

# THE BIGGER PICTURE

## RETHINKING SPENT FUEL MANAGEMENT IN SOUTH KOREA



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ISBN 978-0-9892361-1-9

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Concrete storage vault for high-level radioactive waste. Name of the building is HABOG, owned by the Dutch company for the management of radioactive waste, COVRA, and is located near Vlissingen, Netherlands. The famous Einstein formula,  $E=mc^2$ , is painted in green.

# THE BIGGER PICTURE:

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FEBRUARY 2013



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Concrete storage vault for high level radioactive waste. Name of the building is HABOG, owned by the Dutch company for the management of radioactive waste, COVRA, and is located near Vlissingen, Netherlands. The famous Einstein formula  $E=mc^2$  is painted in green.



## GLOSSARY

TERM/ACRONYM	DESCRIPTION
Actinides	Elements with atomic numbers from 90-103. These are the elements which have isotopes which tend to be fissionable. Uranium/plutonium is a member of this family of elements.
ADS	Accelerator Driven Systems. Used to produce a very high-flux neutron beam to transmute materials.
AFR	Away From Reactor storage
A-KRS	This is the Advanced Korean Reference geological disposal System
AR	At Reactor storage. Often a spent fuel pool near the reactor core.
Boron	Element number 5. This element is very important in nuclear reactors because it has isotopes which easily absorb low energy neutrons.
BRC	Blue Ribbon Commission
Burnup	The total energy released per unit initial mass of fuel as a result of irradiation often quoted in megawatt days (MWd)
BWR	Boiling Water Reactor
CANDU	A Canadian type reactor which uses heavy water as moderator instead of light water
Cesium	Cesium is an element with atomic number 55. The isotope cesium-137 (Cs-137) is a long-lived (30 year half-life) radioactive contaminant in HLW.
CLAB	A central interim storage facility for spent nuclear fuel, which has been in operation in Sweden since 1985
Cladding	A protective layer surrounding the nuclear fuel usually made out of Zirconium
CoRWM	UK committee on radioactive waste management. CoRWM is a group of independent experts appointed by the British government. It is scrutinizing plans for managing UK higher activity radioactive waste now and into the future.
CISF	Centralized Interim Storage Facility
DBD	Deep Borehole Disposal
DOE	US Department of Energy
DSS	Disposal System Specifications
DUPIC	Direct Use of spent PWR fuel In CANDU reactors
EIA	Environmental Impact Assessment
Encapsulation Plant	The facility in which HLW is encapsulated before it is placed into a geological repository
ExternE	The so called "ExternE-Methodology" is an approach developed by the EU for calculating environmental external costs of energy.
Fission	The division of heavy nuclei into 2 or 3 parts with the emission of neutrons and gammas
Fission Products	The nuclei formed after fission or after these nuclei successively decay
Fuel Assembly	A group of fuel elements inside a reactor core which are placed into and taken out of a reactor core as a unit
GDF	Geologic Disposal Facility
GWd/MTHM	Unit of burnup, essentially the energy produced per unit mass uranium

HLW	High-Level Waste
IAEA	International Atomic Energy Agency
IFR	Integral Fast Reactor. The Integral fast reactor (IFR, originally Advanced Liquid-Metal Reactor) is a fast reactor (no moderator). IFR used a fuel cycle where reprocessing is done at the reactor site. A prototype was constructed but was cancelled in 1994 before it was finished.
ILW	Intermediate-Level Waste
Iodine	Element number 53. The isotope Iodine-129 is a long term environmental contaminant in a geological repository and is mobile in water.
KAERI	Korean Atomic Energy Research Institute. KAERI is the principal research institute for nuclear power in South Korea. It has a strong reputation in research and development. It is the driver for pyroprocessing in Korea.
KBS-3	A technology for HLW disposal developed by Svensk Kärnbränslehantering AB (SKB). The design has also been adopted by Finland and the Korean design is based on it.
KEPCO	Korean Electric Power Corporation
KHNP	Korea Hydro Nuclear Power Company, the nuclear energy related division of KEPCO. KHNP is responsible for operating all 23 nuclear power reactors.
KIEP-21	Korean, Innovative, Environment Friendly, and Proliferation Resistant System for the 21st Century. The system including pyroprocessing and fast reactors. The aim is to reduce 99% of the actinide elements while minimizing the amount of waste
KRMC	Korean Radioactive Waste Management Corporation
KRS	Korean Reference disposal system
KURT	KAERI Underground Research Tunnel
LILW	Lower and Intermediate Level Waste
LWR	Light Water Reactor; uses light water as a moderator
MAA	Multi-attribute analysis; techniques for complex decision making with many criteria that need to be weighed.
Minor Actinides	The actinide elements other than uranium and plutonium
MOX	Mixed Oxide fuel. These are the fuels for special reactors that use a mixture of uranium and plutonium.
mSv/year	Unit of radioactive dose per year used to measure the health effects of radiation
MYRRHA	A subcritical reactor that is cooled by lead-bismuth and is powered by an external neutron source (a particle accelerator)
NAS	National Academies of Science
NDA	Non-departmental public body of the United Kingdom formed by the Energy Act of 2004. It came into existence in late 2004, and took on its main functions on 1 April 2005. Its purpose is to deliver the decommissioning and clean-up of the UK's civil nuclear legacy in a safe and cost-effective manner, and where possible to accelerate programs of work that reduce hazard (see: <a href="http://www.nda.gov.uk/">http://www.nda.gov.uk/</a> )
NEA	OECD Nuclear Energy Agency
NIMBY	Not in My Back Yard
NIMTOO	Not in My Term of Office
NRC	Nuclear Regulatory Commission (US)



NWMO	Nuclear Waste Management Organization (Canadian)
OECD	Organization for Economic Cooperation and Development
P&T	Partition and Transmutation of nuclear fuel
Permeability	A measure of a material's ability to allow the passage of fluids
plutonium	Metal with atomic number 94. The isotope Pu-239 is important as a nuclear explosive material used in nuclear weapons but also as a potential fuel source for nuclear reactors.
PRIDE	PyROprocess Integrated inactive Demonstration. KAERI's prototype pyroprocessing facility for non-irradiated nuclear fuel.
PUREX	An acronym for Plutonium - URanium Extraction. The method was used in the Manhattan project for separating plutonium from SNF.
PWR	Pressurized Water Reactors
Pyroprocessing	A process by which plutonium is separated simultaneously with other actinides from HLW.
Pyro-SFR	An unofficial name given to the KAERI proposal to pyroprocess SNF and burn in fast reactors.
Radiotoxicity	Measure of how harmful a radionuclide is to human health.
RED-IMPACT	EU study on the Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal
Reprocessing	The chemical process of separating the plutonium from the HLW
REPU	Uranium recovered from reprocessing used nuclear fuel
Reracking	Placing fuel rod assemblies closer together in spent fuel pools
ROK	Republic of Korea
RWMA	Radioactive Waste Management Act (Korea)
SAPIERR	Pilot Initiative for European Regional Repositories
SF	Spent (nuclear) Fuel
SFR	Sodium Fast Reactor
SIMFUEL	A simulated fuel to represent irradiated fuel
SKB PASS	SKB Project on Alternative Systems Study (PASS)
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
SPAR	IAE Coordinated Research Project (CRP) on Spent Fuel Performance Assessment and Research
Strontium	Chemical element with atomic number 38. A 30 year long half-life fission product strontium-90 is important for HLW.
Subcritical	Will not sustain a chain reaction
Technetium	Element with atomic number 43. The isotope Technetium-99 (Tc-99) is a very long life-time fission product that is a main concern for HLW in a geological repository.
tHM	tons heavy metal (referring to uranium oxide fuel), a measure of spent fuel volume
Transmutation	The conversion of one chemical element or isotope into another through a nuclear reaction or radioactive decay

TRU	Transuranic waste; 90% is plutonium and about 10% minor actinides (actinides that are not uranium or plutonium).
Zircaloy	Alloys of zirconium and other metals. Zirconium is useful because it is essentially transparent in a nuclear reactor to neutrons.
ZWILAG	HLW storage site in Switzerland

## 1 EXECUTIVE SUMMARY

South Korea, currently the world's fifth-largest nuclear energy producer, is in the process of becoming a major nuclear power plant exporter. According to Seoul's current energy planning, South Korea will further increase its reliance on nuclear power in order to continue economic growth without increasing carbon emissions. Although South Korea has benefitted economically and developmentally from its active nuclear power sector, this reliance on nuclear energy over the last three decades has brought about one very negative consequence: an accumulation of spent nuclear fuel.

Although many of South Korea's reactors will likely reach their capacity for storing highly radioactive waste in their pools by the end of this decade, the ROK government has yet to designate additional capacity that would ensure continued operation of the reactors. The inability of Seoul to acquire additional storage capacity is largely a result of domestic politics—past public opposition to previous attempts to resolve the issue has left South Korea's politicians reluctant to take politically or diplomatically risky decisions to address the problem. The political issues are exacerbated by the ROK's tight population density and lack of free space for storage, which makes identifying and building a permanent repository even more complicated than in most other countries with nuclear power plants. Local populations are concerned that any interim storage facilities will indeed ultimately become permanent.

To cope with its spent fuel dilemma, South Korea has been looking at the possibility of reprocessing. Seoul's current preference is to work toward pyroprocessing, which treats spent fuel to remove its extremely radioactive, but relatively short-lived, constituents (such as strontium and cesium) and leaves behind unused uranium and the extremely long-lived “transuranic” alpha-emitters plutonium and americium in fast burner reactors (which in South Korea are still in the conceptual stage), ultimately reducing the overall quantity and heat load of waste requiring permanent storage. Currently, under the US-ROK nuclear cooperation agreement, South Korea is restricted from reprocessing spent fuel. That agreement expires in March 2014, and the two sides are in negotiations for another 40-year agreement. Seoul would like to get Washington's approval to construct new facilities to test the economic and technical feasibility of pyroprocessing and then commercially operate such facilities. U.S. officials have resisted granting this approval.

Countries such as France and Japan have used reprocessing to delay the need for the final disposition of their spent fuel and to use the existence of a reprocessing site effectively as an away-from-reactor (AFR) interim storage site. Many experts in South Korea's nuclear establishment advocate a similar course—shipping South Korea's spent fuel to a future pyroprocessing site in hopes that local residents will be willing to accept the spent fuel in return for the jobs provided by a pyroprocessing plant and associated facilities.

Such schemes may seem attractive but could fail to prove feasible. In Japan's case, for example, the country has found that it has little need for the reprocessing plant at Rokkasho. Nevertheless, the country has continued to move forward with the project to separate tons of plutonium without a clear market outlet in order to assure interim storage for its spent fuel in Aomori Prefecture. This situation has alarmed Japan's neighbors and many other states, including the United States.

Many in the international community are concerned about the proliferation of reprocessing technology since the fuel that the process yields can be used both for nuclear plants and for nuclear weapons. Pyro-

processing, South Korean officials argue, should not be considered reprocessing because the country does not plan to separate pure plutonium from the spent fuel, as is done in traditional reprocessing. Seoul further contends that pyroprocessing will not produce a product suitable for nuclear weapons and therefore should not be restricted in the same way that traditional reprocessing is. US officials disagree and consider pyroprocessing to be equivalent to reprocessing, with corresponding nonproliferation challenges.

It is important to note that both sides of the discussion continue to see pyroprocessing as in the developmental stage and do not have sufficient information to determine if it is appropriate for the larger throughput required to effectively minimize South Korea's spent fuel inventories. Currently, as part of the negotiations for the new nuclear cooperation agreement, the US and South Korea have agreed to examine ways to deal with South Korea's spent fuel challenge. The ongoing joint study, which was agreed to in 2010 and formalized in 2011, is examining pyroprocessing and the development of safe and comprehensive ways of dealing with spent fuel.<sup>1</sup> While the study is supposed to look at a wide range of "back-end" alternatives, the overwhelming emphasis has been on the technical and economic feasibility and nonproliferation suitability of pyroprocessing.<sup>2</sup> The technology sharing agreement is important for moving forward on the overall nuclear cooperation deal; however, even under the most optimistic scenario, pyroprocessing and the associated fast reactors will not be available options for dealing with South Korea's spent fuel on a large scale for several decades. Seoul will need to find other options, most urgently for managing spent fuel in the short to mid-term, but ultimately permanently, to cope with the proper management of its spent fuel or the high-level waste (HLW) that will remain after pyroprocessing.

### 1.1 Short- and Mid-Term Approaches

The building of short- to mid-term storage facilities, either at reactors or AFR locations, should be a major focus of the South Korean nuclear authorities in the immediate future. With or without pyroprocessing, South Korea will need additional storage capacity. South Korean nuclear authorities have already instituted several techniques to boost spent fuel storage capacity in existing pools. These methods include increasing fuel burn-up so such spent fuel remains in the reactor longer before entering a pool and re-racking spent fuel to more tightly pack fuel into the pools. They have also moved spent fuel within plant from older saturated (full) pools to newer reactors with more storage capacity, actions recommended by the Korean Nuclear Society.<sup>3</sup> At Wolsong, they have also built dry cask storage units for that plant's spent CANDU fuel. This report touches on some other alternatives as well. However, these techniques have their limitations, and these pools will likely reach their capacity during the 2020s. Moreover, densely packing spent fuel pools raises nuclear safety and security concerns.

The option of safely relying on dry cask storage for longer periods than previously thought possible has raised the option that this technology could be used to prolong the capacity of current South Korean facilities. Storage of spent fuel in dry casks appears to be safe and secure for decades more than originally thought and is a proven technology used at numerous sites around the world. In the 1980s the US Nuclear Regulatory Commission (NRC) estimated that spent fuel "could be stored safely for at least 30 years after a reactor's operating

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1 Yonhap New Agency, "South Korea, US agree to start joint study on nuclear fuel reprocessing," April 17, 2011.

2 Park Hyong-ki, "South Korea, US move forward on nuclear pact," *Korea Herald*, December 31, 2012.

3 Jungmin Kang, "The ROK's Nuclear Energy Development and Spent Fuel Management Plans and Options," NAPS-Net Special Report, January 22, 2013.

license expired.” That estimate was pushed further out in 1990, when the NRC stated that it was safe “30 years beyond a 40-year initial license and a 30-year license renewal period, for a total of at least 100 years.”<sup>4</sup>

Fundamentally, the obstacles to finding additional storage space are political, not technical, and could be overcome if South Korean policymakers are willing to tackle perceived political challenges. Spent fuel from South Korea’s light water reactors (LWRs) could also be stored in dry cask storage—either at current reactor sites or at a central AFR site—for 60 years or more as advocated last year by the ROK’s Atomic Energy Commission.<sup>5</sup> Furthermore, additional storage sites could be available if South Korean policymakers were willing to overcome the political obstacles against shipping fuel from a plant site in one jurisdiction to a plant site in another. Currently, political uncertainties even could block shipping fuel from parts of the Kori site to the adjacent Shin-Kori reactors located in a different jurisdiction.<sup>6</sup>

Overcoming these political obstacles will require public education and engagement by South Korea’s political and technical communities, pointing particularly to the safety and security benefits that might come from dry cask storage. Previous efforts to win public support have tended to be top-down approaches that did not involve substantial public input and explanation of relative risks and benefits. Continuing this tradition by claiming that pyroprocessing represents a technical solution to what is inherently a political problem—rather than an intriguing if still untested research program—is unlikely to be successful. Moreover, the various strands of South Korea’s spent fuel management system need to be integrated in a comprehensive approach with decisions on fuel burn-up, reactor storage, interim storage, and possible long-term solutions tied together to provide plausible paths forward, while providing South Korean policymakers and the public with the maximum decision space. By contrast, ROK policy to date has been hampered by bureaucratic infighting and constrained to an unnecessarily narrow set of choices.

## 1.2 Long-Term Storage Options

As alluded to above, South Korea is interested in reprocessing, particularly pyroprocessing, as a means of long-term spent fuel management. As part of this plan, the ROK needs to also develop reactors capable of burning the fuel created in pyroprocessing. Seoul’s current efforts build on the considerable experience that the United States has had in developing the Integral Fast Reactor (IFR). However, fast reactors, which have been under development in many countries for decades, have yet to be successfully commercialized. Part of South Korea’s push for reprocessing is the need for nuclear “sovereignty” and energy self-sufficiency. However, the development of a reprocessing capability in South Korea might not be economically feasible. The research is not at a stage where a definitive decision can be made about the viability of these techniques. Therefore, developing solutions that allow for a delay on decisions about commercial-scale reprocessing will leave South Korea’s options open and give Seoul time to optimize the research and development of various technology, as well as greater clarity for ultimate deployment of any given system.

Among the notions that could be explored is “extended storage” even beyond the many decades currently envisioned by the ROK’s Atomic Energy Commission (KAEC), the NRC, and others. Due to delays in many countries related to final disposition of spent fuel or HLW, interest has grown in possibly extend-

4 Winston & Strawn LLP, “Waste Confidence and Spent Fuel Storage Developments,” Nuclear Energy Practise Briefing, 2008. Available at: [http://www.winston.com/siteFiles/publications/Waste\\_Confidence\\_Rule.pdf](http://www.winston.com/siteFiles/publications/Waste_Confidence_Rule.pdf)

5 Kang, “The ROK’s Nuclear Energy Development,” 2013.

6 Ibid.

ing storage for periods lasting centuries or more. To be sure, this “indefinite” or extended storage concept has a number of problems in comparison to other long-term options, since safety and security are only guaranteed if continuing maintenance is assured in perpetuity—an assurance that is nearly impossible to give. However, extended storage does have its benefits. These include postponing the costly expenses of developing reprocessing or disposal sites and the political problem of siting a disposal location, while still safely storing these materials for a long period of time. This option would also allow for the continued availability of other future options, including reprocessing. In any case, the ROK would benefit from participating in research aimed at assessing the technical feasibility of extended storage.

Even without extended storage, spent fuel will need to be stored in the ROK for decades because of the cooling period required for further treatment of the fuel or because advance treatments, such as pyroprocessing, cannot be implemented on a large scale for many years. If spent fuel is to be stored for a long time, then various conditioning methods are available to reduce the volumes to be stored (and ultimately to be disposed of) and to avoid unacceptable long-term degradation of the spent fuel or its packaging. As discussed later in this report, most attention today is devoted to dry storage over a long storage period. We also examine other conditioning methods, including fuel rod consolidation in order to pack more spent fuel into a smaller volume, and metallurgical treatment of the fuel leading.

Another option reviewed for long-term disposition is partitioning and transmutation (P&T). Although P&T has not appeared cost-effective, it could be useful in a scenario that ultimately relied on a long-term disposal technique, such as geological disposal. In this scenario, P&T would reduce the quantities and alter characteristics of the waste to be included in the facility. In general, it may be worthwhile to consider methods of waste reduction as a component of future fuel cycles.

As discussed later in this report, geological disposal is currently the only recognized long-term strategy guaranteeing safety and security without continual care and maintenance. Regardless of whether the ROK opts for a strategy based on direct disposal of spent nuclear fuel or some recycling of its fuel, Seoul definitely faces the challenge of implementing a multi-year program leading to ultimate geological disposal. However, experience in numerous national programs has illustrated vividly that geological disposal is a contentious issue that can severely affect the overall public acceptance of a nuclear power program. Our report identifies the key issues that will need to be considered by the ROK in establishing a geological disposal program.

One broad question on geological disposal is whether to employ a mined geological repository or deep borehole disposal (DBD). Mined geological repositories are underground in stable geological formations and include engineered and natural barriers like rock, salt, or clay. DBD involves emplacement of waste packages in the bottom sections of deep boreholes constructed to depths of several kilometers, with the upper kilometers of the holes not used for disposal, but backfilled and sealed. Relying on a mined repository would take advantage of the fact that it is by far the more established technology, with decades of research conducted by numerous countries around the world. South Korea’s program ultimately envisions such a repository. Compared to conventional mined geological repositories, however, DBD reduces the need for specific types of geology because the depth is much greater in the borehole. Ultimately, DBD would minimize the chances that radioactive materials would be in contact with the outside world. Recent studies have demonstrated that even in boreholes where the sealing was substantially degraded, the maximum dose after 10,000 years was 10,000 times lower than the natural radioactivity expected per year at surface. Therefore, radionuclide releases are extremely small, and thus the DBD concept should be



regarded as a viable alternative to the mined repository concept. However, at this point, DBD is more expensive and will likely stay so until advances in drilling and emplacement technologies occur. One critical question for South Korean policymakers in this regard is whether they want materials in the repository to be retrievable, something that is not really possible for DBD, but still an option with a mined repository.

One of the main tasks when looking at geological disposal is choosing the type of system that best fits the available/appropriate site. Generally, finding a suitable and acceptable site for a GDF is the most difficult aspect of the whole program. It is important for the GD program to maintain a flexible approach to design before a site or geological environment is identified and to begin public discussion about the need and nature of such a site as early as possible.

### 1.3 Recommendations

Based on the research undertaken for this report, CNS can put forth a number of recommendations for national approaches to spent fuel disposition in South Korea. In general, this report has not focused on areas where international cooperation and multinational approaches could be considered, given the additional complexity and challenges involved in such an undertaking. However, options that bring in other partners that aim to deal with this issue on a cooperative basis should not be overlooked.

#### *1.3.1 Short- to Mid-Term Approaches*

- Educate communities near current reactor sites about the safety and security benefits of dry cask storage. Tie interim storage to the lifetime of a reactor by promising to leave no “stranded fuel” when a plant site stops operating.
- Explore further the option of transferring spent fuel from older to newer reactor ponds, including to sites outside the original reactor’s jurisdiction, which could extend current storage capacity for several decades.
- Carry out a more comprehensive 10-year “back-end” study with the United States on new approaches to spent fuel disposition. These new approaches would, aside from pyroprocessing, focus on issues such as research and development on fast reactors, disposal and storage options like DBD and extended storage, and discussions of possibilities for multilateral facilities in or outside of ROK.
- Estimate storage requirements over the next two to three decades, openly recognizing that capacity must be provided, and initiate a campaign with public and political interactions to find suitable volunteer sites.
- Explore the creation of a centralized interim storage facility (CISF) and assess which type of storage—wet or dry—is most appropriate for a subsequent move to interim storage. Consider tying the winning bid for the next nuclear power plant site to a community’s willingness to host a CISF or at least accept spent fuel from other sites.
- Identify potential geological deposit sites that could be developed for long-term disposal.
- Study the implications of different fuel cycle strategies on the timing and the technology needed

for final repository implementation as a key decision aid for future policies.

- Undertake an active engagement program with communities considered appropriate for hosting storage facilities. Brief these populations on the benefits of dry cask and other relevant storage systems. South Korea's focus should be on gaining popular support for spent fuel endeavors and making sure that the process is transparent.

### *1.3.2. Long-Term Approaches*

- South Korea should keep open a range of options for long-term management of spent nuclear fuel, either nationally or through a foreign service provider.
- Develop and publicize a national strategy and accompanying roadmap, leading credibly after several decades to a national repository, should no other viable options be developed in the intervening period. Although South Korea's current preferred strategy is pyroprocessing, it should be acknowledged that, for this strategy too, a final disposal solution in a geological repository will be needed.
- "Indefinite" storage, or 100-plus year storage, cannot be the ultimate goal and a storage siting initiative should be clearly labeled as being for interim storage, implying that credible strategies for further treatment or disposal of the spent fuel must also be developed and publicized. The ROK is encouraged to collaborate with other countries pursuing research in DBD, including research related to pilot testing of practical boreholes, waste package handling methodologies and technologies, borehole sealing and drilling, development of safety assessment scenario analysis, and the development of technical requirements for a DBD program.
- Options for GDF geological environments and for facility design should be developed, but without premature focus on preferred solutions, given the long timescales involved. A broad survey of South Korean geology could help enhance public trust that a final disposal solution is technically feasible within the ROK.

## 2 INTRODUCTION: SOUTH KOREA'S APPROACH TO SPENT FUEL

### 2.1 General Description of the Back-End of the Fuel Cycle

Nuclear fuel fissioned in a typical light water reactor (LWR) generates spent nuclear fuel (SNF) with extremely high levels of radioactivity. A standard LWR discharges 20 tons of SNF annually<sup>7</sup> in the form of fuel assemblies (the unit of fuel of which the reactor core is composed) which are placed in special racks and submerged under water to shield personnel from the radioactivity and to cool the fuel. SNF customarily stays in the cooling pool for 5-10 years.

The water in the cooling pool must be continually recycled to prevent the water from evaporating; if water levels become too low, the fuel assemblies will be damaged, resulting in the release of radionuclides into the environment. After 10 years of cooling in water, the radioactivity of the fuel has been decayed and reduced by a factor of 1000. At this point the spent fuel is still highly radioactive but will not be damaged by its own internal heat if it is not being cooled in a cooling pond. Therefore, operators have the option of transferring the spent fuel out of the pools to “dry cask storage,” where it can be cooled using air flow instead of water, freeing up space in the pond for new spent fuel. Once the SNF has been cooled for several decades, much of it must ultimately be disposed of in a place where it cannot interact with humans for at least 100,000 years in order to avoid posing health risks.

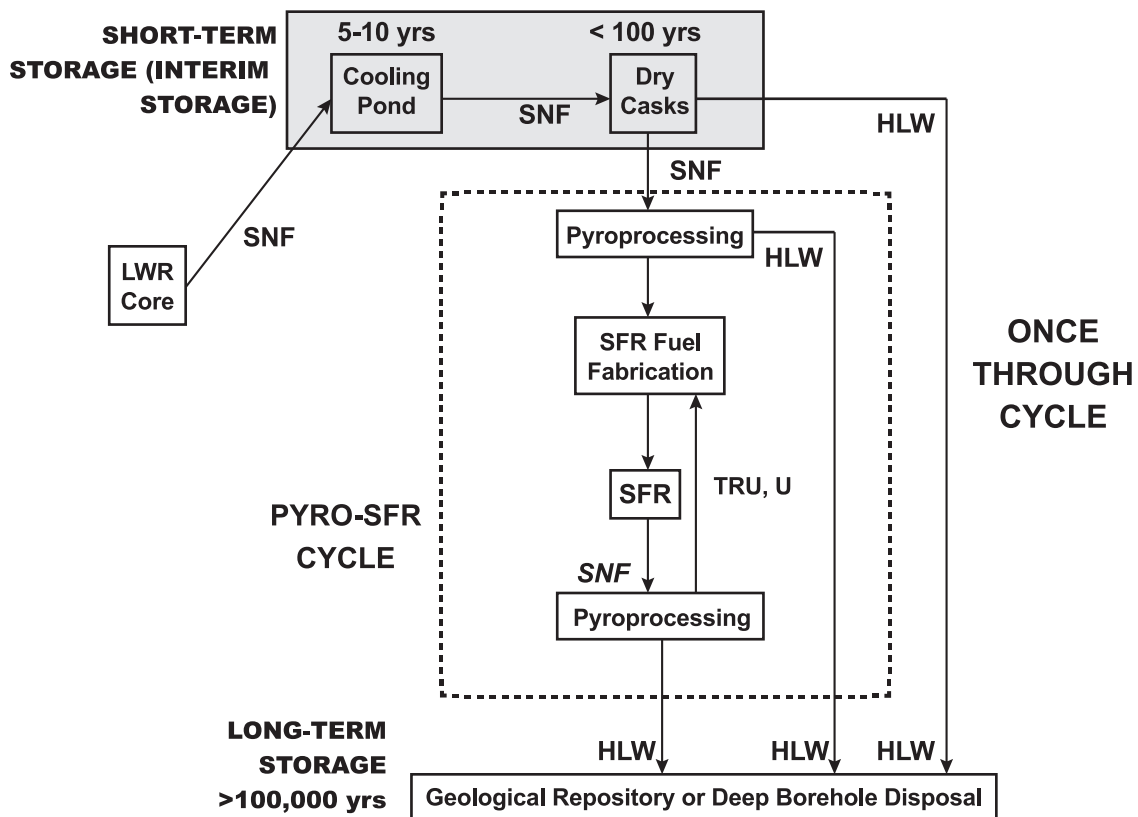
However, spent fuel contains not only several isotopes that can be used as fuel, but also nearly all of the original uranium.<sup>8</sup> Some experts believe that a portion of the fuel should be reused in other nuclear reactors, reducing the amount of waste that will need to be placed in long-term geological storage. Nuclear enterprises or governments can therefore choose to add an additional step to the fuel cycle—a step known as reprocessing—in which the fuel is processed (or recycled) to extract these valuable isotopes and reuse them in reactors as fuel. Alternatively, fuel can be disposed directly into a geologically isolated place—known as the once-through cycle.

Reprocessing can be done in two ways. Plutonium, which is composed mainly of the isotopes plutonium-239 and plutonium-240, can be chemically retrieved from the fuel and re-fabricated for use in ordinary LWRs. Several countries, including France, use spent fuel in this way, as discussed in the next chapter (see Table 6). Alternatively, using an experimental technique known as pyroprocessing, also called Pyro-SFR, plutonium can be separated along with other isotopes and reused in a fleet of dedicated reactors called sodium fast reactors (SFRs). In South Korea, this method has been advocated by some in the nuclear sector to lessen the volume of waste for long-term storage. With both methods of reprocessing, the handling and maintenance of the fuel, and in the construction of specialized reactors that can use the fuel pose environmental and proliferation risks. However, regardless of whether fuel is reprocessed, ultimate disposal of spent fuel or the waste from reprocessing it needs to occur in a geologically isolated place. These sites could include specially constructed underground caves known as geological repositories, or kilometers-

7 See Harold Feiveson, Zia Mian, M.V. Ramana and Frank von Hippel, eds., *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World*, International Panel on Fissile Material, September 2011, [http://fissilematerials.org/library/2011/09/managing\\_spent\\_fuel\\_from\\_nucle.html](http://fissilematerials.org/library/2011/09/managing_spent_fuel_from_nucle.html). As noted in the report, this calculation is based on the assumption of a 1 GWe reactor operating at 90 percent capacity.

8 These useful isotopes are called “fissile,” meaning that the isotope can sustain a chain reaction, which is the principal purpose of the fuel in a nuclear reactor.

deep holes known as deep borehole disposal (DBD). (Both short- and long-term options for disposal are discussed later in dedicated sections in the next two chapters.) The Pyro-SFR cycle before disposal and the once-through cycle are summarized in Figure 1.



**Figure 1:** Flow of materials for two methods of handling spent fuel. The once-through cycle is where the spent fuel is disposed of through long-term storage in a geologically isolated place immediately after interim storage in dry casks. The Pyro-SFR cycle has an additional step that recycles portions of the spent fuel and uses it as fuel in nuclear reactors. Note that HLW (high level waste) refers to highly radioactive waste such as spent nuclear fuel, and TRU corresponds to the transuranium actinides such as plutonium, americium etc.<sup>9</sup>

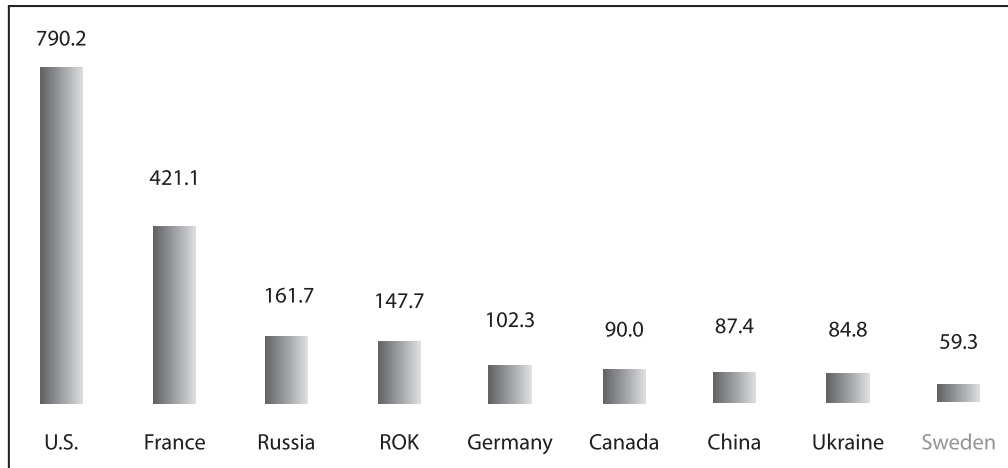
## 2.2 ROK Nuclear Energy and Accumulation of Spent Nuclear Fuel

Korea utilizes 23 nuclear power reactors, which generated 147.6 terrawatt-hours of electricity in 2011, corresponding to about one-third of the country’s total electricity production. South Korea’s nuclear energy production only slightly trails that of Russia, although its output still falls considerably behind that of world leaders the United States and France. (See Figure 2.)

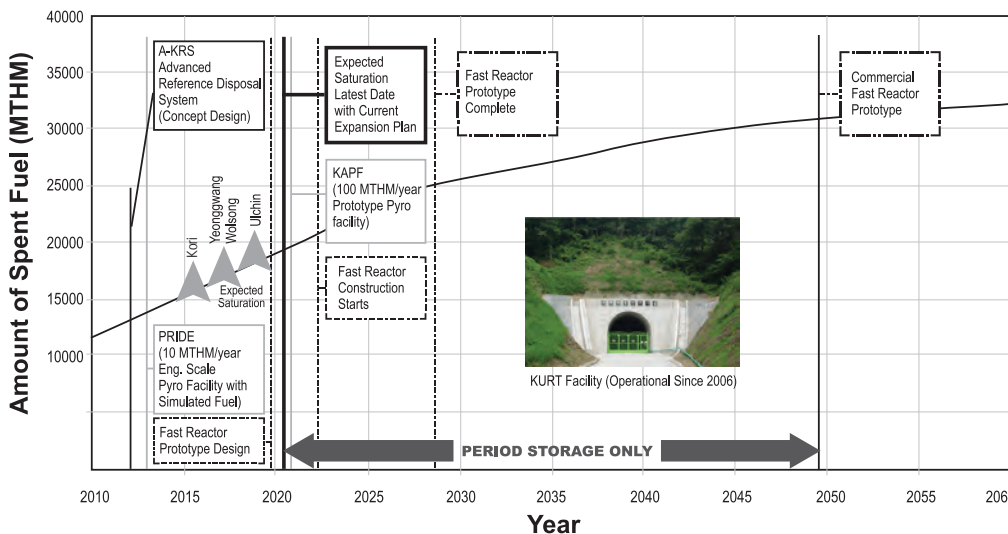
According to the 2008 National Energy Basic Plan, South Korea’s nuclear authority plans to increase nuclear energy’s share of electricity generation to 59 percent by 2030, with plans for building roughly 13 more nu-

<sup>9</sup> Adapted from Figure 1 in Fanxing Gao and Won Il Ko, “Dynamic Analysis of a Pyroprocessing Coupled SFR Fuel Recycling,” *Science and Technology of Nuclear Installations* 12 (2012), <http://www.hindawi.com/journals/stni/2012/390758/>.

clear reactors and four power plants already under construction.<sup>10</sup> South Korea's spent fuel had already reached 10,761 tons at the start of 2010, which is 79 percent of the ROK's total storage capacity. It is expected that the Kori, Ulchin, and Yonggwang nuclear sites will all near their capacity within this decade if no further changes are made. (See Figure 3 for the projected accumulation of spent fuel as a function of time for the three NPP sites. Also shown are the dates for expected milestones for the ROK to have a Pyro-SFR cycle.)<sup>11</sup>



**Figure 2:** Nuclear energy production in top 10 nuclear energy generating countries. (2011) (Billion kWh). Adapted from the Nuclear Energy Institute with Original source of data: IAEA and Energy Information Administration. (<http://www.nei.org/resourcesandstats/documentlibrary/reliableandaffordableenergy/graphicsandcharts/top10nuclegeneratingcountries/>).



**Figure 3:** Spent Nuclear Fuel (SNF) Accumulation in South Korea vs. Spent Fuel Management Options. The graph estimates the quantity of SNF accumulated as a function of time in conjunction with predicted milestones. Also shown as an inset in bottom right is the entrance to the underground laboratory dedicated to investigating site characterization and construction of a future HLW repository.<sup>12</sup>

10 Korean Ministry of Knowledge Economy, "National Energy Basic Plan," Press Release, August 28, 2008. Full text available in Korean at [http://www.naenc.go.kr/sub\\_04/sub04\\_02\\_view.asp?page=1&bNo=87&keyfield=&key=](http://www.naenc.go.kr/sub_04/sub04_02_view.asp?page=1&bNo=87&keyfield=&key=).

11 Kang, "The ROK's Nuclear Energy Development," 2013. This is further discussed in section 3.2.

12 The saturation dates are taken from S. K. Kim, et al., "The economic effects of the deferred disposal of spent fuel in Korea," *Progress in Nuclear Energy* 59 (2012):12-18. Fast Reactor dates are taken from M. Y. Yang, "Korean Strategy for Sustainable Nuclear Energy Development," Presented August 27, 2012 at 2012 International Pyroprocessing Research

The South Korean government has instituted several techniques to delay its spent fuel storage 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.”<sup>13</sup> While there have been difficulties with transshipments between sites because of the transportation hardware,<sup>14</sup> these efforts should allow more time to develop a permanent solution. However, these techniques have their limitations, and the country’s spent fuel pools will likely reach their capacity during the 2020s. Moreover, densely packing spent fuel pools raises nuclear safety and security concerns.

South Korea’s Atomic Energy Commission has indicated that it will search for an interim storage site, beginning in 2024. Previous South Korean attempts to find a site for such a facility, however, have foundered over political protests. Public opposition to previous attempts to resolve the nuclear waste issue resulted in the current reluctance of South Korea’s politicians to take politically or diplomatically risky decisions to address the problem. The political issues are exacerbated by the ROK’s tight population density and lack of free space; moreover, local populations are concerned that any interim storage facilities will ultimately become permanent. This situation makes identifying a site and building a permanent repository even more complicated than in most other countries with nuclear power plants.

### 2.3 The Politics of Nuclear Energy and Spent Fuel in the ROK

The national discussion of nuclear energy, and with it nuclear waste disposal, has often been a tricky political problem in South Korea. Most recently, during the presidential campaign in South Korea, the ultimate winner Park Geun-Hye promised to review the country’s long-term energy plan and noted at one point that she did not necessarily support further building of new reactors.<sup>15</sup> Despite this apparent skepticism from candidate Park, there are voices within her inner circle that still strongly support the country’s current nuclear plans and have expressed support for South Korea maintaining its nuclear “sovereignty.” Since her election, Park has shown little interest in making major changes to the previous administration’s nuclear energy plans. The policy documents released by the president-elect on energy and the environment appear to show no major divergence from what was set forth in the 2008 National Energy Basic Plan.

The current ROK nuclear policy may, however, be affected by concerns about nuclear safety. The 2011 accident at Fukushima, Japan, led to increased scrutiny of the pace that South Korea was building nuclear plants. Soon after the accident, for instance, construction on the country’s fifth nuclear plant was suspended pending safety reviews. Concerns about the safety of nuclear energy in South Korea were further heightened by the discovery of major violations at the nuclear plant in Yeonggwang.<sup>16</sup> In late 2012, inspectors found microscopic cracks in the structure of the plant and the forgery of quality certificates, leading to the shutdown of two of the reactors at that facility. According to South Korean officials, in the last

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Conference Presentation. The latest version of the Korean Reference Spent Fuel Disposal Repository for the case that fuel is recycled using pyroprocessing is known as A-KRS. It is the authors’ understanding that research on the original KRS (Jongyoul Lee et al., “Concept of a Korean Reference Disposal System for Spent Fuels,” *Journal of Nuclear Science and Technology*, 44:12, 1565-1573) is no longer continuing. See OECD-NEA, “Radioactive Waste Management in Rep. of Korea,” OECD 2012 Report, [www.oecd-nea.org/rwm/profiles/Korea\\_report\\_web.pdf](http://www.oecd-nea.org/rwm/profiles/Korea_report_web.pdf).

13 IAEA, “Operation and Maintenance of Spent Fuel Storage and Transportation Casks/Containers,” IAEA-TEC-DOC-1532, 2010, 85.

14 Minor incidents occurred in 1994 and in 1996 preparing for transportation (see *Ibid.*, 87); to the best of our knowledge, no incidents happened while in transport.

15 Charles Lee, “South Korea’s nuclear energy strategy may change following election,” *Nucleonics Week*, November 29, 2012.

16 Donald Kirk, “Cracks at South Korean nuclear plant raise safety concerns,” *Christian Science Monitor*, November 9, 2012.



decade 60 quality certificates were forged on more than 7,600 components. Although officials stressed that these items were “noncore” parts and posed no risk of radiation leakage, concerns about the level of corruption and lack of oversight in the nuclear industry prompted calls for closing plants and halting progress on future plants, at least until safety concerns could be addressed.

In the current political climate, South Korea is likely to see a continued slowdown in the rate of nuclear power generation over the next few years as plants that are currently online temporarily shut down for additional safety checks. Proposed plants will also have their construction start dates pushed back in the short term as greater scrutiny is given to safety considerations in their designs. If the current concern about safety continues to slow down the overall growth in nuclear power generation in South Korea, then the volume of spent fuel that needs to be handled may decrease over the long term; however, the impact at this point is hard to predict.

Based on the current energy plan, and assuming no long-term shut down of South Korea’s nuclear plants, by the end of the century 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 at 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. Finding that much free space in South Korea, the country’s nuclear planners argue, would be enormously difficult, given its population density of 500 people per square kilometer.<sup>17</sup>

## 2.4 The ROK’s Current Nuclear Waste and Spent Fuel Policy

The problem of spent fuel disposition is not a new one; Seoul has been trying to tackle the issue since its first nuclear plant began operating in 1978, when Park Chung-hee, the current president-elect’s father, was in power. However, during that time Seoul saw the siting of a geological disposal facility as something on which it had decades to decide, and therefore South Korean authorities focused primarily on the disposal of low- and intermediate-level nuclear wastes (LILW) and locations for away-from-reactor (AFR) sites for an interim storage facility for spent nuclear fuel.<sup>18</sup>

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 ultimately prove very useful in other countries like Germany and is easier to manage at reactor sites—had not been widely adopted. South Korea chose instead to utilize water-filled pools for its spent fuel. Seoul reasoned that if spent fuel rods were to continue to be housed in such pools after they had cooled, locating them in a single facility would make sense. 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.

17 Seong Won Park, “Why South Korea Needs Pyroprocessing,” *Bulletin of the Atomic Scientists*, October 26, 2009, <http://www.thebulletin.org/web-edition/op-eds/why-south-korea-needs-pyroprocessing>.

18 In South Korea, the Ministry of Education, Science, and Technology decides what qualifies as high-level nuclear waste based on the concentration of radioactivity and heat production rate; low- and intermediate-level nuclear wastes are classified as all nuclear waste below these thresholds. High-level waste is defined as that with a radioactivity concentration of 4,000 Bq/g which emits alpha rays with a half-life of 20 years or more and a heat production rate of 2kw/m<sup>3</sup>. Typically, for example, spent nuclear power plant fuel qualifies as high-level waste, while certain medical waste is classified as lower level waste.

Seoul developed these policies, however, without a great deal of public input, and subsequent attempts to locate a site for centralized facilities were repeatedly bogged down amid public opposition.<sup>19</sup> In 1996, the government decided to split responsibilities for dealing with nuclear waste. It charged the electrical utility Korean Electric Power Corporation (KEPCO) with finding a site for low- and intermediate-level wastes and an interim spent fuel storage facility; in 2001 this responsibility was transferred to Korea Hydro and Nuclear Power (KHNP), a subsidiary of KEPCO and later to the Korean Radioactive Waste Management Corporation (KRMC).<sup>20</sup> KAERI, in turn, was asked to focus on researching technology for ultimate disposition of spent fuel, with the key decisions put off to a later date. The current relationship of these agencies and responsibilities is shown in Figure 4.

This bureaucratic change, however, had little impact on public sentiment about where these facilities should be housed, and South Korean authorities consistently had difficulties convincing communities to host the facilities. In an effort to convince the communities, the government took a new approach starting in 2005, which offered very generous incentives and helped secure a two-square kilometer site for LILW in Gyeongju, a city in the southeastern part of the country. Under the deal, Seoul was able to begin construction of the facility in 2007, which is estimated to cost \$2 billion at its initial capacity of 100,000 drums and considerably more if it reaches its full capacity of 800,000 drums. The incentives used by the South Korean government to convince Gyeongju to host the LILW facility 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 same community;
- Locating a proton accelerator and related R&D facilities in the area; and
- Additional long-term federal support to the area.

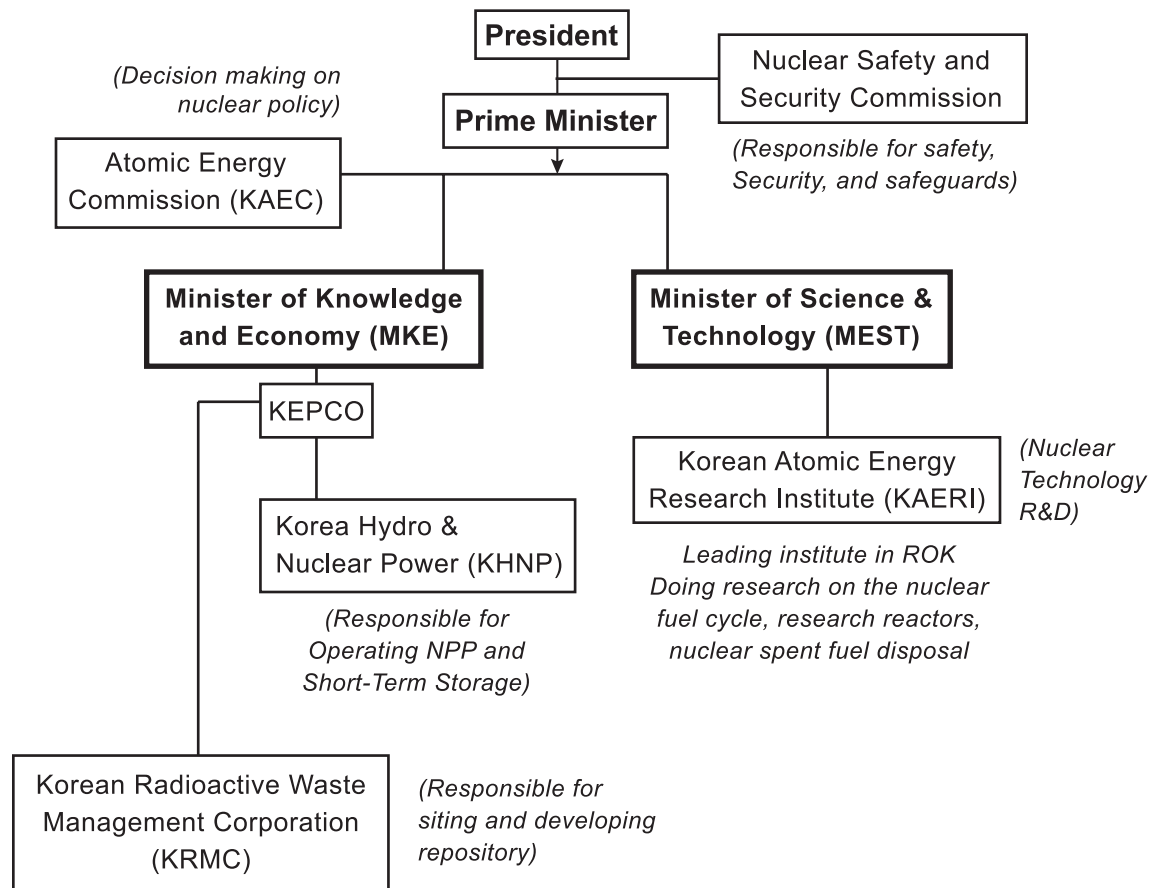
However, this positive step for the storage of LILW has done little to move forward plans for siting of storage of spent fuel facilities. The new approach specifically does not tackle the most dangerous waste and, in fact, the 2005 law passed by Seoul to secure the Gyeongju agreement pledged that no spent fuel storage facilities would be located in an area that would host the LILW. Some South Korean nuclear experts have argued that these restrictions mean that no more dry cask storage can be built at the site after current casks are filled in 2017. But, as noted by Jungmin Kang, “KRMC argues that those dry storage facilities at Wolsong are ‘tentative’ ones, not the types of ‘interim’ storage that are banned by the 2005 Special Act of LILW.” The difference, KRMC argues, is that tentative storage falls under control of KHNP while interim falls under KRMC.<sup>21</sup>

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19 For details 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?*, KEI Academic Papers Series 5, 3 (2010): 3-4.

20 Several years later, Seoul again shifted responsibility for this aspect of handling spent fuel to a new Korea Radioactive Waste Management Corporation. This organization handles the storage, treatment and disposal of radioactive waste, site selection, construction, and eventual closing and decommissioning of a radioactive waste management facility. Costs are paid through user fees. For more information, see Nuclear Energy Agency, “Radioactive Waste Management in the Republic of Korea,” *Radioactive Waste Management Country Profiles* (2012), available at [http://www.nea.fr/rwm/profiles/Korea\\_report\\_web.pdf](http://www.nea.fr/rwm/profiles/Korea_report_web.pdf).

21 Kang, “The ROK’s Nuclear Energy Development,” 2013.



**Figure 4:** Organizational structure of agencies relevant to nuclear policy and spent fuel management in the ROK. KEPCO’s subsidiary KHNP is responsible for managing the spent fuel at the reactor site (short-term storage), while the KRMC is responsible for siting a repository and final disposal. KAERI, as the premier nuclear research institute in the ROK, is responsible for developing the technologies for building research reactors, advanced fuel cycle concepts and long-term storage.<sup>22</sup> Note that at the time of writing, the Park Geun-Hye administration transition team was apparently discussing a new nuclear organizational structure, but those decisions have yet to be finalized.

Building trust within communities about longer-term storage of more dangerous waste, including spent fuel, is likely to be even more difficult than for LILW storage. Public support for nuclear power has plummeted over the last couple of years—from 71 percent in January 2010 to about 35 percent at the end of 2012.<sup>23</sup> Despite this opposition, the South Korean government will need to find a way to build sufficient trust with local populations in order to move forward with site selection for both interim and permanent storage facilities. South Korean authorities will need to focus on the issue of nuclear safety, particularly in light of the recent violations at Yeonggwang. Any outreach will need to inform prospective communities about safety standards within these facilities and include certain financial incentives.

Communities in South Korea that are seen as potential sites for storage facilities are likely to agree only if the positive benefits are clearly communicated to them. Apart from financial incentives, the jobs that such plants would provide can benefit the area. Many in these areas remain concerned, however, that their communities could be “dumps” for nuclear waste if a permanent back-end solution is not found. This

<sup>22</sup> Adapted from OECD-NEA, “Radioactive Waste Management in Rep. of Korea.”

<sup>23</sup> Park Si-soo, “Gov’t to overhaul nuclear policies,” *Korea Times*, January 8, 2013.

tension is strongest at Wolsong, which already houses the country's low- and intermediate-level waste (LILW) disposal site. On the other hand, these communities have received little information about dry cask storage and the safety advantages it provides over current practices of closely packed spent fuel pools. One approach to focus on in the short term would be to convince communities with existing power plants that interim storage at reactor sites is safe. If these issues and the possible benefits are properly explained, these communities might be convinced to allow interim storage at reactor sites, at least until the reactors are decommissioned—which in most cases would be no earlier than the 2040s, and more likely the 2060s at the Yonggwang site, given the current tendency in South Korea to extend plants for a 60-year lifetime.

In short, no solution has been found for dealing with South Korea's spent fuel and high-level waste. Considering the price paid for the LILW facility, South Korea's leaders are naturally worried about the potential cost of finding a final disposal site for more highly radioactive material. The more dangerous waste would require 30-40 times more space than the facility in Gyeongju. For this reason, Seoul also continues to seek other alternatives for spent fuel disposition, such as reprocessing spent nuclear fuel.

## 2.5 The ROK's Interest in Reprocessing

Over the past 40 years South Korea has shown a consistent interest in reprocessing, although its motivations and the type of technology it has pursued have changed over time. Seoul's interest in reprocessing was first stimulated by views then popular in the global community that the world would see the emergence of a nuclear energy economy anchored in plutonium breeder reactors. These reactors would require the reprocessing of conventional reactor spent fuel to provide the mixed plutonium-uranium fuel that would be used in the breeder units.

In the early 1970s, South Korea sought to purchase reprocessing technology, eventually reaching an agreement to buy a small-scale reprocessing plant from France. This initial effort was halted, however, after the 1974 Indian "peaceful" nuclear test prompted the United States and others to change their previous policies and instead view the spread of reprocessing technologies as detrimental to overall nonproliferation and international security goals. South Korea's particular quest for this technology was further thwarted when it became clear that the then-military government in Seoul was actually planning to develop nuclear weapons or, at least, acquire the technology and capability to do so on short notice. Park Geun-Hye's father, Park Chung-hee, backed away from his effort to establish a domestic nuclear weapons capability only after the United States threatened to withdraw its security guarantees if Seoul did not halt its weapons development plans.<sup>24</sup>

Seoul's desire for reprocessing did not end, however, and concerns about national security continued to play a major role in South Korea's efforts to secure this technology. In the 1970s, as the aftermath of the Vietnam War appeared to be threatening Washington's role in Asia, Seoul became increasingly concerned about US plans to draw down its military presence in South Korea, notwithstanding the divided status of the Korean peninsula and continuing tension between North and South Korea at the time. After Jimmy Carter announced in the late 1970s that the United States intended to withdraw all ground troops from the peninsula by the early 1980s, Seoul renewed its efforts to acquire a reprocessing facility from France. Once again, Seoul's pursuit of reprocessing technology was thwarted by Carter's personal intervention

24 Fred McGoldrick, "The Peaceful Nuclear Program of the Republic of Korea and Global Nonproliferation Considerations," paper prepared for CEIP-KAERI-IPC joint seminar on ROK-U.S. Nuclear Cooperation in the 21st Century, July 14, 2008, Carnegie Endowment for International Peace, Washington, D.C., 5–6.

with the French prime minister and his nearly simultaneous decision to halt the withdrawal of US forces from the Korean peninsula.<sup>25</sup>

More recently, South Korea's desire for reprocessing has been in some part rooted in its plans to increase its marketability as a nuclear supplier. In 2010, South Korea beat out leading US 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. After that deal was announced, the Ministry of Knowledge Economy (MKE) proclaimed the South Korean nuclear sector's goals of exporting 80 reactors by 2030 and claiming 20 percent of the world market for nuclear reactors by 2030. Reaching these goals would make South Korea the world's third-largest nuclear supplier. Following the UAE deal, South Korea signed an agreement to construct a nuclear research reactor at the Jordan University of Science and Technology.<sup>26</sup> Seoul has further targeted nuclear newcomers in Southeast Asia, as well as countries like South Africa and Turkey.

## 2.6 Option of Pyroprocessing and Fast Reactors as the Default Mode

The ROK's increased focus on nuclear exports has further pushed its quest for access to reprocessing technology. South Korean officials claim that having the complete fuel cycle (including enrichment and reprocessing) would allow them to provide customers with the full range of services for fueling their reactors and disposing of the spent fuel, making the country a more competitive exporter. South Korea's nuclear industry fears being squeezed out of the global marketplace, sandwiched between competition from lower-cost suppliers in countries like China and India which have complete fuel cycles, and more expensive but longstanding full-service companies from Russia and France.

Keeping in mind the economic importance of nuclear exports, South Korea's interest in reprocessing—particularly pyroprocessing—is primarily a factor of the country's current inability to solve its spent fuel management problem. In December 2008, the Korea Atomic Energy Commission (KAEC), the country's top nuclear policymaking body chaired by the prime minister, called for an investigation into the possibility of using pyroprocessing to treat spent nuclear fuel, with the resulting product to be burned in new fast burner reactors. The plan 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, KRMC was tasked to scout for locations for interim spent fuel storage both at and away from reactor sites.

As discussed above, pyroprocessing treats spent fuel to remove its extremely radioactive, but relatively short-lived, constituents (such as strontium and cesium) and leaves behind unused uranium and the extremely long-lived “transuranic” alpha-emitters plutonium, americium, and neptunium (see Table 6 in Appendix B). These materials would then be burned in fast burner reactors, ultimately reducing the overall quantity of waste requiring permanent sequestration.

Seoul contends that pyroprocessing, a technique pioneered by US national laboratories, does not yield a product suitable for nuclear weapons and should not be restricted in the same way that traditional reprocessing is. In particular, officials from KAERI argue that pyroprocessing should not even be considered reprocessing

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25 Ibid.

26 “Jordan: Seoul to Help Jordan with Nuclear Infrastructure,” *Tenders Info*, April 21, 2010, and Taylor Luck, “Jordan and South Korea Sign Deal on Nuclear Research Reactor,” *Jordan News Agency*, July 26, 2010.



because South Korea does not plan to separate pure plutonium from spent fuel, as is done in traditional reprocessing, but to leave it mixed with other transuranic elements.

Many US officials and nonproliferation experts disagree with this assessment. They note that pyroprocessing provides only a “modest improvement in reducing the proliferation risk” and that a state aiming to separate out the plutonium to produce nuclear weapons would need a short timeframe to do so.<sup>27</sup> US officials also believe that instituting safeguards to prevent future diversion of sensitive materials would be too difficult; concerns remain that any relaxation of US rules on this issue would harm Washington’s global and regional nonproliferation efforts.<sup>28</sup>

The US-ROK nuclear agreement, which expires in 2014, does not allow South Korea to reprocess spent fuel. As the two sides negotiate a new agreement, Seoul hopes Washington will ease the restrictions. As part of the current negotiations for the new nuclear cooperation agreement, the US and South Korea have agreed to examine ways to deal with South Korea’s spent fuel challenge. An ongoing joint study, which was agreed to in 2010 and formalized in 2011, is analyzing pyroprocessing and the development of safe and comprehensive ways of dealing with spent fuel.<sup>29</sup> While the study is supposed to consider a wide range of “back end” alternatives, overwhelming emphasis has been placed on the technical and economic feasibility and nonproliferation suitability of pyroprocessing.<sup>30</sup> The technology-sharing agreement is important for moving forward on the overall nuclear cooperation deal; however, even in the most optimistic scenario, pyroprocessing and the associated fast reactors will not be an available option for dealing with South Korea’s spent fuel on a large scale for several decades.

Despite the on-going debate, the discussion of pyroprocessing remains somewhat premature; both Seoul and Washington acknowledge that they lack sufficient information to determine whether pyroprocessing, which is only now being tested on an engineering scale, makes technical or economic sense at the industrial scale. Higher industrial-scale throughput levels would be required if pyroprocessing were to be used for minimizing South Korea’s growing stockpile of spent fuel. The two sides agreed to a study at the end of 2010 to evaluate the technical, economic, and nonproliferation feasibility of the process. This study is ongoing, and the renewal of the full cooperation agreement due in 2014 should, at least at first, not need to focus on decisions about full-scale pyroprocessing facilities.

Even though the feasibility of the process is still unclear, the South Korean government remains eager to embed US support for pyroprocessing in the 2014 agreement. However, without such support, South Korean nuclear authorities fear they will be unable to win over local communities and the National Assembly for building interim storage facilities that in almost any scenario, will need to be constructed in the coming decades—both at reactor facilities and AFR sites. Some South Korean officials also claim that with no movement toward pyroprocessing, it will be difficult to win support for shipping spent fuel from older reactors to newly built reactor sites where more storage would be available. Additionally, as the current agreement requires any research involving separation of actual spent fuel to occur on US territory, South Korean researchers are eager to gain more control over the process.

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27 Robert Bari et al., “Proliferation Risk Reduction Study of Alternative Spent Fuel Processing Technologies,” Brookhaven National Laboratory Report, BNL-90264-2009-CP (2009). Further details are in section 4.1.9.

28 Interview with a senior U.S. government official, August 23, 2010. U.S. officials also believe that limitations on reprocessing under the 1978 Nuclear Nonproliferation Act and the North-South denuclearization agreement apply to pyroprocessing.

29 Yonhap New Agency, “South Korea, US agree,” 2011.

30 Park, “South Korea, US move forward,” 2012.



## 2.7 Proposed National Alternatives to the Current ROK Spent Fuel Policy

The solution to nuclear fuel accumulation is inherently technical; a group of experts who understand the technical issues and the associated quantitative risks for specific solutions make decisions based on a cost-benefit analysis. However, any solution must also incorporate the views of the public (with consideration for intergenerational equity and perceived risk), since public dissatisfaction leads to low social acceptability—the not-in-my-backyard (NIMBY) and not-in-my-term-of-office (NIMTOO) sentiments—and ultimately to decision-makers delaying the process further. The ROK has tried to investigate the siting of a geological repository numerous times to no avail, leading to societal mistrust and even to violence and further delay of decisions. South Korea officially has a “wait-and-see approach” for spent fuel management, but KAERI has advocated pyroprocessing and burning the spent fuel in fast reactors, which if proven successful may be a long-term solution. However, regardless of whether the Pyro-SFR cycle comes to fruition, it still does not solve the problem of the impending saturation of the cooling pools—which will be at capacity before 2021, and maybe as early as 2016 if no solution is found. According to KAERI, the option of pyroprocessing is well suited for South Korea, since there is no room to site a repository large enough to accommodate all the un-reprocessed spent nuclear fuel. Yet even under the most optimistic scenario, many technical feats<sup>31</sup> will need to be completed before KAERI’s plan can be realized.

Neither KAERI’s plan nor the previously mentioned 10-year study places much emphasis on alternative solutions to the spent fuel problem. Clearly, alternative short- and long-term options must be explored to give ROK the flexibility to make sound decisions in the future. In the interest of facilitating discussion, the focus of this document is to explore such alternatives.

## 2.8 A Note on the National Approach

Along with a number of authors, we have previously examined the feasibility of multilateral options for addressing South Korea’s spent fuel problems, as well as those involving neighboring countries such as Japan and Vietnam. We continue to believe that such approaches could prove a valuable means of addressing national spent fuel dilemmas. However, given that they carry their own sets of issues and are not close to fruition, in this paper we have chosen to focus on purely national concerns.<sup>32</sup>

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31 The following facilities will need to be established at the commercial scale: a pyroprocessing facility, a fast burner reactor, a HLW repository. If a pyroprocessing facility is established without any of these facilities, ROK runs the risk of building up separated plutonium actinides (TRU).

32 For more on the potential multilateral approaches see 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); Charles McCombie and Thomas Isaacs, “The Key Role of the Back-End in the Nuclear Fuel Cycle,” *Daedalus* (Winter 2010); and “Multilateral Approaches to the Nuclear Fuel Cycle,” IAEA Expert Group Report, INFCIRC 640, (February 2005).

### 3 SHORT-TERM AND MEDIUM-TERM OPTIONS: STORAGE

#### 3.1 Introduction to Spent Fuel

The smallest unit of nuclear fuel are small uranium dioxide pellets which are placed in zirconium metal clad fuel rods known as fuel rods. The fuel rods themselves are placed in bundles called fuel assemblies. In turn, these fuel assemblies are placed in a lattice making up the reactor core. During the fission process the fuel produces energy, the composition of the fuel physically changes. Initially a simple composition of various isotopes of uranium, after use in the reactor, the fuel contains as many as 200-300 other isotopes. When the fuel is removed from the nuclear reactor core, it is still highly radioactive and physically hot. (For the contribution of various fuel components to total radioactivity, see Figure 5.) In fact, the heat output from the fuel immediately after removal is still 7% of that produced when running the reactor. This heat is not easily quelled, so the now “spent fuel” must be immediately cooled to prevent degradation. The fuel is also highly radioactive, making protection of personnel from exposure a high priority. Therefore, when the fuel is removed, it is immediately placed into a deep-water pool to shield against the radiation and to cool the fuel to prevent damage to it. The fuel remains in the pool for a minimum of 5-10 years until it is cool enough that water is no longer necessary for cooling. At this point the operator has a number options.

These include:

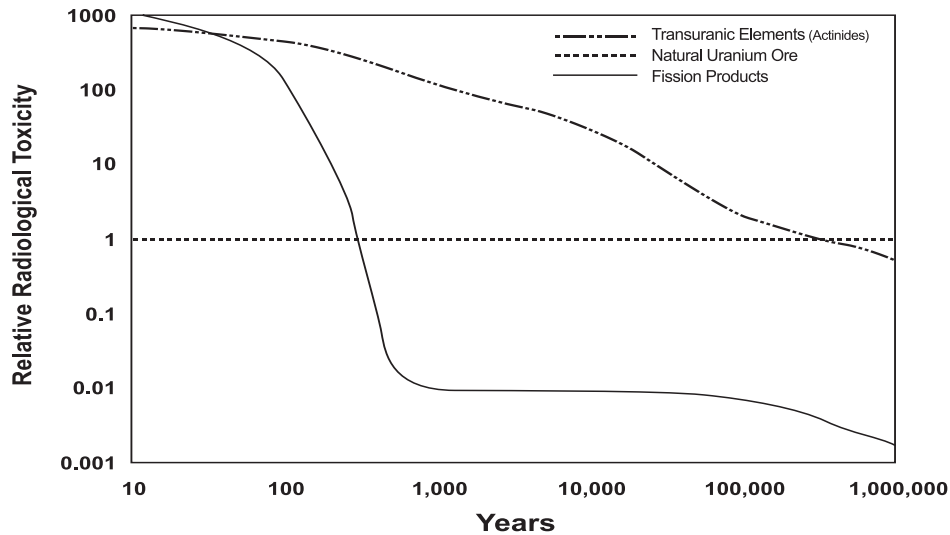
- Continuing to store the spent fuel in the pools;
- Storing the spent fuel outside the pool in specialized containers called dry casks using air instead of water;
- Reprocessing the spent fuel to change the volumes and properties of the materials that must ultimately be disposed of;
- Physically altering the fuel to save storage space—e.g., by fuel rod consolidation;
- Shipping the spent fuel to a foreign service provider for storage or for disposal;
- Proceeding with geological disposal as soon as technically feasible.

#### 3.2 Current ROK Policy and Practice

In 1988, KAEC, the agency responsible for nuclear energy planning and promotion, announced that an AFR wet facility for interim storage would be built by 1997. However, the agency failed to site the facility due to little public engagement in the decision, even local opposition. Consequently, all short-term storage of pressurized water reactor SNF is located in cooling pools beside the reactor core in all 23 reactors. Since no AFR facility was constructed and no contingency plans were carried out, the cooling pools for all reactors are set to reach capacity very soon. In particular, the Kori site is on track to saturate only three years from now if only intra-site transshipment of spent nuclear fuel is considered.<sup>33</sup> The Kori site com-

<sup>33</sup> Kori, Yonggwang, Ulchin and Wolsong will saturate in 2016, 2021, 2018, 2017 respectively. Ki-Chul Park, “Status and Prospect of Spent Fuel Management in South Korea,” Nuclear Industry, August 2008 (in Korean) referenced in Kang, “The ROK’s Nuclear Energy Development,” 2013.

prises four reactors but is less than 1 km away from the newly commissioned Shin-Kori site, which when completed will have an additional four reactors, two of which are already in operation. Shipping the older spent fuel from Kori to Shin-Kori would delay saturation by 11 years. In addition, the Ulchin 6-reactor site also has a sister site, Shin-Ulchin 2, which could also be used to store older spent fuel. In this case, the Ulchin cooling pond saturation date of 2018 could be extended to 2028.<sup>34</sup>



**Figure 5:** Variation in radioactivity (which is closely related to the heat output) as a function of time after the fuel is removed from the reactor. Also, shown is the contribution of various components to total radioactivity. We see that there is essentially a competition between two types of isotopes, the fission products which are important on the time scale of hundreds of years and the actinides that dominate after many thousands of years. Therefore, since these two types of isotopes contribute the most, one way to decrease the radioactivity of the fuel is to separate these types of isotopes from the fuel with a method known as reprocessing (which will be discussed further in Chapter 4). Also shown is the radioactivity from the same amount of natural uranium. Therefore, when the total fuel reaches this line, the radioactivity has decreased to the level of the uranium used to produce it. A more complete description is provided in Appendix B.<sup>35</sup>

Only the Wolsong CANDU heavy water nuclear power plant has modest dry cask facilities near the plant for relieving saturation of the reactor’s spent fuel cooling pool. However, the Wolsong site is very close to the LILW Disposal Facility, and under South Korean law, spent fuel–related facilities cannot be built that close to an LILW site (see discussion of that restriction later in this section). KRMC has argued, however, that this restriction does not apply to dry storage facilities and has therefore continued to expand them at Wolsong.

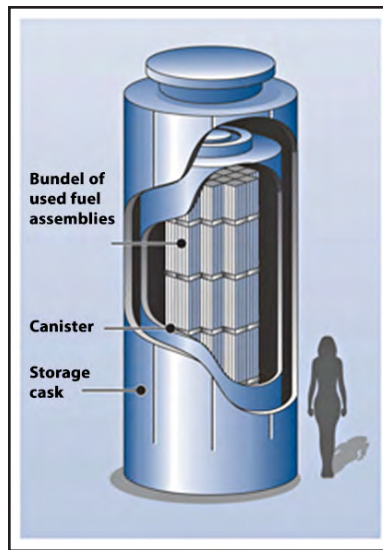
### 3.3 What Kind of Storage—Wet or Dry: Learning from Past Experience

As pointed out above, interim storage is an unavoidable part of short-term management of spent fuel or HLW and can be in two forms: “wet” storage in pools or “dry” storage in dry casks. Dry cask storage employs a defense-in-depth approach with sealed, leak-tight stainless steel containers holding closely spaced spent fuel in a compartmentalized basket. The stainless steel containers are deposited inside larger

<sup>34</sup> Ibid.

<sup>35</sup> Adapted from Edward Blandford, Robert Budnitz, and Rodney C. Ewing, “What does 1 million years mean to a regulator?” *Nuclear News*, November 2011, 43-45.

containers and finally in a concrete cask providing a final level of protection and shielding (see Figure 6). Materials used for shielding are lead and steels to absorb the radioactivity. Dry casks weigh as much as 100 metric tons when fully loaded and can hold 10-15 metric tons of SNF—the equivalent of about 32 LWR SNF assemblies. A 2006 study of the comparative risks of dry casks and spent fuel pools found that dry casks are less susceptible to risk in terms of sabotage or accident, since spent fuel pools hold an order of magnitude more SNF than do casks.<sup>36</sup> In addition, SNF rods in cooling ponds hold younger fuel than do dry casks, and radioactive material released as a result of a zirconium cladding fire would produce deadly radioactive aerosols. In any scenario, after being removed from the reactor, the fuel will need to be cooled for 5-10 years, at which point it can be either reprocessed or stored for several decades in dry casks. Various forms of dry storage will be described further in this chapter.



**Figure 6:** A typical dry cask showing the fuel assemblies and the inner and outer containers which make up the dry cask.<sup>37</sup>

Interim storage of spent fuel assemblies at the site of an operating reactor can take various forms—with no obvious single solution. The problem exists at numerous reactors worldwide; an illustrative practical example from 2002 concerning two Belgian plants<sup>38</sup> shows that a uniform storage solution may not be the optimum strategy, even within a single country. The technical options considered by the Belgians were:

- Re-racking of existing pools;
- Consolidation of the spent fuel assemblies;
- Storage pools in a bunkered building;
- Dry storage in dual-purpose casks (storage and transportation) on pads, or in a bunkered building;
- Dry storage in canisters located in a bunkered building;
- Dry storage in vaults.

The first two solutions were quickly eliminated. Any desirable expansion of storage capacity would have

36 National Research Council, “Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report” (2006).

37 <http://www.nrc.gov/waste/spent-fuel-storage/diagram-typical-dry-cask-system.html>

38 Vermayen R., *Spent Fuel Storage In Belgium*, Tractebel Energy Engineering Belgatom Report, <http://www.dysnai.org/Reports/2000-2004/2002/26.pdf>.

been very limited with re-racking because the existing racks were already of the high-density type. Similarly, consolidation offered too little expansion capability. Moreover, this technique is insufficiently proven.

A structured decision process requires agreement on a list of key criteria and an assessment of how the various options fulfil these criteria. The fact that local boundary conditions can directly affect the choice is illustrated by the results of the cited Belgian study. Dry storage in metallic, dual-purpose casks in a non-bunkered concrete building was chosen for one site, and wet storage in pools in a bunkered concrete building for another.

For the ROK, four commercially available system options can be considered for the storage of spent fuel after the initial cooling period. These are: 1) wet storage, 2) dry storage with dual-purpose transport/storage casks, 3) dry storage in which the transport and storage systems are separated, and 4) dry storage in vaults. For the storage of HLW glass, only dual-purpose transport/storage casks or storage vaults have been utilized to date.

Dry storage is in line with current trends worldwide, although pool systems close to, but not in, the reactor complex have been chosen by countries such as Switzerland (Gösgen), Sweden (CLAB) and Finland. In the Swiss case, it should be pointed out, the justification for building additional wet storage was to allow sufficient cooling of high burn-up fuel—in order to permit the optimized loading of dry casks at ZWILAG, which is the intermediate storage facility for radioactive waste. The main arguments for restricting options for dry storage are that the indefinite future of nuclear programmes makes the choice of required pool capacity uncertain and concrete-based dry storage technologies will be available, modular, and less costly than pool storage.

### 3.4 Pool Storage<sup>39</sup>

Virtually all power reactors worldwide have some form of spent fuel pools associated with reactor operations. These at-reactor (AR) pools have in recent years begun to reach full capacity in some cases, threatening the continued operation of the power plants. Recent designs of reactors now incorporate pools that can accommodate lifetime accumulations over periods of up to 40 years or more.

Both wet and dry storage technologies have to address the following requirements:

- Fuel cladding integrity should be maintained during handling and exposure to corrosion effects of the storage environment;
- Fuel degradation during storage should be prevented through adequate cooling in order not to exceed fuel temperature limits;
- Subcriticality of the spent fuel should be maintained under normal and accidental conditions;
- Radiological shielding of the spent fuel should protect plant operators, the public and the environment from receiving radiation doses in excess of regulatory limits;
- Environmental protection should be assured by minimizing the release of radioisotopes;
- Fuel retrievability must always be available.

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<sup>39</sup> Much of this section is based on the following reference: International Atomic Energy Agency, *Survey of wet and dry spent fuel storage*, IAEA TECDOC 1100 (1999).

Most AR storage pools were built at the same time as the reactor and are fully integrated with reactor operation. Thus, experience with AR wet storage has been available for more than 40 years. The issue of AFR storage of spent fuel, however, is more complicated. A variety of AFR wet storage facilities are in use. Some are at the same site as the reactor and provide extended operational capacity once the AR pool is full of spent fuel; a few are at stand-alone sites.

A typical AFR wet storage facility may have the following features:

- Cask reception, decontamination, unloading, maintenance, and dispatch;
- Underwater spent fuel storage (pool);
- Auxiliary services (radiation monitoring, water cooling and purification, solid radioactive waste handling, ventilation, power supply etc.).

Spent fuel is received (either wet or dry) at the AFR facility contained in a transport cask. Fuel may be removed either assembly by assembly or in a multi-element canister. Two types of cask unloading method are in operation: wet and dry. The wet unloading, being the initially developed type for LWR spent fuel, is performed under water. A hot cell-type facility is used for dry unloading.

The storage pool is a reinforced concrete structure usually built above ground or at least at ground elevation; however, one entirely underground facility is currently in operation in Sweden. Some early pools were open to the atmosphere, but operational experience and the need to control pool water purity has resulted in all pools now being covered. The reinforced concrete structure of the pool, including the covering building, needs to be seismically qualified depending upon national requirements. Most pools are stainless steel lined, some are coated with epoxy resin-based paint. The pools are filled with deionized water with or without an additive, depending on the type of fuel to be stored and the adopted method of treatment.

Two methods in regular use to allow fuel to be isolated from the bulk pool water are single or multi-element bottles, or storage containers. Sub-criticality was originally maintained for LWR spent fuel (assumed to be fresh fuel) by spacing assemblies within the storage racks or baskets. However, with the need to store greater quantities of fuel, higher storage density has been achieved by the introduction of neutron absorbing materials in storage racks and baskets, such as boronated stainless steel, boral or boraflex. The period of time that spent fuel resides in a pool varies between pools (AR and AFR) and the requirements of the overall spent fuel management system. Some Zircaloy clad fuel has been wet stored satisfactorily for more than 50 years.

In the ROK, the fuel pools are entirely above ground and are located next to the reactor dome. These pools are approximately 12 m deep to provide adequate quenching of the radiation for personnel on the periphery of the pool. As mentioned, only the Wolsong plant has dry storage in addition to wet storage.

## 3.5 Dry Storage

### 3.5.1 *Technical Design Options for Dry Storage Facilities*

The dry storage systems that could be used for pressurized water reactor (PWR) fuel are the same whether the facility is implemented at the reactor site or elsewhere. However, some temporary storage facilities



at reactor sites may have only a limited lifetime, requiring the used fuel to be transferred to a long-term storage facility. From the long-term facility, the transfer will either be to an Encapsulation Plant (EncP) or possibly a reprocessing plant.

The full range of commercially available dry storage technologies for both SNF and vitrified (converted into a glass) HLW is outlined in Appendix A, Table A.1. This table is based on an IAEA study,<sup>40</sup> but has been updated and adapted for the current study. The infrastructure for the storage system can take several forms, as illustrated in Table 1.

Required Infrastructure	Example
Simple Hall	Extension to US-type pad system
Robust Hall	ZWILAG, Gorleben
Tunnel	Neckarwestheim NPP
Storage Pad	US NPPs/Spain
Storage Module	US NPPs
Underground Module	Holtec/Energy solutions
Vault	Fort St. Vrain, Paks, COVRA

**Table 1:** Examples of required infrastructure for storage systems.

### 3.5.2 Summary of the Relevant Design Options

Table 8 in Appendix C provides a summary of all identified SF dry storage systems with their manufacturing data and other relevant information. Economic pressures and technical developments mean that the capacity of dry storage systems in terms of number of spent fuel elements per cask/canister and the total heat output has increased significantly since the 1980s. This development is shown in Figure 7. Higher burn-ups and shorter cooling times are pushing the thermal capacity of storage casks beyond 40 kilowatts (kW). The main developments that can be expected in the future are in methods that improve the heat transfer from the center of the casks/canisters. To optimize the transfer of heat, it is better to place the highest, shortest-cooled SF assemblies in the central positions of the cask and lower burn-up longer-cooled SF assemblies in peripheral positions. However, in this case, the temperature of the central fuel assemblies can quickly exceed the limits set to ensure the long-term stability of the spent fuel pin cladding material. For high burn-up fuel assemblies, this situation requires longer cooling times to reduce the SNF heat output, or to the loading of lower numbers of SF assemblies. Indeed, the cooling times required in pools and in casks depend on the burn-up to which the fuel is exposed.

<sup>40</sup> International Atomic Energy Agency, *Selection of Away-From-Reactor Facilities for Spent Fuel Storage - A Guidebook*, IAEA TECDOC 1558 (September 2007).

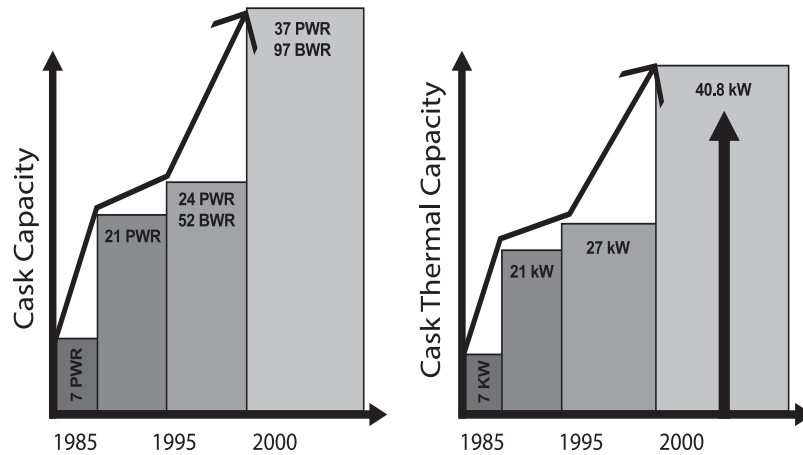


Figure 7: Evolution of cask capacity and thermal capacity.<sup>41</sup>

### 3.5.3 Security Concerns

In all credible scenarios, spent fuel will be kept in storage for years to decades, bringing the security of storage facilities under discussion. Security and terrorist concerns have heightened interest in the advantages of building storage facilities underground. Most storage facilities are built above ground, although there are exceptions, such as the Swedish CLAB spent fuel pool, situated in a rock cavern some tens of metres below surface, with a similar (dry storage) solution currently being proposed in Canada, but at greater depth. This approach has also been considered by the UK government advisory committee, CoRWM, with such stores referred to as “hardened” facilities. Hardened storage facilities can also be built at the surface by increasing physical protection measures. For example, the HABOG vault storage facility in the Netherlands (see cover of report and Figure 8) uses a massive 1.7-m thick reinforced concrete containment. The cooling is done by natural convection, in which the heat causes a flow of air over the container, as is shown in the figure. The fuel is never in contact with the air. The HABOG vault has been designed to withstand airplane crashes, flooding, gas cloud explosions and abnormal natural disasters.

The possibility of hardening the storage facility by constructing missile-resistant casks has also been proposed in the USA. A more far-reaching alternative would be to have spent fuel storage facilities at repository depths of hundreds of metres with the possibility of later converting these stores into final disposal facilities.

### 3.5.4 Centralized vs. Distributed Storage

Some centralized, AFR facilities in some European countries use pool storage. For example, the CLAB facility in Sweden accepts spent fuel from all Swedish reactors. It should be noted that the term away-from-reactor need not indicate a separate site; only that there is additional storage outside the reactor pool itself. Pool storage has some specific disadvantages. One is that a large facility must be constructed at the outset to allow for future accumulation of spent fuel, so that much of the storage space remains unused for a long period. Another is that maintenance can become expensive if final disposal lies far into the future. Some years ago, pool storage was also criticized as being particularly sus-

<sup>41</sup> Adapted from Y. Hwang, “Issues of Radioactive Waste Disposal in Korea: Challenges and Opportunities,” seminar at “Korea’s Low Carbon, Green Growth Vision and the Potential for U.S.-Korea Cooperation: A Policy Seminar,” presentation June 24, 2010.

ceptible to terrorist attacks,<sup>42</sup> although such vulnerability has been refuted by regulatory bodies.<sup>43</sup> Most recently, the Fukushima accident revealed the hazards of large, heavily used fuel pools in any situation where off-site electrical power might be lost for extended periods of time.

Today, spent fuel is increasingly stored in dry storage facilities, which have lower operational costs than fuel pools and can be implemented in a modular fashion. There are little or no economic advantages in centralizing such facilities, since the cost of casks is the main budget item. However, there may be security cost savings in consolidating stored spent fuel at fewer locations, especially at future times when reactors may be shut down.

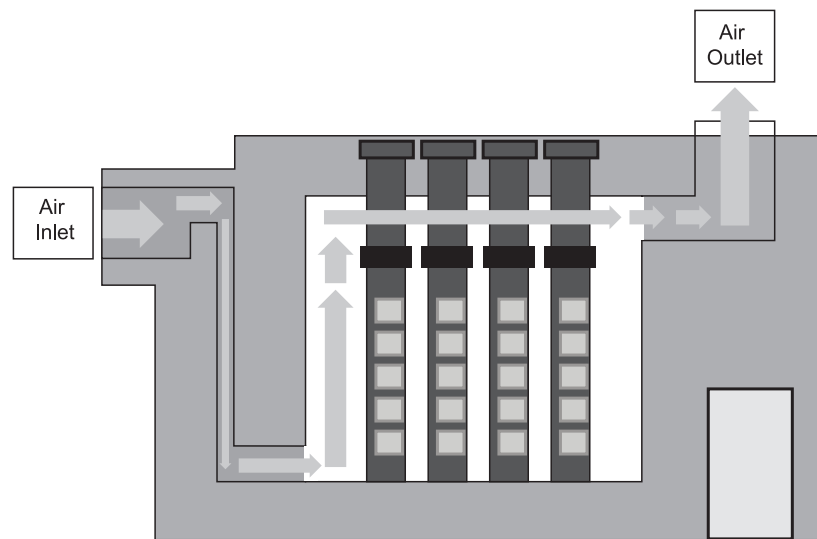


Figure 8: Image of the high-heat generating area of the HABOG vault showing the convection method of cooling the SNF canisters.<sup>44</sup>

### 3.5.5 Conceptual Options for Comparison

Dry storage solutions can be grouped into the following categories, which are not specific to the technology providers.

1. Metal casks arranged on a surface pad, possibly located in a simple building: self-shielded casks are multi-purpose (for transport and storage);
2. Concrete casks with internal metal canister arranged on a surface pad, possibly located in a simple building: self-shielded casks;
3. Concrete modules with internal metal canister, on a surface pad, possibly located in a simple building;

42 R. Alvarez, J. Beyea, K. Janberg, J. Kang, E. Lyman, A. MacFarlane, G. Thompson and F. von Hippel, "Reducing the hazards from stored spent power-reactor fuel in the United States," *Science & Global Security* 11 (2003): 1-51.

43 US Nuclear Regulatory Commission review of the reference is at <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/reducing-hazards-spent-fuel.html> and the response by the authors at: [http://www.irss-usa.org/pages/documents/SGS\\_213-223\\_response.pdf](http://www.irss-usa.org/pages/documents/SGS_213-223_response.pdf).

44 Adapted from COVRA [Central Organisation for Radioactive Waste], "Dismantling Submarines," presentation at IAEA Workshop, February 26, 2010, <http://www.iaea.org/OurWork/ST/NE/NEFW/CEG/documents/ws022010/eng/TechnicalvisitCOVRAPresentation.pdf>.

building: SF placed in containers that are sealed and placed into heavy, fixed concrete modules that provide the necessary shielding;

4. Metal or concrete casks with internal metal canister, in a robust, long-lived building that provides additional security;
5. Concrete modules with internal metal canister, in a robust, long-lived building: SF placed in containers that are sealed and placed into heavy, fixed concrete modules that provide the necessary shielding;
6. Vault on the surface: SF contained in channels within a massive concrete vault that provides shielding and has channels to allow natural convective cooling—located within a robust building;
7. Concrete module with internal metal canister just below surface: SF placed into sealed containers in a concrete-lined pit excavated some metres into the ground and capped;
8. Concrete with internal metal canister casks, in an underground cavern: concrete casks (as option 2) arranged on a pad within a simple cavern at a depth of about 30 to 50 meters;
9. Concrete modules with internal metal canister, in an underground cavern: SF placed in containers that are sealed and placed into heavy, fixed concrete modules (as option 3) constructed in a simple cavern at a depth of about 30 to 50 metres;
10. Vault in a cavern: SF contained in channels within a massive concrete vault that provides shielding and has channels to allow natural convective cooling—located in a cavern at a depth of about 30 to 50 metres.

Grouping these technical options in this way can provide a useful start for a multi-attribute analysis<sup>45</sup> aimed at selection of the most suitable technology for the ROK. Currently the ROK has dry storage only at the Wolsong NPP CANDU reactor, where the spent fuel that is not in cooling ponds is installed in 7 MACSTOR/KN-400 modules and 300 concrete silos. The total at reactor and AFR capacity of the Wolsong NPP is 500,000 assemblies, 70% of which has already been used.<sup>46</sup> Immediate planning for short-term dry storage is necessary, since the reactor storage is near capacity and any long-term solution is several decades into the future.

### 3.6 Export for Interim Storage

The IAEA has produced a report on multinational storage developments.<sup>47</sup> The following storage scenarios were examined:

- Spent fuel stored in a regional facility and returned at a specified time to the originating country;
- Spent fuel stored in a regional facility prior to reprocessing; HLW is returned to the originator or to a regional storage or disposal facility;

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<sup>45</sup> One method often used in these types of analyses is the Analytical Hierarchy Method. See: Thomas L. Saaty, "How To Make a Decision: The Analytic Hierarchy Process," *Interfaces* 24, 6 (November-December 1994):19-43. This method is appropriate for use by a variety of stakeholders.

<sup>46</sup> CANDU plants produce spent fuel at a rate 5 times higher than PWRs. Therefore, the Wolsong reactor quartet produces as much spent fuel as the entire fleet of PWRs, or 380 MTHM/yr.

<sup>47</sup> IAEA, Technical, economic and institutional aspects of regional spent fuel storage facilities, IAEA-TECDOC-1482, IAEA, Vienna (2005).

- Spent fuel stored in a regional facility and transferred directly to a regional disposal facility (in the same or another country).

The report discussed infrastructure issues of relevance, in the following categories: technical, economic/financial, institutional, socio-political, and ethical. In its conclusions, it was recognized that the regional spent fuel storage concept is technically feasible and potentially viable and that storing spent fuel in a few safe, reliable, secure facilities could have safeguards and security benefits. There have been suggestions that multinational storage schemes might be more easily implemented than final disposal projects with their indefinite timescales. However, public and political opposition to accepting foreign fuel for storage has also been strong, unless definite agreements for sending the material back to the owner are in place. Moreover, modular storage systems can be implemented in any country, and dry storage technologies have few benefits from economies of scale. Accordingly, the potential benefits of regional cooperation are judged to be greater for disposal than for pure storage facilities.

In practice, proposals have been made for countries to undertake interim storage of foreign spent fuels. However, none of these has led to practical implementation. Russia is the only country that has made formal offers, but acceptance of these offers would imply agreement that the spent fuel be reprocessed in Russia and that the Russian government has the right to return the HLW if it so chooses. This situation is little different from an earlier one with commercial reprocessing in France and the UK, which will also accept foreign spent fuel with return of wastes as part of the arrangement. Given the high cost of reprocessing, these offers are not attractive. Some countries have, nevertheless, signed up for further reprocessing—often primarily as a means of moving spent fuel from the reactor sites.

### 3.7 ROK-Specific Conclusions and Recommendations on Short-Term Spent Fuel Management

#### 3.7.1 *Inter-Site Transfer of SNF*

In the near term, the ROK is advised to immediately explore further the option of transferring spent fuel from older to newer reactor ponds. The KRMCC claims that this strategy will extend the saturation point of the cooling ponds for several decades—at least for Kori and Ulchin.<sup>48</sup> Another possibility is to transfer spent fuel from one reactor site to dry storage at another site. Although this course of action is currently claimed to be politically impossible, according to Korea Hydro Nuclear Power (KHNP), it should be explored with full public engagement.<sup>49</sup>

#### 3.7.2 *Siting of Centralized Interim Storage Facility*

In a multi-attribute analysis, the ROK should assess the most appropriate wet and dry storage options for a centralized interim storage facility (CISF).<sup>50</sup> Wet and dry versions of these facilities have been successfully constructed in many countries. Initiate a siting program for a CISF by engaging with local communities and providing incentives, in parallel with a coherent strategy for ultimate disposal. Consolidating SNF at singular facilities will decrease the cost of security once the material is at the site; however, overall costs might increase due to the risk of moving spent fuel. Risk would be proportional to the distance travelled.

48 International Panel on Fissile materials (IPFM), *Managing Spent Fuel from Nuclear Power Reactors* (September 2010): p 63.

49 KHNP's view reported in International Panel on Fissile materials (IPFM), *Managing Spent Fuel from Nuclear Power Reactors* (September 2010): p13.

50 Multi-attribute analysis allows complex decisions to be made with multiple options and multiple criteria for making a decision. An example of a multi-attribute analysis algorithm is the Analytical Hierarchy Process developed by Tomas Saaty. See: Thomas Saaty, "Decision making with the analytic hierarchy process," *Int. J. Services Sciences* 1, 1 (2008).

### *3.7.3 Education of Public about Benefits of Dry Cask Storage*

Actively engage in an outreach program with the population in the direct vicinity of the nuclear power plant to brief them on the benefits of dry cask storage as opposed to capacity extension measures, such as “re-racking,” made to cooling ponds. Dr. Jungmin Kang (KAIST), in his investigation of the local communities surrounding nuclear power plants, has observed that they have not been properly briefed on the benefits of dry casks vs. pool storage.<sup>51</sup>

### *3.7.4 Evaluation of Spent Fuel Transport Away from ROK*

Periodically re-evaluate the possibilities for temporary or permanent export of spent fuel to a regional or multinational facility outside the ROK. This measure could involve the ROK in taking an active, perhaps leadership, role in regional developments in the Pacific area and Asia. Since all the nuclear plants are located on the coasts, spent fuel would not have to be transported on Korean soil.

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<sup>51</sup> J. Kang, “South Korea in focus: The politics of spent fuel storage and disposal,” *Bulletin of Atomic Scientists* 67 (2011): 56.



## 4 LONG-TERM OPTIONS

Irrespective of the short- and medium-term options the ROK chooses for managing spent fuel, it will still have to make some long-term choices. One choice will be whether to adhere to the current once-through fuel cycle, with material moving from some form of interim storage directly to geological disposal. Alternatively, Seoul could decide to introduce additional intervening steps involving reprocessing (pyroprocessing) the fuel and burning the resulting product in a fast reactor. Another choice will be whether to limit the interim storage period for spent fuel to current industry practice of up to 100 years after discharge from the reactor, or to extend interim storage periods. The result of either of these choices will ultimately require some form of geological disposal in a geologically isolated location, but the form this site takes—a mined geological repository or deep borehole disposal—constitutes the final choice Seoul will have to make. In the following sections, we explore current ROK policy on these issues and the choices it will need to make.

### 4.1 The Option of Reprocessing and Recycling

#### *4.1.1 Reusing Plutonium Using Fast Reactors*

The origins and history of reprocessing have lessons for decision-makers today. Commercial reprocessing of fuel in a closed fuel cycle was originally promoted in order to improve uranium utilization. All power reactors currently in use are “thermal” systems—mainly using the  $^{235}\text{U}$  isotope (0.7 percent of natural uranium) to produce power. In the case of the enriched systems used in PWRs and boiling water reactors (BWRs), 5-10 times more natural uranium is fed into the enrichment plant than is used in the fuel. It was thought that the use of this limited resource (uranium prices were believed to rise with increasing demand) would limit the size of world nuclear power programs. Fast reactors, which could use the other 99.3 percent of the uranium—the  $^{238}\text{U}$  isotope—along with a wider array of other transuranics and plutonium, were considered to be the answer to the problem. The fact that fast reactors could also be configured not just to burn plutonium, but also to create more plutonium than they consumed, was an additional attraction, according to some experts.

Fast reactors rely on quite large amounts of plutonium to provide their initial fuel charges, and foreseeing a fast reactor future, the United States, Russia, France, Japan, and the UK all embarked on programs to reprocess the fuel from their thermal reactors in order to provide the plutonium to start up the first generation of fast reactor systems. Other countries optimized their programs around efficient thermal reactor generation—notably using USA-derived PWRs and BWRs—but here also, the assumption that fast reactors would follow led to plans to reprocess the oxide fuel from these reactors.

However, experience with prototype fast reactors has been costly because of their low capacity factors and frequent safety-related problems. Costs of reprocessing have also risen. Moreover, the expected uranium price increases did not materialize. The end result is that significant fast reactor deployment, said to be “30 years off” in the early 1960s, is generally reckoned to be at least 30 years off today.

#### *4.1.2 Reusing Plutonium Using LWRs*

As fast (and thermal) reactor programs were cut back, the urgency of acquiring bulk supplies of plutonium disappeared. In fact, countries with plutonium stocks turned to using the material in MOX fuel to be loaded into thermal reactors rather than fast reactors as originally envisioned. Even for countries with recovered plutonium, this approach is not economical, given the high price of MOX fuel relative to uranium dioxide (UO<sub>2</sub>) fuel. In the 1970s, the availability of separated plutonium gave rise to fears of diversion to nuclear weapons production. This led the government of the United States to cancel its own commercial reprocessing projects and (largely unsuccessfully) try to persuade other countries also to desist from commercial reprocessing. However, large reprocessing plants had been constructed in the UK and France, and there was a commitment to domestic reprocessing in Japan. From the 1970s, UK and French plants offered a reprocessing service to other nations, and the contracts to reprocess PWR and BWR fuel became part of the nuclear strategy of these nations. Many utilities used reprocessing as a means of managing their spent fuel. Since storage facilities were scarce and dry cask storage was not widespread commercially, reprocessing contracts enabled spent fuel to be moved off reactor sites. Moreover, in the early days, the reprocessing countries did not insist on returning the reprocessing wastes to their customers, so customer countries believed that they would require only near-surface disposal facilities for operational reactor wastes and could avoid implementing expensive deep geological repositories.

These reprocessing contracts produced separated plutonium and uranium that was no longer needed for fast reactors. However, the plutonium stocks (and the uranium from reprocessing) can be recycled into PWRs and BWRs as MOX fuel, thus reducing the amount of natural uranium required. This “thermal recycle” route was utilized in several countries—including France, Japan, Belgium, and the Netherlands.<sup>52</sup>

However, using MOX fuel in LWRs suffers from the fact that the plutonium quality worsens each time the fuel is cycled through the LWR because of the build-up of neutron absorbing isotopes which compete for fission neutrons. This is not a problem for fast reactors where there are enough extra fission neutrons to not be affected much by the presence of neutron absorbing isotopes. It was hoped that the large-scale use of MOX would incinerate the plutonium stock as commercial breeder reactors were developed, but this did not happen. The fast and thermal fuel recycle options are illustrated in Figure 9.

#### *4.1.3 The Shifting Global Politics of Reprocessing*

In recent years, discussion on reprocessing has intensified as a result of increased interest in nuclear power around the world. The major nuclear nations have voiced concern that this development could lead also to more countries considering enrichment and reprocessing programs—both technologies with a high proliferation risk. Accordingly, these countries have advocated approaches—notably the Global Nuclear Energy Partnership proposal under the George W. Bush Administration—to centralize these technologies in “supplier nations” that would deliver fuel to new nuclear countries and then take back the fuel for reprocessing (normally with a return of HLW to the customer). However, the major suppliers differ on the technologies involved and which countries would be the suppliers. Countries like France and Russia, which already operate reprocessing facilities using the established PUREX (plutonium uranium recovery by extraction) process described above, are trying to persuade others to use their current technologies, which they see as a major selling point for their reactors. Other countries, such as the United States and South Korea, are interested in developing more proliferation-resistant reprocessing technologies that do

<sup>52</sup> Note that Germany and Switzerland have since given up reprocessing.

not necessitate having pure separated plutonium at any stage of the recycling process. However, the United States and South Korea differ on whether the ROK should supply this service. For nonproliferation reasons, the United States wants to limit the supplier states to NPT nuclear-weapon states and prevent NPT non-nuclear-weapon states, such as Seoul, from acquiring stockpiles of plutonium-laden separated material.

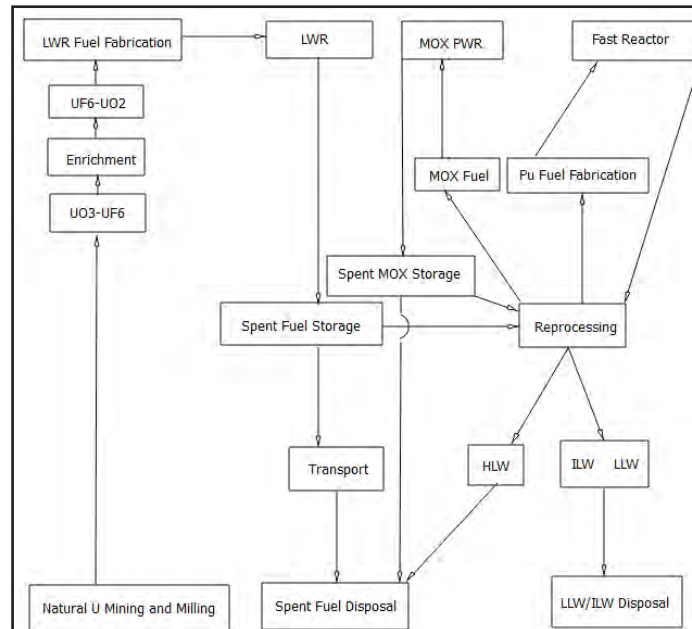


Figure 9: Fast and Thermal Fuel Cycle Options. Source: Gregg Butler (IDM Solutions), for MCM Consulting.

#### 4.1.4 Current ROK Policy and Practice

As the top nuclear energy policy-making body in Korea, KAEC in 2008 promulgated “the long-term plan for the development of the next generation nuclear energy systems in Korea (LTP),” which called for investigating the possibility of using pyroprocessing to treat spent nuclear fuel with the resulting product to be burned in a fleet of fast burner reactors (pyro-SFR).<sup>53</sup> The plan called for the construction of a prototype pyroprocessing facility by 2022 and a demonstration fast burner reactor.

KAERI, South Korea’s main R&D organization, has been actively researching pyroprocessing at laboratory scale since the early 2000s, when the US and the ROK agreed to collaborate on advanced fuel cycle research. KAERI claims, and the KAEC accepted, that the advantage of pyro-SFR is that it will decrease the repository area by two orders of magnitude and reduce radiotoxicity to that of natural uranium in less than several centuries. Compare these data to the once-through cycle, in which the spent fuel would return to natural uranium after 300,000 years of disposal.

KAERI has since implemented a long-term research study focused on developing a prototype high throughput, commercial scale pyroprocessing facility as well as prototype fast reactors as part of the KIEP-21<sup>54</sup> initiative. The idea is to proceed in steps from lab-scale pyroprocessing to engineering-scale

53 C Young Ho and M. Joo Hyun, (n.d.) “Long-term plan for the development of the next generation nuclear energy systems in Korea,” *Atw. Internationale Zeitschrift für Kernenergie* 55, 2.

54 KIEP-21 stands for Korean, Innovative, Environment Friendly, and Proliferation Resistant System for the 21st Century.

demonstration facilities (10 tons of spent fuel annually). In order to avoid separating plutonium in the ROK, the demonstration facility, known as PRIDE (PyRprocessing Integrated inactive Demonstration), does not use actual spent fuel. The current US-ROK nuclear cooperation agreement disallows the “form or content” of US-origin spent fuel to be altered in facilities that are not mutually agreed. Rather, KAERI uses a fuel called SIMFUEL<sup>55</sup> to simulate irradiated reactor fuel, while under the 10-year study agreed to by the two countries in 2011, work on actual irradiated material is carried out only in the United States.<sup>56</sup> The purpose of the PRIDE facility is to test the full remote operation of the argon-filled hot cell for recycling work at the engineering scale. KAERI hopes to attain consent in the new US-ROK agreement to implement engineering-scale tests with real spent fuel (hot tests).

#### 4.1.5 *Advanced Recycling Processes*

As noted above, the United States and South Korea have advocated the development of more advanced reprocessing approaches. These technologies include both aqueous and electrochemical processes. The goal is to recover all long-lived actinides together (i.e. with the plutonium), so as to recycle them in fast reactors so that they end up as short-lived fission products. This policy is driven by two motivations: reducing the long-term radioactivity of high-level wastes, and reducing the possibility of plutonium being diverted from civil use, thereby increasing proliferation resistance of the fuel cycle.

##### 4.1.5.1 *Aqueous Recycling Processes*<sup>57</sup>

A modified version of the PUREX process that does not involve the isolation of a plutonium stream is the UREX (uranium extraction) process. The UREX process was developed to separate only uranium from nuclear fuel, leaving plutonium with the remaining fuel components. Follow-on processes to remove fission products and manage transuranic elements (TRU) were also added on to the UREX process (designated as UREX+). However, studies have indicated that the UREX+ options are very complex and would be difficult to remotely operate on a large scale.

##### 4.1.5.2 *Pyrochemical Recycling Processes*

An alternative to the aqueous reprocessing routes described above is electrolytic/ electrometallurgical processing, or pyroprocessing. This technique has been under development in several states, primarily in the United States, Russia, Japan, and in the ROK by KAERI. Pyroprocessing involves several stages, including: volatilization, liquid-liquid extraction using immiscible metal-metal phases or metal-salt phases, electrolytic separation in molten salt, and fractional crystallization. Separating (partitioning) the actinides contained in a fused salt bath is by electro-deposition on a cathode, so it involves all the positive ions without the possibility of chemical separation of heavy elements such as in PUREX and its derivatives. This cathode product can then be used in a fast reactor. It is readily applied to metal rather than

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55 SIMFUEL is unirradiated UO<sub>2</sub> blended with stable chemical additives to simulate composition and microstructure of real irradiated UO<sub>2</sub>. See C. Ganguly and R.N. Jayaraj (eds.), *Characterization and Quality Control of Nuclear Fuels* (New Delhi: Allied Publishers Pvt. Limited, 2004): 419.

56 Article VIII (F) in the US-ROK nuclear cooperation agreement states that US-origin spent nuclear fuel can be altered only “in form or content” in facilities that are acceptable to both parties. 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?*, KEI Academic Papers Series, 5, 3 (2010).

57 The technical descriptions in this section are drawn from the World Nuclear Association website on “Processing Used Nuclear Fuel,” updated November 7, 2011, available at <http://www.world-nuclear.org/info/inf69.html>.

oxide fuels, and is envisaged for fuels in Generation IV reactors. Using LWR spent fuel would require an up-front process to convert the oxide fuel into metal form.

Electrometallurgical pyroprocessing can readily be applied to high burn-up fuel and fuel that has had little cooling time, since the operating temperatures are already high. However, such processes are at an early stage of development compared with hydrometallurgical (or aqueous) processes already operational.

The KAERI advanced spent fuel conditioning process (ACP) involves separating uranium, transuranics including plutonium, and fission products including lanthanides. It utilizes a high-temperature lithium-potassium chloride bath from which uranium is recovered electrolytically to concentrate the actinides, which are then removed together (with some remaining fission products). The latter product is then fabricated into fast reactor fuel without further treatment. The process has been argued to be more proliferation resistant than current PUREX reprocessing technology<sup>58</sup> because it is highly radioactive, and the curium provides a high number of spontaneous neutrons. The degree of extra-proliferation resistance has, however, been questioned.<sup>59</sup>

The current Korean effort builds on the considerable experience that the United States has had in developing the concept of burning long-lived actinides in the Integral Fast Reactor (IFR). The IFR was a program whereby actinides were separated using pyroprocessing from LWR fuel, fabricated into metallic fuel, and loaded into a dedicated fast reactor. The actinides from the discharged fuel from the fast reactor would then be refabricated into metallic fuel and again recycled in the fast reactor. This process was repeated until most of the actinides were burned and could be disposed in a geological repository. 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. However, we return the problem mentioned earlier, which is that this technique requires a fleet of commercial reactors that are not yet available. Although fast reactors have existed since the beginning of the nuclear age, they have yet to be successfully commercialized. Currently only five fast research reactors (that do not produce electricity) are in operation worldwide: two in Russia (BN-600 and BOR-60), two in Japan (Joyo and Monju) and one in India (FBTR).<sup>60</sup>

#### *4.1.6 Policy Considerations of Reprocessing and Recycling*

Seoul will need to weigh a number of policy considerations, from economic factors to energy security and environmental effects, before deciding whether to move forward with reprocessing of spent fuel. The factors listed should be considered, many of which are discussed in the following sections:

- The intended size of its nuclear power program;
- The desired degree of energy security;
- Intentions to move in the longer term to advanced reactor systems;
- Ambition to be a nuclear technology leader or provider;

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58 Seong Won Park, “Why South Korea Needs Pyroprocessing,” *Bulletin of the Atomic Scientists* Web Edition, October 26, 2009, <http://www.thebulletin.org/web-edition/op-eds/why-south-korea-needs-pyroprocessing>.

59 Bari et al., “Proliferation Risk Reduction Study,” 2009. See discussion in nonproliferation concerns section.

60 Thomas B. Cochran, et al., “Fast Breeder Programs: History and Status,” IPFM Research Report, February 2010.



- Economic considerations;
- Available storage capacities;
- Policies with regard to nonproliferation;
- Developments in the global nuclear fuel cycle “landscape.”

#### 4.1.7 Economics of Reprocessing and Recycling

In an internal unpublished study, MCM first compiled estimated costs for different stages of the fuel cycle under high-, medium-, and low-cost scenarios (Table 2).

	Stage	Unit	High	Medium	Low
1	Natural uranium ore concentrate	USD/lb U <sub>3</sub> O <sub>8</sub>	130	45	9
2	Conversion UOC – UF <sub>6</sub>	USD/kgU	16	12	5
3	Uranium enrichment	USD/kgSWU	200	150	90
4	UO <sub>2</sub> conversion and fuel fabrication	USD/kgLEU	300	250	150
5	Reprocessing	USD/kgHM	2000	1000	600
6	REPU conversion UO <sub>3</sub> – UF <sub>6</sub>	USD/kgU	30	14	7
7	REPU enrichment	USD/kgSWU	250	165	100
8	REPU fuel fabrication	USD/kgLEU	400	300	250
9	MOX fuel fabrication	USD/kgHM	1400	1000	0
10	Spent fuel storage (40 years)	USD/kgHM	120	90	60
11	Reprocessing waste storage (40 years)	USD/kgHM	60	45	30
12	Spent fuel disposal	USD/kgHM	570	430	290
13	Reprocessing wastes disposal	USD/kg original HM	250	190	130

**Table 2:** Assumed unit costs in terms of US dollars per unit mass fuel of the once-through and recycling options.

MCM then compared the costs of a once-through fuel cycle with one in which the initial spent fuel is reprocessed, and the useable products returned as reprocessed uranium or MOX fuel for another irradiation cycle. If carried out for a suite of PWR reactors, as noted in Table 3, a once-through cycle would be the least expensive option.<sup>61</sup> To be sure, this thermal recycle will reduce uranium usage by around 20 per-

61 Frank Von Hippel, “Why reprocessing persists in some countries and not in others: The Costs and Benefits of Reprocessing,” report for the Non-proliferation Education Center, April 9, 2009, [http://www.npolicy.org/article\\_file/Why\\_Reprocessing\\_Persists\\_in\\_Some\\_Countries\\_and\\_Not\\_in\\_Others-The\\_Costs\\_and\\_Benefits\\_of\\_Reprocessing.pdf](http://www.npolicy.org/article_file/Why_Reprocessing_Persists_in_Some_Countries_and_Not_in_Others-The_Costs_and_Benefits_of_Reprocessing.pdf); M. Bunn, S. Fetter, J. Holdren and R. van der Zwaan, “The economics of reprocessing versus direct disposal of spent nuclear fuel,” *Nuclear Technology* 150 (June 2005): 209, available at <http://belfercenter.ksg.harvard.edu/files/repro-report.pdf>; Jean-Michel Charpin, Benjamin Dessus and René Pellat, “Economic Forecast Study of the Nuclear Power Option,” report to the Prime Minister of France, July 2000, [http://fire.pppl.gov/eu\\_fr\\_fission\\_plan.pdf](http://fire.pppl.gov/eu_fr_fission_plan.pdf). One notable exception is a 2006 Boston Consulting Group study carried out for Areva: The Boston Consulting Group, *Economic Assessment of Used Nuclear Fuel Management in The United States*, July 2006, prepared by The Boston Consulting Group for Areva, available at <http://www.bcg.com/publications/files/>.



cent. Moreover, it must be mentioned that this cost approximation probably underestimates the cost differential since it does not account for the fleet of reactors involved, and most studies indicate that a mixed fleet of fast and pressurized-water reactors, or fast reactors alone, would be considerably more expensive than current pressurized water reactors.

Assumptions	Once-through cost USD/kgHM	Thermal recycle cost USD/kgHM	Thermal recycle cost / once-through cost
Low	1509	1754	1.16
Medium	3186	3563	1.12
High	6683	7343	1.10

**Table 3:** Cost differences for various assumptions

It should also be borne in mind that, if the most economic unit plant sizes are not attainable, the costs are more likely to be toward the high side of the estimates. Another important factor is that uncertainty about cost of several of the recycle stages is high. Also, recycling does little to protect against cost increases in the natural uranium cycle, as around 80 percent of the fuel in the recycle case is from natural uranium.

All the figures given are undiscounted but will give a reasonable indication of the cash flow situation, provided that reprocessing and MOX return is carried out relatively promptly. Should delays be encountered (and experience to date has shown delays running into the decades), discounting will be important, and its effects will depend critically on the timing of payments. This matter will require detailed financial analysis, but the “customer ownership” elements and commercial confidentiality of current reprocessing activities makes data on the situation both difficult to obtain and of doubtful relevance to a domestic reprocessing situation. Since disposal of spent fuel or of HLW will likely only occur decades into the future, the disposal cost advantage for reprocessing will be affected by discounting. It is certainly possible to perform analyses that will give recycling an advantage, but ensuring that the terms and assumptions used in the analysis are actually achievable in practice over the long term will be crucially important.

Many analyses do rely heavily on discounting to make their case. The nuclear industry has not been noted for its adherence to long-term programs, so arguments based on discounting must be examined for the levels of risk and uncertainty that they involve. In general, up-front operational costs will be the least discounted, and early recycle operations fall into this category. On the other hand, arguments based on the difference between the disposal of spent fuel and its equivalent amount of reprocessing wastes will inevitably remain conjectural for decades.

As can be seen by the cost assumptions, the costs of 40 years of storage of both wastes and spent fuel are on the order of a quarter of the disposal cost. Therefore, deferral of disposal will almost always be favored on a net present value basis, which is probably part of the reason for the slow rate of progress in disposal worldwide. As with most aspects of the back end of any fuel cycle, “delay is cheap,” and a slower route to a more robust decision may often be the prudent course.

#### 4.1.8 Energy Security Issues

Energy security issues are especially important for a country such as South Korea, which has a large dependence on nuclear power and very limited indigenous resources—including natural uranium—for energy production. Yet, as indicated previously, while reprocessing may reduce uranium usage it is not likely to eliminate it altogether. Moreover, uranium imports from advanced and stable countries such as Canada and Australia do not represent a significant energy security vulnerability for the ROK, especially compared to continued requirements for fossil fuel imports from volatile regions such as the Middle East. In addition, other far easier means exist to reduce any residual energy insecurity, including diversifying suppliers, stockpiling nuclear fuel, and investing in “front end” suppliers involved in mining, milling, and enrichment.

#### 4.1.9 Nonproliferation Concerns

One of the most significant concerns about pyroprocessing is the possibility of processed fuel being diverted for non-peaceful means. An independent assessment of the proliferation resistance of pyroprocessing was done by a group of scientists from the US national labs<sup>62</sup> using criteria such as the “relative difficulty of achieving the objective of reprocessing [to produce nuclear explosive materials that could be fashioned into a bomb], the time required, cost to the adversary, the likelihood of detection, the cost of safeguards and physical protection, and the characteristics of the material acquired. The Bari et al. study found that, for diversion of materials by non-state actors, pyroprocessing “provided some advantage” over PUREX, due to the “additional cost, time and technical difficulty that would be entailed in further processing” in order to obtain plutonium. However, the authors cautioned that these advantages depend “heavily on the assumptions of the capabilities, motivations, and strategies of the adversary.” Contrary to KAERI’s claims, the scientists found “only modest improvement in reducing proliferation risk over existing PUREX technologies and these modest improvements apply primarily for non-state actors.” From the point of view of the study, pyroprocessing cannot be seen as innately more proliferation resistant for state actors determined to develop nuclear explosive materials. Moreover, once states master reprocessing technology, the study postulates, the time to purify material mixtures and separate plutonium “ranges from a few days to a few weeks,” so that break-out of a state in violation of international treaties is a significant concern.

It is often stated<sup>63</sup> by proponents of pyroprocessing that since plutonium is extracted from the SNF in combination with other actinides and fission products, the product is inherently proliferation resistant. Their argument is based on the fact that mass actinides (plutonium-238, americium-242, etc.) tend to make it more difficult to produce nuclear weapons because of the high amount of heat due to particle emission<sup>64</sup> and the copious number of neutrons emitted. Neutrons have the effect of complicating the timing of the triggering of a nuclear explosive device and may cause premature detonation (a “fizzle”). In addition, the high heat can cause “the explosives to decompose unless the assembly is equipped with very elaborate heat-removal features.”<sup>65</sup> While this transuranic mix does make it more difficult to construct nuclear weapons, these technical challenges are not insurmountable, especially with the extensive resources of a state actor that may even receive support or technical know-how from other states.

62 Bari et al., “Proliferation Risk Reduction Study,” 2009.

63 W. Hannum et al., “Nonproliferation and Safeguard Aspects of the IFR,” *Prog. Nucl. Energy* 31 (1997): 203-217. These authors noted: “The IFR fuel cycle uses a technology that produces a recycle product that is useful for peaceful power production but is too dirty for effective weapon use.”

64 For example, alpha decay is one form of nuclear decay in which a heavy helium nucleus is emitted, which gives up all its energy when it is stopped by the medium and thereby locally heats it.

65 William H. Hannum, Gerald E. Marsh, and George S. Stanford, “PUREX and Pyro are not the same,” *Physics & Society* (July 2004).

The well-known physicist Carson Mark, who has worked on developing nuclear weapons in the past, has argued that any grade of plutonium could be used to develop a nuclear weapon. Even if it results in a “fizzle,” significant damage could still result. As Mark points out: “The design of a crude nuclear explosive using reactor-grade plutonium will have to account for the extra heat generation and radiation exposure, but provisions can certainly be devised to cope with these features.”<sup>66</sup> An example that he uses is a thermal bridge to conduct the heat produced by the mixed grade plutonium away from the high explosives. In addition, a National Academies study investigating the disposition of excess weapons plutonium stated that: “In short, it would be quite possible for a potential proliferator to make a nuclear explosive from reactor-grade plutonium using a simple design that would be assured of having a yield in the range of one to a few kilotons, and more using an advanced design. Theft of separated plutonium whether weapons-grade or reactor-grade, would pose a grave security risk.”<sup>67</sup>

Proponents often state that problems with the possibility of clandestine diversion (or “sneak out”) can be solved by current or improved safeguards. To date, however, no safeguard system has been designed that can assure the IAEA that no significant quantity of material has been diverted. For example, Japan’s Tokaimura plant could not account for a loss of 206 kg of weapons-usable plutonium (approximately equivalent to 15 bombs worth<sup>68</sup>). There is no clear explanation of why this much plutonium was lost. The British have reported a similar discrepancy with the reprocessing plant at Sellafield being unable to account for tens of kilograms of plutonium. It is in the nature of high throughput facilities where the uncertainty scales with the throughput, that some—and perhaps substantial—amounts of material will undoubtedly be lost. Therefore, these facilities are inherently risky. KAERI has recognized this as its most significant challenge and has wisely focused on developing sophisticated techniques to decrease the uncertainty in measuring the throughput of pyroprocessing facilities.

Moreover, the complexity of the Pyro-SFR cycle could generate nonproliferation concerns because of the difficulty of synchronizing a complex process that would involve not only the construction of a high throughput pyroprocessing facility, but facilities for fast reactor fuel fabrication, a fast reactor fleet, and a geological repository. Any delay in constructing fast reactors would cause plutonium-laden actinides to be separated but not burned, and the resulting stockpiles to be a proliferation and nuclear security concern.

Finally, South and North Korea signed the 1992 Denuclearization of the Korean Peninsula agreement. Both parties 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.”<sup>69</sup> Unfortunately, North Korea has violated the agreement by operating nuclear reprocessing facilities and enrichment plants and testing nuclear weapons. However, the North’s reckless behavior has not made the ROK follow suit. The South believes, and the US supports the notion, that an ROK renunciation of the agreement “might provide a pretext for Pyongyang to claim that its behavior was no more illegitimate than that of its southern neighbor.”<sup>70</sup> It also fears that a decision by the ROK to abandon the agreement could raise tensions with Japan and China, who for different reasons do not want to see the denuclearization agreement abandoned.

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66 J. Carson Mark, “Explosive properties of reactor-grade plutonium,” *Science & Global Security* 4 (1993): 111-128.

67 Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, (Washington, DC: National Academy Press, 1994). See also discussion at: <http://www.aps.org/units/fps/newsletters/2005/january/articles.html#garwin>.

68 Critical mass of reactor-grade plutonium is approximately 13 kg compared to 10 kg from weapons grade. See: <http://www.fas.org/rlg/980826-pu.htm> for a discussion.

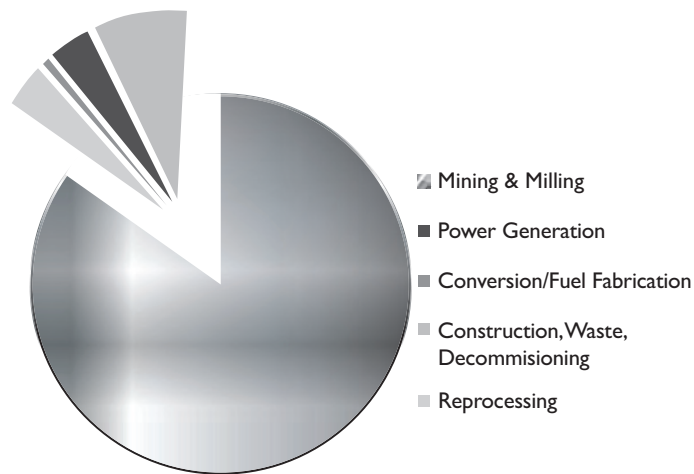
69 Park, Pomper, and Scheinman, *The Domestic and International Politics of Spent Nuclear Fuel in South Korea*, 2010.

70 Ibid.

#### 4.1.10 Environmental and Health Effects

The synchronization issue also has environmental ramifications. Absent a geological repository, high-level waste would be stored at the commercial pyroprocessing facility, which would be unacceptable on public health grounds. In addition, there is still a non-zero significant risk of an accident, which must be taken into account in the final assessment.<sup>71</sup>

More generally, the environmental effects of all aspects of nuclear power and the nuclear fuel cycle have been and are intensely controversial. In all nuclear matters, the public perception of risk greatly influences policy decisions irrespective of any objective assessments of the real risks. However, the scientific consensus on the methods to assess and to control the risks to the public and workforce from nuclear industry operations is fairly strong. The elements to be examined are detriments from assumed accidents and detriments from “business as usual” operations, with the main public concern being discharges of radioactive materials into the environment. All discharges are regulated so that the doses to people and the risks that they entail are kept low, with international standards deriving from the work of the International Commission on Radiological Protection. The situation for assessing health detriment from discharges is complex<sup>72</sup>, but for business as usual, the risks run even by the maximally affected individuals are very low. Health detriment has been monetized, notably by the EU ExternE Project and, while this methodology is not universally accepted, it does give some idea of the distribution of detriment across the fuel cycle. A typical fuel cycle assessment<sup>73</sup> is shown in Figure 10.



**Figure 10:** External Costs

Figure 10 emphasises that by far the largest contributor to detriment from the fuel cycle, including recycling, is the mining and milling stage. The reprocessing stage (near 12 o'clock in the figure) is comparable

71 The Norwegian Radiation Protection Authority calculated that if an accidental release of liquid waste was to occur from the UK's Sellafield reprocessing facility equivalent to 0.1-10% of the total volume, then (simulations show) Norway would receive as much as 0.1-50 times the maximum cesium-137 fallout that it received from Chernobyl after that accident. See Arjun Makhijani, *The Mythology and Messy Reality of Reprocessing*, IEER Report, April 8, 2010, <http://www.ieer.org/reports/reprocessing2010.pdf>. Simulations showed that the fallout would arrive only 9 hours after the incident, but this is highly dependent on the weather conditions for the scenario.

72 See, for example, Gregg Butler and Grace McGlynn, “Radiological Health Detriment and Cost Benefit from Radioactive Discharges,” *Nuclear Future* 5, 1 (2009).

73 J. E. Berry, M. R. Holland, P. R. Watkiss, R. Boyd and W. Stephenson, *Power Generation and the Environment, a UK Perspective* 1, AEA3776 (June 1998), Table 7.37 (mECU/kWh).

with the discharges from power generation. The impact of waste disposal is tiny and is within the construction, decommissioning and waste management sector.

#### 4.1.11 Sustainability

A point under debate is whether reprocessing produces significantly less waste or actually increases the waste production relative to direct disposal. The answer depends on how one measures quantities of waste. Reprocessing and recycling certainly reduce the volumes of most radiotoxic wastes (vitrified HLW has less volume than the equivalent amount of spent fuel), but produce larger volumes of ILW and LLW, which must also be disposed.

A more fundamental sustainability issue concerns the utilization of the primary resource, uranium. Waste prevention activities worldwide over the last 50 years have resulted in more than doubling fuel burn-up while reducing fuel failures to very low levels. At the same time, reactor load factor has increased appreciably. As has been seen, reprocessing with thermal MOX fuel and reprocessed uranium recycle can reduce uranium needs by a further 20-25 percent, but this result must be seen in the context of the overall fuel cycle usage of uranium. The range of possibilities is examined below.

As shown in Table 5 (scenario 5) below, even after full thermal recycle of reprocessed uranium and MOX, the percentage of heavy metal will remain less than 1 percent. Meanwhile, the use of the initial spent fuel by multiple recycling in fast reactors has the potential to increase the heavy metal usage by over a factor of 60.<sup>74</sup> At the strategic level, therefore, the argument on reprocessing could be reframed as a choice between maintaining the potential for improved uranium utilization and foregoing that potential. A series of scenarios can be envisaged and are presented in Table 4.

	Scenario	Spent Fuel Option	%HM used	Notes
1	Once-through LWR then dispose	Dispose	<1%	Retaining option 5 made difficult
2	Once-through LWR then store	Store	<1%	Can retain option 5 for decades
3	Reprocess LWR fuel, recycle refabricated fuel in LWRs	Dispose	~1%	Retaining option 5 made difficult
4	Reprocess LWR fuel, recycle refabricated fuel in LWRs	Store	~1%	Can retain option 5 for decades
5	Reprocess LWR fuel, recycle into fast reactors	Multiple cycle reprocess	Up to 50%	Requires technology and economics not currently available

Table 4: Heavy metal (HM) usage in fuel cycles.

Table 4 is a generalization but it points out some salient facts:

- In thermal reactors such as PWRs, uranium utilization is very low and can be improved by only 20-25 percent by thermal recycle of fuel.

74 World Nuclear Association, "Fast Neutron Reactors," WNA website, <http://www.world-nuclear.org/info/inf98.html>.



- Using sodium fast reactors (SFRs) could increase uranium utilization by a factor of around 50-60.
- Fast Reactors are scientifically proven but are currently neither technically nor economically feasible.
- Interim storage of spent fuel for some decades retains the reprocessing option, and in fact makes reprocessing easier since the fuel is cooled.
- Fuel storage also allows the possibility of an optimally sized reprocessing plant timed to enter the market when its feed of spent fuel is assured, and views of recycle economics may be less uncertain.
- Even disposal of spent fuel in a repository does not totally preclude the possibility of fuel re-use, but it makes re-use substantially more difficult since it will be difficult to retrieve the fuel.

#### 4.1.12 *Summary of Arguments for and against Reprocessing*

The arguments that have been used to promote the closed fuel cycle—and their counter arguments—are as follows:

- Improved uranium utilization – although some dispute the need to conserve the world’s low-price uranium ores beyond the 100+ years they will last;
- Energy security through fuller use of national uranium stocks – although the open market has always provided adequate access to new uranium supplies;
- Reduced radiotoxic inventory in the repository, as illustrated earlier in Figure 5 – although this issue is really only important for direct intrusion scenarios, in which persons come into direct contact with the wastes by unintentionally drilling into the repository or entering the facility;
- Reduced heat emission from the HLW – although extended surface storage of spent fuel can also achieve this;
- Reduced HLW disposal volumes – although other ILW produced must also go to a geological repository;
- A well characterized waste form (glass) – although ceramic spent fuel is also a good waste form;
- Less fissile material in the repository (“plutonium mines”) – although more handling of fissile materials is necessary on the surface where there is a higher risk of accident or diversion.

In addition to challenging above claims, opponents of reprocessing have used the following arguments:<sup>75</sup>

- The eminent physicist Carson J. Mark, who developed nuclear weapons for the United States, has stated that “Reactor-grade plutonium with any level of irradiation is a potentially explosive material.” Therefore, all forms of separated plutonium are a proliferation risk regardless of isotopic composition – although the advanced methods described above can reduce the proliferation risk somewhat.
- It is too costly since commercialization of fast reactors plants has not been proved.
- It is an environmental hazard – although massive reductions in emissions from operating reprocessing facilities have been achieved, significant risk of an accident remains.

<sup>75</sup> J. Carson Mark, “Explosive properties of reactor-grade plutonium,” *Science & Global Security* 4, 1 (1993): 111-128, <http://scienceandglobalsecurity.org/archive/sgs04mark.pdf>.



Today, there is little or no incentive for countries that do not already operate reprocessing facilities to recycle. Many countries have stopped reprocessing their spent fuel (see table 5 below), and even in France and the UK, spent fuel is going into storage rather than for reprocessing. In 1989 Electricite de France (EDF) deemed that MOX fuel would not be competitive with the once-through cycle, reflecting the fact that the price of uranium was still, and continues to be, low. In fact, the French government has investigated the cost of the MOX over a non-MOX fuel cycle in 28 nuclear reactors and found the additional cost to be \$35 billion. In addition, a 2003 Massachusetts Institute of Technology (MIT) study found that if the United States would adopt the use of MOX fuel, the increase in price could be as much as four times the cost as over the counter (OTC) fuels.

The primary arguments are economic as illustrated by the reports referred to above. The high costs of reprocessing and of MOX fuel fabrication, together with the continuing low cost of natural uranium, remove any financial incentive to treat spent fuel at present. The option of simply storing the spent fuel is much more attractive, given that the costs of dry storage are not a large item in the fuel cycle and that storage for decades keeps the option of reprocessing open. Many governments have already reached this conclusion, even if political considerations have prevented them from carrying out the conclusion of their analysis.

Arguments that can lead a country to reprocess are the difficulty in siting future storage facilities or the conviction that medium-term nuclear planning will include fast reactors, so that extracting plutonium for starting them up is a route that must be followed. Other arguments have been used based on simplifying disposal technology (standardized waste packages, lower heat emission), lowering repository costs (less volume) or enhancing long-term safety (shorter hazardous lifetimes, lower radiotoxicity). These arguments are not without merits, but they do not justify reprocessing at present. Table 5 summarizes the present position with respect to reprocessing in countries across the globe. The choices reflect the weighting countries place on the above arguments.

Countries that reprocess (GWe)		Countries that have quit or are planning to quit (GWe)		Countries that have not reprocessed (GWe)	
China (pilot plant)	8.6	Armenia (in Russia)	0.4	Argentina	0.9
France (80%)	63.3	Belgium (in France)	5.8	Brazil	1.8
India (≈50%)	3.8	Bulgaria (in Russia)	1.9	Canada	12.6
Japan (90% planned)	47.6	Czech Republic (in Russia)	3.6	Mexico	1.4
Netherlands (in France)	0.5	Finland (in Russia)	3	Pakistan	0.4
Russia (15%)	21.7	Germany (in France/U.K.)	20.5	Romania	1.3
U.K. (ending)	10.2	Hungary (in Russia)	1.8	Slovenia	0.7
		Slovak Republic (in Russia)	2	South Africa	1.8
		Spain (in France/U.K.)	7.5	South Korea	17.5
		Sweden (in France/U.K.)	9	Taiwan, China	4.9
		Switzerland (in France/U.K.)	3.2	US (since 1972)	100.6
		Ukraine (in Russia)	13.1		
Total	103	Total	71.8	Total	143.9

**Table 5:** Country Status for Spent Fuel Reprocessing. Source: Frank von Hippel<sup>76</sup>

<sup>76</sup> Frank von Hippel, “*The Uncertain Future of Nuclear Energy*”, IPFM Research Report #9, September 2010, <http://>

Compared to the justification for commercial scale reprocessing using aqueous technologies, equally few arguments favor commercial pyroprocessing. However, a future vision including wide deployment of fast reactors presents good reasons for research and development today of reprocessing technologies that are more advanced than the present approaches.

#### *4.1.13 ROK-Specific Conclusions and Recommendations on Reprocessing*

- The ROK should keep open a range of options for long-term management of spent nuclear fuel either, nationally or through a foreign service provider. This policy is being pursued by a number of large national nuclear programs and can be comfortably accommodated in all of them because the target dates for final disposal or reuse of spent fuel are decades into the future.
- The ROK is in a global region that is politically unstable, which has led to specific agreements on nuclear technology, including the ROK-USA bilateral agreement and the 1992 denuclearization agreement. The issue of reprocessing on the Korean Peninsula is clearly more sensitive than in other global regions.
- Reprocessing today is not an economic back-end strategy.
- The ROK has problems implementing sufficient spent fuel storage capacity, but reprocessing will not ease these problems in the short term.
- Continuing R&D on advanced reprocessing technologies will prepare the ROK for possible future introduction of reprocessing as a national strategy; because of the political sensitivities mentioned above, it may be advisable to perform such R&D in a multilateral framework.

## **4.2 Partitioning and Transmutation**

### *4.2.1 Introduction*

Partitioning and transmutation (P&T) separates (“partitions”) long-lived isotopes, followed by their nuclear transformation (“transmutation”) into shorter-lived nuclides, based in part on the precept that this strategy has a safety benefit with respect to waste management. Transmutation involves the conversion of one element or isotope into another through nuclear processes. Most work is done on approaches for transmutation of minor actinides (MAs) and certain long-lived fission products. The former are the primary source of very long-term radiotoxicity of used fuel; the latter often contribute the highest predicted doses from repositories because they are more mobile than the MAs. Transmutation is achieved by subjecting nuclides to an intense flux of neutrons provided by an SFR and/or in an accelerator-driven system (ADS). Work to develop advanced fuel cycles aims to increase the efficiency of this process, but this factor is not conventionally included within the remit of P&T (although this may change, as discussed in the following section).

Reprocessing spent fuel when the aim is to recycle actinides as fuel is effectively a form of P&T—in that it reduces the number of radionuclides with long half-lives in the resulting waste stream—although it was not commonly regarded as such in the past. Work on advanced fuel reprocessing technology is, however, often presented as “partitioning” R&D, while consideration of multiple reprocessing cycles and use of fast reactors to burn a wider spectrum of actinides does, increasingly, fall within “transmutation.”

P&T explicitly aimed at reducing the problems associated with geological disposal is a more esoteric field, especially as it generally concentrates on separating and burning actinides from spent fuel. Such actinides may be important in terms of long-term radiotoxicity, but have little impact on the actual radiation doses calculated in safety assessments of geological disposal facilities (GDFs) situated in saturated, chemically reducing environments. Analyses to show the benefits of waste “burning” for small parts of the total inventory often ignore the hazards of the P&T processes themselves and the large quantities of secondary wastes produced—particularly with the range of ADS concepts, which often incorporate additional reactors to power the entire “transmutation park.” A much more limited effort focuses on burning the long-lived fission products that contribute most to calculated long-term doses (notably iodine-129 and technetium-99). Such analyses tend to be highly idealized, with little consideration for the significance of secondary wastes.

#### *4.4.2 Status of Partitioning and Transmutation As a Waste Management Approach*

Technological developments in P&T have recently been reported in a series of independent reviews.<sup>77</sup> In addition, the European Union funded the RED-IMPACT project, which analyzed the impact of P&T on nuclear waste management, particularly on final disposal. More than 23 organizations from industry, waste agencies, research centers and academia participated in the project. We consider the conclusions of these studies in the context of the justification of the P&T option as an alternative to direct deep geological disposal:

- Although none of the studies raised insurmountable problems with P&T, some were more optimistic than others. In the closing session of the last IAEA information exchange meeting, the chair recommended, “the geological disposal community should accept that P&T is a viable option in radioactive waste management.” However, there have been no indications of any new revelations or proof of concept, and the cost has been disproportionate to benefits. Hence, no objective justification has yet surfaced for the quoted conclusions of the IAEA chair “that P&T is a viable option.”
- The RED-IMPACT study found that the reduction of actinide toxicity is shown to have no significant impact on the assessed performance of a GDF for all normal scenarios. The reference to reduced consequences for human intrusion scenarios must be put into context by considering the low risk and small exposed populations in such scenarios. Doses to the public (via groundwater) from the natural evolution of the repository over very long time scales are expected to be very small, even without P&T, and removal of actinides from the waste will have very little effect on these doses. On the other hand, doses from a “human intrusion” scenario (such as drilling a borehole into the repository) would be significantly reduced by P&T. A further benefit is reduction in the risk from criticality. However, the RED-IMPACT conclusions do not consider either the full inventory of secondary wastes generated during a commercial-scale P&T program or the risks to operators of such waste. Typical results from RED-IMPACT are shown in Marivoet et al. (Figure 11)<sup>78</sup> for the case of assumed disposal in a crystalline host rock. Here, Scenario A1 is a simple

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<sup>77</sup> SERCO, “Literature review of partitioning and transmutation,” Contractor report to NDA /RWMD, 2011; NEA, “Physics and Safety of Transmutation Systems: A status report,” NEA report No. 6090, 2006; IAEA, “Assessment of Partitioning Processes for Transmutation of Actinides,” TECDOC 1648, 2010; Blomgren, J. et al., “Partitioning and transmutation: Current developments – 2010,” SKB TR-10-35, 2010; and NEA, “National programmes in chemical partitioning: A status report,” NEA rep. No. 5425, 2010.

<sup>78</sup> J. Marivoet, M. Cunado, S. Norris, E. Weetgens, “Impact of Advanced Fuel Cycle Scenarios on Geological Disposal,” *Proc. Euradwaste* (2008): 141-151.

once-through cycle and A2 single reprocessing, with burning of MOX fuel. Other P&T options (A3, B1, B2) show some reduction in the (already very low) peak dose before 100,000 years calculated in this very simple assessment. However, this calculation is explicitly only for HLW and SF and hence ignores the critically important long-lived ILW streams, which would mask any differences involved.

- Studies found that the thermal load reduction is less a reflection on P&T than the associated storage and waste separation (see data in Gonzalez-Romero, 2008<sup>79</sup>). Indeed, this claim is clearly false for strict P&T, as it converts long-lived radionuclides (which have a lower contribution to thermal loading) to shorter-lived isotopes, which must give out more heat.<sup>80</sup> The thermal load of high-level waste can in principle be reduced markedly by P&T, hence reducing the space needed for an underground repository; however, surface storage of wastes containing shorter-lived fission products may be necessary to take full advantage of this.
- Nonproliferation claims are, as implied, very difficult to argue in a rigorous manner until a practical scheme for implementation of a full P&T program is demonstrated. In any case, denaturing of Pu in some final waste form must be balanced against the major reprocessing efforts involved, considered in the past to be a major proliferation threat (for a recent assessment of such risks see Makhijani<sup>81</sup>).
- Fuel cycle options and development of regional strategy evaluations are based on highly idealized scenarios and little consideration for the practicalities of extensive movement of SF between European countries. They could be regarded as highly academic, in any case, in the absence of well-established P&T technology.
- Partitioning is a key problem area, as it involves development of novel procedures for handling highly active materials on a commercial scale. The San Francisco meeting mentioned above included reports of real progress in the last two years in advancing chemical partitioning technologies—both aqueous and pyroprocessing. Nevertheless, continuing technical problems with techniques for industrial reprocessing and waste handling—which have been under development for half a century—indicate the difficulty of transitioning from bench studies to full-scale plant operation for such processes (e.g., the constant series of problems and delays in implementation of the Rokkasho reprocessing plant in Japan). As noted, developments based on existing wet-chemical processing are more advanced than pyrochemical methods are and, although the latter have considerable potential, major materials issues need to be addressed before they could be brought into operation on an industrial scale.
- In order to reduce the problems of waste disposal, it is essential that improvements to a primary waste form do not result in production of more problematic secondary waste streams from operation and decommissioning of the required facilities. It should be remembered that, while current spent fuel reprocessing is claimed to result in HLW that is easier to dispose, the secondary long-lived LILW waste streams must also go into a geological repository and can actually result in higher doses when such wastes are co-disposed (e.g. Nagra, 2002<sup>82</sup>).

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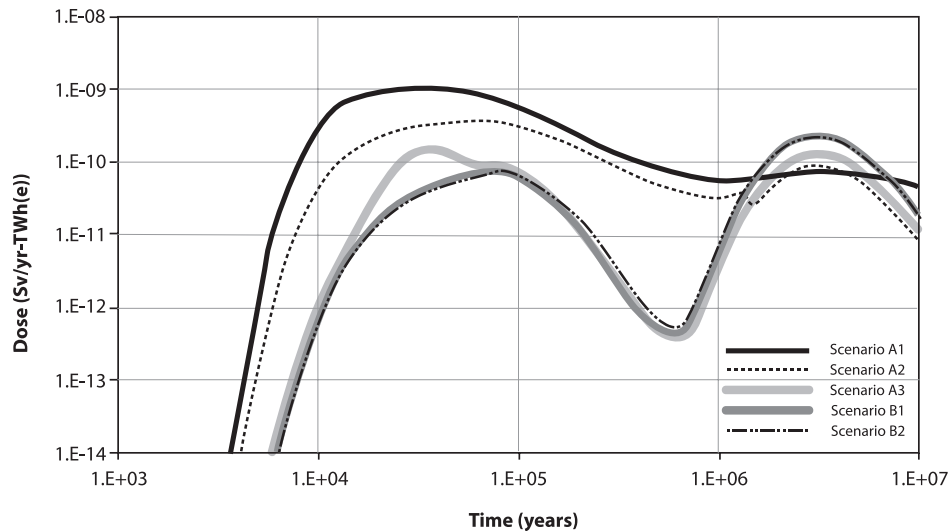
79 E.M. Gonzalez-Romero, “Impact of partitioning and transmutation on nuclear waste management and the associated geological repositories,” *Proc. Euradwaste* (2008): 125-140.

80 The heat output is directly related to the energy that the particles from decay deposit in the medium. Therefore, if a long half-life isotope is converted into another isotope with a much shorter half-life, it must emit more particles per unit time and so the heat must increase (assuming same energy particles for both isotopes).

81 Makhijani, *The Mythology and Messy Reality of Nuclear Fuel Reprocessing*, 2010.

82 Nagra, *Project Opalinus Clay: Safety Report*, Nagra NTB 02-05, 2002.

- Fast reactor development is certainly receiving much more attention and reflects the move away from conventional P&T toward next-generation power programs that can combine optimized use of fissile fuel resources with minimization of actinide inventory in wastes. As noted above, however, the availability of fast reactors is not likely to reduce significantly the challenges for disposal of all resultant wastes, if at all.



**Figure 11:** Typical results from RED-IMPACT (see Fig 7.11 in W. von Lensa et al, RED-IMPACT: Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal, 2007, pg 117) where the dose from several fuel cycle options are compared. Scenario A2 is the single recycling of plutonium in fast reactors as is done in France, scenario B2 is recycling of PWR fuel with ADS.

The countries with major R&D in P&T include Japan, France, Russia, Sweden, India and, especially within the last few years, the USA. In all cases, this activity is closely coupled with commercial interests in reprocessing and/or interest in long-term nuclear power programs. The NEA, IAEA and EU provide initiatives for coordinating and, in the latter case, funding such work. For the EU, however, it is interesting to note that although most of the radioactive waste management budget not going to geological disposal went to formal P&T, a significant amount of money is now spent on “research on other techniques to reduce the quantities and radiotoxicity of nuclear waste (optimised fuel management in power reactors and R&D on the fuel cycle in general, including advanced cycles).”<sup>83</sup>

In fact, the ROK has a longstanding research program, the Pyrogreen project, run by Seoul National University (SNU) for research in P&T, in which the default KAERI pyroprocessing is augmented with several extra steps, including an iodine/technicium separation and transmutation step. The iodine and technicium are fabricated into targets to be transmuted in a dedicated lead-bismuth-cooled reactor known as PEACER (proliferation-resistant, environment-friendly, accident-tolerant, continual and economical reactor).

Finally, although in many ways overlapping with the fast reactor fuel cycles that reduce actinide inventories while producing power, the potential of novel reactor designs that achieve the same result without partitioning (or, at least, with less reprocessing) should be noted. An example here is the “deep burn” mode of

83 S. Webster, “The Euratom research and training programme in radioactive waste management,” *Proc. Euradwaste* (2008): 91-102.



Generation IV very high temperature reactors (VHTR), which can be run either as a once-through option to reduce actinide levels or in multiple cycles to increase actinide burning (see, e.g., Brossard et al.<sup>84</sup>).

#### 4.4.3. ROK-Specific Recommendations on Transmutation of Fuel

The long-standing fundamental criticisms that no clear demonstrations of effective technology have appeared and that costs are disproportionate to benefits are still fully valid for conventional P&T schemes. The claims of benefits in terms of security, thermal loading and safety in some exotic scenarios are based only on consideration of sub-systems. Conventional P&T viewed as a whole, examining all the wastes produced and all the environmental effects, provides no clear indication that any net benefit could be produced from any existing or extrapolated future technology. Indeed, when evaluated in terms of total life cycle hazard, such P&T may actually make waste management more problematic.

Although it is debatable whether it really should be considered P&T, burning actinides in fast reactors is increasingly included under this heading and is a much more credible option, as the detriments from associated reprocessing are balanced by the value of energy produced and by the ethical and environmental benefits of increasing the utilization of limited resources of easily extractable U. For planning alternative scenarios of future accumulation until the point of closing a GDF (e.g., until around the end of this century in some scenarios), such options should be seriously considered, as they will influence both the quantities and characteristics of the waste to be included in the facility (including the fate of materials where there is uncertainty as to whether they will be declared waste or not).

The potential increased use of more novel reactor designs that also aim to reduce actinide inventories should also be considered. In particular, very high temperature reactors, which are also being developed in the ROK,<sup>85</sup> may serve as a means of hydrogen production and might become increasingly attractive as natural gas resources are depleted, or if resistance to fossil fuel combustion increases due to climate change concerns. Such reactors may not only result in a different fuel inventory, but also a requirement to deal with rather novel types of waste.

As noted above, no technical justification exists for P&T to be considered an alternative to direct geological disposal and, indeed, no evidence that any of the conventional P&T schemes could, even if they could be implemented, remove the need for deep geological disposal or even make disposal significantly easier or safer. Although maintaining a watching brief on developments in this field is prudent, no data indicate that direct investment in R&D is necessary. Nevertheless, it may be worthwhile to consider waste reduction as a component of future fuel cycles and their impacts on the inventories of HLW and other forms of waste that could arise from long-term expansion of nuclear power programmes. Here, we emphasize that, although the theoretical benefits of actinide reduction have been advanced as a justification of P&T, enhanced actinide burning in future fuel cycles may well result in larger volumes of reprocessing wastes, containing long-lived fission products that may actually be more difficult to dispose than normal spent fuel.

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84 P. Brossard, et al., "The VHTR fuel and fuel cycle project: status and ongoing research," Proc. GIF Symposium (2009): 103-108.

85 The Very-High-Temperature Reactor (VHTR) is a graphite-moderated, helium-cooled reactor with a thermal neutron spectrum, Gen IV International Forum, <http://www.gen-4.org/Technology/systems/vhtr.htm>; Kee-Nam Song, Sung-Deok Hong, and Hong-Yoon Park, "High-Temperature Structural Analysis of a Small-Scale PHE Prototype under the Test Condition of a Small-Scale Gas Loop," *Science and Technology of Nuclear Installations* (2012): 1-10.



### 4.3 Storage as a Long-Term Option

As discussed previously, storage of spent nuclear fuel or HLW is a proven technology that has been in use at numerous sites around the world for several decades and appears to be feasible for at least a century or more (See Appendix D for overview of major storage programs). Recently, interest has grown in the feasibility of extending storage out for many more decades or even for a few hundred years, primarily because of the increasing delays in major disposal programs and also because of the recognition that new nuclear programs will not be able to implement geological disposal for many years. Some have even discussed the concept of “indefinite storage.” Whether such extended storage can be regarded as a real alternative to geological disposal is debatable, since it can provide permanent safety and security only if continuing maintenance is assured into the future. In any case, extended storage can affect spent fuel disposition choices and can postpone decision-making indefinitely.

Otherwise, a decision to opt for extended storage of any specific category of waste simply affects the schedule for a GDF. An example would be assessment of the storage requirements for high burn-up fuel from new build reactors. GDF options that depend on technologies that are not yet developed (e.g., advanced partitioning or transmutation that can drastically affect waste volumes and forms) can be justified only if safe and secure storage can be guaranteed for the possibly very long time until the technologies are mature.

Exactly how long storage should last reflects political considerations as much as technical ones. Both considerations are discussed in the following sections, beginning with technical considerations.

#### *4.3.1 Technical Issues Related to Extended Storage*

##### *4.3.1.1 Open Questions and Possible Future Developments in Extended Storage*

Today, the most active R&D area related to dry cask storage concerns the long-term stability of the storage system. Storage of spent fuel in pools at reactors is an established technology that has been practiced for decades. Storage in dry casks is also well tested and is confidently expected to present no problems for decades into the future. This point is well illustrated by the development of the so-called “waste confidence rule” of the US NRC.<sup>86</sup> In 1984, the NRC determined that spent fuel could be stored safely for at least 30 years after a reactor’s operating license expired. In 1990, the NRC changed this timeline to 30 years beyond a 40-year initial license and a 30-year license renewal period, for a total of at least 100 years. In 2008, based on the NRC’s review of spent fuel pools and dry cask storage along with post-9/11 security enhancements and study results, the NRC proposed revising its finding to state that spent fuel can be stored safely for at least 60 years beyond the life of a reactor’s license in spent fuel storage basins or dry storage facilities, and this updated rule was finalized in December 2010. The exact wording of the NRC finding follows:

The Commission finds reasonable assurance that, if necessary, spent fuel generated in any reactor can be stored safely and without significant environmental impacts for at least 60 years beyond the licensed life for operation (which may include the term of a revised or renewed license) of that reactor at its spent fuel storage basin or at either onsite or offsite independent spent fuel storage installations.<sup>87</sup>

<sup>86</sup> Winston & Strawn LLP, “Waste Confidence and Spent Fuel Storage Developments,” 2008.

<sup>87</sup> USNRC, “Waste Confidence Decision Update,” *Federal Register* 75, 246 (December 2010): 81038, <http://www.gpo.gov/fdsys/pkg/FR-2010-12-23/pdf/2010-31637.pdf>.

In reaching its conclusions, the NRC commission reviewed the long-term integrity of spent fuel under water pool storage conditions, structure and component safety for extended facility operation for storage of spent fuel in water pools, the safety of dry storage, and the potential risks of accidents and acts of sabotage at spent fuel storage facilities.

However, objections to the 2010 revision were filed, and the US Court of Appeals for the District of Columbia Circuit threw out the revision to the NRC's waste confidence rule. The main objection was to the NRC statement that "a final repository for nuclear waste would be available 'when necessary'" ("by 2025" was the original language of the rule). The court found that the update to the waste confidence decision could not provide sufficient guarantee that a final waste repository would be ready or indeed ever built at all. It further found that the NRC had failed "to properly examine the future dangers and key consequences" of storing fuel on nuclear sites for up to 60 years after license expiration. The court decided that the commission must assess the potential environmental effects of a failure to find a repository site. In its reaction to the court decision, the NRC decided that it can no longer issue licenses for lifetime extension or for new reactors, since acceptance of the waste confidence rule is an integral part of such licenses. This development opens the door for further assertions that long-term interim storage is not sufficiently safe. In fact, the commission is already looking at much longer storage periods and has started a consultation exercise<sup>88</sup> on this topic. Although the commission has decided to develop a plan for a longer-term rulemaking and an Environmental Impact Statement (EIS) to assess the environmental impacts and safety of long-term SNF and HLW storage beyond 120 years, it notes that studies performed to date have not identified any major issues with long-term use of dry storage.

The history to date indicates the technical conviction that long-term storage of spent fuel is not a critical safety concern, so there are no pressing R&D needs. However, with repository plans moving ever further into the future, several countries have begun to study the long-term behavior of stored spent fuel—in particular, possible impacts on later disposal. In 1997, the IAEA initiated the Co-ordinated Research Project on Spent Fuel Performance Assessment and Research (SPAR), which is designed to:

- Collect and exchange spent fuel storage experience of the participating countries;
- Build a comprehensive international database supporting the licensing of present and future technologies;
- Carry out research work which will evaluate and justify the storage of spent fuel for long periods of time (more than 50 years);
- Assist in defining how the requirements for spent fuel storage and for the whole back end of the fuel cycle are connected.

The SPAR-II programme, which ran from 2002 to 2010 and in which the ROK<sup>89</sup> also participated, looked to extend this justification to 100 years. The documentation on this project indicates that, for wet storage, no immediate R&D needs exist, summarized by the following statement:

For zirconium alloy clad fuel, data exists for continuous pool storage of greater than 40 years. This data indicates that cladding corrosion to be extremely low ( $1\text{E}-06 \mu\text{m/a}$ ) and, therefore,

88 USNRC, "Draft Report for Comment: Background and Preliminary Assumptions For an Environmental Impact Statement—Long-Term Waste Confidence Update," December 2011, <http://pbadupws.nrc.gov/docs/ML1134/ML11340A141.pdf>.

89 Details of how ROK participated are described in the document: IAEA, "Fuel performance assessment and research," TECDOC 1343 (2003): 7.

is not viewed to be the time-limiting factor for prolonged wet spent fuel storage; even in poor chemistry conditions.<sup>90</sup>

However, increased interest in the possibility of dry storage extending out to many decades has spurred several on-going studies of potential problems.

#### *4.3.1.2 Technical Measures to Facilitate Long-Term Storage for Spent Fuel*

For long-term spent fuel storage, various conditioning methods are available to reduce the volumes to be stored and to avoid unacceptable long-term degradation of the spent fuel or its packaging; however, most attention today is devoted to dry storage. Section 2 describes the technologies for these methods and the efforts to confirm that the containers employed, or the fuel within them, will not degrade. Other conditioning methods examined include fuel rod consolidation in order to pack more spent fuel into a smaller volume and metallurgical treatment of the fuel leading, in some cases up to its complete reconstitution. These approaches are briefly described below, using text extracted from IAEA documentation.<sup>91</sup>

*Fuel rod consolidation for long-term storage.* Rod consolidation was researched in the German program for packaging spent fuel in a POLLUX disposal cask, which was conceived as a multi-purpose container.<sup>92</sup> By consolidating fuel rods into a compact package, there is less space for water moderator and so criticality risk is reduced. Further development of the POLLUX cask has become inactive, however, due to political decisions in Germany. Current NRC regulations still permit re-racking of the spent fuel pool grid and fuel assembly consolidation, subject to NRC review and approval, to increase the amount of spent fuel that can be stored in the pool. In the 1980s, it was generally anticipated, in particular in the USA, that after maximum re-racking in SF pools, the next step would be consolidation of assemblies. This was to be done by removal of the rods from fuel assemblies and inserting them into open baskets, commonly called canisters, that would occupy only one rack location. On the surface, this consolidation could potentially double the storage capacity of the pool. However, storage of empty fuel assembly structural components posed a problem. Designs to cut the structural material and compact it were envisioned. It was believed that 10 of these structures could be consolidated into a single basket or canister, fitting in one rack position. If only a five to one compaction of the structural material were possible, the pool capacity would increase by only 43 percent. Much work was done throughout the 1980s, including issuing of numerous patents on consolidation technologies,<sup>93</sup> and the US government reviewed the technologies and their costs at the end of that decade.<sup>94</sup>

*Metallurgical treatment.* An extreme option is to dissolve the fuel chemically, with treatment of the resulting liquid and solidification of the end products. Spent fuel in oxide pellet form can be further compacted by reduction into metallic form. Without separating any constituents of the dissolved fuel, this method

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90 Ibid.

91 IAEA, "Operation and Maintenance of Spent Fuel Storage and Transportation Casks/Containers," TECDOC 1532, 2007.

92 IAEA, "Consolidation of Spent Fuel Rods from LWR (Current Procedures and Future Plans With Reference to Work in the USA and Germany)," IAEA TECDOC 679; IAEA, Subject Classification: 0602-Fuel fabrication and storage, IAEA-TECDOC-67915.00, 1992.

93 See for example: <http://www.osti.gov/energycitations/servlets/purl/5807117/Statusofrodconsolidation.pdf>

94 TRW Environmental Safety Systems, Inc., "Civilian Radioactive Waste Management System Management & Operating Contractor: Cost Impact of Rod Consolidation on the Viability Assessment Design," A00000000-01717-5708-00004 REV 00, March 29, 1999, <http://www.osti.gov/bridge/servlets/purl/862232-HGyRtO/862232.pdf>.

would be able to provide the ultimate in fuel consolidation. It may be possible to store six or more times as much fuel in the same volume after treatment. This process can provide the additional advantage in the total waste management system of separating the short half-life or heat-producing materials from the long half-life materials, which can significantly affect the packaging, transportation, and disposal parts of the waste management system. Korea has looked at such treatments as a method of spent fuel volume reduction, as well as for the first steps in pyroprocessing.<sup>95</sup>

*Refabrication.*<sup>96</sup> Related to the conditioning methods for spent fuel is the concept of refabrication, in which a new fuel is produced from the LWR spent fuel. No industrial refabrication of spent fuel from a power reactor has occurred for reuse in another reactor. However, laboratory-scale research activities have been conducted, a representative case being the ROK's DUPIC project intended for reuse of spent fuel from PWR in CANDU reactors without separation of sensitive materials like plutonium. The basic rationale behind the DUPIC fuel cycle is that the typical remnant fissile contents of spent PWR fuel (approximately double those of natural uranium) can be reused in a CANDU reactor, which is designed to be fueled with natural uranium. From a technological point of view, the DUPIC fuel cycle concept bears some interesting features that are anticipated from innovative fuel cycle options. All the fuel fabrication processes are remotely conducted in a shielded hot cell facility.

The transfer from LWR to CANDU can literally be direct, involving only the cutting of spent LWR fuel rods to CANDU length (~50 cm), resealing (or double-sheathing) the rods, and reengineering them into cylindrical bundles suitable for CANDU geometry.<sup>97</sup> After removal of the cladding, a thermal-mechanical process is used to reduce the spent LWR fuel pellet to a powder, which is then sintered and pressed into CANDU-sized pellets. However, South Korea's nuclear energy utility has shown little interest in this fuel, as the reprocessed fuel tends to be too radioactive to use without further precautions and is more expensive. Moreover, its use would require the utility to win additional government licenses.

#### 4.3.2 Policy Issues

Some potential benefits of extended storage are:

- Costs of expensive actions, including reprocessing or disposal, are postponed to the far future and thus have very little impact on conventional costing estimates based on net present value;
- The thorny societal problem of finding acceptable disposal sites is postponed;
- If uranium resources become scarce enough to make reprocessing with current technologies economic, then this course can be taken;
- If new reprocessing technologies become cheaper and cleaner, then these can also be implemented;
- International or multinational disposal options may become available, in particular as large nuclear technology providers inaugurate their own disposal facilities;
- Options remain open for the eventuality that new technologies emerge.

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95 Y-S. Hwang and J-H. Park, "Role Of P&T On Permanent Disposal Of HLW in Korea, Korea Atomic Energy Institute report, (n.d.), <http://www.oecd-nea.org/pt/docs/iem/jeju02/session1/SessionI-01.pdf>.

96 IAEA, "Data Requirements and Maintenance of Records for Spent Fuel Management: A Review," IAEA TECDOC 1519.

97 Jeremy J. Whitlock, "The Evolution of Candu Fuel Cycles and Their Potential Contribution to World Peace," Atomic Energy of Canada Limited, [http://www.nuclearfaq.ca/brat\\_fuel.htm](http://www.nuclearfaq.ca/brat_fuel.htm).

On the other hand, moving toward geological disposal, rather than simply prolonging current storage policies, can:

- Help to counter the public and political argument that there is no demonstrated “solution to the waste problem” by showing that an active strategy toward a final solution is being pursued;
- Enhance safety and security (e.g., in times of civil unrest) by moving spent fuel from surface ponds to more secure dry cask storage or even to underground stores;
- Ensure that the expertise built up over the past decades on geological disposal will not be lost or vastly diminished because the scientists involved finish their careers before being able to pass the acquired knowledge and expertise to the next generations;
- Avoid transferring the financial and other burdens of arranging final disposal to future generations;
- Maintain R&D knowledge and train young scientists and technologists in spent fuel treatment and disposal.

A paper produced by the IAEA in 2003 still represents the consensus view of the major waste management programs on storage and disposal. It records that storage of radioactive waste has been demonstrated to be safe over some decades and can be relied upon to provide safety as long as active surveillance and maintenance are ensured. Geological disposal, however, promises long-term safety without surveillance and maintenance and, moreover, emplacing the spent fuel or waste in a GDF increases the security of the materials. The paper concludes that:

Active controls cannot be guaranteed in perpetuity because there is no guarantee that the necessary societal infrastructure can be maintained in perpetuity. Therefore, for the type of radioactive wastes considered here — wastes that remain hazardous for thousands of years — perpetual storage is not considered to be either feasible or acceptable.<sup>98</sup>

The presidentially appointed US Blue Ribbon Commission<sup>99</sup> considered extended storage as a spent fuel management option. The members agreed that:

...experience shows that storage—either at or away from the sites where the waste was generated—can be implemented safely and cost-effectively. Indeed, a longer period of time in storage offers a number of benefits because it allows the spent fuel to cool while keeping options for future actions open.<sup>100</sup>

They recommended that efforts be made to develop one or more consolidated storage facilities and also to prepare for the eventual large-scale transport of spent nuclear fuel and high-level waste to the facilities. However, they also urged prompt efforts to develop geological disposal facilities and recommended that:

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98 IAEA, “The Long Term Storage of Radioactive Waste: Safety and Sustainability: A Position Paper of International Experts,” IAEA 2003. See: <http://www-pub.iaea.org/books/IAEABooks/6858/The-Long-Term-Storage-of-Radioactive-Waste-Safety-and-Sustainability-A-Position-Paper-of-International-Experts>.

99 BRC, “Report to the Secretary of energy,” Blue Ribbon Commission on America’s Nuclear Future, Washington, DC, January 2012.

100 BRC, “Transportation and Storage Subcommittee Report to the Full Commission,” Updated Report, Blue Ribbon Commission on America’s Nuclear Future, Washington, DC, January 2012.



...a program to establish consolidated storage must be accompanied by a parallel disposal program that is effective, focused, and making discernible progress in the eyes of key stakeholders and the public.<sup>101</sup>

Indefinite storage with continuous institutional control has been suggested as an alternative to disposal. Objections to this option are both ethical and technical and are discussed further in an earlier study by Nirex, which clearly notes that:

Storage on an indefinite timescale is advocated by proponents of guardianship concepts, and has been rejected in most studies of long-term radioactive waste management.<sup>102</sup>

### 4.3.3 *Security Concerns*

Another long-term storage issue concerns safeguards and physical protection. The former is less controversial. IAEA safeguards are designed to ensure that fissile materials are kept under close surveillance and cannot be diverted and misused. Adherence to IAEA Safeguards requirements is standard practice. There is clearly a need to facilitate agency inspections as much as possible, and this requirement should be catered for in the design of any future storage facilities.

The issue of physical protection of spent fuel—especially in storage pools—has been more controversial. The aim of physical protection is to protect the facility not only against terrorist attacks or any other form of willful sabotage, but also against accidental events such as aircraft crashes. The typical robustness of SF storage systems, as well as the passive conditions under which they are kept, should already provide a high degree of protection.

Intensive studies of the security of spent fuel storage were initiated in the US as a result of controversial assertions on the vulnerability of pool storage to terrorist attacks, including by the use of aircraft. A paper published by Alvarez and co-workers was contradicted by the NRC, and the original authors responded to this rebuttal. The National Academy of Sciences (NAS) then held a workshop on the issue and subsequently performed a specific study, whose results were published in 2006.<sup>103</sup>

The assertion was that, while dry cask storage is not particularly vulnerable to terrorist attacks because of its robust design, spent fuel pools are potentially at risk from accidents or terrorist attacks that could result in loss of cooling water. A loss-of-coolant event could allow decay heat in spent fuel to build up, creating the possibility that the zirconium cladding could catch fire under circumstances in which additional measures to cool it were not put into place. In the extreme, such a fire could release large inventories of volatile radionuclides, such as <sup>137</sup>Cs. As a result of the controversy, the National Academy's study was designed to provide an assessment of:

- Potential safety and security risks of spent nuclear fuel stored in cooling pools at commercial reactor sites;

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101 Nirex, "Literature review of approaches to long-term storage of radioactive waste and materials," Nirex report N/107, 2004.

102 Ibid.

103 Alvarez, et al., "Reducing the hazards from stored spent power-reactor fuel in the United States," 2003. For the NRC response see: USNRC, "Fact Sheet on NRC Review of Paper on Reducing Hazards from Stored Spent Nuclear Fuel," <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/reducing-hazards-spent-fuel.html>.



- Safety and security advantages, if any, of dry cask storage versus wet pool storage at reactor sites;
- Potential safety and security advantages, if any, of dry cask storage using various single-, dual-, and multi-purpose cask designs.

In the public version of the report, published in 2006, the conclusion asserted that spent nuclear fuel stored in pools at some commercial nuclear reactors might be at risk of terrorist attacks. The report called on the NRC to conduct additional analyses to obtain a better understanding of potential risks and to ensure that power-plant operators took prompt and effective measures to reduce the possible consequences of such attacks. The National Academy committee found that an attack that partially or completely drained a plant's spent fuel pool might be capable of starting a high-temperature fire that could release large quantities of radioactive material into the environment. The committee recommended that two measures be taken promptly to reduce the potential for such fires: reconfiguring the position of fuel assemblies in the pools to more evenly distribute decay-heat loads, and making provisions for water-spray systems to cool the fuel that could continue to operate even after the pool or the building in which it was housed was damaged.

The nuclear industry reacted to the report by emphasizing that the NAS did not recommend unloading of used fuel from storage pools into dry storage containers, and that in its response to the report, the NRC, even after conducting additional risk analyses, "consider[ed] the likelihood of a zirconium fire capable of causing large releases of radiation to the environment to be extremely low." Nuclear opponents, on the other hand concluded that nuclear waste at power plants is vulnerable to attack and that the US Congress should pass legislation to remove waste from overcrowded pools.<sup>104</sup>

#### *4.3.4 ROK-Specific Recommendations on Extended Storage*

Spent fuel will, in all conceivable scenarios, be stored in the ROK for decades. Long-term storage is necessary because of the cooling period required for most further treatment of the fuel and/or because advanced treatments, such as pyroprocessing cannot be implemented on a large scale for many years. A long storage period has some advantages, as pointed out in Section 3.3.1. For the ROK, some of the potential benefits are of less relevance than for many other countries, which have smaller and less ambitious nuclear programs. For example, delaying expenditures or avoiding controversial repository siting initiatives may be less important than illustrating by positive actions that the ROK has a dynamic and credible nuclear program. On the other hand, with its strong interest in establishing an advanced reprocessing capability, the ROK has good reason to store spent fuel and thus keep this option open. Given the unavoidable long storage period, the prime question is whether the ROK should, as part of its official back-end policy, deliberately extend the decades-long period to even longer storage times of a hundred years or more. An approach with 100 to 300 years of storage has been proposed for the US and may appeal also to small or new nuclear countries. For the ROK, however, this approach would lead to a loss of credibility and to yet more difficulties in arranging adequate storage capacity.

An appropriate ROK strategy with respect to extended storage of spent fuel could include the following principles:

- The ROK should estimate storage requirements over the next two to three decades, openly recognizing that capacity must be provided for this, and initiate a campaign with public and political interactions to find suitable volunteer sites.

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104 Ibid.

- Since spent fuel will be in dry storage for long periods, the ROK should follow the research under way elsewhere on potential long-term degradation of stored fuel and assess opportunities available to participate in such research.
- “Indefinite” storage, or 100-plus-year storage, should not be the ultimate goal. The storage siting initiative should be clearly for interim storage, which implies that credible strategies for further treatment or disposal of the spent fuel must also be developed and publicized.
- The preferred strategy can be the reprocessing of the spent fuel in order to recover fissile materials. However, it should be acknowledged that, for this strategy too, a final disposal solution in a geological repository will be needed for some long-lived residues.
- Accordingly, a credible roadmap leading several decades in the future to implementation of a repository must be part of the overall national storage and disposal strategy.

#### 4.4 Geological Disposal

All of the technologies described above ultimately give rise to some wastes that are highly active and/or long-lived. For such wastes, geological disposal is the only recognised approach that can provide safety and security in the future. Geological disposal of the spent fuel or of HLW derived from its reprocessing is judged by almost all countries, and also by international organizations such as the IAEA, the Nuclear Energy Agency (NEA) at the Organization for Economic Co-operation and Development (OECD) and the European Commission (EC), to be a safe solution. However, plans for siting deep repositories have encountered opposition so that, today, sites have been selected only in Sweden and Finland (for spent fuel disposal) and in France (for HLW). The process of developing suitable technical concepts and of arriving at socially acceptable sites has taken more than 20 years in these cases. Other countries are decades away from repository implementation. However, storage in pools at the reactor or in dry casks has been shown to be safe for long periods, leaving little technical urgency for repository implementation. On the other hand, public and political pressure has led national programs to push toward this goal, and international bodies have recommended that all nuclear countries have a credible strategy leading to geological disposal for the long-lived radioactive wastes that it produces.

Regardless of whether the ROK opts for a strategy based on direct disposal of SNF or some recycling of its fuel, the ROK definitely faces the challenge of implementing a multi-year program leading to geological disposal (GD). In fact, there have already been Korean studies of repository systems for conventional spent fuel<sup>105</sup> and also for pyroprocessed spent fuel.<sup>106</sup> However, experience in numerous national programs has illustrated vividly that GD is a contentious issue that can severely affect the acceptance of a nuclear power program. The following text addresses the GD challenge and is based on in-depth experience with a large number of advanced national disposal programs as well as on international guidance. The report thus identifies the key issues that will need to be considered in establishing a geological disposal program for used nuclear fuel, provides information that will help the ROK by identifying the main options and choices that can constrain a program, and makes suggestions about appropriate choices.

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105 Cho, et al., “Development of the Korean reference vertical disposal system,” 2006.

106 Heui-Joo Choi, Minsoo Lee, and Jong Youl Lee, “Preliminary Conceptual Design of A Geological Disposal System for High-Level Wastes From the Pyroprocessing of Pwr Spent Fuels,” *Nuclear Engineering and Design* 241 (2011): 3348-3356.

#### 4.4.1 Current ROK Policy and Practice

Beginning in the late 1980s, the ROK tried to site a shallow LILW facility. Each time, however, the government made little attempt to include local communities in the decision-making process, leading often to violent opposition and eventual abandonment of the projects. Finally, in 2005 the Special Act on Support for Areas Hosting Low and Intermediate Level Radioactive Waste Disposal Facility was instituted, which exempted a community that hosts a LILW from also having a HLW geological repository. This act and a set of very lucrative incentives allowed an LILW to finally be accepted after numerous failed attempts. Unfortunately, efforts to site an HLW geological repository have not had the same success.<sup>107</sup>

The siting of a permanent HLW geological repository is the responsibility of the KRMC. The organization was established under the Radioactive Waste Management Act (RWMA), which came into practice in 2010, and is funded by the KHNP under the “polluter pays” principle. KAERI, as the premier nuclear technology organization in Korea, is responsible for the R&D of a geological repository, and in 2006 after a decade of research, established a reference disposal system for crystalline rock known as the Korea Reference System (KRS). KAERI constructed the KURT (KAERI Underground Research Tunnel) facility in 2006 to do material and environmental testing to validate the KRS concept. The KURT facility does not use radioactive sources to measure the transport of radionuclides in conducting its experiments. Rather, a series of experiments are conducted to investigate “groundwater flow and rock mass characteristics,” which with the participation of the local population, could help to build trust.<sup>108</sup> In 2007, KAERI shifted focus from KRS to what it calls the Advanced KRS (A-KRS), a modified reference design to take into account the waste materials from the Pyro-SFR cycle. The A-KRS system has two floor repositories, one at 200 m and another at 500 m depth.<sup>109</sup> No deadline for the siting of a final disposal facility has been set, although it is clear that a deep geological disposal is required regardless of fuel management strategy.<sup>110</sup>

#### 4.4.2 GDF Concept Selection

One of the main tasks of the GD program will be to consider how to select an appropriate GDF concept (multibarrier system and safety concept). Clearly, the choice of concept must be matched closely to the site selection program, as the site will define the eventual geological environment in which the GDF will be constructed, the main constraint on choice of concept being the host rock and surrounding rock formation properties. (See Appendix A for discussion on the geological environment in Korea based on a KAERI report.)

Solutions can be found that meet regulatory requirements in different ways for different environments, as there are various ways to build an integrated multibarrier system using different combinations of the various strengths of barrier functions. Some national programs have focused on only one geological environment, mainly because their national geological conditions restricted the choices available (e.g. Sweden, Finland). This approach, in turn, has led to a focus on just one or a few GDF concepts. Others have chosen to focus the majority of effort on a particular geological environment, even though they have had a range available (e.g., Germany on salt). Where countries possess a wide range of possible geological environments and

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107 Herman Damveld and Dirk Bannink, “Management of spent fuel and radioactive waste State of affairs: A world-wide overview,” *Nuclear Monitor* 746/7/8 (2012).

108 Pomper, et al., “Nuclear Power and Spent Fuel in East Asia,” 2010.

109 Yongsoo Hwang and Chul-Hyung Kang, “The Development of a Safety Assessment Approach and Its Implication on the Advanced Nuclear Fuel Cycle,” *Nucl. Eng. and Tech* 42 (Feb 2010).

110 OECD, “Radioactive waste management in Republic of Korea,” 2010: 10

adopt a voluntarism approach to siting (e.g. UK and Japan), then the matrix of possibilities is wider and these countries may have to retain a range of GDF options active throughout the development stage, until a final site is identified.

Thus, identifying the approach to concept selection is intimately linked with the approach to GDF siting and needs to be considered at the outset of the program. Deciding on how many concepts to propagate through the GD program will be an important topic for the ROK program. In addition, defining the point at which ‘concepts’ give way to ‘design’ must also be considered. It is important for the GD program to maintain a flexible approach to design before a site or geological environment is identified.

Another influence of concept selection is the possibility of co-disposal of other long-lived wastes (HLW from reprocessing and ILW) in the GDF and how this may affect design considerations. Among other factors it will affect the land area required, the engineering requirements for different sizes of tunnel/vault/cavern, the materials used and their interactions.

#### *4.4.3 Deciding If and When to Dispose of SNF*

Many factors will come into the strategic decision on whether to dispose of SNF without reprocessing and, if not, how to devise a schedule for disposal. What follows should be regarded only as a checklist of factors and factors that will need to be considered.

##### *4.4.3.1 Implications of the Inventory of SNF, Location and Future Accumulation*

The SNF inventory will have important implications for the time schedule and costs of a GD program. It also is a critical input to GDF concept selection and impacts every other area of the GD program in some way. The main aspects that need to be considered are discussed below.

Amounts of SNF in store today and future accumulation. The ROK reference value of about 100,000 tons of heavy metal (tHM) arising as PWR and CANDU fuel is a considerable quantity of SNF to dispose of when compared to most other national programs. Apart from the US and Canadian programs, all other national programs for SNF disposal are near an order of magnitude smaller than the ROK reference inventory (e.g., Finland, Sweden, Switzerland, and the UK—if SNF is disposed). The total inventory affects:

- GDF size and layout and the availability of suitable volumes of rock;
- Those aspects of variable GDF cost that scale directly to the number of waste packages;
- GDF operational period—KAERI had earlier estimated<sup>111</sup> a disposal emplacement rate of about 1.5 tHM/day, which equates with a minimum operational period of over 300 years;
- GDF long-term safety—radiological dose impacts will depend in part on the total radionuclide inventory.

Burn-up and cooling profiles leading to indication of earliest date a GDF might be required. SNF needs to be cooled for a prolonged period before it can be accepted for disposal in practically all current GDF concepts. Apart from the practical aspects of handling, the heat output of the waste needs to be low enough that, for reasonable packing densities of fuel in disposal containers, the temperatures of the surrounding engineered barrier systems in the GDF remain within acceptable bounds. Even though the

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<sup>111</sup> K.S. Chun, J.W. Choi, C.H. Kang and H.S. Park, Approaches for developing the reference concept of a geological disposal system and the relevant R&D status in Korea, IAEA-SM-357/63, 1999.

peak “thermal period” in the GDF is relatively short (a few hundred years), these requirements are critical aspects of design.

SNF heat output will depend on the burn-up of the specific fuel assemblies and the time that they have been in storage before disposal. Heat output of SNF waste packages will depend on the number of assemblies they contain and the size, shape and material of the package, as well as any decisions on whether to mix assemblies with different burn-up or different composition (e.g., UOX and MOX) within the packages. The spacing of waste packages within the GDF affects both the near-field temperature within the engineered barrier system (EBS) materials and the temperatures attained in the nearby repository host rock. These issues can be important for the repository designer. The spacing of waste packages is also a critical factor in defining the size and, by implication, the cost of a GDF.

The majority of national programs for SNF disposal consider pre-disposal storage times of at least 40 to 50 years. With the increasing use of higher burn-ups, these storage times will have to increase, unless GDF and EBS designs can be adapted to take the higher thermal loads. In any case, a design concept can be chosen so as to allow reasonable storage times. From the viewpoint of the ROK, it would seem reasonable at the moment to assume that ex-reactor storage periods of about 50 to 60 years will be necessary. Developing a scheme to relate SNF age and burn-up to package designs and thermal loads is an important element of work leading to the estimation of the most appropriate time for first SNF disposal—with consequent implications for interim storage requirements.

Interim storage capacity and potential storage bottlenecks if GDF is not available. There are obvious economic and transport advantages to having any centralized interim storage facility at the eventual SNF disposal site. However, potential drawbacks also exist: the facility will be required much earlier than the GDF, and this relative urgency may interfere with a more measured GDF siting program. Another consideration is where to locate the SNF encapsulation plant—at a centralized storage facility or, if at a separate location, at the GDF. Encapsulation (i.e. overpacking for disposal) could potentially generate massive containers (e.g. prefabricated EBS modules) that may be difficult to transport between widely separated facilities.

Future nuclear energy policy. Many national programs are effectively ignoring the impact on GD programs of extended nuclear power generation over the next 50 to 100 years. GD programs continue to focus on existing wastes plus planned operational lifetimes of existing NPPs, without considering the likelihood that plant lives will be extended and, more importantly, that new NPPs will be built. The GD program should begin with a flexible and “eyes open” approach to SNF generation scenarios that can accommodate a range of boundary conditions—particularly important because the timescales of GD programs (from launch to GDF closure) are typically estimated to be in the range of 50 to more than 100 years.

Impact of reprocessing policy. If a reprocessing program begins, then SNF will be replaced in a GDF by ceramic HLW from domestic pyroprocessing (or vitrified HLW from reprocessing overseas). In some management scenarios, it is conceivable that, even with an early start on reprocessing, there will be some SNF that is unsuitable for reprocessing and might be directed to a GDF. Any scenario will include LILW-LL from NPP operations and elsewhere, which could be joined by metallic LILW-LL from a domestic reprocessing program.



#### *4.4.3.2 Possibility of Co-locating a GDF with Other Facilities*

Having nuclear facilities such as an NPP or a centralized interim storage facility at the eventual SNF disposal site has obvious economic and transport advantages. Some of the issues raised earlier could affect GDF scheduling if its development were to be linked to the siting of a related facility, but other considerations could result from national policy decisions. Depending on the availability of potentially suitable geological environments for disposal, it might be decided to focus GDF development on an existing nuclear site such as an NPP. This approach can affect GDF scheduling if it is found that obtaining societal approval and permitting can be accelerated on such a site. In addition, obtaining regulatory permits for elements of the GDF on a site that is already licensed for certain activities may be more straightforward. However, potential drawbacks arise when a facility, such as a centralized interim disposal facility, will be required much earlier than the GDF, and this relative urgency interferes with a more measured GDF siting program.

#### *4.4.4 Siting a GDF*

It is often said that finding a suitable and acceptable site for a GDF is the most difficult aspect of a GD program. Siting difficulties worldwide is well recognized. Possibly the most important decision of the whole GD program will be the chosen approach to finding a GDF site: will the process be technically led, volunteer community led, or led by volunteer communities within preferred areas that are first identified using technical guidelines? The lessons learned from all national programs focus on the second two approaches. The essence of any successful siting program is that it is consensual and inclusive at all stages, and that all aspects of the repository project are transparent.

The following guiding principles are suggested. The siting approach should:

1. Be based on a transparent selection process associated with agreed and well-defined siting factors;
2. Seek volunteer host communities from within the wide regions that are not excluded a priori by siting factors and evaluate them on their merits;
3. Published in advance any work and allow a period for consultation;
4. Be structured in clear steps with clear decision points and well-defined responsibilities;
5. Be flexible enough to adapt to changing requirements over the course of the project;
6. Provide up-to-date information to the public and stakeholders at each stage;
7. Not aim at finding the safest site (as this can never be demonstrated) but at finding safe sites that are the most suitable, taking all siting factors into account;
8. Be able to compare alternative sites transparently using the siting factors;
9. Involve the regulatory agencies from the outset;
10. Achieve a solution on the required timescales at reasonable cost and with reasonable use of resources.

##### *4.4.4.1 Technical Aspects of Finding Potentially Suitable Sites*

An element of the approach suggested above is to use exclusion criteria to initiate the siting program. Such criteria have been used recently in both Japan and the UK, and are designed to remove clearly



technically unsuitable regions of a country from consideration at the outset. They are generally based on considerations of tectonic and geological stability or resource potential and identify areas that are highly likely to be perturbed in the next thousands of years by major natural events or human activity. A nationwide volunteer program should consider any location that comes forward, on its merits, provided that it is not excluded a priori by these measures. Possible exclusion guidelines for consideration in the ROK are uplift rates, rock deformation style/rate, proximity to faulting, geothermal potential, resource potential and presence of major bodies of exploited groundwater. In the current UK siting program, the national British Geological Survey is responsible for testing whether any volunteer sites pass the exclusion guidelines, and it has recently published its first evaluation of an area that has expressed an interest in being considered for a GDF.<sup>112</sup>

If more than one potential site emerges from the site identification program, then they will need to be compared at some stage. Approaches to this process depend on strategic decisions as much as technical factors. Whatever the approach, decisions need to be transparent, and the approach needs to be published in advance.

At some stage, sites may need to be compared on the basis of a wide range of factors (environmental impacts, safety, cost, engineering feasibility, local issues, etc). Multi-attribute analysis (MAA) is a possible and well-tested method to compare a set of contending sites. The technique provides quantitative support to inform decision-makers and can help to justify their choices and make them more transparent. Other stakeholders can be involved in the MAA process so that their views and preferences can be clearly expressed and accounted for.

In establishing the site selection methodology, while it may be useful to define preferred thermal, hydrological, mechanical and chemical properties for host rock and surrounding formations, it is likely to be unhelpful to set up rigid, quantitative bounds for these properties in terms of what would be acceptable/unacceptable. It is the integrated behavior of the total system that is important, not one property in isolation—it is possible to achieve acceptable performance with various combinations of property values for the specification or performance of the different system components. Nevertheless, some programs have found it useful to define a limited number of technical “stop” criteria from these properties for use during site investigations—the discovery of a particular property would make a site difficult to develop (e.g. hard to make a safety case).

#### *4.4.4.2 Societal Aspects after GDF Site Selection*

During GDF design development work, local communities are likely to have a considerable interest in the investigations and how the GDF and its surface facilities might look. Some programs have identified an early and important role for a site liaison committee, which meets regularly to keep communities informed and to discuss issues that arise. In particular, such committees can play an important role in decision-making. Obtaining community buy-in to planning decisions will be critical to good working relationships over the long operational lifetime of the GDF. Areas where the community representatives may have a particular interest include the location design and appearance of specific facilities, operational schedules, local transport arrangements and aspects of GDF inspectability and retrievability. Retrievability, inspectability and closure policy will be of considerable interest, and the views of both the communities

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112 J.H. Powell, C.N. Waters, D. Millward, and N.S. Robins, “Managing Radioactive Waste Safely: Initial Geological Unsuitability Screening of West Cumbria,” British Geological Survey Commissioned Report CR/10/072, 2010.

and the implementer will evolve through the many decades of the GD program. A gently progressive, phased approach needs to be considered, which does not foreclose on any possibilities until all parties feel comfortable to make commitments on decisions.

One of the most difficult aspects of siting is deciding which communities should reap benefits. It is accepted today that it is not only the host community (defined by some political boundary, such as a municipality) that should benefit. The importance of involving communities surrounding the host communities is now well-recognized, in order to avoid the so-called “donut effect,” whereby the host community feels content, the rest of the nation feels content, but the immediately surrounding communities are discontent, because they feel significantly affected but inadequately compensated.

The SAPIERR<sup>113</sup> project identified a range of possible benefits that might be considered; a project might wish to have elements of all of these in a total package. Of course, it is the cash incentives that are often most talked about and receive the widest media attention.

Sorting out the most appropriate approach to community benefits is a major issue in the GD program and should be given early consideration, as it will inevitably become a bargaining chip in the site selection process. Of course, the ROK already has gained experience in negotiating local community benefits in the scope of its LLW repository program, and the implementer will need to consider whether this model is, or should be, transferable to a GDF and the other GD facilities.

#### *4.4.5 Elements of the Initial Stages of a GD Program*

The GD program should be planned in stages, closely linked to critical milestones such as launching a siting program, narrowing down to sites for detailed investigation, selecting a final site, licensing, constructing the GDF, etc. Deciding the precise nature of these stages is an important initiating step in the GD program and needs to be done in collaboration with key stakeholders, such as the government and the regulating agencies.

##### *4.4.5.1 Disposal System Specification*

An entry point to defining the program as a whole is to establish a specification for the GD system (the disposal system specification, or DSS). This process will evolve and become more detailed and prescriptive as the program matures. The aim of a specification is to set out requirements on the whole system and consequent requirements on all components of the system.

##### *4.4.5.2 GDF Siting and Site Work, To the Point of Operation*

Integrating the site identification, approval and SI work into the main program can dominate scheduling. Frequent unplanned delays in obtaining permissions can occur at every step of the siting work, making difficult a robust time plan for the other elements of the program that may be waiting for information

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113 Chapman, N. A., McCombie, C. and Richardson, P., “SAPIERR Strategic Action Plan for Implementation of European Regional Repositories: Stage 2, Work Package 3: Economic Aspects of Regional Repositories,” European Commission. See: [ftp://ftp.cordis.europa.eu/pub/fp6-euratom/docs/sapierr-2-3-economic-aspects-of-regional-repositories\\_en.pdf](ftp://ftp.cordis.europa.eu/pub/fp6-euratom/docs/sapierr-2-3-economic-aspects-of-regional-repositories_en.pdf).

from the siting program (e.g., design and safety assessment). Without unreasonable delays and licensing problems, a typical total duration for a smooth project based on voluntarism is between 15 and 25 years.

#### *4.4.5.3 GDF Design*

GDF design begins at a conceptual level and evolves into site-specific designs and, eventually, into a pre-operational design. If a voluntarism approach to siting is adopted, the geological environment of the GDF might remain open until several years into the GD program. Even without the flexibility that is necessitated by the uncertainties introduced by the voluntarism approach, it is advisable to maintain self-imposed flexibility in terms of concept options, at least in the first years of the program. For any given host rock, different concept options can be utilized, and it would be sensible to allow the GD program to explore these options and their implications for the ROK. This flexible approach differs from one that would, for example, import a GDF design option directly from another program at the beginning of the ROK GD program. This latter approach might not be the most efficient or economical way forward.

Narrowing down to a preferred concept and then to a specific design needs to keep pace with the growing uncertainties that arise from the siting program and, of course, each step must match the evolving DSS requirements.

#### *4.4.5.4 System Safety Assessment*

The first version of the DSS will establish a basic safety requirement that will be related, for example, to standard IAEA fundamentals of geological disposal. The next step will be to establish a safety concept that is linked to a specific concept option (or set of concept options) and that explains how the concept and its execution can meet the basic goals of short- and long-term safety. Once a safety concept is established, it is possible to explore the performance of the GDF system in more detail and produce a first safety case. A safety case will be based on safety assessments that will need to consider each element of the system and will develop progressively, from generic to increasingly specific as the siting program proceeds. Based on the experience of advanced disposal programs, it might be expected that three or more full system assessments would be produced from the start of the program to the point of license application.

#### *4.4.5.5 Environmental Impact Assessment*

Environmental impact assessments (EIAs) may be required by regulators and needed for various activities and internal planning purposes and for presenting the GDF program to local communities. Generally, an EIA would address the non-nuclear environmental impact assessments, although some countries wrap the radiological impacts into the overall EIA process. Some countries also require a strategic environmental assessment (SEA), which looks at the broader impacts of disposal and at alternatives to disposal (e.g. long-term storage) and is intended to justify the whole disposal program in a wider national or international context.

Well before the main stages of GDF activity that begins with the first underground construction work, it is advisable to have begun a comprehensive program of baseline environmental monitoring. The aim is to have a thorough characterization of the undisturbed natural conditions at the site prior to the start of major site work which could potentially affect these conditions.

#### *4.4.5.6 R&D Program*

An active R&D program is an essential aspect of a GD program. It both supports the developing design and assessment work and is a means of involving scientists and engineers from academia and national institutions in the project. The R&D program will evolve over the many decades of the GDF program, and one of the main tasks with defining the activities is to match the timescales for delivery of results to end-users in the project. The ROK already has a disposal R&D program, including underground experimentation in the KURT facility at KAERI. It will be important to establish a robust means of defining and evaluating the ROK R&D program, bearing in mind the key link to safety assessment and design work. One of the most difficult aspects of establishing an R&D program is to define the priorities, as funding will always be limited.

R&D can be more efficient by coordinating some aspects with other national organizations in shared R&D projects or facilities (such as underground research laboratories (URL)). It will be important for ROK disposal organizations to have an influential role in defining such work, in order to ensure its relevance to the national GD program.

#### *4.4.5.7 Management System*

An efficient and flexible GD program management system lies at the core of a successful project. Other national programs have considerable experience in this area—some good and some poor. Two important aspects should be considered: internally, the implementing agency needs to have a strong and well-integrated team to manage the various strands of technical program development; it also needs a strong outward-looking team to manage the essential stakeholder relations (e.g., regulators, government, waste producers, local communities) and communicate the GD program to them. Critically, strong overlap between these teams allows each to be familiar with the drivers and constraints of the other.

Many national programs make use of expert advisory groups to help establish, steer and review their GD program. Such groups can be extremely useful, not only in bringing their experience into the organization, but also in providing an independent, outside view on issues. A requirement to have independent review of parts of a GD program is sometimes specified by government or regulator, and it can also assist an implementer considerably in managing public and stakeholder perception by showing use of impartial expert advice (i.e., listening to and formally responding to the views of independent experts).

National programs often make use of IAEA and OECD NEA reviews at milestones in their GD programs. These organizations offer another type of external, independent review and the considerable cachet such agencies carry.

A final point under the heading of management is staff training, which is often overlooked, especially at times when resources are limited and workload is high. Nevertheless, having adequately skilled staff with up-to-date knowledge is vital, whether work is in-house or whether the agency is adopting the intelligent customer model.

#### *4.4.5.8 Relationship with Regulatory Authorities*

The implementing agency will need to maintain an appropriate relationship with both nuclear safety and environmental regulators. The way these relations are managed is critical to the credibility of a

program. Both parties (implementer and regulator) need to be fully aware of each other's requirements and constraints, but not to appear to be compromising the impartiality of the regulatory process. This balance can be difficult to achieve and requires considerable openness and understanding on both sides. In addition to national regulators, the implementer will need to deal with nuclear safeguards authorities, including international agencies, as SNF will be subject to safeguards at every stage of the GD program. Safeguards requirements are likely to develop alongside the evolving GD program and will place constraints on design and operational planning for stores and for the GDF. The issue of post-closure surveillance and monitoring of the GDF for safeguards will need careful consideration.

#### *4.4.5.9 Documentation Objectives*

Deciding on the corporate policies for maintaining and releasing information is a vital topic for the start of the GD program. Modern practice is to have as open and transparent an information system as is practical, without prejudicing proper management procedures or intellectual property rights. Making all approved reports available electronically, connected by an efficient search engine, is an obvious goal. As well as milestone documents, there may be a requirement from regulators to have clearly documented procedures within the program, especially those leading to comparing and discarding options, defining preferences and making decisions. The implementer's approach to staging the program and the techniques that will be used to assist in making decisions and involving other organizations may need to be defined and documented. Other important aspects that will require separate, dedicated documentation include the definition of the R&D program and the basis for the GD safety case.

#### *4.4.6 ROK-Specific Conclusions on Mined Geological Disposal*

The only widely accepted technical solution for safe and secure disposal of the long-lived wastes that result from any spent fuel management strategy is geological disposal in mined repositories, situated in a region that is geologically suitable and socially acceptable. For this reason, the ROK, independent of any other approaches that it considers, should have a credible strategy that could eventually lead to a national repository. In order to achieve this aim, the following steps are recommended:

- Clearly allocate responsibilities for policy, regulation, R&D and repository implementation. In particular, delineate clearly the roles of the utilities, the implementer (KRMC) and the research body (KAERI).
- Develop and publicize a national strategy and accompanying roadmap; this step should credibly lead after several decades to a national repository, should no other viable options be developed in the intervening period.
- Study the implications of different fuel cycle strategies for the necessary timing and technology for final repository implementation; this task will be a key decision aid for future policies.
- Develop options for GDF geological environments and for facility design—but without premature preference for specific solutions, given the long timescales involved. A broad survey of Korean geology could help enhance public trust that a final disposal solution is technically feasible within the ROK.
- Develop and publicize a siting policy, based on achieving consent of the local population, and revise it in light of local reactions.



## 4.5 Deep Borehole Disposal

### 4.5.1 Status of DBD

The option of deep borehole disposal (DBD) of spent fuel, HLW and other radioactive wastes has been discussed actively for many decades. DBD involves emplacing waste packages in the bottom sections of deep boreholes the depth of several kilometers—with the upper kilometers of the holes not used for disposal, but backfilled and sealed—and possibly obliterating the uppermost sections to make relocation difficult and re-access problematic. Typically, waste is emplaced in sections of the borehole at depths from 3 to 5 km, the safety principle being the considerable isolation provided by the great depth. Theoretically, DBD is an irreversible option—or at least an option that makes retrieval of wastes extremely difficult. For this reason, it has been viewed as an especially appropriate solution for disposal of fissile materials such as separated Pu, where nuclear safeguards are of central concern. Because the volume of even a very deep borehole is limited, DBD is not considered a solution for large volume waste streams (most ILW streams). All work has concentrated on the use of DBD for disposal of HLW and SF (plus conditioned Pu waste forms).

In recent years, interest in DBD has grown, as illustrated by the conclusions of some recent reviews of the topic. The most comprehensive recent evaluations of DBD have taken place in the US. Murphy and Diodato of the US Nuclear Waste Technical Review Board concluded in 2010 that DBD is a “technically viable type of geologic disposal”<sup>114</sup> (i.e., they consider it a variant of geological disposal). MIT carried out a review,<sup>115</sup> Sandia National Laboratories (SNL) conducted an extensive study,<sup>116</sup> and von Hippel and Hayes of the US Nautilus Institute prepared an evaluation.<sup>117</sup> The drivers for the SNL and MIT reviews have mainly resulted from the demise of the Yucca Mountain Project for disposal of (mainly) commercial SF from the US nuclear power program. The impetus behind the Nautilus Institute study was an exploration of ways to dispose of SF in East Asia to support a prospective nuclear weapon-free zone in the region and avoid security and sustainability dilemmas associated with the management of rapidly growing quantities of SF. The most recent evaluation of DBD has also taken place in the US. Based on their 2009 report, Arnold et al., 2011<sup>118</sup> provided a comprehensive state-of-the-art overview comprehensively documenting the reference design and operational procedures for deep borehole emplacement.

A measure of the renewed interest in DBD in the current discussions in the US is in comments from two of the US Nuclear Regulatory Commission commissioners who referred specifically to DBD when deliberating their positions in a waste confidence update of September 2009. Commissioner Klein observed:

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114 W.M. Murphy and D.M. Diodato, “Some observations on deep borehole disposal of spent nuclear fuel and high level nuclear waste,” Workshop on research needs for borehole disposal, March 15, 2010, Washington, DC. See Patrick V. Brady and Michael J. Driscoll, “Deep Borehole Disposal of Nuclear Waste: Report from a Sandia-MIT Workshop on March 15, 2010 in Washington, DC,” May 7, 2010, [www.mkg.se/uploads/SNL\\_MIT\\_borehole\\_workshop\\_report\\_final\\_100507.pdf](http://www.mkg.se/uploads/SNL_MIT_borehole_workshop_report_final_100507.pdf).

115 B. Sapiie and M.J. Driscoll, *A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Waste* (Cambridge, MA: Massachusetts Institute of Technology, 2009), MIT-NFC-TR-109.

116 Patrick V. Brady, Bill W. Arnold, Geoff A. Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechar, and Joshua S. Stein, “Deep Borehole Disposal of High-Level Radioactive Waste,” Sandia National Laboratory, 2009, Report No. SAND2009-4401.

117 David von Hippel and Peter Hayes, “Borehole disposal of nuclear spent fuel and high level waste as a focus of regional East Asia nuclear fuel cycle cooperation,” Nautilus Institute Report, 2010, <http://www.nautilus.org/publications/essays/napsnet/reports/Deep%20Borehole%20Disposal%20von%20Hippel%20-%20Hayes%20Final%20Dec11-2010.pdf>

118 Bill W. Arnold, Patrick V. Brady, Stephen J. Bauer, Courtney Herrick, Stephen Pye, and John Finger, “Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste,” Sandia National Laboratories Report, October 2011, SAND2011-6749.



I am also willing to support an invitation for comment on whether the Commission's waste confidence update can reasonably allow for consideration of a broader range of disposal options. A variety of potential technological solutions to ultimate disposal may be considered in the near future, even though the principal assessments, as well as the dominant policies in the US and abroad, concern a mined geologic repository. For instance, I have heard the thoughtful suggestion that a deep borehole might be among the disposal paths for wastes remaining under some reprocessing and transmutation scenarios.<sup>119</sup>

Commissioner Apostolakis also supported a watching brief on DBD:

The federal government is charged with providing for permanent disposal of high-level radioactive waste such as spent fuel. In exercising this responsibility, it is conceivable that the future path for the disposal of high level waste such as spent fuel may not even involve a mined repository. It might include, for example, a deep borehole. This approach would not be, as I would define it, a "mined repository." However, it most certainly could be considered under some reprocessing and transmutation scenarios for the remaining amount of waste. Therefore, staff should continue to monitor closely the activities of the Department of Energy's Blue Ribbon Commission on America's Nuclear Future to ensure that we can respond to potential modifications of national policy."<sup>120</sup>

Nevertheless, it should be noted that DBD received no mention in the final update to the waste confidence decision when it was released in December 2010.<sup>121</sup> However, the US DOE Office of Nuclear Energy reopened consideration of the DBD option in 2009.

When the BRC Disposal Subcommittee submitted its final report in January 2012,<sup>122</sup> it concluded that DBD, as another form of deep geological disposal, may offer benefits for special waste forms, but the concept requires more exploration. The report outlines briefly the advantages and disadvantages of DBD compared to the mined repository approach. However, it was noted that, for a more comprehensive and conclusive evaluation of the DBD concept, it is necessary to continue and accelerate a programme of research, development and the investigation of alternative means and technologies for the permanent disposal of high-level radioactive waste.

Beside technical operational and scientific issues to be further addressed, it is recommended that 'EPA and NRC should support RD&D efforts by beginning work on a regulatory framework for borehole disposal, in parallel with their development of a site-independent safety standard for mined geologic repositories to support the RD&D effort leading to licensed demonstration of the borehole concept.'<sup>123</sup>

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119 NRC, Office of the Secretary, "Final Update of the Commission's Waste Confidence Decision," September 15, 2010, <http://www.nrc.gov/reading-rm/doc-collections/commission/cvr/2009/2009-0090vtr.pdf>.

120 Ibid., 3.

121 NRC, "Waste Confidence Decision Update," US Nuclear Regulatory Commission Report NRC-2008-0482, <http://pbadupws.nrc.gov/docs/ML1033/ML103350186.pdf>.

122 BRC, "Disposal Subcommittee Report to the Full Commission: Updated Report," Blue Ribbon Commission on America's Nuclear Future, Washington, DC, January 2012, [http://brc.gov/sites/default/files/documents/disposal\\_report\\_updated\\_final.pdf](http://brc.gov/sites/default/files/documents/disposal_report_updated_final.pdf).

123 BRC, "Report to the Secretary of Energy," Blue Ribbon Commission on America's Nuclear Future January 2012, 30, [http://brc.gov/sites/default/files/documents/brc\\_finalreport\\_jan2012.pdf](http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf).

The main BRC Report (BRC 2012)<sup>124</sup> then advocated the further development of deep geological disposal, including both the mined geological repository and the DBD concept.

DBD-related work has developed slowly in other countries, although interest has remained active. In December 2006, Åhäll<sup>125</sup> reviewed the state of knowledge for the Swedish NGO Office of Nuclear Waste Review, MKG, (its interest being in DBD as an alternative to Swedish Nuclear Fuel and Waste Management Company SKB's plans for disposal of Sweden's inventory of SF in a conventional GDF). Åhäll observed that DBD might offer important advantages compared to conventional geological disposal, in that it has the potential of being more robust:

The reason for this is that very deep borehole disposal appears to permit emplacement of the waste at depths where the entire repository zone would be surrounded by stable, density-stratified groundwater having no contact with the surface, whereas a KBS-3 repository would be surrounded by upwardly mobile groundwater.

This hydrogeological difference is a major safety factor, which is particularly apparent in all scenarios that envisage leakage of radioactive substances. Another advantage of a repository at a depth of 3 to 5 km is that it is less vulnerable to impacts from expected events (e.g., changes in groundwater conditions during future ice ages) as well as undesired events (e.g. such as terrorist actions, technical malfunction and major local earthquakes). Decisive for the feasibility of a repository based on the very deep borehole concept is, however, the ability to emplace the waste without failures. In order to achieve this further research and technological development is required.<sup>126</sup>

This opinion was rather contradicted in another Swedish publication from the waste management organization. Grundfeld 2010<sup>127</sup> made a comparison of the KBS-3 and DBD, aiming to identify the most relevant differences on a "fair basis," addressing safety functions, the status of construction techniques, and design, handling and operational aspects. The summary concludes that, essentially no major international interest exists and there is a lack of in-depth studies, e.g., related to stress effects (to the canister) caused by glaciations, earthquakes, and accident scenarios (canister stuck and damaged during emplacement operation, verification of correct emplacement, hydrogeochemical characterization of the disposal zone at depth, etc.). A critical reply to Grundfeld 2010 (and the SKB licence application documents) asserting "weaknesses" in SKB's arguments against the DBD concept, can be found in Gibb 2012.<sup>128</sup> One line of argument is that Grundfeld ignores recent developments and progress, by comparing the KBS-3 with old DBD concepts as documented in the SKB PASS project.<sup>129</sup>

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124 Ibid.

125 Karl-Inge Åhäll, "Final Deposition of High-level Nuclear Waste in Very Deep Boreholes: An evaluation based on recent research of bedrock conditions at great depths." MKG Report No 2, December 2006, Miljöorganisationernas kärnavfallsgranskning, Stockholm, Sweden.

126 Ibid., 1.

127 B. Grundfeldt, "Jämförelse mellan KBS-3-metoden och deponering i djupa borrhål för slutligt omhändertagande av använt kärnbränsle Bertil," Kemakta Konsult AB, September 2010, SKB R-10-13 (Summary in English).

128 F. Gibb, "Miljöorganisationernas kärnavfallsgranskning," MKG Underlag för kompletteringskrav rörande alternativa metoden djupa borrhål Prof em Fergus, University of Sheffield, May 2012.

129 Lars Birgeresson, Kristina Skagius, Marie Wiborgh, and Hans Widén, "Project Alternative Systems Study – PASS: Analysis of performance and long-term safety of repository concepts," SKB Technical Report, September 1992, Report No. 92-43.

In the UK, in 2007, the NDA <sup>130</sup> commissioned a study of deep borehole construction technology to consider the feasibility of drilling large diameter holes to great depth and carrying out operations in such holes. The report<sup>131</sup> considers four cases relevant to DBD at the final depth of the waste deployment zone (4 km and 5 km), depending on the geological environment, with internal diameters of 300 mm, 500 mm, 750 mm and 1000 mm. The report gives some guidance on the time scale and cost of construction, discusses risk during the drilling and waste disposal phase, outlines some expected future developments in drilling technology relevant for DBD and highlights some research and development needs. The waste emplacement concept and packaging are not considered in this report. The key conclusion is that:

...deep borehole disposal is a valid option, under certain circumstances, although a large amount of detailed work would be required to develop the concept into a technically acceptable solution.<sup>132</sup>

The depth diameter combinations required for DBD are seen as a serious challenge, but some believe that concepts with diameters of 300 to 500 mm could be successfully designed and implemented. The report also concluded that:

...only vertical boreholes should be considered at this stage as directional or the more exotic multi-lateral or fanned arrays of wells introduce unacceptable risks during waste deployment.<sup>133</sup>

The report identified casing technology and cementation/sealing in the casing-rock annulus procedures as one of the greatest challenges (or weakness) of DBD.

In the Canadian RD&D program, the Nuclear Waste Management Organization (NWMO) addresses DBD as one alternative waste management strategy. Acknowledging some of the basic advantages of the concept, NWMO concludes that, so far, when evaluating the DBD concept, the focus has been on drilling feasibility, with less focus on other aspects such as operational handling and operational safety. Other critical issues, such as the retrievability potential, limitation in the size of disposal canisters and the limited possibilities for monitoring the emplacement operation are mentioned as well. NWMO concludes that:

...to date no practical demonstration of the deep borehole concept has taken place, and bringing it to the same level of understanding as the current deep geological repository concepts would require considerable additional R&D.<sup>134</sup>

However, to overcome some of the critical aspects, NWMO outlines briefly a variant of the DBD concept (sub-horizontal boreholes), which should be feasible utilizing existing technologies. Finally, it suggested following and monitoring developments in alternative waste management technologies.

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130 The Nuclear Decommissioning Authority is an agency in the United Kingdom with the primary purpose to deliver decommissioning and clean-up of the UK's civil nuclear legacy in a safe and cost-effective manner, and where it is possible to accelerate programmes of work that reduce hazard. See the NDA website, <http://www.nda.gov.uk/>.

131 John Beswick, "Status of Technology for Deep Borehole Disposal, EPS International contractor report to UK Nuclear Decommissioning Authority, April 2008.

132 Ibid.

133 Ibid.

134 J. Villagran, et al., "RD&D Program 2011 – NWMO's Program for Research, Development and Demonstration for Long-Term Management of Used Nuclear Fuel," Nuclear Waste Management Organization Technical Report, April 2011, Report No. NWMO TR-2011-01.

In all of the work listed above, a key gap continues to be a comprehensive operational and post-closure safety assessment of DBD. Several authors also recognize that the lack of full-scale trials of certain aspects of the technology (not necessarily at envisaged disposal depths) is holding up further development. This issue, along with the findings of the studies mentioned above, is discussed in the following section.

#### *4.5.2 Developments in DBD Concepts and Technology*

A report by Beswick for the UK-NDA<sup>135</sup> concluded that a 500-mm to 600-mm–diameter borehole to a depth of 5000 m in crystalline rock is not far outside the current experience envelope of the drilling industry and is achievable with tool and process development. Appropriate drilling rigs are available and vertical drilling systems can now assure verticality, notwithstanding stress breakout influences. Casing through the full length of the borehole would be essential. Beswick considers that the time for drilling, waste emplacement and completion of a single 600-mm–diameter DBD borehole could be as little as three years. Summarizing the development needs, Beswick identifies:

- Large diameter drilling tools and drill string;
- Casing design and installation procedures for large diameters;
- Casing design for deployment zone;
- Cementation methods for upper large diameter casing;
- Waste deployment procedure and handling tools;
- Annulus sealing in the deployment zone;
- Upper borehole seals and near-surface abutment.

A pilot scheme for developing processes, systems and tools is considered to be relatively inexpensive, with casing-cement-rock integrity issues and sealing needing special attention. Beswick also acknowledges that deep borehole disposal will probably be cheaper (than conventional geological disposal) for the wastes that can be accommodated, citing a cost of \$55 to \$65 million for construction of the first boreholes, reducing significantly with subsequent holes. The 2009 MIT summary report suggests that developments in drilling techniques in coming years could significantly reduce costs.

Comprehensive information from the US studies was assembled in the 2009 report by SNL, which also reported the results of the first performance assessment that has been carried out for DBD, using techniques common to those used for conventional geological disposal (GD).

The SNL report was concerned with disposal of the US inventory of SF. It concluded that all used fuel from the existing US LWR reactors could be emplaced in approximately 1,000 deep boreholes (109,300 tHM of SF) and HLW could be disposed of in ~950 boreholes with a total cost that is competitive with mined repositories (roughly \$70 billion). SNL also concluded that long-term performance is likely to be excellent, with estimated peak doses from a single disposal borehole containing 400 PWR assemblies of  $10^{-12}$  mSv/year.<sup>136</sup> The report states:

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<sup>135</sup> John Beswick, “Deep borehole disposal of radioactive waste,” presentation to the 11<sup>th</sup> Radioactive Waste Immobilisation Network meeting, Sheffield, April 2009, <http://www.rwin.org.uk/presentations.html>.

<sup>136</sup> mSv/yr (mili-Sievert or 1/1000<sup>th</sup> Sv) is unit of radioactive dose per unit time used to measure the health effects of radiation.

Significant fluid flow through basement rock is prevented, in part, by low permeabilities, poorly connected transport pathways, and overburden self-sealing. Deep fluids also resist vertical movement because they are density stratified. Thermal hydrologic calculations estimate the thermal pulse from emplaced waste to be small (less than 20 C at 10 meters from the borehole, for less than a few hundred years), and to result in maximum total vertical fluid movement of ~100 m. Reducing conditions will sharply limit solubilities of most dose-critical radionuclides at depth, and high ionic strengths of deep fluids will prevent colloidal transport.<sup>137</sup>

As noted above, this study was the first to attempt a quantitative performance assessment of DBD, although it was simplified and conservative. The radionuclide release scenarios were two “up the hole” pathway analyses (requiring failure of borehole seals or a continuous, high permeability damaged zone along the borehole wall) and one involving lateral movement from the disposal region of the borehole through fractures in the host rock. Criticality scenarios were omitted as they were considered to be of very low probability or not credible. The safety study focused on the up-hole scenarios, with releases being driven by thermal convection up a poorly sealed borehole into a region where water was abstracted by a well. The only radionuclide to give rise to doses was <sup>129</sup>I, with doses at extremely low levels (see above).

The SNL report concluded that further work is needed to test preliminary observations about long-term performance, including work on:

- Scenarios involving other release pathways;
- More accurate modeling of the thermal-hydrogeological-chemical-mechanical behavior of the borehole and surrounding rock;
- Seal design;
- Engineered materials that sequester iodine;
- Performance assessment of arrays of multiple emplacement holes.

Since the publication of this study, new work on modelling of DBD concepts has subsequently been reported by Arnold and co-workers at the Sandia group,<sup>138</sup> in a report that examines volumetric strains and displacements in the rock surrounding the disposal borehole.

The 2009 SNL study further concluded that:

- Detailed cost analysis would be beneficial;
- Consideration of changes in legal and regulatory requirements will be needed;
- Detailed analyses of engineering systems and operational practices for emplacement are needed;
- A full-scale pilot project should be undertaken.

Work at MIT has covered a range of prospective applications of DBD. The 2009 MIT summary focuses on 40 to 50 cm–diameter holes drilled into crystalline granitic bedrock using available oil/gas/geothermal industry technology. The holes are fully lined using grouted in-place standard steel drill-pipe, with a maximum depth of 3 km, and a 1-km waste emplacement zone. The MIT group suggests the use of graph-

137 Brady, et al., “Deep Borehole Disposal of High-Level Radioactive Waste,” 2009.

138 B.W. Arnold, D.J. Clayton, C.G. Herrick, and T. Hadgu, “Thermal-Mechanical Modelling of Deep Borehole Disposal of High-Level Radioactive Waste,” American Geophysical Union Fall Meeting 2010, abstract #H31G-1086.



ite “sand” as a lubricating/thermally conducting infill between the waste canister string and borehole wall liner, to increase the prospects for retrievability. The somewhat shallower depths now being considered (3 km rather than 5 km), result in lower bottom-hole lithostatic and hydrostatic pressures. A 1,000-m emplacement zone is estimated to result in canister stack weights that will not crush the bottom-most canisters, with a significant factor of safety. Since 2003 the main focus at MIT has been on disposal of separated minor actinides and “troublesome” fission products (e.g.,  $^{99}\text{Tc}$  and  $^{129}\text{I}$ ) as a strategy for facilitating conventional disposal in near-surface mined repositories. A ceramic waste form containing minor actinides, plus  $^{99}\text{Tc}$  and  $^{129}\text{I}$ , emplaced in a 2 km–deep waste zone could hold 100 reactor-years’ worth per borehole, in which case only 12 boreholes could deal with the minor actinides of the current ROK 20-reactor fleet over an (extended) lifetime of 60 years. Descriptions of the various methods under consideration for DBD were presented by Arnold and co-workers<sup>139</sup> and Gibb<sup>140</sup> in early 2010, and these summarize well the recent refinements in DBD technology concepts.

In the UK, a research program continues at the University of Sheffield, mainly focused on thermal modeling of the so-called “high temperature” DBD concepts, in which the heat emitted by the waste is used to develop seals of various natures in the disposal zone. Gibb describes a current classification of low- and high-temperature disposal concepts: in low-temperature concepts, the heat emitted by the SF or HLW is conducted away through the near-field rock without causing any significant changes in the properties of natural barrier, although being sufficient in some concepts to cause melting of a dense backfill matrix, which then re-solidifies to form part of the engineered borehole system; in high-temperature concepts, the heat emitted by the wastes is much greater and is utilized to cause melting of the rock which, upon cooling and solidification, contributes to the containment of the wastes. In high-temperature concepts, HLW or SF is disposed earlier than in conventional GD concepts, while its heat output is greater. Whereas the DBD concept began its life principally as a high-temperature, rock-melting and solidification model, proponents of DBD appear to be more interested in passive, low-temperature solutions, as it is not possible to monitor or control active rock melting processes to the extent that is likely to be required in developing a safety case. Nevertheless, rock-melting concepts continue to attract some attention, and Ojovan et al.<sup>141</sup> proposed using high-density, self-sinking capsules that would melt their way down into deep rock formations as a means of disposing of some the highest activity (albeit, short half-life) spent radiation sources that are used in industrial and medical applications and as thermoelectric generators.

These UK studies were completed in 2012, concentrating on higher heat outputs and the test of complete assemblies. Gibb’s proposed modified DBD concepts to handle high burn-up wastes, including novel canister designs and alternative support matrices. This recent modeling study further extends the scientific database to evaluate and compare the DBD option with the mined repository concept. The authors concluded that:

...the thermal modelling performed indicates DBD is a viable option for higher burn up spent fuel...and...would be feasible to dispose complete fuel assemblies after much shorter predisposal times.<sup>142</sup>

139 Bill W. Arnold, Peter N. Swift, Patrick V. Brady, S. Andrew Orrell, and Geoff A. Freeze, “Into the deep,” Nuclear Engineering International online, March 25, 2010, <http://www.neimagazine.com/storyprint.asp?sc=2055856>.

140 Fergus Gibb, “Deep borehole disposal (DBD) methods,” Nuclear Engineering International online, March 25, 2010, <http://www.neimagazine.com/storyprint.asp?sc=2055862>.

141 M. Ojovan and F. Gibb, “Feasibility of very deep self-disposal for sealed radioactive sources,” In: Proc. Waste Management ’05 Conference, Tucson, USA, March 2005.

142 F.G.F. Gibb, K.P. Travis, and K.W. Hesketh, “Deep borehole disposal of higher burn-up spent nuclear fuels,” *Min-*

Work on DBD that has occurred over several decades has recently been brought into sharper focus by the above-mentioned collaborative work by SNL and the MIT Department of Nuclear Science and Engineering. This cooperation led to an international review workshop on DBD in March 2010, the first time DBD proponents had come together to identify issues and R&D needs if DBD were to be considered seriously for deployment. The MIT group has issued a number of progress reports describing their R&D programme over recent years, and the results of the March 2010 workshop were outlined by Brady and Driscoll.<sup>143 144</sup>

At the March 2010 SNL-MIT workshop, discussion focused on four main areas: borehole operations, retrievability, site characterization and licensing. It should be noted that this workshop was concerned mainly with the disposal of SF and with the US siting and licensing situation, so the conclusions are not comprehensive with respect to the UK situation (inventory etc.). Among the perceived favorable characteristics of DBD, the MIT group assessed the concept to be inherently modular (drill as required, “pay as you go”) and widely applicable, leading to the possibility of sharing international R&D. It also noted that a simpler safety case can be made and there is the possibility of separately licensing the borehole technology and the disposal facility (analogous to generic reactor design licensing). The perceived disadvantages included two that are often cited: the difficulty of managing large-diameter boreholes (c. 0.5 m) and the difficulty of retrieving waste—although this could also be an advantage, as mentioned earlier when considering nuclear safeguards. The key MIT findings during the 20 years they have considered DBD were that the prospects for very effective sequestration of radioactive wastes are high, the concept is cost-effective and the two main concerns in safety evaluation are the mobility of <sup>129</sup>I in SF and the quality of the borehole seal.

Brady and Driscoll record discussions on borehole operations focused on the need to understand drilling damage (extent and properties of the disturbed zone close to the borehole) and on the need for high-integrity, low-permeability seals to assure long-term isolation. Characteristics of the interface between the seals and the borehole wall will be particularly important. Potential operational problems during emplacement, including damage to canisters and waste during the trip down the borehole, should be minimized, and it may be desirable to line the hole for its entire length with steel casing. A reference design concept to provide a baseline for evaluating performance and impacts of alternative approaches may be useful.

The workshop concluded that retrievability should be maintained up to the time the borehole is sealed. A slotted emplacement-zone hole liner could facilitate grouting the liner to the borehole wall and to the canisters. This approach would also provide support against crushing bottom-most canisters and permit use of the simplest configuration: filling a single-branch vertical hole in stages, allowing the grout (cement) to dry before inserting the next upper set of canisters.

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*erological Magazine* 76, 8 (December 2012): 3003-3017 (Pre-Publication).

143 Brady and Driscoll, “Deep Borehole Disposal of Nuclear Waste,” 2010.

144 Christopher Ian Hoag, “Canister design for deep borehole disposal of nuclear waste,” master’s degree thesis, Department of Nuclear Engineering, MIT, 2006; K.G. Jensen and M.J. Driscoll, *Plugging of Deep Boreholes for HLW Disposal* (Cambridge: Massachusetts Institute of Technology, 2010), MIT Report MIT-NFC-PR-121; Michael J. Driscoll and K.G. Jensen, “Deep Borehole Attributes and Performance Requirements,” MIT Technical Report, May 1, 2010, Report No. MIT-NFC-PR-120; K.G. Jensen and Michael J. Driscoll, *HLW Deep Borehole Design and Assessment: Notes on Technical Performance*, (Cambridge: Massachusetts Institute of Technology, April 2010), Report No. MIT-NFC-PR-116; K.G. Jensen and M. J. Driscoll, *A Framework for Performance Assessment and Licensing of Deep Borehole Repositories*. MIT Report MIT-NFC-PR-115, 2010. B. Sapiie, M.J. Driscoll, and K.G. Jensen, *Regional Examples of Geological Settings for Nuclear Waste Disposal in Deep Boreholes*, (Cambridge: Massachusetts Institute of Technology, January 2010), Report No. MIT-NFC-TR-113.

Examples of favorable site characteristics include tectonic stability, homogeneity of features such as permeability, high salinity porewater at depth, and absence of over-pressured zones. Site characterization will be an important aspect of licensing. The use of natural analogues and evidence such as U-Pb indicators of transport can make major contributions to evaluating radionuclide mobility. Both small- and full-diameter boreholes can be used for acquiring key scientific information and for demonstrating key engineering and procedural features.

In view of the primary recommendation to perform a pilot demonstration, it is useful to note the conclusions of the 2009 Sandia report that preceded the workshop, which states:

It is recommended that ultimately a full-scale pilot project be undertaken, perhaps with surrogate waste, in order to fully explore the viability of a borehole disposal concept. The scientific and engineering advances gained from a single pilot project, and the applicability to subsequent borehole disposal implementations, are in contrast to site-specific mined repositories and their unique site characterization demands with relatively little transferable knowledge to subsequent repositories. Given the potential for standardizing the borehole design, and thus the ready extension to multiple borehole facilities, a single pilot project could provide significant gains on the scientific and engineering issues needing to be resolved, enable the development of international standards, and accelerate the evaluation of the viability of deep borehole disposal of spent nuclear fuel and high-level radioactive waste.<sup>145</sup>

Recent work has focused on performance assessment aspects of DBD. In March 2012, the Nuclear Waste Technical Review Board (NWTRB) held a public meeting addressing DOE work related to geological disposal.<sup>146</sup> A session was dedicated to reviewing the status of the DBD concept, illustrating progress during the last couple of years and indicating continuous interest in DBD as an alternative to disposal in mined repositories.

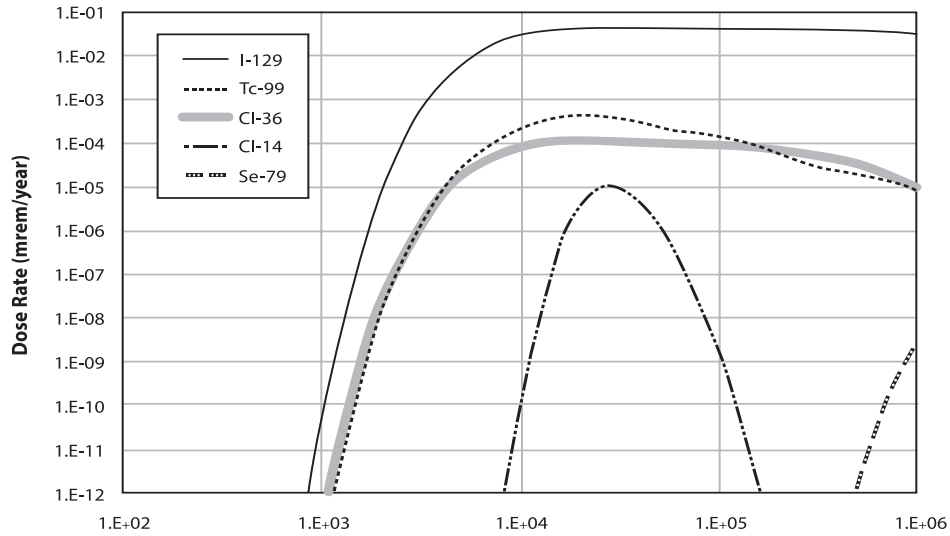
A 2011 paper by Swift et al.<sup>147</sup> presents a first quantitative analysis for releases from deep boreholes applying the same systematic approach as used for mined repositories. They modeled several cases, including one scenario in which the borehole system had a proper seal and one case in which the seal was degraded and the permeability of the surrounding rock and seal had a permeability no higher than fine sand. They found in their assessment that the radionuclide releases are extremely small. For the case in which the seal worked as expected, the dose rate one million years after sealing due to <sup>129</sup>I was 100 billion times smaller than the natural radioactive dose per year with other isotopes many orders of magnitudes smaller (see Figure 13). In the case with substantially degraded sealing, the maximum dose was after 10,000 years, 10,000 times lower than the natural radioactivity expected per year at surface (see Figure 12). Therefore, radionuclide releases are extremely small, and thus DBD should be regarded as a viable alternative to the mined repository concept. Even though the model results show release rates for one borehole only (multiple borehole arrays might lead to higher doses) the release rates are extremely small for the cases analyzed.

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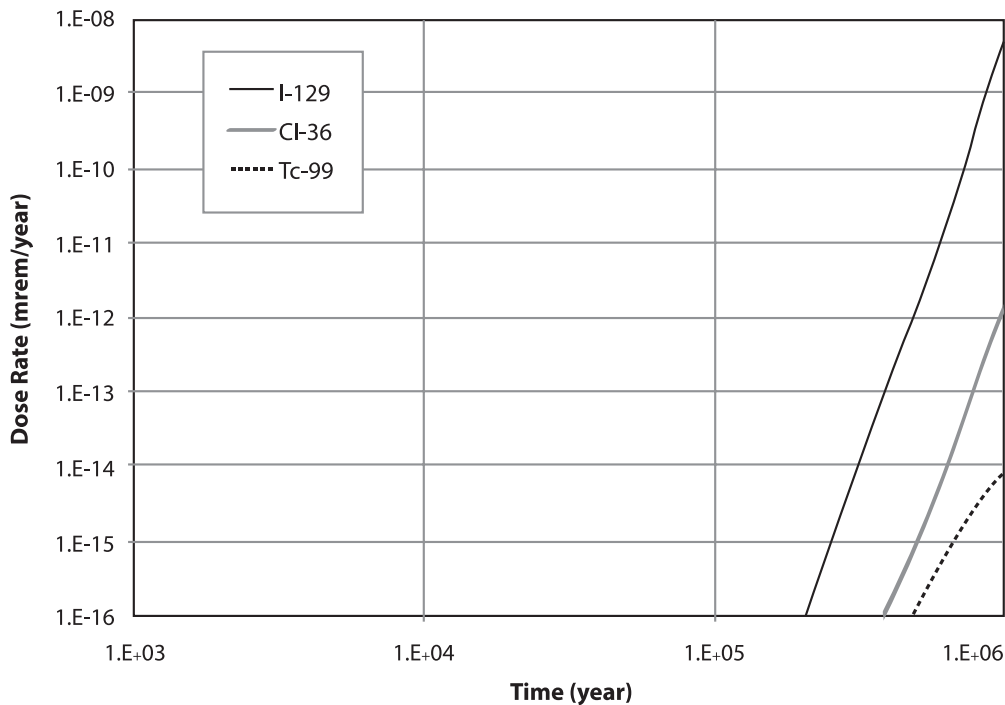
145 Brady, et al., "Deep Borehole Disposal of High-Level Radioactive Waste," 2009: 48.

146 Nuclear Waste Technical Review Board public meeting in Albuquerque, New Mexico, on Wednesday, March 7th, 2012 - Transcripts of the meeting. Available at: <http://www.nwtrb.gov/meetings/2012/march/12mar07.pdf>.

147 Peter N. Swift, Bill W. Arnold, Patrick V. Brady, Geoff Freeze, Teklu Hadgu, and Joon H. Lee, "Preliminary Performance Assessment for Deep Borehole Disposal of High-Level Radioactive Waste," proceedings of the Material Research Society (MRS) 2012 MRS Spring Meeting.



**Figure 12:** Estimated mean annual dose to a hypothetical receptor located above a borehole repository, fully degraded material properties for the host rock and seal system (seal permeability equivalent to fine sand). Caption and figure taken from: Swift, N. P., Arnold, B. W., Brady, P. V., Freeze, G., Hadgu, T., and Lee, J. H.: Preliminary Performance Assessment for Deep Borehole Disposal of High-Level Radioactive Waste, Material Research Society (MRS) Fall Meeting Nov. 2011.



**Figure 13:** Estimated mean annual dose to a hypothetical receptor located above a borehole. Caption and Figure taken from Swift, N. P., Arnold, B. W., Brady, P. V., Freeze, G., Hadgu, T., and Lee, J. H.: Preliminary Performance Assessment for Deep Borehole Disposal of High-Level Radioactive Waste, Material Research Society (MRS) Fall Meeting November 2011.

Driscoll and Jensen<sup>148</sup> make policy recommendations to develop the deep borehole disposal concept further. For example, any regulatory or societal requirement for wastes to be retrievable could exclude the licensing of deep borehole disposal. The authors recommend specific guidelines applicable to licensing deep borehole development. They suggest that separate sites could be licensed based on one generic borehole facility license. The authors argue that such an approach, in combination with implementing several disposal sites, could facilitate the adoption of a volunteering process. They conclude that the next step is a drilling test for demonstration and validation of key aspects of DBD and using synergies with other industries (oil/gas and geothermal<sup>149</sup>) when initiating a demonstration project.

In June 2012 a presentation by the US Department of Energy<sup>150</sup> highlighted DOE's plans to conduct research on deep borehole disposal. Sandia published a Roadmap for Deep Borehole Disposal in August 2012, which provides the DOE and policymakers with information on the resource commitments and budget necessary to deploy the DBD demonstration project. The roadmap is intended to:

...advance the deep borehole disposal (DBD) from its current conceptual status to potential future deployment as a disposal system for spent nuclear fuel (SNF) and high-level waste (HLW). The objectives of the DBD RD&D roadmap include providing the technical basis for fielding a DBD demonstration project, defining the scientific research activities associated with site characterization and postclosure safety, and defining the engineering demonstration activities associated with deep borehole drilling, completion, and surrogate waste canister emplacement.<sup>151</sup>

The comprehensive roadmap should serve as a basis to plan RD&D activities required to resolve the main uncertainties of the DBD concept. In September 2012 Sandia published a complementary report outlining the rationale, methodology and site characterization needs for the DBD, in order to support the safety case. The authors conclude that:

The greater isolation afforded by deeper emplacement ... means that the characterization necessary for the site selection and the safety case would be less than for a mined repository, ... the waste canister system would serve only as a delivery system and not as a primary containment barrier system.<sup>152</sup>

#### *4.5.3 Developments in Possible Applications in other GD Programs*

The lead organization promoting the concept is SNL, in collaboration with scientists at MIT and the University of Sheffield, UK. The SNL group is working toward setting up a consortium of interested parties and proposing pilot tests and demonstrations of aspects of the technology, including a borehole test

148 M.J. Driscoll and K.G. Jensen, "Policy Issues Associated with Deep-Borehole HLW Disposal, *Radwaste Solutions* 19, 3 (July-August 2012): 42-45.

149 The Korea National Oil Company (KNOC) could be a possible partner. The company drills offshore in the Korean Peninsula and operates the Donghae-1 gas field. See: <http://www.knoc.co.kr>.

150 M.C. Regalbuto, "Office of Used Fuel Disposition Activities FY 2012 and FY 2013," US Department of Energy, Nuclear Energy Advisory Committee, Washington, DC. June 12, 2012, <http://energy.gov/sites/prod/files/Monica.pdf>.

151 B.W. Arnold, P. Vaughn, R. MacKinnon, J. Tillman, D. Nielson, P. Brady, W. Halsey, and S. Altman, "Sandia National Laboratories Research, Development and Demonstration Roadmap for Deep Borehole Disposal," Sandia National Laboratories report prepared for U.S. Department of Energy Used Fuel Disposition Campaign, August 31, 2012, Report No. FCRD-USED-2012-000269 SAND212-8527P.

152 P. Vaughn, B.W. Arnold, S.J. Altman, P.V. Brady, and W.P. Gardner, "Site Characterisation Methodology for Deep Borehole Disposal," Sandia National Laboratories Report, September 2012, Report No. 12-7981.



to evaluate engineering and operational aspects. Since DBD has emerged from the BRC deliberations as an option worth pursuing, it would seem likely that other topics from the list of R&D requirements discussed in the previous section might also be addressed in the US.

As noted above, the Nautilus Institute is proposing DBD as a possible solution for SF management in some Asian countries, with a major emphasis on the nonproliferation advantages of the concept. SF inventories in the region are growing rapidly, and the report asserts that the DBD approach would avoid many of the proliferation-prone steps involved with reprocessing and recycling fissile material from SF, as well as possibly proving more acceptable socially and politically, more economical in the short and long runs, and less hazardous with respect to the technological and ecological risks arising from the disposition of large amounts of radioactive material. Possible institutional configurations for DBD in East Asia are suggested to include the use of the technology by each nation going it alone, by some nations contracting for disposal with a few service supplying nations, or through the coordinated development and operation of one or a few central deep borehole facilities used and governed by all of the key nuclear user nations (present and future) of the region. The study concludes by proposing a multi-disciplinary collaborative program of research designed to evaluate, systematically and comprehensively, the relative attributes of the technical, cost, security, safeguard, and other benefits of different nuclear fuel cycle-management approaches, including DBD, with a view to determining which of these approaches best supports a prospective nuclear weapon-free zone in East Asia.

In Sweden, DBD has been evaluated at a relatively low level for many years, as a possible alternative to conventional geological disposal for SNF. SKB is required to consider and report on alternatives when it makes a license application for disposal so that given the interest in DBD displayed by Swedish NGOs, it seems likely that the concept will be discussed actively over the next two to three years as part of the licensing and approvals process.

A parallel study by Kang<sup>153</sup> has analyzed more specifically the DBD option for disposal of the SF generated by the ROK. Current plans for ROK reactor deployment mean that approximately 51,000 t of spent PWR fuel and 20,000 t of spent HWR fuel will be generated over the lifetimes of the NPPs by 2030. The report estimated (very approximately) that the cumulative cost of DBD disposal of cooled spent fuel would be in the range of some \$4 to \$9 billion from 2030 through 2050.

#### **4.5.4 Recommendations for ROK on DBD**

Under any circumstances, a GDF in the ROK will not be operational for many decades. The continued interest and potential for further developments in DBD over the short to mid-term described in the previous sections (largely focused on the U.S.) means that this alternative to conventional GD may become a more feasible candidate. We encourage further consideration and research on DBD in the ROK already initiated by KAERI.<sup>154</sup> The potential benefits of DBD include:

- Reduced requirements on the specifics of the geology if the wastes can be emplaced at the very much greater depths than those for conventional GDF;
- Very low predicted release rates over all future times and lower dose incurred in case of failure of sealing material;

153 Jungmin Kang, "An Initial Exploration of the Potential for Deep Borehole Disposal of Nuclear Wastes in South Korea," Nautilus Institute Report, December 13, 2010, [http://www.nautilus.org/publications/essays/napsnet/reports/JMK\\_DBD\\_in\\_ROK\\_Final\\_with\\_Exec\\_Summ\\_12-14-10.pdf](http://www.nautilus.org/publications/essays/napsnet/reports/JMK_DBD_in_ROK_Final_with_Exec_Summ_12-14-10.pdf)

154 Sung-Hoon Ji, Yong-Kwon Koh and Jong-Won Choi, "The State-of-the Art of the Borehole Disposal Concept for High Level Radioactive Waste," *J. of the Korean Radioactive Waste Society* 10, 1 (March 2012): 55-62 (in Korean).

- Lower costs if the inventory is not emplaced too low and if advances in drilling and emplacement technologies are realized;
- Fewer long-term security or proliferation concerns due to the greater isolation of the nuclear materials.

If DBD becomes feasible, then conventional HLW/SF GDF design options might no longer be required. It is clear that, should DBD ever become acknowledged as a safe, secure and feasible technology for some categories of long-lived wastes, then significant impacts on disposal programs currently based on mined repository implementation could be expected. However, the technical feasibility, including operational safety aspects, has not yet been proved, and long-term safety performance requires further study.

The ROK is encouraged to collaborate with the United States and other countries pursuing research in DBD. Areas where the ROK could collaborate with the U.S. are in pilot testing of practical boreholes in a variety of geological settings, waste package handling methodologies and technologies, sealing and drilling, development of safety assessment scenario analyses, and technical requirements for a DBD program. KAERI is also encouraged to collaborate with the geothermal well industry and other industries to research the feasibility of DBD. Deep boreholes as deep as 2,265 m have been drilled in the Pohang low-temperature geothermal zone in South-East Korea, drilling as deep as 5 km appropriate for geological disposal is planned.<sup>155</sup>

#### 4.6 General Recommendations for the ROK on Long-Term Solutions

The ROK should keep open a range of options for long-term management of spent nuclear fuel, either nationally or through a foreign service provider. Although the ROK's current preferred strategy is pyroprocessing, it should be acknowledged that, for this strategy too, a final disposal solution in a geological repository will be necessary. Therefore, the ROK should develop a national strategy and accompanying roadmap and prioritize steps. Experience has shown that excluding the public on decisions regarding spent fuel management are certain to fail. Therefore, the ROK spent fuel management plan should be publicized, and the public should be included in developing the strategy. One important goal should be to construct a geological depository after several decades of development and construction. The research program at the KURT facility is encouraged.

The public must be assured that “indefinite” storage is not the ultimate goal, and a storage siting initiative should be clearly labeled as interim storage—implying that credible strategies for further treatment or disposal of the spent fuel must also be developed and publicized.

The ROK is encouraged to collaborate with other countries pursuing research related to pilot testing of practical boreholes, waste package handling methodologies and technologies, borehole sealing and drilling, development of safety assessment scenario analysis, and technical requirements for a DBD program. Finally, options for GDF geological environments and for facility design should be developed, but without the premature selection of preferred solutions. The R&D activities for DBD and the development of a mined repository should be done in parallel. Given the long timescales involved, the ROK must be certain that options are chosen which satisfy a range of stakeholders and criteria. A broad survey of South Korean geology could help enhance public trust that a final disposal solution is technically feasible within the ROK.

<sup>155</sup> See Annual Report of the International Energy Agency: International Energy Agency Implementing Agreement for Cooperation in Geothermal Research & Technology, 27 January 2012, 175, <http://iea-gia.org/wp-content/uploads/2012/08/2010-GIAAnnRept-Final-27Jan12.pdf>.

## 5 CONCLUSIONS

### 5.1 Introduction

South Korea's public discourse on spent fuel management has tended to focus on long-term plans for a fuel cycle involving pyroprocessing of spent nuclear fuel and the reuse of some of the separated metals (plutonium and uranium) in sodium fast reactors. This discussion has tended to obscure the fact that this long-term approach will not offer short- and medium-term solutions to South Korea's pressing spent fuel concerns, and will not obviate the need to find a site to permanently hold either spent fuel or high level waste. Nor has this discussion taken into account some of the very real concerns about the viability of this untested technological approach, from the nature of the waste stream generated by pyroprocessing to the need to overcome longstanding obstacles to cost-effectively commercialize the required set of sodium fast reactors. At the same time, the discourse has given relatively little discussion to some proven technologies, particularly dry cask storage, that can provide South Korea ways to manage spent fuel safely, securely, and inexpensively at current reactor sites or elsewhere while continuing research on long-term options, including pyroprocessing and fast reactors.

It is not clear why the public debate in South Korea has limited itself to the rather narrow focus on pyroprocessing rather than taking a more comprehensive approach to spent fuel management. This focus has not been the declared intent of ROK government policy, which has always taken a wait-and-see approach while supporting pyroprocessing as a long-term research and development program. For instance, in December 2008, South Korea's Atomic Energy Commission, the country's top nuclear policymaking body chaired by the prime minister, issued a long-term research and development plan for a next-generation domestic nuclear system on pyroprocessing and fast reactors. The commission mandated that a demonstration of the technical and economic viability of both technologies be completed by 2028. However, the thrust of the ROK's Basic Energy Plan for the decades leading up to 2030 was not this program but issues related to spent fuel storage and encouraging public discussion on the management of spent fuel.

Some of the current public debate about pyroprocessing no doubt reflects the influence of the media, which has tended to emphasize the controversy between the United States and South Korea over the negotiations for a new nuclear cooperation agreement. The goal of pyroprocessing is set forth as something that allows Seoul a greater level of energy sovereignty, while South Korean national pride is perceived as threatened by the US denying ROK this option—one that is currently open to Japan and a few others. The press coverage may also reflect South Korea's faith in and fondness for new technologies and technocratic approaches.<sup>156</sup> The lack of a fuller public discussion on the overall issue of spent fuel disposition also appears to reflect the past experience of South Korean officials and experts, rebuffed in their previous efforts to win public support for interim storage for high-level waste or spent fuel. Ignoring recent evidence from countries such as Canada, Finland, and Sweden, these officials appear to lack confidence that an effort to engage relevant stakeholders in finding a consensus approach to these issues will succeed and prefer to use the illusion of a technological solution to resolve what is ultimately a political problem. Such an approach is unlikely to succeed. Instead, Seoul risks not only a public backlash but also the same political dead end where Japan now finds itself—Japan has not solved its ultimate spent fuel management

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156 Scott Victor Valentine, "The Socio-Political Economy of Nuclear Power Development in Japan and South Korea," *Energy Policy* 38 (2010): 7971-7979.

problems and is now hostage to a technological solution which no longer makes economic or technological sense while raising nonproliferation concerns.

South Korea's new government has the opportunity to do better. Its first priority should be to seek broad and open engagement with the public and other relevant stakeholders. A year ago, the Ministry of Knowledge and Economy promised to set up a public consultation committee by March of this year. The new government should follow through on this promise. In addition, President Park Geun-hye should consider establishing a body equivalent to the independent US Blue Ribbon Commission, which could provide it and Korean society with high-level political direction. The public discourse in Korea has been too dominated by engineers and scientists with a vested interest in one or the other technological approach. Assuring the public that its concerns are being sufficiently addressed will require more direct involvement of current and former public officials who can represent and respond to those concerns. In addition, the ROK should consider the following particular policies over the short, medium, and long terms.

## 5.2 Short Term (Up to 2020)

### *5.2.1 Public Outreach Campaign to Educate Communities about Spent Fuel Options*

Seoul needs to focus on gaining popular support for spent fuel endeavors, most effectively by assuring information is transmitted to the public and that the process is transparent and involves all relevant stakeholders. The new administration should establish a body similar to the Blue Ribbon Commission that the US set up on related issues to examine issues related to spent fuel and other HLW disposition. This group's agenda should include the development of an effective strategy for the nuclear authority to follow with regard to public outreach. This outreach should focus on communities near current reactor sites as well as those that might be appropriate for AFR storage facilities, and involve regional public interests as well. The involvement of all relevant stakeholders should help to prevent the so called "donut effect" in which all individuals agree with the policy except the community that suffers the consequences of an incident, but not near enough to gain from the immediate benefits. For those locales with existing sites, the public should receive more information on the options for spent fuel storage, particularly the safety and security benefits of dry cask storage. Public outreach to these communities should also tie interim storage to the lifetime of a reactor by promising to leave no "stranded fuel" when a plant site stops operating. For these communities as well as those under consideration for future storage or disposal facilities, this commission, or another body, should assist the nuclear authorities in developing an active engagement program that fully explains the benefits and costs of siting one of these facilities.

### *5.2.2 Review Storage Requirements and Possible Interim Storage Sites*

As part of the mandate of the commission mentioned above (or another similar body), South Korean experts should make a clear estimation of domestic storage requirements for the next two to three decades so as to properly assess the needs in the short to near term. This assessment will help with properly identifying needed facilities and further strengthen efforts to increase public and political interactions aimed at finding suitable volunteer sites. Similarly, South Korean authorities should explore the creation of a centralized interim storage facility (CISF) and assess which type of storage—wet or dry—is most appropriate for a subsequent move to interim storage.

### *5.2.3 Transferring Spent Fuel to Newer Reactor Ponds*

As noted in this report, the South Korean nuclear authority should explore in more detail the option of transferring spent fuel from older to newer reactor ponds, including to sites outside the original reactor's jurisdiction. This option could extend the saturation point of the cooling ponds at existing reactors by several decades. The government must make clear that everybody has a stake in spent fuel management, and should engage and accommodate all involved, including communities along spent fuel transportation routes. Alternatively, spent fuel could be transferred from one reactor site to dry storage at another site. Although this option appears difficult politically because of feared public opposition, when combined with an active public engagement strategy, this option could prove very effective in extending the capacity of existing facilities.

## **5.3 Medium term (2020-2030)**

### *5.3.1 Extensive Study by the US and ROK of the Back-End of the Nuclear Fuel Cycle*

The US and ROK nuclear authorities should expand their efforts to identify options for spent fuel disposition by expanding the current 10-year study examining the back-end of the fuel cycle and new approaches to spent fuel disposition. While pyroprocessing should still be considered within this study, equal weight should be given to other approaches such as research and development on fast reactors, disposal and storage options like DBD and extended storage, and discussions of possibilities for multilateral facilities in or outside of the ROK.

### *5.3.2 Creation of a National Storage and Disposal Strategy*

No matter what strategy the ROK ultimately chooses for spent fuel disposition, nuclear waste materials will need to be stored in the ROK for decades, because of the cooling period required before further treatment of the fuel can occur. With South Korea's current interest in establishing an advanced reprocessing capability, the ROK has good reason to store spent fuel in a way that would allow the future technology to be used when ready. Considering that technologies like pyroprocessing still require decades to develop into an effective option, extending the current storage time into the medium or long term would be beneficial. In order to establish a strategy that is appropriate for South Korea, a credible roadmap leading several decades in the future to implementation of a repository must be part of the overall national storage and disposal strategy. Even if pyroprocessing becomes a viable option and is undertaken in South Korea in the decades to come, a final disposal solution at a geological repository will be necessary for some long-lived wastes. Any strategy must therefore take seriously the siting of such a repository and the political and public outreach that will be necessary. As noted in the report, "indefinite" storage, or 100-plus-year storage, should not be the ultimate goal. The storage siting initiative should be clearly labeled as interim storage—implying that credible strategies for further treatment or disposal of the spent fuel will also be developed and publicized.

## **5.4 Long Term (2030 onwards)**

### *5.4.1 Geological Disposal*

Disposing of spent fuel and HLW in mined geological repositories is currently the only widely accepted technical solution for safe and secure disposal of long-lived wastes. The sites for these repositories should



be situated in regions geologically suitable and socially acceptable. The overall strategy that the ROK needs to create for spent fuel disposition must, independent of any other approaches under consideration, eventually lead to a national repository. As noted in this report, transparency needs to be part of this overall strategy: The responsibilities for policy, regulation, R&D and repository implementation must be clearly allocated within the South Korean bureaucracy. In particular, the roles of the utilities, the implementer (KRMC) and the research body (KAERI) should be clearly delineated. A siting policy, based on achieving consent of the local population should be developed, publicized and revised in the light of local reactions.

#### *5.4.2 Deep Borehole Disposal*

While research on DBD of spent fuel, HLW and other radioactive wastes continues, this approach has not been sufficiently examined that it can be yet be considered a workable future option for South Korea. Should it prove to be so, one crucial question confronting policymakers will be whether spent fuel or other wastes placed in such facilities need to be retrievable.

South Korea should continue research on DBD concurrently with planning a mined geological repository. As noted previously in this report, the potential benefits of DBD include reduced requirements on geology of the chosen site (and therefore more choice on where to site); low predicted release rates; lower costs, particularly if advances in drilling and emplacement technologies come to pass; and lower overall concerns about security or proliferation. If DBD becomes feasible, then conventional geological disposal might not be required. Therefore, South Korea should collaborate with the United States and other international partners on DBD research. KAERI is also encouraged to collaborate with established drilling industries to research the feasibility of DBD.

#### *5.4.3 Keep Options Open*

As noted throughout this report, while South Korean nuclear planners should immediately move on finding interim storage solutions, it should keep open a range of options for long-term management of spent nuclear fuel. The implications of different fuel cycle strategies on the timing and the technology needed for final repository implementation should be studied as a key decision aid for future policies. These options can include both domestic and international arrangements. Although reprocessing is currently not an economical method for dealing with spent fuel, South Korea should continue R&D on advanced reprocessing technologies. However, development by South Korea of reprocessing technology is a sensitive issue in a politically charged region of the world. For that reason, it is advisable to perform such R&D in a multilateral framework. It is of critical importance that the South Korean public is better informed and is part of the debate. The public must be assured that “indefinite” storage is not the ultimate goal and that credible strategies for further treatment or long-term disposal will be developed. South Korea needs to look at this issue from a long-term perspective, and the decisions it makes need to work for various stakeholders and be viable and sustainable.



## APPENDIX A: THE KOREAN GEOLOGICAL ENVIRONMENT

A crucial factor in public confidence that an appropriate geological disposal has been chosen is assurance that the geology in the area is suitable for any plan to protect the environment from the radiation danger of spent nuclear or high-level waste for hundreds, thousands, or even hundreds of thousands of years. Geologically, the repository must be built in appropriate rock to prevent water with dangerous radionuclides migrating to the surface and be able to protect against natural events such as earthquakes and volcanos.

### A.1 Seismic Activity

The Korean peninsula is part of the Eurasian plate, which borders the Filipino and North American tectonic plates near Japan. Therefore, seismic activity in the ROK is due to intra-plate (earthquakes on the plates themselves) seismicity rather than those occurring near the plate boundaries. These earthquakes tend to be attenuated less because of the coherent rock medium compared to looser rock near plate boundaries. Studies of seismic activity demonstrate that:

Seismicity is stronger in the southern and western parts of the peninsula than in other regions. However, deep sources of earthquakes are distributed in the northeastern part and in the east sea.<sup>157</sup>

The first criterion of a repository is that it must be sited in a long-term geologically and tectonically stable setting. Historic seismic records indicate that seismic activity tends to have strengthening periods of 500 years and weakening periods of 200 years. The largest earthquakes in recent times were the 1936 Sanggyesa and 1978 Hongsung earthquakes. See Figure A.1 for the earthquake density and contour plot of historic earthquakes from the year AD 2 until 1995. In the figure we see a concentration of earthquakes in the Southwest near Pusan, and near major historic cities. It is important to realize that these cities are historically large population centers in Korea, so these areas would have observed the earthquakes and recorded them. However, while only 28 earthquakes with magnitude greater than 7 have occurred in the 2000-year history of Korea, damaging earthquakes of magnitude 5-7 occur much more frequently. From the point of view of siting a future geological repository, South Korea is fortunate, because it does not suffer from major seismic activity, unlike Japan, which is on the confluence of three major tectonic plates.<sup>158</sup>

### A.2 Volcanism

Volcanos have not been common on the Korean Peninsula in recent times. However, in the Quaternary (over the last 1.6 million years), there has been activity in the Jeju Island area and other areas in Korea.

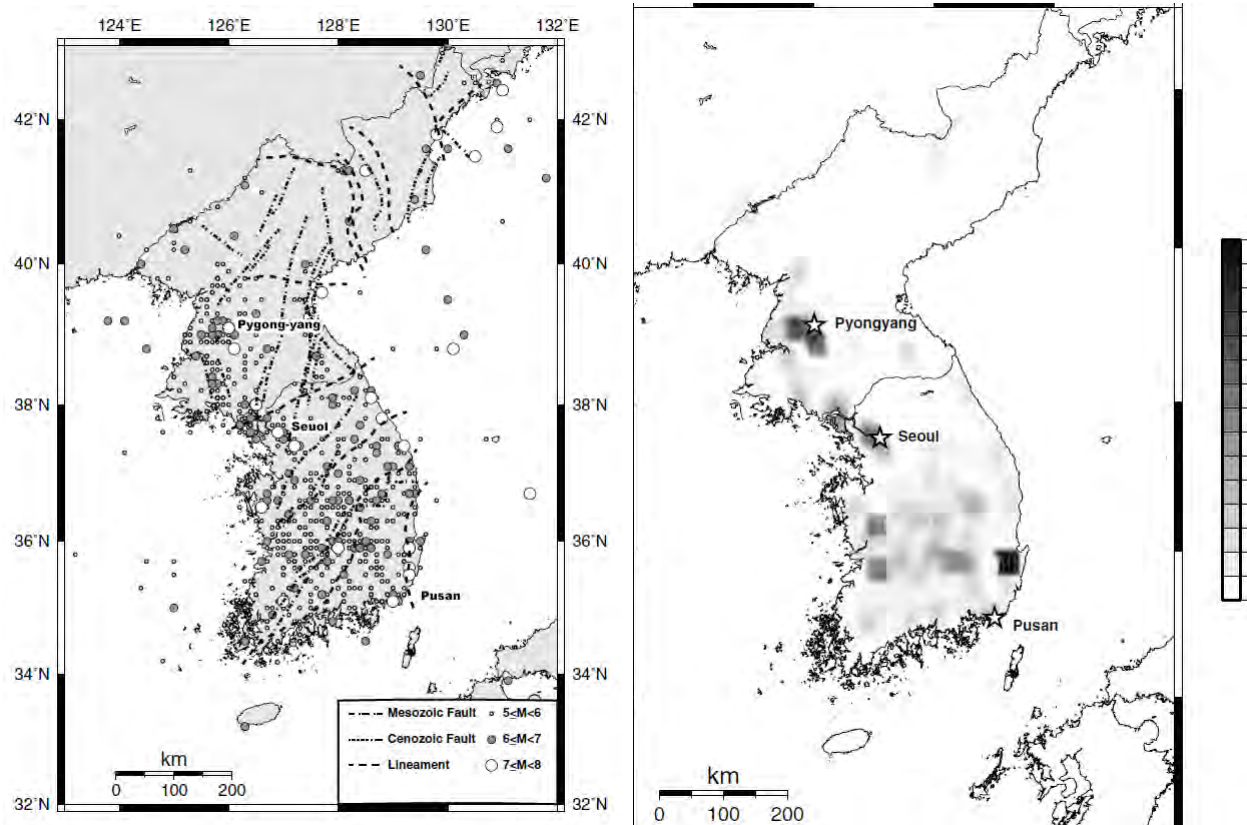
157 C.S.Kim, D.S. Bae, K.S. Kim, and Y.K. Koh, "Lithological Suitability for HLW Repository in Korea," proceedings of Symposium, Technologies for the Management of Radioactive Waste from Nuclear Power Plants and Back End Nuclear Fuel Cycle Activities, Taejon, Republic of Korea, August 30 - September 3, 1999. This is an important paper which describes the technical conditions for long-term geological disposal in Korea. Much of the discussion in this section is based on this paper.

158 J. M. Chiu and S. G. Kim, "Estimation of Regional Seismic Hazard in the Korean Peninsula Using Historical Earthquake Data between A.D. 2 and 1995," *Bulletin of the Seismological Society of America*, 94, 1 (February 2004): 269-284.

According to historical records volcanic activity in Korea has been seen as recently as 1000-1600 AD.<sup>159</sup>

### A.3 Host Rock and Location Requirements

The location of host rock for supporting a geologic repository must be free of fractures and continuous. Fractures, which cover much of the Korean Peninsula, have been identified as shown in Figure 15.



**Figure 14:** Left side is a contour presentation of seismicity on the Korean Peninsula. The study area is divided into 0.1 by 0.1 square blocks, roughly 10 km by 10 km. The total number of historical earthquakes with M 5.0 inside each block is counted first and then smoothed by averaging with the numbers of the adjacent eight blocks. Gray scale is scaled to the maximum number of earthquakes among all blocks. The right side map shows historical earthquake activity on the Korean Peninsula between A.D. 2 and 1995, from Kim and Gao (1995). Known Cenozoic and Mesozoic faults and structural lineaments are also shown (Masaitisa, 1964).<sup>160</sup>

159 Much of this section was taken from Kim, et al., "Lithological Suitability for HLW Repository in Korea," 1999, and from private communications with KAERI employees.

160 Ibid. References cited in the caption: V.N. Masaitisa, *Geology of Korea*, (Nedra, Moscow, 1964) (in Russian) (is this a book? If so, keep as edited); S.G. Kim and F. C. Gao, *Korean Earthquake Catalogue*, Seismological Institute, Hanyang University, Seoul, Korea, 1995.





## APPENDIX B: WHY IS HLW A CONCERN?

A typical LWR with 4.5 percent enrichment will convert uranium fuel to approximately 1-2 percent plutonium through neutron absorption onto the dominant uranium isotope  $^{235}\text{U}$ , as well as a variety of other fission products and transuranic actinides. The composition of the fuel immediately at discharge is shown in Table 1 below and consists of a mixture of 1.3 percent transuranic actinides (TRU),<sup>164</sup> and 5 percent fission products.<sup>165</sup> The contributions of different isotopes to the total radioactivity and heat from the fuel will change as certain isotopes with common daughters decay. However, this fuel continually produces heat, even after the reactor is turned off and the fuel is removed from the core. This internal heat produced by the radioactivity cannot be turned off and is a characteristic of spent nuclear fuel (SNF). However, it will decrease with time as isotopes decay.

Species	Composition	Pyro-SFR Material Management	Once Through Material Management
Uranium	92.9% (4.5% Enrichment (LEU))	Reuse/Burn in fast Reactor	Dispose in Geological Repository or in Deep Borehole.
Plutonium	1.2%		
Minor Actinides	0.2%		
Long Lived: Iodine/Tech- netium	0.16%	Transmute in Fast Reactor	
30 Year Half-Life, High Heat Cesium/Strontium	0.53%	Place in Geological Repository or in Deep Borehole	
Other Fission Products	5.01%		

**Table 6:** The SNF composition after a burn-up of 55 GWd/MTHM with 4.5 percent enrichment in a Westinghouse LWR. Data from presentation by Dr. Ji-sup Yoon, Korean Nuclear Energy and Fuel cycle R&D cooperation between US and S. Korea, GABI, May 10, 2012. The final two column shows how these isotopes are handled in the Pyro-SFR cycle and Once-Through cycles.

One of the primary concerns with geological emplacement is that over thousands of years a pathway might be created which allows radionuclides to be transported upward into the food system. Therefore, one way of measuring the adverse effect of these radionuclides is the volume of water used to dilute the isotope to produce the maximum allowable concentration for ingestion. This property of an isotope is called the radiotoxicity index and is shown in Figure 16 reproduced from the 1996 National Academies Study Nuclear Wastes.

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Korea,” Nautilus Institute Report, December 13, 2010, [http://www.nautilus.org/publications/essays/napsnet/reports/JMK\\_DBD\\_in\\_ROK\\_Final\\_with\\_Exec\\_Summ\\_12-14-10.pdf](http://www.nautilus.org/publications/essays/napsnet/reports/JMK_DBD_in_ROK_Final_with_Exec_Summ_12-14-10.pdf)

<sup>164</sup> TRU are all the actinides with atomic number exceeding 92, which corresponds to the element uranium, such as neptunium, plutonium, americium and curium. TRU actinide isotopes are produced by successive neutron interactions and decay onto the uranium isotopes (excluding fission) in the reactor.

<sup>165</sup> Nuclides generated by fission or subsequent radioactive decay of nuclides directly generated by fission; for example krypton-85, cesium-137, strontium-90, etc. (Source: European Nuclear Society).

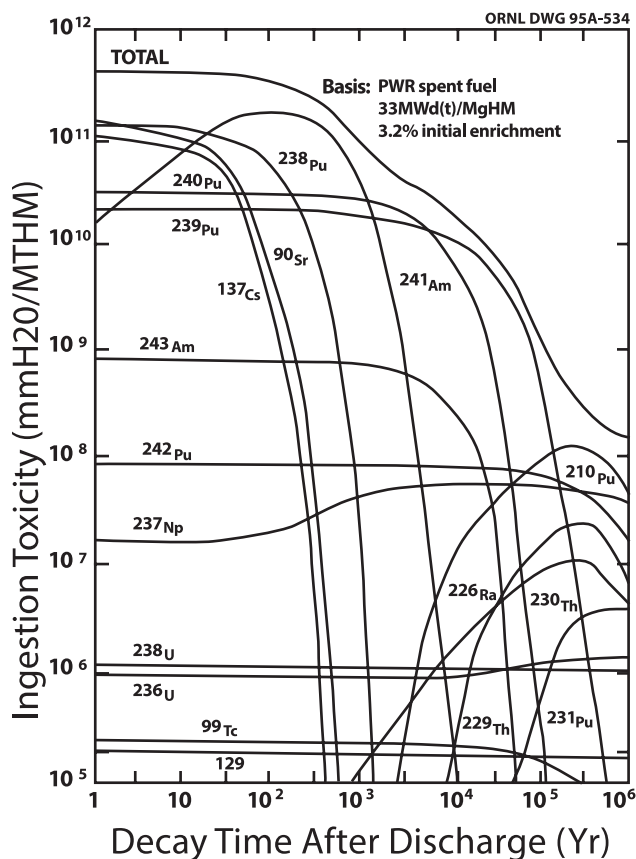


Figure 16: The ingestion toxicity (see text for definition) as a function of time after discharge.<sup>166</sup>

Figure 16 is similar to Figure 5 in Chapter 2; however, the individual components (isotopes) that are shown contribute to the total radioactivity. Notice how the isotopes cesium-137 and strontium-90 dominate the total radioactivity for the first several hundred years. These isotopes are known as fission products, since they are produced after the nucleus splits due to fission. After several hundred years of storage, the transuranium actinides start to dominate which are the isotopes that are produced not through fission but by neutron interactions in the reactor. Actinides are known as “bone seekers” and tend to stay in the body for a long time when ingested. Also, the long-lived isotopes technetium-99 and iodine-129 remain a contaminant in the fuel for tens of thousands of years and tend to be mobile in groundwater, unlike most actinides.<sup>167</sup> The actinides, despite their high toxicity index, tend to be insoluble in water and hence contribute less to risk when groundwater pathways are considered.

In this sense, in order to estimate the risk posed by different isotopes, the solubility<sup>168</sup> of the radionuclides in the water must also be taken into account.

166 National Research Council, *Nuclear Wastes, Technologies for Separations and Transmutation* (National Academy Press, Washington, DC, 1996): 24.

167 Ibid.

168 Solubility is the chemical property of an element or a collection of elements (compounds) which describes how easily they dissolve in water. Note that the chemical properties of different isotopes of the same element are identical.

## APPENDIX C : DRY STORAGE CASK INFORMATION

ID No.	Design	Transport	Storage	Heat Transfer	Containment	Shielding	Feature	Example
<b>Spent fuel storage</b>								
1a	Cast metal cask	Bolted Secondary (transport) lid with elastomer seals and primary lid with metallic seals	Bolted Secondary (storage) and primary lid with metallic seals	Conduction through basket and cask walls	Double bolted lids with metallic seals	Metallic wall	Dual purpose	GNS
1b	Massive or composite forged metal cask	Bolted Secondary (transport) lid with elastomer seals and primary lid with metallic seals	Bolted Secondary (storage) and primary lid with metallic seals	Conduction through basket and cask walls	Double bolted lids with metallic seals	Metallic wall	Dual purpose	ES, Holtec, MHI, NAC, TNI
1c	Concrete cask	Concrete cask with bolted lid(s) and elastomer seals	Concrete cask with bolted lid(s) and metallic seals	Conduction through basket and cask walls	Double bolted lids with metallic seals	Concrete wall	Dual purpose	GNS
2a	Forged metal transport cask & concrete over pack	Forged metal transport cask with bolted lid and elastomer seals	MPC in Concrete over pack	Air convection around canister	Double welded lids	Concrete wall	Vertical	ES, Holtec, NAC
2b	Forged metal transport cask & simple metal over pack	Forged metal transport cask with bolted lid and elastomer seals	MPC in simple metal over-pack	Air convection around canister	Double welded lids	Metal wall + additional neutron shielding	Vertical	TNI
2c	Forged metal transport cask & concrete module	Forged metal transport cask with bolted lid and elastomer seals	MPC in concrete module	Air convection around canister	Double welded lids	Concrete wall	Horizontal	TNI
2d	Forged metal transport cask & underground concrete over pack	Forged metal transport cask with bolted lid and elastomer seals	MPC in concrete module	Air convection around canister	Double welded lids	Concrete wall	Vertical Under ground	ES, Holtec
3	Vault	Forged metal transport cask with bolted lid and elastomer seals	Steel lined tubes in massive concrete block	Air convection around tubes	Thimble tube	Concrete	1 FA per tube	Fort St Vrain, Paks
<b>HLW Glass storage</b>								
1a	Cast metal cask	Bolted Secondary (transport) lid with elastomer seals	Bolted Secondary (storage) and primary lid with metallic seals	Conduction through basket and cask walls	Double bolted lids with metallic seals	Metallic wall	Dual purpose	GNS
1b	Forged metal cask	Bolted Secondary (transport) lid with elastomer seals	Bolted Secondary (storage) and primary lid with metallic seals	Conduction through basket and cask walls	Double bolted lids with metallic seals	Metallic wall	Dual purpose	TNI
3	Vault	Forged metal transport cask with bolted lid and elastomer seals	Steel lined tubes in massive concrete block	Air convection around thimble tube	Thimble tube	Concrete wall	9 glass canisters per tube	COVRA, Repro facilities

Table 7: Dry Storage System Options for SF and HLW – adapted and amended from IAEA TECDOC 1558.

Supplier/Owner	Cask/Canister					Technical Requirements			
	ID No.	Product Model	No. PWR Fuel elements	Licensing Country + IAEA reg.	Date of license renewal	Maximum Burnup (GWd/tHM)	Maximum Heat Load (kW)	Associated cooling time (Years)	Total weight (MT)
Energy Systems	2a	MSB (Canister) TS-125 (Transfer) VSC-24 (storage)	24	USA	07.05.2013	<45	24	>5	139 (L?) 144 (L?)
	2a	Fuel Solutions: W21 (Canister) W100 (Transfer) W150 (Storage)	21	USA	15.2.2021	15 - 60	22	3.3 - 17	36.8 (L) 60 (E) 115 (E)
GNS	1a	Castor V/19*	19	Germany – 85	20.11.2012	65	39		126
	1a	Castor-X28*	28	South Africa – 85	?	37.5	17.2		108
	1a	Castor-V21	21	USA	17.08.2010	<40	21	>6	116
	1c	CONSTOR	VVER SF						
Holtec	2b	PC (Canister) HI-TRAC (Transfer) HI-STORM 100 M (Storage)	24/32	USA	31.05.2020	<68	34	3 – 20	100/125
	2b	HI-STORM 100U	24/32	USA	Undergoing licensing	61.63/50	34/36.9	?	?
	1b	HI-STAR 180	32/37	USA - 96		15 - 66	32	3 - 24	
MHI	1b	MSF-21P*	21	Japan	?	60	41		121
NAC	1b	NAC-S/T	26/28	USA	17.08.2010	<35	<26/20		74
	2a	NAC-MPC	36		10.04.2020	<36	12.5	>8	
	2a	NAC-UMS TSC (Canister) Transfer Cask VCC (Storage)	24	USA	20.11.2020	60	23	12 - 34	33 (L) 55 (E) 108 (E)
	2a	MAGNASTOR	37	USA	04.02.2029	60	35.5	>4	161

Supplier/ Owner	Cask/Canister					Technical Requirements			
	ID No.	Product Model	No. PWR Fuel elements	Licensing Country + IAEA reg.	Date of license renewal	Maximum Burnup (GWd/tHM)	Maximum Heat Load (kW)	Associated cooling time (Years)	Total weight (MT)
TNI	1b	TN-24 (series P)*	24	USA	04.11.2013	35/45	24		100
		TN24	37	France					
			24	France					
	1b	TN-32	32	USA	19.04.2020	<45	32.6	>7	115.5
	1b	TN-40	40	USA	Under relicensing	<45	<21	15 - 25	113
	1b	TN DUO	24/37	France	To be licensed (available 2015?)	<65	?	?	?
2b	TN NOVA	37	USA/ France	Currently being Licensed (in operation 2013)	<65	?	?	?	
2c		NUHOMES-24-PHB (Canister)	24	USA	23.01.2015	<55	40.8 (34.8)	>3	
		NUHOMES-32-PTH1 (Canister)	32	USA	23.01.2015	<60		>5	37.3 (L)
		HSM-H (Storage module)							139
		OS187H (on site transfer cask)							114.5 (L)

**Table 8:** Details of SF Dry Storage System. A summary of all identified SF dry storage systems with their manufactures. In each case the type of system is indicated with an ID No. Following this, for each system, the name, number of SF assemblies, licensing country and IAEA regulation year (if known), date of license renewal (if known) are provided. Following this, the maximum burn-up, heat loading, the minimum SF cooling time and total weight are given.



## APPENDIX D: DEVELOPMENTS IN STORAGE USE/ROLE IN OTHER NATIONAL PROGRAMMES

Interest in storage technologies is growing rapidly in many countries as a result of various causes, as illustrated from the example countries below:

**USA:** The long delays in the Yucca Mountain Project have already led, over the past several years, to extensive use in the US of dry cask storage on pads, since the relatively old nuclear plants have insufficient pool capacity, even after re-racking. The complete demise of the project in 2010, and the realization of the public and political hurdles to be overcome before an alternative is to be identified, has even led to calls to extend spent fuel storage for up to hundreds of years. This issue was addressed by the Blue Ribbon Commission report to the US Government in 2012. The US DOE has recently published its response to the BRC report.<sup>169</sup> Its strategy now includes aiming for centralized interim storage while simultaneously moving ahead with an adaptive phased strategy leading toward geological disposal.

**Germany:** The German government has decided that spent fuel is to be stored at the reactor sites in order to avoid transport to the existing centralized dry cask storage facilities at Ahaus and Gorleben. The assertion was that this decision was made on safety grounds, but the objective reason is the massive public opposition in Germany to transports of nuclear materials (and the resulting enormous costs).

**Sweden:** The CLAB underground wet storage facility was extended in 2004 to increase its capacity from the original 5000 t up to 8000 t.

**Finland:** The surface pool storage for spent fuel at Olkiluoto has only a 1,270 t capacity and must be expanded to allow for the growing nuclear power program. An extension is scheduled for 2011-2014.

**South Africa:** ESKOM will run out of storage space at its Koeberg NPP within a few years and is now assessing options for adding dry storage or shipping fuel off site to foreign reprocessors.

**Japan:** The JNFL facility spent fuel storage facility at Rokkasho is capable of storing spent nuclear fuel equivalent to up to 3,000 tons of uranium. But it is nearly filled. A further temporary storage facility is being built in Mutsu, also in the Aomori Prefecture. The facility will have a storage capacity of about 5,000 tons and is scheduled to start operations in October 2013, receiving 200-300 tons annually.<sup>170</sup> Japan has also studied a concept (CARE<sup>171</sup>) in which spent fuel or waste is placed in extended underground stores in casks that can also be used as disposal containers, thus allowing the store to be converted at some future time to a final disposal facility.

**Netherlands:** If the operator of the Borssele NPP continues reprocessing after 2015, a modular extension of COVRA's HABOG vault storage facility would be required. In case the operator opts for direct disposal, a new building will have to be designed, as the HABOG is not suitable for storage of spent fuel assemblies.

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169 US DOE, *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*, <http://energy.gov/downloads/strategy-management-and-disposal-used-nuclear-fuel-and-high-level-radioactive-waste>.

170 Nikkei.com, Analysis: "Tohoku Filling Up Fast With Nuclear Waste," June 2012, <http://e.nikkei.com/e/fr/tnks/Nni20120606D06HH626.htm>.

171 Sumio Masuda, Hiroyuki Umeki, Ian McKinley, and Hideki Kawamura, "Management with CARE," *Nuclear Engineering International* online, November 6, 2004, <http://www.neimagazine.com/features/featuremanagement-with-care>.

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