DISPOSAL OF PARTITIONING-TRANSMUTATION WASTES IN A YUCCA-MOUNTAIN-TYPE REPOSITORY WITH SEPARATE MANAGEMENT OF HIGH-HEAT RADIONUCLIDES (^{90}Sr AND ^{137}Cs)

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ABSTRACT

The United States is investigating Accelerator Transmutation of Waste[1]—a type of waste partitioning and transmutation (P-T). A modified repository concept[2] is proposed for disposal of P-T wastes in a Yucca-Mountain-type repository to (a) reduce repository costs, (b) improve repository performance, and (c) extend the repository capacity. These benefits are in addition to reductions in toxicity from P-T. The repository would contain three sections with different design characteristics: a section identical to the existing repository design, a section designed for high-heat radionuclides (HHRs) with limited lifetimes, and a section designed for long-lived very-low-heat radionuclides (VLHRs).

Repository design is primarily controlled by radioactive decay heat. There are five repository significant HHRs: cesium, strontium, plutonium, americium, and curium. P-T destroys the long-lived HHRs (plutonium, americium, and curium). The remaining HHR wastes (^{137}Cs and ^{90}Sr) have relatively short half-lives ($T_{1/2}$. 30 years). Selected P-T wastes can be divided into a HHR waste and a VLHR waste. The elimination of the long-lived HHRs (plutonium, americium, and curium) enables the use of inexpensive methods to dispose of the remaining HHR wastes in a separate section of the repository. Inexpensive methods may also exist for geological disposal of long–lived VLHR wastes.

INTRODUCTION

The United States is investigating Accelerator Transmutation of Wastes[1]—a type of waste partitioning-transmutation (P-T). A modified repository[2] concept is proposed for disposal of P-T wastes in a Yucca-Mountain (YM) -type repository.

Repositories[3] have historically been designed for intermediate-heat radionuclide wastes such as spent nuclear fuel (SNF) and high-level waste (HLW). These wastes are mixtures of high-heat radionuclides (HHRs) and very low-heat radionuclides (VLHRs). The proposed YM repository will cost several tens of billions of dollars. This high cost is partly the consequence of the decay heat from SNF and HLW. If such wastes are placed close together in a repository, the decay heat will increase the local temperature and, consequently, degrade the repository waste isolation system. The resultant degradation will reduce both the capacity of the repository to isolate radionuclides from the accessible environment and the predictability of the repository performance. To prevent such events, the wastes are to be dispersed over a large area. In the proposed YM repository, the temperatures will be limited by placing the wastes in -10,000 waste packages (WPs) and spacing the WPs over -100 km of underground tunnels. The many WPs and long tunnels add significantly to disposal costs.

Almost all repository decay heat from SNF is produced from five elements: cesium (^{137}Cs), strontium (^{90}Sr), plutonium (multiple isotopes), americium (multiple isotopes), and curium (multiple isotopes). There are several temperature limits[4] on the repository: (1) waste-form limit, (2) package limit, (3) near-field rock limit, and (4) various far-field limits. The temperature limits in and near the WP are controlled by decay heat from the shorter-lived ^{90}Sr and ^{137}Cs. The temperature limits far from the WP are often controlled by the longer-lived actinides. It takes a significant amount of decay heat over a long time to heat large quantities of rock to unacceptable temperatures. In recent years, most repository designers have chosen to reduce the temperatures near the WP to minimize uncertainties about WP performance. Consequently, the decay heat from ^{90}Sr and ^{137}Cs has increasingly controlled repository designs.

If the heat-generating characteristics of the waste are changed, the repository design can change. P-T, by destruction of long-lived heat-generating actinides (plutonium, americium, and curium), is an enabling technology that creates new options in repository design. This can be understood by comparing the wastes and disposal methods for three different fuel cycles (Fig. 1).

SNF Disposal

If SNF is to be disposed of, limited quantities of SNF are placed in each WP to limit repository temperatures. The WPs are widely spaced in long, parallel underground tunnels.

Traditional P-T Waste Disposal

Traditional approaches to P-T do not change the basic repository design. In a typical P-T system, the SNF is processed and separated into (1) a product stream containing actinides and possibly other selected long-lived radionuclides and (2) an HLW stream that contains the long-lived VLHRs and HHRs with limited lifetimes (^{90}Sr and ^{137}Cs). The actinides that include the other HHRs are fabricated into targets, irradiated with neutrons, and fissioned. The actinide targets are processed into (1) an actinide stream, which is recycled, and (2) a secondary HLW stream. The HLW is disposed of in a repository, which is essentially identical to a SNF repository. Consequently, the repository costs for either SNF or a conventional actinide P-T waste repository will be roughly similar.

Modified P-T Waste Disposal

There is an alternative approach to P-T repository design. The P-T wastes from SNF processing can be divided into a VLHR waste and a HHR waste. The HHRs are ^{90}Sr and ^{137}Cs. The other HHRs in the SNF that generate significant decay heat (plutonium, americium, and curium) are destroyed by the P-T fuel cycle. This separation of the primary P-T wastes into two categories—defined by heat generation rates and half-lives—creates new options for disposal of these wastes.

The destruction of the heat-generating actinides results in a small reduction in the near-term decay-heat generation rate and a larger reduction in the longer-term decay-heat generation rate. More importantly, the remaining HHRs (cesium and strontium) have limited lifetimes ($T_{1/2}$ = 30 years) and small masses. This changes the disposal requirements and allows for alternative repository designs.

- *HHR disposal requirements*. Without the long-lived HHRs (plutonium, americium, and curium), the cesium and strontium do not need to be packaged in expensive WPs, which are designed to last thousands of years.[2] It is not required that the geology be shown to retain the many long-lived radionuclides from the decay of plutonium, americium, and curium. For low-volume HHR capsules, low-cost disposal options exist, such as repository boreholes.

- *VLHR disposal requirements*. After removal of the HHRs, the remaining wastes contain some long-lived radionuclides but no major heat generators. Without significant decay heat, the size of the WP is not limited. There is no need to spread the VLHR wastes out over 10,000 WPs located in -100 km of tunnels. Large underground silos may be used for disposal.

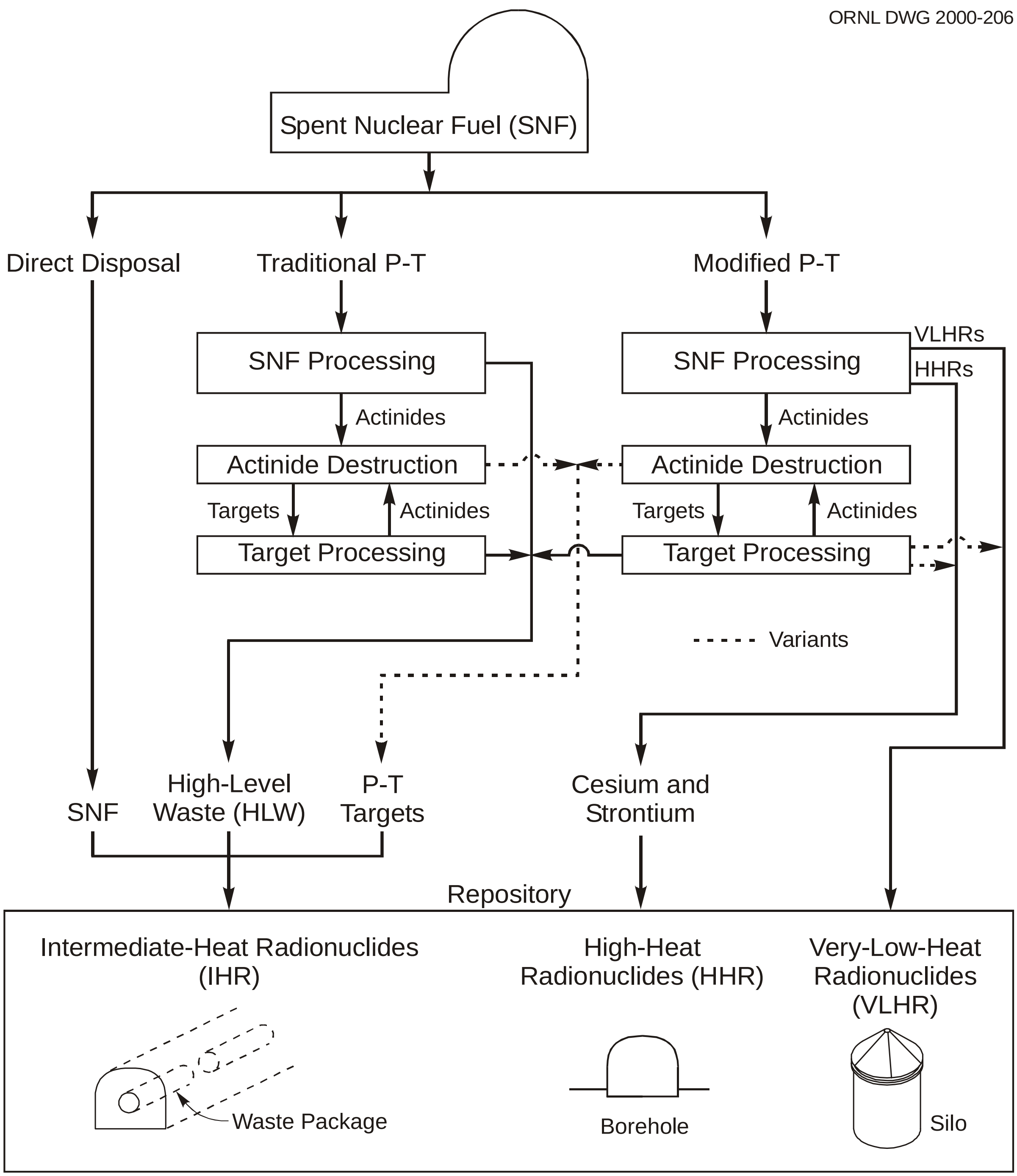

Fig. 1. Alternative Waste Management Options

The different characteristics of HHR, intermediate-heat radionuclide, and VLHR wastes from such a P-T fuel cycle suggest that the repository should contain three sections-each optimized for disposal of wastes with a particular set of thermal, mass, and radionuclide (half-life) characteristics.

WASTE CATEGORIES AND CHARACTERISTICS

The modified repository design would accept three categories of wastes.

- *HHRs.* The HHR wastes (^{137}Cs and ^{90}Sr) have two properties: high decay-heat generation rates and relatively short half-lives. Table 1 shows the heat-generating characteristics of the radionuclides in SNF as a function of time. The radionuclides are divided into four categories. With P-T, the heat-generating actinides are destroyed. Consequently, after 50 years, the ^{137}Cs and ^{90}Sr comprise -99% of the decay heat.

- *VLHRs*. The VLHRs have two properties: very low decay-heat generation rates and long-lived hazardous radionuclides, which require geological disposal. The VLHR wastes in Table 1 include all the components of SNF except the HHRs (cesium, strontium, plutonium, americium, and curium) and uranium. The uranium is a VLHR but is usually managed separately.

- *Intermediate heat radionuclides*. These wastes have two properties: significant decay-heat generation rates and long-lived hazardous radionuclides requiring geological disposal. This category includes:

    - *HLW glass*. There are significant inventories of defense HLW glass. The actinide content of these wastes is relatively low. These wastes would likely be disposed of directly.

    - *SNF*. This includes any SNF that for any reason would not be practical to process.

    - *P-T wastes from target processing*. P-T fuel cycles have several steps. SNF is processed to recover actinides. The actinides are then fabricated into targets and irradiated by neutrons. The actinide targets may be processed with recycle of the actinides that were not initially destroyed. The processing technologies for the LWR SNF and the targets are different.[1] Practical technologies currently exist to extract cesium and strontium during processing of LWR SNF. Thus, LWR processing operations can easily produce an HHR waste, a VLHR waste, and an actinide stream. However, it is unclear whether proposed actinide target-processing technologies could economically remove the cesium and strontium to the low levels that are required for VLHR wastes. Such target wastes may be HLW.

    - *P-T targets*. Several proposed P-T systems recover actinides from SNF, convert them to targets, irradiate the targets to very high burnups with destruction of most of the actinides, and disposal of the targets as waste. In this type of system, the targets would require the same type of disposal as that planned for SNF or HLW.

Table 1. Decay heat (W) from products of processing 1 t of pressurized-water reactor (PWR) SNF[a]

Time[b] (at *x* years)	SNF	Uranium and plutonium	HHRs (Sr and Cs)	VLHRs	Minor actinides
At 10 years	1,443	185	1,024	64	113
At 20 years	1,096	211	755	22	90
At 50 years	658	228	373	2	55
At 100 years	355	201	115	«1	39
At 1,000 years	63	54	«1	«1	9

[a]Assumptions: The LWR SNF burnup is 40,000 MWd/MTIHM; processing is done 5 years after SNF discharge from the reactor; volatiles such as ^{85}Kr and the SNF structural materials are not shown.

[b]Years following discharge from the reactor.

DISPOSAL OF INTERMEDIATE HEAT RADIONUCLIDES

The proposed YM repository is designed for SNF and HLW, which have decay heat loads between (a) HHRs [cesium and strontium capsules] and (b) VLHRs. If a P-T fuel cycle was adopted, this component of the repository would remain unchanged to accept HLW glass, any SNF that was not processed, and various P-T target wastes. Design, licensing, and construction would begin first on this section of the repository for disposal of SNF and HLW. If a decision was eventually made to implement P-T, the VLHR and HHR sections of the repository would be constructed at that time. Repositories are constructed in an incremental manner as wastes are to be disposed of. Without P-T, this section of the repository would grow in time to be the entire repository.

DISPOSAL OF VLHRs

Following the removal of the cesium, strontium, plutonium, americium, and curium, the decay heat from the remaining P-T wastes is very low. Unlike heat-generating SNF, there is no need to spread this waste over ~100 km of tunnels and ~10,000 expensive WPs to limit repository temperatures. The VLHR wastes can be disposed of in a few (<10) lower-cost, high-performance silos without exceeding temperature limits.

There is experience with waste silos.[5] Sweden (Fig. 2) and Finland have constructed and are operating underground silos for the disposal of intermediate-activity wastes. The heat-generating characteristics of these wastes are somewhat similar to VLHR wastes. The Swedish waste silos are about 50 m high and 25 m-diam. The costs per unit volume are a fraction of the cost of traditional WPs.

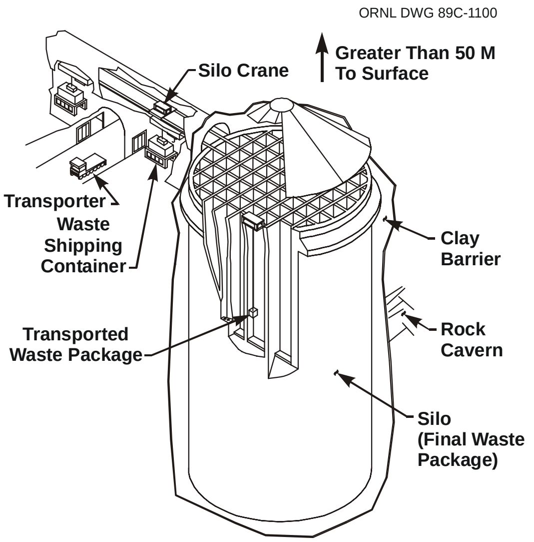

Fig. 2. Swedish SFR silo for intermediate-level radioactive waste.

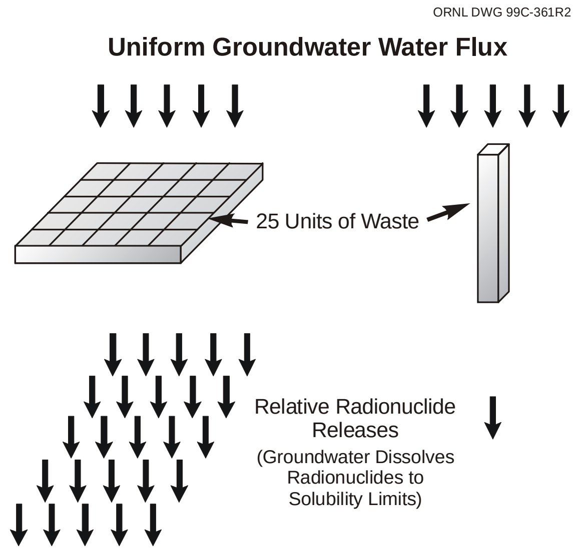

Fig. 3. The geometry of the waste (surface to volume ratio) strongly impacts long-term radionuclide release rates.

VLHR silos would be located in the middle of the repository at full repository depth to take advantage of the waste-isolation capabilities of the repository. The repository provides a major barrier against human intrusion, and the geology provides several barriers against radionuclide releases to the accessible environment. Silos are an alternative WP, not a replacement for the repository.

The replacement of WPs with large silos may result in major improvements in the performance of the engineered barriers to radionuclide releases. The release of radionuclides from a failed WP is proportional to (1) the groundwater flow through the WP and the (2) solubility limits of the radionuclides in groundwater. By concentrating the VLHR wastes from up to 10,000 t of SNF in one silo rather than spreading it over -1,000 WPs, the groundwater flow through the wastes per unit volume is reduced by a factor of 100 to 1,000. With the reduction of groundwater flow per unit quantity of waste, radionuclide releases are proportionally reduced (see Fig. 3). The large waste silo has a smaller surface-to-volume ratio than does each WPs.

Recent analysis[6] has identified additional VLHR wastes from reactor decommissioning and other operations as potentially requiring geological disposal. Consequently, there are incentives in terms of existing wastes and proposed P-T fuel cycles to examine how a separate section of the repository would be designed for VLHR wastes. The decision as to whether to implement such an approach depends upon the quantities of such wastes to be disposed of. If there are small quantities of wastes, a separate repository section for VLHR wastes would not be cost effective. If there are larger quantities of such wastes, a separate section would be cost effective.

DISPOSAL OF HHRs

The masses of HHRs are small. One metric ton of 40,000-MWd LWR SNF contains 4.1 kg of cesium and strontium. There is experience in separating and packaging HHRs in 6.67-cm-diam capsules. Cesium and strontium were separated from defense HLW at Hanford, Washington, to minimize the cost of storing HLW in tanks. Over 1×10^8 Ci of HHRs were separated and packaged.[7]

The HHR capsules could be disposed of in a separate section of the repository (Fig. 4). Boreholes of several hundred meters would be drilled into the rock from a central tunnel and then filled with small-diameter (6.67 cm) HHR capsules. The heat-load would be spread out by placing low-volume HHR capsules in small-diameter, horizontal boreholes (<15 cm-diam) rather than placing large HLW or SNF WPs in 5.5-m-diam disposal tunnels. The boreholes could be drilled in a horizontal plane or in a vertical array. Boreholes are less expensive than tunnels.

The HHR section of the repository would be designed as an "extended-dry" repository in unsaturated rock. By placing the boreholes closely together (<40% of the spacing of WPs in the proposed YM repository), the local rock temperature would be raised above the boiling point of water for thousands of years. Most of the decay heat is generated within a few hundred years. However, this heat raises the temperature of a large mass of rock. It takes thousands of years for the rock mass to cool below the boiling point of water. If the rock temperature is above the boiling point of water, there can be no groundwater flow and no migration of radionuclides in groundwater. The HHRs decay before the high-heat section of the repository cools below the boiling point of water and allows transport of HHRs by groundwater.

The YM repository project investigated SNF extended-dry repository concepts[8] because of potential economic advantages. Such concepts have not been adopted for SNF or HLW disposal because of the uncertainties in predicting long-term, extended-dry repository behavior after the repository cools. These uncertainties are minimized for HHRs consisting of cesium and strontium, which decay before the high-heat section of the repository cools down.

The HHR section of the repository has other implications for the repository. VLHR waste silos require very little area. The SNF, HLW, and HHR wastes require most of the repository area to dissipate heat. However, for an HHR extended-dry repository to function, the areal heat load must be much higher than in a conventional repository. Furthermore, the heat-generating actinides have been destroyed. Consequently, the total repository area for disposal of the cesium and strontium is much smaller (-1/3) than that required for the equivalent SNF. The footprint of the repository shrinks. Alternatively, the capacity of the repository increases and thus delays or eliminates the need for a second repository.

There are evaluations underway of methods to dispose of existing cesium and strontium capsules and cesium streams generated in the processing of HLW streams. Consequently, there are incentives to investigate HHR disposal for (a) existing wastes and (b) possible future P-T HHR wastes.

SCALING PARAMETERS AND ECONOMICS

The relative size of repository components to manage SNF and HLW or the equivalent HHRs and VLHRs, after destruction of the heat-generating actinides, is shown in Table 2. For every 100 m of tunnel required for disposal of SNF, <1 m of tunnel and about 71 m of boreholes would be required to dispose of the HHR-VLHR wastes from the SNF. For every 100 SNF WPs, 71 HHR capsules of similar length and a small fraction of a silo would be required for disposal of the HHR-VLHR wastes from that SNF. In effect, there are two major changes: (1) substitution of 5.5-m disposal tunnels with 15-cm boreholes for the HHRs and (2) substitution of thousands of WPs with a few silos.

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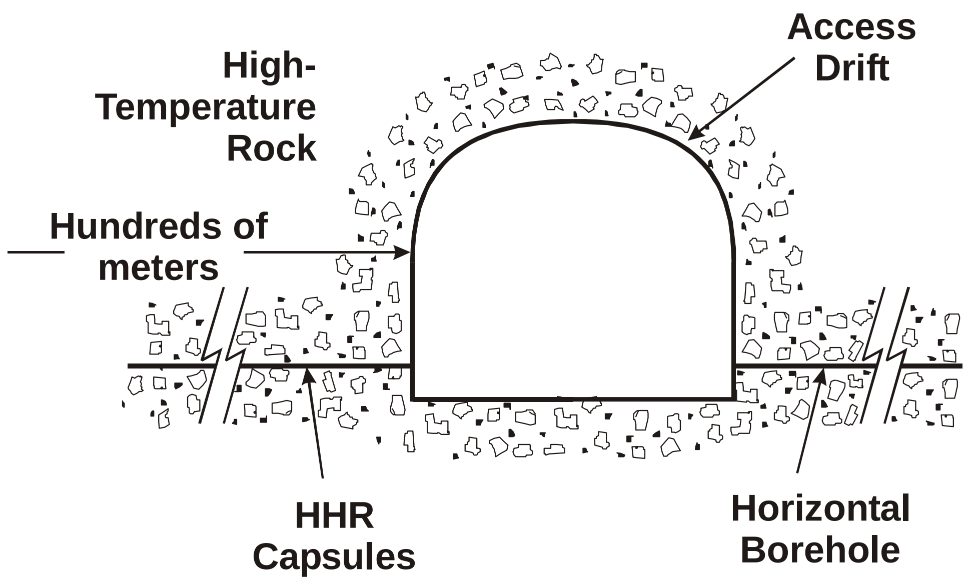

Fig. 4. High-heat radionuclide (^{90}Sr and ^{137}Cs) repository section with boreholes (rather than tunnels) used to distribute decay heat load.

The impact of these changes would be to drastically reduce the operational costs for the repository. It may not significantly impact siting or licencing costs—a significant fraction of the total costs. The economic incentives are strongly dependent upon the size of the repository. As the repository capacity increases and the cost per unit of waste decreases, operational costs become a larger fraction of disposal costs. Siting and licencing costs are essentially fixed costs.

The HHR–VLHR repository can have one other potentially large economic impact. The HHR section of the repository is about a third the area of an equivalent SNF repository. The area of the VLHR section is very small. Consequently, the site capacity is increased by a factor of 2 or more. If the increased capacity can avoid the siting, licencing, and operation of a second repository, there would be very large repository cost savings.

The economic cost for the repository gains in an actinide P-T fuel cycle is the necessity to separate the cesium and strontium from the other waste streams. This cost is dependent upon the specific separations processes.

Table 2. A comparison of the relative size of a SNF repository to an equivalent HHR-VLHR repository when the plutonium, americium, and curium have been destroyed[a]

Parameter	Conventional SNF repository	Combined HHR-VLHR repository		
		HHR	VLHR	HHR-VLHR
Disposal length				
Tunnels	100	<1	<1	<1
Boreholes	0	71	0	71
Containers				
WP (SNF)	100	0	0	0
Silo (VLHR)	0	0	<0.1	<0.1
Capsule (HHR)	0	71	0	71

[a]Assumptions: SNF is processed 5 years after SNF discharge. HHR disposal occurs 10 years after discharge. VLHR occurs disposal 50 years after discharge or earlier disposal with repository ventilation until 50 years after discharge. YM repository tunnel diameter is 5.5 m. Borehole diameter is 15 cm. Disposal length compares linear feet of tunnels and boreholes. One silo accepts VLHR wastes from 10,000 t of SNF.

CONCLUSIONS

Any P-T option that destroys heat-generating actinides (plutonium, americium, and curium) is an enabling technology that will allow the use of a repository with separate sections for disposal of VLHR and HHR wastes. In a large repository, the P-T technology may significantly reduce operating costs and improve repository performance—independent of the reduction in radiotoxicity caused by destruction of long-lived radionuclides. There would be a significant reduction in the size of the repository. For the United States, such an approach might eliminate the potential need for a second repository. These repository benefits may exceed the other waste management benefits of actinide P-T fuel cycles. The cost for these benefits is the requirement to separate cesium and strontium from the other P-T wastes. An understanding of the costs and benefits of a repository—with different sections for wastes with different heat-generation rates and half-lives—should be a high priority within any investigation of actinide P-T fuel cycles.

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