Discussion on the Merits of Deep Borehole Disposal, Especially with Recycling – 15389

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ABSTRACT

With the continued global expansion of the nuclear industry, disposal of spent nuclear fuel (SNF) and high level waste (HLW) continues to be a largely unimplemented (but extensively studied) activity throughout the world and can continue to do so due to the safe practices of “interim” SNF/used nuclear fuel (UNF) and HLW storage. However as the industry continues to operate and expand in both existing and new countries, the accumulated SNF/UNF and HLW will continue to grow in both quantity and locations across the globe; hence, requiring more effort to control and monitor. Countries with nuclear power programs, or are considering starting nuclear power programs, must consider the potential financial and the engineering burden associated with both the interim storage and the disposal of SNF/UNF and HLW produced by these programs: can the cost of disposal be reasonably captured in the cost of electricity produced from nuclear programs and are there suitable sites for disposal in their country, such as a mined-geologic site, for the expected accumulated quantity of SNF and HLW? Answering these questions may be particularly vexing for countries with small nuclear programs where establishing viable disposal sites for SNF and HLW and funding of the development of these sites may be a challenge. In an effort to establish an alternative to traditional, expensive, mined-geologic disposal sites, the deep borehole option has been (re-)considered by multiple countries and entities to be a relatively simple solution to disposal of SNF and HLW. However, disposal of SNF in deep boreholes must overcome several issues including: (1) limiting-sized borehole diameters; (2) limited ability for retrieval; and (3) potential hang-up issues associated with lowering longer (e.g., > 180 inches) canisters down into a deep borehole. Since most SNF is a resource when recycled (i.e., UNF) and to dispose of it in an irretrievable manner would be wasteful, a more optimal alternative that could overcome these issues and maximize the benefits of the UNF is to recycle the UNF and dispose of the resulting HLW into deep boreholes. The multiple and mutual benefits of this approach are elucidated in this paper.

INTRODUCTION

As the nuclear power industry continues to globally expand, the quantity of SNF/UNF continues to accumulate in “interim” wet and dry safe storage facilities, while the disposal of SNF/UNF and HLW continues to be an unimplemented (but extensively studied) activity. For countries with small nuclear power programs or are considering developing nuclear power programs, the development of mined-geologic disposal facilities for SNF and HLW are hidden or potentially ignored costs passed on to future generations and may make nuclear power a cost prohibitive option if the costs of developing such programs are comparable to existing programs and must be integrated into their electricity costs. Furthermore, these countries are often of a size that may not lend them to have sites suitable for disposal in the traditional or commonly perceived sense (i.e., a mined geologic repository). In this context, this paper considers the benefits to these smaller nuclear power programs of the combination of international recycling of UNF with a domestically developed deep borehole disposal program. The combination of a relatively simple disposal concept for the disposal of domestic waste with an international safeguarded program to recycle UNF and produce a waste form suitable for disposal, while also providing additional fuel for the nuclear power program, would resolve issues for these small programs and would likely make nuclear power economically attractive to those considering it.

POTENTIAL LIMITATIONS OF MINED-GEOLOGIC DISPOSAL SITES

According to the American Nuclear Society [1], there are 35 countries currently with operating, under construction, or on order nuclear power plants. There are also 3 countries with only shutdown reactors (i.e., Italy, Kazakhstan, Lithuania) and several other countries interested in procuring nuclear power plants (e.g., Jordan and Saudi Arabia) that currently have none. Of these countries, approximately half have, or will have, a small number of power plants (e.g., fewer than 5 reactors) which will make affording a mined-geologic repository program a potentially difficult proposition. Furthermore, some of these countries have limited geological resources available for mined-geological disposal sites and hence, an alternative approach such as the deep borehole, which could be utilized in most countries, could be a positive development.

Currently the U.S. has raised over $35 billion for disposal of commercial SNF and was raising over $750 million per year in fee revenue from a 1.0 mil per kilowatt-hour ($0.001/kWh) fee on nuclear generation. In France, a similar fee on nuclear generation of $0.0016/kWh is charged by EdF to its clients to prepare for mined-geological waste disposal that will be smaller than the one in the U.S. and in Sweden the fee has increased to $0.0075/kWh for mined-geological waste disposal that will be smaller than the one in France [2]. Although there are many factors that impact the fixing of these fees, the general trend is that the cost of a mined-geological waste disposal site for the disposal of smaller quantities of SNF increases per metric ton (MT) of SNF. Thus, for countries with smaller nuclear power programs, accounting for the cost of mined-geologic waste disposal could make the price of nuclear power uncompetitive.

Finding a suitable site for a mined-geologic waste disposal site for SNF and HLW poses another issue that some countries are or may find difficult to overcome. According to the International Atomic Energy Agency’s (IAEA) Specific Safety Requirements No. SSR-5 [3], the fundamental safety objective in the disposal of SNF and HLW is to contain it and isolate it from the accessible biosphere, which includes those elements of the environment (e.g., ground water) that are used or accessible to people. One element associated with reaching this objective is ensuring the disposal site is located in a stable geological formation that will provide long-term protection against the effects of geomorphological processes and away from significant mineral resources, geothermal water, and other valuable subsurface resources. Furthermore, to limit future human intrusion and/or migration of radionuclides into the accessible biosphere from a potential disposal site, the disposal site needs to be sited away from or insulated from significant population bodies. Although an objective of SSR-5 was to allow for flexibility in siting disposal sites, these criteria may limit the ability of some countries to locate a mined-geologic waste disposal site within their borders.

As a result of these potential cost burdens and siting limitations associated with mined-geologic waste disposal sites, the deep borehole option has been (re-)considered by multiple countries and entities as a relatively simple, alternative solution to the disposal of SNF and HLW.

BENEFITS OF DEEP BOREHOLE DISPOSAL

Numerous documents describe the deep borehole approach (e.g., [4], [5], [6]) and in essence, it can be summarized as drilling a hole deep beneath the Earth’s surface (e.g., about 5 kilometers) into crystalline basement rock and filling some portion of the bottom of this hole (e.g., 1 to 2 kilometers) with the waste material and filling the remainder of the borehole with a sealing material. The boreholes are fully lined using grouted-in-place standard steel drill pipe. Figure 1 provides a generalized view of the deep borehole concept. Current literature [4] suggests 100 to 200 MT of SNF could be disposed per borehole, depending on parameters such as the packaging efficiency, robustness of the package to sustain loads placed above it, and thermal limitations.

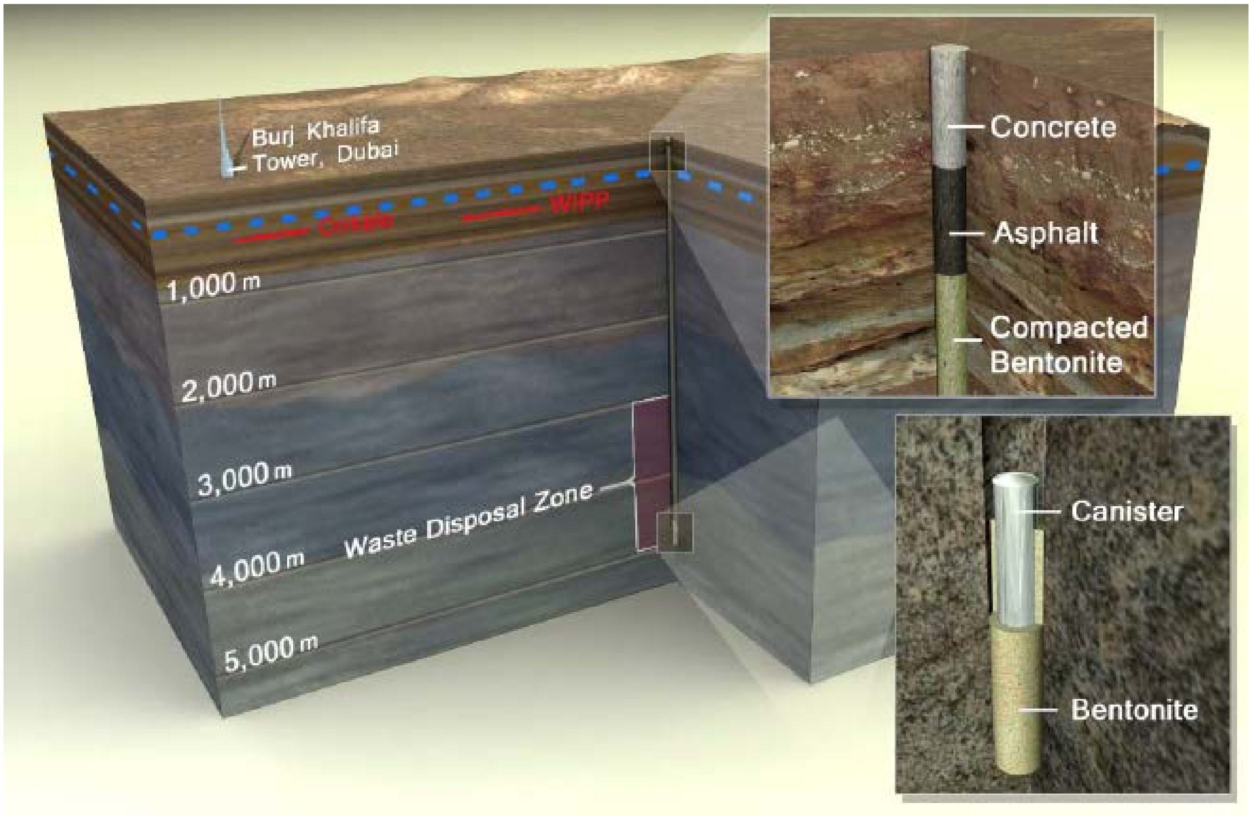

Figure 1. Generalized Concept for Deep Borehole Disposal (from [4])

Some of the principle benefits of deep borehole disposal include: (1) providing multiple viable locations throughout the world for disposal of SNF and HLW; (2) reducing potential disposal costs (relative to mined-geologic disposal programs); (3) allowing for the use of existing drilling technology for construction of the disposal borehole; (4) reducing potential transportation requirements and risks if deep boreholes are located in strategically located sites; (5) allowing for incremental deployment of disposal sites; and (6) providing very robust isolation and hence, not requiring waste packages made of valuable and expensive metals (e.g., copper and titanium). Many locations throughout the world have geologic strata suitable to deep boreholes (e.g., those with sedimentary, igneous, and metamorphic rock types) and ideal sites include those with low permeability, reducing geochemistry, and negligible seismic activity. Figure 2 shows the relatively common existence of sedimentary rock across the globe that may be suitable for deep boreholes.

Current literature estimates deep borehole costs of \$20M per borehole [4] and between \$1 – 4M per kilometer [6], which makes deep borehole disposal costs (\$100 – 200k/MT SNF) at least competitive, if not cheaper, than mined-geologic disposal (based on U.S. nuclear waste fee ~\$400k/MT SNF [9]). Other potential cost benefits associated with deep borehole disposal include: utilization of a well-established technology (e.g., petroleum boreholes are routinely drilled to multi-kilometer depths) to minimize the need for development of specialized equipment; taking advantage of very robust natural isolation to minimize the need for expensive, long-lasting engineered barriers; and taking advantage of the potentially increased number of available sites for deep borehole disposal to strategically position sites to reduce transportation costs (e.g., no 300 mile long railroad spurs needed to a disposal site) and to incrementally deploy disposal sites on an as-needed basis.

Considering these benefits, deep borehole disposal appears to be technologically and potentially cost attractive for the disposal of SNF and HLW, especially for countries without large inventories of SNF and HLW.

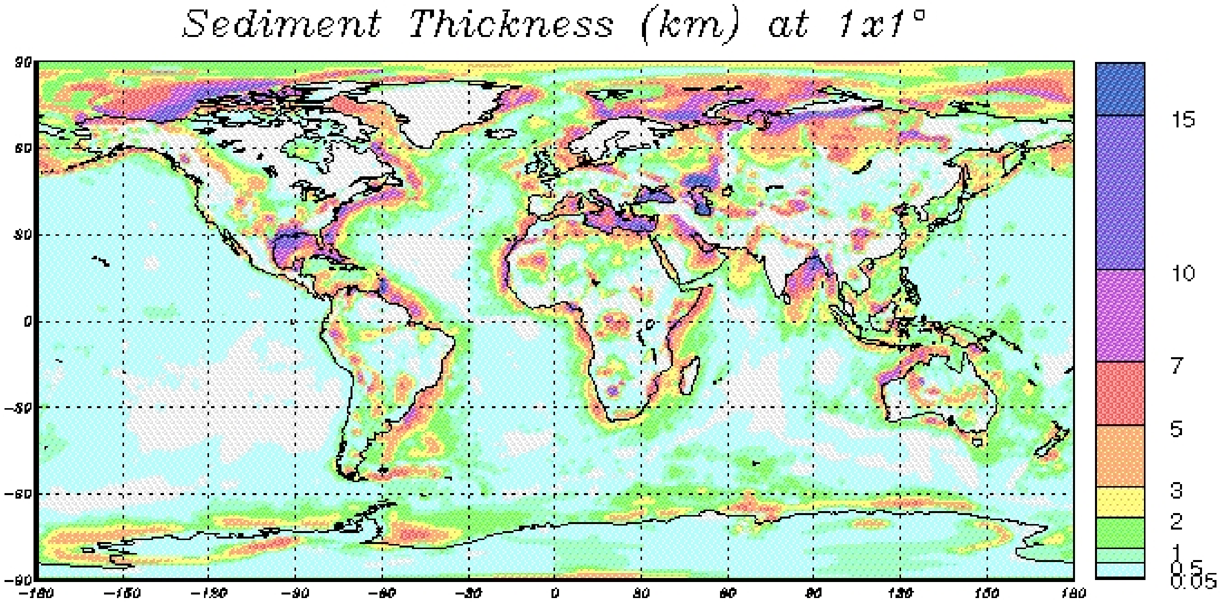

Figure 2. World Map of Sediment Thicknesses (from [8])

DRAWBACKS OF DEEP BOREHOLE DISPOSAL

Deep borehole disposal however does have some potential drawbacks including: (1) the size of the disposable waste package is limited (drilling constraints limit diameter of hole to about 50 cm); (2) the potential for hanging-up or dropping waste packages during the lowering into the deep borehole; and (3) the limited ability to retrieve the waste packages once emplaced in a borehole. The limited diameter of the borehole limits the size of the waste package that can be inserted into the borehole and will result in a significant number of waste packages containing a limited number of intact SNF assemblies (1 to 2 PWR or 2 to 4 BWR assemblies) and/or a significant amount of fuel rod consolidation prior to packaging SNF into a waste package. With the larger number of waste packages, there are corresponding increases in the amount of handling activities of waste packages, which result in increased doses to operators and increased risks associated with drop events, and increases costs associated with a greater number of operating activities, larger quantities of waste packages, and larger numbers of boreholes. Similarly increases are associated with fuel rod consolidation, but there is also the added complication of establishing where to perform the consolidation activities: at a dedicated facility which further increases costs or at reactor site spent fuel pools which may be limited by, for example, crane availability. These issues can be avoided for the most part with HLW if this HLW is of a form suitable for packaging in a waste package designed for deep borehole disposal (i.e., waste diameter, waste length, robust waste form, and waste container designed to optimize performance for deep boreholes).

The potential depth of the deep borehole also poses several issues including: the risk of dropping or hanging up a waste package as it is lowered down into the borehole; the collapsing of a waste package as other waste packages are stacked on top of it, resulting in a release from an unsealed borehole; and the limited ability to retrieve a waste package once it has been emplaced into the borehole. To reduce the risk of hanging up a waste package, the length of a waste package should be limited to make lowering into a borehole easier and less susceptible to hanging-up in gradual bends that may exist in the borehole. Furthermore, by minimizing the weight of a waste package, the risk of a drop event may be reduced by placing less stress on the components (e.g., cable) lowering the waste package. However, the reduction of the weight has to be balanced against maintaining the ability of the waste package to sustain the weight of the waste packages placed above it in the deep borehole (note: bridge plugs would be placed between strings of waste packages to limit the amount of weight waste packages would need to support).

The limited ability to retrieve a waste package, once it has been emplaced into a borehole, poses two issues (will not allow for recovery of the waste package in case of an abnormal event and requires a regulatory exemption), but also has the positive impact of limiting the ability of retrieval of material that requires safeguarding when not in the disposal unit. In the U.S., the current disposal regulations (10CFR60 and 10CFR63) require waste packages to be retrievable for any time up to 50 years after waste emplacement operations are initiated. For deep borehole disposal, meeting this criterion will be difficult to ensure once the borehole has been sealed; so logically an exemption would likely be requested and hence, only wastes not foreseen to require retrieval (e.g., wastes with no future value) should be considered for deep borehole disposal.

Finally, emplacement of hot waste into deep boreholes can cause buoyant upwelling of groundwater at depth or may otherwise perturb the natural environment over long time periods. This may create additional challenges to establishing confidence in waste isolation predictions and will require some performance assessments to establish if thermal limits are required for the wastes to be emplaced in the borehole.

Based on these limitations, deep boreholes appear to be most suitable for waste packages: of a diameter and length that may preclude the loading of SNF to minimize the number of packages to dispose of and the potential for hanging-up during lowering; containing HLW designed to an optimized diameter, length, weight, thermal output, and form; and wastes with no foreseeable need for retrieval.

BENEFITS OF RECYCLING UNF

Recycling/reprocessing of UNF is commercially performed in several countries (e.g., France, Russia, UK, and planned in Japan) and described in numerous documents (e.g., [10], [11]) and in essence, can be described as the chemical process used to extract fissile materials from UNF for recycling into mixed oxide (MOX) fuel and enriched recycled uranium (ERU) fuel and to treat the remaining materials (e.g., fission products) into a stable and robust HLW form. Figure 3 provides an overview of the valuable and waste materials that are separated by a recycling plant from UNF (as opposed to SNF which is fuel designated for disposal).

Recycling of UNF offers the following benefits for mined-geologic disposal options: (1) a reduction in the volume of HLW (by a factor of approximately five); (2) a reduction in the toxicity of the HLW (by a factor of approximately 10); (3) the elimination of criticality hazards and IAEA safeguard issues of the HLW; (4) production of a standardized waste form (e.g., suitably sized for disposal and designed for handling specific to the disposal program); and (5) production of a robust and stable waste form that can be designed for the disposal medium (e.g., specific isotopes that may impose limits on disposal could be separated into a different waste stream). In addition to these benefits, recycling UNF also: (1) provides a savings of approximately 25% in the use of natural resources (i.e., less mining); (2) enhances the security of a domestic supply of fuel for reactors; and (3) allows for the opportunity to move to GEN(IV) reactors when ready.

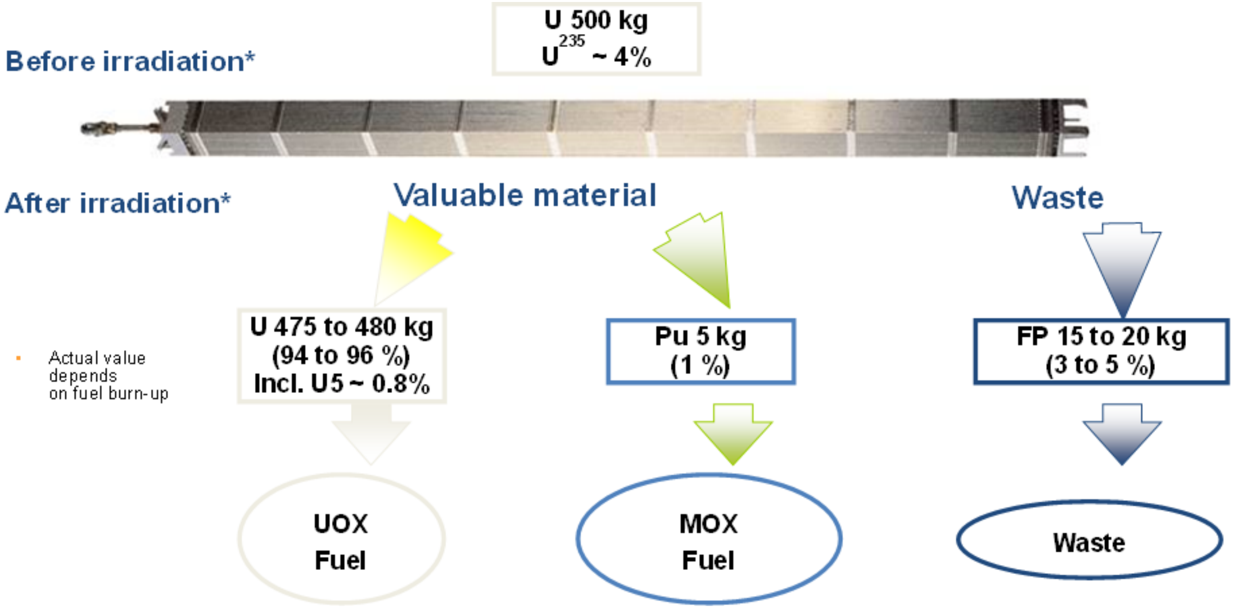

Figure 3. Summary of Recyclable Material from UNF

Recycling of UNF provides a level of energy security and independence as 95 to 97% of UNF is recyclable, providing an immediate, domestic resource for countries that perform recycling. Countries sending their UNF to a recycling and fuel fabrication plant receive MOX and ERU fuel that reduces their need for fresh uranium and enrichment services for this fresh uranium. As an example, if the U.S. were to recycle 60,000 MT of its UNF, then enough fuel could be produced to supply the entire U.S. nuclear fleet with ~8 years' worth of fuel and produce power equivalent to the power produced from ~10B barrels of oil (approximate reserve in the Artic National Wildlife Refuge). This recycled material also has a positive environmental impact related to the reduction of mining required to supply fresh uranium to the power plants and as a result further reduces the already low carbon footprint of nuclear power.

Recycling also benefits disposal activities, as it produces a vitrified HLW in the form of a borosilicate matrix that is extremely stable and durable, it reduces the volume of material requiring disposal, it eliminates criticality safety issues due to the removal of fissile materials that allows for densification of the stored wastes, it reduces the toxicity of the HLW through the removal of the plutonium and its subsequently produced daughter products, and it eliminates the need for applying safeguards to the HLW. Since the recycling process has removed the fissile materials, this HLW will contain only waste materials (e.g., fission products) that have little to no value and can be disposed of without need for safeguarding or retrieval.

HLW currently is poured into a standard Universal Canister for vitrified HLW (UC-V) as shown in Figure 4. The dimensions of the UC-V are 430 mm (16.9 inches) diameter and 1338 mm (52.7 inches) in total length (compatible with deep borehole dimensions), but the UC-V were not designed to be stacked. The vitrification process at the recycling plant can be redesigned to produce a waste form optimized and better tailored for any disposal medium (including deep borehole, salt, clay, et al.).

Glass canister (UC–V) Cutaway of a glass canister

Figure 4. Standard Universal Canister used for Vitrified HLW from Recycling

Thus the benefits of recycling of UNF are numerous and include providing fuel (MOX, ERU) produced from the recycled constituents of the UNF and a waste form tailored to optimize domestic waste disposal.

COMBINING DEEP BOREHOLE DISPOSAL AND RECYCLING

The combination of a deep borehole disposal program with a recycling/reprocessing program may produce an ideal fuel cycle for countries with limited geological opportunities and financial resources for pursuing mined-geologic disposal. The benefits identified for a deep borehole disposal program for HLW, as identified above, are fully compatible with a recycling program and the benefits of a recycling program, as identified above, are also fully compatible with a deep borehole disposal program. In fact, the combination of these two programs can overcome many of the drawbacks identified above for the deep borehole disposal program. Specifically, the benefits of a combined recycling program with a deep borehole disposal program include production of a robust, standardized waste form optimally designed: (1) for the limited diameter of a deep borehole; (2) for the stacking of multiple waste packages over one another at the bottom of the borehole; (3) with a length designed to minimize issues associated with hang-ups and drops while being lowered into the borehole and thereby removing the need to directly dispose of SNF assemblies whose length could pose a challenge to lowering into a deep borehole and whose quantity would require a significant number of waste packages to be lowered into boreholes and potentially requiring dose intensive pretreatment (e.g., consolidation) to satisfy waste package size limitations; and (4) with useful materials having been removed and hence having no foreseeable need for safeguards or future retrieval. In addition, if thermal limits are placed on the waste packages, the HLW produced from recycling can be decayed stored, as currently occurring at the La Hague plant, prior to being sent to disposal.

Thus, a domestic deep borehole disposal program utilizing the benefits of an international recycling program could: (1) benefit countries with limited viable geologic locations for a mined-geologic repository for SNF and/or HLW; (2) benefit countries with limited financial resources to invest in a mined-geologic repository program (e.g., those with only a few nuclear reactors); (3) provide a reasonably simple construction approach (i.e., drilling with existing technology) for disposing of HLW; (4) provide very robust isolation without the need for expensive waste packages; (5) allow for incremental deployment of disposal sites; (6) reduce quantities of UNF and HLW requiring control and monitoring under “interim” storage conditions; (7) provide a robust waste form tailored for deep borehole disposal; and (8) remove materials that could further simplify deep borehole disposal (e.g., eliminate criticality, safeguards, and retrievability issues). In addition to these benefits to disposal, the other benefits associated with recycling would also be realized (e.g., reutilizing the uranium and plutonium found in UNF to produce MOX and ERU fuel).

CONCLUSIONS

Potential limitations associated with mined-geologic disposal sites for countries with financially and geologically limited resources were identified and how deep borehole disposal sites may be a viable alternative to these types of disposal sites. The benefits and drawbacks of deep borehole disposal were elaborated and the merits of combining a recycling/reprocessing program with a deep borehole disposal program were analyzed. The combination of these two programs could produce an ideal fuel cycle for any country, but especially for countries with insufficient geological features and financial resources to pursue a mined-geologic disposal site. Simply summarized, an international safeguarded recycling program would produce a HLW form optimally designed and suitable for deep borehole disposal, while also providing fuel for nuclear power programs.

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