Chapter 8
Recent Evaluation of Early Radioactive Disposal Practice

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Contents

Abstract Developing safe radioactive waste disposal practice is a crucial issue worldwide due to the large amounts of generated wastes of wide chemical, physical, and radiological characteristics that accompany research and application of nuclear

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sciences and technology in different fields. This work aims to identify learned lessons from early radioactive disposal practice and how these lessons improved the design of disposal facilities. Within this context, early approaches toward safe disposal of radioactive wastes will be summarized. The principals of these approaches and its applications with a special reference to major events in its evolution will be presented. Old regulations and methods for regulating these practices will be addressed, and recent evaluation of these approaches will be given by emphasizing the need for corrective action procedures.

Keywords Radioactive waste disposal • Near surface • Cavities • Marine disposal • Assessment studies

1 Introduction

Throughout the twentieth century, a variety of nuclear activities have been carried out around the world. Initially these activities focused on research to understand radioactivity and the nature of the atom. In the Second World War, activities directed at nuclear weapon production were initiated in Germany, the Soviet Union, the UK, and especially in the USA, where it was known as the Manhattan Project [1]. These activities resulted in a massive increase in the amount of radioactive wastes produced compared to pre-war activities. Following the war, the focus of nuclear activities expanded further to include a large and progressively increasing set of peaceful uses, including nuclear energy and the use of radioactive materials in industry, medicine, and research.

These wide varieties of activities were associated with the generation of radioactive wastes of different chemical, physical, and radiological characteristics which need to be managed in different ways to assure safety of workers, the public, and the environment. Some of these characteristics, which affect the handling requirements, include concentrations and half-lives of radionuclides in the waste, external dose rates, heat generation from decay, and volumes of material to be managed. Many countries have developed national approaches for identifying appropriate management practice for various classes of waste as defined in their national regulations. The International Atomic Energy Agency (IAEA) has issued consolidated guidance on waste classification that represents good practices from national approaches, the most recent of which was issued in 2009 [2]. Within this classification scheme, the wastes are divided into six classes based on their activity and half-life; Fig. 8.1 presented these classes.

In 2007, a study estimated the global inventory of the generated radioactive wastes; it concluded that the estimated volume of the accumulated wastes is 1.9×10^9 m^3 [3]. Figure 8.2a shows that the majority of the volume of these wastes is mostly generated from mining and milling uranium, whereas the majority of the generated activity is associated with spent nuclear fuel (Fig. 8.2b). These estimates

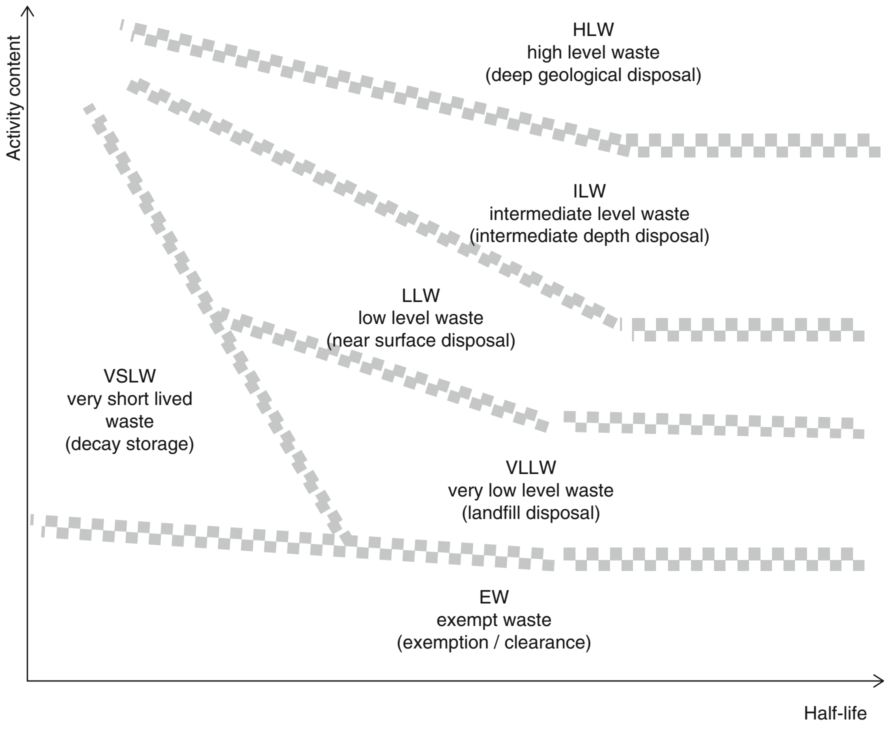


Fig. 8.1 IAEA waste classification scheme (Source: IAEA [2])

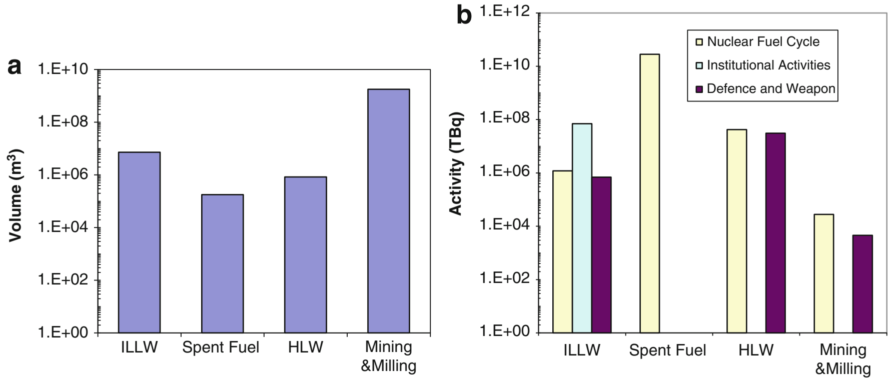


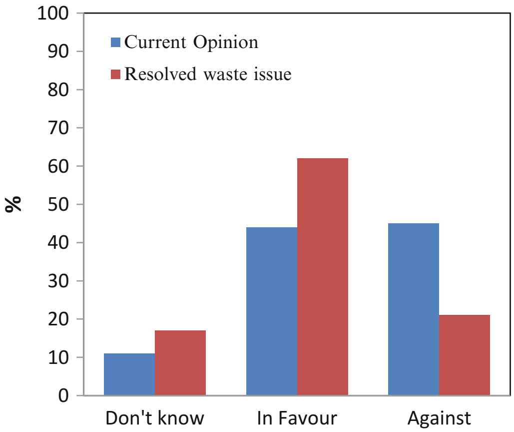
Fig. 8.2 Estimated volumes and activities of radioactive wastes (Derived from [5])

were derived based on the following assumptions: relatively minor amounts of the spent fuel generated by nuclear power plants have been reprocessed, and most of these reprocessed wastes were vitrified, while most of the high-level wastes generated from defense programs were stored as liquid. From that study, it is clearly shown that the estimated volumes and activities of radioactive wastes represent a great challenge for the future of the nuclear industry. This fact was also noted from the examination of the results of the European commission perception on nuclear safety. This perception showed that lack of security to protect nuclear power plant against terrorist attacks and the disposal and management of radioactive waste remain the major threats associated with nuclear energy [4]. Also, it was found that European citizens would like to know more about radioactive waste management and environmental monitoring procedures; and they believe it would be useful to have European legislation regulating nuclear waste management within the European Union and their national territory. That study indicated that if the radioactive waste issues were resolved, the percentage of the public in favor of the nuclear industry will increase with a decrease in the people against this industry (as could be seen from Fig. 8.3).

During early days of the nuclear era, the efforts were focused on the development of nuclear reactor technologies. Long-term management of the associated radioactive waste was not considered a significant problem. Instead, most waste management activities focused their attention on assuring worker safety, with long-term isolation provided either by storage, intended to isolate the wastes, or by disposal methods that were reliant on dilution in the environment to achieve safety. Early disposal practices included the following disposal options for management of radioactive wastes: marine disposal, near-surface disposal, and underground disposal as illustrated in Fig. 8.4.

This work is focused on summarizing early approaches toward the safe disposal of radioactive wastes. Within this context, the principals of early disposal approaches and its applications with a special reference to major events in the evolution of each approach will be summarized. Old regulations and methods for regulating these practices will be addressed, and recent evaluation of these approaches will be given by emphasizing the need for corrective action procedures. Then, concluded summary of the learned lessons will be briefly presented.

Fig. 8.3 Results of public perception on the future of the nuclear industry (Derived from [6])



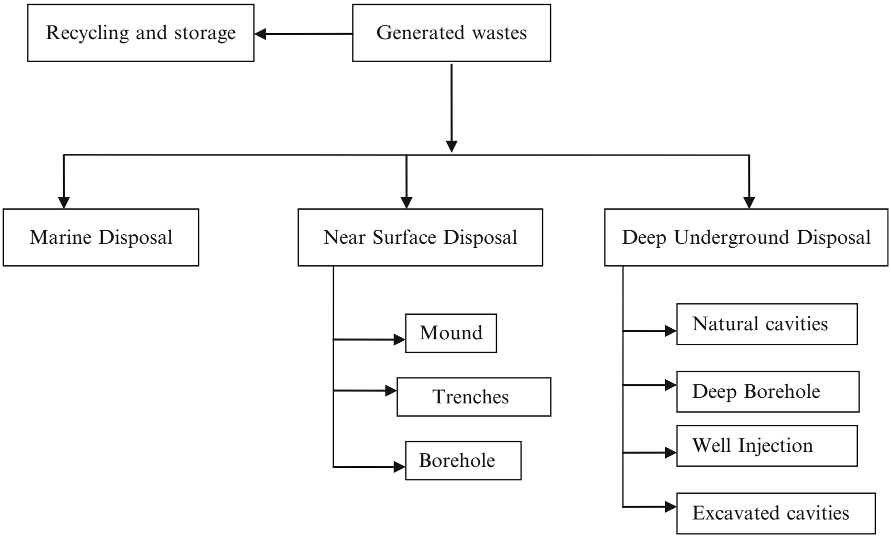


Fig. 8.4 Early disposal options

2 Marine Disposal

Seas have been used to dispose the wastes from human activities. A number of countries used the sea for disposal in the early days of radioactive waste management, in the belief that the sea would rapidly dilute the waste to innocuous levels. The first marine disposal operation took place in 1946 in the USA, about 80 km off the coast of California [5]. The last known dumping operation was in 1993, at the Sea of Japan [6]. Between these two dates, 14 countries have used more than 80 sites to dispose radioactive waste coming from research, medicine, and nuclear industry activities. Three types of radioactive waste were disposed of at seabed, namely, liquid waste, solid waste, and nuclear reactor pressure vessels, with and without fuel. Liquid wastes were disposed either as unpackaged and diluted in surface waters or as contained, but unconditioned, to sea bottom at designated sites. For solid radioactive wastes, two subcategories were disposed at sea; the first is low-level wastes, i.e., paper and textiles from decontamination processes, resins and filters, etc. This subcategory was solidified in cement or bitumen and packaged in metal containers then disposed. The second subcategory included unpackaged large parts of nuclear installations such as steam generators, main circuit pumps, lids of reactor pressure vessels, etc. Finally, reactor vessels containing damaged spent nuclear fuel and reactor vessels without nuclear fuel were disposed at seas. These pressure vessels were usually filled with a polymer-based solidification agent (furfural) to provide an additional protective barrier. In most cases reactor pressure vessels with damaged fuel were further contained in a reactor compartment [6].

The dumping operations were performed under the control of national authorities, and radiological surveys of the sites were carried out from time to time. Samples of seawater, sediments, and deep-sea organisms collected from various disposal sites in the Pacific and North West Atlantic Ocean have rarely shown increase in radionuclide levels above background. However, on several occasions, cesium and plutonium were detected at higher levels in samples taken close to packages at the dumping site [7]. The observed concentrations were considered consistent with safety objectives for marine disposal, but led to increased questions and concerns about the potential dispersion of radionuclides leading to damage to marine resources. This concern had been raised in particular by countries without nuclear energy, which were concerned by the inequity of sea disposal: they could receive the detriment of potentially contaminated seas without receiving the benefits of the nuclear energy. These concerns led to a consensus in 1958, expressed in Article 48 of the Law of the Sea: "every State shall take measures to prevent pollution of the seas from the dumping of radioactive waste, taking into account any standard and regulation which may be formulated by the competent international organizations" [7]. In the 1960s, commercial interest in ocean disposal in USA began to decline and had ended completely by 1970. One of the principal reasons for the decline beside public concern about marine pollution was economics. Ocean disposal was reported to cost $48.75 per 55-gal (200 L) drum compared to $5.15 per drum for burial on land [7]. Table 8.1 illustrates the chronological sequence of major events that lead to the complete ending of sea disposal in 1994 [6, 8].

IAEA has developed an inventory database for the radioactive material disposed in marine environment [6]. This database considers five practices leading to potential dispersion of radionuclides in the sea: seabed and deep seabed disposal, accidents and losses at sea involving radioactive materials, controlled coastal discharges of low-level radioactive liquid effluents, releases from nuclear weapon testing, and accidental releases from land-based nuclear installations [6]. Figure 8.5a-c represents the total activity of radioactive wastes disposed in the oceans and country contribution of these activities, whereas the used method to assess doses is illustrated in Fig. 8.5d [6–11]. Table 8.2 shows the waste types that were disposed in the ocean.

Table 8.1 Chronological sequence of major marine disposal events

Year	Event
1946	First sea dumping operation
1958	First United Nations Conference on the Law of Sea (UNCLOS I)
1972	Adoption of the convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter
1985	Resolution calling of a voluntary moratorium on radioactive waste dumping
1993	Resolution on Sea Disposal of Radioactive wastes and other radioactive matter
1994	Total prohibition on radioactive waste disposal at sea came into force

2.1 Early Assessment of Old Practice

The London Convention (LC) prohibited disposal of high-level radioactive wastes in seas and establishes IAEA responsibility to identify which wastes will be prohibited from being dumped. Based on Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP), a modeling methodology was proposed to assess the radiological impact of marine disposal practices [12]. This methodology divides the disposal system into two subsystems, namely, near field (the region in the vicinity of the release, where the concentration is significantly greater than the ocean average) and far field (the rest of the ocean). The source includes the waste form and the package, which consist of the canister and lining. The main processes that lead to the release were identified to include canister corrosion, degradation of the lining and cap, and finally release of radionuclides from the waste form. The potential media of importance were identified as bottom sediment, benthic boundary layer, and open oceans. Table 8.3 lists some recommended models to assess the performance of the marine disposal [12]. The GESAMP methodology led to the recommended constraints on marine disposal shown in Table 8.4.

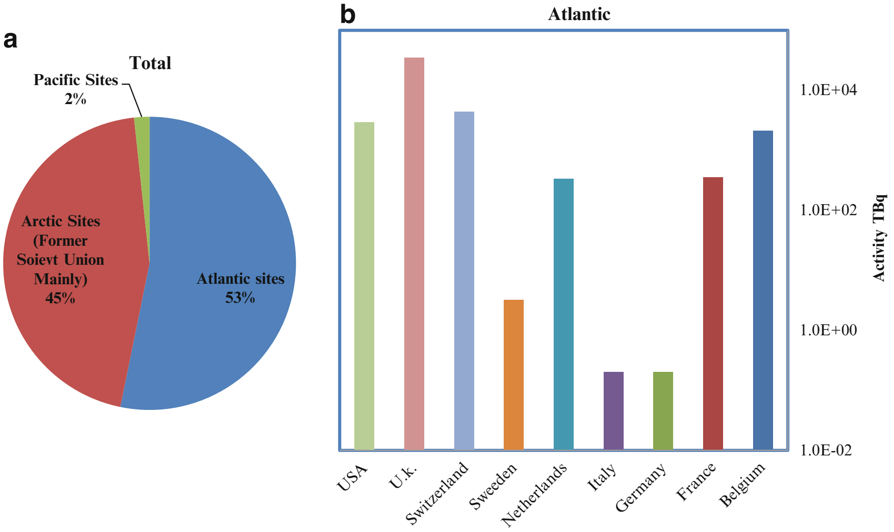


Fig. 8.5 (**a**) percentage distribution of the radioactive wastes disposed in marine sites, (**b**) activity distribution of the disposed wastes in the Atlantic sites, and (**c**) activity of radioactive wastes dumped in Pacific sites, (**d**) Source–pathway–receptor analysis for marine disposal option

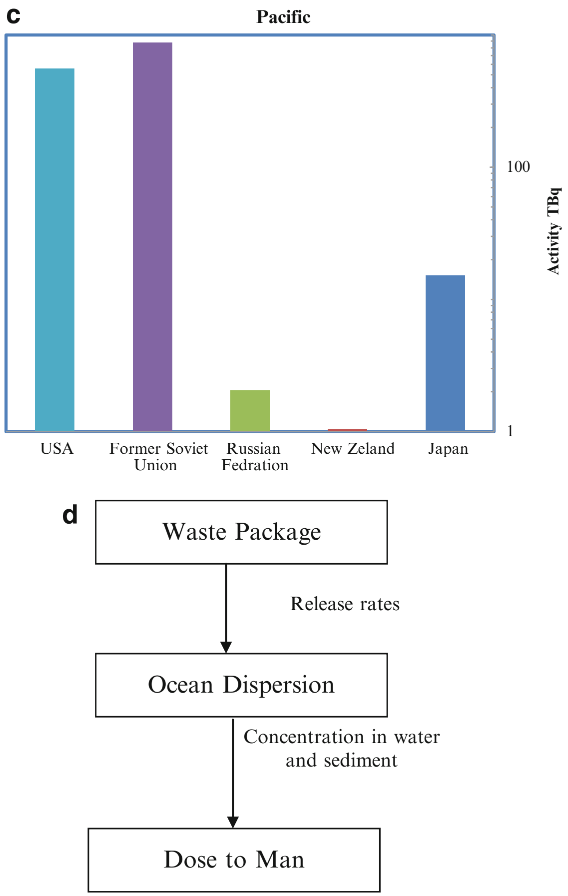


Fig. 8.5 (continued)

Table 8.2 Activity of the dumped wastes in marine disposal (TBq)

Waste type	Atlantic	Pacific	Arctic	% Activity
Reactor with spent fuel	–	–	36,867	43.34
Reactor without spent fuel	1221	166	143	1.80
Low-level solid wastes	44,042.5	820.9	585.4	53.42
Low-level liquid wastes	<0.001	458.5	764.7	1.44
Total	45,263.5	1445.4	38,369.1	

Table 8.3 Recommended GESAMP models to assess the radiological impact of marine disposal

Near field	Far field
Simple finite ocean diffusion model	Contaminant with a long residence time is modeled using well-mixed box
Modified version of the model to account for source size and scavenging	One-dimensional scavenging model
Plume solution if the size of near field exceeds the scale within which diffusion dominates	Simple three-dimensional diffusive model with scavenging
	Medium resolution box model
	Two- and three-dimensional finite difference models

Table 8.4 Summary of the GESAMP-derived limits

Near field	Far field
Dose limits	1 millisievert per year[a]
Dumping period	1000 year[b]
Concentration limit	The concentration limits and limit on mass-dumping rate were set as a cap on the total amount of activity that could ever be dumped per year in a single ocean basin. The mass-dumping rate of 108 kg/year
Dumping mass	1000 tons[c]
Source upper bound	No specific value for a dose upper bound was selected

[a] This limit was consistent with the International Commission on Radiological Protection (ICRP) recommendation at that time

[b] Consistent with the time periods over which the use of nuclear power may be used

[c] Derived based on the average mass dumped in 1978

2.2 Recent Environmental Assessment of Historical Marine Disposal

A number of studies were conducted to estimate the consequences of old disposal practice in oceans. These studies were conducted on international, regional, and national scales. This section will summarize these efforts and their most important findings.

A coordinated research project was initiated within the International Atomic Energy Agency (IAEA). This program was conducted to estimate the average concentration of some radionuclides in surface waters of the Pacific and Indian Oceans [13]. The assessment was conducted by dividing the oceans into 17 regions, which were chosen according to ocean circulation, global fallout patterns, and the location of nuclear weapon test sites. Present levels and time trends in radionuclide concentrations in surface water for each region were studied, and the corresponding "effective half-lives" were estimated. These effective half-lives include both the radiological half-life and the rate of removal of radionuclides by natural transport

Table 8.5 Surface water concentration and effective half-life in the Indian and Pacific Oceans

Element	^{90}Sr	^{137}Cs	$^{293, 240}$Pu
Surface water (μBq/L)	100-150	100-280	0.1-5.2
Effective half-life			
North Pacific (year)	12 ± 1		7 ± 1
South Pacific (year)	20 ± 1		12 ± 4
Equatorial Pacific (year)	21 ± 2		10 ± 2
Indian	N.A.	21 ± 2 years	9 ± 1

Source: Povinec et al. [13]

and chemical processes. The estimated surface water concentrations of ^{90}Sr, ^{137}Cs, and ^{239,240}Pu in latitudinal belts of the Pacific and Indian Oceans for the year 2000 were suggested to be used as baseline levels, against which any new contribution from nuclear facilities, nuclear weapon tests, radioactive waste dumping, or possible nuclear accidents can be evaluated. Table 8.5 lists the average values of the surface water concentration and the effective half-life for these radionuclides in the studied oceans.

2.2.1 Arctic Ocean

The joint Russian–Norwegian expeditions, in 1992–1994, visited four principal radioactive waste dumping sites in Kara Sea in the Arctic. Seawater, sediment, and biota samples were collected for activity analysis. The results of these expeditions showed that the influence of the dumped radioactive waste on the general levels of radioactive contamination in Kara Sea was insignificant [14], but the sediment samples taken in the immediate vicinity of waste containers showed elevated levels of Co, Sr, Cs, and Pu. In 2012, other joint expeditions lunched to update the investigations at nuclear submarine K-27 and solid radioactive waste dumps. In- and ex-radiological measurements revealed that no leak indication in the vicinity of the reactor unit K-27 and the activity concentration in seawater, sediment, and biota are lower than those reported in 1990s. The study concluded that despite the current environmental levels of radioactivity are not of concern, there should be continuous monitoring for the sites [15]. The former Soviet Union also disposed of radioactive waste in the Far Eastern Seas, although, unlike in the Arctic, no reactors containing fuel were dumped there. The joint Japanese–Korean–Russian expeditions carried out during 1994 and 1995 took samples of seawater, seabed sediments, and biota from dump sites and from reference sites. The results show that the concentrations of ^{90}Sr, ^{137}Cs, and ^{238,239,240}Pu in the Far Eastern Seas were low and were predominantly due to global fallout [16–19].

The Arctic Nuclear Waste Assessment Program was implemented at the end of the last century. This program aimed to assess the impact of the disposed nuclear waste in the Arctic Ocean. Within this project, the major sources of nuclear contamination to the Arctic were identified. These sources include global fallout

Main Arctic process

1) Ice uptake & movement of radionuclides and sediment;
    - Density-driven currents on Arctic shelves;
    - Sediment dynamics in the Kara Sea;
    - Interactions between colloids and radionuclides in the Arctic river systems;
    - Corrosion and impairment of disposal barrier materials:
2) Identification of sentinel organisms for the monitoring and evaluation of Arctic radionuclide contamination;
3) Radionuclide levels, bio-concentration factors, and food chain interaction in Arctic animals;
4) Deposition of radionuclides due to interactions with phytoplankton; and
5) Sublethal biological effects from radionuclide contamination

The ANWAP risk assessment addressed the following Russian wastes, media, and receptors:

- Dumped nuclear submarines and icebreaker in Kara Sea: marine pathways;
- Solid reactor parts in Sea of Japan and Pacific Ocean: marine pathways;
- Thermoelectric generator in Sea of Okhotsk: marine pathways;
- Current known aqueous wastes in Mayak reservoirs and Asanov Marshes: riverline to marine pathways; and
- Alaska as receptor

For these wastes and source terms addressed, other pathways, such as atmospheric transport, could be considered under future-funded research efforts for impacts to Alaska. The ANWAP risk assessment did not address the following wastes, media, and receptors:

- Radioactive sources in Alaska (except to add perspective for Russian source terms);
- Radioactive wastes associated with Russian naval military operations and decommissioning;
- Russian production reactor and spent-fuel reprocessing facilities nonaqueous source terms;
- Atmospheric, terrestrial and nonaqueous pathways; and
- Dose calculations for any circumpolar locality other than Alaska

Fig. 8.6 Main processes and waste sources addressed in the Arctic sea project

arising from anthropogenic sources, ocean dumped or discharged wastes, and disposal and discharge in open fields, pits, landfills, wetlands, and reservoirs [20–23]. The program comprised 80 different research projects covering field surveys, laboratory experiments, modeling studies, and archival data analysis. The main processes and waste sources studied in the project are illustrated in Fig. 8.6. The results of the program are summarized as follows:

- Chernaya Bay on southwestern end of Novaya Zemlya was found to contain localized high-concentration zones [24–28].
- Russian rivers were not introducing radionuclides to the Arctic Ocean in any great quantity [29–31].
- Elevated concentration levels for Cs-137 were found near the mouth of the Yenisey River, but most of the radioactivity is trapped in bottom sediments of the lower river estuaries [32, 33].
- Ob and Yenisey watersheds were found to have considerable capacity to retain any releases with possible exception of radionuclides such as strontium-90 that are closely associated with the aqueous phase [34, 35].
- Discovering ^{137}Cs in sediment-laden sea ice close to Alaska in Chukchi Sea suggested that ice formation processes in Kara Sea have the potential to entrain Cs-rich fine-grained sediments and indicate that some contamination could be transported by ice into the Canadian Basin of the Arctic Ocean or initiate from Chernobyl or similar accidents [36, 37].

- Concerning waters closer to Alaska, anthropogenic radionuclide levels were not due to Soviet-era dumping of nuclear waste but due to atmospheric testing of nuclear weapons [38–40].

A risk assessment study was conducted to evaluate the risk to the biota and humans; in this study [23, 41], the source–pathway–receptor analysis was conducted through which potential sources of release and contributors were identified, the radionuclide transport and deposition were modeled, and the uptake into Arctic fishes and marine mammals was estimated. The assessment identified the sources of radionuclides to include former Soviet Union sources of Kara Sea and the Northwest Pacific and potential sources through river transport from Russian watersheds to the Arctic Ocean. Results of the risk assessment can be summarized as follows:

(a) The identified sources were compared to the already existing fallout levels of key radionuclides, wastes from the Chernobyl incident, releases from the European fuel-reprocessing facilities at Sellafield (UK) and La Hague (France), and naturally occurring radioactivity. Except for localized instances in the Kara Sea near dumped reactors and nuclear testing sites, the existing fallout levels and the Sellafield reprocessing source terms were found to dominate in the Arctic.

(b) Over 95 % of the potential human and ecological risks in Kara Sea, Northwest Pacific, and inland is from ^{137}Cs, ^{239}Pu, ^{241}Am, and ^{90}Sr.

(c) The primary potential risk from the submarine reactor cores in Kara Sea were found to arise from ^{137}Cs, and the primary potential risks from the land-based sources arise from ^{90}Sr.

(d) The estimated maximum total release of radionuclides under the worst-case scenario is summarized in Table 8.6.

Table 8.6 Results of the worst-case release scenario for the Arctic Ocean disposed wastes

Site	Scenario	Duration of max. release *(year)*	Max. total release (GBq/year)
Kara Sea	Breaching of containment occurs and all of the materials are released instantaneously	*At year* 2050	>1300
Sea of Japan Pacific Ocean East Coast of Kamchatka	Reactor solid objects are subject to direct corrosion, at a rate of 0.05 mm/year	After 1000 years	≈1 >0.01
Sea of Okhotsk	Radioisotopes in thermoelectric generator will decay before they are released and not be a source of concern		
West Siberian basin	Mayak reservoirs releasing radioactivity to near-surface groundwater		1,400,000 for only 1 year

(e) Dose from worst-case release scenarios was used to assess the potential for radiological effects to marine organisms, including potential detrimental effects on reproductive success in sensitive Alaskan marine species. The predicted concentrations of radionuclides from former Soviet sources are not expected to affect the survival of reproducing populations of marine mammals, fish, and other biota of human dietary importance in Alaska coastal waters. The predicted dose rates were found to be too low to cause any loss of endangered species or any significant ecological impacts.

(f) A worst-case scenario assessment of risk to humans was performed for people in north and northwestern coastal Alaska whose subsistence diet includes fish and marine mammals from the Arctic Ocean. It was found that the largest doses occurring in the Alaskan coastal communities who subside on seafoods came from naturally occurring ^{210}Po, ^{137}Cs, and ^{90}Sr from global fallout. The estimated doses were found to be below background levels and global fallout.

(g) A newly published research modeled the transport of iodine (^{129}I) from Sellafield and La Hague processing plants during 1966–2012 and estimated the values ^{129}I that introduced to the Arctic Ocean to be 5.1 and 16.6 TBq [42].

Elevated cesium concentrations were found in fine-grained sediments entrained in multiyear sea ice floes grounded in Resolute Bay near the center of Northwest Passage through the Canadian Arctic Archipelago. These high-specific activities (1800–2000 Bq kg^{-1} dry weight) are about two orders of magnitude higher than average specific activities detected in previous studies of sea ice-rafted sediments from the Arctic Ocean [43]. The study suggested that the sediments were probably from different sources and were likely mixed during sea ice transport. In 2007, the radionuclide levels were determined for underwater disposal sites in Kara Sea and Oga, Tsivolky, Stepovoy, and Abrosimov Bays. The measurements were carried out in zones both near to and remote from buried solid radioactive waste in the outer and inner parts of the bays. It was found that at the repository of the solid radioactive waste containers in the inner part of the Stepovoy Bay and Abrosimov Bay, the concentration of Cs is higher than background [44].

2.2.2 Pacific Ocean

Between 1946 and 1970, approximately 47,800 large containers of low-level radioactive waste were dumped in the Pacific Ocean west of San Francisco. These containers, mostly 55-gal (200 L) drums, were dumped at three designated sites in the Gulf of Farallones, but many were not dropped on target, probably because of inclement weather and navigational uncertainties. The drums are spread over 1400 km^2 area of seafloor. In 1990, the US Geological Survey (USGS) and the Gulf of Farallones National Marine Sanctuary began a cooperative survey for 200 km^2 of the waste dump using side-scan sonar technique [45]. Radiological surveys of the Northeast Pacific and North West Atlantic Ocean sites are carried out from time to time by the US Environmental Protection Agency and US National

Oceanic and Atmospheric Administration. So far, samples of seawater, sediments, and deep-sea organisms collected near various sites have not shown any excess in the level of radionuclides above background, except in certain instances where isotopes of cesium and plutonium were detected at elevated levels in sediment samples taken close to disposed packages [46].

The long-term benthic infaunal monitoring for the dredged disposal material in northern California was conducted [47]. At this work 135 benthic infaunal samples were collected from San Francisco Deep-Ocean Disposal Site (SF-DODS) over a period from January 1996 to September 2004. The monitoring of the Eastern Pacific deep sea showed that no regional impact or degradation of benthic fauna was detected due to dredged material disposal. Within SF-DODS species, richness and diversity were found to be reduced. The study demonstrated that dredged material disposal at SF-DODS has not caused regional degradation outside of the disposal site nor even at the boundaries of the site. The data clearly indicated that benthic communities in the vicinity of SF-DODS are highly resilient and capable of reworking small amounts of dredged material and recovering rapidly from larger deposits.

2.2.3 Atlantic Ocean

IAEA carried out a project to understand the distribution of radionuclides in the Atlantic [48]. In this project, the high concentrations of ^{137}Cs, ^{99}Tc, and ^{129}I radionuclides were attributed to the discharge from the reprocessing facilities and Chernobyl.

3 Near-Surface Disposal

Near-surface disposal of radioactive waste has been started more than 70 years ago [49]. The first disposal facility, which was in the USA, dates back to the mid-1940s; land repositories followed in many other countries in the 1950s and 1960s (in the UK, India, the former Soviet Union Republics, the Czech Republic, Hungary, Poland, Bulgaria, Norway, South Africa, and others). These disposal facilities were constructed using at-surface designs (mounds) or shallow trenches and then vaults and boreholes.

3.1 Early Disposal Practices

In these practices, safety assessments were not used to derive systematic site selection criteria or design requirements intended to contain and isolate the wastes. Instead, on a site-specific basis, some sites carried out ad hoc studies to show that the disposal would be adequate, while in others rather less evaluation was conducted. In the science of the time, there was a general belief in the capacity of geological systems to provide sufficient retention and dilution to assure safety. This attitude was accentuated for many of the early sites by their remote locations, far from potentially exposed people. Waste safety in the early days often accentuated worker safety far more than concern about potential releases into the environment.

Early trench disposal generally involved clearing and grading the land surface and excavating shallow unlined trenches, generally less than 15 m deep, to be used for waste disposal. The waste was generally placed into trenches on a first-come, first-served basis. In many of the early trenches, disposal resembled municipal landfill disposal, and waste was simply dumped in with minimal packaging or structure and without detailed information about the contents. Trenches were then backfilled using material removed during trench excavation, compacted, and graded to create an earthen mound cap to prevent rainwater ponding and to promote runoff. The principle for this disposal option was the assumption that the nature and rates of natural processes acting on the earthen trench system would be sufficient to slow the movement of radionuclides from the disposal trenches to allow dilution and dispersion and until the wastes decayed to acceptable background levels found in nature [50].

This philosophy gradually began to change, and a perception grew that the use of engineered barriers and more careful disposal practices is a better technical solution for waste disposal. The motivation for some of these changes was practical, to solve operational difficulties with early trenches, and for some changes, the motivation was an increased perception of the waste hazard. Still, radioactive waste often remained unconditioned, and there were sometimes no specific packaging requirements for the waste. It was often packaged in a variety of container types and randomly dumped or stacked into the trenches and vaults, with different approaches taken by different national organizations and sites. The waste was generally placed into the repository on a first-come, first-served basis.

A further evolution of these old facilities came with the introduction of waste conditioning methods. Solid waste would be cemented or encased in bitumen to reduce its leachability, improve its structural strength, and/or minimize surface dose rate. These changes were instituted in different countries at different times, but were generally driven by improvements in technology and worker safety rather than environmental concerns.

3.2 Recent Environmental Impact of Old Near-Surface Disposal Practice

Historical near-surface repositories reflected the understanding of safety at the time they were constructed. Subsequently, ideas about safety evolved, and current regulatory structures and approaches differ from the historical norms. International and national safety requirements were developed based on the practical experience, lessons learned, and scientific and technological progress. Now historical facilities can be assessed using modern concepts in site suitability studies, assessment methodologies and tools, quality assurance systems, and strategies for building confidence. In the mid 1990s, several countries had started to develop formal methodologies for assessing the safety of near-surface disposal facilities for low- and intermediate-level radioactive waste [51]. Internationally, IAEA initiated a series of four projects between the 1990s and 2015 to improve confidence in the results of safety assessment approaches for near-surface disposal facilities [52–57]. IAEA safety assessment methodology for near-surface disposal used in these programs was based on prior national experience developed over several decades [58–60]. The methodology comprises a series of interrelated steps, leading to improved understanding of the system and its uncertainties, namely; assessment context, disposal system description, development and justification of scenarios, formulation and implementation of models, and analysis of the assessment results and building confidence.

Recognizing the problem of legacy waste in some countries initiated different programs to evaluate or upgrade old near-surface disposal facilities. These programs in general aimed to achieve compliance with modified regulatory requirements and are often focused on specific decisions such as repairing existing unsafe conditions, preventing unsafe conditions from developing in the future, permitting continuing operation, applying new technological developments, restarting operations after suspension, and responding to public and stakeholder demands. These upgrade programs may include one or more of the following actions: adopting new waste acceptance criteria and container specifications, building additional engineered barriers, installing hydrogeological cutoff walls, and improving cover systems or partial or complete waste retrieval. These programs include the identification, assessment, and selection of remedial alternatives, as needed, development of action plans, and identification and implementation of appropriate technologies to be used.

IAEA had identified the key steps to perform an upgrade process for corrective action, which includes: definition of the initiating event, identification and assessment of potential corrective actions, planning and implementation of preferred actions, and confirmation of effectiveness [61]. The initiating events are defined as the circumstances at a specific disposal that lead to the need for corrective actions. These events may be categorized as follows:

(a) Changes in regulatory and standards requirement
(b) Detection or prediction of releases that exceed safe limits
(c) Stakeholder concerns

The identification of root causes might be a simple process of evaluating the assembly and analysis of existing information. If the existing information is not sufficient to identify the causes, there will be a need to identify gaps in information, including:

(a) Baseline site characterization
(b) Changes over time to site or repository conditions
(c) Records on the types and amounts of waste emplaced in the repository
(d) Knowledge of the physical and chemical characteristics of waste forms and related degradation
(e) Knowledge of the performance of engineered barriers utilized in the repository
(f) Extent of water ingress and egress
(g) Environmental monitoring data for all relevant media

A wide range of corrective actions may be applied to a specific initiating event, and selection of a specific action is a complex process that involves many factors. An example of a decision-making process is illustrated in Fig. 8.7 [61]. Figures 8.8 and 8.9 illustrate the initiating events related to the change in the regulatory requirements and detection of unsafe releases, along with their corresponding possible actions. Table 8.7 lists the typical methods to retrieve the radioactive wastes from a near-surface repository found to need corrective actions.

Widespread types of old disposal facilities, some of which have been found to need corrective actions, are the Radon-type facilities. These facilities were historically used in the former Soviet Union and some eastern European countries for near-surface disposal of institutional waste of low- and intermediate-activity level. Established in the early 1960s, the Radon system included 35 specialized facilities

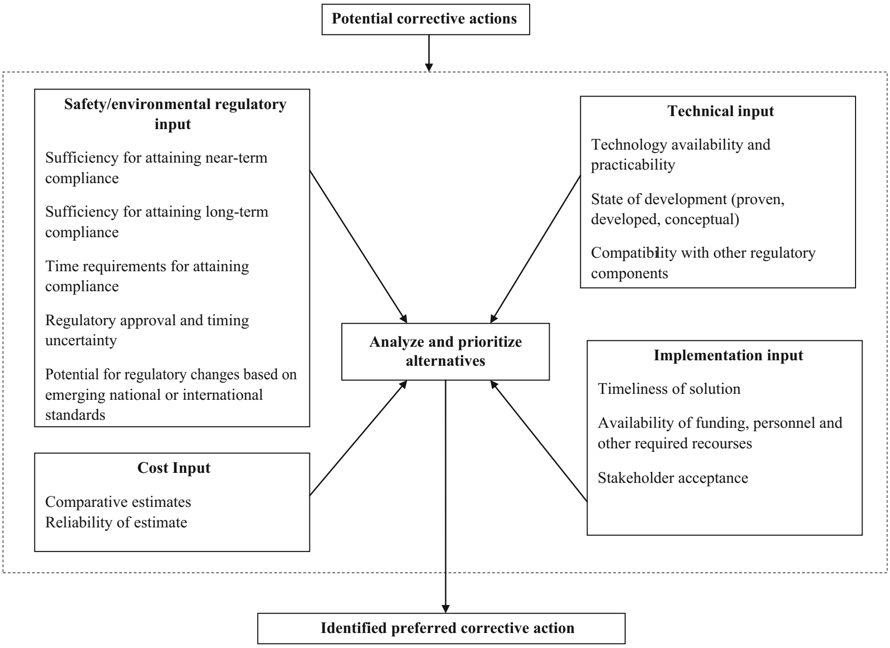


Fig. 8.7 Example of a decision-making approach for selection of corrective actions (Source: IAEA [59])

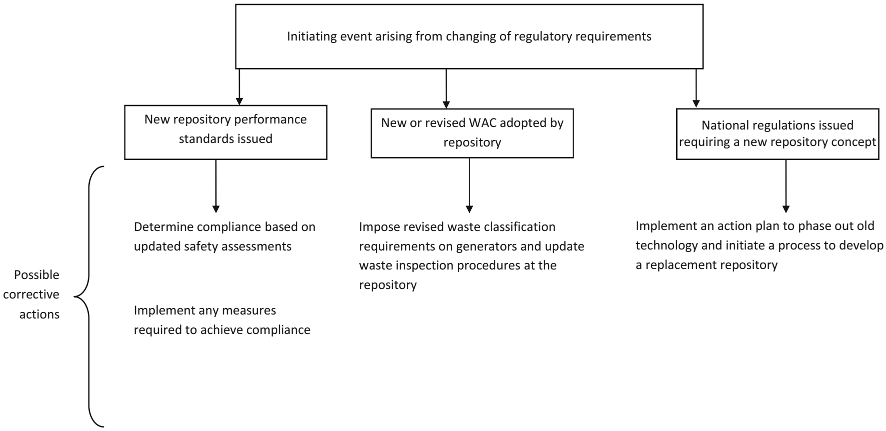


Fig. 8.8 Initiating events and corrective action options for changes in the regulatory requirements

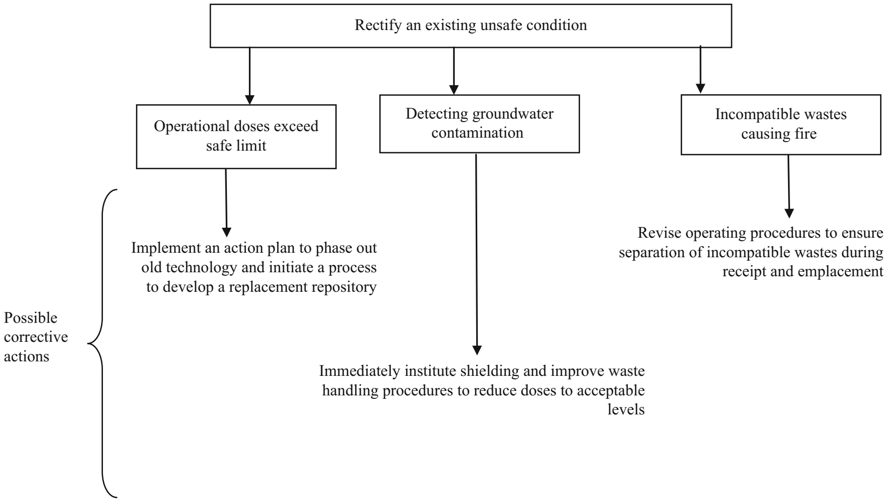


Fig. 8.9 Initiating events and corrective action options for releases of radionuclides exceeded the safe limits

in the Soviet Union with 16 Radon facilities in the territory of Russian Federation, including the two largest facilities – the MosNPO RADON and Leningrad Special Combine. Currently, 14 out of the original 16 Russian facilities are still in operation and have about 10 % of their repositories available for future waste storage.[1] Fifty years' experience in low- and intermediate-level radioactive waste isolation in

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[1] Beginning in 2000, new regulatory requirements in the Russian Federation specify that Radon facilities are licensed to "store" rather than "dispose" the waste.

Table 8.7 Method to retrieve the wastes during upgrade of old shallow land disposal

Waste category	Technique	Equipment	Procedure
Loose LLW, low dose rate	Manual	Bucket Small crane	Initial segregation and characterization Waste is packed in containers awaiting for further actions[a]
Waste in intact containers	Manual	Crane Forklift truck	Depending on the condition of the container, it may be over packed awaiting for further action
High dose rate	Remote	Custom designed robotics, remote grapple, shielded tasks	The retrieved wastes placed immediately in shielded casks
In situ conditioned wastes	Manual or remote depending on the dose rate	Cutting equipments such as diamond saws Crane	Measure should be taken to minimize the risks of cutting the waste and minimize exposure to airborne contaminant during cutting and transport
Sand, soil, and gravel backfill		Small diggers, vacuum equipment	Measure should be taken to detect contamination
Liquids		Suitable pump, suitable tanks with shield if necessary	Collected water should await for further actions

[a] Further actions are taken based on the dose rate of the retrieved wastes and may include one or more of the following actions, sending the wastes to treatment plant, conditioning of the wastes, and transferring the waste to storage or disposal

typical near-surface repositories at Russian Radon facilities has shown that a lot of operational and natural factors can influence the natural and engineered barriers of the disposal system and may lead to releases from the facility or other real or perceived difficulties in operation. Examples of issues seen at Radon facilities include biological intrusion, perched water in combination with freeze–thaw cycles, potential erosion, and flooding [62]. Based on the lessons learned, two new types of near-surface facilities were recently constructed and are in operation at the site of MosNPO RADON. Both of them were designed and constructed as storage facilities that can be transformed into final disposal, if the regulatory environment allows such a transition. The first one is the vault constructed above the ground level, whereas the second one is a large-diameter borehole (LDB). Two LDB-type storage facilities with diameter of 1.5 m and depth of 38 m are filled with cemented low- and intermediate-level RAW in retrievable form for about 7 years under continuous monitoring to define future perspectives of their wide implementation. Some corrective actions were performed for historical Radon-type facilities, including re-cementation of unconditioned waste and construction of multilayer cap above the facility (MosNPO RADON), recovering protective properties of the natural barrier in near field, retrieval, conditioning, packaging, and emplacement into existing repositories, those packages that are acceptable for near-surface localization.

4 Deep-Well Injection

Deep-well injection of liquid radioactive waste was based on the practice of deep injection of nonradioactive waste widely used in the middle of the 1950s in the USA and was used for significant volumes of liquid radioactive waste generated associated with the nuclear arms race. Attempts to establish facilities for deep injection of liquid radioactive waste in the USA (Idaho, Oak Ridge, New Mexico) failed, and studies suggested that the geologies of these locations were not favorable for deep injection. Another concept (hydro-fracture groutting) was developed to suit the geology of these areas, which relies on pumping premixed cementitious waste form into underground shale layer. The pumped grout pressure will cause fractures in the shale allowing the cementitious waste to penetrate along the horizontal bedding planes of the shale in layers. The operations of Oak Ridge disposal continue from 1964 to 1984 to dispose low- and intermediate-level radioactive wastes composed of mixture of all kinds of generated liquid wastes including those generated from hot cell, pilot plant, and reactor operations besides organic reagents and solvents [63].

In Soviet Union, a governmental decision was taken in the mid-1950s to start geological survey at four sites to study and establish deep-injection facilities. The principle of this option relies on confining liquid wastes in deep geological formations by injecting them in reservoir horizons [64]. It was proposed that this option will:

1. Obviate the need for surface construction of additional liquid radioactive waste and industrial waste storage sites
2. Reduce environmental contamination resulting from discharging these wastes into lakes and rivers
3. Lead to significant cost savings
4. Allow time for the natural decay of radionuclides and isolate the waste by geochemical reactions of the waste with host rocks

Table 8.8 lists the deep-well injection practice in Russia and its evolution.

Table 8.8 Examples for deep-well injection in Russia

Place	Injection depth (m)	Type of reservoir	Beginning at	Waste volume (10^6 *m^3)
Siberian Chemical Combine	270–320	Sand, sandstone, freshwater	1963	43.5
	314–386			
Krasnoyarsk-26	180–280	Sand, freshwater	1967	6.1 LLW 2.25 ILW&HLW
	355–500			
Research Institute of Nuclear Reactors	1130–1410	Limestones, brines	1966	2.5
	1440–1550			

4.1 *Early Assessment of the Old Practice*

4.1.1 Hydro-Fracture Groutting in Oak Ridge

The performance of the practice was evaluated by constructing experimental injection wells (HF-1 and HF-2) and 24 observation and monitoring wells. Cement grout doped with radioactive tracer was injected into the Pumpkin Valley Shale, and the tracing results indicated the acceptability of the grout performance to isolate radio-contaminate hazards [63]. Two hydro-fracture facilities were installed, and the stabilized radioactive wastes that resulted from the operation of the old facility formed grout sheet at 240–300 m below ground which is estimated to be up to 480–980 m wide and 6×10^{-3} m thick. The new facility produced a stabilized grout sheet about 300–340 m underground which is estimated to be 1200 m in diameter [64].

4.1.2 Deep Liquid Injection in Experimental–Industrial Test Site (Former Soviet Union)

In 1958, the decision was made to undertake research investigations by creating a disposal system to inject drainage water, wash water, and decontamination water [65]. The site was named the Experimental–Industrial Test Site (EITS). Two sand reservoir horizons were used at depths of 270–320 m and 314–386 m. Preliminary geological investigations were conducted near the Siberian Chemical Combine, and these studies confirmed predictions and data from earlier geological investigations. These positive results led to the creation of a deep-well injection facility (at industrial scale) for low-level wastes and intermediate-level wastes. Additional deep-well injection facilities were developed at RIAR at Dimitrovgrad, commissioned in 1967, in the Ulyanoskaya Region, commissioned in 1966–1973, and at the Mining and Chemical Combine (Krasnoyarsk-26) in 1967–1969.

EITS occupies approximately 6.5 km^2, surrounded by an exclusion zone of 52 km^2. It is situated within an ancient erosional depression filled with sand–clay strata reaching 550 m below the ground surface. Interspersed are three aquifers of quartz-feldspar, gravelites, sands, and sandstones. The lower two aquifers, Horizons I and II, at 355–500 m and 180–280 m below ground, are used for injection of intermediate-level waste (ILW)/high-level waste (HLW) and low-level waste (LLW), respectively [65]. The injection system for HLW and ILW consists of eight injection wells, eight relief wells, and 54 monitoring and observation wells. HLWs were injected one to two times per year in batches of 1000–2000 m^3. ILWs were regularly injected from spring to fall at rates of up to 300 m^3 per day. The increase of pressure in Horizon I due to injection operations is relieved by relief wells located approximately 1 km to the south of the injection array. The LLW system consists of four injection wells, four relief wells, and 37 monitoring wells. Low-level wastes were injected from spring to fall at rates of up to 600 m^3 per day.

However, the site continues to hold a mining license allowing disposal of all classes of wastes (LLW, ILW, and HLW). The license is renewed every 5 years.

4.2 Recent Environmental Impact and Assessment of Deep-Well Injection

4.2.1 Hydro-Fracture Groutting in Oak Ridge

A recent hazard assessment document concluded that no credible accident scenario could release the stabilized material inventory due to the physical properties of the grout and the lack of credible energy resource that could impact the material under soil, rock, and shale [63, 66].

4.2.2 Deep Liquid Injection in Experimental–Industrial Test Site (Former Soviet Union)

Russian institutes, such as All-Russian Design and Research Institute of Production Engineering (VNIPIPT), the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry of the Russian Academy of Science (IGEM), and the International Institute for Applied Systems Analysis (IIASA), have assessed the concept and implementation of deep-well injection. These three groups made very different assumptions, and the degree of confidence they have in their results also differs. Despite these differences, there is a remarkable convergence of the results from the three studies, indicating that the existing system of deep-well injection at Krasnoyarsk is functioning as designed. Under the current best understanding of site conditions, there is very little likelihood that the injected wastes would reach the earth's surface at concentrations above standards set for drinking water [67].

Results from mathematical modeling of the deep-well injection of radioactive and nonradioactive wastes, carried out at of SSC RF–NIIAR and Chepetsk mechanical plants, have confirmed the feasibility and safety of deep-injection disposal of toxic and radioactive wastes into permeable aquifers. These results have been used to justify continuing such disposal of wastes and the development of measures for monitoring this method [68]. Another study that was directed to model the distribution of the injected low-level radioactive organic waste was performed [69]. It was found that the distribution of waste does not exceed tens of meters from the injection well and is associated with the transfer of the organic phase into an immobile condition. The presence of the radiation field in the zone of maximum radionuclide accumulation on the rock causes radiological decomposition of the organic contaminants. When the aqueous radioactive wastes are injected, they are more easily transported from the injection zone. Hence, repeated injection of waste will not increase the concentration of organic material within the injection zone. The presence of the waste does not markedly increase the temperature in the injection zone. The maximum temperature is significantly less than boiling point under formation conditions. Thus, this injection technology is regarded by the operators as a radiolysis reactor for treating liquid-organic radioactive waste. The effectiveness and safety of the low-level radioactive organic waste decomposition processes are defined by the radioactivity accumulated in the rock and the waste injection cycle length.

5 Preexisting Cavities and Mine Disposal

Mines and excavated tunnels were used to dispose LLW since the 1940s in several countries. During the conversion of some mines for disposal purposes, it was necessary to reinforce some parts with concrete and to construct drainage systems for any water entering the mine. Limestone, salt, and uranium mines were extensively used in the 1960s; some have since been closed, but others remain in operation [70]. Both solid and liquid LILW were disposed in caverns. Various waste conditioning and closure strategies were followed in different countries. Table 8.9 summarizes this disposal practice worldwide.

As indicated in Table 8.9, in Germany salt mines were selected to host a repository for LLW and ILW radioactive wastes. LLW drums were stacked in old mining chambers by loading vehicles or simply emplaced dumped (tip disposal).

Table 8.9 Summary of some underground disposal

Place	Depth (m)	Type of reservoir	Begin of the practice	Waste volume
Czechoslovakia				
Hostim	30	Limestone mine	At 1940 end 1997	400 m^3
Richard	70–80	Limestone mine waste	1964 in operation	2700 m^3
Bratrstvi	–	Uranium mine	1974 in operation	700 drum
Germany				
Asse	725–750	Salt mine	1967–1978 chamber will be backfilled till 2013	47,000 m^3
Morsleben	400–600	Potash and salt mine	1978 in operation	36,752 m^3
Swedish final repository	50 below Baltic Sea	Metamorphic bedrock	1988	60,000 m^3
Finland				
Olkiluoto	60–100	Crystalline bedrock	1992	8400 m^3
Loviisa	70–100	–	1997	4000 m^3
USA WIPP	655	Rock salt formation	1999	–

Generally, the remaining voids were backfilled by crushed salt or brown coal filter ash. ILW was lowered into inaccessible chambers through a borehole from a loading station above using a remote control. Thirty years ago, the feasibility of both borehole and drift disposal concepts were studied and proved in the Asse mine [71]. The emplacement of HLW has been investigated since 1980, and the investigations included several full-scale in situ tests that were conducted to simulate borehole emplacement of vitrified HLW canisters and the drift emplacement of spent fuel in Pollux casks. Quasi-closed system (QCS) approach was used to study LLW disposal in a German salt mine with a focus on disposed waste forms, geo-engineered barriers, and backfill strategies [72]. The study focused on geochemical tools and a thermodynamic database for modeling highly concentrated salt systems. It was shown that QCS approach provides essential data to study the long-term geochemistry and related radionuclide concentrations to be used in performance assessment and safety analysis.

Richard repository, in the Czech Republic, currently contains about 10^{15} Bq [73] of waste. In 2003, the Czech Radioactive Waste Repository Authority (RAWRA) launched a project that aims to reduce the burden from past practices during the first phase of Richard repository operation and at improving its overall long-term safety. Reviews of the preliminary closure concept and its related safety assessment indicated that the existing concept was deficient in regard to postclosure performance. A decision was made to develop a new concept for the closure of individual waste chambers. The main technological element of this concept is the installation of an additional engineered barrier called a “hydraulic cage” around the waste chambers. The hydraulic cage was designed to decrease the hydraulic gradient and minimize advective flow through the repository.

6 Lessons Learned from Early Disposal Practices

Many of the early approaches for disposing the radioactive wastes were simple, conducted without engineered barriers or with simple engineered barriers. These practices have the following common characteristics:

(a) They were developed before modern national laws, international guidance, or conventions were in place.
(b) They were developed before current regulatory requirements took effect, or they are inconsistent with modern site suitability guidance, technological advances, safety assessment methodologies, or quality assurance systems.
(c) In many cases, unpackaged bulk waste was disposed.
(d) Waste packages, if existed, were often emplaced nonuniformly or through simple tip disposal.
(e) A heterogeneous mixture of waste packages, waste types, waste forms, or waste classes was often disposed in the same facility. Waste items may also

have unexpectedly high-dose rates, or other unexpected features such a pyrophoricity, owing to the lack of standardized waste acceptance criteria.

(f) Poor documentation of the wastes, their radiological and chemical content, their characteristics, the waste forms used, and the location of the wastes in the repository is normal for these facilities.

(g) Unknown or poorly documented information on non-radiological hazards (e.g., asbestos, organic solvents, pathological agents, and toxic chemicals).

Some past practices need action to meet modern regulatory requirements, correct an existing unsafe condition, prevent any unsafe condition from occurring in the future, and respond to societal demands. However, the difficulties in working with such facilities means that worker risks associated with undertaking such activities may be high, and it may be necessary to balance potential risks in the far future to hypothetical members of the public with real risks to workers undertaking remedial actions. Based on these lessons, recent disposal practices have been developed with greater consideration for record keeping, waste isolation, and facility control, all with a view to minimize the potential need to modify repositories in the future as the result of future changes in understanding and regulatory philosophy.

Lessons learned from the operation of early disposal facilities have resulted in development of new designs for radioactive waste disposal facilities that aims to provide adequate isolation of these wastes using containment and confinement strategy. These designs rely on the multi-barrier concept to achieve isolation of the disposed waste for appropriate time taking into account the waste and site characteristics and safety requirements [74–79]. This concept helps in avoiding overreliance on one component of the disposal system (i.e., natural barriers) to provide the necessary safety and allow for certain component to fail without compromising the overall safety of the disposal system [78, 79]. These designs are developed in accordance of holistic and graded approaches, and the process of design development is having iterative nature that allows the designer to modify the design to achieve optimum performance consistence with good engineering practice and meet regulatory requirements [80].

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