessary. But it is also due in part to U.S. nonproliferation efforts. If South Korea were to launch a reprocessing program, it would threaten to begin the unraveling of this great nonproliferation success.

Implementation of pyroprocessing in South Korea also would be inconsistent with the 1992 Joint Declaration of South and North Korea of the Denuclearization of the Korean Peninsula. Under this agreement, the two countries agreed to "not possess nuclear reprocessing and uranium enrichment facilities."[29] Pyroprocessing advocates in South Korea point out that North Korea has repeatedly broken the 1992 agreement and that there is little hope that it will denuclearize any time in the foreseeable future. If South Korea were to launch its own pyroprocessing program, however it would, at best, further complicate efforts to persuade North Korea to carry through on the commitment it made in 2005 to end its nuclear program.[30] At worst, it could lead to a nuclear arms race between South and North Korea.

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[24] "Limited Proliferation-Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-water Reactor Spent Fuel," op. cit. In practice, a proliferating country might well prefer to separate out pure plutonium from the mix. This would be much easier than separating plutonium from spent fuel.

[25] The Eurochemic pilot reprocessing plant at Dessel, Belgium was built as a joint facility with 12 other OECD states and operated from 1966 to 1974, World Nuclear Association, "Nuclear Power in Belgium," http://www.world-nuclear.org/info/inf94.html, viewed 20 Nov. 2009. The WAK pilot reprocessing plant at Karlruhe, Germany operated from 1971 to 1991, "The Karlsruhe Reprocessing Plant Decommissioning Project at a Glance," http://www.fzk.de/fzk/idcplg?IdcService=FZK&node=0701&lang=en, viewed 20 Nov. 2009. Italy's EUREX reprocessing plant operated from 1970 to 1983, M. Gili et al, "Direct Dismantling of Reprocessing Plant Cells: The EUREX Plant Experience," *Waste Management 2003 Conference,* Tucson, Arizona, Feb. 23-27, 2003. Taiwan built a pilot reprocessing plant in the early 1970s and operated it briefly during 1976 before shutting it down because of U.S. pressure, John W. Garver, *The Sino-American alliance: Nationalist China and American Cold War strategy*, M.E. Sharpe, 1997, pp. 279-80.

[26] Argentina launched construction on a reprocessing plant at Ezeiza in 1978 but the plant was not completed, Mitchell Reiss, *Bridled Ambition,* Woodrow Wilson Center Press, 1995, p. 47.

[27] France agreed to sell South Korea a pilot reprocessing plant in 1975 but U.S. pressure on South Korea resulted in a termination of negotiations in 1976, "South Korea's Shifting and Controversial Interest in Spent Fuel Reprocessing," op. cit. On the 1975 nuclear contract between Brazil and Germany, see, for example, Mitchell Reiss, *Bridled Ambition, op. cit*., p. 49.

[29] http://www.nti.org/db/china/engdocs/snkdenuc.htm

[30] North Korea had a reprocessing plant at the time of the 1992 agreement but, as a result of its 1994 agreement with the U.S., did not operate the plant for a decade. In 2003, that agreement broke down, however, and North Korea resumed reprocessing. In 2005, North Korea promised to end its entire nuclear program, "Joint Statement of the

Opinion within South Korea's government is supportive of pyroprocessing research and development but divided on actual deployment. South Korea's Ministry of Knowledge Economy, which oversees KHNP, opposes any early large-scale deployment because of cost and other concerns.

The remainder of this report discusses South Korea's spent fuel situation and options. We find that:

1. Technically, construction of new power reactors and their associated pools and the installation of higher-capacity racks at could postpone the crisis of full pools for about two decades. In at least some cases, however, these measures might be blocked by the local governments. Similarly, construction of additional dry-cask storage for the spent fuel from the heavy-water reactors at the Wolsong site may have been blocked by legislation to facilitate the location there of South Korea's national depository for intermediate and low-level radioactive waste.
2. A full-scale pyroprocessing plant could not be built in time to ameliorate the storage problem.
3. Pyroprocessing is not significantly more proliferation resistant than standard aqueous reprocessing;
4. Pyroprocessing likely would cost at least ten times more than dry-cask storage of spent fuel; and
5. The radioactive-waste-management benefits of pyroprocessing are minor at best.

We also find that it would not be so difficult *physically* for South Korea to accommodate central surface storage or geological repositories for its spent fuel. As already noted, however, radioactive waste politics are intractable in South Korea as in many other countries. South Korea does indeed need a national consensus process on spent fuel management.

Japan is already reprocessing its spent fuel – or at least attempting to do so[31] -- because it faces the same type of local opposition to expanded at-reactor storage. South Korea and China have been deeply suspicious of Japan's motives for reprocessing and some Japanese security analysts acknowledge privately that it provides Japan with a nuclear-weapon option, even if Japan does not intend to use that option for the foreseeable future. Japan, China and North Korea similarly would be deeply suspicious of a decision by South Korea to respond to reprocess.

Concerns that South Korea's interest in reprocessing could destabilize the nonproliferation regime should stimulate the United States, China, Japan and South Korea and the U.S. – and perhaps Russia -- to discuss together alternatives to a proliferation of national reprocessing plants. The U.S. Government must also resist demands from Congressional Republicans that spent fuel reprocessing be part of any U.S. program to deal with climate change.[32] If the U.S. decided that it

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Fourth Round of the Six-Party [DPRK, China, South Korea, Japan, Russia and the United States] Talks, Beijing, 19 September 2005," http://www.state.gov/p/eap/regional/c15455.htm. That agreement too broke down and was followed by North Korea's nuclear tests in October 2006 and May 2009.

[31] In August 2009, the startup of full operations of Japan's new Rokkasho plant was postponed for the 17th time by continuing technical problems till at least the end of 2010, "Reprocessing plant startup delayed," *Asahi Shimbun*, 31 August 2009.

[32] Glenn Pearston, "Nuclear Reprocessing Amendment Defeated in Close Vote, *Nuclear Safety,* 21 May 2009.

needed to reprocess its own spent fuel, it would become hard for it to tell other countries that they don't need to do so. The business of reprocessing of spent fuel for other countries has failed because of its cost and the unwillingness of the reprocessing countries to keep the reprocessing waste.[33]

Physical and political constraints on at-reactor spent-fuel storage

Policymaking concerning spent-fuel management in South Korea is being driven by the fact that the spent-fuel storage pools at the nuclear power plants are filling up. How fast they fill up depends, however, in considerable degree on how they are managed.

Table 1 shows the generating capacities and initial operating dates of South Korea's power reactors,[34] the current capacities of their spent-fuel storage pools and the capacity expansion due to the re-racking announced in December 2007 of the spent fuel pools of the Kori 3&4, Yonggwang 1-4 and Ulchin 1-4 reactors. Table 2 shows the spent fuel inventories at the four sites as of the end of 2008. According to an analysis by the operator, Korea Hydro and Nuclear Power (KHNP), the saturation dates for the current storage at the Kori, Yonggwang and Ulchin sites for (PWRs), and Wolsong site for PWR fuel and Wolsong site for Candu fuel will be 2016, 2021, 2018 and 2017 respectively.[35]

Although dense-racking raises safety issues,[36] further re-racking would be possible. Also, older reactors could shift some of their spent fuel into the pools of the new reactors that are being built at the same sites. In the past, spent fuel has been shifted from pool to pool at the same site in South Korea. Such measures would gain a decade or so before pool saturation.[37] More years of storage could be obtained by dense-racking the pools of the new reactors. In the case of the CANDU heavy-water reactors at the Wolsong site, although the pools of are full, about 7,000 tons of dry storage capacity for older spent fuel has been built on the site and more could be built (Figure 2).[38] In principle also, on-site dry cask storage could be built for light-water-reactor fuel, as is being done in the United States and many other countries.

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[33] Frank von Hippel, "Why reprocessing persists in some countries and not in others: The Costs and Benefits of Reprocessing," in *Expanding Nuclear Power: Weighing the Costs and Risks,* Henry Sokolski, ed., Non-proliferation Education Center (2009, forthcoming)

[34] 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.

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

[36] It has been known for more than two decades that, in case of a loss of water in the pool, convective air cooling would be relatively ineffective in a "dense-packed" pool. Recently discharged spent fuel generates radioactive heat at such a high rate that, without cooling, it could heat up to temperatures at which its zirconium-alloy fuel cladding could catch fire, in which case, the fuel's volatile fission products, including 30-year half-life cesium-137, would be released. The fire could well spread to older spent fuel. The long-term land-contamination consequences of such an event could be significantly worse than those from Chernobyl, Robert Alvarez, et al, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science & Global Security*, Vol. 11, No.1, (2003) p. 1.

[37] 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).

[38] The pools of heavy-water reactors fill quickly because the amount of fission energy extracted from their unenriched uranium fuel per ton is only about 15 percent as much as is extracted from the low-enriched uranium fuel used in the light water reactors.

All this would be physically possible but there are political obstacles. At the Kori site, for example, although the new reactors that are being built are adjacent to the old ones, they are in a different local jurisdiction. At Wolsong, South Korea has established a national repository for intermediate and low-level radioactive waste. When a proposal was made to establish a dry-cask storage for spent PWR fuel there as well, however, there was strong local resistance South Korea's Atomic Energy Committee proposed that dry-cask spent-fuel storage not be co-located with the low-level waste storage facility, a policy that became law in 2005.[41] This law also would appear to make it impossible to expand the dry-cask storage for the heavy-water-reactor spent fuel at Wolsong.

Thus, because of political constraints, the KHNP projections that the on-site spent-fuel storage capacity will be full within about a decade may be valid at some of the sites at least. As a consequence, either these political constraints will have to be relaxed or an off-site destination will be required for some of South Korea's spent fuel.

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[41] "Special law regarding support to the local community hosting a LILW disposal site," 31 March 2005 (in Korean).

Table 1. **Current and planned nuclear power capacity in South Korea through 2021**[43]

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)[44]
	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 capacity for a full reactor core that is held free in case all the fuel in the reactor core has to be unloaded quickly.

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

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

Table 2. **Inventory of spent fuels in South Korea as of the end of 2008**[45]

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

Figure 2. **Dry-cask storage for CANDU heavy-water reactor (HWR) spent fuel at the Wolsong nuclear power plant.** A dense array of about 200 white cylindrical spent-fuel casks, containing about 10 tons of spent fuel each, can be seen at the upper left. The white square structures to the right of north end of the casks are another form of dry storage in which the spent fuel canisters are emplaced in a monolithic concrete structure with internal channels for air-cooling. The cylindrical containment buildings of two of the four heavy-water reactors are visible at the bottom center. (Google Earth, 15 November 2009).

Pyroprocessing too far in the future to help

One figure on KAERI's website shows full-scale pyroprocessing of South Korea's LWR spent fuel at about the rate at which it is discharged (about 800 tons per year) beginning in 2026 (Figure 3). KAERI's actual proposed schedule for deploying pyroprocessing, however, is as follows:[47]

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[45] J.H. Mok et al., *op. cit*.
[47] http://ehome.kaeri.re.kr/snsd, Fuel Cycle Process Division, viewed 15 November 2009.

- Construction of an engineering-scale facility with the capacity to reprocess 10 tons of PWR spent fuel per year between 2010 and 2016; and
- Construction of a prototype facility with the capacity to reprocess 100 tons of spent fuel per year between 2017 and 2025.

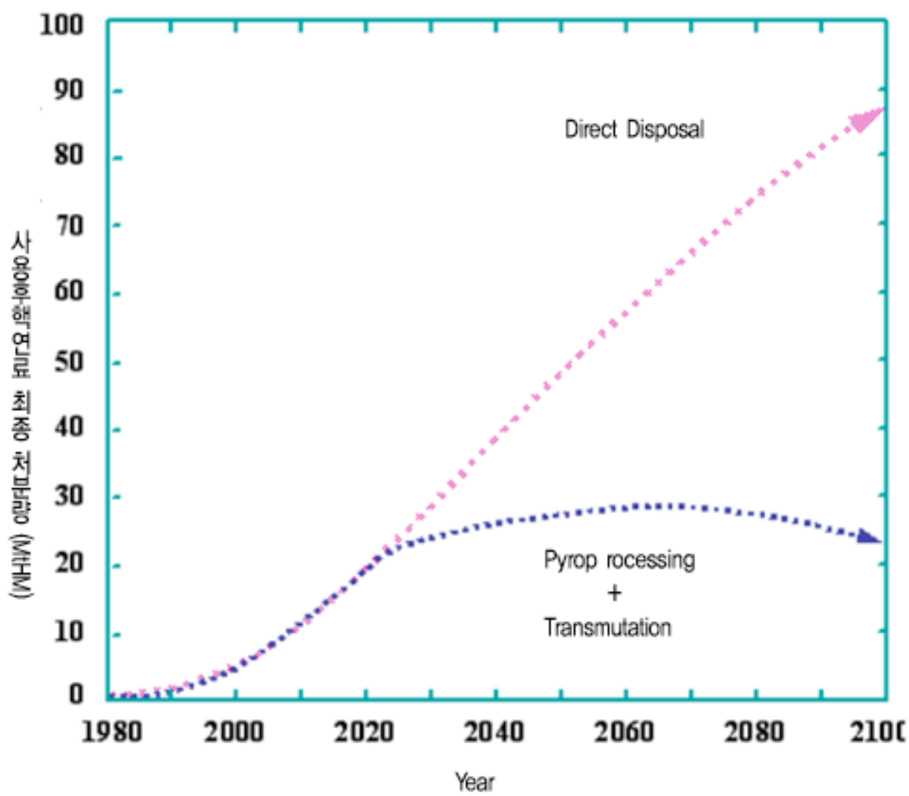

Figure 3. **Scenario on KAERI website shows full-scale pyroprocessing of South Korea's spent light-water-power-reactor (LWR) fuel, starting in 2026**. In 2030, the ROK would have about 40 GWe of LWR capacity discharging about 800 tons of spent fuel per year.[52]

No date is projected for when experience with the prototype facility would be sufficient for a decision to be made to build a full-scale facility but Japan's experience may be relevant. Japan built a prototype conventional reprocessing plant that was completed in 1974 but did not go into full operation until 1981 and never operated above 40 percent of its design capacity.[53] The Rokkasho Reprocessing Plant, a full-scale reprocessing plant, was originally scheduled to be completed by 1985.[54] It was actually completed in 2006 but, because of design problems, is not

[52] http://ehome.kaeri.re.kr/snsd, Fuel Cycle Development Strategy Research Division, Development of National Management of Spent Nuclear Fuel, viewed 15 November 2009.

[53] David Albright, Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford University Press, 1997) pp. 177-8.

[54] Masafumi Takubo, "Wake Up, Stop Dreaming, *op. cit*.

expected to go into full operation until December 2010 at the earliest.[55] A similar schedule would put operation of a full-scale reprocessing plant in South Korea well beyond 2050.

KAERI's proposed schedule for deployment of the fast-neutron reactors that would be fueled by the transuranics separated by pyroprocessing is consistent with a date beyond 2050 for full-scale pyroprocessing. The schedule would have a demonstration reactor built by 2028 and commercialization of fast-neutron reactors starting around 2050.[56]

KAERI's current proposal is that South Korea's demonstration fast-neutron reactor would have a generating capacity of 0.6 GWe.[57] Such a design would require about 2.3 tons of plutonium initially in its fuel cycle and about 0.75 tons per year for refueling, assuming operation at an average 75 percent capacity and that the spent fast-reactor fuel is not reprocessed.[58] This demand would be reasonably well matched with the output of the prototype reprocessing facility.

The nominal purpose of pyroprocessing, however, is to recover the transuranic material in the PWR spent fuel and recycle it in fast-reactor fuel until it is completely fissioned except for process losses. This would require the transuranics in the fast-reactor fuel to be recycled repeatedly. A 0.6-GWe fast-neutron reactor could consume only the transuranics discharged by 0.8-1.5 GWe of PWR capacity.[59] Operating at full capacity, the prototype pyroprocessing facility would reprocess the spent fuel generated by about 5 GWe of PWR capacity. For South Korea's projected 40-GWe of PWR capacity discharging about 800 tons of spent fuel a year, 16-30 GWe of fast-reactor capacity would be required.

Based on the experience of other countries, however, it is unlikely that South Korea would build more than a demonstration fast-neutron reactor. France, Japan, Russia and the U.K. produced huge stockpiles of separated plutonium with reprocessing plants that were originally proposed in the 1970s on the basis of expectations that, by 2000, more than a hundred gigawatts of fast-

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[55] http://cnic.jp/english/topics/cycle/rokkasho/activetests.html; "Reprocessing plant startup delayed," *Asahi Shimbun*, 31 August 2009.

[56] http://www.kaeri.re.kr/english/sub/sub01_04_02_01_01.jsp, viewed 15 November 2009.

[57] http://www.kaeri.re.kr/english/sub/sub01_04_02_01_01.jsp

[58] International Nuclear Fuel Cycle Evaluation, *Fast Breeders: Report of Working Group 5* (International Atomic Energy Agency, 1980), p. 58, for metal fuel.

[59] A 1-GWe PWR with a capacity factor of 0.9 and a spent-fuel burnup of 53-MWt-days/kgHM discharges about 0.24 tons of transuranics in its spent fuel each year. A 0.6-GWe fast-neutron reactor with a thermal-to-electric power conversion efficiency of 40% would have a thermal power of 1.5 GWt. If it operated at a capacity factor of 0.9, it would generate about 500 GWt-days of fission heat annually, which would require the fissioning of about 0.5 tons of heavy metals (i.e. transuranics and uranium) per year. However, if the transuranics were mixed with uranium, as proposed for safety reasons, some of the uranium would be fissioned directly and some would be converted into transuranics. The net destruction rate of transuranics would therefore be 0.5(1-CR), where CR is the reactor conversion ratio. The U.S. National Academy of Sciences study, *Nuclear Wastes: Technologies for Separations and Transmutation*, 1996. pp. 205-6 quotes a minimum safe conversion rate for a General Electric fast-reactor design of 0.6. Fast-neutron reactor advocates at Argonne National Lab argue that a conversion ratio as low as 0.25 can be achieved safely with added control rods and twice-annual refueling, J. E. Cahalan et al, "Physics and Safety Studies of a Low Conversion Ratio Sodium Cooled Fast Reactor," *Proceedings of the PHYSOR 2004 Conference*, American Nuclear Society, Chicago, April 2004. For CR in the range 0.25-0.6, the net destruction rate of transuranics would be 0.2 – 0.37 tons per year.

neutron reactor capacity would be built each year. Today, less than 1-GWe of demonstration fast-neutron-reactor capacity is in operation worldwide and 1.2 GWe is under construction.[60]

The global stockpile of separated plutonium that has resulted from the reprocessing of LWR fuel is today about 250 tons -- enough to make 30,000 first-generation (Nagasaki-type) nuclear weapons (see Table 3). India's stockpile is small in comparison to those of France, Russia and the United Kingdom but has attracted attention because of India's unwillingness to declare that it will not be used for weapons. India is building a 0.5-GWe Prototype Fast Breeder Reactor and plans to build more.[61] Historically the need to provide startup plutonium for these breeder reactors has been the justification for India's separation of plutonium from the spent fuel of its heavy-water reactors. In its nuclear deal with the U.S., however, India declared its breeder program to be of "national security significance" and refused to place it under IAEA safeguards.[62] India is therefore free to use its separated power-reactor plutonium directly for weapons or to use the breeder reactors to convert it to weapon-grade plutonium.[63] France used its first demonstration breeder reactor, *Phénix,* in this way to produce plutonium for its weapon program.[64]

Table 3. **Stockpiles of separated civilian plutonium in countries that reprocess, end of 2007**[65]
(metric tons)

	China	**France**	**India** (est)	**Japan**	**Russia**	**U.K.**	**Total**
In country	0	82.2	7	8.7	44.9	108	250.8
(of which foreign-owned)	-	(27.3)	-	-	-	(26.8)	(54.1)
Stored abroad	0	0	0	37.9	0	0.9	

The fundamental reason why liquid-sodium-cooled fast-neutron reactors have failed economically is that refueling, repairs and maintenance require much more complex arrangements than for water-cooled reactors because of the need to prevent sodium exposure to air or water. Such contact has resulted in major fires in the steam generators of France's *Phoenix* and Russia's BN-600 fast-neutron reactors. In steam generators, molten sodium is separated from high-pressure water and steam only by thin metal. A leak and sodium-air fire in Japan's 0.28-GWe *Monju* breeder reactor has shut it down since 1995, a few months after it began operation.[66]

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[60] Russia's 0.6-GWe breeder, which constitutes most of the existing capacity is, for safety reasons, fueled by HEU and not plutonium. Russia and India are building 0.8-GWe and 0.5-GWe fast-neutron reactors respectively *Fast Breeder Reactor Programs: History and Status,* International Panel on Fissile Materials, (2009).

[61] M. V. Ramana, "India and Fast Breeder Reactors" in *Fast Breeder Reactor Programs: History and Status, op. cit.*

[62] "Suo-motu Statement by the [Prime Minister] on Civil Nuclear Energy Cooperation with the United States, 27 Feb. 2006, http://pmindia.nic.in/lspeech.asp?id=284, viewed 20 Feb. 2009.

[63] Zia Mian, A.H. Nayyar, R. Rajaraman, and M.V. Ramana, *Fissile Materials in South Asia: The Implications of the U.S.-India Nuclear Deal,* International Panel on Fissile Material, 2006

[64] *Fast Breeder Reactor Programs: History and Status, op. cit.* p. 23-24.

[65] *Global Fissile Material Report 2009,* Appendix 1C and Figure 1.3. The 14.4 tons of foreign-owned separated plutonium in France and the U.K. that is not Japanese plutonium belongs to European customer countries (mostly Germany).

[66] *Fast Breeder Reactor Programs: History and Status, op. cit.*

The overall operational and cost experience with liquid-sodium-cooled breeder reactors is captured by a statement made by Admiral Rickover after his attempt to use a compact sodium-cooled reactor as a power plant in an early nuclear submarine. He concluded that such reactors are "expensive to build, complex to operate, susceptible to prolong shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair."[67]

Another problem that has plagued the licensing of fast-neutron reactors is the possibility of an explosive dispersal of radioactivity. If a water-cooled reactor looses its coolant, it will go subcritical. Even if it melts down, it will remain subcritical because the low enrichment of its fuel (4-5 percent U-235). The fuel of fast-neutron reactors is much more highly enriched, however – more than 20-percent plutonium in uranium. If a melt-down therefore results in the core assuming a more compact configuration it can go supercritical and a small nuclear explosion can result.[68] The explosion would have a power equivalent to less than the explosion of a ton of TNT but the concern is that it might cause the reactor containment to fail and cause a major release of radioactivity to the environment. Since it is costly to design containments against the maximum possible release, fast-neutron reactor designers have attempted to prove that the energy release would be much less than the maximum. Their calculations are assumption dependent, however, and therefore controversial.

Although "prototype" and "demonstration" fast-neutron breeder reactors are being built by the governments of India and Russia respectively, the development of fast-neutron reactors is currently receiving only rhetorical support from the governments of France and Japan and has been given up in the other OECD countries (Germany, the United Kingdom and the United States) that had breeder R&D programs into the 1990s (figure 4).[69] South Korea's support for fast-neutron reactor development at this point is only for paper studies.

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[67] Richard G. Hewlett and Francis Duncan, *Nuclear Navy: 1946-1962* (Chicago: University of Chicago Press, 1974), p. 274, quoted by Thomas B. Cochran.

[68] H.A. Bethe and J.H. Tait, "An estimate of the order of magnitude of the explosion when the core of a fast reactor collapses," UKAEA-RHM 56 (1956).

[69] Fast Breeder Reactor Programs: History and Status, op. cit.,

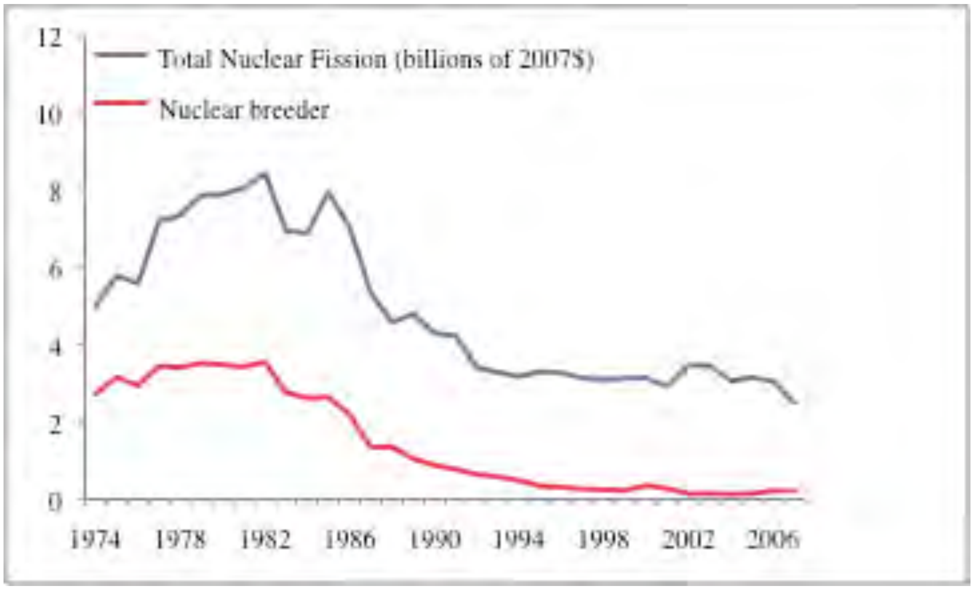

Figure 4. **The history of fission and fast-neutron breeder reactor R&D in the OECD countries.** In the late 1970s and early 1980s, fast-neutron breeder reactor research and development accounted for about half of fission-energy R&D spending in the OECD countries. It has since declined to almost zero after major demonstration projects were cancelled (Germany and the US) or completed without follow-on projects (France, Japan and the United Kingdom).[70]

Pyroprocessing and proliferation

Although pyroprocessing would not have a significant impact on South Korea's spent fuel problem until well after 2050, its proposed engineering-scale pyroprocessing plant, if operated at full capacity, would separate out annually about 100 kilograms of plutonium – enough for more than 10 Nagasaki bombs. South Korea's pyroprocessing R&D program therefore would deliver a nuclear-weapon option quite quickly -- as did India's.[71]

On the advice of pyroprocessing experts from the Argonne National Laboratory, Vice President Cheney's 2001 Energy Commission declared pyroprocessing more "proliferation resistant" than conventional reprocessing.[72] For some time Bush Administration officials who were sympathetic to South Korea's interest in pyroprocessing, even tried to argue that "pyroprocessing is not reprocessing."[73] KAERI has made similar claims.

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[70] From International Energy Agency R&D Statistics Database, http://www.iea.org/Textbase/stats/rd.asp, accessed 21 March 2009, unavailable values have been replaced with zeros.
[71] The plutonium for India's nuclear weapons was separated using an engineering scale reprocessing plant at India's Bhabba Atomic Research Center.
[72] *Energy Policy*: *Report of the National Energy Policy Development Group* (The White House, May 2001) p. 5-17.
[73] Miles Pomper, "Concerns Raised as South Korea Joins GNEP," *Arms Control Today* January/February 2008.

The primary basis for the claim that pyroprocessing is proliferation resistant is that it does not produce pure plutonium.[74] Since the standard aqueous PUREX reprocessing was originally developed by the United States to recover pure plutonium for weapons, however, the question is "*How much* more proliferation resistant is pyroprocessing?"

Pyroprocessing, like PUREX reprocessing, separates plutonium from the fission products that account for most of the gamma radiation field around spent fuel. As a result, the radiation field around the plutonium in its transuranic mix would be reduced to about 0.1 percent of that around the spent fuel and to less than one percent of the IAEA's self-protection standard (Figure 5). It therefore would be possible to separate the plutonium, which makes up more than 80 percent of the transuranic mix, from that mix in an unshielded glove box. For comparison, plutonium in spent fuel is quite dilute (less than one percent by mass) and, because of the high gamma-radiation field from the fission products with which it is mixed, its separation must be done remotely behind meter-thick shielding.

Pyroprocessing therefore is slightly more proliferation resistant than traditional PUREX reprocessing but it is *much* less proliferation resistant than not reprocessing at all.

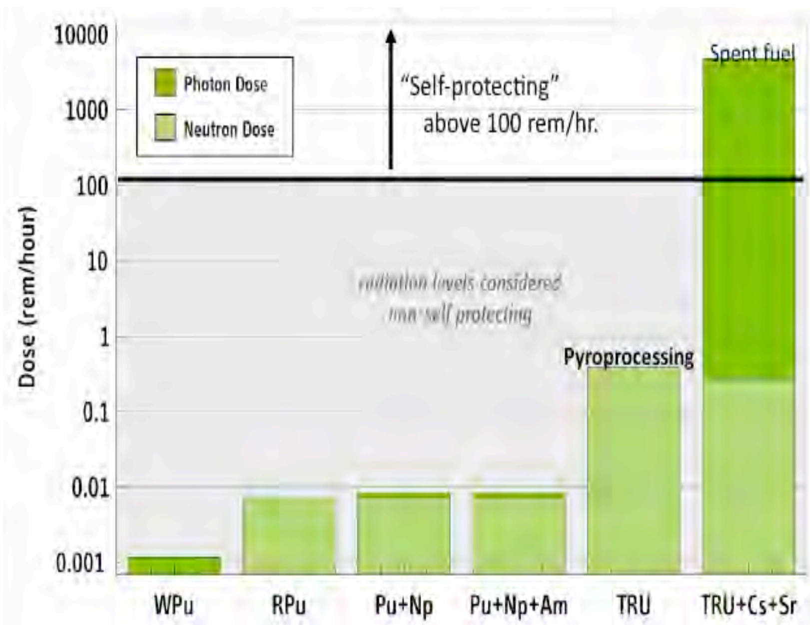

Figure 5. **Dose rates from 4.4 kg of various transuranic mixes** without and with the two 30-year half-life fission products, cesium-137 (Cs) and strontium-90 (Sr) that make spent-fuel self-protecting for 100 years after discharge. (WPu = weapon-grade plutonium; RPu = plutonium from high burnup light-water reactor fuel; Np = neptunium-237; Am = Americium-241 and -243; TRU = the mixture of the transuranics in spent light-water-reactor fuel.)[75]

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[74] "[I]ts proliferation resistance has been internationally recognized due to the impossibility to recover plutonium," http://www.kaeri.re.kr/english/sub/sub04_03.jsp, accessed 15 November 2009.

[75] Robert Hill, Argonne National Laboratory, "Advanced Fuel Cycle Systems: Recycle/Refabrication Technology Status," 7 September 2005. See also, E.D. Collins, Oak Ridge, "Closing the fuel cycle can extend the lifetime of the high-level-waste repository," American Nuclear Society, 2005 Winter Meeting, Washington, DC; and Jungmin

Comparison of pyroprocessing and storage costs

If South Korea went forward with pyroprocessing of LWR fuel on a large-scale, it would most likely, like France and Japan, end up with a large stockpile of separated transuranics and no substantial fast-neutron reactor capacity. Mostly likely, it then would decide, like France and Japan, to recycle the plutonium into the fuel of its PWRs. For France, the extra cost of a program in which 100 percent of the plutonium is recycled into mixed-oxide (MOX, uranium-plutonium) spent fuel relative to simply disposing of the unreprocessed spent fuel was estimated in a 2000 study by the government of France as $570 per kilogram of uranium in the original low-enriched-uranium fuel (2006 $).[76] In Japan, the extra cost has been estimated by Japan's Atomic Energy Commission as $2400/kgU.[77] Of course, South Korea would be pyroprocessing instead of traditional aqueous PUREX reprocessing but a U.S. national laboratory comparison has found that the cost of pyroprocessing is likely to be considerably higher.[78]

The high cost of PUREX reprocessing has led a dozen countries that had sent their spent fuel to France, Russia or the United Kingdom to be reprocessed to not renew their contracts (Table 4). Their first contracts made it possible for the customer countries to export their spent fuel problems. The relief was only temporary, however, because the reprocessing vendors mostly required that their customers take back the high-level radioactive waste from reprocessing. The customers have not found storing this waste any less politically problematic than spent fuel and therefore have not renewed their reprocessing contracts.

Kang and Frank von Hippel, "Limited Proliferation-Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-water Reactor Spent Fuel," *op. cit*.

[76] J.M. Charpin, B. Dessus and R. Pellat, *Report to the Prime Minister: Economic Forecast Study of the Nuclear Power Option*, 2000, as summarized in *Managing Spent Fuel in the United States: The Illogic of Reprocessing* (2006), Appendix. One 1999 French Franc assumed equal to $0.20 (2006 $).

[77] Japan Atomic Energy Commission, Long-term nuclear energy program planning committee report, 2004, assuming one Yen = $0.01.

[78] D. E. Shropshire et al, Idaho National Laboratory, *Advanced Fuel Cycle Cost Basis* INL/EXT-07-12107, 2007, Tables F1-4 and F2-3. The largest scale on which pyroprocessing has been conducted thus far is in the treatment of 2.4 tons of driver fuel and 22.4 tons of blanket of U.S. Experimental Breeder Reactor II (EBR II) in an existing facility at a rate of about one ton of heavy metal per year. In 2006, the total project cost was estimated at $363 million or about $15,000/kg, U.S. Department of Energy, *Report to Congress: Preferred Disposition Plan for Sodium-Bonded Spent Nuclear Fuel,* 2006, http://www.ne.doe.gov/pdfFiles/DisPlanForSodBondedSNFMarch2006.pdf.

Table 4. **Status of reprocessing power-reactor fuel in the countries with nuclear-power reactors**[79]

Countries that reprocess or plan to	Customer Countries that have not renewed their contracts	Countries that have never reprocessed
China (pilot plant not yet operating)	Armenia (in Russia)	Argentina
	Belgium (in France)	Brazil
France (full-scale)	Bulgaria (in Russia)	Canada
India (≈50%)	Czech Republic (in Russia)	Lithuania
Japan (90% planned)	Finland (in Russia)	Mexico
Netherlands (only remaining customer country, in France)	Germany (in France and UK)	Pakistan
	Hungary (in Russia)	Romania
Russia (≈15%)	Slovak Republic (in Russia)	Slovenia
United Kingdom (full-scale but probably quitting)	Spain (in France and UK)	South Africa
	Sweden (in France and UK)	South Korea
	Switzerland (in France and UK)	Taiwan
	Ukraine (in Russia)	U.S. (since 1972)

Recently, AREVA offered to reprocess South Korea's spent fuel and keep the plutonium but send the back the high-level radioactive waste at a total cost that has been estimated to be at least $1100 per kilogram of uranium originally in the spent fuel.[80] As with nuclear utilities in other countries, Korea Hydro and Nuclear Power could conceivably find this offer of interest as a way to buy time to deal with its radioactive-waste storage problem – but only until the high-level waste started to come back.

From this perspective, it is not accidental that, with the exception of the Netherlands, which operates a single small (0.5-GWe) nuclear power reactor, all the other countries that are still committed to spent-fuel reprocessing have their own reprocessing plants. For countries with their own reprocessing plants, their own radioactive wastes from reprocessing can be left at the reprocessing plant, along with the recovered uranium and plutonium that is not recycled. Thus far, of the reprocessing countries, only France has recycled a significant fraction of the plutonium and uranium separated from its spent fuel. In the case of Japan, the only country that has switched from reprocessing abroad to reprocessing at home, the Rokkasho Reprocessing Plant also provides storage for the high-level radioactive waste being shipped back from the reprocessing of Japan's spent fuel in France and the U.K.

Nevertheless, despite the political convenience, separating spent fuel into transuranics, uranium and high-level waste at a reprocessing plant and then storing most of the recovered material there is a very costly alternative to storing spent fuel. As noted above, the cost difference between

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[79] Frank von Hippel, "Why reprocessing persists in some countries and not in others: The Costs and Benefits of Reprocessing," *op. cit*.
[80] Mark Hibbs, "Reprocessing cost might exceed KHNP's spent fuel management fees," *Nuclear Fuel,* 13 July 2009, p. 1.

reprocessing and interim storage and then direct disposal has been estimated at $600-2400/kgU. The cost of centralized dry cask storage for LWR spent fuel is about $100/kg.[81]

Questionable radioactive-waste-disposal benefits

KAERI claims that pyroprocessing would reduce the volume of South Korea's PWR high-level radioactive waste by 95 percent, and the long-term radiotoxicity of the waste to such an extent that the required period of monitoring of the disposal site could be reduced from hundreds of thousands to hundreds of years.[82] KAERI also argues that South Korea is not large enough to accommodate the repositories that would be required for the quantity of unreprocessed PWR spent fuel projected for 2100.[83]

As already noted, despite decades of effort and huge expenditures on research and development and on "demonstration" liquid-sodium-cooled fast-neutron reactors, no country has yet successfully deployed a fleet of such reactors. Based on this experience, the most likely result of South Korea's pyroprocessing program would be that its separated plutonium would be recycled in light-water reactors in mixed-oxide (MOX, uranium-plutonium) fuel as is done in France and Japan. In France, this process involves one recycle. The result is that the total amount of plutonium in the spent fuel is reduced by about one half.[84]

To date, the plutonium in the spent MOX fuel has not been recycled again except in tests because it has much poorer isotopic quality for light-water-reactor fuel than plutonium from low-enriched uranium fuel.[85] According to an analysis funded by Areva, despite the fact that reprocessing and recycle in MOX results in one spent MOX fuel assembly where before there were seven LEU spent-fuel assemblies, the radioactive-waste-management advantage would be minimal. The reason is that a single spent MOX fuel assembly puts out about as much heat in the first two thousand years or so as the original seven spent LEU fuel assemblies.[86] Spent MOX fuel is therefore stored in France in the hopes of the commercialization of fast-neutron reactors that could fission all the isotopes of plutonium relatively efficiently.

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[81] Boston Consulting Group, *Economic Assessment of Used Nuclear Fuel Management in the United States* (report paid for by Areva, 2006) Table 4. The numbers are for 20-year storage in a 50,000-ton central storage facility but about 90 percent of the cost is "marginal capital expense," i.e. the cost of the dry casks.

[82] http://www.kaeri.re.kr/english/sub/sub04_03.jsp; and http://ehome.kaeri.re.kr/snsd/eng/organization/organization2.htm, viewed 15 November 2009.

[83] Won Il Ko et al, KAERI, "Implications of the New National Energy Basic Plan for Nuclear Waste Management in Korea," *Energy Policy* Vol. 37 (2009) p. 3484.

[84] MOX fuel fabricated with plutonium from LEU fuel with a burnup of 43 MWt-days/kgU that has been stored for ten years would contain 8.5% plutonium when fresh and 5.7% when spent. In addition, the creation of 1.2 percent plutonium in the LEU fuel that otherwise have been used would be avoided, *Plutonium Fuel: An Assessment* (OECD, 1989), Tables 9 and 12.

[85] The even isotopes of plutonium do not fission well in a slow-neutron reactor, Plutonium from 43 MWt-day/kgU spent fuel contains 66 percent of the odd isotopes Pu-239 and Pu-241 after ten years of storage. The plutonium in spent MOX fuel with a burnup of 53 MWt-days/kg contains 50 percent after ten years storage, *Plutonium Fuel: An Assessment,* op. cit.

[86] Boston Consulting Group, Economic Assessment of Used Nuclear Fuel Management in the United States, 2006, Appendix 10.

What if South Korea succeeded in commercializing a fleet of fast-neutron reactors where all other countries have failed? Today, advocates of fast-neutron reactors promote them not as plutonium breeder reactors but with reconfigured cores that make them net consumers of transuranic isotopes, i.e. "burner" reactors that, if commercialized in large numbers, could efficiently fission all of the transuranic isotopes in spent fuel and can therefore largely eliminate the presence of long-lived transuranics in radioactive waste. KAERI claims that reprocessing and transuranic recycle would reduce the volume of South Korea's radioactive waste by 95 percent.[87] Almost all of the reduction, however, would be due to the separation of the uranium that constitutes 93 percent of the mass of the spent fuel. The transuranics constitute only about one percent. KAERI apparently only counts as wastes the concentrated fission products, which constitute about 5 percent of the mass of the spent fuel.

But the mass of the fission products does not determine either the mass or the volume of the ultimate wastes or the volume they would occupy in a deep geological radioactive-waste repository. First of all, the fission products would have to be immobilized in some waste form. To date, all reprocessing countries immobilize the fission products in glass. France has the most experience in this regard and has worked very hard to reduce the volume of its "vitrified" high-level waste per ton of spent fuel. The volume of consolidated spent fuel pins originally containing one metric ton of uranium would be 0.16 cubic meters.[88] France has succeeded in reducing the volume of vitrified high-level waste from reprocessing a ton of spent fuel to 0.13 cubic meters. In addition, however, each ton of reprocessed spent fuel results about 0.8 cubic meters of long-lived intermediate and low-level waste that requires deep burial and 1.21 cubic meters of short-lived radioactive waste that requires shallow burial.[89]

In any case, the area covered by an underground repository has no direct relationship to the volume of the waste. KAERI's claims for reductions in repository size that could be achieved by pyroprocessing[90] are based on analyses that have been done by U.S. pyroprocessing advocates for Yucca Mountain. In these analyses, the area of a spent-fuel repository is determined by the requirement that the peak temperature in the rock midway between the waste-holding tunnels in a repository not exceed the boiling temperature of water, in order allow the passage of water downwards between the tunnels. For spent fuel, this peak temperature is determined by the integrated heat output of the spent fuel over the first 1600 years, which is dominated by the

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[87] http://www.kaeri.re.kr/english/sub/sub04_03.jsp; and http://ehome.kaeri.re.kr/snsd/eng/organization/organization2.htm, cited above.

[88] The density of uranium in a PWR uranium-oxide pellet is 8.8 grams/cc. Its radius is typically about 0.41 cm and the length of a fuel rod is about 4 meters. A single fresh fuel rod therefore contains about 1.86 kg of uranium and 540 would contain one metric ton (1000 kg) of uranium. The radius of a fuel rod, including its cladding, would be about 0.467 cm. If the fuel were hexagonal dense packed, there would be 1.32 fuel rods per square centimeter area perpendicular to the rod axes. Germany proposed to dispose of spent fuel by separating the pins from the hardware that holds them in the assembly in this fashion. The U.S. Yucca Mountain design would have disposed of the intact fuel assemblies, which would take up more space.

[89] *Advanced Nuclear Fuel Cycles and Radioactive Waste Management* (OECD/NEA, 2006) Table 3.4. 0.8 m^3 of long-lived low and intermediate-level waste and 1.21 m^3 of short-lived low and intermediate-level waste per ton of spent fuel. See also Michael Schneider and Yves Marignac, *Spent Fuel Reprocessing in France* (International Panel on Fissile Materials, 2008), Table 10, for the volumes of waste per ton of spent fuel reprocessed in France in 2004.

[90] See e.g. Won Il Ko and Eun-ha Kwon, KAERI, "Implications of the New National Energy Basic Plan for Nuclear Waste Management in Korea," *Energy Policy* Vol. 37 (2009) p. 3484.

transuranics (Figure 6). But this analysis is for a repository in volcanic tuff hundreds of meters above the ground-water level and is irrelevant to the type of geological repository being considered by KAERI, in which spent fuel would be buried in copper canisters embedded in clay in water-saturated granite.[91] For KAERI's design, the capacity limit would be determined by the requirement that the clay around the canister not dry out and crack. An analysis for 40-year spent LWR fuel finds that the temperature of the clay would peak about 20 years after emplacement.[92] The amount of spent fuel that can be emplaced in a cask is therefore determined by the current heat output of the spent fuel rather than its output over millennia.

It will be seen from Figure 6 that the transuranics (also known as "actinides") account for slightly less than half of the radioactive heat generation from spent fuel at 40 years. Eliminating them therefore would increase the capacity of a repository by approximately a factor of two. Figure 6 also shows, however, that the same result could be accomplished by waiting until the spent fuel is one hundred years old before burying it.

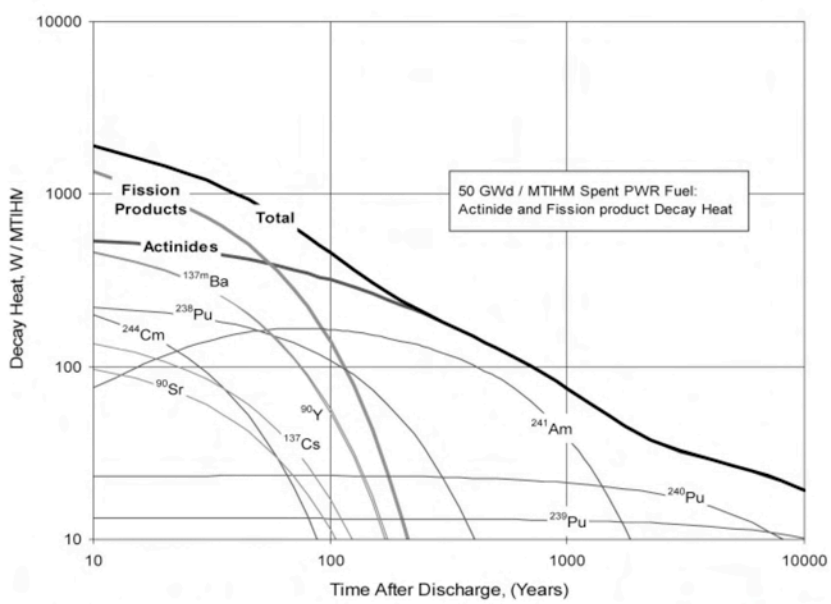

Figure 6. **Contributions to decay heat from apent fuel as a function of time.** The fission products dominate for the first 50 years. They are down to less than 50 percent at 100 years and about ten percent after 200 years.[93]

It is often argued by KAERI that South Korea is too small to accommodate the spent-fuel repositories that would be required to accommodate all the spent fuel that will be generated by South Korea's PWRs by 2100. One KAERI paper lays out scenarios in which South Korea's

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[91] S.K. Lee, et al, KAERI, "Concept of a Korean Reference Disposal System for Spent Fuels," *Journal of Nuclear Science and Technology*, Vol. 44, No. 12 (2007) p. 1565.
[92] Jongyoul. Kim et al, "A comparison of the HLW underground repository cost for the vertical and horizontal emplacement options in Korea," *Progress in Nuclear Energy* Vol. 49 (2007) p. 79.
[93] Roald A. Wigeland et al, "Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository," *Nuclear Technology*, Vol. 154 April 2006 , p. 95, Figure1.

PWR capacity grows to 45-75 GWe and discharges cumulatively 73,000-97,000 tons of spent fuel by 2100.[94]

A reference geological repository has been designed for Korea that would accommodate 36,000 tons of spent fuel: 20,000 tons of PWR spent fuel and 16,000 tons heavy-water spent fuel (approximately the expected lifetime discharges by the CANDU reactors) with the fuel emplaced after the PWR fuel had cooled for 40 years and the HWR fuel for 30. The repository would have an area of approximately 4.6 km^2.[95] Because of its lower rate of decay-heat generation, the storage density of the CANDU fuel, measured in kilograms per square meter of repository, would be about six times that of the PWR fuel. If the fuel were all PWR fuel therefore, the capacity of the repository would be about 23,000 tons.

The amount of PWR spent fuel projected in the KAERI scenarios to be discharged by 2100 would be enough to fill about four such repositories with a total area of about 20 km^2. If South Korea waited till 100 years after discharge to bury the spent fuel, two would suffice with an area of 10 km^2.

Is this a large area? The area of South Korea is about 100,000 km^2. The country is densely populated but a repository at a depth of 500 meters could co-exist with most activities on the surface. In figure 7, we show the 2.1 km^2 area of South Korea's low-level waste repository next to the Wolsong nuclear power plant. As in Finland and Sweden, it was found in South Korea that a communities that already host a nuclear power plant are the most willing to host an underground repository, which presents a much smaller hazard to the local population than the already-operating power plant.

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[94] "Implications of the New National Energy Basic Plan for Nuclear Waste Management in Korea," *op. cit*. It is assumed that South Korea will build no more CANDU heavy-water reactors.

[95] 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) and S.K. Kim et al, "A comparison of the HLW underground repository cost for the vertical and horizontal emplacement options in Korea," *Progress in Nuclear Energy* Vol. 49 (2007) p. 79. Won Il Ko et al, "Implications of the New National Energy Basic Plan for Nuclear Waste Management in Korea," *op. cit.,* state that the design spent fuel density in Sweden's proposed Forsmark geological repository is 3.53 kg/m^2, which would result in a repository area for 24,000 tons of spent PWR fuel of 6.8 km^2.

Figure 7. **Approximate site of South Korea's 2 square kilometer Underground Low and Intermediate Level Waste Repository** next to the Wolsong Nuclear Power Plant site. The four Candu reactors are at the lower left. Two PWRs are being built to their right.

Conclusions

Because of political constraints imposed by local governments on the amount of spent fuel that can be stored at its reactor sites, South Korea faces the need to either find a way to relax those constraints or find an off-site location to which spent fuel can be shipped by around 2020. The Korea Atomic Energy Research Institute (KAERI) has proposed spent-fuel pyroprocessing as a solution. But it is unlikely that a full-scale pyroprocessing plant could be brought on line before 2050. Furthermore, pyroprocessing would have a number of disadvantages:

- It would be on the order of ten times more costly than interim spent-fuel storage;
- Its supposed radioactive-waste benefit: the fissioning of plutonium and the other transuranic elements, is premised on the assumed commercialization after 2050 of large

numbers of fast-neutron reactors that other OECD countries have failed to commercialize despite the expenditure of more than $50 billion; and

- It would make plutonium much more accessible, exacerbating the danger of nuclear-weapon proliferation —- both by South Korea and by other non-nuclear-weapon states that might decide to emulate the examples of Japan and South Korea.

South Korea requires an interim storage option in any case. Its government has launched and then suspended a public consultation on its spent-fuel management options. It should resume this public consultation and see whether there are conditions under which one or more local governments would be willing to provide additional interim storage – and potentially a geological repository -- for its spent fuel.

A reprocessing plant is simply an enormously costly form of interim storage. In Japan, Aomori Prefecture, which hosts Japan's reprocessing plant, received 190 billion Yen ($1.7 billion) in incentive payments by 2004 before the plant was completed and has been promised 24,000 Yen ($216) for every kilogram of spent fuel shipped to the plant.[96] That will total another 760 billion Yen ($7 billion) for the projected 32,000 tons of spent fuel that are to be reprocessed during the lifetime of the plant. The total subsidy will be thirty times the $300 million incentive that was part of the package that helped persuade the local governments around the Wolsong site to host a repository for low and intermediate-level radioactive waste[97] but it is still small in comparison to the 11,000 billion Yen ($100 billion) estimated cost of building, operating and decommissioning the Rokkasho Reprocessing Plant.[98]

Given the inherently low danger from stored spent fuel in comparison with that from an operating nuclear power plant, it is quite possible that, if compensated on a scale comparable to the compensation of Aomori Prefecture for hosting the Rokkasho Reprocessing Plant, a jurisdiction already hosting a nuclear power plant might be willing to host an interim spent-fuel storage site as well.

South Korea also should discuss the problem of spent-fuel management with the United States, Japan, China and Russia. None of these countries wants to see a proliferation chain reaction in East Asia. That danger, in addition to the huge costs of reprocessing, should give them an added incentive to agree on a less costly and dangerous solution to the region's spent fuel management problems.

What about research and development on pyroprocessing and fast-neutron reactors? Since these technologies are so far from economic viability and because of the proliferation concerns, it does not make sense to have them developed in national programs. An alternative would be to emulate the fusion-energy community where the countries with major fusion-energy programs

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[96] "Wake Up, Stop Dreaming: Reassessing Japan's Reprocessing Program," *op. cit.*

[97] The incentives provided to the region for accepting the low-level-waste site also included the transfer of the headquarters of KHNP to Gyeongju (population 280,000) the nearest city to Wolsong, Ji Bum Chunga, "Competition, economic benefits, trust, and risk perception in siting a potentially hazardous facility," *Landscape and Urban Planning*, Vol. 91 (2009) p. 8.

[98] This estimate by the Federation of Electric Power Companies of Japan of the total cost of reprocessing at Rokkasho is reported in *Nuke Info Tokyo* No. 98, Nov. 2003 - Feb. 2004.

have decided to build a single experimental reactor. Indeed, because of the decline in fission R&D funds, nine OECD countries have joined in a "Generation IV Forum" to coordinate their R&D on advanced fission reactors. Five of these countries (France, Japan, South Korea, the US and China) and the EU have expressed interest in joint work on sodium-cooled fast-neutron reactors. France, Japan, Switzerland and the EU have expressed an interest in gas-cooled fast-neuton reactors and Japan and the EU in lead-cooled fast-neutron reactors.[99] These countries could join in building a single fast-neutron reactor in one of the non-weapon states (i.e. South Korea or Japan) and in doing pyroprocessing R&D with actual spent fuel in one of the weapons states (i.e. China, France or the US). To minimize the transport distance for the fuel between the reactor and pyroprocessing facility, if the fast-neutron reactor is built in South Korea or Japan, it might make sense to do the pyroprocessing R&D in China.

Such collaboration among the three East Asian countries with major commitments to fission energy might also lay a basis for multinational cooperation in other sensitive aspects of the nuclear fuel cycle., including uranium enrichment and spent-fuel management.

[99] Gen IV International Forum, "Introduction to Generation IVNuclear Energy Systems and the International Forum, 2008, http://www.gen-4.org/PDFs/GIF_introduction.pdf