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Speculative High-Level Nuclear Waste Processing Methods

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Abstract

With the exception of recent progress in Sweden and Finland, traditional and planned high-level nuclear waste processing disposal methods have yet to be successfully implemented on a commercial scale. Failure to solve the high-level waste issue is an impediment to the expansion of nuclear power production particularly in North America and Europe. Given these issues, this paper presents three speculative methods and an accelerator/reactor approach to process high-level nuclear waste.

The first speculative approach explores the possibility of incorporating an underground nuclear detonation as a means to process the waste. A second method uses antiprotons and antineutrons to transmute the high-level waste. The third utilizes plasma to obliterate the isotopes comprising the radioactive waste. A somewhat less speculative approach involving nuclear waste transmutation using a reactor or accelerator is also presented. However, this approach has several issues to overcome and is not a likely a near-term solution to the waste disposal/processing issue.

1.0 Introduction

Nuclear waste has been a continuing issue associated with nuclear power expansion. The terms nuclear waste, high-level waste (HLW), and spent fuel are often used in a pejorative manner. These material forms contain valuable materials (e.g., rare earths, fissionable materials, and medical isotopes). Although the aforementioned terms are a misnomer, we employ them due to their common utilization, but note that these materials have considerable value, and should be recycled to recover their intrinsic worth.

Waste disposal is not the optimum option for the disposition of HLW. Reprocessing or recycling this material is preferable from an economic and environmental perspective. However, reprocessing in the US has been a dead issue since President Carter banned that technology, via Executive Order, as a policy to discourage nuclear proliferation. Although President Reagan reversed the Carter Order, reprocessing of commercial fuel is not currently a viable political option in the US.

Although the author prefers that HLW be reprocessed, current US policy is directed toward potential waste disposal approaches. Current waste processing methods[1-16] focus on storage, and reliance on radioactive decay to reduce the

associated radiological hazard. This approach has been the default methodology because technologies that are more advanced have not been successfully implemented. With the exception of Sweden[17] and Finland[18], minimal progress has been made in resolving the high-level waste issue that includes both processing and disposal activities.

Much of the high-level waste is associated with commercial nuclear power operations. The waste arises from the production of fission and activation products, and includes plutonium and minor actinides (e.g., isotopes of neptunium, americium, and curium). These materials are primarily produced by neutron interaction mechanisms.

As an example, the $^{59}Co(n, \gamma)^{60}Co$ reaction occurs copiously in many Generation II fission reactors, and is responsible for most of the worker radiation exposure at these facilities[7,9,10,13,15]. With its 5.27 yr half-life, ^{60}Co is important, from a radiation exposure perspective, during power operations as well as decontamination and decommissioning activities. Eliminating ^{60}Co from waste streams would also reduce waste disposal and burial costs for associated low-level waste. In addition, the elimination of other fission and activation products further reduces operating costs, minimizes worker radiation exposures, and minimizes the volume of waste requiring further processing and disposal.

This paper outlines three speculative approaches to achieve the minimization of both low- and high-level wastes, but the focus is on the high-level component. Although speculative, these methods have significant potential to process high-level nuclear waste. The first explores the possibility of incorporating an underground nuclear detonation as a means to process the waste. A second method uses antiprotons and antineutrons to transmute the high-level waste. The third technique utilizes the fast neutron spectrum produced from a fusion reactor.

This paper only provides a first order review of these approaches. Significant research and development are required to assess the viability of these techniques. In addition, numerous obstacles exist for their implementation. These include and are not limited to technological advances, sustained funding, and overcoming national and international political concerns.

Prior to addressing these approaches, a brief review of waste treatment and disposal and transmutation methods will be outlined. Following this discussion, the nuclear detonation, antinucleon, and fusion options are presented. Currently, antinucleon beams can only be produced at specialized accelerator facilities. In addition fusion technology has not been developed at a production level scale to support HLW processing. This paper presumes technological advances will lead to more accessible antinucleon beams and a viable fusion facility. However, nuclear weapons are a proven technology and exist in sufficient quantity to support the nuclear disposal option.

2.0 Waste Treatment and Disposal Options

A number of interim and long-term waste treatment and disposal options have been utilized or proposed as methods to process high-level nuclear waste[1-16]. These approaches include, but are not limited to 1) temporary storage to permit decay of short-lived radionuclides, (2) temporary burial in designated facilities, (3) spent fuel storage at commercial reactor fuel pools, (4) spent fuel storage in dry casks at the commercial reactor facility, (5) accelerator techniques for

waste transmutation, (6) transmutation of radionuclides using Generation IV reactors, (7), monitored storage in deep boreholes, (8) storage in geologically stable salt domes, (9) deep space disposal, (10) deep sea disposal, (11) burial of spent fuel in frozen terrain such as Antarctica, and (12) monitored interim storage.

The aforementioned methodologies have received a variety of reviews and include positive and negative features. Evaluation of these technologies is complicated by differences of scientific evaluations driven by assumptions regarding a variety of factors including terrestrial stability, climate change, waste stability, and waste container stability. These evaluations are performed within a political atmosphere has often drives the selection of parameter assumptions as well as fostering a desired outcome. In spite of these complications, transmutation of high-level radioactive waste has been a popular processing option. However, none of the aforementioned approaches have materialized into a viable strategy in the US. Sweden and Finland have developed viable approaches for geological burial facilities. However, these facilities and their public support are unique to the host nations[17,18].

This paper evaluates three unique HLW approaches to minimize the radiological hazards. These unique methods include (1) underground nuclear detonations, (2) anti-activation using antimatter, and (3) plasma techniques. A somewhat less speculative approach involving nuclear waste transmutation, using a reactor or accelerator, is also presented in Section 3.0. However, this approach has several issues to overcome, and is not a likely near-term solution to the waste disposal/processing issue.

3.0 Nuclear Waste Transmutation Utilizing Contemporary Technology

Nuclear waste transmutation has the potential to become an important step in the nuclear fuel cycle[15,19-26]. One of the main goals of the transmutation process is the reduction or elimination of long-lived radionuclides and their associated decay heat. Elimination of minor actinides (e.g., neptunium, americium, and curium), remnant uranium and plutonium, and long-lived fission products (e.g., ^{14}C, ^{26}Al, ^{99}Tc, ^{126}Sn, and ^{129}I) would reduce the design requirements for high-level waste storage facilities. Several conventional transmutation approaches are considered. These include: (1) plutonium and minor actinide (PMA) burning in Generation IV reactors, (2) accelerator methods, and (3) gamma-ray free electron lasers.

The partitioning and transmutation approach depends on the neutron spectrum utilized in the process. An overview of the spectrum characteristics is outlined in Refs. 7 and 15.

In general, partitioning and transmutation (PAT) of nuclear material either completely or partially removes a specific isotope or group of isotopes from the high-level waste. As an example, consider PAT operations that transmute actinides to a less radiotoxic material. In principle, once the actinides are eliminated as a hazard in the waste stream, the long-lived fission products (e.g., ^{90}Sr and ^{137}Cs) become the dominant concern. For a facility having an inventory of about 10 EBq of these fission product isotopes (e.g., the Hanford Site in the US), the time to reduce the radiotoxicity to a manageable level is less than 1,000 y. This is illustrated by considering the time for 10 EBq of ^{90}Sr and ^{137}Cs to undergo 20 half-lives (about 600 y). During the 600 years, 10 EBq decays to about 10 GBq.

Transmutation strategies include minor actinide burning and plutonium recycling. Each of these steps and their primary driving forces are examined in subsequent discussion. Prior to reviewing these steps, it is necessary to review the neutron requirements for actinide transmutation strategies.

One of the principle driving forces for plutonium and minor actinide burning is minimizing the nuclear proliferation potential. During reprocessing, uranium and other actinides are separated from the spent fuel. Following separation from uranium and fission products, the other actinides are recycled in reactors or accelerators. A number of specific strategies can be utilized for PMA burning including reactors and accelerator systems using thermal or fast neutrons.

3.1 PMA Burning in Generation IV Reactors

Plutonium recycling has both a resource management as well as nonproliferation motivation. Recycled plutonium extends fissile resources and eliminates material that might be diverted to nuclear weapons. The separation of uranium and plutonium from spent light water reactor (LWR) fuel is performed using various reprocessing methods[7,9,10,13,15].

In the initial reprocessing step, plutonium is recycled in thermal reactors. Later recycling steps are accomplished using fast reactors with the option to utilize a limited number of thermal reactor cycles. In addition, an advanced fuel cycle includes partitioning other materials including (1) improved reprocessing of LWR uranium oxide fuel with additional neptunium removal, (2) separation of minor actinides from the reprocessing solutions, (3) fabrication of minor actinide targets for irradiation in LWRs, and (4) recycling of uranium and plutonium into mixed oxide LWRs. Other partitioning options include the separation of long-lived fission products including ^{90}Sr, ^{99}Tc, ^{129}I, and ^{137}Cs.

PAT could play an essential role in future advanced fuel cycles which would reduce the long-term radiotoxic waste inventory, and the radiation dose to workers and the environment. By removing the minor actinides and long-lived fission products from reprocessing waste or burning them in a Generation IV reactor, the licensing basis for a high-level waste repository is simplified[13]. Reducing the HLW concern from $10^4 – 10^6$ y to about 10^3 y would remove a significant concern associated with the expansion and continued development of fission reactors.

3.2 Accelerator Destruction of Actinides and Fission Products

There are numerous options for an accelerator driven systems (ADS) for waste incineration[15,19-26]. These include a proton accelerator to transmute actinides via spallation reactions. As an example, the Japan Atomic Energy Research Institute (JAERI) investigated a transmutation system using an accelerator driven subcritical system. The system has a general objective to minimize the hazards associated with fuel reprocessing and the disposition of the residual high-level waste.

The JAERI approach[15,19-26] utilizes a subcritical reactor with the thermal power of 800 MW that transmutes 250 kg of minor actinides (MA) annually. As proposed by JAERI, the reactor fuel includes MA-nitride and is cooled using a Pb-Bi eutectic. A 1.5 GeV, 20-30 MW accelerator directs protons into the Pb-Be target to produce spallation reaction products including neutrons. The neutrons transmute the MA fuel. Initial core loadings contain fissile plutonium to optimize neutron production while limiting the reactor to a subcritical configuration.

A number of technical challenges must be overcome to lead to a production-scale ADS facility. These issues include accelerator reliability, beam transport, window system development, high power spallation target development, subcritical reactor physics performance, control verification, minor actinide transmutation performance, and fuel handling system development. In addition, the system cost and economic viability must be demonstrated.

A fuel cycle without Generation IV reactors or ADS would vitrify HLW and then dispose of this waste in a long-term geologic repository. With ADS and PAT, the fuel cycle would partition the HLW into two major waste streams. These are fission products and minor actinides.

The actinide fraction is fabricated into fuel. This fuel is transmuted into relatively small amounts of fission product waste using Generation IV reactors[13].

Fission products are separated into long-lived and short-lived fractions. The long-lived fraction is composed primarily of ^{90}Sr and ^{137}Cs. Medical isotopes such as $^{90}Sr/^{90}Y$ could also be extracted from this waste stream. After sufficient radioactive decay, the long-lived fraction is suitable for commercial land burial at a low-level radioactive waste facility. The short-lived fission product stream is separated into a valuable metals fraction (e.g., ruthenium, rhodium, palladium, and technetium), and medical isotopes. Remaining fission products are suitable for burial at a commercial low-level waste facility following sufficient decay to meet the facility's licensing restrictions.

Table 1 provides a summary of key parameters for the JAERI ADS facility[21-24]. Variants and optimization of this design are likely.

Table 1

Initial Design Parameters for the Proposed JAERI ADS Facility[a]

Design Parameter	Design Selection/Value
Beam Particle	Protons
Beam Energy	1.5 GeV
Beam Power	20 – 30 MW
Spallation Target	Pb-Bi
Coolant	Pb-Bi
Maximum k_{eff}	0.97
Thermal Output	800 MW
Core Height	1 m
Active Core Diameter	2.34 m
Minor Actinide Initial Inventory	2.5 t
Fuel Composition	60% Minor Actinides 40% Plutonium in Mono-Nitride Form
Transmutation Target	Minor Actinides

[a] Refs. 21-24.

The development of ADS would have positive benefits in other fields. These benefits include energy generation, isotope production, and creation of an intense neutron source.

3.3 Gamma-Ray Free Electron Lasers

When sufficiently developed, gamma-ray free electron lasers (GRFELs) offer the potential for large fluence rate values and high photon energies[7]. The energies are sufficient to initiate photon-induced reactions, and the high fluence rates would ensure reasonable reaction rates for the photodisintegration of minor actinides. These reactions accomplish the desired end state of eliminating the minor actinides from high-level waste.

The photodisintegration of ^{244}Cm illustrates the GRFEL approach. When irradiated by a GRFEL source, ^{244}Cm would undergo a number of nuclear reactions including (1) sequential (γ, n) reactions to non actinide nuclides, (2) photofission, (3) photospallation, and (4) sequential (γ, α) reactions to non-actinide nuclides.

Photon induced reactions provides an alternative route for the elimination of plutonium and minor actinides. In order to be successful, the photons must have sufficient energy and fluence to irradiate the PMA fuel assembly throughout its volume. For a PMA atom density of n atoms/cm^3, a photoinduced reaction cross-section (σ), and photon fluence rate (Φ), the reaction rate (R) in dis/cm^3-s is:

$$R = n\sigma\phi \approx \frac{n}{\tau} \quad (1)$$

where τ is the time to transmute a significant portion of the PMA.

For an incident fluence rate (Φ), the fluence rate after penetrating a depth x into the PMA material is:

$$\phi(x) = \phi_o B(\mu x, E, Z)\exp(-\mu x) \quad (2)$$

where B(μx,E,Z) is the gamma-ray buildup factor, μ is the linear attenuation coefficient, E is the photon energy, and Z is the atomic number of the material shielding the photon radiation. The fluence must be sufficient throughout the PMA material to provide uniform transformation of the HLW material.

Using Eq. 2, the time τ required for the transformation of a significant portion of all PMA nuclei in the irradiated fuel is:

$$\tau = \frac{n}{R} \quad (3)$$

This time is minimized by increasing the photon fluence rate.

3.4 Neutron Requirements for Various Fuel Cycle Options

From a neutron utilization perspective, not all generating devices efficiently operate to remove actinides from the fuel cycle. The production-to-absorption ratio of the actinides in the equilibrium core (η_{ec}) is a useful parameter to assess the suitability of a reactor or accelerator in terms of neutron utilization. Alternatively, the overall neutron balance for the complete fission of actinides can be measured in terms of the fuel neutron production parameter (– D). These two parameters provide an indication of the capability of a technology to initiate and sustain a successful actinide transmutation technology[20].

An η_{ec} value smaller than unity means that the fuel of the equilibrium core cannot maintain a chain reaction. A negative -D value indicates that an actinide or an actinide mixture cannot be completely fissioned. The inability to sustain a fission reaction or failure to achieve complete fission indicates the technology is not a viable option for actinide transmutation. These parameters are influenced by the neutron spectrum and flux of the system. Evaluating a technology using either the η_{ec} or –D approaches leads to the same conclusions regarding its viability for actinide transmutation[20].

The η_{ec} and -D values provided in Table 2 are derived from realistic transmutation concepts. These values demonstrate that minor actinides cannot be completely burned in thermal systems. Fast reactors and accelerators are effective in transmuting plutonium and minor actinides, and have the potential to significantly reduce the volume of high-level waste. However, their economic viability and engineering efficiency must be demonstrated before fast reactors and accelerators become an effective component of an advanced nuclear fuel cycle.

Table 2 Neutron Performance of Plutonium, Minor Actinide and Transuranic Approaches[a]

Actinide Feed Compenent	Thermal Accelerator		Fast Reactor		Fast Accelerator	
	η_e	-D	η_{ec}	-D	η_{ec}	-D
Plutonium	1.15	0.40	1.64	1.18	1.80	1.34
Minor Actinides	0.89[b]	-0.37[c]	1.28	0.71	1.33	0.79
Transuranics	1.11	0.30	2.00	1.52	1.75	1.29

[a] Ref. 20.

[b] Cannot maintain a chain reaction.

[c] Cannot be completely fissioned.

3.5 PAT Health Physics Considerations

A PAT facility processing high-level waste contains fission products and actinides in concentrations that present a health physics hazard. Many of these hazards are common in any radiological facility, and include the control of worker effective doses (e.g., internal and external) and limiting the release of radioactive material to the environment. These common health physics issues are discussed in numerous references and are not repeated in this text[7,9,10,13,15].

Issues to be addressed in subsequent discussion focus on unique health physics issues associated with a PAT facility. These issues include criticality safety and the unique radionuclides that result from PAT operations.

3.6 Criticality Safety

The spent fuel inventory includes fissile materials (i.e.,^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu) and these radionuclides present a criticality hazard. A criticality event is a major consideration for the storage of spent fuel, during fuel reprocessing operations, and during post reprocessing PAT activities. A criticality produces an intense burst of neutron and photon radiation[9,10].

Criticality safety is enhanced using a subcritical PAT system with $k_{eff} < 1$. Subcriticality is based on a set of controls that ensure the system does not achieve a critical mass or geometry. These controls must be protected to ensure that a critical configuration is not achieved. For example, the introduction of unborated water into the system is controlled by isolating these water sources (e.g., by providing double valve isolation of unborated sources). In addition, the boron concentration of the water required to ensure subcriticality is verified by periodic sampling.

3.7 Limiting Radionuclides

The discussion in this section assumes that minor actinides have been removed from the waste, and fission products are now the limiting waste disposal consideration. With current technology, the neutron capture process is the only practical reaction for transmuting fission products. Other candidate processes are in their initial stage (e.g. fusion neutron sources) or in development (e.g., Generation IV fast reactors and gamma-ray free electron lasers). The transmutation of a fission product is only feasible if the reaction rate is greater than the natural decay rate of the nuclide. With the available or developing neutron sources and their associated fluence values, this feasibility requirement cannot be achieved for the most abundant fission products (e.g., ^{137}Cs and ^{90}Sr) which preclude their transmutation to a less significant radiological hazard[20]. However, these fission products can be stored for a sufficient period (e.g., 20 half-lives) which is a significant time reduction when compared to the $10^4 – 10^6$ y licensing basis for a high-level waste repository.

Long-lived fission and activation products affect radiological assessments for a geologic repository and some of these radionuclides are not effectively removed using existing PAT techniques. A summary of selected properties of ^{14}C, ^{36}Cl, ^{79}Se, ^{93}Zr, ^{99}Tc, ^{126}Sn, ^{129}I, and ^{135}Cs and their associated health physics hazards are provided in Table 3[20]. Eliminating these isotopes from the high-level waste stream has a significant benefit for reducing the licensing requirements for a PAT facility. Issues associated with the transmutation of these radionuclides are also noted in Table 3.

Table 3 Selected Fission and Activation Products Important in Geologic Repository Partitioning and Transmutation Assessments

Isotope	Source	Half-Life (y)	Environmental Behavior	PAT Issues
^{14}C	$^{14}N(n, p)^{14}C$ activation reaction from nitrogen contamination in UO_2 fuel	5,715	^{14}C can enter the environment though its solubility in groundwater and plant intakes via photosynthesis.	Low neutron capture cross-sections suggest transmutation will not be effective.
^{36}Cl	$^{35}Cl(n, \gamma)^{36}Cl$ activation reaction from chlorine impurities in zirconium alloy cladding	$3.01x10^5$	Due to its chemical characteristics, ^{36}Cl gradually dissolves in ground water.	Low neutron capture cross-sections suggest transmutation will not be effective. Separation is a possible approach.
^{79}Se	Fission product	$3.5x10^5$	Selenium behaves chemically like sulfur and is incorporated into vitrified waste. Leaching from vitrified waste presents a potential environmental hazard.	Accurate cross-sections must be determined for an assessment of the transmutation potential of this nuclide. Separation is a possible approach.

Table 3 (Continued) Selected Fission and Activation Products Important in Geologic Repository Partitioning and Transmutation Assessments

Isotope	Source	Half-Life (y)	Environmental Behavior	PAT Issues
^{93}Zr	Fission product	$1.5x10^6$	Aquatic plants rapidly uptake soluble zirconium, but land plants tend not to adsorb it.	Effective transmutation is not likely. Separation is a more likely approach.
^{99}Tc	Fission product	$2.13x10^5$	TcO_4 is soluble and presents a groundwater pathway.	Partitioning of ^{99}Tc is difficult. Given a relatively large neutron capture cross-section, transmutation is feasible.
^{126}Sn	Fission product	$2.3x10^5$	^{126}Sn is partially soluble in groundwater.	Effective transmutation is not likely. Separation is a more likely approach.

Table 3 (Continued) Selected Fission and Activation Products Important in Geologic Repository Partitioning and Transmutation Assessments

Isotope	Source	Half-Life (y)	Environmental Behavior	PAT Issues
^{129}I	Fission product	$1.57x10^7$	Iodine is one of the first radionuclides to emerge in the biosphere due to its high mobility.	Transmutation of ^{129}I is difficult. Confinement may be the best method to reduce its radiological impact.
^{135}Cs	Fission product	$2.3x10^6$	Once it enters the environment, cesium is very mobile.	Effective transmutation is not likely. Separation is a more likely approach.

[a] Ref. 20.

The results of Table 3 suggest that only a portion of the long-lived radionuclides in high-level waste will be successfully treated with currently available neutron PAT designs. However, PAT represents an approach that has yet to be optimized. If supplemented with other separation techniques, PAT could be used to enhance waste processing and minimize the number of long-lived radionuclides in high-level waste.

Using contemporary technologies, the neutron transmutation of fission products and actinides is a plausible approach because neutrons can be copiously produced using a variety of approaches. High neutron fluence rates could be derived from high flux reactors, fission reactors, controlled nuclear fusion reactors, accelerators, and devices producing spallation reactions[7,9,10,15]. Although current technology has significant limitations, Section 4 offers potential, but speculative, solutions.

Burner reactors would ideally transmute a radioactive species at a rate faster than its creation. However, the reduction will often be too small to produce a significant effect. Burner reactor systems also have the disadvantage of the large inventory of radionuclides requiring handling, processing, and storage.

A fusion reactor would also produce a source of high energy neutrons using reactions including $^2H + {}^3H \rightarrow {}^4He + n$ (14.1 MeV). However, the economics of a fusion approach would not be viable for a general transmutation approach until this technology reaches maturity. A time frame for a viable fusion system has yet to be established

A spallation approach could produce high fluence rates required for a viable transmutation approach. However, spallation methods have economic issues and require technological advances to be viable[1].

Other transmutation approaches can be utilized including proton induced reactions. Ref. 1 suggests that proton techniques would be better utilized as a production driver to facilitate neutron induced transmutation.

Gamma-rays and electrons are additional transmutation probes that utilize (γ, n) or electron induced nuclear reactions. However, the reaction cross-section magnitude is a limiting factor with gamma-rays and electron induced transmutation.

The aforementioned transmutation approaches have economic limitations and are currently costly. Considerable research and development are required to establish a viable production scale transmutation technology. Given this limitation, other speculative techniques utilizing cutting-edge technologies merit attention. The speculative technologies noted previously are addressed in Section 4.

4.0 Nuclear Waste Transmutation Utilizing Speculative Technology

Given the issues noted in Section 3.0, this paper presents speculative methods to process high-level nuclear waste. These techniques have not received extensive evaluation or discussion.

The first explores the possibility of incorporating an underground nuclear detonation as a means to process the waste. A second method uses antiprotons and antineutrons to transmute the high-level waste. The third incorporates fast reactions from plasma to obliterate isotopes comprising radioactive waste.

Although nuclear weapons have been demonstrated to produce a significant neutron yield, there are also obvious political and geopolitical issues associated with the use of these devices to transmute waste. There are technology limitations associated with the production and storage of antimatter and generating stable plasma to transmute HLW. The efficacy of using a nuclear detonation to transmute waste must also be demonstrated.

4.1 Transmutation Using an Underground Nuclear Detonation

The underground detonation would occur in a cavity that would contain the HLW. Cavity sizes and depths would depend on the weapon's yield and quantity of waste to be transmuted.

Nuclear weapons are well established technologies that are designed to produce destructive effects during an armed conflict. Their use for transmuting waste is a unique application that has not been extensively explored. Following the detonation, copious neutron radiation having a fission/fusion energy spectrum is produced. The neutrons generate activation reactions that convert radionuclides to a less hazardous form utilizing a variety of neutron induced pathways including (n, γ) reactions. In addition, nuclear detonations could also be utilized to incinerate toxic wastes.

The radiation output from a conventional fission nuclear weapon is governed by the basic fission process. For applications in waste transmutation, the radiation output of the device could be altered to enhance the radiation yield, but limit the blast output. This enhancement could focus on enhancing a particular radiation output (e.g., gamma or neutron) governed by the energy dependent cross sections to facilitate the transmutation characteristics of the device.

Complete cross-section data will likely not be available for all radionuclides comprising the high-level waste. This is important because the reaction rate depends on this data. The reaction rate (R) for transmutation of an individual radionuclide is

$$R = N\sigma\phi (4)$$

where N is the number of atoms / cm^3, σ is the microscopic cross-section (b / atom), and φ is the activating flux or fluence

rate (n/cm^2-s). An advantage of a nuclear detonation is the large neutron fluence rate that is generated. This factor enhances the capability of a nuclear detonation to transmute high-level waste.

Ref. 27 provides the neutron fluence per unit kiloton yield (n/cm^2-kT) of the device as a function of distance from the detonation location for fission spectrum neutrons between 3.3 keV and 10 MeV and for a thermonuclear spectrum between 3.3 KeV and 15 MeV. The report uses English distance units. At 400 yards (x), the fission (thermonuclear) spectrum is in the range of 10^{10} - 10^{13} n/cm^2-kT (10^{11} – 5x10^{13} n/cm^2-kT). The neutron fluence at the HLW location (r) is

$$\phi(r) = \phi(x)\frac{x^2}{r^2} \quad (5)$$

Using Eq. 5, and a distance of about 10 m from the detonation site would lead to fission (thermonuclear) fluences on the order of 10^{13} - 10^{16} n/cm^2-kT (10^{14} – 5x10^{16} n/cm^2-kT). These fluence values are significantly above currently achievable reactor or accelerator capability. For a 100 kT detonation, fission (thermonuclear) fluences of 10^{15} - 10^{18} n/cm^2-kT (10^{16} – 5x10^{18} n/cm^2-kT) would be obtained. Larger yield weapons would lead to a proportional increase in neutron output.

These values suggest that nuclear detonations have significant potential to transmute high-level waste. However, significant research and development would be required to demonstrate viability. In addition, numerous national and international issues would need to be overcome.

Nuclear detonations also have the potential to treat other waste forms including low-level nuclear waste, toxic chemicals, and various industrial wastes. Again, significant research and development would be required to demonstrate viability.

To assess the effectiveness of a nuclear detonation, a review of transmutation of long-lived fission products (LLFP) in a fast reactor[26] is illustrated in Table 4. Since a nuclear detonation produces significantly more flux than a reactor, the nuclear detonation represents an optimum application of this transmutation approach.

Table 4

Evaluated Parameters Obtained from Monte Carlo Code MVP Output Data of Transmutations of LLFPs[a]

LLFP	LLFP Natural Half-life (yr)	Effective Half-life (yr)	Transmutation Rate (%/yr)	Production (g /yr)	Transmutation (g /yr)	Support Ratio
^{79}Se	3.27×10^{5}	15.6	3.20	4.20×10^{1}	4.32×10^{3}	102.80
^{99}Tc	2.11×10^{5}	37.0	1.35	5.71×10^{3}	2.98×10^{4}	5.21
^{107}Pd	6.5×10^{6}	1.65	0.4	3.27×10^{3}	9.27×10^{3}	2.84
^{129}I	1.57×10^{7}	22.8	2.19	1.67×10^{3}	9.05×10^{3}	5.42
^{93}Zr	1.53×10^{6}	145.1	0.34	3.60×10^{3}	1.16×10^{4}	3.24
^{135}Cs	2.3×106	165.2	0.31	1.03× 104	1.53×104	1.49

[a] Ref. 26.

Table 4 summarizes the effective half-life($T^{eff}_{1/2}$), transmutation ratio (TR), and support ratio (SR) for selected LLPFs. The effective half-life is an important parameter for illustrating the effectiveness of transmutation for a given radionuclide. An effective half-life influences the transmutation reaction.

The traditional half-life ($T_{1/2}$) and effective half-life ($T^{e}_{1/2}$) are defined as:

$$T_{1/2} = \frac{ln2}{\lambda} \quad (6)$$

$$T^{eff}_{1/2} = \frac{ln2}{\lambda + \sigma\phi} \quad (7)$$

where λ is the physical decay constant of the target LLFP, σ is the effective neutron capture cross section, and φ is the neutron flux. As noted in Eq. 7, increasing neutron flux decreases the effective half-life and increases the effectiveness of the transmutation process. This effect is a portion of the basis for the nuclear detonation transmutation approach.

Table 4 notes two additional important parameters regarding the effectiveness of the transmutation system. These parameters are the transmutation rate (TR) and support ratio (SR)[26]. The TR is defined as the ratio[26]

$$TR = \frac{N(0) - N(T)}{TN(0)} \quad (8)$$

where N(0) and T are the number of initial atoms of a LLFP in the target and the irradiation period, respectively. Eq. (8) can be simplified if the burn-up chain of a LLFP only has a capture reaction

$$TR = \frac{N(0) - N(0)\exp(-\sigma\phi T)}{TN(0)} = \frac{1 - \exp-\sigma\phi T}{T} \quad (9)$$

For a nuclear detonation, σ φ T is small and Eq (9) can be simplified by expanding the exponential in a power series and

only retaining the lowest order terms

$$TR \approx \frac{1-(1-\sigma\phi T)}{T} \approx \sigma\phi \quad (10)$$

Again, the large fluence rate from a nuclear detonation leads to an enhanced transmutation rate.

Table 4 also lists the support ratio defined as the ratio of the amount of transmuted LLFPs to the amount of LLFPs produced in the core fuel over the same period of time in a reactor[26]

$$SR = \frac{N(0)-N(T)}{\gamma MT} \quad (11)$$

where γ and M are the LLFP yield per fission of fuel materials and the total fission rate of the core, respectively. Following arguments related to the transmutation rate, Eq. (11) can be simplified if the burn-up chain of a LLFP only has a capture reaction

$$SR = \frac{N(0)-N(0)\exp(-\sigma\phi T)}{\gamma MT} \quad (12)$$

For a nuclear detonation, σ φ T is small and Eq (12) can be simplified by expanding the exponential

$$SR \approx \frac{N(0)-N(0)(1-\sigma\phi T)}{\gamma MT} \approx \frac{N(0)\sigma\phi}{\gamma M} \quad (13)$$

Again, the large fluence rate from a nuclear detonation leads to an enhanced support ratio.

A low yield detonation, (< 100 kT) also produces thermal radiation (~35%) and blast energy (~60%) in addition to the ionizing radiation (~5%)[27]. The thermal component vaporizes the material, and the blast wave embeds the waste into the walls of the detonation cavity. Any HLW not transmuted is immobilized within the detonation cavity walls. The blast and thermal components are additional tools to enhance the detonation approach. All three components require optimization to efficiently utilize the underground nuclear detonation approach to transmute HLW.

A nuclear detonation has the potential to form the basis for a viable approach to address the HLW issue. Considerable effort will be required to optimize this approach, but there are fewer technical barriers to its implementation than the other two speculative approaches. However, significant political and geopolitical issues must be addressed before it becomes a viable HLW option. Moreover, the present discussion only outlines a first-order evaluation of the nuclear detonation HLW application

4.2 Transmutation Using Antimatter

A second speculative approach is the anti-activation method using antineutrons or antiprotons. The current cost of producing antinucleons in significant quantities is prohibitive and presents a major impediment to the application of this technology. The advancement of the use of this approach depends on technology development, and scientific approaches to generate usable quantities of antimatter in a cost effective manner. Antimatter technology advancement is not only

speculative, but also highly uncertain. Considering the limited research regarding this antimatter application, this paper only provides an initial first-order overview of the approach.

Activation reactions, fission, and neutron capture reactions are responsible for the production of radionuclides in a reactor including long-lived systems. For example, the thermal neutron generated ^{59}Co(n, γ)^{60}Co activation reaction produces copious quantities of ^{60}Co. The ^{60}Co activity can be reduced through the anti-activation reaction ^{60}Co(n-bar, ξ)^{59}Co(stable). ξ represents the various annihilation products produced from the antineutron interaction.

Collisions of antinucleons (e.g., antineutrons and antiprotons) lead to a variety of reactions with nuclei X[28,29]. These reactions include: (1) elastic scattering [X(n-bar, n-bar)X], (2) charge exchange [X(n-bar, p-bar)Y], (3) inelastic scattering charge exchange [X(n-bar, p-bar + mesons)Y], and (4) annihilation producing various systems Z_i as X shatters [X(n-bar, nuclear fragments + mesons)Z_i].

Specific cross-section values for these reactions depend on the target nucleus, antinucleon selected to induce the reaction, and the antinucleon energy. At lower energies, mesons would be likely be produced in pairs including the combinations $\pi^+ \pi^-$, $\pi^0 \pi^0$, $K^+ K^-$, $K^0 K^0$-bar, $K^+ K^0$-bar, and $K^- K^0$-bar. Additional mesons and other reaction products would be produced as the antinucleon energy increases.

The effectiveness of antinucleon reactions depends on the interaction cross-section for antineutrons and antiprotons. Data are not available for all requisite fission products, activation products, and actinides. Fortunately, theoretical efforts suggest these antinucleon cross sections are similar in magnitude to nucleon induced reactions[28-37,39]. This result suggests that these antinucleon induced reactions offer a theoretical alternative for processing high-level waste.

From a theoretical perspective, anti-activation can be described in terms of a core plus valence nucleon model. In this model, the antinucleon annihilates the valence nucleon, and produces an excited residual core. For example, antiprotons incident of ^{14}C (5700 y) leads to short-lived ^{13}B (17.33 ms) through the reaction p-bar + (^{13}B + p) → ^{13}B + ξ. The final product ξ represents the various p – p-bar annihilation products. ^{13}B could also be produced in an excited state that would rapidly decay to its ground state. This annihilation reaction would effectively remove ^{14}C from the high-level waste.

Table 5 outlines selected reactions induced by an antineutron or antiproton. As an illustrative example, Table 5 only considers reactions of the form

$$\textbf{p-bar + N(A, Z) = p-bar + [N(A-1, Z-1) + p]} \rightarrow \textbf{N(A-1, Z-1) + ξ (14)}$$

$$\textbf{n-bar + N(A, Z) = n-bar + [N(A-1, Z) + n]} \rightarrow \textbf{N(A-1, Z) + ξ (15)}$$

where the nucleus N(A, Z) is modeled as a core plus proton for an antiproton induced reaction, and a core plus neutron for an antineutron induced reaction. ξ represents the various reaction products (e.g., meson pairs).

The results summarized in Table 5 suggest antinucleon reactions involving selected activation products have the potential to limit the radiotoxicity of the transmuted high-level waste. As noted in Table 5, there is significant potential to reduce the high-level waste hazard, including storage time frames, using antinucleon induced reactions.

Table 5 Selected Activation Products Residing in High-Level Waste Transmuted Using The Reactions of Eqs. 14 and 15

Target Nucleus		Incident Antinucleon	Residual Nucleus	
System	Half-Life[a]		System	Half-Life[a]
^{3}H	12.32 yr	n-bar	^{2}H	stable[b]
^{3}H	12.32 yr	p-bar	^{2}n	887 s[b]
^{14}C	5700 yr	n-bar	^{13}C	stable[b]
^{14}C	5700 yr	p-bar	^{13}B	17.33 ms[b]
^{7}Be	53.22 d	n-bar	^{6}Be	$5x10^{-21}$ s[b]
^{7}Be	53.22 d	p-bar	^{6}Li	stable[b]
^{26}Al	$7.17x10^{5}$ yr	n-bar	^{25}Al	7.183 s[b]
^{26}Al	$7.17x10^{5}$ yr	p-bar	^{25}Mg	stable[b]
^{36}Cl	$3.01x10^{5}$ yr	n-bar	^{35}Cl	stable[b]
^{36}Cl	$3.01x10^{5}$ yr	p-bar	^{35}S	87.37 d[b]
^{59}Ni	$7.6x10^{4}$ yr	n-bar	^{58}Ni	stable[b]
^{59}Ni	$7.6x10^{4}$ yr	p-bar	^{58}Co	70.86 d[b]
^{60}Co	5.27 yr	n-bar	^{59}Co	stable[b]
^{60}Co	5.27 yr	p-bar	^{59}Fe	44.495 d[b]
^{63}Ni	101.2 yr	n-bar	^{62}Ni	stable[b]
^{63}Ni	101.2 yr	p-bar	^{62}Co	1.5 min[b]

[a] Refs. 38 and 39.

[b] Potential for high-level waste activity reduction.

Table 6 provides a review of selected fission products plus antinucleon reactions. The residual nuclear systems suggest that reduced radiotoxicity and half-lives result from the proposed antinucleon induced reactions. This positive transmutation prediction is similar to the activation product results.

Table 6 Selected Fission Products Residing in High-Level Waste Transmuted Using The Reactions of Eqs. 14 and 15

Target Nucleus		Incident Antinucleon	Residual Nucleus	
System	Half-Life[a]		System	Half-Life
^{79}Se	3.26×10^{5} yr	n-bar	^{78}Se	Stable[b]
^{79}Se	3.26×10^{5} yr	p-bar	^{78}As	90.7 min[b]
^{90}Sr	28.9 yr	n-bar	^{89}Sr	50.563 d[b]
^{90}Sr	28.9 yr	p-bar	^{89}Rb	15.32 min[b]
^{93}Mo	4.0x10^{3} yr	n-bar	^{92}Mo	Stable[b]
^{93}Mo	4.0x10^{3} yr	p-bar	^{92}Nb	3.47x10^{7} yr
^{93}Zr	1.61×10^{6} yr	n-bar	^{92}Zr	Stable[b]
^{93}Zr	1.61×10^{6} yr	p-bar	^{92}Y	3.54 h[b]
^{99}Tc	2.111x10^{5} yr	n-bar	^{98}Tc	4.2x10^{6} yr
^{99}Tc	2.111x10^{5} yr	p-bar	^{98}Mo	Stable[b]
^{107}Pd	6.5×10^{6} yr	n-bar	^{106}Pd	Stable[b]
^{107}Pd	6.5×10^{6} yr	p-bar	^{106}Rh	30.07 s[b]

Table 6 (Continued) Selected Fission Products Residing in High-Level Waste Transmuted Using The Reactions of Eqs. 14 and 15

Target Nucleus		Incident Antinucleon	Residual Nucleus	
System	Half-Life[a]		System	Half-Life
^{109}Cd	461.4 d	n-bar	^{108}Cd	>1.9x10^{18} y
^{109}Cd	461.4 d	p-bar	^{108}Ag	2.382 min[b]
^{113m}Cd	14.1 yr	n-bar	^{112}Cd	stable[b]
^{113m}Cd	14.1 yr	p-bar	^{112}Ag	3.130 h[b]
^{121m}Sn	43.9 yr	n-bar	^{120}Sn	stable[b]
^{121m}Sn	43.9 yr	p-bar	^{120}In	3.08 s[b]
^{126}Sn	2.3x10^{5} yr	n-bar	^{125}Sn	9.64 d[b]
^{126}Sn	2.3x10^{5} yr	p-bar	^{125}In	2.36 s[b]
^{129}I	1.5x10^{7} yr	n-bar	^{128}I	24.99 min[b]
^{129}I	1.5x10^{7} yr	p-bar	^{128}Te	2.4x10^{24} yr[b]
^{135}Cs	2.3×10^{6} yr	n-bar	^{134}Cs	2.0652 yr[b]
^{135}Cs	2.3×10^{6} yr	p-bar	^{134}Xe	> 5.8×10^{22} yr[b]
^{137}Cs	30.08 yr	n-bar	^{136}Cs	13.04 d[b]
^{137}Cs	30.08 yr	p-bar	^{136}Xe	>2.4x10^{21} yr[b]

[a] Ref. 38 and 39.

[b] Potential for high-level waste activity reduction.

The results are less encouraging for the selected actinides summarized in Table 7. Since actinide removal presents a significant concern with high-level waste facilities, the use of antinucleon induced reactions summarized in Eqs. 14 and 15 do not offer a likely universal success pathway. However, other antinucleon induced reactions are possible.

Table 7 Selected Actinides Residing in High-Level Waste Transmuted Using The Reactions of Eqs. 14 and 15

Target Nucleus		Incident Antinucleon	Residual Nucleus	
System	Half-Life[a]		System	Half-Life
^{237}Np	2.144x10^{6} yr	n-bar	^{236}Np	1.53x10^{5} yr
^{237}Np	2.144x10^{6} yr	p-bar	^{236}U	2.342x10^{7} yr
^{238}Pu	87.7 yr	n-bar	^{237}Pu	45.64 d[b]
^{238}Pu	87.7 yr	p-bar	^{237}Np	2.144×10^{6} yr
^{239}Pu	24110 yr	n-bar	^{238}Pu	87.7yr
^{239}Pu	24110 yr	p-bar	^{238}Np	2.117 d[b]
^{240}Pu	6561 yr	n-bar	^{239}Pu	24110 yr
^{240}Pu	6561 yr	p-bar	^{239}Np	2.356 d[b]
^{241}Pu	14.329 yr	n-bar	^{240}Pu	6561yr
^{241}Pu	14.329 yr	p-bar	^{240}Np	61.9 min[b]
^{242}Pu	3.75x10^{5} yr	n-bar	^{241}Pu	14.329 yr
^{242}Pu	3.75x10^{5} yr	p-bar	^{241}Np	13.9 min[b]

Table 7 (Continued) Selected Actinides Residing in High-Level Waste Transmuted Using The Reactions of Eqs. 14 and 15

Target Nucleus		Incident Antinucleon	Residual Nucleus	
System	Half-Life[a]		System	Half-Life
^{241}Am	432.6 yr	n-bar	^{240}Am	50.8 h[b]
^{241}Am	432.6 yr	p-bar	^{240}Pu	6561 yr
^{242}Am	16.02 hr	n-bar	^{241}Am	432.6 yr
^{242}Am	16.02 hr	p-bar	^{241}Pu	14.329 yr
^{243}Am	7364 y	n-bar	^{242}Am	16.02 hr[b]
^{243}Am	7364 y	p-bar	^{242}Pu	3.75x10^{5} yr
^{242}Cm	162.8 d	n-bar	^{241}Cm	32.8 d[b]
^{242}Cm	162.8 d	p-bar	^{241}Am	432.6 yr
^{243}Cm	29.1 yr	n-bar	^{242}Cm	162.8 d[b]
^{243}Cm	29.1 yr	p-bar	^{242}Am	16.02 hr[b]
^{244}Cm	18.1 yr	n-bar	^{243}Cm	29.1 yr
^{244}Cm	18.1 yr	p-bar	^{243}Am	7364 y

Table 7 (Continued) Selected Actinides Residing in High-Level Waste Transmuted Using The Reactions of Eqs. 14 and 15

Target Nucleus		Incident Antinucleon	Residual Nucleus	
System	Half-Life[a]		System	Half-Life
^{245}Cm	8423 yr	n-bar	^{244}Cm	18.1 yr
^{245}Cm	8423 yr	p-bar	^{244}Am	10.1 hr[b]
^{246}Cm	4706 yr	n-bar	^{245}Cm	8423 yr
^{246}Cm	4706 yr	p-bar	^{245}Am	2.05 hr[b]
^{247}Cm	1.56×10^{7} yr	n-bar	^{246}Cm	4706 yr
^{247}Cm	1.56×10^{7} yr	p-bar	^{246}Am	39 min[b]
^{248}Cm	3.48×10^{5} yr	n-bar	^{247}Cm	1.56×10^{7} yr
^{248}Cm	3.48×10^{5} yr	p-bar	^{247}Am	23.0 min[b]
^{249}Bk	330 d	n-bar	^{248}Bk	> 9 yr
^{249}Bk	330 d	p-bar	^{248}Cm	3.48×10^{5} yr

Table 7 (Continued) Selected Actinides Residing in High-Level Waste Transmuted Using The Reactions of Eqs. 14 and 15

Target Nucleus		Incident Antinucleon	Residual Nucleus	
System	Half-Life[a]		System	Half-Life
^{249}Cf	351 yr	n-bar	^{248}Cf	333.5 d[b]
^{249}Cf	351 yr	p-bar	^{248}Bk	> 9 yr
^{250}Cf	13.08 yr	n-bar	^{249}Cf	351 yr
^{250}Cf	13.08 yr	p-bar	^{249}Bk	330 d[b]
^{251}Cf	898 yr	n-bar	^{250}Cf	13.08 yr
^{251}Cf	898 yr	p-bar	^{250}Bk	3.212 hr[b]
^{252}Cf	2.645 yr	n-bar	^{251}Cf	898 yr
^{252}Cf	2.645 yr	p-bar	^{251}Bk	55.6 min[b]

[a] Ref. 38 and 39.

[b] Potential for high-level waste activity reduction.

In particular, these reactions include (p-bar, p) that could be utilized to facilitate the destruction of PMAs[40]. The effect of these (p-bar, p) reactions on selected actinides from Table 7 is summarized in Table 8. A (p-bar, p) reactions has the form

$$\text{p-bar} + N(A, Z) = \text{p-bar} + [N(A\text{-}2, Z\text{-}2) + p{+}p] \rightarrow N(A\text{-}2, Z\text{-}2) + p + \xi \quad (16)$$

where ξ represents the various reaction products of the p + p-bar annihilation as noted in Eqs. 14 and 15.

Table 8 illustrates that a variety of reactions are possible with antinucleons. For example, the (p-bar, p) reaction destroys many of the PMAs addressed in Table 7 that were not successfully altered by the Eq. 14 and 15 reactions. The (p-bar, p) reaction is only one of many that can occur, and the variety of interactions increases as the antiproton energy increases.

Table 8 Selected Actinides Residing in High-Level Waste Transmuted Using The (p-bar, p) Reaction				
Target Nucleus		Incident Antinucleon	Residual Nucleus	
System	Half-Life[a]		System	Half-Life
^{237}Np	2.144x10^{5} yr	p-bar	^{235}Pa	24.4 min[b]
^{240}Pu	6561 yr	p-bar	^{238}U	4.468x10^{9} y[c]
^{241}Pu	14.329 yr	p-bar	^{239}U	23.45 min[b]
^{242}Pu	3.75x10^{5} yr	p-bar	^{240}U	14.1 h[b]
^{241}Am	432.6 yr	p-bar	^{239}Np	2.356 d[b]
^{245}Cm	8423 yr	p-bar	^{243}Pu	4.956 h[b]
^{246}Cm	4706 yr	p-bar	^{244}Pu	8.00x10^{7} y
^{247}Cm	1.56×10^{7} yr	p-bar	^{245}Pu	10.5 h[b]
^{248}Cm	3.48×10^{5} yr	p-bar	^{246}Pu	10.84 d[b]
^{249}Cf	351 yr	p-bar	^{247}Cm	1.56x10^{7} y
^{251}Cf	898 yr	p-bar	^{249}Cm	64.15 min[b]

[a] Refs. 38 and 39.

[b] Potential for high-level waste activity reduction.

[c] Naturally occurring radionuclide.

4.3 Transmutation Using Fast Neutrons from a Stable Plasma

A third speculative solution to the high-level waste issue utilizes plasma technology to transmute radioactive materials. The plasma approach involves various applications of fusion technology. Baseline fusion reactions are characterized in terms of their high temperatures and energetic neutrons (e.g., 14.1 MeV neutrons derived from the DT reaction[7,9,10,13]).

One approach, often referred to as the Fusion Torch[41], converts waste material into plasma, and utilizes magnetic fields to direct the plasma stream to appropriate collection locations. This process separates the various elements in the nuclear wastes, and these various waste constituents can be directed to an accelerator. The accelerator is utilized to transmute the high-level waste into materials that have significantly less radiotoxicity. The technology is unproven and has yet to be demonstrated as an effective or economical solution to the high-level waste issue. Basic cross-section data as a function of energy for various HLW constituents must be determined to fully evaluate the Fusion Torch concept.

A fusion-fission hybrid reactor[42] would use a fusion reactor to direct neutrons into an encapsulating blanket of HLW materials. This is essentially an actinide burner that utilizes the fusion process as the transmuting agent.

Fusion neutrons can also be used for burning actinides in a sub-critical blanket located at the periphery of the device. This configuration minimizes the risk of a criticality excursion, and reduces reactor control requirements. As noted in Ref. 42, no fertile material is required for device functionality. Any fertile material (e.g., ^{238}U) would produce transuranic elements that would negate the design objective of reducing the hazard of the high-level waste.

Actinides located in the sub-critical blanket would capture fusion neutrons[42]. Neutrons would be captured and initiate actinide fission resulting in reduction of the radiological hazard of the high-level waste. A variation of the actinide burner would dissolve the actinides into a molten salt eutectic.

Am, Cm, Pu, Cs, and Sr dominate the heat production source term of spent fuel. The goal of the actinide burner is the production of fission products with considerably shorter half-lives. Transmutation can reduce the heat load and radiotoxicity of the high-level waste by factor of 50-100[42]. The actinide burner concept is technically feasible because the fission cross section is greater than capture cross section above 1 MeV. Therefore, high energy neutrons (e.g., the 14.1 MeV neutrons from DT fusion) are essential for the implementation of the actinide burner concept.

There are numerous technology issues associated with an actinide burner. Issues associated with the coolant composition and structural material corrosion are significant concerns. The effects of impurities on high temperature structural materials have yet to be fully evaluated. Manufacturing issues associated with welding and joining for ferritic steels and high temperature Ni superalloys remain unresolved[42]. The effects of material response under prolonged irradiation are uncertain including resistance to neutron damage. High temperature materials design requirements have yet to be fully defined. Most importantly, a self-sustaining fusion reaction capable of generating a continuous source of neutrons has yet to be achieved.

5.0 Challenges to Implementing These Speculative Approaches

Each of the speculative HLW approaches has the potential to address the long-term processing issue. These issues include, but are not limited to, economic viability of the approach, sustainable funding, geopolitical and political concerns, technology development, materials development, data and process verification, and research and development costs. These issues are further outlined in Table 9 - 11.

Table 9

Challenges to Implementing Underground Nuclear Detonations as a High-Level Waste Processing Method

Positive Aspects	Negative Aspects
Nuclear weapons exist and are a proven technology. Designs can be optimized to enhance the radiation output. A sufficient number of weapons exist to support implementation. Incremental research and developing costs are less challenging than the other two speculative methods. This suggests the approach is economically feasible. The approach can likely be implemented in the near term using existing technology. Blast and thermal effects offer a stable end state following detonation, but these effects require further evaluation and optimization.	The use of nuclear weapons presents political and geopolitical challenges and has international implications. Optimizing the technique requires research and development.

Table 10

Challenges to Implementing Antimatter Beams as a High-Level Waste Processing Method

Positive Aspects	Negative Aspects
Antimatter creation is feasible, but is only available in limited quantities requiring specialized accelerator technology A variety of antinucleon induced reactions suggest the feasibility of an antimatter approach	Accelerator design to produce the requisite antiprotons and antineutrons with sufficient intensity is not established. Antimatter production is costly. Funding the antimatter technique presents challenges due to open technical issues. The efficiency of the approach has yet to be demonstrated. Antimatter technology can not likely be implemented in the near term. Significant research and development are required to demonstrate the viability of the antimatter technique. Costs are uncertain and demonstration of the approach will require significant investment.

Table 11

Challenges to Implementing Fusion Reactors as a High-Level Waste Processing Method

Positive Aspects	Negative Aspects
Fusion reactions have been demonstrated. Sustaining a plasma has been achieved for a very limited duration. but without an extended self-sustaining reaction. Research programs are actively pursuing fusion technology.	A production scale fusion reactor does not exist. Materials issues require resolution to ensure feasibility. Significant research and development are required to demonstrate the viability of the fusion approach. Costs are uncertain and demonstration of the approach will require significant investment. The approach can not likely be implemented in the near term.

6.0 Conclusions

Existing technologies and approaches have provided limited success in resolving the high-level waste issue. With the exception of apparent success in Finland and Sweden, little progress has been made.

The speculative technologies of antinucleon induced reactions and fusion neutrons are not likely near term solutions. The use of nuclear weapons to resolve the high-level waste issue presents a possible near term solution. However, optimization is required to facilitate the development of a nuclear weapons approach. In addition, significant political and geopolitical issues must be resolved including both domestic and international concerns. In spite of these issues, the use of nuclear weapons presents a potential disposition method for disposal of these devices while transmuting high-level wastes. Perhaps, an international treaty could be developed authorizing the use of nuclear weapons as a sanctioned HLW disposal methods.

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