Nuclear Technology

ISSN: 0029-5450 (Print) 1943-7471 (Online) Journal homepage: https://ans.tandfonline.com/loi/unct20

Coupling the Back End of Fuel Cycles with Repositories

Charles Forsberg

To cite this article: Charles Forsberg (2012) Coupling the Back End of Fuel Cycles with Repositories, Nuclear Technology, 180:2, 191-204, DOI: 10.13182/NT12-A14633

To link to this article: https://doi.org/10.13182/NT12-A14633

COUPLING THE BACK END OF FUEL CYCLES WITH REPOSITORIES

FUEL CYCLE AND MANAGEMENT

KEYWORDS: *fuel cycle, repository, spent nuclear fuel*

CHARLES FORSBERG*

Massachusetts Institute of Technology, 77 Massachusetts Avenue
Cambridge, Massachusetts 02139-4307

Received August 5, 2011
Accepted for Publication December 20, 2011

Fuel cycles have not historically been integrated with repository design. Four alternative combinations of fuel cycles and repository systems are assessed in the present work: (a) traditional repositories, (b) repositories with spent nuclear fuel retrievability for recycle or as insurance against unforeseen repository failure, (c) colocation and integration of reprocessing and repositories, and (d) colocated specialized disposal facilities such as boreholes for different wastes. System design choices have major impacts on fuel cycle economics, accident risk, repository performance, nonproliferation, and repository siting. Consequently, there are large incentives to understand the different ways to couple fuel cycles and repositories.

The evidence suggests that a repository as only a disposal site (the current system) is the least desirable option given current requirements for the United States. There are large incentives to develop repository sites that colocate and integrate all back-end fuel cycle facilities with the repository—independent of the fuel cycles that are ultimately chosen or how these fuel cycles evolve over time. Colocation and integration change the interface requirements between facilities by eliminating many storage and transport requirements such as the need for waste forms with high waste loadings. That, in turn, can result in reductions in cost, reductions in risk, and improved repository performance. For closed fuel cycles, colocation and integration may eliminate repository safeguards. This also suggests a repository business model similar to that of many airport authorities. Airport authorities manage the runways with colocated public and private airline terminals, aircraft maintenance bases, and related operations—all enabled and benefiting from the high-value runway asset. The common high-value back-end fuel cycle asset is the repository. For the local community and state government, such a strategy couples back-end fuel cycle benefits (high-technology jobs, tax revenue, etc.) with the repository site.

I. INTRODUCTION

Relative to other energy sources such as coal and natural gas, the introduction of nuclear energy was unusual. Much of the technology was developed rapidly by military programs in World War II and the Cold War. This included development and large-scale deployment of enrichment and reprocessing technologies before waste management challenges were addressed. This history led to the traditional fuel cycles where various facilities generate wastes that are then to be shipped to disposal facilities. While recent studies[1,2] examine alternative fuel cycles, alternative system architectures that couple fuel cycles and waste management together in different ways have not generally been considered.

*E-mail: cforsber@mit.edu

In the United States we have not yet sited a geological repository. There is the proposed Yucca Mountain repository (YMR) site, but it is surrounded with political controversies and its future is unknown. Similarly, we do not know what fuel cycles we will choose for the future. Given these realities, it is appropriate to ask how we should fit together a system that integrates the fuel cycle with waste management. Is the concept of separate fuel cycle and waste management facilities appropriate? Are there better options? Four possible systems to couple fuel cycles and waste management have been identified. Only one of these options has been examined in any depth—the repository as a stand-alone disposal facility. The other options have not been seriously investigated. The analysis herein describes the technical and economic considerations associated with the four options, proposes an alternative structure for the back end of the fuel cycle (integrated site), and assesses the institutional issues.

II. TRADITIONAL REPOSITORY

The functional requirement is safe disposal of radioactive wastes shipped from reactors and fuel cycle facilities. The primary wastes are spent nuclear fuel (SNF), high-level waste (HLW) from closed fuel cycles, or some combination. This is the traditional fuel cycle system design because fuel cycles were developed and deployed before waste management systems were developed and deployed. The proposed YMR (Ref. 3) in the United States is a classical example of such a repository. Relative to other options for coupling fuel cycles with repositories, this option minimizes the benefits to the local community and state that are hosting the repository.

III. REPOSITORY WITH SNF RETRIEVABILITY

We do not know today if light water reactor (LWR) SNF is a valuable resource or a waste. Given this uncertainty, one option is to dispose of SNF in a repository but design the repository to allow future SNF recovery if it is needed. The repository becomes a fuel vault and a disposal facility—a different way to couple fuel cycles with the repository. There are three questions to address:

1. Why is there uncertainty about the future disposition of SNF?

2. Why store SNF in a repository rather than surface storage if its final disposition is unknown?

3. What are the repository storage options?

III.A. Is LWR SNF a Waste or a Resource?

The Massachusetts Institute of Technology study *The Future of the Nuclear Fuel Cycle*[1] examines alternative nuclear futures in the context of a greatly expanded use of nuclear energy. A key conclusion is that we do not know today if LWR SNF is a waste or a resource for technical, economic, and policy reasons. From a commercial perspective, a reactor owner wants the lowest-cost fuel. Today that is the once-through fuel cycle using uranium fuel. Uranium prices would have to rise by a factor of 4 or 5 for the economics to begin to change.

From the perspective of the nation-state, there are other considerations such as assured access to nuclear fuel. The added cost of a closed fuel cycle is small relative to the total cost of electricity; thus, national security considerations may dictate other fuel cycle choices that are more expensive but that do not greatly impact the cost of electricity. Several countries recycle LWR SNF back into LWRs—an option that can lower natural uranium consumption by up to 25% if both plutonium and uranium are recycled from LWR SNF (Ref. 1). This is a modest savings given that uranium costs are typically 2% to 5% of the total cost of nuclear electricity (but with significant price volatility). SNF recycle reduces the environmental impacts of uranium mining and milling.

The traditional vision of nuclear futures assumed plutonium would be recovered from LWR SNF, the plutonium would be used to start commercial fast reactors (FRs), and fissile materials in FR SNF would be recycled to FRs. Unlike LWRs, FRs with conversion ratios (CRs) equal to or greater than 1 produce fissile fuel as fast as or faster than it is consumed. A CR of 1 implies that one FR SNF assembly has sufficient fissile material to produce one new FR fuel assembly. In a classical FR this is done by conversion of ^{238}U to ^{239}Pu faster than the plutonium is burned. It implies that all the uranium can be burned, not just fissile ^{235}U. Recent research[1,4] suggests a better FR startup strategy is to use low-enriched uranium.

Fast reactor design. Advances in FR design[4] indicate that FRs can be started on low-enriched (<20% ^{235}U) uranium if the CR is near 1, the neutron-absorbing fertile blanket is eliminated, and MgO is used as an efficient neutron reflector. The use of low-enriched uranium avoids the political controversies and added security associated with high-enriched (>20% ^{235}U) uranium fuels. These advances have lowered the required FR uranium enrichment levels for startup cores and made such fuel much less expensive than fuel made from LWR SNF plutonium. The newest designs[5] suggest a once-through FR fuel cycle may have the same cost per kilowatt-electric as existing once-through LWR fuel cycles.

Uranium consumption. For scenarios with significant growth in nuclear electricity production, the startup of FRs on low-enriched uranium reduces the total uranium consumption by removing plutonium availability constraints when FRs are started up on LWR plutonium. This allows earlier adoption of FRs that substitute for future LWRs. That, in turn, reduces long-term uranium consumption versus traditional fuel cycles where LWR plutonium starts up FRs.

With this alternative startup strategy for FRs, FR SNF would be recycled in a sustainable fuel cycle fully utilizing the energy available in natural uranium and depleted uranium (DU). The LWR and FR fuel cycles would be fully decoupled. The concentration of fissile fuel in FR SNF is an order of magnitude higher than the fissile content (<2%) in LWR SNF; thus, FR SNF as a higher-assay source of fissile material may be economic to recycle while LWR SNF is uneconomic to recycle. Approximately eight LWR fuel assemblies must be reprocessed and the plutonium recovered to produce one new LWR fuel assembly—more are required to produce one FR assembly. In contrast, one FR fuel assembly must be reprocessed to produce one new FR fuel assembly.

Fast reactors imply converting fertile ^{238}U into fissile ^{239}Pu or converting fertile ^{232}Th into fissile ^{233}U. A decision to maintain future FR options logically requires that DU from uranium enrichment operations be stored for future use. The worldwide inventory of DU exceeds 1.5 million tonnes. For technical and policy reasons,[6] there are incentives to store the DU in a repository with the SNF—an option that allows recovery with the SNF if required or left as a waste if not needed.

1. *Safe disposal*. The requirements for disposal of large quantities of DU in the United States are unclear; however, geological disposal is required in many European countries. A repository meets the requirements for DU disposal.

2. *Repository performance*. Depleted UO_2 has been proposed as a component of the waste package (WP) and as a fill material to slow the degradation of LWR SNF. Depleted UO_2 is the only material that has exactly the same chemistry as SNF UO_2. If the SNF is embedded in depleted UO_2, whatever may chemically attack the SNF will first reach and attack the depleted UO_2 and thus delay the degradation of the SNF and allow more time for radioactive decay.

3. *Repository criticality control*. SNF contains fissile materials (plutonium, neptunium, etc.) that over time decay to ^{235}U or ^{233}U. If DU is incorporated into the WP, the DU will mix with any enriched uranium as the SNF and WP degrade and lower the fissile enrichment level to below that where nuclear criticality can occur.

Natural uranium is today the low-cost source of fissile fuel. Recent studies[1,7] indicate that low-cost uranium resources are greater than originally believed with sufficient uranium for much of this century assuming robust growth in the use of nuclear power. There are longer-term unconventional sources of uranium, from coextraction of uranium and rare earths from phosphate ores to seawater uranium. The ocean contains ~4 billion tonnes of uranium—sufficient uranium for a global nuclear enterprise for millennia. Various studies[1,8,9] indicate potential long-term recovery costs of several hundred dollars per pound of uranium—with large uncertainties in such cost estimates. At these prices it is not competitive with mined uranium today but is similar to current estimated costs of FRs with startup on plutonium from LWR SNF. Such uncertainties also make it unclear whether LWR SNF is a waste or resource.

III.B. Repository with Recoverable SNF

Given the uncertainties in the value of LWR SNF, there are policy incentives to store LWR SNF for up to a century. The cost is small and the upside benefits in maintaining energy options are large. While SNF can be safely stored at the reactor, at a centralized facility, or in a repository, there are incentives to design a repository with two goals: (a) prompt and safe disposal of waste including SNF and (b) an economic capability to recover the SNF if it becomes a valuable resource.

1. *Greater public acceptance of the nuclear enterprise*. Because of United States waste management failures, a policy of SNF surface storage appears to the public as kicking the can down the road and not addressing waste management challenges. Because of that public perception, storage of SNF in a repository is attractive relative to surface storage.

2. *Intergenerational equity*. A reversible repository while maintaining options for future generations minimizes costs to future generations if SNF is a waste.[10,11]

3. *Security*. Repositories are the ultimate in safe storage because they are far underground where even catastrophic events such as nuclear war[12] have little impact. Repositories provide superior physical security against theft or diversion because of their limited access. A major barrier against SNF theft is the high radiation level associated with SNF that necessitates heavy shielding. However, the intense gamma radiation field decreases within a century and that, in turn, may imply more expensive SNF security requirements with time[13] for other storage systems.

4. *Aids repository acceptance*. France[14,15] has included waste retrievability in their repository design based on French social and cultural studies that such repository characteristics provide a higher level of public confidence and thus public acceptance of the waste management enterprise. If mistakes occur, they can be rectified. Finland[16] requires retrievability of SNF from their planned repository for similar reasons.

5. *Aids repository siting*. A policy to design a repository for long-term recovery of SNF is a statement that any future closed-fuel-cycle facilities will likely be built at the repository site. The condition of retrieved SNF may or may not allow easy transport off-site creating large incentives to colocate and integrate any future reprocessing facilities at the repository site. Reprocessing plants have much larger staffs than repositories and thus would be a major economic incentive to the community and state to accept a repository.

There are downsides. Repositories are designed for waste isolation. A legitimate concern is that the dual mission could impact long-term repository performance. There will be some additional costs to maintain such options. Recent Organisation for Economic Co-operation and Development studies[11] examine many of the policy and technical issues associated with reversibility and retrievability.

There are different definitions of SNF retrieval. At one extreme is retrieval if there are major site difficulties where economics is not a driver. At the other extreme is a repository designed for retrieval of specific SNF WPs for reprocessing based on customer needs where economics is a major consideration. For the analysis herein, we define the following requirements.

1. *The repository must meet safe disposal requirements*. For public credibility, the design should allow disposal of the fuel and repository closure with relatively little effort.

2. *The retrieval process must not compromise the larger repository site for the disposal of HLW and other radioactive wastes*. It would be acceptable for sections of the repository to become unusable for waste disposal.

3. *Recovery of SNF must not require extraordinary engineering, have high costs, or create high worker risks*.

III.C. Retrievable Repository Options

Engineering studies indicate repository SNF retrieval is a practical option in multiple geologies.

III.C.1. Repositories with SNF Retrievability

Spent nuclear fuel can be recovered from hard-rock repositories as are being developed in Finland[16] and Sweden[17] and as are proposed for Canada. Retrievability is a legal requirement for the hard-rock repository in Finland.

Spent nuclear fuel can be recovered from salt repositories. Salt is plastic and thus disposal drifts will close around WPs over time. However, salt is inexpensive and easy to mine with the lowest estimated repository costs.[18] As a consequence, remining drifts to recover WPs is potentially attractive. This option was examined in the early U.S. salt repository program and found to be viable. The final salt repository design before cancellation of the program included SNF WPs designed for retrieveability made of ASTM 216 low-carbon cast steel with a design lifetime of 1000 years.[19]

Spent nuclear fuel can be recovered from repositories in clay and a wide variety of shales. One option is drilling large horizontal boreholes between two disposal drifts, lining the boreholes, and placing the WPs in those long horizontal boreholes. The space between the borehole walls and the WPs allows limited ventilation. This is the proposed French repository design[14,15] in clay that is designed to enable waste recovery for extended periods of time.

Last, SNF can be recovered in a wide variety of geologies using lined tunnels designed to maintain tunnel access for long periods of time. In some geologies, the disposal drifts may not remain open for long periods of time. Premature closure can be avoided by lining the disposal drifts to maintain easy retrievability. Lining also reduces air pressure drops for ventilation systems and can prevent water entry into the repository. When it is decided to close the repository, the disposal drifts can be backfilled. There are many options.

At one extreme of such designs is the proposed YMR (Ref. 3). This design uses steel braces, rock bolts, and other structures to prevent drift collapse. Bare WPs fill the center of the tunnel. Remotely operated equipment is used to place WPs. The proposed plan was to fill the repository over 30 years and then use active ventilation for 50 years to reduce the WP decay heat to acceptable levels before repository closure. The facility was designed to allow retrieveability if site or design problems were identified after waste emplacement operations were initiated (a U.S. regulatory requirement[a]) but not designed for SNF recovery for reprocessing.

At the other extreme are designs that allow full access to any WP in a highly engineered underground structure. An example of such a design[20,21] is the use of concrete-lined disposal drifts with WPs in concrete shields allowing contact operations and quick SNF retrieval. The shielded WPs allow removal of any specific WP from the repository by (a) moving packages with a heavy-lift forklift truck or (b) use of rail-mounted cranes going into a drift, lifting the desired WP, and moving it out of the drift over the other WPs.

III.C.2. Decay Heat

The primary long-term complication associated with SNF recovery is that decay heat raises the temperature of the rock. This can be addressed two ways.

1. *Hot rock mining*. The SNF can be emplaced in long-lived WPs and the repository backfilled with consideration of what is required for retrieval—most importantly, precision descriptions of the as-built repository. Modern mining techniques using various cooling systems allow removal of backfill and recovery of WPs at high temperatures. This technology was originally developed in South Africa for mines as deep as 3900 m with temperatures as high as 60°C.

2. *Actively cooled repository to limit temperature rise*. Repositories such as the proposed YMR are designed to allow long-term cooling. This reduces the long-term cumulative decay heat and allows higher waste loadings per meter of disposal tunnel. Because of the potential cost benefit, there have been many studies in different geologies on how to accomplish this.

III.D. Changing Perspectives on SNF Retrievability

Spent nuclear fuel retrievability has historically been a consideration in repository design as (a) a form of safety in the event unexpected repository failure modes are identified after start of repository operations and (b) a method to improve public acceptance. Many repository designs have been developed to enable SNF retrievability. Today there are additional incentives to enable SNF

[a] *Code of Federal Regulations*, Title 10, "Energy," Part 60, "Disposal of High-Level Radioactive Wastes in Geologic Repositories," Sec. 60.111, "Performance of the Geologic Repository Operations Area Through Permanent Closure," Subsec. b, "Retrievability of Waste," U.S. Nuclear Regulatory Commission (1996).

retrievability because we do not know if SNF is a waste or a resource. Many of the existing designs can meet this added requirement with only small changes. New technologies, particularly new cements designed to improve repository performance, have created new classes of repository design options that may enable SNF recovery at relatively low cost.

IV. CLOSED FUEL CYCLE WITH COLOCATED INTEGRATED BACK-END FACILITY

If one sites a repository before choosing to deploy a closed fuel cycle, the option exists to colocate and integrate reprocessing, fabrication, and waste disposal into a single back-end fuel cycle facility.[22] The functional requirements are to (a) produce fuel elements for reactors using fissile and fertile materials recovered from SNF and (b) safely dispose of all wastes.

This option has received almost no attention. Defense fuel cycle facilities and the early commercial fuel cycle facilities were sited before the development of methods to dispose of long-lived waste; thus, waste management was not considered in the siting of these facilities. The single exception was in Germany,[23] where in the 1970s it was proposed to colocate reprocessing and disposal facilities at Gorleben. Those assessments indicated major economic and social benefits by colocation and integration of facilities.

Colocation may ease the siting of geological repositories. The proposed YMR would have employed ~2000 people—most at the site. If all back-end facilities are colocated, the community and state accepting a repository would receive thousands of added jobs associated with reprocessing and fuel fabrication. In this context, there are large incentives to determine the magnitude of the cost savings and risk-reduction benefits by colocation and integration of back-end facilities. If the economic case is overwhelming, it would provide assurance that if a community and state accept a repository, they would be the beneficiaries of any decision to later adopt a closed fuel cycle.

If facilities are colocated and integrated together, it avoids the shipment of wastes from reprocessing plants to repositories on public roads. This single change has favorable impacts on economics, repository performance, security and safeguards, and public acceptance. Today the selection of reprocessing technologies, waste treatment processes, and waste forms is driven by two goals: (a) creating a stable waste form for safe storage, transport, and disposal and (b) minimizing waste quantities. Large waste volumes are expensive to store and have high transport costs because shielding requirements imply small waste quantities per transport package. However, if there is on-site disposal of wastes, the constraints on waste volumes are relaxed, with major implications as discussed below.

There are several lines of evidence to support this hypothesis. In the Cold War, the PUREX reprocessing plant at the Hanford site in the United States processed 7000 tonnes of SNF per year.[24] In comparison the commercial French La Hague reprocessing plant (a much larger facility and the largest commercial reprocessing plant in the world) has a capacity of 1700 tonnes per year. While the Hanford SNF had low burnup, the SNF was typically processed in 180 days—implying levels of radioactivity similar to high-burnup, longer-cooled commercial SNF at La Hague. The biggest difference is that the Hanford defense complex used on-site disposal that simplified and reduced the cost of reprocessing and waste management operations. Because of decisions to minimize short-term waste management costs, a massive cleanup effort is underway at the Hanford site. However, the question is: What would be the economics of such a facility if it were colocated with a repository meeting today's waste management standards?

In this context, there is a need to define "large quantities of wastes." A reprocessing plant processing ~5 tonnes of SNF per day supports ~50 LWRs; thus, the nuclear reprocessing definition of "large quantities of waste" is small (tonnes or tens of tonnes per day) compared to the chemical plant definitions of waste volumes. As discussed later, repositories can be designed for large waste volumes at low costs.

There is a second line of evidence to support colocation of reprocessing and repository facilities to reduce SNF recycling costs. Table I shows the cost breakdown for a commercial PUREX reprocessing plant.[25,26] Some functions such as receiving are required by reprocessing facilities and repositories; thus, colocation can avoid facility duplication.

Equally important, <7% of the cost of a reprocessing facility is associated with separation of fissile and fertile material from the SNF—the purpose of the reprocessing plant. About half of the cost of reprocessing is associated with waste management—either processing wastes or storing wastes. Major improvements in reprocessing economics are only possible with major changes in waste management because that is where most of the costs are. Many of the design choices have been driven by the need to minimize waste volumes. There are alternative processes[27–30] and the potential for more economic systems if the design constraints, particularly with waste management, are changed.

IV.A. Process Implications of Reduced Waste Volume Constraints

Reducing waste volume constraints with on-site waste disposal can reduce the cost of reprocessing facilities. Several examples can clarify this.

1. *Chemical decladding of LWR SNF*. SNF cladding is typically one-third of the mass of a SNF assembly;

TABLE I

Cost Breakdown of Reprocessing LWR SNF

Area	Cost (%)	Subarea	Cost (%)
Receiving	7.8		
Front end	25.5	Mechanical feed preparation	13.00
		Tritium confinement	3.65
		Dissolution	8.16
		Feed preparation	0.69
Off-gas	5.74	Dissolver off-gas	4.17
		Vessel off-gas	1.22
		Head-end off-gas	0.35
Separations	6.59	Solvent extraction uranium	1.39
		Solvent extraction plutonium	1.56
		Solvent treatment	1.04
		Acid and waste recovery	1.91
		Low-enrichment uranium purification	0.69
HLW	10.42	HLW concentration	1.04
		Intermediate-level waste concentration	1.39
		HLW solution storage	3.13
		HLW solidification	4.86
Product conversion	6.6	Low-enriched uranium conversion	3.99
		Plutonium conversion	2.26
		Plutonium storage	0.35
SNF/HLW storage	26.9		
Cladding storage	10.4		

thus, removal of the cladding (part of mechanical feed preparation) and storage of the cladding are major cost components of reprocessing plants. Cladding can be separated from fuel materials by mechanical or chemical methods. Chemical decladding of Zircaloy-clad SNF has been done on an industrial scale for defense SNF at the Hanford site using the Zirflex process.[30] However, the higher waste volumes have made chemical decladding nonviable for commercial facilities that ship wastes off-site to repositories. If waste volumes are not a constraint, chemical decladding of some fuels becomes a viable option with reductions in reprocessing plant capital costs and simpler operations. Immediate on-site disposal would eliminate most or all cladding storage costs independent of the choice of process or choice of cladding material.

2. *Processing of high-temperature reactor fuel*. Reprocessing coated-particle graphite-matrix fuel is expensive because of the need to separate the bulk graphite from the fissile fuel. One option developed in the 1970s was to burn off the bulk graphite—an efficient way to remove >90% of the mass of this SNF. However, the resultant carbon dioxide contains radioactive ^{14}C. Experiments[31] demonstrated low-cost removal of the carbon dioxide from the off-gas by scrubbing with calcium hydroxide, but this creates a high-volume waste stream. That waste stream can be easily solidified in cement and disposed of in an on-site repository. However, the volumes are sufficiently large that this is not a practical option if wastes must be shipped to a repository.

3. *Operational and decommissioning wastes*. The high-volume wastes are from operations (failed equipment, maintenance, etc.) and decommissioning where much of the cost is in size reduction and packaging for transport. On-site disposal drastically reduces both cost and radiation exposure to the staff.

Relaxing waste volume constraints can have major impacts on the size and complexity of waste treatment operations. Several examples can illuminate this point.

1. *Volatile fission products*. Volatile fission products are released during reprocessing of SNF. Many processes have been tested for removal and immobilization of krypton, iodine, ^{14}C, and tritium, but most waste forms were rejected because of their low waste loadings—the specific fission products only fitted into a few locations in the molecular structure of the waste forms. Relaxing volume restrictions would increase waste-form options and enable the use of many previously identified lower-cost, low-waste-loading waste forms—some with better performance.

An example is krypton containing ^{85}Kr. This gas with a 10-year half-life can be stored in pressurized cylinders; however, there are significant safety advantages to storing krypton on a solid[32,33] because it avoids the possibility of rapid release if there is a leak in a gas cylinder. The solid absorber options with high waste loadings are expensive. If higher waste volumes are acceptable, there are low-cost absorbents with low waste loadings and potentially better performance.

2. *Tritium control*. Tritium control is a challenge in aqueous reprocessing plants. Much of the tritium can be removed as water in front-end processes. However, some tritium enters the dissolver and the rest of the plant. Water is recycled within the plant, but recycling increases the concentrations of tritium in recycle streams and thus creates the potential for higher radiation doses to the workforce and greater releases to the environment. With relaxed waste volume constraints, more tritiated water can be sent to waste and solidified in cement. This reduces the equipment required for recycle, the buildup of tritium and other impurities in recycle streams, and plant tritium inventories at the cost of larger waste volumes.

IV.B. Waste-Form Performance and Processing

Repository performance is determined by the waste form, WP, engineered barriers, and the geology. By definition, colocation and integration of reprocessing and the repository implies that the disposal geology is well understood. The waste-form chemistry and packaging can be customized to improve waste-form performance while lowering costs because the waste form is designed for a specific site and a specific geology. A recent U.S. National Academy of Sciences study[34] emphasizes the strong dependence of waste-form performance on the near-field geochemistry and the potentially large gains in repository performance by matching waste form to the repository.

The maximum allowable waste loading for a specific waste form depends upon its chemical structure. A requirement for very high waste loadings implies limited waste-form choices and the need to carefully control the composition of the initial waste. If volume constraints are reduced, there is a wider set of waste forms to choose from. Many of these waste forms have potentially better performance and lower costs. Lower waste loadings also open up two other strategies to improve repository performance.

1. *Solubility-limited waste forms*. The release rates of many radionuclides from a repository are limited by the solubility of the specific radionuclide in groundwater. If the specific radionuclide is diluted by a factor of 1000 with the nonradioactive isotopes of that element, its concentration in groundwater is reduced by a factor of 1000, which should lead to a commensurate reduction in radionuclide releases to the environment. Isotopic dilution is the most direct way to improve repository performance for solubility-limited radionuclides.

For example, radioactive ^{14}C can be removed from reprocessing off-gas streams by scrubbing with calcium hydroxide to create calcium carbonate.[31] The calcium carbonate can be incorporated into cement with nonradioactive calcium carbonate. Because the actual mass of most radioactive isotopes in SNF is small, high isotopic dilution factors are possible ($>10^3$). The same can be done for other isotopes such as those of iodine by isotopic dilution with nonradioactive iodine and conversion into a barium iodate[35] in a cement matrix or other forms with low groundwater solubility.

2. *Limiting radiation damage*. Waste forms with high concentrations of radionuclides are degraded by (a) long-term radiation damage to the waste form and (b) change in the chemical composition of the wastes caused by the decay of radionuclides into different elements. Both effects are reduced by using waste forms with low waste loadings. Increasing volumes by a factor of 10 reduces the cumulative radiation dose to the waste form per unit volume by a factor of 10. Low waste loadings can reduce or eliminate concerns about waste-form radiation damage over time.

If waste volume constraints are relaxed by integrating the reprocessing, fuel fabrication, and repository system, the most likely change would be an increased use of lower-cost, high-performance, low-waste-loading cement waste forms. The last decade has seen the development of high-performance cements where inorganic additives control the internal bulk pH, control the redox potential, and absorb specific radionuclides.[20,36–38] The control of cement chemistry enables its wide use as (a) a waste form for many different types of waste and (b) the matrix material to create the appropriate geochemical environment to minimize the release of radionuclides from embedded waste forms. Some examples can clarify this.

1. *Grout in place*. In the 1960s and 1970s Oak Ridge National Laboratory disposed of its liquid radioactive wastes ($2.5 \cdot 10^{16}$ Bq) by cement hydrofracture.[38,39] Specially formulated cements were mixed with liquid waste and slurries. The mixture was pumped underground into a shale formation and solidified in place. The process was remarkably cheap—a few dollars per gallon of waste. The technology worked but there were operational failures. The technology would be simplified and most drawbacks eliminated by pumping the grout from reprocessing facilities into engineered silos within the repository.

2. *High-performance waste forms*. Cement formations have been developed to solidify transuranic waste and HLW by use of special formulations and steam curing of the cement.[40,41] Such low-cost waste forms have not been considered for higher-activity waste streams because of transport volume constraints—constraints that disappear with colocation.

Integrating reprocessing and repositories implies a reversal of the 40-year strategy for development of waste forms based on waste-form requirements of (a) good performance and (b) high waste loadings to minimize waste storage and transport costs. For colocated integrated facilities the requirements become (a) high waste performance and (b) minimization of back-end fuel cycle costs. Changing requirements for waste loadings opens up new but only partly explored alternative options.

IV.C. Operational Safety

Colocation and facility integration has safety benefits. Since the Bhopal chemical accident in India, there has been a revolution in chemical plant safety philosophy.[42] The emphasis is on (a) minimizing in-process inventories of hazardous materials and (b) rapid conversion of hazardous materials to chemically stable (noncombustible), nondispersible, insoluble forms. Potential accident consequences depend upon the inventory of potentially mobile radioactive materials. Colocation and facility integration enable implementation of this chemical engineering safety strategy to reduce risks and occupational radiation exposures.

For example, lower-activity dispersible liquid wastes could be mixed with special cement grouts and pumped underground into large lined silos as generated with minimum interim storage, handling, and processing. This type of processing reduces costs while reducing inventories of mobile radionuclides—the accident source term.

IV.D. Safeguards and Nonproliferation

If wastes contain significant quantities of plutonium and other fissile materials, there is a requirement for multigenerational long-term repository safeguards. However, dilution of such wastes can make the fissile materials "not practically recoverable,"[43,44] and safeguards can be terminated before disposal. Required levels of dilution in various waste matrixes have been defined[45,46] by the International Atomic Energy Agency for safeguards termination. The economic requirement is cositing facilities so one can afford waste forms with lower waste loadings.

Many studies[1] support nuclear fuel leasing where fuel cycle companies manufacture fuel, lease that fuel to power companies, and then manage the back end of the fuel cycle. This would (a) ease the use of nuclear power by smaller countries with only a few reactors by avoiding the need to create their own SNF waste management system and (b) strengthen the nonproliferation regime by limiting fuel cycle facilities to countries with large nuclear power programs. Colocation and facility integration can support fuel leasing.

1. *Economics*. Large integrated colocated facilities have potentially better economics favoring a limited number of large fuel cycle companies.

2. *Coupled waste-fuel cycle*. Integration of reprocessing with the repository makes waste disposal an integral, nonseparable component of the reprocessing plant. The option of shipping many wastes back to the country of origin is not a technical option.

3. *Public acceptance*. The historical challenge to fuel leasing is the unwillingness of host countries to accept wastes. Integration and colocation implies that the community accepting the wastes gains the maximum benefits—from tax revenue to jobs.

IV.E. Repository Design

Repositories dispose of two waste classes[47]: high-decay-heat wastes and low-decay-heat wastes. High-decay-heat wastes include SNF and HLW. To avoid excessive repository temperatures that can degrade the waste form, package, and geology, these wastes are spread over parallel tunnels to enable decay heat to be conducted from the waste form through the WP and through the repository environment to the earth's surface. Integrating reprocessing and repositories may not change the treatment or disposal of HLW but does change the treatment and disposal strategy for all other back-end radioactive wastes—the low-heat wastes.

Low-decay-heat wastes can be disposed of in large engineered caverns that have low costs[47] as has been demonstrated in several operational facilities. The low disposal costs for low-heat wastes are a major factor in the economics of colocation and integration of reprocessing and the repository. While there is no operating geological repository for SNF or HLW, there are operating geological repositories for the disposal of low-heat transuranic and chemical wastes (Table II).

The first operating geological repository in the world was the Herfa-Neurode repository for chemical wastes in Germany.[48] Many of the chemical wastes are heavy metals that remain toxic forever. Since the opening of Herfa-Neurode, additional geological repositories have opened elsewhere in Europe for chemical wastes. The first repository for long-lived radioactive wastes was the Waste Isolation Pilot Plant (WIPP) in New Mexico.[49] WIPP is designed for low-heat transuranic wastes—primarily plutonium-contaminated wastes. The designs of WIPP and Herfa-Neurode are similar. Both are located in salt. The WIPP facility is relatively small reflecting the small quantities of wastes to be disposed of.

There are other types of operational high-volume underground facilities for the disposal of radioactive wastes. In 1988 Sweden opened the Final Repository for Short-Lived Radioactive Wastes[50] (SFR) for low- and intermediate-level radioactive wastes. It is located under the Baltic seabed in granite ~1 km off the Forsmark Nuclear Power Plant site with access by tunnel. Low-activity wastes are disposed of in large mined caverns while higher-activity wastes are disposed of in concrete silos with bentonite clay barriers between the silos and rock (Fig. 1). Silo diameters are ~26 m with heights of ~50 m. Waste packages up to 100 tonnes in weight are placed in silos. A cement grout is used to create monolithic structures with low water permeability. The low surface-to-volume ratio minimizes the groundwater that can contact the silo and the wastes in the silo. The silos are high-performance packages for disposal of high-volume, low-heat wastes.

In such facilities, the local geochemistry is controlled to minimize radionuclide release rates. The composition of the cement and aggregate can be chosen to minimize radionuclide releases[20,36,37] by control of internal bulk pH, controlling the redox potential, and the

TABLE II

Operational Geological Repositories

Repository type	Chemical	Radioactive
Facility	Herfa-Neurode (Germany)	WIPP (United States)
Operational	1975	1999
Capacity	200 000 tonnes/year	175 570 m^3 (lifetime) (~350 000 tonnes)
Hazard lifetime	Forever	>10 000 years

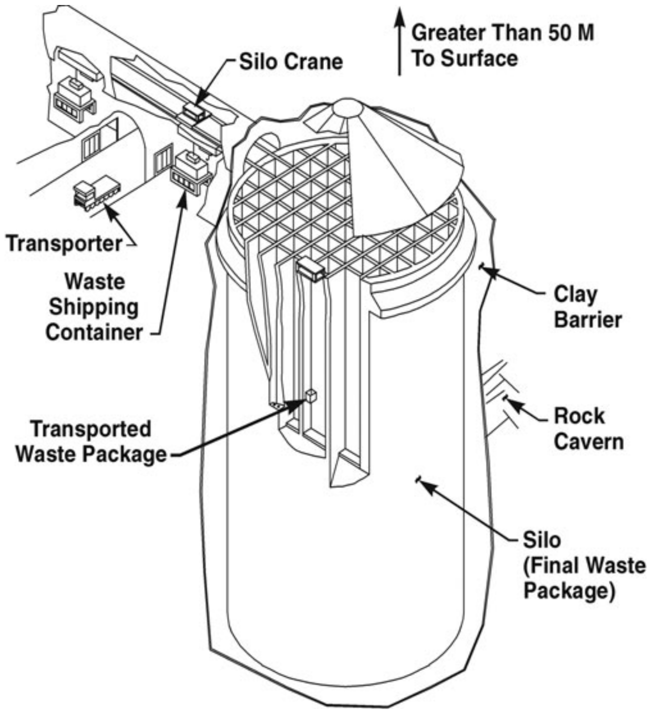

Fig. 1. Swedish SFR silo facility for intermediate-activity wastes.

absorption of specific radionuclides. Alternatively, special reagents can be mixed with wastes to assure performance. For example, WIPP, a repository primarily for plutonium wastes, places magnesium oxide around the WPs to reduce the solubility of plutonium and thus reduce the potential for release of plutonium from the repository.[51] The choice of additives depends upon the wastes, the local geology, and the geochemistry.

There is the option to provide active cooling of large underground waste monoliths.[52] The curing of cement generates heat that in large concrete pours raises temperatures and can degrade the cement. Since the construction of the Hoover Dam in the 1930s, many mass pours of concrete have included cooling coils with flowing water to control cement temperatures during the curing process. This technology enables selection of cement compositions to maximize radionuclide containment without concern about the heat generation and excessive temperatures when the cement cures. It also enables the cooling of low-heat wastes for several decades if there is heat generation from short-lived radionuclides (tritium, krypton, etc.). The capability to cool such monoliths avoids the need to store such wastes before disposal—with potential cost and safety advantages. Dilute wastes imply low heat generation rates per unit volume that, in turn, imply that any cooling system can have a failure and it will be weeks to months before there is a significant increase in local temperatures—sufficient time for maintenance operations.

V. COLOCATED SPECIALIZED DISPOSAL FACILITIES

The fourth option is a repository system consisting of at least two disposal facilities such as a conventional repository for high-volume wastes and a colocated borehole[53–56] or equivalent disposal facility[47] for enhanced isolation capabilities. A borehole is a drilled well where the waste would be typically buried 4 to 5 km underground. The practical diameter of drilled wells limits the waste volumes that can be disposed of. It would be suitable for SNF, HLW, and other selected wastes such as minor actinides but not the higher-volume wastes (with much less radioactivity) requiring geological disposal. There are several incentives for such a technology.

1. *Nonproliferation*. Deeper disposal makes it more difficult to recover plutonium or other weapons-usable materials in wastes.

2. *Disposal of high-heat wastes*. Radioactive decay generates heat that raises repository temperatures. Repository designers limit temperatures to (a) avoid degradation of waste forms, WPs, and geology and (b) minimize uncertainties in predicting future performance. Temperatures are limited by the underground spacing between WPs; thus, more decay heat implies more space between WPs, which implies larger repositories that have higher costs. There is an economic incentive to reduce decay heat in a repository. High-heat radionuclides include selected actinides (^{241}Am) and fission productions (^{90}Sr/^{137}Cs). There have been proposals to separate these isotopes from other wastes and separately dispose of them. Because boreholes are narrow in diameter with long lengths, they have the ideal geometry to efficiently dissipate heat from high-heat waste forms. Boreholes have potentially lower disposal costs for these wastes than conventional repositories.

3. *Disposal of high-hazard radionuclides*. There have been many proposals to use reactors to destroy selected long-lived radionuclides,[1,57] but using reactors for waste transmutation is an expensive, lengthy, and complex strategy. The geological alternative to partitioning and transmutation is partitioning and special isolation with borehole technology—an option with potentially lower costs and risks.

4. *Disposal of mixed-oxide SNF*. Mixed-oxide SNF contains higher concentrations of plutonium and generates considerably more long-term decay heat than LWR SNF because of the presence of ^{238}Pu and ^{241}Pu (and its decay product ^{241}Am). The higher long-term decay heat makes it more expensive to dispose of in a typical geological repository where heat load significantly impacts disposal costs. As a consequence, this may be a waste form where economics favor borehole disposal.

While borehole disposal has been considered for decades, advances in drilling technologies have begun to convert it into a real option. It is not currently a demonstrated technology. The scientific basis for superior isolation relative to a conventional repository is based on two considerations.

1. *Depth*. Deeper disposal implies a longer travel length for radionuclides from the repository to the environment. Moreover, deeper granitic bedrock provides a chemically reducing environment with a range of pH values that minimizes the solubility of many long-lived radionuclides.

2. *Groundwater salt gradient*. In most of the world the salt concentration in groundwater increases with depth.[54] Salt water has a higher density than freshwater; thus, the salt water does not mix with freshwater. Any radionuclides that escape a WP and are dissolved in the deep higher-density salt water have no mechanism to mix with the lower-density freshwater and escape to the environment. Deep salt water is unlikely to be pumped to the surface because it cannot be used for irrigation and its recovery is expensive.

There are large incentives for colocation of a borehole facility with a conventional repository. Most of the candidate wastes are by-products of reprocessing. The characteristics that make them candidates for borehole disposal (high decay heat, high radiation levels, etc.) imply difficulties in transport. Furthermore, the likely borehole WP is 40 or 80 ft long with a diameter slightly less than a borehole. While field assembly is possible, such operations are much simpler at an integrated site.

The expectation would be that any site suitable for a low-heat geological repository is likely to be suitable for borehole disposal at greater depths because the upper geology has the capability to isolate radionuclides by itself. Borehole disposal would reduce the footprint of the conventional repository because that footprint is determined primarily by heat-generating wastes. Colocation would reinforce the concept of a back-end nuclear fuel cycle facility.

VI. REDESIGNING THE BACK END OF THE FUEL CYCLE

It is not known what fuel cycle or fuel cycles the United States will adopt in the future. The fuel cycle will evolve over time, but the need for a repository will remain a constant, for there will always be some wastes requiring disposal.[1] These considerations plus the benefits of colocation lead to the conclusion that we should site integrated back-end facilities with the future capability to serve all four functions described above: (a) repository waste disposal, (b) underground SNF storage/disposal, (c) integrated SNF reprocessing-repository production facilities to produce fuel assemblies and dispose of wastes on-site, and (d) implementation of advanced disposal systems such as borehole disposal of selected wastes.

If a repository accepts SNF and is designed to enable later recovery of that SNF, the best location for any future reprocessing plant will be at the repository site. After decades or a century of disposal, it is unlikely that any recovered SNF would be shipped off-site without inspection. The costs of qualifying SNF for shipment create economic incentives to avoid those costs by locating the reprocessing plant on the repository site.

For large countries such as the United States, there would be an incentive for regional facilities with such combined capabilities. Such facilities are large, long-term investments measured in many tens of billions of dollars. A single reprocessing plant to process half the SNF that is currently produced each year would require an investment of approximately $20 billion (Ref. 1). The potential scale of operations and the advantages of redundancy suggest development of multiple sites.

Colocation and integration of back-end facilities implies a different business model. One model for such a complex are airport authorities with publicly and privately colocated airline terminals, aircraft maintenance bases, and related operations—all enabled and benefiting from the high-value, government-owned runway asset. Many airports (Albuquerque, New Mexico; Knoxville, Tennessee; etc.) include both civilian and defense/government facilities—typically with the commercial operations on one side of the airport and the air force bases on the other side with shared runways.

A local repository authority[58,59] would be similar with the repository SNF receiving, waste packaging, and underground disposal facilities being the runway equivalent of the airport. If a closed fuel cycle were adopted, the largest tenant would be the reprocessing facility, which in the United States would most likely be privately owned. However, there are a large number of other organizations with economic incentives to colocate and integrate their operations with the repository complex. For example, the United States has a large safeguards program that involves working with the International Atomic Energy Agency. It involves training of inspectors and developing new safeguards technologies. The SNF receiving facility of a repository will have the largest quantity and largest selection of SNF in the United States. Because of that, the best location for a safeguards training facility is right next to the repository SNF receiving facility with access to that SNF. Similarly, there are many other activities where there are large technical and economic incentives to colocate with the repository. A partial list of other such facilities to couple to the repository includes:

1. government and private SNF inspection facilities to determine performance of SNF
2. government pilot reprocessing plant to (a) process troublesome materials such as high-enriched research reactor SNF and the Three Mile Island

core debris and (b) test new technologies—such as those required to build an integrated-colocated commercial reprocessing-repository facility

3. government research facilities on repository behavior
4. private waste treatment facilities for commercial wastes
5. private radioisotope production.

The local economic impacts of these other activities can be large. It is estimated that the single-purpose YMR would have employed ~2000 people to dispose of SNF from a once-through fuel cycle. Recent estimates[60] indicate that the addition of other activities associated with either an open or a closed fuel cycle would add 2000 to 4000 workers to the site. The biggest savings for most users would be sharing a common SNF receiving facility. Common use of expensive facilities can result in large savings to the nation, but it requires a repository authority that sees its mission as supporting local business by (a) supporting public and private enterprises using repository facilities for many missions and (b) operating a repository. A multipurpose back-end facility will not work if the repository authority sees the facility as primarily a disposal site and other operations only to be tolerated as necessary. The secret of the airport authority success is the broad view of its mission—not just launching airplanes. The same broad view is required of a repository authority.

Airport authorities are creations of state governments run by boards of directors. Typically, the governor appoints some members of the board with other members appointed by local city and county governments. Because the boards represent both state and local interests, they can bridge the divide between state and local interests. There is a strong emphasis on maximizing jobs and taxes for the state and local governments while addressing local concerns. A repository authority would be similar. It would be the local partner with any federal waste management authority. Each repository would have its own repository authority reflecting local institutions.

VII. INSTITUTIONAL ASSESSMENTS

The four options herein have different technical and thus different institutional characteristics that can have major impacts on the ease or difficulty of siting a geological repository. Facility colocation implies larger investments and more jobs associated with the repository. It enables all radioactive wastes to be placed in the repository (including all low-level waste[61]) if desired and a higher assurance of prompt and complete decommissioning of obsolete facilities because of the availability of local disposal facilities and substantially lower costs for disposal of such wastes.

Recent studies[62] on siting repositories emphasize the importance of the process to site facilities and "added value" as part of the siting process. Added-value policies include mitigation, compensation, and incentives. Mitigation policies include local decision-making power, partnerships with the nuclear industry, and stakeholder development. Compensation is for damages that may be done. Incentives include funding instruments (funds), public monetary instruments (tax revenues), employment, and development projects.

A repository with the capability to retrieve SNF is a technical mitigation policy to assure performance. Colocating facilities is an incentive policy. As an incentive policy it has major advantages relative to funding instruments. Funds and grants can be interpreted as bribes for accepting dangerous facilities and thus backfire by raising questions about safety. In contrast jobs and tax revenues are consistent with the benefits of other industrial facilities. It is similar to airports with runways, coal plants with ash piles, and chemical plants with evacuation plans in the event of accidents.

In the context of repositories with the option of retrievability of SNF and potential future closed fuel cycles with reprocessing, there is one unique incentive policy. Future recycle of SNF from a repository would most likely imply the SNF has acquired significant value, thus, the question of who has title (ownership) of SNF in the repository. In the United States with a federal system, there is the option to provide the state government first right to take title of SNF in the repository anytime in the future. It would be a mechanism to guarantee that if a state government agreed to the construction of a repository within its boundaries, any future reprocessing plant using that SNF would be built in that state.

Public opinion polls by Jenkins-Smith et al.[63] indicate greater acceptance of a repository if (a) the repository is designed for SNF retrievability and (b) other fuel cycle facilities are colocated with the repository. By a 2 to 1 margin, the U.S. public prefers repositories designed to allow SNF retrieval to maintain future options (recycle or future waste management systems). This conclusion has been reinforced by other U.S. (Ref. 64), Finnish,[16] and French studies. There is also increased support for a repository if it is colocated with other facilities such as waste management research facilities and reprocessing plants. As shown in Table III, there is a large increase in support for a repository if a reprocessing plant is colocated with the repository—particularly by those initially neutral to or opposed to geological repositories. Several recent reports and books provide case studies that support this perspective.[65,66]

VIII. CONCLUSIONS

For historical reasons, fuel cycle and waste management facilities in the United States have been envisioned

TABLE III

Change in Support for Base Repository Designs with Reprocessing Facilities*

Initial Preference	Support (58%)	Neutral (26%)	Opposed (16%)
Support increased	66%	47%	48%
Support unchanged	21%	43%	16%
Support decreased	13%	10%	36%

*Base case assumes two national facilities.[63]

as separate facilities at dispersed sites. There are, however, other ways to organize fuel cycle and waste management facilities. Because the United States has yet to site a repository and has not made long-term decisions on what fuel cycles to adopt, it has choices on how integrate fuel cycles and waste management.

Four ways to couple the back end of the fuel cycle with the repository were examined. Given today's requirements, there are large incentives to colocate and integrate all back-end facilities to improve economics, improve public acceptance, lower risks, and support nonproliferation objectives. Such a facility can evolve with time as fuel cycles change. Such options have not been previously examined (except for a limited effort in Germany in the late 1960s). The options imply large technical and institutional changes—thus the need for analysis, research, and development to understand the options and identify the best paths forward.

ACKNOWLEDGMENTS

I would like to thank the following individuals for their advice and review of this paper: J. Conca, A. G. Croff, B. W. Dixon, M. J. Driscoll, R. Einziger, D. Greneche, S. Ion, J. Kotek, E. Lahoda, E. Shwageraus, and R. Wymer.

REFERENCES

1. M. KAZIMI et al., *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study*, Massachusetts Institute of Technology (2011).

2. R. WIGELAND, B. DIXON, and J. GEHIN, "Identification, Description, and Characterization of Existing and Alternative Nuclear Energy Systems," Report to the Blue Ribbon Commission, Idaho National Laboratory (2011).

3. "License Application for a High-Level Waste Geological Repository at Yucca Mountain," U.S. Department of Energy (June 3, 2008).

4. T. FEI, E. SHWAGERAUS, and M. J. DRISCOLL, "A Cost-Effective U-235 Once-Through Startup Mode for SFRs," *Trans. Am. Nucl. Soc.*, **104**, 734 (2011).

5. T. FEI et al., "A Survey of Alternative Once-Through Fast Reactor Core Designs," *Proc. Int. Congress Advances in Nuclear Power Plants (ICAPP 2012)*, Chicago, Illinois, June 24–28, 2012, American Nuclear Society (2012).

6. C. W. FORSBERG and M. ZUCCHETTI, "The Backend Question for Depleted Uranium," *Proc. Int. Congress Advances in Nuclear Power Plants (ICAPP 2011)*, Nice, France, May 2–5, 2011.

7. I. A. MATTHEWS and M. J. DRISCOLL, "A Probabilistic Projection of Long-Term Uranium Resource Costs," MIT-NFC-TR-119, Center for Advanced Nuclear Energy Systems, Massachusetts Institute of Technology (June 2010).

8. F. R. BEST and M. J. DRISCOLL, "Prospects for the Recovery of Uranium from Seawater," *Nucl. Technol.*, **73**, 55 (1986).

9. "Technology and Applied R&D Needs for Nuclear Fuel Resources: Resource Document for the Workshop on Nuclear Fuel Resources," U.S. Department of Energy, Office of Nuclear Energy (Oct. 2010).

10. B. TAEBI and A. C. KADAK, "Intergenerational Considerations Affecting the Future of Nuclear Power: Equity as a Framework for Assessing Fuel Cycles," *Risk Anal.*, **30**, *9*, 1341 (2010).

11. *Proc. Int. Conf. Dialogue Reversibility and Retrievability in Planning Geological Repositories*, Reims, France, December 14–17, 2010, Organisation for Economic Co-operation and Development, Nuclear Energy Agency.

12. C. V. CHESTER and R. O. CHESTER, "Civil Defense Implications of the U.S. Nuclear Power Industry During a Large Nuclear War in the Year 2000," *Nucl. Technol.*, **31**, 326 (1976).

13. E. D. COLLINS and M. H. EHINGER, "Nonproliferation Uncertainties, a Major Barrier to Used Nuclear Fuel Recycle in the United States," *Proc. 52nd Annual Mtg. Institute of Nuclear Materials Management*, Palm Desert, California, July 17–21, 2011.

14. Official French Waste Repository Web Site: www.andra.fr/international/index.html (current as of August 5, 2011).

15. "Andra Research on the Geological Disposal of High-Level Long-Lived Radioactive Waste: Results and Perspectives," Dossier 2005, ANDRA (2005).

16. P. HOKKANEN and M. KOJO, "Ymparistovaikutusten arviointimenettelyn vaikutus paatoksentekoon" ("Influence of the EIA on decision making"), *Suomen Ymparisto (Finish Environment)*, **612** (2003).

17. Official Swedish Waste Repository Web Site: www.skb.se (current as of August 5, 2011).

18. J. CONCA and J. WRIGHT, "Deep Geological Nuclear Waste Disposal—No New Taxes," *Proc. Waste Management 2012*, Phoenix, Arizona, February 26–March 1, 2012.

19. "Conceptual Designs for Waste Packages for Horizontal or Vertical Emplacement in a Repository in Salt," BMI/ONWI/C-145, Office of Nuclear Waste Isolation, Battelle Corporation (June 1987).

20. L. R. DOLE and C. H. MATTUS, "Low pH Concrete for Use in the US High-Level Waste Repository: Part I Overview," *3rd Workshop R&D on Low-pH Cement for a Geological Repository*, Paris, France, June 13–14, 2007.

21. C. W. FORSBERG and L. R. DOLE, "A Low-pH Cement-Based Combined Spent-Nuclear-Fuel Storage and Repository Facility," *Proc. Int. High-Level Radioactive Waste Management Conf.*, Las Vegas, Nevada, September 7–11, 2008.

22. C. W. FORSBERG and L. R. DOLE, "Collocation and Integration of Reprocessing, Fabrication, and Repository Facilities to Reduce Closed Fuel Cycle Costs and Risks," *Proc. Int. Congress Advances in Nuclear Power Plants*, San Diego, California, June 13–17, 2010.

23. F. BARNABY, "Gorleben Revisited," *Ambio*, **8**, *4*, 182 (1979).

24. M. S. GERBER, "A Brief History of the Purex and UO_3 Facilities," WHC-MR-0437, Westinghouse Hanford Company (1993).

25. M. J. HAIRE, "Nuclear Fuel Reprocessing Costs," *Proc. Advances in Nuclear Fuel Management III*, Hilton Head Island, South Carolina, October 5–8, 2003, American Nuclear Society (2003).

26. M. J. HAIRE, G. L. RITTER, and R. E. TOMLINSON, "The Economics of Reprocessing Alternative Nuclear Fuels," presented at National American Institute of Chemical Engineers Mtg., San Francisco, California, November 25–29, 1979.

27. G. SELVADURAY, M. K. GOLDSTEIN, and R. N. ANDERSON, "Separation Technologies Reviewed," *Nucl. Eng. Int*. (Aug. 1978).

28. "Processing of Used Nuclear Fuel," World Nuclear Organization; http://www.world-nuclear.org/info/inf69.html (Accessed June 16, 2011).

29. M. BENEDICT, T. H. PIGFORD, and H. W. LEVI, in *Nuclear Chemical Engineering*, 2nd ed., McGraw-Hill, New York (1981).

30. J. T. LONG, *Engineering for Nuclear Fuel Reprocessing*, Gordon and Breach (1967).

31. C. W. FORSBERG, "Theoretical Analysis and Preliminary Experiments on the Feasibility of Removing CO_2 Containing C-14 Selectively with a $Ca(OH)_2$ Slurry from a ^{85}Kr-Contaminated HTGR Reprocessing Plant Off-Gas Stream," ORNL/TM-5825, Oak Ridge National Laboratory (Oct. 1977).

32. A. THIJS and E. F. VANSANT, "Storage Possibilities for Radioactive Krypton (^{85}Kr)," *J. Inclusion Phenom.*, **5**, 289 (1987).

33. T. YAMAMOTO, K. TSUKUI, and N. OOTSUKA, "Storage of Krypton-85 by Absorption Method," *J. Nucl. Sci. Technol.*, **21**, *5*, 372 (May 1984).

34. "Waste Forms Technology and Performance: Final Report," The National Academies Press (2011).

35. W. E. CLARK, "The Isolation of Radioiodine with Portland Cement. Part I: Scoping Leach Studies," *Nucl. Technol.*, **36**, 215 (1977).

36. *3rd Workshop R&D on Low-pH Cement for a Geological Repository*, Paris, France, June 13–14, 2007, European Commission (2007).

37. L. R. DOLE et al., "Cost-Effective Cementitious Material Compatible with Yucca Mountain Repository Geochemistry," ORNL/TM-2004/269, Oak Ridge National Laboratory (2004).

38. E. W. McDANIEL et al., "Strontium Leachability of Hydrofracture Grouts for Sludge-Slurries," ORNL/TM-8198, Oak Ridge National Laboratory (Mar. 1982).

39. C. S. HAASE and S. H. STOW, "Status of the Oak Ridge National Laboratory New Hydrofracture Facility: Implications for the Disposal of Liquid Low-Level Radioactive Wastes by Underground Injection," *Proc. Waste Management '87*, Tucson, Arizona, March 1–5, 1987, Vol. 3, p. 227, American Nuclear Society (1987).

40. L. R. DOLE and J. MOORE, "Cementitious Radioactive Waste Hosts Formed Under Elevated Temperatures and Pressure (FUETAP Concrete)," *Proc. 4th Symp. Scientific Basis for Nuclear Waste Management*, Boston, Massachusetts, November 16–19, 1981, Materials Research Society.

41. J. G. MOORE et al., "Transuranic (TRU) Nuclear Waste Immobilization in FUETAP Concrete," *Am. Ceram. Soc. Bull.*, **60**, *9*, 933 (1981).

42. T. A. KLETZ and P. AMYOTTE, *Process Plants—A Handbook of Inherently Safer Designs*, 2nd ed., Taylor and Francis, Philadelphia, Pennsylvania (2010).

43. G. LINSLEY and A. FATTAH, "The Interface Between Nuclear Safeguards and Radioactive Waste Disposal: Emerging Issues," *IAEA Bull*. (Feb. 1994).

44. D. C. CHRISTENSEN and M. A. ROBINSON, "Development and Implementation of Attractiveness Level E Criteria and the Plutonium Disposition Methodology," LA-13425-MS, Los Alamos National Laboratory (Mar. 1998).

45. "Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems: INPRO Manual—Proliferation Resistance," IAEA-TECDOC-1575, Vol. 5, International Atomic Energy Agency (2007).

46. "Consultants' Report on Meeting for Development of Technical Criteria for Termination of Safeguards for Material

Categorized as Measured Discards," STR-251, Rev. 2, International Atomic Energy Agency (Mar. 1990).

47. C. W. FORSBERG, "Rethinking High-Level Waste Disposal: Separate Disposal of High-Heat Radionuclides (^{90}Sr and ^{137}Cs)," *Nucl. Technol.*, **131**, 252 (2000).

48. N. T. REMPE, "The Herfa-Neurode Hazardous Waste Repository in Bedded Salt as an Operating Model for Safe Mixed Waste Disposal," *Proc. Waste Management '91*, Tucson, Arizona, February 24–28, 1991, Vol. 1, p. 465, American Nuclear Society (1991).

49. United States Waste Isolation Pilot Plant Web Site: www.wipp.energy.gov/ (current as of August 5, 2011).

50. SFR: Swedish Repository for Short-Lived Radioactive Wastes: http://www.skb.se/Templates/Standard____25485.aspx (current as of August 5, 2011).

51. A. C. SNIDER, "Hydration of Magnesium Oxide in the Waste Isolation Pilot Plant," *Proc. Symp. Scientific Basis for Nuclear Waste Management XXVI*, Boston, Massachusetts, December 2–5, 2002, p. 757, Materials Research Society (2003).

52. C. W. FORSBERG, "Regional Waste Treatment Facilities with Underground Monolith Disposal for All Low-Heat-Generating Nuclear Wastes," *Nucl. Technol.*, **59**, 119 (1982).

53. F. GIBB, "Deep Borehole Disposal (DBD) Methods," *Nucl. Eng. Int*. (Mar. 25, 2010).

54. P. V. BRADY et al., "Deep Borehole Disposal of High-Level Radioactive Waste," SAND2009-4401, Sandia National Laboratories (Aug. 2009).

55. K. G. JENSEN and M. J. DRISCOLL, "HLW Deep Borehole Design and Assessment: Notes on Technical Performance," MIT-NFC-PR-116, Center for Advanced Nuclear Energy Systems, Massachusetts Institute of Technology (Apr. 2010).

56. B. SAPIIE, M. J. DRISCOLL, and K. G. JENSEN, "Regional Examples of Geological Settings for Nuclear Waste Disposal in Deep Boreholes," MIT-NFC-PR-113, Center for Advanced Nuclear Energy Systems, Massachusetts Institute of Technology (Jan. 2010).

57. *Nuclear Wastes: Technologies for Separations and Transmutation*, U.S. National Research Council (1996).

58. C. W. FORSBERG, "Coupling Repositories with Fuel Cycles," *Nucl. News*, **54**, 40 (Nov. 2011).

59. C. W. FORSBERG, "Integrating Repositories with Fuel Cycles: The Airport Authority Model," *Proc. Int. Congress Advances in Nuclear Power Plants (ICAPP 2012)*, Chicago, Illinois, June 24–28, 2012, American Nuclear Society (2012).

60. C. W. FORSBERG, "What Should Be Collocated at Repository Sites for Once-Through Fuel Cycles," *Trans. Am. Nucl. Soc.*, **107** (2012) (submitted for publication).

61. J. T. CARTER et al., "A Generic Salt Repository for Disposal of Waste from a Spent Nuclear Fuel Recycle Facility," SRNL-RP-2001-00149, Rev. 0, Savannah River National Laboratory (Jan. 2011).

62. M. KOJO and P. RICHARDSON, "The Added Value Approach in Nuclear Waste Facility Siting Processes," *Proc. Int. High-Level Radioactive Waste Management Conf.*, Albuquerque, New Mexico, April 10–14, 2011, American Nuclear Society (2011).

63. H. C. JENKINS-SMITH et al., "Enhancing Acceptability and Credibility of Repository Development for Spent Nuclear Fuel," *Proc. Int. High-Level Radioactive Waste Management Conf.*, Albuquerque, New Mexico, April 10–14, 2011, American Nuclear Society (2011).

64. G. H. BASSETT et al., "What Have We Learned" (1998) (unpublished research summary available from the authors: hjsmith@ou.edu).

65. T. WEBLER, S. P. TULER, and E. A. ROSA, "Options for Developing Public and Stakeholder Engagement for the Storage and Management of Spent Nuclear Fuel (SNF) and High-Level Waste (HLW) in the United States," Report to the Blue Ribbon Commission (2011).

66. R. B. STEWART and J. B. STEWART, *Fuel Cycle to Nowhere: U.S. Law and Policy on Nuclear Waste*, Vanderbilt University Press, Nashville, Tennessee (2011).