Viewpoint

South Korea's Shifting and Controversial Interest in Spent Fuel Reprocessing

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From the beginning of its nuclear power program in the 1970s, the Republic of Korea (South Korea) has been intermittently interested in the reprocessing of nuclear-power spent fuel. Such reprocessing would typically separate the spent fuel into three constituent components: the unfissioned uranium remaining in the spent fuel, the plutonium produced during reactor operation, and the highly radioactive fission products and transuranics other than plutonium. The plutonium, which like uranium-235 (U-235) is a fissile material, could then, once it is separated during the reprocessing, be fabricated into reactor fuel or used to produce a nuclear weapon. Initially, South Korea's interest in reprocessing was sparked by the general worldwide enthusiasm for plutonium breeder reactors, and then soon afterwards by consideration of reprocessing as a potential route to nuclear weapons. By the late 1980s, South Korea remained interested in reprocessing but focused on the prospect that plutonium recycling could reduce dependence on imported uranium. During the 1990s, the South Korean government remained concerned about energy security but also began to see reprocessing as a way to address South Korea's spent fuel disposal problem. Throughout this entire period, the United States consistently and effectively opposed all reprocessing initiatives on nonproliferation grounds. We review South Korea's evolving interest in spent fuel reprocessing, and argue that there are alternatives to reprocessing and recycling that can better achieve uranium savings and better rationalize spent fuel disposal. Such alternatives also would not require South Korea to overcome U.S. objections to reprocessing.

EARLY EXUBERANCE

The South Korean government, when it started its nuclear power program in the late 1960s, reflected the great optimism of the worldwide nuclear industry, which had impressively expansive hopes for nuclear power. South Korea's first long-term nuclear energy development plan of 1968[2] called for the construction of two 500-megawatt electric (Mwe) nuclear power plants by 1976, a plan later altered to support construction of one 600 MWe plant to be operated by the Korea Electric Power Corporation (KEPCO).[3] In March 1976, the Korea Atomic Energy Research Institute (KAERI) called for the construction of 22 nuclear power plants (23 gigawatt electric [Gwe]) by 2000, corresponding to 50 percent of total projected electric generating capacity.[4] In January 1978, the Ministry of Commerce, Industry and Energy (MOCIE) announced that, given the uncertainty of international prices of petroleum and insufficiency of domestic coal production, it would make sense for South Korea to construct 46 nuclear power plants by 2000.[5]

While these plans turned out to be overly ambitious, South Korea did begin to establish a strong nuclear power program in the 1970s. During this period, KEPCO contracted with Westinghouse for six pressurized-water reactors (PWRs) (5.0 GWe total),[6] with Framatome for two PWRs (1.9 GWe),[7] and with Atomic Energy Canada Limited (AECL) for one Canadian Deuterium Uranium reactor (CANDU) (0.7 GWe).[8] The deal with Framatome increased South Korea's range of nuclear technology and fuel supply.[9] Moreover, South Korea's purchase of the CANDU, which uses natural uranium as fuel, if it led to further orders, would help to reduce dependence on foreign enrichment.[10] By the end of the 1970s, South Korea had one PWR (Kori-1) that became operational in 1978. It also had two research reactors, TRIGA Mark II (250 kilowatt [kW]-thermal) that operated from 1962 to 1996, and TRIGA Mark III (two MW-thermal) that was purchased from General Atomics (GA), and operated by KAERI from 1972 to 1996. These research reactors were for basic research, radioisotope production, and personnel training.[11]

During the 1970s, South Korea also began to think about plutonium recycling. Its 1968 long-term nuclear plan called for feasibility studies on nuclear fuel fabrication and reprocessing to be completed by 1976. The plan projected that a reprocessing plant would be deployed by 1981. This projection reflected the then widespread concern in the world nuclear establishment that world uranium reserves would soon be depleted, and the assumption that the commercialization of fast breeder reactors would be realized in the 1990s.[12] KAERI's "Third Five-Year Nuclear Energy Development Plan (1972-1976)," published in 1972, called for the construction of a pilot reprocessing plant (32 metric tons of heavy metal [tHM] in spent fuel per year) by 1976.[13]

SOUTH KOREA'S DREAMS OF NUCLEAR WEAPONS

Although the South Korean government's interest in reprocessing doubtless reflected in part a worldwide infatuation with the prospect of breeder reactors, there was also another, more immediate, factor driving the government's plans for reprocessing. In 1970, the United States announced plans to withdraw part of its forces stationed in South Korea, based on the so-called "Nixon Doctrine" that called for Asian allies to take more responsibility for defending themselves.[14] Following this announcement, the United States began reducing its forces from 70,000 to 44,000.[15] This shocked the South Korean government, which immediately established two defense agencies: the Agency for Defense Development (ADD) and the Weapons Exploitation Committee (WEC).[16] The WEC reportedly voted unanimously in the early 1970s to proceed with the development of nuclear weapons. [17]

Soon afterwards, the South Korean government sought to purchase a pilot reprocessing plant from France.[18] As noted earlier, reprocessing is an indispensable step to the acquisition of plutonium, which along with U-235, is a weapons-usable material. A safeguards agreement between the International Atomic Energy Agency (IAEA), France, and South Korea entered into force on September 1975, and thereafter the French government notified the South Korean government of its readiness to provide a pilot reprocessing plant.[19] However, the South Korean government under strong U.S. pressure ended negotiations in January 1976.[20]

This did not end South Korea's search for reprocessing technology entirely. In 1976, South Korea started negotiations with France for the purchase of a Post-Irradiation Examination Facility (PIEF), consisting of four heavy concrete cells and two lead-lined cells.[21] The purpose of this facility was to test and evaluate the performance and integrity of spent fuels. The U.S. government requested that the size of the PIEF be limited because of concerns that South Korea could be laying the foundation for a domestic plutonium separation capability.[22]

In parallel with its efforts to purchase reprocessing technologies, KAERI also began negotiations with Canada in 1973 for the purchase of an NRX research reactor, and with Belgium after 1975 for the purchase of a mixed-oxide (MOX) fuel fabrication facility. However, the Canadian government halted negotiations with South Korea after the explosion in April 1974 of an Indian nuclear device using plutonium produced in the Canadian-provided CIRUS research reactor, a clone of the NRX.[23] The negotiations with Belgium also were ended in November 1977,[24] again due to U.S. intervention.[25]

South Korea at some point appears to have abandoned the projects designed to provide it with a nuclear weapons option. In January 1977, President Park announced, "We will not go nuclear…" at his annual inspection of the Ministry of National Defense.[26] President Jimmy Carter's 1977 announcement of plans to withdraw all U.S. ground troops by 1982 again provoked South Korean officials to raise the prospect of acquiring nuclear weapons.[27] However, Carter soon thereafter in 1978 canceled the withdrawal plan.[28] Since then, there have been no public statements by South Korea about possible nuclear armaments acquisition.[29] The clandestine nuclear weapons program evidently ended for good after the assassination of President Park in October 1979.[30]

ECHOES OF REPROCESSING IN THE 1980S: THE "TANDEM" FUEL CYCLE

President Chun (1980-1988), who took power in a military coup in December 1979, scaled back civilian nuclear energy development during his administration.[31] In the 1980s, South Korea contracted for only two PWRs (2.0 GWe).[32] In January 1986, KAERI also contracted with AECL to construct a multi-purpose research reactor "HANARO" (30 MW-thermal).[33]

In the 1980s, there was one interesting replay of South Korean interest in reprocessing followed by U.S. opposition. In 1983, KAERI with AECL performed a joint study of a "TANDEM fuel cycle," in which PWR spent fuel would be fabricated into fuel to be used in CANDU reactors.[34] In the TANDEM fuel cycle, the spent PWR fuel is dissolved, as in conventional reprocessing, but the plutonium and uranium are co-precipitated without separation, while the fission products and higher actinides are removed. However, only one additional step would be required to separate the uranium and plutonium. As a consequence, the U.S. government opposed the joint study, and it ended in late 1983.[35] In October 1989, South Korea proposed a trilateral arrangement for the development of the TANDEM fuel cycle involving South Korea, the United States, and Canada at the ROK/USA Joint Standing Committee on Nuclear Energy Cooperation, but no agreement was reached.[36]

RENEWED INTEREST DURING THE 1990S IN REPROCESSING FOR ENERGY SECURITY AND SPENT FUEL DISPOSAL

In the 1990s, KEPCO contracted with AECL for three additional CANDUs (2.1 GWe)[37] and with HANJUNG, a South Korean vendor, for six PWRs (6.0 GWe).[38] At the end of 1999, 12 PWRs (10.9 GWe) and four CANDUs (2.8 GWe) were in operation, while four PWRs (4.0 GWe) were under construction.[39] According to the 1999 Long-Term Power Supply Plan, 23 PWRs (24 GWe) and three CANDUs (2.1 GWe) will be in operation in 2015, corresponding to 33 percent of South Korea's total electricity capacity.[40]

This substantial nuclear power capacity, existing and projected, will result in a large and growing spent-fuel inventory. At the end of 1999, 2,165 tHM (tonne of heavy metal) of PWR spent fuel were stored in reactor spent fuel storage pools at three nuclear power plant sites (Kori, Yonggwang, and Ulchin), while 1,919 tHM of CANDU spent fuel were stored in pools and concrete silos at the Wolsong site.[41] At the Kori site, spent fuel in excess of the storage capacity of the pool of the oldest plant, Kori-1, has been moved into the pools of Kori-3 and Kori-4.[42] A 1997 analysis projected that all spent fuel storage pools at the Kori site would be saturated by 2003-2005 and at the Yonggwang and Ulchin sites by 2004-2009.[43] It thus appeared that additional storage facilities for PWR spent fuel would be required before South Korea had constructed a permanent spent fuel repository, currently planned for 2030.[44] To confront this problem, KEPCO began to explore the possibility of sending spent fuel overseas for reprocessing, with the returned plutonium then recycled in fresh MOX fuel.[45]

Suppliers have shown interest in this reprocessing option. Indeed, in 1995, COGEMA and BNFL, the giant reprocessing companies of France and Britain, reportedly offered to reprocess South Korean spent fuel and to facilitate the use of MOX fuel in South Korean PWRs.[46] KEPCO was apparently persuaded by the low prices offered by COGEMA and BNFL for reprocessing,[47] although even at these prices a simple analysis shows that plutonium recycling is still more costly than the once-through fuel cycle.[48]

In any event, KEPCO thought the idea had sufficient promise that in 1997, it hired a U.S. law firm, Hogan & Hartson, to intercede on its behalf with the U.S. Department of State to obtain U.S. consent to the reprocessing of South Korean spent fuel. It was understood that, absent such intercession, the United States would not consent to reprocessing.[49] KEPCO also considered the possibility of sending to COGEMA for reprocessing the non-U.S.-origin spent fuel irradiated at Framatone-supplied PWRs at the Ulchin site. This spent fuel is exempt from the U.S. prior consent rights under the Korean-U.S. nuclear cooperation agreement.[50] Ultimately, however, South Korean government officials decided that South Korea would not try to reprocess even non-U.S.-origin spent fuel without U.S. consent.[51]

With reprocessing therefore not a short-term option, the South Korean government decided that all spent fuel discharged from its PWRs and CANDUs could after all be stored on site through 2016 by re-racking pools, intra-site transshipment of spent fuel, and in yet-to-be-constructed dry-storage facilities.[52] After 2016, the government plans to have a centralized away from reactor (AFR) interim storage facility in operation.[53]

The South Korean government considered options in addition to foreign reprocessing. Starting in 1992, the government began to establish several long-term nuclear energy development plans to enhance the utilization of nuclear energy.[54] The plans call for construction of a 330 MW-thermal fast reactor after 2010 on the assumption that commercialization of fast reactors would occur about 2025. They also call for a feasibility study on the use of MOX fuel for plutonium recycling to be done by 2010, and for a study of the so-called DUPIC fuel cycle, discussed below. All of these programs implicitly assume reprocessing or other separation technology. However, the research and development (R&D) budget outlays for these initiatives were relatively small.[55]

THE DUPIC PROGRAM: AN ALTERNATIVE TO CONVENTIONAL REPROCESSING?

In 1991, KAERI and AECL with the participation of the U.S. national laboratories undertook a feasibility study of the DUPIC fuel cycle in order to improve uranium utilization and to reduce spent fuel volume.[56] The basic idea of the DUPIC fuel cycle is to re-fabricate PWR spent fuel (which still contains approximately two times the fissile material content of natural uranium as well as non-volatile fission products and higher actinides) into fuel for heavy water reactors, without separating plutonium from either the uranium or non-reactive fission products.[57] The DUPIC fuel cycle offers a higher degree of proliferation resistance than the TANDEM fuel cycle by virtue of the high radioactivity of the DUPIC fresh fuel.[58] However, it requires large hot cells and remote manipulation equipment that could also be used also for small-scale reprocessing.

In 1999, South Korea set up facilities at the KAERI site for dismantling small amounts of PWR spent fuel in hot cells at the PIEF and for fabricating DUPIC fuel bundles in hot cells at the Irradiated Material Examination Facility (IMEF).[59] The formal ceremony marking the opening of the DUPIC facility was held at KAERI on March 17, 2000.[60]

However, KEPCO has stated that it has no specific schedule for commercialization of the DUPIC fuel cycle.[61] Even though KAERI favors the DUPIC fuel cycle, KEPCO is highly critical of it and clearly prefers to move forward with reprocessing and plutonium recycle.[62] KEPCO's skepticism about the DUPIC fuel cycle is due to several factors. Some technical issues remain unsolved, especially radiation protection for workers while they are loading DUPIC fuel into existing CANDU reactors,[63] and economic viability is uncertain.

SOUTH KOREA DOES NOT NEED REPROCESSING AND RECYCLING

The DUPIC fuel cycle notwithstanding, South Korea's most intensively examined candidate to provide improved uranium savings and spent fuel management remains reprocessing and plutonium recycling. Plutonium recycling in PWRs would achieve approximately 15 percent uranium saving with plutonium recycle only, and 31 percent uranium saving with plutonium and uranium recycle, compared to the once-through fuel cycle.[64] Since South Korea depends on imported natural uranium and foreign enrichment services for its nuclear fuel,[65] such savings would help somewhat to reduce that dependence. However, unless South Korea has both a domestic reprocessing capacity and a MOX fabrication facility, the value of plutonium recycle is very limited as a measure to buffer against uranium supply interruption due to a sudden policy change of supplier governments. In any case, even if South Korea were determined to secure a supply of uranium, there appear to be several alternatives available that would not involve reprocessing and a head-on confrontation with the United States.

Consider first the DUPIC fuel cycle. Uranium saving by the DUPIC fuel cycle would be approximately 18 to 25 percent, compared to the once-through uranium fuel cycle, or roughly the same as the savings through plutonium recycle.[66] The DUPIC fuel cycle similarly would not enhance energy security unless it also included significant new domestic facilities for separations of spent fuel. However, with respect to proliferation resistance, the DUPIC fuel cycle appears to have advantages over plutonium recycling.

There are other alternatives available to South Korea that could obviate the need for any separation of spent fuel and recycling, either in a DUPIC or plutonium fuel cycle, while achieving the same or nearly the same benefits afforded by plutonium recycle or DUPIC.

One such possibility is presented by the promise of advanced fuels for CANDUs. In 1996, KAERI and AECL started a joint research program, which was joined by BNFL in 1997, to develop an improved CANDU (CANFLEX) fuel using uranium recovered from reprocessed light water reactor fuel.[67] The recovered uranium (RU) contains about 0.9 percent U-235, which can be burned in a CANDU to obtain about double the burnup of natural uranium fuel.[68] In late 1997, a BNFL research team fabricated RU into a fuel element for the CANFLEX fuel bundle.[69] In addition, KAERI has underway an R&D program for developing advanced CANDU fuels using slightly enriched uranium of 1.2 percent and 1.5 percent U-235.[70] Such fuels would allow burnups three to four times greater than that of natural uranium fuel.[71] With such burnups, the use of slightly enriched uranium of 1.2 percent and 1.5 percent U-235 in CANDUs would require approximately 25 percent less natural uranium than natural-uranium fueled CANDUs.[72]

Consider another example, the use of thorium-uranium fuel (a 3:7 mixture of 19.5 percent-enriched uranium and thorium) in PWRs in a once-through fuel cycle. Such a fuel cycle would require approximately 12 percent less natural uranium than a uranium fuel cycle with a 45 thermal megawatt-day (MWd)/kgHM (kilograms of heavy metal) burnup. If one compared the uranium-thorium fuel cycle to uranium with a comparable burnup of 70 MWd/kgHM, the savings would be still greater–about 25 percent.[73] This cycle also requires thorium equivalent to about five percent of the natural uranium required. However, the natural occurrence of thorium (9.6 ppm [parts per million]) is more than three times that of uranium (2.7 ppm) in the earth's crust, and high-grade thorium ores appear to be equivalently abundant.[74] This fuel cycle does produce U-233, which is a fissionable material. But the fissile mixture of U-233 and U-235 of the spent fuel will always be diluted by the U-238 to concentrations below that necessary for direct weapons use. The U-233 in spent fuel will also be accompanied by U-232. This isotope decays with a 69-year half-life to a daughter isotope, which upon decay emits a very high-energy gamma ray, making the use of the material for a weapon very difficult.

Other measures also are potentially usable if uranium security becomes a problem, for example, the establishment of a strategic uranium stockpile. Assuming a constant real uranium price of $30 per kilogram of uranium and a real discount rate of five percent a year for 10 years, the extra uranium charge at the end of 10 years would be $19.50 per kilogram. This translates to about six cents per kilowatt-hour (kWh).[75] This is much less than the extra cost of reprocessing in plutonium recycle.

As a final illustration, pressures on uranium resources could be eased considerably if progress is made on the recovery of uranium from seawater. The most recent Japanese and French estimates of the cost of recovering uranium from seawater are in the range of $80 to $100/kgU. Based on this cost (about $90/kgU), using seawater uranium would add an increment to the total generating cost of electricity of only 0.28 cents per kWh.[76]

Aside from uranium savings, a second reason for interest in reprocessing is to relieve the burden of PWR spent fuel storage. However, overseas reprocessing of PWR spent fuel would postpone the additional storage burden only by about eight to 10 years[77] because storage would have to be provided for the returning high-level waste (HLW) produced by spent fuel reprocessing.[78] Moreover, the cost of management and disposal of HLW from reprocessing will not be significantly less than those of disposal of spent fuel because the cost of repository depends not on the physical volume of the waste but on the heat release from the waste.[79] The DUPIC spent fuel emits nearly the same decay heat as PWR spent fuel and generates volatile and some semi-volatile fission products removed during the DUPIC fuel fabrication process.[80]

In any case, any requirements for additional PWR spent fuel storage can be delayed until at least 2030 by allowing *inter*-site transshipment.[81] Domestic transportation of spent fuel could be provided by sea because all South Korean nuclear power plant sites are located along the seacoast. Recent proposals for international spent nuclear fuel storage in Russia[82] or Australia[83] provide other potential long-term alternatives to solve South Korea's spent fuel management problems.

REPROCESSING IN THE FUTURE? TWO WILDCARDS

With few energy security or economic reasons for South Korea to pursue reprocessing and recycle and with the United States firmly opposed to such activities, there appears little prospect for South Korean reprocessing any time in the foreseeable future. However, two polar developments could conceivably upset this prognosis, or so some have argued. These developments are the resumption of reprocessing by North Korea, or in contrast, a reunification of the Korean Peninsula.

In regard to the first of these wildcards, since the mid-1980s, South Korea and the United States have considered various measures to persuade North Korea to abandon its nuclear weapons ambitions.[84] In December 1991, South and North Korea signed the Joint Declaration on Denuclearization of the Korean Peninsula, pledging not to test, manufacture, produce, receive, possess, store, deploy, or use nuclear weapons, as well as promising to abandon domestic nuclear reprocessing and enrichment capabilities.[85] In May 1992, North Korea reported to the IAEA that it had about 90 grams of plutonium subject to safeguards from a one-time reprocessing of defective fuel rods. However, shortly afterwards IAEA inspections led the agency to suspect that North Korea had actually reprocessed spent fuel on several occasions since 1989. This finding and a subsequent threat by North Korea in 1993 to withdraw from the Treaty on the Non-Proliferation of Nuclear Weapons precipitated a crisis, which then led to a diplomatic initiative by the United States that came to be known as the Agreed Framework, formalized in 1994.[86] Under this framework, North Korea will suspend various nuclear activities, including most importantly reprocessing efforts at its Yongbyon facility. In return, South Korea, the United States, and Japan established the Korean Peninsula Energy Development Organization (KEDO) to provide North Korea with two Korean reactors with a capacity of 1,000 MWe each.[87] But if North Korea resumed reprocessing, South Korea might well reconsider its no-reprocessing pledge under the Joint Declaration in order to hold open a nuclear option if it appeared that North Korea were moving toward such an option.[88]

With respect to the prospect of an end to the conflict between the Koreas, would the United States, in such an event, drop its opposition to the reprocessing of South Korean spent fuel? As noted above, the United States has consistently blocked South Korea's exploration of both domestic and foreign reprocessing, using its legal rights over U.S.-origin spent fuel as well as political pressure.

The case of Japan adds fuel to speculation that the United States might be willing to relent in this opposition if the Korean conflict were ended. Due to lack of indigenous energy sources, Japan, like South Korea, has emphasized nuclear energy as a major energy source and has also pursued reprocessing and plutonium recycling. However, in contrast to South Korea, Japan has been permitted, under a bilateral agreement signed in 1988 with the United States, to reprocess U.S.-origin spent fuel, domestically and overseas.[89] This permission supercedes a U.S.-Japan nuclear cooperation agreement that was essentially the same as the present bilateral nuclear cooperation agreement between South Korea and the United States. Why then should the United States treat Korea differently than it does Japan even if the Korean conflict is ended by reunification or otherwise?

One certainly could argue that the United States should be willing to drop its opposition to reprocessing in the event of reunification.[90] However, the United States is highly unlikely to take this step as it would be contrary to the long-held U.S. opposition to reprocessing and commercial use of plutonium (even if the United States has pragmatically accepted reprocessing in Europe and, as noted, in Japan). Moreover, the United States would be wary of a domino effect. After South Korea, Taiwan, which has in the past pursued a reprocessing option, would in all likelihood want to reprocess; and there might be other countries as well. Fred McGoldrick, a former

U.S. State Department official who was for a long period centrally engaged in U.S. nonproliferation policy, made the following point:

> …At most, I could visualize the U.S. agreeing to the transfer of Korean spent fuel to the UK or France for reprocessing but only if the plutonium were not returned to Korea. This, of course, raises its own problems because it is not at all clear what could be done with the plutonium. There is a glut of plutonium in Western Europe, Russia and the United States and there is no market for it. Hence I see little likelihood that the U.S. would agree to reprocessing Korean spent fuel in Europe unless the Europeans would agree to keep the plutonium. In such an eventuality, Korea would presumably have to pay for the storage costs which are likely to be high – the physical protection measures would be quite costly.[91]

The Japan analogy is also not convincing. As McGoldrick stressed, when the United States concurred in reprocessing in Japan, the Japanese had already made a heavy investment in reprocessing and recycling facilities. Also, Japan, unlike South Korea, did not have a nuclear weapons program after World War II. In any case, the present U.S.-South Korean agreement does not expire until 2014, and it would seem that neither the United States nor South Korea has much incentive to renegotiate the agreement at this time.[92]

CONCLUSIONS

In the 1970s, South Korea's interest in plutonium was driven primarily by national security concerns and by the infatuation of a whole generation of nuclear engineers worldwide with the plutonium-breeder reactor. More recently, South Korea's interest has been driven largely by considerations of energy security and spent fuel management (though no doubt the breeder reactor dream remains alive to some extent). In both these cases, there are better alternatives than reprocessing and recycling. It is very likely then that any South Korean move to reprocessing will be seen by the United States and other countries as reflecting South Korea's renewed interest in developing a nuclear weapons option. On these grounds, such a move would certainly be opposed by the United States. In sum, there appears to be no rationale on energy security, spent fuel management, or economic grounds for South Korea to pursue reprocessing and plutonium recycle at this time, and little prospect that it will do so in the face of international opposition.

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[2] Korea Atomic Energy Commission (AEC), *Long-Term Plan of Research, Development and Use of Nuclear Energy (1968-1989)*, January 1968 (Korean).

[3] Korea Atomic Energy Research Institute (KAERI), *A History of Korea Atomic Energy Research Institute (1959-1989)* (Taejon: KAERI, 1990), p. 157, p. 170 (Korean).

[4] Ibid., p. 176.

[5] Young-Sun Ha, *Nuclear Proliferation, World Order and Korea* (Seoul: Seoul National University Press, 1983), p. 102.

[6] Kori-1 (587 MWe), Kori-2 (650 MWe), Kori-3 and Kori-4 (950 MWe each), and Yonggwang-1 and Yonggwang-2 (950 MWe each) in June 1970, in November 1976, in April 1978 and in October 1979, respectively. KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 679-692.

[7] Ulchin-1 and Ulchin-2 (950 MWe each) in July 1979. Ibid., p. 691.

[8] Wolsong-1 (679 MWe) in January 1975. Ibid., p. 684.

[9] Ministry of Commerce, Industry and Energy (MOCIE), *White Book of Nuclear Power Generation* (Seoul: MOCIE, 1998), p. 60 (Korean).

[10] KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 158; Ha, *Nuclear Proliferation, World Order and Korea*, p. 93; However, this motive evidently was not very strong since South Korea waited 16 years to deploy a second CANDU.

[11] Ministry of Science and Technology (MOST), <http://www.most.go.kr/inforoom/unclear/research/5-1.htm> (Korean). The reactors were too low in power to make a substantial contribution to nuclear weapon production. Office of Technology Assessment (OTA), *Nuclear Proliferation and Safeguards: Appendix Volume II, Part One* (Washington, D.C.: U.S. Government Printing Office, June 1977), p. I-31. Since 1998, all spent fuel from TRIGA Mark II and III has been returned to the United States. U.S. Department of Energy (DOE), "Spent Fuel Shipment from South Korea to the Idaho National Engineering and Environmental Laboratory," Fact Sheet, July 1998.

[12] KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 170.

[13] Ha, *Nuclear Proliferation, World Order and Korea*, p. 104.

[14] Michael J. Engelhardt, "Rewarding Nonproliferation: The South and North Korean Cases," *The Nonproliferation Review* 3 (Spring-Summer 1996), p. 32.

[15] Ibid.

[16] U.S. House, Subcommittee on International Organization, *Investigation of Korean-American Relations* (Washington, D.C.: U.S. Government Printing Office, October 1978), p. 79.

[17] Ibid., p. 80. According to the South Korean government sources, the South Korean government had run a secret research program to develop a clandestine nuclear weapons capability for years. Mark Hibbs, "Legacy of Secret Nuclear Program Led U.S. to Blunt ROK Cooperation," *Nucleonics Week*, January 7, 1998.

[18] KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 418.

[19] Ha, *Nuclear Proliferation, World Order and Korea*, pp. 131-132. In April 1975, the South Korean government ratified the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), seven years after it signed the NPT in July 1968. KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 676.

[20] KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 419; OTA, *Nuclear Proliferation and Safeguards: Appendix Vol-*

ume II, Part One, p. I-31; Peter Hayes, "The Republic of Korea and the Nuclear Issue," in Andrew Mack, ed., *Asian Flashpoint: Security and the Korean Peninsula* (Canberra: ANU Printery, 1993), p. 52.

[21] The commissioning test finished at the end of 1985. KAERI, *Post-Irradiation Examination Facility* (Taejon, KAERI, 1998), p. 1 (Korean).

[22] The PIEF hot cells do not normally separate plutonium, although they could be adapted to do so. David Albright et al., *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (New York: Oxford University Press, 1997), p. 365.

[23] U.S. House, Subcommittee on International Organization, *Investigation of Korean-American Relations,* p. 80.

[24] KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 419-421.

[25] Hayes, "The Republic of Korea and the Nuclear Issue," p. 52.

[26] Ha, *Nuclear Proliferation, World Order and Korea*, p. 128.

[27] Engelhardt, "Rewarding Nonproliferation: The South and North Korean Cases," p. 32.

[28] Ibid.

[29] Mitchell Reiss, *Without the Bomb: The Politics of Nuclear Nonproliferation* (New York: Columbia University Press, 1988), p. 106.

[30] "Nuclear-Related Trade and Cooperation Developments for Selected States, July-October 1995," *The Nonproliferation Review* 3 (Winter 1996), p. 151.

[31] As one example, in January 1981, the Chun administration merged the Korea Atomic Energy Research Institute (KAERI) and the Korea Nuclear Fuel Development Institute (KNFDI) into the Korea Advanced Energy Research Institute. KAERI retrieved its original name in January 1990. See KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 694, and Korea Atomic Industrial Forum (KAIF), *1999 Nuclear Yearbook* (Seoul: KAIF, 1999), p. 701 (Korean).

[32] KEPCO contracted with Combustion Engineering (CE) and Korea Heavy Industries and Construction Company (HANJUNG) for Yonggwang-3 and Yonggwang-4 (1,000 MWe each) in April 1987. KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 705.

[33] Ibid, p.703. HANARO achieved its first criticality on February 8, 1995, <http://kis21.kaeri.re.kr/research/rru.htm>.

[34] KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 255.

[35] Ibid., p. 256. President Chun, upon taking office, stressed the need for strong security ties between South Korea and the United States, and was not inclined to battle the United States on this point. Tae-Hwan Kwak and Wayne Patterson, "The Security Relationship between Korea and the United States, 1960-1982," in Yur-Bok Lee and Wayne Patterson, eds., *Korean-American Relations 1866-1997* (Albany: State University of New York Press, 1999).

[36] KAERI, *A History of Korea Atomic Energy Research Institute (1959-1989)*, p. 256.

[37] Wolsong-2 (700 MWe) in November 1991 and Wolsong-3 and Wolsong-4 (700 MWe each) in September 1992. KAIF, *1999 Nuclear Yearbook*, p. 702-703.

[38] Ulchin-3 and Ulchin-4 (1,000 MWe each) in August 1991, Yonggwang-5 and Yonggwang-6 (1,000 MWe each) in 1995, and Ulchin-5 and Ulchin-6 (1,000 MWe each) in November 1996. Ibid, p. 702-712.

[39] MOST, *Current Status and Statistics of Nuclear Energy*, February 2000 <http://www.most.go.kr/> (Korean).

[40] Plans call for two old reactors, Kori-1 and Wolsong-1, to be shutdown in 2008 and 2013, respectively. Maximum electricity demand in 2015 is projected to be double that in 1998. MOCIE, *The Fifth Long-Term Power Supply Plan (1999-2015)*, December 1999, p. 3 (Korean).

[41] This total combines 1,073 tHM, 667tHM, and 425 tHM of PWR spent fuels at the Kori, Yonggwang and Ulchin sites, respectively. MOST, *Current Status and Statistics of Nuclear Energy*, February 2000.

[42] KAIF, *1999 Nuclear Yearbook,* p. 539.

[43] Young-Eal Lee and Myung-Jae Song, "Expansion of Spent Fuel Interim Storage Capability in Association with Back-End Fuel Cycle Policy in Korea," paper delivered to Symposium on Waste Management 97, Tucson, Arizona, 1997.

[44] Storage of CANDU spent fuel is considered less of a problem than the PWR spent fuel, since South Korea expects to place all or most of the CANDU spent fuel into dry storage for 50 years or more while it looks for a geological repository site. Mark Hibbs, "Shifting Spent Fuel Policy from Reprocessing Toward Interim Storage: Case Studies in Germany, Japan, and Korea," in William G. Sutcliffe, ed., *Proliferation Prevention in the Commercial Fuel Cycle* (Livermore: Lawrence Livermore National Laboratory, UCRL-ID-133896, April 9, 1999), p. 57. Although spent CANDU fuel has much smaller decay heat per unit mass of heavy metal compared to PWR spent fuel, the dry-storage costs for CANDU spent fuel per megawatt-day ($5.7/MWd [thermal megawatt-day]) are higher than for PWR spent fuel ($2.4/MWd), assuming dry-storage prices of $40/kgHM for seven MWd/kgHM of CANDU spent fuel and $110/kgHM for 45 MWd/kgHM of PWR spent fuel. (Jungmin Kang, "Alternatives for Additional Spent Fuel Storage in South Korea," *Science and Global Security* [forthcoming]. South Korea's relative hurry to place the CANDU fuel in dry storage is probably a result of two factors other than cost: 1) the spent-fuel pool of a CANDU reactor will be saturated earlier than the same capacity pool of a PWR, and 2) the fissile-plutonium concentration in CANDU spent fuel is much less than in PWR fuel.

[45] Mark Hibbs, "KEPCO Wants to Reprocess Offshore, Take Back MOX and Recycle Pu, RepU," *NuclearFuel* 22, April 7, 1997, p. 3.

[46] Mark Hibbs, "Korea's Long-Term Ambition is Fresh Nuclear Pact with U.S.," *NuclearFuel* 21, December 2, 1996, p. 4.

[47] Mark Hibbs, "KEPCO Wants to Reprocess Offshore, Take Back MOX and Recycle Pu, RepU," p. 3. Due to competition between COGEMA and BNFL, prices for new reprocessing contracts have fallen to the range of $400-500/kgHM, while early post-base-load contracts prices were around $1,000/kgHM. Steve Fetter et al., "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel: Short-term and Long-term Prospects," presentation at the International Conference on Future Nuclear Systems Global '99, Jackson Hole, Wyoming, August 29-September 3, 1999.

[48] Cost penalties incurred by reprocessing spent fuel and fabricating MOX fuel will not be offset by cost reductions due to savings in uranium and in uranium enrichment and fabrication. Nor will they be offset by lower costs of disposal, since the cost of management and disposal of HLW from reprocessing will not be significantly lower than that of disposal of spent fuel (Fetter et al., "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel: Short-term and Long-term Prospects." The cost of a kilogram of low-enriched uranium (LEU) (4.5 percent U-235) is approximately $1,150 ($30/kg for purchase of natural uranium, $100/kgSWU for enrichment, and $200/kg for fabrication of LEU fuel). The cost of fabricating a kilogram of MOX fuel is approximately $1,500/kgHM. So even without any reprocessing charge at all (that is, considering plutonium to be "free"), a kilogram of MOX fuel would be more expensive. If one then added the cost of reprocessing, the gap would be still greater. It requires the reprocessing of about six kilograms of spent PWR fuel to produce the plutonium in one kilogram of MOX, and with a reprocessing cost of $1,000/kgHM, the reprocessing-cost contribution to the cost of MOX would be about $6,000/kgHM. Thus the total cost penalty for MOX compared to LEU is approximately $6,350/kgHM. At a burnup of 45 MWd/kgHM, this corresponds to a penalty of 1.72 cents/kWh. Even if reprocessing costs were cut in half, the cost penalty for reprocessing and recycle would still be nearly $.01/kWh. K.A. Williams et al., *A Comparative Assessment of the Economics of Plutonium Disposition Including Comparison with Other Nuclear Fuel Cycles*, (Washington, D.C.: U.S. Department of Energy, CONF-970613-1, May 1997), p. 17; OECD/NEA, *Plutonium Fuel: An Assessment*, 1989, p. 127.

[49] Mark Hibbs, "No Spent Fuel Reprocessing, New KEPCO CEO Chang Declares," *NuclearFuel* 23, October 19, 1998.

[50] Mark Hibbs, "Reprocessing Bid after Chang to Center on Ulchin Spent Fuel," *NuclearFuel* 24, April 19, 1999.

[51] Mark Hibbs, "Chang's Successor Will Reopen Reprocessing Option, Officials Say," *NuclearFuel* 24, June 18, 1999.

[52] MOST, *Current Status and Statistics of Nuclear Energy*, p. 17.

[53] Ibid.

[54] AEC, *Long-Term Nuclear R&D Program (1992-2001)*, June 1992 (Korean); AEC, *Long-Term Nuclear Energy Policy Directions toward to 2030*, July 1994 (Korean); *Comprehensive Nuclear Energy Promotion Plan,*

Atomic Energy Act, October 1995 (Korean); AEC, *Long-Term Nuclear R&D Program (1997-2006)*, June 1997 (Korean).

[55] The R&D budgets for developing a fast reactor, the DUPIC fuel cycle, and future nuclear fuel (including MOX fuel) were 6.3 percent, 1.6 percent, and 2.6 percent of a total nuclear R&D budget of about $1.4 billion during 1997-2006 (1,100 won per U.S. dollar). MOST, *Nuclear R&D Results and Plan*, South Korea, December 1999 (Korean).

[56] Chang-Kook Yang and Byung-Oke Cho, "Fuel Cycle Technology in Korea," The 9th Pacific Basin Nuclear Conference, Sydney, Australia, May 1-7, 1994.

[57] Choi Hangbok et al., "Parametric Analysis of the DUPCI Fuel Cycle," 1994 Nuclear Simulation Symposium, Pembroke, Canada, October 12-14, 1994.

[58] P.G. Boczar et al., "CANDU Fuel Cycle Options in Korea," Korean Nuclear Society Spring Meeting, Cheju, South Korea, May 31-June 1, 1996.

[59] Operating since 1994, IMEF, was constructed using domestically developed technology. KAERI, *Irradiated Materials Examination Facility* (Taejon: KAERI, 1998), p. 1 (Korean); KAIF, *1999 Nuclear Yearbook*, p. 336.

[60] KAERI, *TCNC Newsletter* 2 (March/April, 2000), <http://www.tcnc.kaeri.re.kr/Newsletter/NL000304/Newsletter-000304.htm>. Earlier, KAERI had fabricated several DUPIC fuel bundles in cooperation with Canada, the United States, and the IAEA, followed by an irradiation test at the HANARO reactor, which achieved its first criticality in 1995. (KAIF, *1999 Nuclear Yearbook*, p. 335.)

[61] Mark Hibbs, "KEPCO Says It Has No Plans to Implement DUPIC Fuel Cycle," *NuclearFuel* 21, December 16, 1996, p. 11.

[62] Hibbs, "KEPCO Wants to Reprocess Offshore, Take Back MOX and Recycle Pu, RepU."

[63] Chang-Hyo Kim, "Technical Issues Unresolved for Realization of DUPIC Fuel Cycle in Korea," The 11th Pacific Basin Nuclear Conference, Banff, Canada, May 3-7, 1998.

[64] The Pu-239 and Pu-241 content in 45 MWd/kgHM PWR spent fuel after five years cooling will be 0.7 percent by weight. This was calculated employing the widely-used reactor fuel cycle code, ORIGEN2, developed by Oak Ridge National Laboratory. *ORIGEN 2.1: Isotope Generation and Depletion Code Matrix Exponential Method* (Radiation Safety Information Computational Center, Oak Ridge National Laboratory, CCC-371, 1996). This plutonium could replace about 15.6 percent of the feed uranium, considering 4.5 percent initial U-235 enrichment. There will also remain 0.94 kg uranium (1.1 percent U-235 and 0.6 percent U-236) per kg of initial uranium in the 45 MWd/kgHM spent fuel after five years cooling. This uranium has to be enriched up to 5.08 percent to be equivalent to 4.5 percent enriched without U-236. (OECD/NEA, *Plutonium Fuel: An Assessment*, p. 129). Assuming 0.3 percent tails, it takes 6.1 kg of recycled uranium to make one kg of 5.08 percent enriched uranium vs. 10.4 kg of natural uranium to make one kg of 4.5 percent enriched uranium. Therefore, 15.4 percent (=0.94/6.1) of the feed uranium could be replaced on a first recycle of RU.

[65] South Korea imports natural uranium from the United States, Canada, Australia, France, Russia, and South Africa and foreign enrichment services from the United States, Britain, France and Russia. MOCIE, *White Book of Nuclear Power Generation*, p. 138.

[66] The uranium saving would be 25 percent when the fresh DUPIC fuel is made from 35 MWd/kgHM burnup PWR spent fuel, and approximately 18 percent when fuel is made from 45 MWd/kgHM burnup spent fuel. Calculations based on the data in Hangbok, Choi et al., "Parametric Analysis of the DUPCI Fuel Cycle."

[67] H.C. Suk, "Development of Improved CANDU fuel and Its Prospects," *Nuclear Industry* 16, (December 1996) (Korean).

[68] P.G. Boczar, et al., "CANDU Fuel Cycle Options in Korea," Korean Nuclear Society, Spring Meeting, Cheju, Korea, May 31-June 1 1996.

[69] *BNFL News*, December 1997.

[70] H.C. Suk, KAERI, personal communication, July 18, 2000.

[71] P. Baumgartner et al., "Disposal Costs for Advanced CANDU Fuel Cycle," The 11th Pacific Basin Nuclear Conference, Banff, Canada, May 3-7, 1998.

[72] See Boczar et al., "CANDU Fuel Cycle Options in Korea."

[73] Jungmin Kang and Tatsujiro Suzuki, "Proliferation Resistance and Energy Security Advantages of a Thorium-Uranium Dioxide Once-Through Fuel Cycle for Light Water Reactors" presented at the International Conference on Probabilistic Safety Assessment and Management PSAM 5, Osaka, Japan, November 27-December 1, 2000.

[74] *Handbook of Chemistry and Physics, 78th Edition (1997-1998)* (Boca Raton, FL: CRC Press, 1997), p. 14. The price of thorium today is about $25/kg. U.S. Department of Energy, *Restricted Data Declassification Decisions 1946 to the Present (RDD-5)*, January 1, 1999, <http://www.osti.gov/opennet/rdd-5.html>.

[75] This calculation assumes 0.3 percent enrichment tail assay and 34 percent thermal efficiency and 45 MWd/kgHM burnup of spent fuel in a PWR.

[76] Fetter et al., "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel: Short-term and Long-term Prospects."

[77] Lee and Song, "Expansion of Spent Fuel Interim Storage Capability in Association with Back-End Fuel Cycle Policy in Korea." However, BNFL and COGEMA could offer to keep the waste much longer as an incentive to South Korea to sign a reprocessing contract with them. Fred McGoldrick, Bengelsdorf, McGoldrick and Associates, LLC, personal communication, May 2, 2000.

[78] The volumes of HLW, ILW, and low-level radioactive waste (LLW) from reprocessing are 2-4, 20-45 and 70-95 m^3/GWe-yr, respectively, while the volume of LEU spent fuel is 26 m^3/GWe-yr. Brian G. Chow and Gregory S. Jones, *Managing Wastes With and Without Plutonium Separation* (Los Angeles: RAND, 1999). The current (controversial) practice is to return only HLW containing only a slightly increased number of Curies equivalent to the Curies in the ILW and LLW left in the reprocessing country.

[79] The early heat from HLW is only modestly less than that from spent fuel. Fetter et al., "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel: Short-term and Long-term Prospects."

[80] Baumgartner et al., "Disposal Costs for Advanced CANDU Fuel Cycle"; Yun-Goo Kim et al., "Source Intensity Analysis of DUPIC Fuel," *Journal of the Korean Association for Radiation Protection* 21 (June 1996). In the DUPIC process, 99 percent of the Cs-137 (and Ba-137m) is extracted from the spent fuel.

[81] Kang, "Alternatives for Additional Spent Fuel Storage in South Korea."

[82] The Russian Ministry of Atomic Energy has drafted a proposal to import 20,000 tonnes of spent nuclear fuel from Asia and Europe for storage. *IAEA Daily Press Review*, March 13, 2000.

[83] Elaine Hiruo, "Proposals for International Facilities Blend Security, Commercial Interests," *NuclearFuel* 24, March 8, 1999, p. 3.

[84] Michael J. Mazarr, *North Korea and the Bomb: A Case Study in Nonproliferation* (New York: St. Martin's Press, 1995), pp. 35-77.

[85] *Joint Declaration of the Denuclearization of the Korean Peninsula*, Government of Republic of Korea, December, 1991.

[86] See for example, General Accounting Office, "Nuclear Nonproliferation: Difficulties in Accomplishing IAEA's Activities in North Korea," GAO/RCED-98-210, July 1998.

[87] The governments of South Korea, the United States, and Japan signed the agreement on the establishment of the KEDO in March 1995. *Korean Peninsula Energy Development Organization, Annual Report 1996/1997*.

[88] Mark Hibbs, "South Korea Must Reprocess If DPRK has Weapons Program, Minister Says," *NuclearFuel* 19, June 6, 1994, p. 6.

[89] Kumao Kaneko, "Can Nuclear Energy Live in Asia in the 21st Century–and How? A Proposal of ASIATOM," *For the Renaissance of Nuclear Power in Asia*, in Kumao Kaneko, ed., The Japan Council on Nuclear Energy, Environment & Security (CNEES), March 1998.

[90] Mark Hibbs, "ROK Told KEPCO to Postpone Offshore Reprocessing Quest," *NuclearFuel* 22, April 21, 1997, p. 12.

[91] Fred McGoldrick, Bengelsdorf, McGoldrick and Associates, LLC, personal communication, May 2, 2000.

[92] Fred McGoldrick, Bengelsdorf, McGoldrick and Associates, LLC, personal communication, June 14, 2000. McGoldrick also makes the point that South Korea has been reluctant to negotiate a new agreement, which would require them to accept still more stringent and intrusive arrangements as required by the U.S. Nuclear Non-Proliferation Act of 1978.