The Asia-Pacific Journal | Japan Focus

Volume 8 | Issue 25 | Number 2 | Article ID 3376 | Jun 21, 2010

Nuclear Power and Spent Fuel in East Asia: Balancing Energy, Politics and Nonproliferation 東アジアにおける原子力と使用済み燃料――エネルギー・政治・不拡散のバランス

Lawrence Scheinman, Miles Pomper, Ferenc Dalnoki-Veress, Stephanie Lieggi

Nuclear Power and Spent Fuel in East Asia: Balancing Energy, Politics and Nonproliferation

Miles Pomper, Ferenc Dalnoki-Veress, Stephanie Lieggi, and Lawrence Scheinman[1]

Summary:

Growth in nuclear power generation in East Asia will increase significantly in the next few decades, as will regional stockpiles of spent nuclear fuel. The need for regional cooperation in dealing with the back-end of the nuclear fuel cycle is becoming critical as the key players in the region—China, Japan, South Korea and Taiwan— face the growing challenge of managing their spent nuclear fuel.

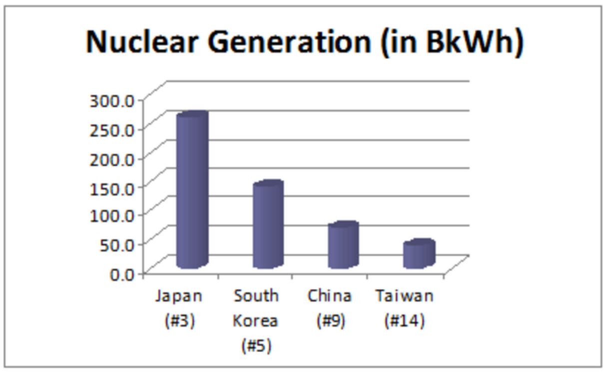
North Korea's nuclear weapons development is not the only nuclear crisis plaguing East Asia. There is also the less visible, but nearly as intractable problem of what to do with the region's accumulating spent fuel from its burgeoning fleet of nuclear plants, a problem whose proposed solutions are sending economic and diplomatic shockwaves throughout the region and throughout the world.

In the East Asian region there are four players with established nuclear energy programs—China, Japan, South Korea, and Taiwan. Each of these faces its own unique challenges with regard to spent fuel management. In South Korea, the government wants to pursue a form of "reprocessing" spent fuel to reduce its growing volume despite the fact that Seoul pledged not to conduct reprocessing in a 1992 agreement with North Korea.[2] Reprocessing uses an industrial process to recycle the energy imbedded in the plutonium in spent nuclear fuel. This process can be used to both provide additional fuel for nuclear plants or fissile material for nuclear weapons. Seoul's stance has sounded alarm bells in Washington, which has shut down previous attempts by South Korea to reprocess and does not want to provide additional excuses for North Korea to further its nuclear ambitions. Yet Seoul is far from the only government in the region to consider reprocessing. Reprocessing efforts in China, the region's nuclear-weapon state, may be of lesser nonproliferation concern because it already has stockpiled fissile material. However military officials, diplomats, and nonproliferation experts have long worried that Japan's reprocessing program and its tons of separated plutonium represent a significant proliferation danger.[3] Taiwanese authorities are not actively considering reprocessing which would likely garner little support in Washington or elsewhere. However Taiwan, which flirted with a weapons program in the past, has still not devised a solution to its spent fuel problem.

The rush to reprocess spent fuel and develop a "closed" nuclear fuel cycle[4] in some countries in East Asia is occurring despite evidence that the process is far more costly than the "once-through" nuclear fuel cycle, which involves ultimately storing the spent fuel in a permanent repository. And it is occurring despite international efforts to prevent the spread of reprocessing to new countries.

The four East Asian powers that we will focus on all rank within the world's top 14 for nuclear power generation (see Figure 1).

Figure 1: Total Nuclear Power Generation 2009[5]



Number under name denotes world ranking. Amounts in billion kilowatt hours (BkWh)

Even more notable with regard to current and future disposition of spent nuclear fuel is the fact that 33 more reactors are in construction in these four countries alone—making up about 50 percent of the world's reactors under construction.[6]

Despite the fact that disposition of spent fuel is a common problem, there have been few serious attempts at shared solutions. To be sure, the major nuclear energy players in the region will have to develop their own plans for addressing their stockpiles of spent fuel and these will have to be tailored to the particular needs of each domestic program. But the possibility exists for key actors in the region to cooperate and collaborate in addressing accumulated spent fuel to minimize proliferation dangers, technical obstacles, and economic costs.

The Problem of Spent Fuel and Reprocessing[7]

Since the onset of the nuclear age in 1945 attention has focused on how to provide an institutional framework for peaceful nuclear activity, most notably power generation, which would minimize the risk that nuclear knowledge, technology and assets would be misused to produce atomic weapons. The 1946 Acheson-Lilienthal Report on the International Control of Atomic Energy concluded that "a system of inspection superimposed on an otherwise uncontrolled exploitation of atomic energy by national governments would not be an adequate safeguard" and could not assure effective separation of civil and military uses of nuclear technology.[8]

Nonetheless, when the United States first began to build nuclear plants in the 1950s, the Atomic Energy Commission (AEC), fearing a potential uranium supply shortage, encouraged spent fuel reprocessing to produce plutonium for breeder reactors. In 1966, the AEC approved a license for a commercial reprocessing plant in West Valley, New York, which only operated for six years. Two other plants under construction in the same period—in Morris, Illinois and Barnwell, South Carolina—never reached commercial operation. However, the feared uranium supply crunch never materialized, while India's 1974 "peaceful nuclear explosion" which used plutonium produced with a reactor and components supplied by Canada and the United States, opened a new chapter in nonproliferation. In particular, it led to a renewed focus on institutional initiatives to constrain the use of civil nuclear cooperation for explosive purposes whether intended for civil purposes (e.g. digging canals) or military use. In 1977, the Carter administration decided not to encourage reprocessing and recycling, at home or abroad, because of proliferation concerns. The changes were reflected in the Nuclear Nonproliferation Act of 1978 (NNPA) that required prior consent for reprocessing in all cases.[9]

A singularly important initiative led by the United States and supported by the Soviet Union, which took place soon after the Indian test, was the establishment of the Nuclear Suppliers Group (NSG) to bring the major nuclear suppliers together to agree on a code of conduct regarding the requirement for International Atomic Energy Agency (IAEA) safeguards on designated transfers. In addition NSG members agreed to exercise restraint in the transfer of sensitive facilities and technologies, and to “encourage” recipients to accept, as an alternative to national enrichment and reprocessing, supplier involvement and/or other appropriate participation in any facilities that might be built.

There have been three key exceptions to U.S. policy aimed at discouraging transfer of enrichment and reprocessing capabilities. Two of these concerned nuclear cooperation with EURATOM and Japan, which had reprocessing programs underway before the change in U.S. policy. A third instance, and one that by many accounts most seriously undermined U.S. credibility in opposing foreign reprocessing, was the Bush administration’s decision to conclude a nuclear cooperation agreement with India and the Obama administration’s actions to finalize a related reprocessing agreement with New Delhi. This agreement pledges that, pending subsequent negotiations, India, a state possessing nuclear weapons that has not signed the Nuclear Nonproliferation Treaty (NPT), will be granted the right to reprocess U.S.-origin fuel for exclusively peaceful purposes at one or more future reprocessing facility as long as they are placed under effective IAEA safeguards. It should be noted that the suspension provisions in the Indian deal are less stringent than previous agreements with EURATOM and Japan and uniquely would provide compensation to India for any U.S.-decision to suspend the agreement.[10]

In 2003 then IAEA Director General Mohamed ElBaradei urged member states to consider the “merits of multinational approaches to the management and disposal of spent fuel and radioactive waste.”[11] In June 2004, the IAEA established the International Expert Group on Multilateral Approaches to the Nuclear Fuel Cycle, with members from 26 countries. The goal of this expert group was to identify approaches across the nuclear fuel cycle and strengthen nonproliferation without disrupting market mechanisms. The expert group proposed five approaches in order to fulfill the “objective of increasing nonproliferation assurances associated with the civilian nuclear fuel cycle, while preserving assurances of supply and services around the world.”[12] The proposals include ones aimed at: promoting fuel leasing and “take-back” offers; commercial offers to store and dispose of spent fuel; creating multinational (particularly regional) agreement for new facilities for front-end and back-end nuclear fuel cycle; fuel reprocessing; and disposal and storage of spent fuel.[13]

Many nuclear and nonproliferation experts agree that the most likely inducement for “new comers” to nuclear power to give up efforts to create their own domestic fuel cycle is the offer of “a safe, secure, and affordable route for disposal based on a multinational repository in another country.”[14] Over the past three decades many initiatives were launched aimed at identifying locations, terms and conditions for storing spent nuclear fuel with a view to finding alternatives to, and discouraging development of, the spread of national reprocessing activities, while still facilitating national access to the benefits of atomic energy.[15] However, none have come to fruition. A key issue has been, and remains, finding an appropriate location for disposition of spent fuel. To be acceptable the site would have to be geologically stable, able to accommodate spent fuel in the short term and/or permanently; meet certain nonproliferation criteria, and be politically acceptable to the governing state (and to its neighbors) in terms of proximity to populations centers and to the movement of spent fuel itself.

To date, no state has been willing to make a commitment in that regard, although there are two potential exceptions. Russia has been willing to take back spent fuel from the countries to which it has provided enriched uranium. Whether that would extend to other than Russian-origin spent fuel remains an open question. Insofar as U.S.-origin fuel is concerned, should a U.S-Russian bilateral nuclear cooperation agreement now pending in Congress be approved, that would open the door to shipping to Russia spent fuel from South Korea and Taiwan that depends on reactor fuel imported from the United States or have their reactor fuel irradiated in U.S.-supplied reactors. Mongolia, although currently lacking necessary infrastructure, also has expressed some interest in hosting a repository.

Recent multilateral efforts in which the East Asian countries profiled in this paper have been involved have focused less on finding storage sites than on sharing research and shaping policy into advanced recycling (reprocessing) technologies, associated reactors, and related questions of proliferation resistance.[16] These have included the U.S- initiated Global Nuclear Energy Partnership (GNEP), the Generation IV International Forum (GIF), and the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).[17] GNEP was proposed by the Bush administration in 2006 and aimed to, among other goals, develop proliferation-resistant reprocessing technology, minimize nuclear waste, develop advanced fast reactors and establish reliable fuel supply and "take-back" services.[18] GIF is a cooperative international endeavor organized to share research and development information, and experiences on performance and capabilities relevant to the development of the next generation of nuclear reactor systems.[19] INPRO focuses on strengthening the proliferation resistance of the nuclear fuel cycle through development of advanced reactor technology.[20]

Despite these initiatives there has been no effort to build true multilateral back-end facilities, in part because of the political sensitivities involved in importing foreign spent fuel for either storage or reprocessing. Faced with these pressures, the Obama administration has indicated that it is inclined to rely on interim storage of U.S. spent fuel at reactor sites for the foreseeable future while looking at the possibility of centralized interim storage sites and conducting research on long-term alternatives including advanced reprocessing options. It is also encouraging other states to first rely on interim storage at disposal sites.[21]

Some of the region's nuclear energy powers are trying to move forward with various forms of reprocessing. Most controversially, Seoul, is trying to win Washington's blessing for constructing new facilities to test the economic and technical feasibility of utilizing pyroprocessing. Seoul contends that pyroprocessing, a technique pioneered by the U.S. national laboratories, does not produce a product suitable for nuclear weapons and should not be restricted in the same way as traditional reprocessing. But the U.S. government has yet to give its blessing, worried that the process or its output could be too easily altered to produce a less benign product, that it will be too difficult to institute safeguards to prevent such changes, and that any relaxation of U.S. rules would harm Washington's global and regional nonproliferation efforts.

East Asia Policies for the Back-end of the Fuel Cycle[22]

As many as thirty new countries, have declared their interest in building nuclear power plants in the future.[23] Others, including all of the four

East Asian players profiled in this paper are looking to expand existing nuclear power programs. However, key to the acceptance of nuclear power by the public is the safety of the nuclear power plants and a carefully developed, cradle-to-grave, comprehensive nuclear waste management strategy. The three main strategies currently open to governments are:

- Once-Through where the back-end of the fuel cycle consists of storing spent fuel on racks in a cooling pond for about a decade, followed by removal to an interim storage facility such as dry casks until a final geological repository is secured;

- Traditional Reprocessing and Recycling where actinides (such as plutonium) extracted from spent fuel is recycled one or more times in thermal neutron reactors; this process can, according to some estimates, save about "30 percent of the natural uranium otherwise acquired;"[24] and

- Pyroprocessing where light water reactor (LWR) fuel is reprocessed and converted to metal fuel to be cycled through sodium fast reactors[25] until the long life-time actinides are burned. Proponents of this process suggest that this cycle will not only burn waste in so called "burner" reactors but will also generate electricity in the process solving two problems.

Of the three strategies mentioned above, the latter two recycles spent nuclear fuel—treating it is as a resource and not as waste—although it should be noted that these two methods also still require final disposal of high level nuclear waste and perhaps also interim storage. The third option, pyroprocessing, is still in a developmental stage and its overall viability as a commercial enterprise remains a question. It would also require the need for further development of advanced reactors capable of burning the resultant fuel.

In judging the acceptability of any strategy by the four players profiled below aimed at the back-end of the fuel cycle a number of factors must be reviewed, including economic and technical feasibility, proliferation resistance, impact on storage and disposal, regional and international impacts, and public perceptions of (and in many cases opposition to) the methods chosen.

Japan

Japan ranks third in the world in nuclear power generation; it has an extensive civilian nuclear industry with 54 reactors spread throughout the country.[26] In 2009, nuclear energy supplied approximately 30 percent of Japan's electrical power production.[27] The disposition of spent fuel has been a challenge for Japan's nuclear policy since the commissioning of its first nuclear reactor in Tokai in 1966. Japan has an estimated 17,000 tons of spent fuel in storage.[28] Tokyo's policy for dealing with the back-end of the nuclear fuel cycle has focused primarily on the reprocessing of spent fuel for re-use in its nuclear reactors. Japan's goal with regard to recycling is the establishment of a closed nuclear fuel cycle in order to maintain a secure domestic energy supply.

Japan's first "Long-Term Program for Research, Development and Utilization of Nuclear Energy" was published in 1956 and set out a national policy on the nuclear fuel cycle. The principles put forth in this plan, and reiterated in Japanese policy reviews over the last 50 years, have been that Japan should develop both spent fuel reprocessing and fast breeder reactor (FBR) technology. Japanese nuclear energy policy does not consider spent nuclear fuel as waste but as a recyclable energy source.

In 1958, foreign reprocessing was selected as a near-term approach for dealing with spent fuel and domestic reprocessing as the long-term approach, with the first shipment of nuclear fuel abroad occurring in 1966. The reprocessing of Japanese spent fuel was outsourced to nuclear facilities in the United Kingdom and France although these shipments ended in 2001. The reprocessed fuel, once returned to Japan, will be used to fuel domestic reactors. Japan had up to 37 tons of spent plutonium in France and the UK, as well as another 8.7 tons stored in Japan—both in at-reactors storage and away from reactor (AFR) facilities.[29]

In the 1960s, Japan began developing a reprocessing facility and the Power Reactor and Nuclear Fuel Development Corporation (PNC) was established for the development of fast breeder reactors, uranium enrichment and spent fuel reprocessing. In 1977, the experimental Joyo FBR (140 MWt) reached criticality, and remains in operation. From 1977 to 2006, the pilot reprocessing plant at Tokai using PUREX technology[30] treated a total of 1,116 tons of spent fuel.[31]

Japanese nuclear authorities chose a site near the village of Rokkasho for a commercial reprocessing plant. The storage pool of the Rokkasho reprocessing facility began receiving spent nuclear fuel from Japanese utilities in 1998. In 2004, Japan's Atomic Energy Commission (JAEC) agreed to allow commercial operation of the plant, which was designed to reprocess 800 tons of spent fuel per year. The plant is still in its testing phase and is not expected to be operational until October 2010, a delay of 14 months from the original target date.[32] According to Japanese planners, once this facility is fully operational it will remove the need for Japan to outsource its reprocessing to other countries. However, Japan reportedly plans to reprocess only 32,000 tons of spent fuel at Rokkasho by 2050 (at an estimated cost of 12,700 billion yen) which will only account for about half of the total spent fuel Japanese reactors will have produced by that point. Estimates point to an additional 30,000 tons of spent fuel needing long-term storage.[33] Japanese officials have stated that Tokyo may consider developing a second reprocessing plant and expanding storage capacity.[34]

Japanese nuclear authorities established a vitrification plant and storage facility attached to the Rokkasho reprocessing plant in 2007.[35] Vitrified waste is placed in cooling storage at the Rokkasho storage facility for 30 to 40 years before being buried underground at an as yet undecided location. Japanese nuclear authorities also operate a high level waste vitrification plant at Tokai.[36]

JAEC established a technical subcommittee in 2004 to study the costs of nuclear fuel cycle scenarios until 2060. This was the first comprehensive economic study in Japan on nuclear fuel cycle options. The options considered were: reprocessing all spent fuels, which would require use of Rokkasho and one other yet to be built reprocessing plant; reprocessing only at Rokkasho combined with direct disposal; and interim storage of all spent fuels. The JAEC study noted that reprocessing and plutonium recycling was more costly than the once-through fuel cycle.[37] However, the subcommittee of JAEC concluded that, overall, reprocessing would be the less costly option for Japan. This decision was based on the premises that: since the Rokkasho plant was already built and the $20 billion for its construction plus the projected $13 billion decommissioning cost would have to be paid in any case; and if Rokkasho became unavailable as an off-site destination for the spent fuel from Japan's nuclear power plants, they would have to shut down as soon as their spent fuel storage pools filled up and replacement electricity would have to be generated by fossil-fueled plants.[38]

Even with this decision by the JAEC, economic issues have continued to garner criticism for Japan's reprocessing policy. Current estimates have Japan's on-site storage nearing capacity in the next few years; however, an "away from reactor" (AFR) storage facility commissioned in Mutsu has helped extend Japan's capacity for interim storage until 2025.[39] This facility will have an initial capacity of 3,000 tHM extendable to 5,000 tHM. The current plan is for the facility to start operating in 2012.[40] This increase in storage capacity has raised further questions about the push for Japan's reprocessing program, especially considering the fact that JAEC's own report notes that direct disposal is considered economically more feasible than reprocessing. Moreover, Japanese recycling of spent fuel has been criticized as setting a bad precedent that could "legitimize the actions of other countries to pursue similar technologies and ultimately attain 'breakout' capability."[41]

As part of its recycling policy, Japan began developing FBR technology in the 1950s.[42] Problems with domestic R&D, however, including a major accident at a prototype reactor in Monju in 1995, has meant that FBR development has lost significant steam—and funding—in Japan over the last decade. Recent estimates put the likely date for a commercial FBR as being no earlier than 2050.[43]

In order to cope with the delays related to the FBR and other advanced reactor technology programs, the Japanese government funded the development of "pluthermal power generation" which allows for the burning of mixed oxide (MOX) fuel in ordinary reactors. Japan's nuclear industry is considering the use of pluthermal generation in up to 18 reactors by the middle of this decade. Pluthermal, however, saves less than 20 percent of uranium needed for reactor fuel, making it a relatively inefficient technology for power generation.[44]

South Korea

South Korea has emerged as the world's fifth largest nuclear energy producer—with nuclear energy supplying over one-third of ROK electricity generation—and, recently, a significant nuclear power plant exporter. The ROK utilizes 20 nuclear power reactors and has six more under construction. In the coming years, South Korea plans to further increase its reliance on this low-carbon source of power as Seoul seeks continued economic growth without increasing carbon emissions. While nuclear power has brought important benefits to South Korea, it has also brought an accumulation of spent nuclear fuel that will soon outstrip the country's storage capacity.[45]

South Korea's spent fuel reached 10,761 tons at the start of 2010, which is 79 percent of its total storage capacity. It is expected that the Kori, Ulchin, and Yonggwang nuclear sites will all reach capacity by 2018.[46] By the end of the century (assuming the new planned reactors come online), the cumulative amount of spent fuel produced by South Korean reactors is expected to exceed 110,000 tons. In order to dispose of such a large amount of spent fuel in a single site, some South Korean experts have claimed that an underground repository (and an exclusion zone surrounding the site) would need to cover as much as 80-square kilometers, an area considerably larger than Manhattan.[47]

Seoul has been trying to tackle the issue of spent fuel disposal since its first nuclear plant began operating in 1978. The early decisions not to construct interim storage facilities at reactor sites reflected both historical circumstances and political judgments. When Seoul made these decisions in the mid 1980s, dry cask storage technology, which would elsewhere prove to be easy to manage at reactor sites, had not been widely adopted; instead water-filled pools were seen as the model. Seoul decided that if spent fuel rods were to continue to be housed in such pools after they had cooled, it would make more sense to locate these pools in a single facility. Likewise, Seoul calculated that it would be easier to decommission nuclear plants and clean up the sites when they were no longer functional if no interim spent fuel storage sites were located at the facilities.

Seoul made these decisions, however, with little public input, and subsequent attempts to locate a centralized storage site repeatedly foundered amid negative public perceptions.[48] Public opposition to nuclear waste disposal sites in South Korea has been longstanding, leading on one occasion to rioting. Seoul's dilemma has also been exacerbated by the ROK's high population density, which makes it more difficult to build a single large permanent underground repository for nuclear waste.

In 2005, the ROK government secured a 2-square kilometer site for low-level waste in Gyeongju, a city in the southeastern part of the country. To finalize the deal, however, the ROK government had to promise numerous sweeteners—such as millions of dollars in payments to the community and relocation of a number of high-tech facilities to the area. The government also had to promise that no spent fuel storage facilities would be located in the area.[49] South Korea's leaders worried about the potential cost if they were to use a similar process to find a final disposal site for more highly radioactive material, which would require 30-40 times more space.

ROK is limited by pre-existing agreements with the United States about what it can and cannot do with its spent fuel. Ever since U.S. pressure shut down an incipient South Korean program aimed at producing plutonium for potential weapon development in the 1970s, the United States has used both legal restrictions embedded in provisions of nuclear cooperation agreements concerning the disposition of U.S.-origin spent fuel and political pressure to ensure that Seoul does not follow that path again.

The current nuclear cooperation agreement between South Korea and the United States is set to expire in 2014. Only a few years later, South Korean scientists predict, the spent fuel pools at South Korea's nuclear plants will begin to reach capacity. Seoul is trying to win Washington's blessing for constructing new facilities to test the economic and technical feasibility of pyroprocessing. Pyroprocessing treats spent fuel to remove its extremely radioactive, but relatively short-lived, beta-emitter constituents (such as strontium, cesium, and iodine), and leaves behind irradiated uranium and the extremely long-lived "transuranic" alpha-emitters, plutonium, americium, and neptunium. The ROK would then burn these materials in yet-to-be-designed fast burner reactors, ultimately reducing the overall quantity of waste requiring permanent sequestration.

In its December 2008 long-term research and development plan, the Korea Atomic Energy Commission (KAEC), the country's top nuclear policymaking body chaired by the prime minister, called for investigating the possibility of using pyroprocessing to treat spent nuclear fuel with the resulting product to be burned in new fast burner reactors. It called for the construction of a prototype pyroprocessing facility and demonstration fast burner reactor by 2028 in order to test this proposed system's economic and technical viability. Meanwhile, the Korea Radioactive Waste Management Corporation is scouting for locations for interim spent fuel storage both at, and away from, reactor sites.

Moving forward with the fast reactor and pyroprocessing facilities would require Seoul to convince the Obama Administration to alter its views on pyroprocessing and reprocessing.

Unlike the last U.S. administration—which was willing to review the viability of pyroprocessing (but ultimately raised concerns about its proliferation resistance)— the Obama Administration has been explicit in its doubts about the techniques.

The South Korean government has instituted several techniques to delay capacity from being reached, such as "burn-up extension, storage rack expansion, installation of a dry storage facility and transshipment between neighboring units, to solve the spent fuel storage problem."[50] While there have been difficulties with transshipments between sites concerning transportation hardware, this should continue to allow more time to develop a more permanent solution.[51] However, thus far strong anti-nuclear protests in South Korea have prevented efforts to secure a site for an interim storage facility.

As part of its research and development effort, South Korea has constructed the Korea Atomic Energy Research Institute (KAERI) Underground Research Tunnel (KURT), which is a laboratory explicitly for "developing a Korean disposal system for the high-level repository, which will be constructed with public acceptance in the future." The KURT facility will not need to use radioactive sources to validate HLW approaches which are strictly prohibited by law. Rather, the facility will conduct a series of experiments to investigate "groundwater flow and rock mass characteristics" which with the participation of the local population could help to build trust.

A consideration that will likely play an increasing role in the ROK's spent fuel policy is the emergence of South Korea as a nuclear exporter. South Korea recently beat out leading U.S. and French nuclear-exporting firms to win its first major nuclear export agreement—a $20 billion deal to export four nuclear reactors to the United Arab Emirates—and South Korea aims to capture 20 percent of the world market for nuclear reactors by 2030. It has also clinched a smaller deal to supply a research reactor to Jordan. Developing full nuclear fuel cycle services, including reprocessing, could be important for entry into the international nuclear market.[52]

China

Although still a small amount of China's current energy supply—less than 2 percent in 2009—nuclear power is expected to increase significantly over the next few decades. China currently has more nuclear power plants under construction than any other country.[53] With 11 reactors in operation and up to 21 under construction, disposition of spent fuel will soon become a major challenge for Beijing.[54] In July 2009, the government-controlled China Daily reported that Chinese nuclear authorities were planning for an installed nuclear power capacity of 86 GWe by 2020; this target would represent a tenfold increase over China's 2008 nuclear generation capacity and more than double earlier targets set by Beijing.[55]

In the mid 1980s, China selected a closed fuel cycle strategy to reprocess spent fuel.[56] The major motivations for China's pursuit of plutonium recycling included benefits such as full utilization of uranium resources, reduced cost of mining, milling, and enrichment, reduced energy security concerns, reduced waste repository volume, minimization of radioactive toxicity, safe disposal of radioactive waste, and reduced burden of spent fuel at reactor pools.

While China's plans for nuclear power generation are bold, their plans for back-end of the fuel cycle are not.[57] The country is estimated to have 3,800 tons of spent fuel in storage, and this amount is expected to increase to about 12,300 tons by 2020.[58] Both central planners in Beijing and local authorities are focused more heavily on building nuclear reactors than on dealing with spent fuel.

Therefore a number of unsolved problems in spent fuel management plague China, especially in light of the announced increase in capacity expected by 2050. These problems include an underdeveloped ability to reprocess spent fuel, insufficient storage capacity, and outdated regulations that do not fully cope with the steady growth of nuclear energy.[59]

Spent fuel in China is primarily stored at the reactor sites, although China plans to establish a centralized AFR storage facility in the far west of the country. China's first AFR site—part of the Lanzhou Nuclear Fuel Complex—is a wet storage facility established by the China National Nuclear Corporation (CNNC) in the western province of Gansu; however this facility is meant only for low- to intermediate-level waste. CNNC plans to use vitrification for high-level waste at a site in the Beishan area of Gansu province; however high-level waste AFR disposal is not expected to commence until 2050.[60]

Although most of China's nuclear power plants are located in the more populated eastern regions, CNNC and other nuclear authorities have chosen to locate storage facilities in the far west. This policy is likely aimed at avoiding local opposition to locating these facilities near populated areas, signaling at least a marginal impact that public opinion might have on Chinese policies. However, as one Chinese nuclear expert observed, unlike democratic systems where public opinion holds significant sway, the decision of the Chinese government is really "the only decisive factor for spent fuel management in China."[61] Since 2003, the spent fuel from two nuclear power plants in the southeastern province of Guangdong has been shipped to the Gansu facility – a distance of about 4000 kilometers. This is consistent with CNNC policy to ship spent fuel by rail to centralized storage facilities for interim storage and reprocessing.[62]

In 2006, construction was completed on a pilot PUREX reprocessing plant, also at the Lanzhou complex. The facility's initial capacity is 50 tons per year but can reportedly be expanded to 100 tons per year. However no separation of plutonium from spent fuel has been conducted.[63] The CNNC signed a deal with the French company AREVA in 2007 to study the feasibility of constructing "a spent fuel reprocessing-recycling plant in China."[64] According to one report, this plant would "manufacture fuel for power reactors using the plutonium and uranium separated from spent fuel in the reprocessing unit."[65] However, as of December 2009, no final agreement had been reached between China and France on the transfer of the relevant technologies; the plant construction appears to remain on hold.[66]

China's civilian nuclear establishment has increased research and development of advanced fuel cycle technologies aimed at alleviating the challenges of disposing of spent fuel. In cooperation with Atomic Energy of Canada Limited (AECL), the Nuclear Power Institute of China (NPIC) in Chengdu (Sichuan province) began work in 2008 on DUPIC technology pioneered by Canada and South Korea. DUPIC stands for "Direct Use of Pressurized Water Reactor Spent Fuel in CANDU"; CANDU is the Canadian heavy water reactor. The Canada-China agreement refers to "recycling recovered uranium from spent Pressurized Water Reactors fuel."[67] Although the initial phase of the cooperation would not touch directly upon DUPIC technologies, AECL's president called the agreement with China a "step towards DUPIC", adding that "Chinese authorities have recognized the value of [DUPIC], and are very interested in working with us."[68]

AECL also signed an agreement in 2009 with NPIC and other relevant Chinese entities aimed at developing technology for recycling Chinese spent fuel and using thorium in China's CANDU reactors.[69] In March 2010, AECL announced that first "re-use of nuclear fuel in a CANDU reactor" had occurred at China's Qinshan nuclear power plant, when "fuel bundles containing recovered uranium from used fuel" were inserted into one of Qinshan's reactor units.[70]

China's overall nuclear energy policy aims to maximize the utilization of uranium resources. As part of this focus, China has emphasized the introduction of fast reactors. Fast breeder development has been divided into three phases—the first involves the development of the China experimental fast reactor (CEFR); the second China's prototype fast reactor (CPFR); and third China's demonstration fast reactor (CDFR).[71]

China started researching fast neutron reactors in the 1960s. The CEFR—located at the China Institute of Atomic Energy (CIAE) in Beijing—is expected to be operational in 2010.[72] The CEFR is a 65 MWt sodium-cooled fast neutron reactor with a 25 MWe turbine generator. China also plans to build an 800 MWe demonstration fast breeder reactor by 2020, and up to three commercial FBRs by 2030.[73] In 2009, CIAE, along with the China Nuclear Energy Industry Corporation (CNEIC), established cooperation with Russia's Atomstroyexport for the planning of a commercial nuclear power plant with two BN-800 fast breeder reactors. Construction is scheduled to start in 2011.[74]

Taiwan

Taiwan has a total of six reactors at three nuclear power plants, with a total installed capacity of 5,144 MWe. Two 1350 MWe Advanced Boiling Water Reactors have been under construction at Lungmen, near Taipei, for over a decade. The facility is currently in its testing phase and is expected to start commercial operations by 2012.[75]

Nuclear power has had a turbulent history in Taiwan. In 2002, under the former administration of Chen Shui-bian, Taiwan announced a plan to have a "Nuclear-Free Homeland" and the Bureau of Energy drew up a statute to bring forward the phasing out of the three existing nuclear power plants. However, with the election of Ma Ying-jeou in 2008, Taipei has again looked favorably on nuclear power.[76] Despite changes in government, popular opinion on moving forward with nuclear power expansion is mixed.

Taiwan is estimated to have 3,320 tons of spent fuel, of which 29 tons are plutonium.[77] Taiwan's current policy calls for dry storage of spent fuel at the reactor site until final disposal, although it is recognized that additional storage facilities will be needed soon to deal with the growing amount of spent fuel being produced. Taiwan is also looking at sending its fuel overseas for reprocessing. However, U.S. government opposition to Taiwanese reprocessing has so far blocked significant movement on this; since Taiwanese reactors and fuel are of U.S. origin, bilateral agreements require Taiwan to obtain U.S. consent for reprocessing.[78]

Taiwan built its first research reactor in the mid-1950s. After mainland China successfully tested a nuclear weapon in 1964, the Taiwanese leadership began a covert nuclear weapons program at the island's Institute of Nuclear Energy Research (INER) and the Chungshan Institute of Science and Technology. This early program included efforts in reprocessing and plutonium separation. INER acquired a 40 MWt, natural-uranium heavy-water moderated research reactor from Canada.[79]

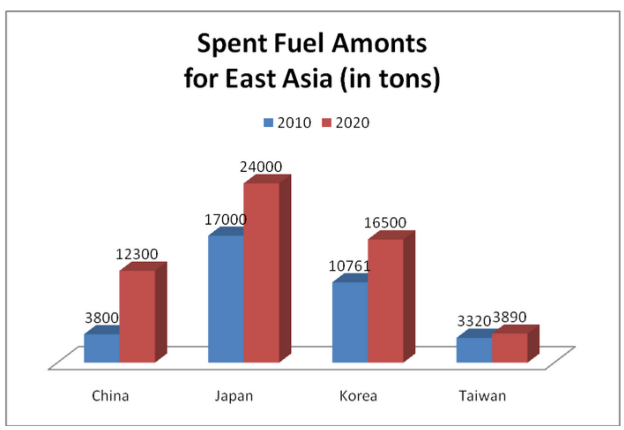
Taiwan has primarily accumulated spent fuel in on-site storage pools, however off-site storage facilities have also been used. A low level radioactive waste storage facility was established on Lanyu Island off the southeastern coast of Taiwan in 1982. According to Taiwan's Atomic Energy Council (TAEC), the facility has "a storage capacity of about 98,000 55-gallon drums in 23 semi-underground engineered trenches."[80] The site, however, reached capacity in 1996.

Recognizing the problem of managing its spent fuel with only on-site storage and limited off-site possibilities, Taiwanese authorities began looking toward cooperation on the development of dry storage technology, with mixed success. China offered to take over Taiwan's spent fuel inventory in the late 1990's but Taiwan refused due to fears that Beijing would demand political concessions in exchange.[81] In 2001, Taiwan also explored the possibility of storing its spent fuel on Russian territory; however, this would have required U.S. approval. Due to concerns the U.S. government had about Russian interaction with Iran at the time, Taiwanese authorities saw this authorization as unlikely in the short term and dropped negotiations with Moscow.[82] Should the pending U.S.-Russia Civilian Nuclear Cooperation Agreement survive congressional review, however, Taiwan would face fewer legal and political barriers to sending its fuel to Russia.

Taiwan has made some progress in extending the spent fuel storage capacity at current reactor sites. In two of Taiwan's nuclear power plants – Kuosheng and Chinshan—Taiwan Power Company (TPC) and TAEC focused on extending the capacity of at-reactor storage. The extension of the Kuosheng reactors spent fuel storage pool was completed in 2005, providing additional capacity to keep the reactors operating until about 2015.[83] TPC plans to commission a dry storage facility in Kuosheng by 2013. Also in 2005, Taiwanese nuclear authorities finalized an agreement with U.S. firm NAC International to set up a dry storage facility at Chinshan. Although the TAEC approved the project in 2008, local authorities were slow to grant a building permit for the canister construction.[84] However, Taiwanese nuclear authorities indicate they expect the dry storage canisters to be in place by August 2010.[85] Once completed, the Chinshan facility is expected to provide storage for 1366 spent nuclear fuel assemblies which should be sufficient to store all the spent nuclear fuel generated by the two Chinshan reactors for approximately 40 years. TPC has also indicated that it plans to identify a domestic repository site for disposing spent fuel, with completion envisioned in 2055; however, a location has not yet been chosen.[86]

Taiwan's current policy with regard to spent fuel management is to develop "dry interim storage followed by geological disposal." However, as one Taiwanese official stated, Taiwan needs other options that could include the movement of spent fuel to a foreign location for reprocessing and storage.[87] Taiwanese officials have expressed interest in participating in multilateral efforts, such as GNEP in order to create a long term solution for Taiwan's spent fuel.[88] However, a number of issues likely stand in the way of Taiwan's participation in the group—most importantly GNEP member China's likely objection to Taiwanese inclusion. Taiwanese officials are also discussing with AREVA the feasibility of reprocessing some of Taiwan's spent fuel in France.[89]

Figure 2: Current and Future Stockpiles in East Asia



Conclusion: Addressing East Asia's Spent

Fuel Dilemma

Some countries, such as Finland and Sweden, appear to have found long-term national solutions to their spent fuel problems by winning public support for building permanent repositories, but finding permanent storage has been an uphill battle for most governments. Other countries, such as France, have relied on national programs that postpone the day of reckoning by reprocessing and recycling spent fuel into light-water reactors. Countries in East Asia could conceivably follow one of these two paths. China, for one, appears poised to have its own national repository, likely combining this approach with reprocessing. Japan clearly has followed the reprocessing/recycling path, while South Korea and Taiwan have yet to determine how to proceed.

There may be incentives to seek a regional solution. Many different kinds of multilateral cooperation on the back-end of the fuel cycle could be envisioned with different levels of domestic political and economic costs, proliferation risks, and technology challenges.

Multinational Options

Storage: Interim and Permanent

From a nonproliferation point of view, the preferred options for dealing with the back-end of the nuclear fuel cycle would be those that would leave the spent fuel intact. Doing so maintains a "radiation barrier"—that is a mix of materials that emit sufficient radiation to kill or disable anyone attempting to steal or divert the fissile material contained in the spent fuel. It would not matter significantly where such interim or permanent facilities are located, whether in the United States, East Asia or perhaps some uninhabited atoll. Dry cask storage, according to the chair of the U.S. Nuclear Regulatory Commission (NRC), is safe and secure for "100 years" and "maybe -- beyond that."[90] If the spent fuel could be stored for 100 years before being placed in a repository, the radioactive heat generation from the fuel (the key determinant for sizing a repository) would be largely equivalent to that of separating out the transuranics through pyroprocessing, making a repository in land-constrained areas of East Asia more feasible. If opportunities develop to move the material to a third location, the spent fuel would take up about half as much space in such a repository.[91]

One could envision several ways in which regional states could cooperate in an arrangement focused on long-term interim storage of spent fuel. For example, given the knowledge that other states were prepared to provide a permanent repository, the non-nuclear weapon parties in the region—i.e. South Korea, Taiwan and Japan—would presumably be able to win domestic support for the construction of an AFR interim facility. Similarly, if another country were to provide sufficiently long-term interim storage, the domestic authorities in these places—particularly in South Korea—could provide the same kind of repository for high-level waste that it would have needed to provide if it followed a policy of using pyroprocessing and fast neutron reactors.

The preferred location for such a site from both a nonproliferation and land-use point of view would be a recognized nuclear-weapon state (NWS).[92] Russia's Far East and its established (albeit less than adequate) storage and reprocessing facilities would make it a logical location. The question, of course, is whether either Russia, or any other country, would be willing to accept foreign spent fuel that was not tied to their exports of nuclear power plants. In the late 1990s, Russian authorities looked favorably on the idea of storing and reprocessing up to 20,000 tons of imported spent fuel as a means of gaining much needed foreign currency. However, as Russia's economy improved, this business venture appeared less agreeable to Russian leaders.[93] Russia has indicated a willingness to "take-back" spent fuel of Russian origin or when the sales agreement provides for the return of the spent fuel from foreign customers. Most foreign contracts now pending on spent fuel imports, however, do not allow for long-term storage in Russia.[94] If the U.S.-Russian Civilian Nuclear Cooperation Agreement goes forward, then the United States will allow U.S.-origin fuel from elsewhere—like Japan, South Korea and Taiwan—to be reprocessed and stored in Russia; the handling of spent fuel from these three Asian players could prove profitable for Russia.[95]

Mongolia has also expressed some willingness to host such a facility. A Mongolian facility would be less attractive than a Russian site given the added expense of creating appropriate infrastructure in Mongolia. However, Mongolia's geology (and relatively low population density) might make it a viable site for long-term storage for high level nuclear waste.

U.S. Undersecretary of State Ellen Tauscher has publicly speculated about the possibility of asking Congress to change U.S. law so the United States can provide interim storage for spent fuel from countries that renounce sensitive fuel cycle technologies. She acknowledged that this effort would face substantial political opposition. However, given the Obama administration's desire to avoid the spread of reprocessing technology, U.S. officials could ask Congress to consider such an option. It would be useful, at least, for the Blue Ribbon Commission on America's Nuclear Future announced in January 2010 by the Obama administration to consider such a possibility as it looks at the appropriate way to manage domestic U.S. spent fuel.[96]

In the absence of an available permanent disposal site in Russia, the United States, or some other country, it may be difficult to persuade East Asian players to forsake reprocessing or pyroprocessing. In addition, U.S credibility in opposing foreign reprocessing has been undermined by the Bush administration's decision to conclude a nuclear cooperation agreement with India and the Obama administration's actions to finalize a related reprocessing agreement with New Delhi. Given that agreement, Obama administration officials will be hard pressed to fend off demands from regional players that they too be permitted to reprocess U.S.-origin spent fuel.[97]

PUREX Reprocessing in France, U.K., or Russia

A second possibility is suggested by the May 2009 nuclear cooperation agreement between the United States and the United Arab Emirates.[98] That agreement permitted the UAE to ship any U.S.-origin spent fuel to France or the United Kingdom for PUREX wet reprocessing but included a pledge that the UAE would not build enrichment or reprocessing facilities on its soil and that any plutonium that might be separated in France or the UK would be used in Europe, not returned to the UAE. The United States could consider offering South Korea or Taiwan a similar package and possibly include Russia as a potential reprocessing destination if and when the U.S.-Russian nuclear cooperation agreement enters into force. Including Russia in the deal would give East Asian actors the option of reducing shipping costs by having a destination closer to its borders than Western Europe. However, the U.S. Congress is likely to be less supportive of shipping such fuel to Russia than to NATO allies.

This option, however, has a number of political and economic drawbacks. Overall, PUREX reprocessing is about four times more expensive than the once-through fuel cycle.[99] More importantly, current policy in any of the potential reprocessing states would still require the return of high level waste to the state that sent the fuel and, rather than providing a reduction in the waste, advanced

PUREX reprocessing would increase the volume of waste in a geological repository by a factor of 6.2 according to a Department of Energy study.[100] Moreover, if the contract returned MOX fuel to Japan, South Korea or Taiwan it would only offer a limited nonproliferation benefit over allowing national reprocessing. MOX is considered "direct use" material by the IAEA (meaning it can quickly be converted to be used in nuclear weapons), since the plutonium in the mixture can be easily separated from the uranium.

Pyroprocessing in Russia or the United States

A third possibility would be for regional players to cooperate in establishing a multinational pyroprocessing facility in Russia or in the United States. The virtues of such a facility from a nonproliferation point of view would be that it would eliminate or reduce the possibility of two "breakout scenarios" that could be carried out under a national pyroprocessing program such as the one in South Korea—the reconfiguration of the reprocessing system to produce pure plutonium or the "sneak out" of such material from such a facility. It would bring with it built in monitoring of the facility in addition to IAEA safeguards, raise the barrier to the risk of diversion of nuclear material, and raise the level of confidence in neighboring states regarding the peaceful use of the facility. It would also establish a benchmark for future fuel processing enterprises elsewhere thereby strengthening the case for a limited number of multinational fuel cycle facilities. Such a facility could serve as a test bed for strengthened verification technologies and practices and contribute to setting standards for any such future facilities as well as for upgrading existing facilities. The greater the extent of integrated management and operational responsibilities the greater the level of confidence would be in the integrity of the system.

Some South Korean experts have suggested the possibility of U.S.-ROK multinational facilities in the United States. Such a scheme would offer some practical benefits given the longstanding and extensive cooperation between U.S. and South Korean researchers, their shared investigation of a U.S.-initiated process, the security relations between the two countries, and the ability of the United States to control the flows of material and processes on its own territory. But such a scheme would offer less reassurance to neighboring states, could retain some of the general nonproliferation problems, and would involve higher costs for shipping spent fuel.

Regional Facility for Spent Fuel Management

A fourth multilateral option would be the establishment of a multilateral facility in East Asia that might be the back-end equivalent of a recent German proposed Multilateral Enrichment Sanctuary Project (MESP).[101] The concept proposes the development of an enrichment facility, founded by states and their nuclear industries interested in assuring reliable supplies of nuclear fuel that would be owned and operated by an international commercial company located on extraterritorial space administered exclusively by the IAEA. A single technology holder would make the relevant technology available to the enterprise on a black-box basis. Participation would be open to states in good standing with the IAEA, preferably without enrichment capacity of their own. Russia's recently created Angarsk International Uranium Enrichment Center (IUEC) is another example of institutional fuel cycle arrangements being pursued.[102] While not explicitly requiring potential partners to not pursue enrichment or reprocessing on their own, at present all states that are or are preparing to become partners do not have such facilities on their territory. The IUEC, however, does not go as far as the MESP proposal which asserts that parties "remain free to develop their own enrichment technology if they choose to do so and circumstances require."

An even more ambitious proposal recently put forward suggests the establishing of an International Nuclear Fuel Agency (INFA) "under the aegis of the UN…alongside the IAEA to license the construction and operation of all uranium enrichment enterprises that seek to receive or supply nuclear fuel cycle services from or to the global marketplace."[104] As described by some experts:

> the best way to improve safeguards over enrichment activities is to establish a new freestanding INFA … to certify that the design, construction and operation of all uranium enrichment facilities worldwide are conducted in accordance with strict nonproliferation and physical security criteria; insure that all enrichment activities are conducted within long-term Sovereign Secure Leased Areas (SSLAs) controlled by the INFA; and have INFA 'certify' the legitimate producers and closely track the certified end uses of key enrichment technology components.[105]

While these proposals focus on the front end of the fuel cycle, their principle can be transposed to the back-end insofar as structural, legal, operational aspects of the fuel cycle are concerned.

Beyond Reprocessing or Storage: Other Forms of Back-End Cooperation

Given the technical difficulties and economic costs of developing commercially-viable fast neutron research reactors greater regional cooperation in R&D and the potential joint operation of test facilities would benefit all states in the region. Once again, nonproliferation and economic criteria would appear to argue for basing any joint facilities in China and Russia; however, given that Japanese facilities are already operating and South Korea has an active effort in this area, greater ROK-Japanese cooperation in this sphere might also be an alternative.

Recommendations

Before pursuing any of these options, a new regional forum for more consistently and openly discussing possible options for dealing with regional spent fuel stockpiles needs to be established. Many regional players are facing similar back end challenges and some of their nuclear authorities are proposing similar solutions; sharing of best practices and lessons learned would be beneficial. Numerous smaller Asian economies are contemplating nuclear power development (such as Vietnam and Indonesia), yet there is little regional discussion or coordination of such issues.

On the issue of pyroprocessing, further study should be undertaken in order to evaluate the technical, economic, and nonproliferation benefits. Greater regional cooperation on fast neutron reactors needs to be carried out, and the United States, as a key actor in the region, should actively encourage such efforts. Additionally, since the utility of the pyroprocessing option as a means of reducing spent fuel management problems depends on the practicality of the fast neutron reactors, the United States should seek a better understanding of the viability of this technology before approving further development of the system that would provide its fuel. Lastly, the United States, and particularly the newly established Blue-Ribbon Commission, should consider what might be done about U.S.-origin spent fuel overseas, with that in South Korea and Taiwan being given top priority.

Absent greater attention, urgency, and coordination among the region's players, the developing crisis in spent fuel could soon join the North Korean crisis on the front page of the world's newspapers.

About the authors:

Miles Pomper is a Senior Research Associate at the James Martin Center for Nonproliferation Studies (CNS) Washington, DC office. Mr. Pomper joined CNS in 2009 after serving as Editor-in-Chief of Arms Control Today, a post he held since March 2003. Previously, he was the lead foreign policy reporter for CQ Weekly and a Foreign Service Officer with the U.S. Information Agency. His career has also included several years spent covering national security and political issues at the Legi-Slate News Service and the publication of book chapters, analytical articles, and reports for publications, such as Foreign Service Journal, Survival, Bulletin of the Atomic Scientists, World Politics Review, Nuclear Engineering International, and the Centre for International Governance Innovation. He holds a master's degree in international affairs from Columbia University and a master's degree in journalism from Northwestern University.

Ferenc Dalnoki-Veress joined CNS in April 2009 as a Research Scientist to work on issues of nuclear disarmament and aspects of global proliferation of fissile materials. Dr. Dalnoki-Veress holds an MSc and PhD in high energy physics from Carleton University, Canada, specializing in ultra-low radioactivity background detectors. He has professional experience in the field of astroparticle physics and has focused primarily on fundamental research in neutrino physics. In 2008, he worked at the Princeton Program on Science and Global Security, Woodrow Wilson School of International and Public Affairs at Princeton University on verification methods and novel detection schemes for checking the declared HEU inventories of naval-reactor cores by simulating detection systems.

Stephanie Lieggi joined CNS as a Research Associate in the East Asia Nonproliferation Program in 2003. Her research has focused on nonproliferation issues in Asia and has included WMD-related developments in the region, Asia's growing nuclear industry, and related nonproliferation and export control policies. Ms. Lieggi worked on CNS export control-related publications, first as managing editor of the Asian Export Control Observer and later as Associate Editor-in-Chief of the International Export Control Observer. She received her master's in International Policy Studies from the Monterey Institute of International Studies. Her work has been published in the Nonproliferation Review, Strategic Studies Quarterly, Korea Journal of Defense Analysis, Bulletin of Atomic Scientist, South China Morning Post, and WMD Insights.

Lawrence Scheinman is Distinguished Professor of International Policy at the Monterey Institute of International Studies, Emeritus Professor, Cornell University, and Adjunct Professor, Georgetown University. He also has been a member of the tenured faculties at the University of Michigan and the University of California at Los Angeles. His government service includes appointment as Assistant Director of the U.S. Arms Control and Disarmament Agency, responsible for Nonproliferation and Regional Arms Control during the Clinton Administration, and earlier appointments in the Department of Energy, Department of State and Energy Research and Development Administration. He also served for two years as Special Assistant to Director General Hans Blix at the International Atomic Energy Agency. Dr. Scheinman has published extensively on nuclear proliferation, arms control, safeguards, international relations and international organization.

They wrote this article for The Asia-Pacific Journal.

Recommended citation: Miles Pomper, Ferenc

Dalnoki-Veress, Stephanie Lieggi, and Lawrence Scheinman, "Nuclear Power and Spent Fuel in East Asia: Balancing Energy, Politics and Nonproliferation," The Asia-Pacific Journal, 25-2-10, June 21, 2010.

Notes

[1] The authors would like to recognize the contribution of Park Seong-won, and the research assistance of Phillip Schell.

[2] See text of the "Joint Declaration of South and North Korea on the Denuclearization of the Korean Peninsula," available here, which entered into force February 19, 1992. In this agreement, North and South Korea agreed "not to test, manufacture, produce, receive, possess, store, deploy, or use nuclear weapons; to use nuclear energy solely for peaceful purposes; and not to possess facilities for nuclear reprocessing and uranium enrichment." With two nuclear tests and a declared nuclear weapons program that includes reprocessing facilities, North Korea has clearly violated the Joint Declaration; yet, to date, South Korea has been reluctant to renounce the agreement altogether, hoping that North Korea can be lured back into the Six-Party Talks aimed at eliminating North Korea's nuclear weapons program.

[3] See related discussions in Shinichi Ogawa and Michael Schiffer, "Japan's Plutonium Reprocessing Dilemma," Arms Control Today, October 2005, and Gavan McCormack, "Japan as a Nuclear State," Japan Focus, August 1, 2007.

[4] A "closed nuclear fuel cycle" refers to the process in which natural uranium is refined, converted, enriched, and then reconverted and fabricated before being utilized as fuel in the reactor; once it is irradiated, the spent fuel is reprocessed and the residual uranium and newly produced plutonium are recovered and re-used as fuel, normally in specialized advanced power reactors.

[5] Data from "World Nuclear Generation and Capacity (2009)," Nuclear Energy Institute website.

[6] "Nuclear Power Plants Information," IAEA's Power Reactor Information System (PRIS) here.

[7] This section draws on Miles A. Pomper, "U.S. International Nuclear Energy Policy: Change and Continuity," Nuclear Energy Futures Paper No. 10, Centre for International Governance Innovation, January 2010.

[8] The full text of this report is available from the International Panel on Fissile Materials (IPFM) website. For background and analysis on the matter see Lawrence Scheinman, "Equal Opportunity: Historical Challenges and Future Prospects of the Nuclear Fuel Cycle," Arms Control Today, May 2007; and for a more extensive analysis see Lawrence Scheinman, "The Nuclear Fuel Cycle: A Challenge for Nonproliferation," Disarmament Diplomacy, March/April 2004.

[9] Sharon Squassoni, "The U.S. Nuclear Industry: Current Status and Prospects under the Obama Administration," Nuclear Energy Futures Paper No. 7, Centre for International Governance Innovation, November 2009.

[10] Cole J. Harvey, "The U.S.-India Reprocessing Agreement and Its Implications" Issue Brief, Nuclear Threat Initiative, May 5, 2010, available here.

[11] "Statements of the Director General to the Forty-Seventh Regular Session of the IAEA General Conference," IAEA website, September 15, 2003.

[12] "Multilateral Approaches to the Nuclear Fuel Cycle"; Expert Group Report, INFCIRC 640, IAEA website, February 2005.

[13] "Expert Group Releases Findings on Multilateral Nuclear Approaches," IAEA website, February 22, 2005.

[14] Charles McCombie and Thomas Isaacs, "The Key Role of the Back-End in the Nuclear Fuel Cycle," Dædalus, Winter 2010.

[15] Efforts over the years have included: a proposed storage facility on Palmyra Island, an uninhabited U.S. possession, with a view to managing nuclear waste from Japan, South Korea and Taiwan; consideration of an offer from the Marshall Islands to provide space for spent nuclear fuel; and a proposal by the Australian firm Pangea Resources for identifying a suitable location for a spent fuel repository with Australia and South America being seen as potential locations.

[16] Proliferation resistance is a measure of the degree of impediments to deliberate misuse of civil nuclear energy technology and materials to produce nuclear weapons. It must be noted that proliferation resistance does not imply proliferation proof. Rather, the term proliferation resistance must be seen as a method for comparing how difficult it would be for states and non-state actors to acquire or divert fissile materials and technology by using a particular fuel cycle technology.

[17] These three initiatives have seen involvement of China, Japan and South Korea. Taiwan, due to its ambiguous political status, has not been able to participate in these multilateral endeavors.

[18] For more on GNEP see this link. Although initiated by Washington, GNEP is a multilateral program. GNEP promotes cradle-to-grave nuclear fuel services in which the suppliers would agree to "take-back" the spent fuel for the final disposition of the spent fuel.

[19] For further discussion on GIF see this link.

[20] More details on INPRO can be found here.

[21] Ellen Tauscher, "Addressing the Nuclear Fuel Cycle: Internationalizing Enrichment Services and Solving the Problem of Spent Fuel Storage," Remarks Delivered at the Hoover Institution, Stanford University, January 19, 2010, available here.

[22] The order of this section is based on the ranking in world-wide power generation—from highest ranked downwards—as represented in Figure 1 of this report.

[23] Sharon Squassoni, "Nuclear Renaissance: Is It coming? Should It?" Carnegie Endowment for International Peace report, October 2008.

[24] "Processing of Used Nuclear Fuel," World Nuclear Association website, updated March 2010.

[25] Sodium coolant reactors are not the only proposed reactor design; other liquid metal reactors are also proposed. The liquid metals have a high thermal conductivity and will not slow down neutrons as is done in LWR's which is desired for fast spectrum reactors.

[26] IAEA's Power Reactor Information System (PRIS) here.

[27] Ibid.

[28] Leonard Spector, "Letter to the Editor: The Coming Glut of Japanese Spent Fuel," Arms Control Today, April 2010.

[29] Tatsujiro Suzuki, "Japan's Plutonium Breeder Reactor and its Fuel Cycle," in Fast Breeder Reactor Programs: History and Status, a research report of the International Panel on Fissile Materials, February 2010.

[30] The PUREX technique dissolves spent fuel in nitric acid and then separates the uranium and plutonium using liquid-liquid extraction. Liquid-liquid extraction exploits the difference in solubility of plutonium in the two phases in order to separate them. The plutonium can then be recycled for use in reactors.

[31] Tadahiro Katsuta and Tatsujiro Suzuki,

"Japan's Spent Fuel and Plutonium Management Challenges," a research report of the International Panel on Fissile Materials, September 2006.

[32] Mark Hibbs, "Japan's Fuel Cycle Work to Go Unchallenged," Nuclear Fuels, September 7, 2009.

[33] Spector, April 2010.

[34] Discussions between authors and Japanese delegation, March 2010, in Washington, DC.

[35] "Nuclear Power in Japan," World Nuclear Association website, updated May 2010.

[36] "Ship with Reprocessed Nuclear Waste Arrives in Japan from UK," Kyodo News Service via BBC Worldwide Monitoring, 9 March 2010, in Lexis Nexis.

[37] "Nuclear Power in Japan," World Nuclear Association website.

[38] Katsuta and Suzuki, September 2006; and Japan Atomic Energy Commission, "Interim Report Concerning the Nuclear Fuel Cycle Policy," November 12, 2004, available here.

[39] Ibid.

[40] "Nuclear Power in Japan," WNA website; and Katsuta and Suzuki, September 2006.

[41] Ogawa and Schiffer, October 2005.

[42] Tatsujiro Suzuki, "The Fast Reactor and Its Fuel Cycle Developments in Japan: Can Japan Unlock its Development Path?" Science & Global Security, January 2009.

[43] Ibid.

[44] "Problematic 'Pluthermal' Era," Japan Times, November 11, 2009, in Lexis-Nexis.

[45] For more information see Park Seong-won, Miles A. Pomper, and Lawrence Scheinman, "The Domestic and International Politics of Spent Nuclear Fuel in South Korea: Are We Approaching Meltdown?" Academic Paper Series, Korea Economic Institute, Vol. 5, No. 3, March 2010.

[46] Based on the standard calculation for the quantity of spent nuclear fuel, capacity factor and efficiency.

[47] Seong Won Park, "Why South Korea Needs Pyroprocessing," Bulletin of the Atomic Scientists, October 26, 2009.

[48] For details see Park, Pomper, and Scheinman, pp. 3-4.

[49] The final package from the government included: providing a one-time $300 million contribution along with additional contributions of $600 per waste drum accepted (with a total potential contribution of nearly $500 million if the site reaches full capacity); relocating KHNP headquarters to the community; locating a proton accelerator and related R&D facilities in the area; and additional long-term federal support to the area.

[50] "Operation and Maintenance of Spent Fuel Storage and Transportation Casks/Containers", IAEA-TECDOC-1532, 2010, IAEA website, p 85.

[51] Minor incidents occurred in 1994 and in 1996 preparing for the transportation (see ibid, p. 87). To the best of our knowledge, no incidents happened while in transport.

[52] For further discussion of South Korea's plans for nuclear exports see David Adam Stott, "South Korea's Global Nuclear Ambitions," Japan Focus, March 22, 2010.

[53] Mycle Schneider et al., The World Nuclear Industry Status Report 2009, August 2009.

[54] Reactor numbers taken from the IAEA's Power Reactor Information System (PRIS) here. However, another source notes that the actual

number was likely less than 16. See Schneider et al., The World Nuclear Industry Status Report 2009.

[55] "Nuclear Power Goal Revised to 86 GW," China Daily, July 2, 2009.

[56] Zheng Hualing and Ye Guo'an, "The Status and Prospect of Nuclear Fuel Cycle Back–End in China," paper presented at the Atalante 2000 Conference on Scientific Research on the Back-End of the Fuel Cycle for the 21st Century, October 2000.

[57] According to one Chinese nuclear energy expert, China's nuclear industry does not "have a very good plan for dealing with spent fuel," noting further that "the nuclear interest group wants to push this technology, but they don't understand the risks for the future. They want to make money. But we scientists, we want to take a very comprehensive approach, including safety, environment, dealing with waste and other factors, and not rush into anything.'' See Howard W. French, "China Promotes Another Boom: Nuclear Power," New York Times, January 15, 2005.

[58] "China's Nuclear Fuel Cycle," World Nuclear Association website, updated March 2010.

[59] Qiang Wang, "China Needing a Cautious Approach to Nuclear Power Strategy," Energy Policy, Vol. 37 (2009).

[60] See Mark Hibbs, "Chinese Experts Continue Work Exploring Possible Repository Sites," Nuclear Fuel, August 1, 2005; Zheng and Ye, October 2000; and "China's Nuclear Fuel Cycle," World Nuclear Association website.

[61] Qiang, 2009.

[62] Mark Hibbs, "CNNC Favors Remote Site for Future Reprocessing Plant," Nuclear Fuel, April 7, 2008.

[63] Mark Hibbs, "China Plan Envisions Commercial Reprocessing in 2025," Nuclear Fuels, May 18, 2009.

[64] "China: AREVA and CGNPC sign the biggest contract ever in the history of nuclear power and enter into a long-term commitment. AREVA and CNNC strengthen their links," AREVA Press Release, November 26, 2007.

[65] Ann MacLachlan, "AREVA, China Seal Long-term Mining, Fuel Cycle Pact," Nuclear Fuel, December 3, 2007.

[66] Ann MacLachlan, "EDF, AREVA Finalize Joint Ventures with Chinese Nuclear Companies," Nucleonics Week, December 24, 2009.

[67] Tyler Hamilton, "A Chance for Nuclear Industry to Clean Up its Act," Toronto Star, January 14, 2008.

[68] Ibid.

[69] "China's Nuclear Fuel Cycle," World Nuclear Association website; see also "Expert Panel Recommends CANDU as Best Choice for China's Alternative Nuclear Fuel Program," News Release, AECL website, December 18, 2009.

[70] "Chinese CANDU Reactor Trials Uranium Reuse," World Nuclear News, March 24, 2010.

[71] Xu Mi, "Fast Reactor Technology R&D Activities in China," Nuclear Engineering and Technology, June 2007.

[72] "China Experimental Fast Reactor to Connect to Grid in 2010," People's Daily, December 12, 2008.

[73] Hui Zhang, "On China's Commercial Reprocessing Policy," paper presented at the Institute for Nuclear Materials Management 50th Annual Meeting, Tucson, Arizona, July 12-16, 2009.

[74] "Chinese Fast Reactor Nears

Commissioning," World Nuclear News, April 7, 2009; and Xu Mi, June 2007.

75 "Taiwan New Power Plant Starts Trial Operation," China Post, January 19, 2010, in Lexis Nexis.

76 Kalyan Kemburi, "A Taiwanese Nuclear Revival," Bulletin of the Atomic Scientists, March/April 2009.

77 "Spent Fuel and Plutonium in East Asia," Nuclear Control Institute website.

78 Mark Hibbs, "Long-Term Spent Fuel Dilemma at Issue in Taiwan-U.S. Renegotiation," Nuclear Fuels, June 1, 2009.

79 David Albright and Corey Gay, "Taiwan: Nuclear Nightmare Averted," Bulletin of the Atomic Scientists, Jan/Feb 1998. According to this article, the reactor transferred to Taiwan was "the same Canadian model that India used to produce plutonium for its first nuclear explosion in 1974. Canada also supplied Taiwan with U.S.-origin heavy water and 25 metric tons of natural uranium fuel rods."

80 "Lan-yu Storage Site Status," Taiwan's Atomic Energy Council website, updated February 2010.

81 Mark Hibbs, "Taiwan Rejected Chinese Offer of Fresh Fuel for Waste Disposal," Nuclear Fuel, April 20, 1998.

82 Mark Hibbs, "Taiwan to Wait on U.S.-Russian Deal Before Taking Spent Fuel Initiative," Nuclear Fuel, 9 July 2001.

83 Mark Hibbs, "Taiwan Looks to GNEP for Answers to Threatening Spent Fuel Dilemma," Nuclear Fuel, 7 May 2007.

84 Mark Hibbs, "Long-term Spent Fuel Dilemma at Issue in Taiwan-U.S. Renegotiation," 1 June 2009.

85 "Dry Storage Management in Taiwan," Taiwan's Fuel Cycle and Materials Administration website, March 15, 2010.

86 Hibbs, June 1, 2009.

87 Ibid.

88 Hibbs, May 7, 2007.

89 Mark Hibbs, "Taiwan Investigating Feasibility of French Reprocessing Option," Nuclear Fuel, February 25, 2008.

90 "International Nuclear Energy Resurgence: A Conversation With Dale Klein", Council of Foreign Relations, February 13 2009. It should be noted the that NRC licenses casks in 20 years interval.

91 Frank Von Hippel, "Spent Fuel Management in South Korea: The Illogic of Pyroprocessing," Annual Conference of the Institute of Nuclear Materials Management, Baltimore, July 11-15, 2010.

92 Under the Nuclear Nonproliferation Treaty, "recognized" NWS are China, France, Russia, the United Kingdom and the United States.

93 Miles Pomper, "The Russian Nuclear Industry: Status and Prospects," Nuclear Energy Futures Paper #3, Centre for International Governance Innovation, January 2009.

94 Russia has "take back" deals for fuel from Russian-made reactors or related to Russian-origin fuel with the Czech Republic and Bulgaria. "Чешское ОЯТ на ПО Маяк" (Czech SNF is at Mayak), Ozersk Daily, December 11, 2007; "Стоимость вывоза ОЯТ с АЭС Козлодуй в Россию возрастёт" (The cost of transporting spent nuclear fuel from Kozloduy NPP to Russia will rise), Atomic Energy.ru, February 15, 2010; and "Норвегия выбирает между Маяком и Францией для переработки партии ОЯТ" (Norway chooses between Mayak and

France for reprocessing SNF), Atomic Energy.ru, February 25, 2010.

95 The U.S.-Russian nuclear cooperation agreement was recently resubmitted to Congress by the Obama administration. See “Obama Resubmits U.S.-Russia Nuclear Energy Pact to Congress,” AFP, May 10, 2010.

96 This commission is meant “to provide recommendations for developing a safe, long-term solution to managing the Nation's used nuclear fuel and nuclear waste.” See “Secretary Chu Announces Blue Ribbon Commission on America's Nuclear Future,” U.S. Department of Energy website, January 29, 2010.

97 Harvey, May 5, 2010.

98 Aaron Stein, “U.S.-UAE Nuclear Cooperation,” Issue Brief, Nuclear Threat Initiative website, August 13, 2009.

99 The cost of the PUREX reprocessing cycle is estimated to be about $2400/kg HM according to a Japanese study which should be compared to the once-through process estimated to cost $555/kg HM. See Japan Atomic Energy Commission, “Interim Report Concerning the Nuclear Fuel Cycle Policy,” November 12, 2004, available here, and U.S. Congressional Budget Office, “Costs of Reprocessing Versus Directly Disposing of Spent Nuclear Fuel,” Statement of Peter R. Orzag before the Committee on Energy and Natural Resources, United States Senate, November 14, 2007.

100 Arjun Makhijani, "The Mythology and Messy Reality of Nuclear Reprocessing,” IEER Report, April 8 2010. The total volume of waste estimated to be placed into a geological repository, rather than decreasing, would increase by a factor of six when the thermal recycle option using an advanced aqueous process compared to the once-through option.

101 “Safe Uranium Enrichment Under International Supervision,” Germany’s Federal Foreign Office website.

102 See Anya Loukianova, “The International Uranium Enrichment Center at Angarsk: A Step Towards Assured Fuel Supply?” Issue Brief, Nuclear Threat Initiative website, October 2007 (Updated November 2008).

103 Dietrich Becker “The German Proposal for a Multilateral Enrichment Sanctuary Project,” Seventh ROK-UN Joint Conference on Disarmament and Nonproliferation, November 24-26, 2008, Jeju, Republic of Korea.

104 Thomas D. Cochran and Christopher E. Paine, “Proliferation Resistant Uranium Enrichment”, Discussion Draft (November 25, 2009); slides of presentation available here.

105 Ibid.