The Resurgence of Nuclear Power

Impact on the Health Physics Profession

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This is the seventh and final installment in a series of articles in *Health Physics News* that provides an overview of nuclear power so that the effect of a resurgence of this energy source on the profession of health physics can be anticipated. The previous six articles (*Health Physics News* July, September, and November 2008 and January, March, and September 2009) have presented an overview of the different elements of nuclear power generation, including uranium recovery, uranium conversion and isotopic enrichment, fuel fabrication, and nuclear power plant design, construction, operation, and decommissioning. This final article in the series covers the so-called back end of the fuel cycle—the ultimate disposition path for irradiated nuclear fuel.

As you will read in this article, the path contains a number of options and no small amount of uncertainty about which options may be selected. As with our previous articles in this series, we are fortunate to have an author, Andrew Sowder, PhD, CHP, who is an expert on the subject matter. In light of the fluidity of our own national policy on used nuclear fuel management, *Health Physics News* Editor-in-Chief Gen Roessler and I encouraged Sowder to convey his own well-informed views on how the political and sociological challenges associated with the development of a national used nuclear fuel management policy may play out, in addition to providing us with an in-depth understanding of the underlying science and technology of this issue.

Used Nuclear Fuel Management: The Back End of the Fuel Cycle

Andrew Sowder, PhD, CHP

Introduction

The termination of the Yucca Mountain program moves the construction and operation of a high-level radioactive waste (HLW) repository in the United States into the future once more. This development reinforces a belief among some that there is no answer to the question of what to do with the nation's used fuel from its commercial nuclear power plants. The "no solution to the waste problem" refrain is often cited as a primary argument against continued use and expansion of nuclear as a source of carbon-free electricity. And while recent polling has indicated public support for nuclear energy has returned to levels not seen in decades, the subject of used nuclear fuel continues to figure heavily into the public's view of nuclear.[1]

From a technical perspective, the "no solution" refrain ignores the international scientific consensus developed over the past five decades that deep geologic disposal of used fuel and HLW in a suitable geologic formation can provide adequate protection of the environment and human health over sufficiently long time frames, i.e., thousands to hundreds of thousands of years.[2] To this end, most countries seriously pursuing a nuclear waste management strategy have chosen deep geologic disposal as the approach of choice for managing inventories of used nuclear fuel and/or residual high-level wastes arising from reprocessing. Efforts to site such facilities invariably present social, political, economic, and technical challenges and require slow, deliberate, and difficult decision-making processes. As inventories of used nuclear fuel have accumulated in many countries, dry storage is increasingly seen as a necessary intermediate step in the nuclear fuel cycle (Figure 1). Depending on your point of view, dry storage can be seen as a prudent step that will allow for the United States to make key decisions regarding the ultimate path for used fuel (as a waste or resource) or as an interim measure until a permanent geologic repository is operational.

Through the Nuclear Waste Policy Act (NWPA) of 1982, the U.S. Department of Energy (DOE) selected deep geologic disposal of used nuclear fuel and HLW in a mined repository as the technology of choice. The Act required electric utilities (and their customers) to pay 1/10 of a cent per kW-hr of nuclear power generated into a Nuclear Waste Fund to cover the cost of the repository program. Contributions to the Fund and interest now exceed $33 billion. For its part, the federal

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[1] 2009 results of an industry tracking poll of nuclear plant neighbors. Bisconti Research, July 2009, http://www.nei.org/resourcesandstats/documentlibrary/newplants/reports/third-biennial-nuclear-power-plant-neighbor-public-opinion-tracking-survey.

[2] This international technical consensus has its roots in a 1957 report issued by the U.S. National Academy of Sciences titled "The Disposal of Radioactive Waste on Land." National Research Council, Publication 519, National Academies Press, Washington, DC; 1957.

government agreed to begin removing used nuclear fuel from commercial reactor sites beginning in 1998—a contractual timeline explicitly incorporated in a formal arrangement between the government and nuclear utilities known as the Standard Contract for disposal of commercial used fuel. The NWPA also called on DOE to develop plans for transportation and for interim storage of used nuclear fuel if needed, called for siting of a second repository, and set a waste inventory cap of 70,000 metric tons of heavy metal (MTHM) for the first repository until the second was operational (League of Women Voters 1993). In 1983, DOE selected nine candidate sites (comprising five distinct geohydrological environments in six states) with the intent of narrowing the field to five for further characterization and submitting three finalists for Presidential approval for full-scale characterization. The three finalists were sites at Hanford, Washington (basalt), Yucca Mountain, Nevada (tuff), and Deaf Smith County, Texas (bedded salt). Amendment to the law in 1987 narrowed the evaluation of appropriate host sites from three to one: Yucca Mountain, Nevada. Congress and the Bush Administration formally approved Yucca Mountain in 2002 as the first national repository site following DOE confirmation of the site suitability. DOE submitted a license application for construction of the repository to the U.S. Nuclear Regulatory Commission (USNRC) in June 2008. In early 2009, the new Obama Administration indicated that "nuclear waste storage at Yucca Mountain is not an option"[3] and accompanying policy shifts have effectively terminated the Yucca Mountain program, although the licensing process has continued. This major shift in U.S. waste policy has been accompanied by an Executive Branch proposal to establish a blue-ribbon commission that would reevaluate the options for managing the U.S. inventory of commercial used nuclear fuel.

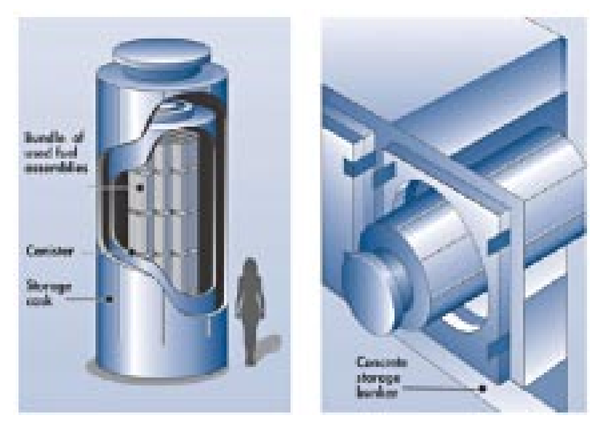

Figure 1. Dry storage of used fuel[4] (Source: USNRC)

Societal Issues

If there is a technical solution, what then is the problem? Simply put, social and political factors heavily impact siting decisions for a facility like a geologic repository. In the United States, two decades of site characterization and associated research have resulted in the description of Yucca Mountain as "the most studied real estate on the planet" (U.S. Senate Committee on Environment and Public Works 2006). Yet, the repository program faces termination before the license application has been fully reviewed largely due to political opposition from the state of Nevada, which has steadily grown in intensity since the narrowing from three candidate sites to one took place with the passage of the 1987 NWPA amendments.

Some of the key social and political obstacles and challenges presented by the siting and design of a geologic repository for disposal of used fuel and HLW are:

- Unprecedented regulatory compliance periods for geologic repositories (10,000 to 1,000,000 years) that far exceed the recorded history of humans on Earth and expectations of institutional control.
- Public distrust of government agencies and programs that have roots in secrecy, such as the nuclear weapons complex.
- Intragenerational, geographical, and procedural equity, i.e., the challenges presented when one geographic region, generation, or social group assumes a burden that it did not benefit from in relation to the costs or other impacts.
- National decisions on the value of used nuclear fuel as a resource versus a waste and reversibility of any siting and design decisions should policy change.
- Responsibility on generator of wastes for dealing with wastes (polluter pays principle) balanced against the ethics of restricting options for future generations, including the option to use the irradiated fuel as an energy resource.

These issues and more must be balanced and accounted for in a transparent selection process that

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[3] 26 February 2009 release of administration's draft budget reveals severe cuts to Yucca Mountain program; DOE press secretary announces "nuclear waste storage at Yucca Mountain is not an option." 5 March 2009—Energy Secretary Steven Chu's remarks at Senate hearings confirm the "not an option" position and suggest "blue ribbon commission" formation.

[4] Used nuclear fuel is stored underwater in lined concrete basins to provide cooling and shielding immediately after it is removed from the reactor core. After sufficient time has passed to allow for decay of the shorter-lived radionuclides responsible for much of the initial heat load (on the order of five years for uranium oxide fuel), used fuel can be moved into dry storage with cooling provided by natural convection of ambient air and shielding provided by the engineered container system (typically concrete or steel).

dovetails with the technical elements of the repository program.

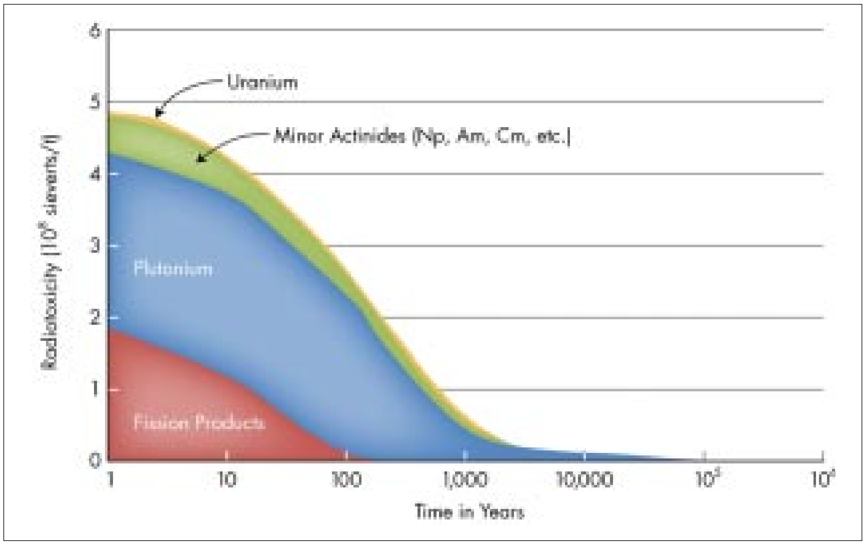


Figure 2. The radiotoxicity of used nuclear fuel decreases with time due to radioactive decay.

There are positive examples for the site-selection process of a geologic repository that have negotiated or appear likely to successfully negotiate the formidable challenges. The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is currently operational, accepting transuranic wastes from U.S. defense programs after being certified by the U.S. Environmental Protection Agency (EPA) under its authority in 40 CFR 194. More recently, voluntary participation of communities in Sweden (motivated in part by economic benefits and government incentives) in a competitive site-selection process resulted in the successful selection of a candidate-used fuel repository site at Forsmark. Approaches that focus on building genuine local and regional support among the public and politicians early in the process may offer the greatest promise for construction and operation of a deep geologic repository for used nuclear fuel or HLW in the early 21st century.

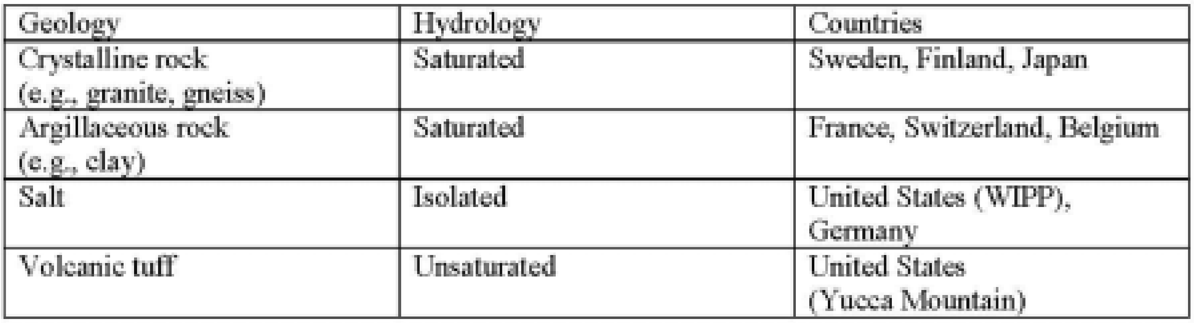
There Is a Solution for the Waste Problem

Why is there broad international scientific consensus that the solution for disposal of used nuclear fuel and/or HLW involves deep geological disposal in a suitable geologic formation/environment? Because many formations are known to have been stable for sufficiently long time frames and are likely to remain so. For example, the bedded salt formation in which the WIPP repository resides has been stable since its deposition with the evaporation of an ancient ocean during the Permian Age some 250 million years ago. The fact that the salt deposit exists is evidence that flowing groundwater, which would have dissolved the salt, has not been present over this geologic time frame and will likely not be present for the 250,000 years required for decay of the transuranic wastes (DOE 2003) (Figure 2).

What Is a Suitable Geologic Formation?

There is no simple or single answer to the question of what comprises an appropriate host site for a repository, as many different geological environments could prove suitable, as indicated by the diversity in candidate sites among international programs (Table 1) (IAEA 2003; NAS/NRC 2001). Moreover, the ultimate performance of a repository will be driven by both the intrinsic properties of the geology and environment and by the features of the engineered barrier system, which can augment, supplement, and complement those of the natural system (Figure 3). Therefore, it is important to evaluate a potential host site in light of an appropriately matched

Table 1. Candidate geology, hydrology, and host country for international high-level radioactive waste repository programs[5]



Geology	Hydrology	Countries
Crystalline rock (e.g., granite, gneiss)	Saturated	Sweden, Finland, Japan
Argillaceous rock (e.g., clay)	Saturated	France, Switzerland, Belgium
Salt	Isolated	United States (WIPP), Germany
Volcanic tuff	Unsaturated	United States (Yucca Mountain)

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[5] Adapted from Table I, Technical Reports Series no. 413, Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes, International Atomic Energy Agency, Vienna, 2003.

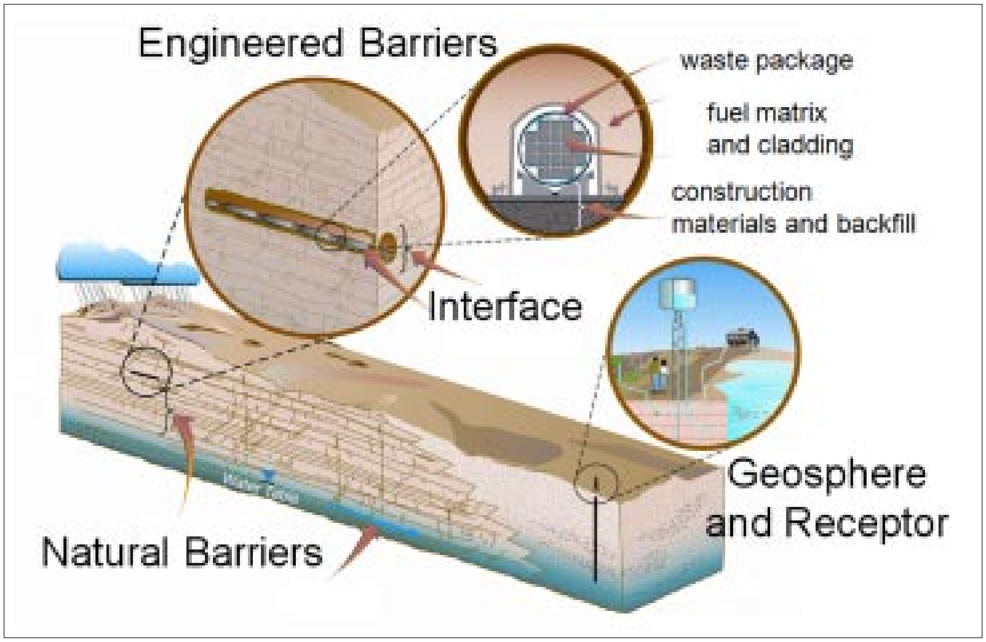


Figure 3. Long-term repository systems will rely on natural and engineered barriers to isolate, contain, and delay the release of radionuclides from used nuclear fuel and high-level waste. Repository system designs are necessarily site-specific, as engineered features need to be tailored to fit the geology, hydrology, seismicity, and other features of the candidate site.

(Adapted from DOE/OCRWM graphic)

repository design and components by focusing on site characteristics, engineering design, and wasteform properties; maintaining "defense in depth"; and keeping a prudent eye on the overall performance of the total system versus individual system components.

Seeking a Suitable or Adequate Site

The appropriate question to ask about a candidate location is whether it is suitable or adequate, not whether it is the best location. Requiring a site to be "the best" implies a level of knowledge that is unattainable without characterizing a large number of locations to a degree that is not feasible, affordable, or wise in terms of resource utilization (NAS/NRC 2001; OTA 1985).

Also, as pointed out in 1990 by the National Academy of Sciences (NAS) Board on Radioactive Management, "Surprises are inevitable in the course of investigating any proposed site, and things are bound to go wrong on a minor scale in the development of a repository" (NAS/NRC 1990). Thus the pursuit of a perfect site inevitably fails as detailed investigations can be expected to reveal some nonideal features or characteristics. The purpose of a repository is to provide adequate protection of human health and the environment by maintaining releases below some defined level, which is greater than zero. Accordingly, the repository concept necessarily allows for some releases to the environment.

All Nuclear Fuel-Cycle Options Will Require Some Form of Permanent Disposal

Another common argument is that fuel-cycle alternatives and advanced reactor technology can obviate the need for a permanent geologic repository. Quite simply, all nuclear fuel cycles and alternatives will require geologic disposal (or other form of permanent disposal) for some form of used fuel or high-level waste at some point in the future. Many recent arguments for pursuing advanced fuel cycles, recycling, and eventual closure of the fuel cycle have been heavily predicated on significant reduction of waste inventories and radiotoxicity. However, dynamic modeling of fuel-cycle strategies generally shows that waste-management benefits are modest and offer only a secondary, not primary, justification for the pursuit of more advanced fuel cycles. For example, Electric Power Research Institute (EPRI) modeling of a fuel cycle optimized for destruction of actinides through the use of fast reactors as burners (as opposed to breeders) indicates that while modest gains are achievable in the first 100 years of operation, truly substantial reductions in actinide inventories can require time frames on the order of 100s to 1,000s of years (Figure 4). This

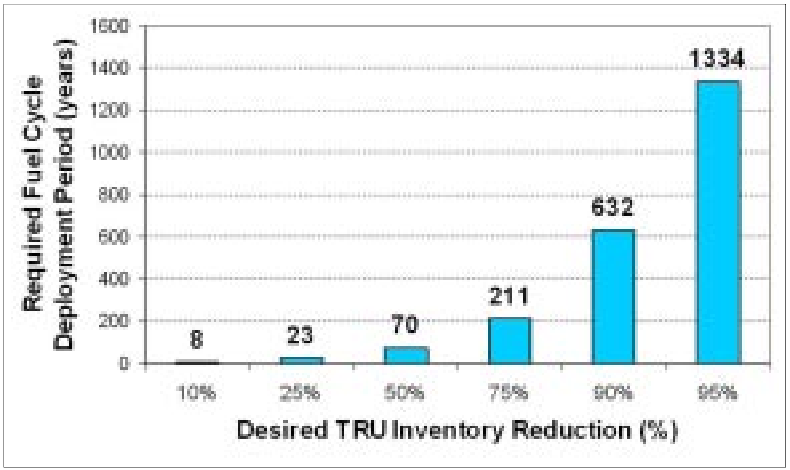
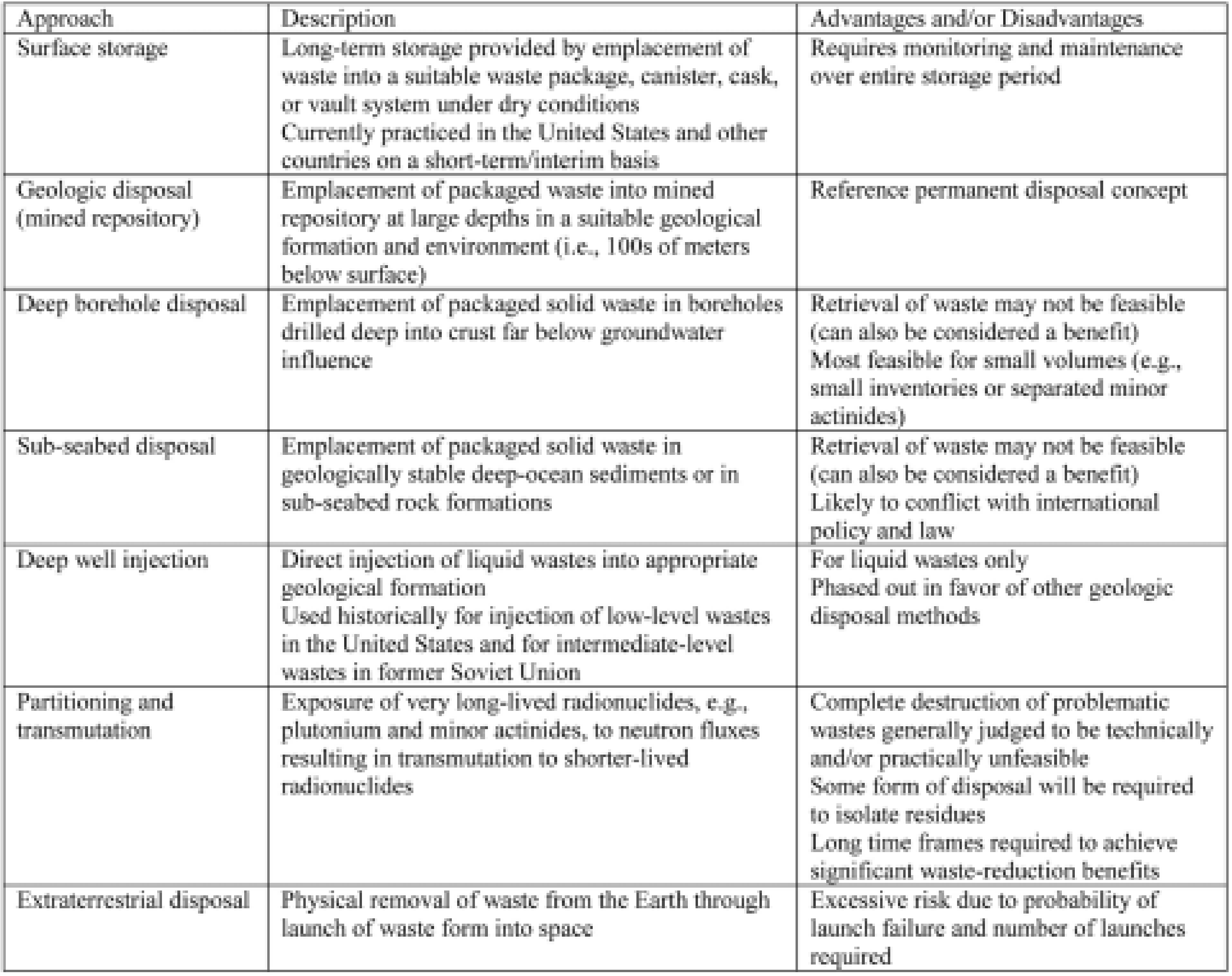


Figure 4. Dynamic modeling of the entire fuel cycle by EPRI indicates that substantial reductions in transuranic (TRU) nuclides require long time frames that can exceed centuries or millennia.

Table 2. Disposition options for high-level radioactive waste[6]



Approach	Description	Advantages and/or Disadvantages
Surface storage	Long-term storage provided by emplacement of waste into a suitable waste package, canister, cask, or vault system under dry conditions Currently practiced in the United States and other countries on a short-term/interim basis	Requires monitoring and maintenance over entire storage period
Geologic disposal (mined repository)	Emplacement of packaged waste into mined repository at large depths in a suitable geological formation and environment (i.e., 100s of meters below surface)	Reference permanent disposal concept
Deep borehole disposal	Emplacement of packaged solid waste in boreholes drilled deep into crust far below groundwater influence	Retrieval of waste may not be feasible (can also be considered a benefit) Most feasible for small volumes (e.g., small inventories or separated minor actinides)
Sub-seabed disposal	Emplacement of packaged solid waste in geologically stable deep-ocean sediments or in sub-seabed rock formations	Retrieval of waste may not be feasible (can also be considered a benefit) Likely to conflict with international policy and law
Deep well injection	Direct injection of liquid wastes into appropriate geological formation Used historically for injection of low-level wastes in the United States and for intermediate-level wastes in former Soviet Union	For liquid wastes only Phased out in favor of other geologic disposal methods
Partitioning and transmutation	Exposure of very long-lived radionuclides, e.g., plutonium and minor actinides, to neutron fluxes resulting in transmutation to shorter-lived radionuclides	Complete destruction of problematic wastes generally judged to be technically and/or practically unfeasible Some form of disposal will be required to isolate residues Long time frames required to achieve significant waste-reduction benefits
Extraterrestrial disposal	Physical removal of waste from the Earth through launch of waste form into space	Excessive risk due to probability of launch failure and number of launches required

challenge is due in part to the fact that new inventories of actinides continue to be generated even as actinides are destroyed and large inventories of actinides are maintained in operating reactors (EPRI 2008).

If Yucca Mountain Is Off the Table, What Is Plan B?

While permanent geologic disposal represents a fundamental component of the nuclear fuel cycle, it is just one element of used fuel and HLW management and is not technically required for the other elements of the back end to function (Table 2). Accordingly, the termination of the current repository program does not mean that utilities are suddenly without options. The back end of the fuel cycle is an integrated system consisting of on-site storage, potential centralized storage, advanced nuclear fuel options, and permanent disposal for final waste forms resulting from commercial nuclear power operation and recycling.

Used Fuel Can Be Safely Kept in Dry Storage for a Long Time

The challenge associated with managing used nuclear fuel is driven primarily by the large quantity of radioactivity contained in a relatively small volume, heat generation from decay of short-lived radionuclides, and the long-lived nature of the actinides and a handful of other nuclides. It is also important to recognize that some of these challenges are inextricably linked to important advantages and benefits of nuclear energy, particularly with respect to waste volumes and emissions.

Used fuel represents an extremely small volume/quantity relative to the energy produced and in comparison to other comparable generation technologies. For example, a model 1,000 MWe pressurized water reactor operating at an 80 percent availability factor requires on the order of 25 metric tons of

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[6] Information in Table 2 adapted from NAS/NRC, 2001.

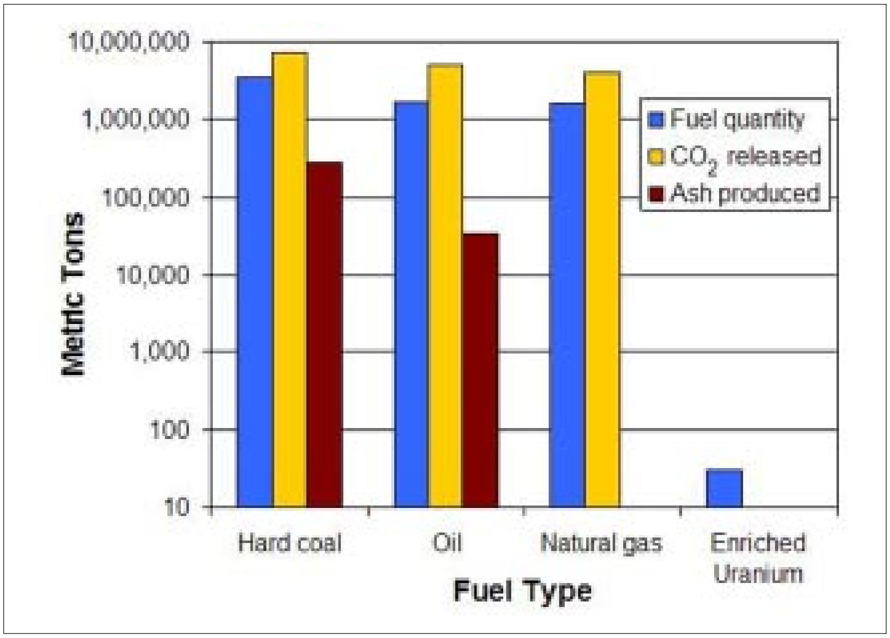

Figure 5. Quantities associated with generation of 7 TWh of electricity (1,000 MWe power plants operating at an 80 percent load factor)[7]

fresh uranium oxide fuel annually, whereas a comparable coal-fired power plant consumes three million metric tons of coal annually (or roughly 36,500 railcars) (OECD/NEA 2007). Essentially all byproducts of nuclear-generated electricity are contained in the relatively small volume of the original fuel. Figure 5 illustrates the high energy density and small quantities of byproducts for uranium oxide fuel versus fossil sources. Nuclear energy also has the benefit of internalizing many of the costs and impacts of energy production in terms of pollution and waste; for example, consumers of nuclear-generated electricity pay for the waste management of the fuel through the Nuclear Waste Fund fees, whereas the costs of pollution from other comparable baseload sources of electricity mostly remain external to electricity pricing.

In principle, there is no technical limit to dry storage during the period of institutional controls. Currently deployed systems can be licensed under the present USNRC regulations up to 60 years, and work is underway to understand longer-term aging issues. Numerous statements from USNRC staff and the commission suggest that U.S. regulators have confidence in dry storage system lifetimes of 100 years or more (Klein 2009).

Metal and concrete structures built by humans are known to persist for millennia, as shown in Table 3. The Eiffel Tower, an iconic Parisian landmark, was constructed of iron using 19th century erection methods and technology. Yet the 120-year-old, 324-meter, 10,000-metric-ton attraction remains standing and in use with the help of a fresh coat of paint every seven years (Visit Guide: The Eiffel Tower Web site). It is worth noting that concrete and metal alloys employed in dry storage systems are designed with degradation/corrosion resistance in mind and that the field of material science has greatly enhanced the durability and corrosion resistance of concrete and metal alloys. With routine inspection and maintenance, robust engineered systems such as dry cask storage systems can be expected to remain operable over periods extending well beyond a century (EPRI 2003; Miller et al. 2006).

If necessary, any limitations on canister/cask system lifetimes and performance can be overcome through periodic repackaging. While feasible, repeated handling of the same fuel is not desirable because it will incur additional occupation exposures and will present substantial logistical challenges in situations where wet storage facilities are no longer available for conducting fuel transfers and inspections.

Table 3. Examples of archaeological structures and artifacts that indicate persistence of structural materials over millenia

Material	Analog	Estimated Date of Manufacture (years before present)
Cement	Roman structures	> 1,900
Copper	The Kronan cannon	> 400
Iron	Roman nails	> 1,900
	Iron pillar in Dehli, India	> 1,600

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[7] Data from Table 1.1, OECD/NEA, 2007. Management of Recyclable Fissile and Fertile Materials. NEA No. 6107.

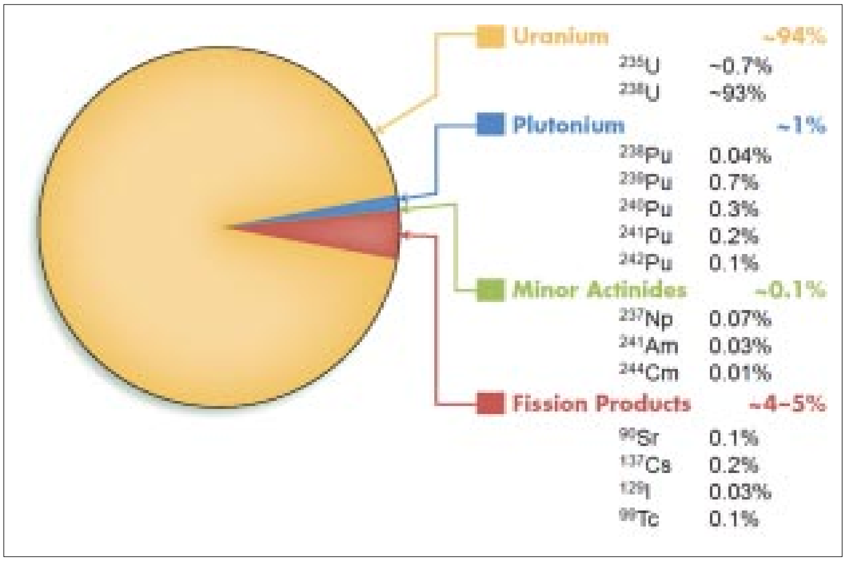

Figure 6. Representative composition of uranium oxide fuel (nominally 3 percent ^{235}U initial enrichment) following irradiation in a light water reactor for electricity generation

Used Fuel: Waste or Resource?

After low-enriched uranium oxide fuel is irradiated in a light water reactor (LWR) to a point where increasing neutron poison concentrations and decreasing fuel reactivity become limiting, the used or "spent" fuel is discharged and replaced by fresh fuel. However, as illustrated in Figure 6, very little of the total uranium resource is consumed in the reactor, and other actinides are produced that have potential value for recovery and use in nuclear fuels. The remaining ^{235}U persists at or near natural enrichment levels, ^{238}U continues to represent the bulk of fuel material (at ~93 percent), and fissile plutonium isotopes (^{239}Pu and ^{241}Pu) comprise almost 1 percent of the used fuel inventory by mass. The 4-5 percent fission product fraction represents the truly unusable portion—requiring disposal regardless of the fuel-cycle option selected. The remaining 95-96 percent of material in the used fuel could potentially be recovered. In short, used fuel can be considered a waste if the existing technology continues to dominate the fuel cycle, i.e., LWRs that can only make secondary and minimal use of the ^{238}U present.

However, used fuel could offer an untapped and very large energy resource if advanced commercial reactor technologies, such as fast reactors, are deployed on a sufficient scale to make full use of ^{238}U as a fertile source of fissile ^{239}Pu.

Ultimately, the necessary fuel-cycle decisions must be made at the national level. Major fuel-cycle facilities are large, complex, high-risk, and expensive projects not well suited for private investment. Fuel-cycle goals, attributes, and waste-disposal requirements ultimately touch on issues and policies that must be addressed at the national level, such as nonproliferation, energy, disposal, economic development, and national security.

With the apparent end to the Yucca Mountain program, the United States has surrendered an international leadership role in the nuclear waste management arena, as other countries with nuclear technology continue down the path blazed in large part by the United States (NWTRB 2009).

In any case, some form of permanent disposal of HLW will be required for all fuel-cycle options. The decision not to proceed with Yucca Mountain, therefore, cannot erase the fact that the United States will need to develop a permanent disposal route for its nuclear fuel cycle, and this route will likely be a deep geologic repository.

Conclusion

From a technical perspective, the question isn't, What *can* we do with the used nuclear fuel from commercial nuclear power generation? Technical answers to this question exist. Rather, the relevant question remains, What *will* we do with used nuclear fuel?

The key to answering this question lies not only in defining what is technically possible, but also in determining which option (or options) can receive sufficient public and political support to maintain viability over the multidecade time frame that any credible solution will take to implement. In a democratic society such as ours, this is primarily a question for elected and duly-appointed decision makers, although hopefully, the final answer will be well informed by science and engineering.

Editors' Note: We would like to express our utmost appreciation to the authors of this series for their patience, hard work, and dedication to high standards of excellence in producing their articles. We sincerely hope that we have achieved our mutual goal of conveying the challenges and opportunities arising in nuclear power health physics to our friends and colleagues across the Health Physics Society.

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He conducted postdoctoral environmental research at the Savannah River Ecology Laboratory located on the Department of Energy's Savannah River Site, where he also collaborated extensively with environmental microbiology researchers at the Medical University of South Carolina.

He entered the realm of science policy in 2000 as an American Association for the Advancement of Science environmental fellow at the U.S. Environmental Protection Agency's (EPA) Office of Radiation and Indoor Air in Washington, DC. While at the EPA, Andrew had the honor of participating in educational outreach programs on the Navajo Nation for communities impacted by abandoned uranium mines.

Andrew lives in Charlotte, North Carolina, in a cozy house under a really big tree with his wife, Dean, two daughters and a son, three dogs, and a cat. When he has time, he likes to read, go on walks with kids and/or dogs, and mess about in the yard.