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Disposal as the End Point of Radioactive Waste Management

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ABSTRACT

We present a brief overview of the current state of radioactive (or nuclear) waste (RW) management (RWM), focusing on its end point and international advice provided by the International Atomic Energy Agency (IAEA). RW, defined as waste that contains, or is contaminated with, radionuclides at activity concentrations greater than clearance levels set by the national regulatory organisations with guidance from the IAEA, is a by-product of nuclear energy generation, research, the production of life-saving radiopharmaceuticals and industrial applications (e.g., disused radioactive sources from geophysical logging instruments). RW is also produced from processing of materials containing naturally occurring radioactive materials (NORMs) such as those typically occurring in oil and gas production (e.g., mineral scale, produced water), ore beneficiation (e.g., tailings and sludges) and water purification (e.g., filter media, reverse osmosis membranes). RWM envisions all administrative and operational activities involved in the handling, pretreatment, treatment, conditioning, transport, storage and disposal of RW. Disposal involves emplacement of RW in a dedicated facility without the intention of retrieval, requiring waste matrices and waste packages, which conform with waste acceptance criteria (WAC); safety of disposal is demonstrated on the basis of operational and postclosure safety cases. By international consensus, the disposal is the end point of RWM activities. We discuss RW classification, give examples of RW inventories, summarise general considerations regarding RWM and provide an overview of global experience and current trends in geological disposal.

1 | Introduction

Nuclear energy plays a key role in the transition to a low-carbon economy [1, 2], with growing investments in nuclear power plants (NPPs) worldwide being currently on the same magnitude as those based on hydrocarbon fuels [3]. Overall, low-carbon energy sources to which nuclear power belongs are most important in combating air pollution and global warming caused by greenhouse gas emissions [4, 5], with its share in the world expected to reach 50% by 2026, with about 25% of it coming from NPPs [6, 7]. Nuclear energy is statistically the cleanest source of power in terms of CO₂ emissions and the safest along with wind

and solar power sources, compared with coal, oil, gas, biomass and hydropower, as shown in Figure 1, modified after [8].

The contribution of nuclear power should increase by 2050, reaching a total capacity of up to 890 GW(e) [6]. However, the implementation of these plans may be questioned by problems associated with safe management of radioactive waste (RW), especially in the case of high-level waste (HLW). HLW comprises highly radioactive materials that require permanent isolation from the biosphere, continuous heavy shielding and active thermal cooling. Globally, HLW takes two primary forms depending on a nation's nuclear fuel cycle (NFC) strategy: It

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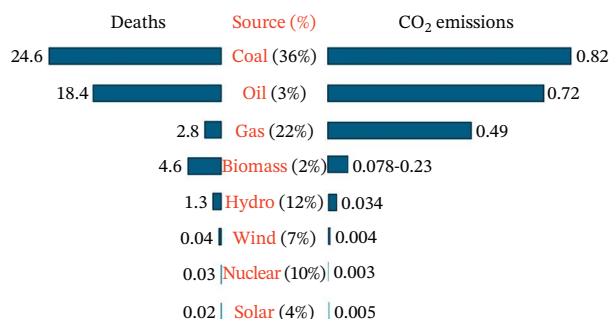


FIGURE 1 | Rates of death due to accidents, pollution and CO₂ emissions (tonnes), both normalised per energy of 1 TW × h(e), which is produced by different energy sources during the electrical power generating plant lifecycles. Global source contributions in the production of electricity globally are shown in parentheses.

encompasses both spent nuclear fuel (SNF) designated for direct disposal, and the concentrated liquid or vitrified solid by-products generated during the chemical reprocessing of that fuel. Management of such by-products currently involves its immobilisation in alkali-borosilicate or alkali-alumina-phosphate glasses produced using direct electric and induction-heated melters [8–14], after which they are cooled and stored until final disposal [15–17]. Effective RW disposal is hence crucial for strengthening public confidence in nuclear energy as a cornerstone of sustainable, large-scale, nuclear energy-based carbon-neutral energy generation [18]. This paper discusses RW classification, provides examples of RW inventories, summarises general considerations regarding RW management (RWM) and provides an overview of global experience and current trends in geological disposal.

2 | RW Classification

Both “RW” and “nuclear waste” terms are generically used as synonyms in the context of safety and waste management. RW is by defining a material that contains, or is contaminated with, radionuclides at activity concentrations greater than clearance levels, as established by the regulatory body, for which, for legal and regulatory purposes, no further use is foreseen [19]. RW differs from non-nuclear waste arising in any other than nuclear application only by the level of radioactivity, which for nuclear waste is above the clearance levels; otherwise, all materials and living species, including humans, naturally bear some radioactivity. The difference in radioactivity levels can span from practically negligible to significant and extremely high; therefore, RWM employs a graded approach dependent on the level of hazard. National clearance levels are based on IAEA recommendations and are conservatively defined, with values that are extremely low relative to typical background radionuclide levels, except for naturally occurring radionuclides, whose clearance levels are of a similar magnitude to natural background concentrations.

The IAEA has developed an internationally accepted classification scheme for RW completely based on its final destination (end point). This is used worldwide as a guidance [20] and envisages the following classes of potentially or really RW:

- i. Exempt waste (EW): It contains radionuclides below the clearance levels being therefore conventionally non-RW;

- ii. Very short-lived waste (VSLW): It is readily stored for natural decay, typically over a short period of time no longer than a few years;
- iii. Very low-level waste (VLLW): It is readily suitable for disposal in near-surface landfill type facilities;
- iv. Low-level waste (LLW): It is amenable for emplacement into dedicated near-surface disposal facilities (NSDFs);
- v. Intermediate-level waste (ILW): It requires a greater degree of containment compared to LLW, although it does generally not need any provision for radiogenic heat dissipation, although exceptions exist such as for vitrified ILW waste from research reactor spent fuel [21];
- vi. HLW: It is most radioactive, long-lived, requires shielding in handling operations and also generates significant levels of radiogenic heat.

HLW, despite its rather small volume, is the most dangerous and troublesome waste. It requires disposal into geological disposal facilities (GDFs) located deep underground (several hundred metres or more below the surface) in stable geological formations able to provide very long-term containment and isolation (at geological timeframes) from the biosphere [19, 20, 22].

The IAEA classification scheme is worldwide used with or without some country-specific amendments in all countries including China [23] and the UK [17, 24].

3 | RW Inventories

RW is a by-product resulting from many useful applications of nuclear technologies or ionising radiations starting from widely used procedures involving radionuclides and radiations in medical diagnosis and therapy [25] and ending with nuclear power for electricity and heat generation [26]. RW is also resulting from the use of various materials, which contain naturally occurring radioactive materials (NORMs), such as uranium and thorium and their decay products, although NORM waste is not always and necessarily a RW [27]. Nuclear technologies are typically perceived as related to electricity generation by NPPs. Indeed, the largest RW source by both volume and radioactivity is the NFC, in the core of which operating NPPs are located (Figure 2).

However, it shall be noted that the waste generated by NFC is, by volume, mainly EW. Then, in descending order of volume, the waste categories are LLW, ILW, and finally HLW, which includes SNF declared as waste for disposal without reprocessing, as well as HLW generated from SNF reprocessing [24, 29].

The greatest hazard associated with RW arises from the presence of long-lived actinides, such as Np, Pu, Am, Cm, and their daughter products; for example, ²⁴¹Am has a half-life ($T_{1/2}$) of 432 years and decays to the radioactive long-lived ²³⁷Np, which has a $T_{1/2} = 2.1 \times 10^6$ years. The long-lived radionuclides cannot be indefinitely stored and require geological times of retention in the disposal, leading to the need of GDF use [9, 24, 30, 31].

The most troublesome radionuclides of RW arising in the NFC are the decaying rare earth elements (REEs) and trivalent minor actinides (MAs) such as Am and Cm. Their content in SNF and correspondingly in the fuel reprocessing HLW depends on fuel enrichment, burn-up and storage time. Table 1, modified after

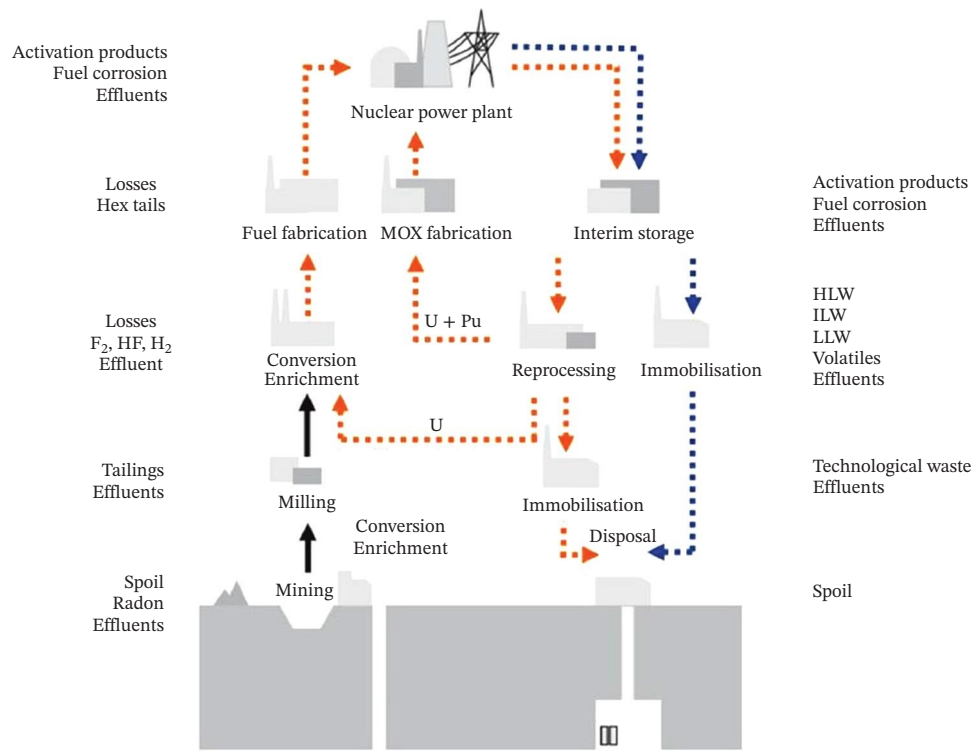


FIGURE 2 | NFC activities and associated RW streams [16, 28].

[32], presents data on the most important REE and actinides, including MA, in the SNF of light-water reactors. Depending on burn-up of the fuel and its storage time, the activity of key radionuclides in SNF will change as shown in Figure 3 (see, e.g., [33]).

RW produced from applications other than nuclear energy generation is much more diverse in isotope composition and radioactivity compared with RW generated from nuclear energy production; data regarding radionuclide composition and waste volumes are available from the IAEA and other publications [24, 34–37]. RW inventories containing data on already accumulated and expected radionuclides, masses and volumes are at the basis of policies and strategies of RWM [22], where the IAEA classification scheme is indicative of end points for each RW stream. The global RW inventory, including SNF declared as waste and therefore intended for disposal [38], has been estimated by the IAEA [39]. According to the IAEA, approximately 301×10^3 tonnes of SNF, expressed as heavy metal (tHM), are currently in storage worldwide. In addition, the global inventory comprises approximately 32×10^6 m³ of solid RW, of which 26.6×10^6 m³ (83%) has been permanently disposed of, while the remaining 5.6×10^6 m³ (17%) is still in storage awaiting disposal. More than 92% of the volume of solid RW is classified as VLLW or LLW classes, with most of the remainder being ILW. Approximately 95% of the radioactivity is however associated with ILW and HLW, indicating the highest hazard associated with these wastes [30]. Table 2 presents data on the UK national inventory of RW [40, 41].

China is intensively growing its NPP fleet (Figure 4), with data on LLW stored and disposed of shown in Table 3.

In future, HLW in China is expected to be finally disposed of in the GDF in Beishan, Gansu Province, Gobi Desert, with stable

TABLE 1 | Main rare earth elements (REEs) and actinides including MA (g/t) in the SNF of light-water reactors.

SNF data Element	After 5 years of storage at burn-up, GW × d/t		After 30 years of storage at burn-up, GW × d/t	
	45	60	45	60
Gd	150	310	180	346
Eu	190	260	170	230
Sm ¹	1060	1370	1120	1430
Pm	63	62	– ³	—
Ce	3210	4230	3210	4220
Pr	1540	2010	1540	2010
Nd ²	5570	7310	5570	7310
La	1670	2190	1670	2190
Σ REE	13,453	17,742	13,460	17,736
U	941,000	923,000	941,000	923,000
Pu	11,200	12,600	10,200	11,500
Np	570	780	570	780
Am	510	740	1380	1780
Cm	33	113	14	50
Am + Cm, MA	543	853	1394	1830
MA share ⁴	4%	5%	9%	9%

¹There is a long-lived ¹⁴⁷Sm ($T_{1/2} = 1.06 \times 10^{11}$ years) and a small amount of ¹⁵¹Sm ($T_{1/2} = 90$ years).

²Long-lived ¹⁴⁴Nd ($T_{1/2} = 2.4 \times 10^{15}$ years) and ¹⁵⁰Nd ($T_{1/2} = 7 \times 10^{18}$ years) can be considered stable.

³Absent.

⁴It is the share of actinides in the REE–MA fraction and their contribution to heat release.

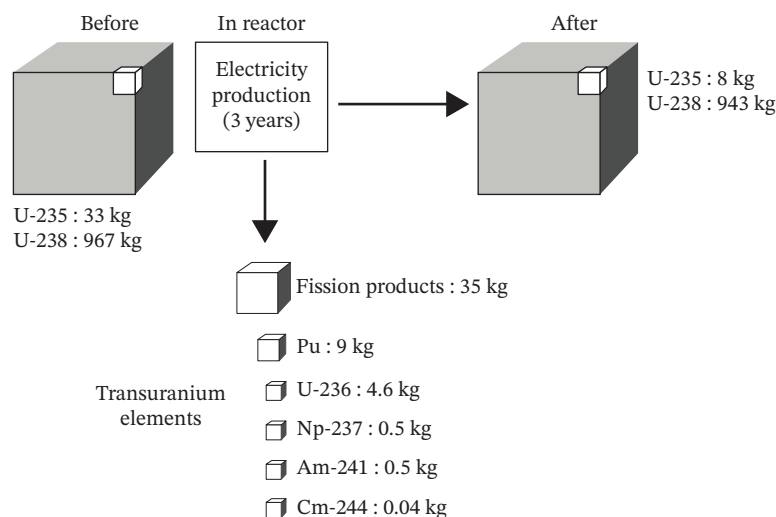


FIGURE 3 | Typical composition of uranium oxide SNF of a 1000-GW(e) pressurised water reactor with an annual charge of 1000 kg of U with 235 U enrichment 3.3% after roughly 3 years of operation (burn-up 33 GW × d/t).

granite bedrock [42, 43], and the Beishan Underground Laboratory at the disposal site is about to complete construction in 2026.

4 | RWM

The RWM activities (see Figure 5) comprise all administrative A and operational B activities involved in the characterisation, handling, pretreatment, treatment, conditioning, transport, storage and disposal of RW [17, 44].

The predisposal part of RWM usually, although not necessarily, involves the following steps [45]:

Pretreatment. It includes all operations carried out with waste prior to treatment and aims to facilitate the selection and further use of waste processing technologies.

Treatment. It comprises all operations which improve both the safety and the economy of NWM by changing the characteristics of nuclear waste and aims to: (i) reduce the waste volume, (ii) remove the radionuclides from the waste and (iii) change the waste composition.

Conditioning. It produces a waste package suitable for further safe handling, transportation, storage and/or disposal. Conditioning envisages conversion of raw liquid or dispersed waste materials into a solid monolithic waste form via immobilisation, i.e., using solidification, embedding or encapsulation. RW vitrification is currently the main immobilisation technology for HLW and is extended to process both LLW and ILW [8–14, 46, 47]. Waste vitrification is attractive because of its technological flexibility, providing a vitreous material

characterised by high mechanical and radiation durability and high corrosion resistance in water. Vitrification effectively reduces the volume of the resulting waste form [46]. Moreover, composite glass crystalline materials (GCMs) incorporating disperse crystalline phases are currently the most reliable waste forms effectively used on an industrial scale for nuclear waste immobilisation [14].

RW storage provides confinement, isolation, environmental protection and monitoring of nuclear waste, in a dedicated storage facility, for certain periods of time (storage periods), ensuring its retrievability.

Transportation is the deliberate physical movement of nuclear waste in a dedicated manner, i.e., a manner specifically designed for the safe transportation of packages from one place to another, and apart from on-site transportation, follows the international transport regulations of radioactive materials set by the IAEA [48].

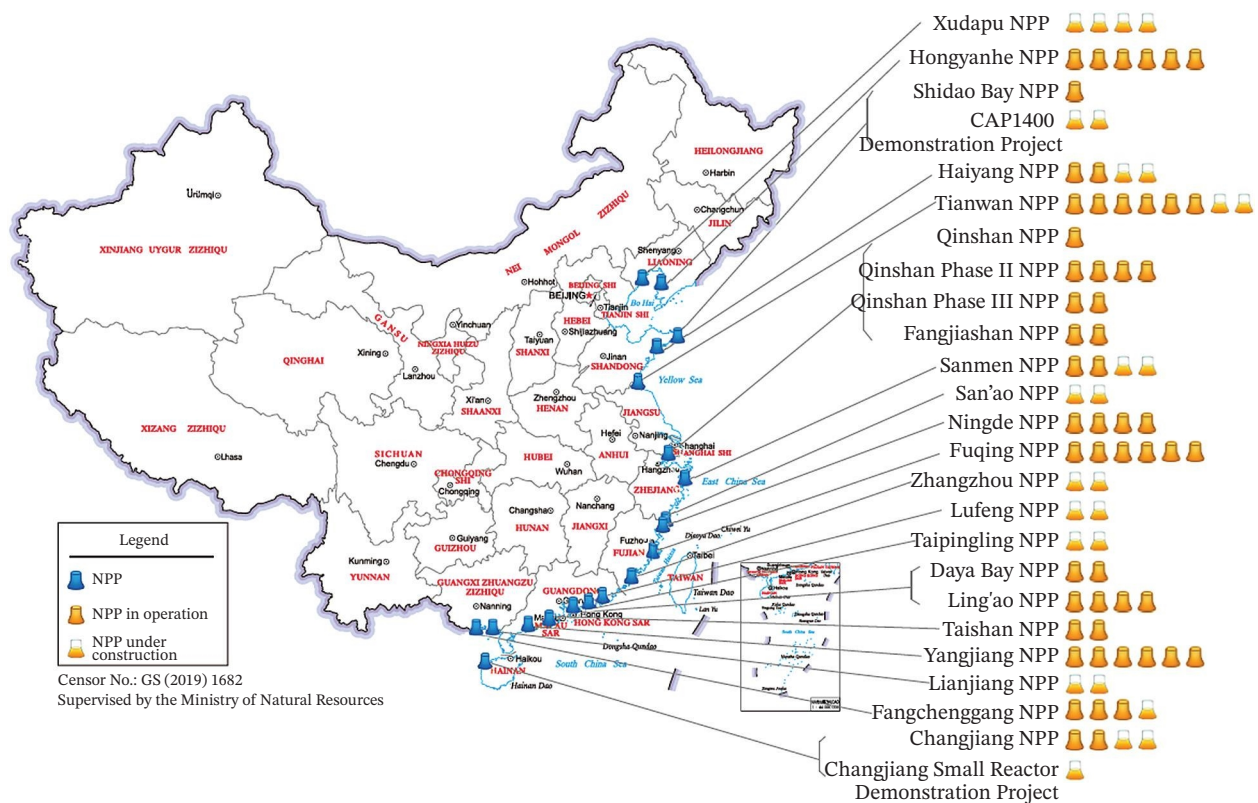
Disposal is the end point of RWM. It envisages the emplacement of nuclear waste in an appropriate disposal facility without the intention of its retrieval [45]. Apart from the waste that may be cleared from regulatory control when its radionuclide content is below the clearance levels [49, 50], the RW lifecycle always ends with disposal. The key to achieving this safely is to have in place and follow an integrated waste strategy [51].

5 | Disposal Stage

There is broad international consensus that the final end point for the long-term management of RW is disposal in appropriately engineered facilities. For high-level RW and SNF, deep geological disposal is widely regarded as the safest long-term solution. Disposal is hence crucial for strengthening public confidence in nuclear energy as a cornerstone of sustainable, large-scale, carbon-neutral energy generation. Although requiring substantial upfront investment, a GDF is widely regarded as the most viable long-term solution for the management of high-level RW and SNF. Its safety case is based on a multibarrier system in which engineered barriers (waste form, disposal container, buffer and backfill materials) work together with the surrounding host

TABLE 2 | Summary of UK radioactive waste inventory.

Class of RW	Volume ($\times 10^6 \text{ m}^3$)	Radioactivity (TBq)
VLLW	2.75	12
LLW	1.34	130
ILW	0.496	1×10^6
HLW	0.00147	14×10^6



A map of nuclear power plants in chinese mainland (as of 31 December 2023)

FIGURE 4 | Map of China with NPP operating and in construction as of 31.12.2023.

geology to contain radionuclides, limit their release and migration and provide passive long-term isolation from the biosphere [18, 52–56]. The first barrier is the waste form, where glasses were selected as primary hosts for HLW having rather extended lifetimes in contact with groundwaters. For example, in China, long-term leaching tests of HLW glasses in the underground-water-invaded glass-canister-bentonite-granite barrier system have shown that the glass would last for 66,000 years until complete corrosion occurs [57–60].

Depending on the RW class, disposal facilities could be of various types such as trenches, vaults, tunnels, shafts, boreholes or mined repositories with a graded approach relating the depth of their location, with the level of waste radionuclide hazard [35, 55, 56] as illustrated in Figure 6 [61].

The design of disposal facilities usually relies on the utilisation of multibarrier defence systems to isolate the RW from the biosphere, which comprises both natural geological barrier and engineered barrier subsystems, which include the waste form, containers, backfilling and repository materials (NBS and EBS correspondingly) [24, 62–64].

The effectiveness and safe isolation of RW depend on three major components of disposal system:

- I. The site which provides the NBS;
- II. The disposal facility with EBS;
- III. The waste package as a crucial part of EBS.

The siting, design, operation and closure of GDFs are guided by internationally recognised IAEA Safety Standards [30, 62–65]. While the underlying safety principles are broadly agreed internationally, the detailed regulatory requirements and site-selection criteria are established by individual countries.

Preparation of RW for safe storage, transport and final disposal involves waste characterisation, treatment, conditioning and packaging in accordance with regulatory requirements and facility-specific waste acceptance criteria (WAC). These criteria ensure that the waste form and package meet the safety requirements of the intended storage, transport or disposal facility. The system envisages various processing activities, including immobilisation, which converts radioactive waste into a stable waste form by solidification, embedding or encapsulation [66]. WAC schematically shown in Figure 7 are quantitative or qualitative criteria, approved by the regulator, for a waste to be accepted by the operator of a processing, storage or disposal facility [67–69].

TABLE 3 | NSDF in operation in China.

Site	North-west (Gansu)	Beilong (Guangdong)	Feifengshan (Sichuan)
Volume, m ³	22422.47	2526.44	19767.92
Radioactivity (TBq)	638	7950	1310

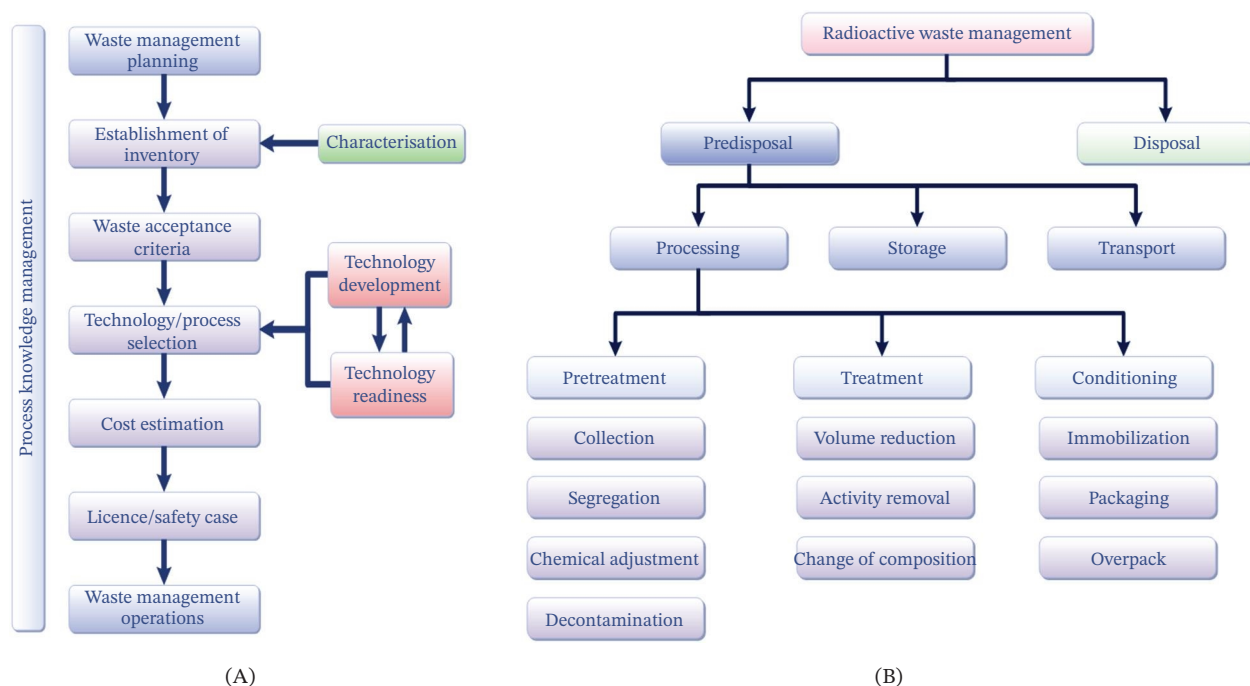


FIGURE 5 | Schematic of RWM including administrative (A) and operational (B) activities.

Before disposal, the RW is first transformed into a passive safe state, which is typically achieved via immobilisation using durable waste forms (matrix materials with radionuclides confined in its structure). The engineered barrier system (EBS) is a key component of the multiple-barrier concept used in a NSDF. Together with the waste form, waste package and natural site barriers, the EBS limits water infiltration, contains radionuclides and reduces their migration, thereby protecting people and the environment from radiological impacts. In a GDF, the EBS is designed to provide long-term containment of HLW and to delay

radionuclide release while many short-lived radionuclides decay. Over geological timescales, repository safety is achieved through the combined performance of the engineered barriers and the natural barrier system (NBS), with the host geology providing long-term isolation and limiting radionuclide migration. In line with the graded approach used within NWM, there is a distinct correlation between the durability and EBS materials (Figure 8) [24].

Figure 9 demonstrates the concept of NBS and EBS in the Chinese GDF in Beishan [40, 41].

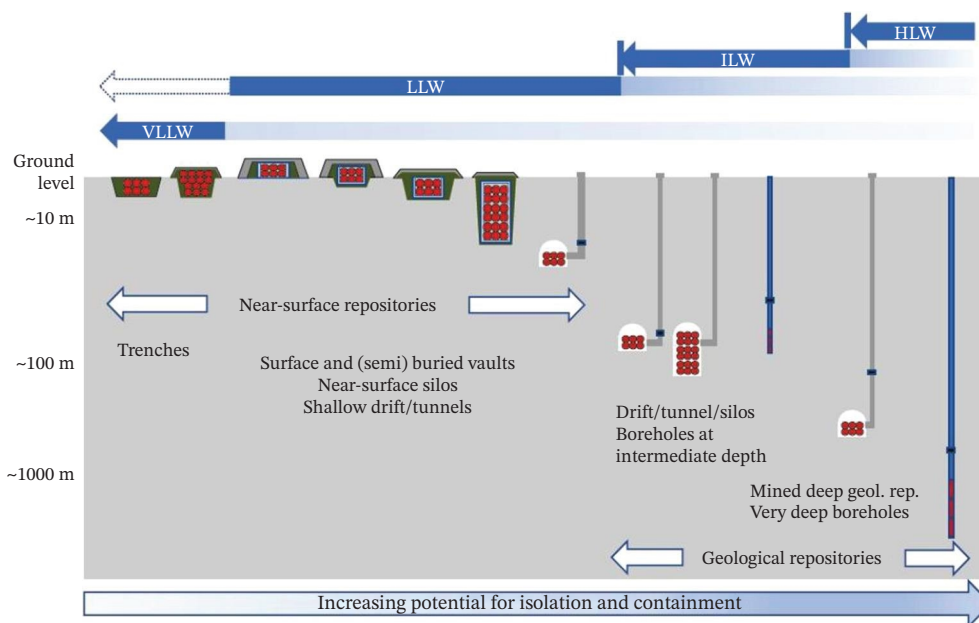


FIGURE 6 | Graded approach in the RW disposal usually assigns a deeper disposal to more hazardous waste, which is formally described in terms of a classification scheme reproduced from [61] with copyright permission by IAEA.

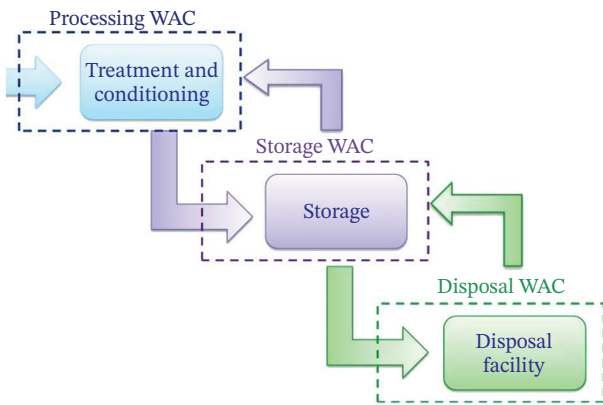


FIGURE 7 | Schematic of waste acceptance criteria (WAC) which are the links between RWM operators.

6 | Disposal Experience

Disposal facilities accept only the RW packages conforming with WAC that are compliant with the operational and postclosure safety cases, which are always site- and facility-specific. WAC generally requires that the waste is solid, characterised by stable chemical and physical properties, and as compatible with the engineered and natural barriers [52, 53] as is possible. The WAC usually specifies radionuclides and radioactivity limits, waste forms or encapsulation requirements, and waste container properties. Disposal facilities are kept under institutional control for certain periods of time, which aims to provide for public safety and protection of the environment, as well as security from any intrusion, including both accidental and deliberate scenarios [30, 52, 53, 61, 70]. Following the institutional control period ranging from several decades to longer, disposal facilities are closed and are designed to achieve passive long-term safety without reliance on continued human intervention. Postclosure safety assessments demonstrate that radionuclide releases and migration to the biosphere are either prevented or reduced to levels that result in negligible radiological impacts on humans

and the environment and comply with regulatory requirements [71, 72].

RW disposal is aimed at maximum retention capacities of facilities [51, 52] with disposal practices worldwide accounting for many decades of successful operation. Operating disposal facilities include VLLW trenches as simplest type NSDF in France, Spain and Sweden; LLW trench-type NSDF in arid areas of Argentina, India, Iran, South Africa and the United States; LLW engineered NSDF in China, the Czech Republic, France, India, Japan, the Russian Federation, Slovakia, Spain, the UK, Ukraine and the United States; subsurface low- and intermediate-level waste (LILW) NSDF in Sweden and Finland; LLW borehole-type disposal facilities in the United States; and LILW GDF in Germany and the United States [24, 73]. Table 4, modified after [17, 61, 78–80], shows several examples of RW streams and disposal facilities of different types in different countries.

The recent publication of World Nuclear News [81] has summarised the progress of GDF implementations as follows: In Canada, the Wabigoon Lake Ojibway Nation and the Township of Ignace were selected in November 2024 as the host communities for the proposed GDF, with precicensing activities, including stakeholder engagement, pre-environmental assessment and technical reviews taking place. Finland is currently in the process of commissioning the Onkalo GDF in crystalline rock with SNF kept in copper canisters surrounded by a bentonite buffer to be disposed of at a depth of 400–430 m. France plans to construct the GDF at Centre Industriel de Stockage Géologique (Cigéo) in the form of an underground system of disposal tunnels—in a natural layer of clay near Bure, to the east of Paris in the Meuse/Haute Marne area aiming to dispose of 10,000 m³ of vitrified HLW and 75,000 m³ of ILW. The first operation of the pilot phase of GDF is expected in 2035. Sweden has selected the GDF site at Forsmark, where surface works are currently underway. The GDF is in crystalline rock at a depth of 500 m with copper canisters containing SNF, each surrounded by bentonite clay. In Switzerland, the national RW disposal cooperative Nagra applied to the Swiss Federal Office of Energy for a general permit for the construction of the GDF (Figure 10) at Nördlich Lägeren

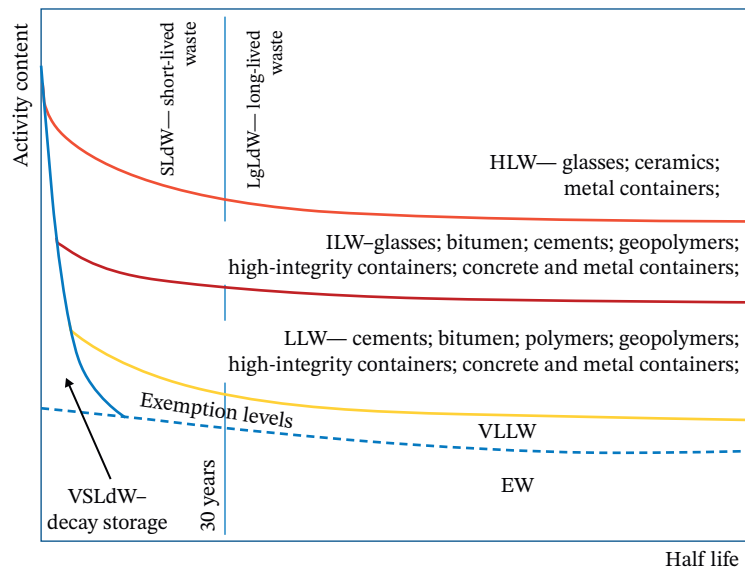


FIGURE 8 | Typical waste form and container materials used for RW conditioning.

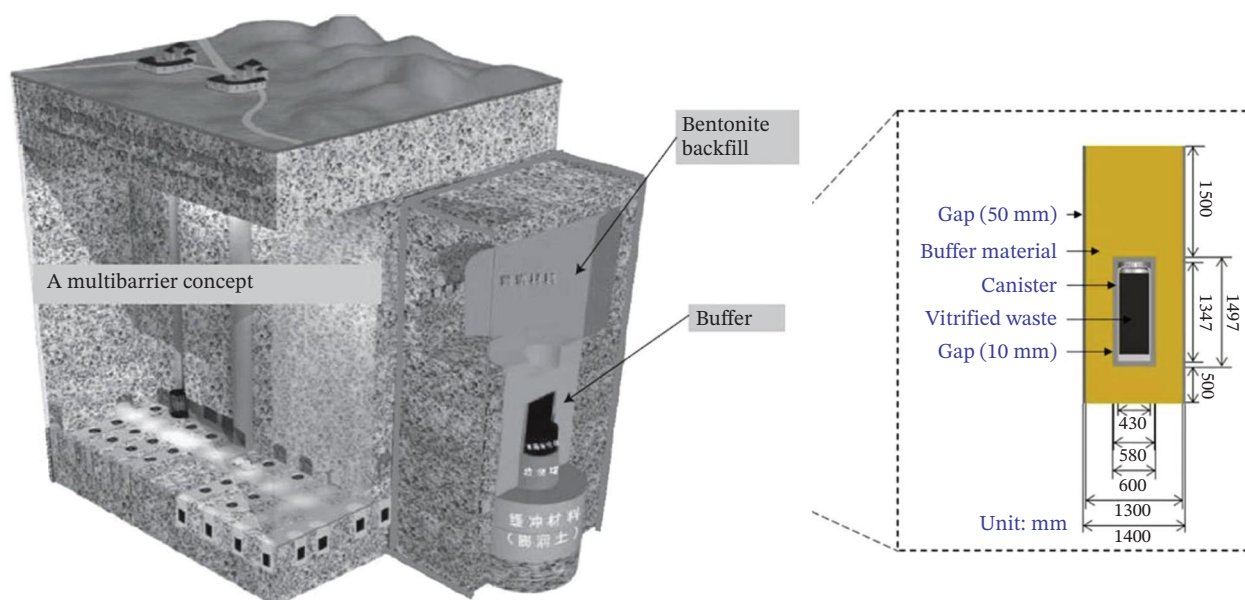


FIGURE 9 | Schematic of NBS and EBS of the disposal concept in China.

with an SNF encapsulation plant at the existing Zwilag interim storage facility in Würenlingen.

In China, the Beishan Underground Laboratory is about to complete construction in 2026, which will facilitate a variety of on-site experiments, ranging from geological to chemical phases, to better evaluate the safety and reliability of the selected site for HLW disposal. Xinchang site in the Beishan area is currently an Underground Research Laboratory, and there is no final decision yet on whether it will become the country's GDF. The final GDF is expected to be built up in 2050. In addition, the utilisation of clay rocks for HLW disposal is also under investigation [82].

According to current planning, the GDF of Switzerland could come into operation in 2050. In the United States, Yucca Mountain has since 1987 been nominated as the sole initial repository for disposal of the country's SNF and HLW. The DOE

submitted a construction licence application to the Nuclear Regulatory Commission in 2008, but the Obama Administration subsequently decided to abort the project, and there have been various twists and turns since then, with the upshot that it has not been built.

The RW disposal has already been practised for almost 8 decades, demonstrating a high degree of operational safety and environmental protection [83].

7 | Current Trends

As shown in Table 4, the GDFs in most national approaches to deep disposal of HLW and SNF are mined-type facilities located in stable geological formations of granitic, salt or clay type at a depth of several hundred metres. The RW packages in the mined GDFs are emplaced in either vertical or horizontal wells

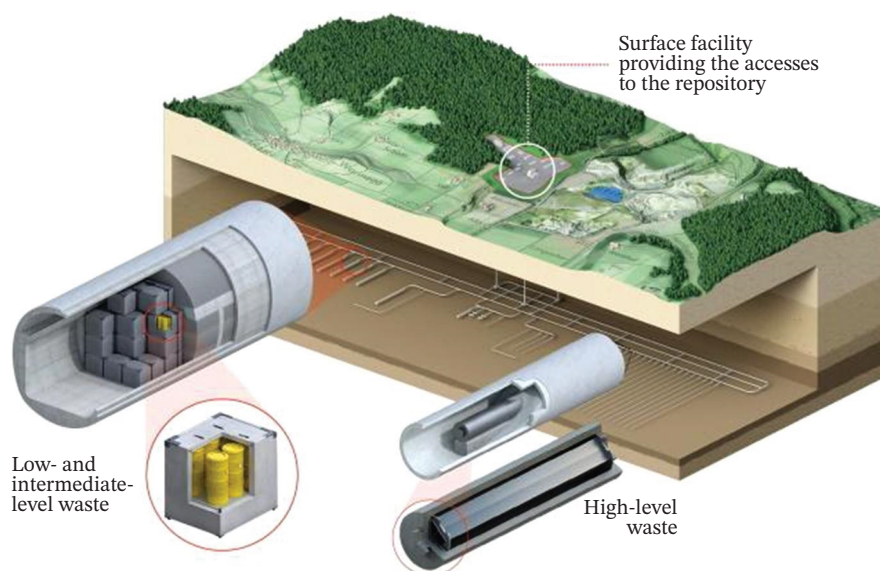


FIGURE 10 | The concept of the GDF in Switzerland, open access reference [81].

TABLE 4 | Disposal facilities used and planned for use.

Type of facility	Name	Type of RW	Country
NSDF, trench	CIRES, Morvilliers	VLLW	France
NSDF, trench	El Cabril	VLLW	Spain
NSDF, engineered	CSA, De l'Aube	Short-lived LILW	France
NSDF, engineered	CSM, La Hague	Short-lived LILW	France
NSDF, engineered	Dukovany	LLW from NPPs	Czechia
NSDF, engineered	National Radioactive Waste Repository, Mochovce	Solid and solidified low-activity waste from the operation and decommissioning of NPPs, research institutes, laboratories and hospitals	Slovakia
NSDF, engineered	El Cabril Disposal Facility	LLW and ILW from hospitals, research centres, industries and NPPs	Spain
NSDF, engineered	Low-level waste repository, Drigg, Cumbria	LLW from nuclear industry, Ministry of Defence, non-nuclear industries, educational, medical and research establishments	UK
Former limestone mine, access via horizontal drifts	Richard repository, Litoměřice	Institutional waste from healthcare, industrial, agricultural and research sectors	Czechia
Former uranium mine, access via horizontal drifts	National Repository for LILW—Baița-Bihor	LILW	Romania
Intermediate depth, tunnels	Loviisa VLJ repository	LILW generated at the Loviisa NPP	Finland
Intermediate depth, tunnels	Bataapati	LILW generated at the Paks NPP	Hungary
Intermediate depth, silos	Olkiluoto VLJ repository	LILW generated in state-run industry, medical care and research; in the future also waste from the Olkiluoto NPP	Finland
Intermediate depth, vaults and silos	SFR Forsmark	LILW from the operations of Swedish NPPs but also from hospitals, veterinary medicine, research and industry	Sweden
Intermediate depth, boreholes	Planned	Disused sealed radioactive sources (DSRSs)	Brazil, Ghana, Malaysia, Philippines
GDF, mined	Xinchang site in the Beishan area. Currently an Underground Research Laboratory.	HLW, SNF	China
GDF, mined	Asse II (salt formation, abandoned salt mine). Disqualified from becoming a permanent geological disposal facility with RW intended for retrieval.	Waste with negligible heat generation	Germany
GDF, mined	ERAM (Morsleben) (salt formation, former salt mine, to be closed)	Waste with negligible heat generation	Germany
GDF, mined	Konrad (former iron mine)	Waste with negligible heat generation	Germany
GDF, mined	Onkalo SNF repository (granite formation)	SNF	Finland

(Continues)

TABLE 4 | (Continued)

Type of facility	Name	Type of RW	Country
GDF, mined	Cigéo, Bure site (clay formation)	HLW, SNF, Long-lived ILW	France
GDF, mined	Yeniseiskiy site in the Krasnoyarsk Krai (granite formation)	HLW, SNF	Russia
GDF, mined	Forsmark disposal facility (granite formation)	SNF	Sweden
GDF, mined	Nördlich Läger (clay formation)	HLW, SNF	Switzerland
GDF, mined	Waste Isolation Pilot Plant (salt formation, WIPP, Carlsbad, New Mexico)	Transuranic nuclear waste	US
GDF, mined	Yucca Mountain (tuff formation) is a research facility, not confirmed as a repository	HLW, SNF	US
GDF, deep boreholes	Concept is one of several other geological disposal concepts being evaluated [15, 74–77]	HLW, SNF, DSRS	Australia, Denmark, Finland, Germany, Indonesia, Malaysia, Netherlands, Norway, Russia, Slovenia, Ukraine, UK, US

(sumps, tunnels) typically 10–100 m long at the bottom of horizontal galleries [84, 85]. An alternative disposal concept is based on borehole-type disposal facilities in which RW packages are disposed of into the lower parts of deep (up to several kilometres) boreholes [15, 17, 86–90]. The RW packages in this case are directly emplaced into the disposal boreholes (deep wells) via their near-surface borehole reception sections and then transported through the borehole to their final location deeply underground. The deep borehole disposal considers disposal in stable geologic formations at depths ranging from several hundred metres as in the case of a mined GDF to depths of several kilometres, virtually inaccessible for mined repositories because of prohibitive costs. It needs to be noted that some national regulations may consider retrievability of RW packages as a part of the disposal stage of RWM for one or another reason, e.g., in the event of an incident or emergency [91]. The retrieval of packages from a borehole was usually considered a more difficult operation compared with mined disposal facilities [92], which was among obstacles for wider implementation of borehole disposal projects, which are mainly used to dispose of disused sealed radioactive sources [34, 93]. Dedicated tools (so-called ‘fishing tools’) are nowadays available aiming to retrieve defective components of drilling equipment from boreholes within oil and gas industries [94], which can readily solve the retrievability problem for borehole disposal facilities if needed during the operational phase [95]. Moreover, in the postclosure phase, retrieval of waste packages from a deep borehole may be more straightforward than from a mined repository. Hence, deep boreholes become realistic and much more effective alternatives to mined repositories [89, 96]. They provide a more effective and reliable isolation of RW from the biosphere mainly due to the following reasons [97, 98]:

- i. Much deeper location reaching up to 5 km
- ii. Lower construction costs
- iii. Lower operational costs
- iv. Lesser requirements for infrastructure
- v. Small surface footprint
- vi. Decentralised modular composition
- vii. Shorter time for construction, loading and sealing
- viii. Viable option to be in close proximity to the sites of RW generation
- ix. Insignificant probability of unauthorised access to waste

The IAEA launched in 2023 dedicated coordinated research project T22003 (CRP-2406) aiming to support the deep borehole disposal of RW globally [77]. The IAEA noted that mined GDFs may not be the most cost-effective solution for some inventories of ILW and HLW, which, according to the IAEA classification [20], include SNF that is not intended for reprocessing and has been declared as waste. This can be the case for small inventories in countries, which could benefit from alternative disposal options—options that provide for the same protection levels, while potentially having lower associated programme costs and an earlier implementation [77]. The borehole disposal option is a very safe and cost-effective solution (Figure 11A) enabling utilisation of both vertical and horizontal locations within stable geological formations (Figure 11B) [15, 78, 96].

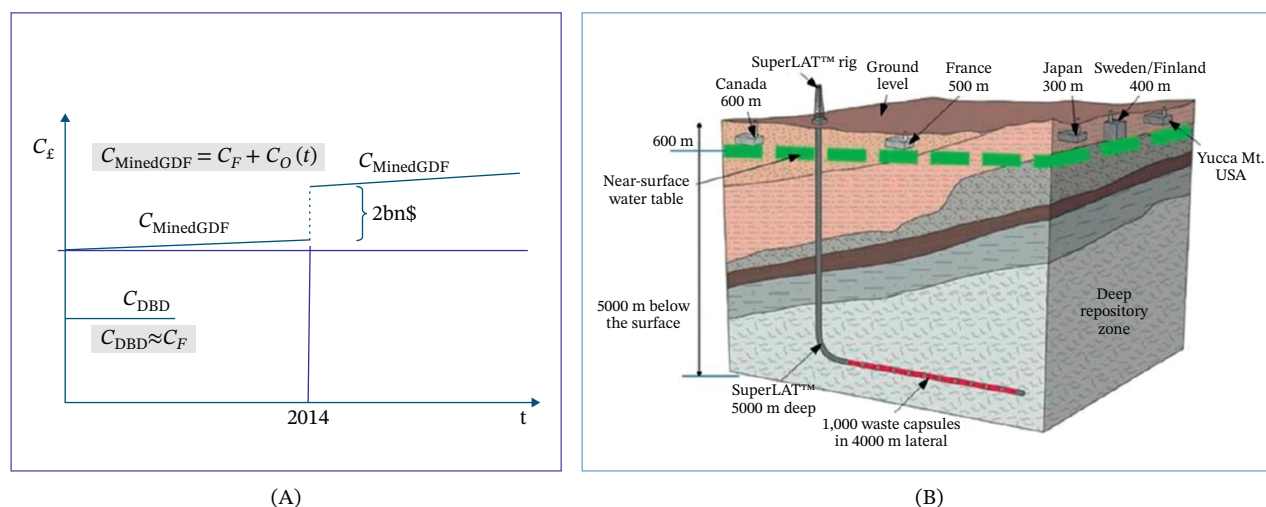


FIGURE 11 | Borehole geological disposal option versus mined GDFs. (A) Disposal cost comparison (C_f) accounting for an accident within the mined disposal option which, e.g., occurred in 2014 [99], where $C_{MinedGDF}$ is the cost of mined option consisting of sum of construction cost C_F and operational part $C_O(t)$, and C_{DBD} is the cost of deep borehole disposal option, and t is time; (B) horizontal borehole option compared to mined repositories [92].

Advantages provided by the borehole disposal for both vertical and horizontal options are basically due to the nuclear waste package placement technology straight into the boreholes—tunnels (wells) via near-surface reception sections of GDFs. Mined GDFs utilise instead accessing the disposal wells after transportation of nuclear waste packages into the disposal section of the repository located deeply underground in large-sized galleries. This requires significant infrastructure deep underground, which results in high maintenance costs and actual or potential upgrading expenditures, as shown schematically in Figure 11A based on the operational history of the Waste Isolation Pilot Plant repository in the United States [94].

8 | Conclusions

RW disposal is the final step—end point—of nuclear waste management, aiming to permanently place the RW in a dedicated disposal facility.

The multibarrier approach to the disposal of nuclear waste envisages utilisation within disposal facilities, a combination of both natural geological barrier and engineered barrier subsystems that effectively confine radionuclides and ensure an adequate level of protection for people and the environment.

The global track record of RW disposal demonstrates a significant disparity between shallow operations and deep geological repository (DGR) deployment. Extensive, mature experience exists regarding LILW repositories. For decades, dozens of shallow and intermediate-depth facilities worldwide have operated safely, showcasing excellent engineering performance with minimal, tightly controlled environmental impacts.

In contrast, actual operational experience with DGRs for higher activity waste remains highly constrained. Globally, operational DGR history is limited to just two major facilities built in salt formations: WIPP (USA) for transuranic waste and Morsleben (Germany) for ILW.

Furthermore, there are no long-term operational data for the permanent disposal of highly radioactive SNF. The world's first dedicated crystalline-rock SNF repository, the Onkalo facility in Finland, is almost ready for operation. Until Onkalo and subsequent international repositories compile decades of field data, assessments of long-term DGR postclosure performance must continue to rely on predictive computer modelling, accelerated laboratory testing and geological analogues.

Author Contributions

Conceptualisation: Michael I. Ojovan; methodology: Michael I. Ojovan and Kai Xu; validation: Michael I. Ojovan, Kai Xu and Shengheng Tan; formal analysis: Michael I. Ojovan, Kai Xu and Shengheng Tan; investigation: Michael I. Ojovan, Kai Xu and Shengheng Tan; resources: Kai Xu and Shengheng Tan; writing—original draft preparation: Michael I. Ojovan, Kai Xu and Shengheng Tan; writing—review and editing: Michael I. Ojovan, Kai Xu and Shengheng Tan; supervision: Michael I. Ojovan; project administration: Kai Xu.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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