Nuclear Waste Disposal: An Exploratory Historical Overview

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A brief review of the development of radioactive waste management concepts The success or failure of projects or programs depend largely on the quality of the ideas and concepts developed. If these prove to be inadequate or prone to error, their deficiencies and shortcomings rebound on such programs and projects after a certain period of time and result in serious and expensive consequential damage and costs. Often, when problems occur, planners and project managers still try to salvage such projects or programs by taking technical measures to mitigate the undesirable and negative effects. However, if the weak points are inherent in the conception, even these downstream support and accompanying measures are of little help. A cycle occurs between efforts to remedy consequential damage and the emergence of new incidents and difficulties. Finally, it becomes apparent that conceptually flawed projects can no longer be salvaged. The bitter end of such projects is thus foreseeable.

For many decades, the disposal of radioactive and chemo-toxic waste also followed this trend of trial and error. Many of these highly toxic wastes were deposited in landfills built in old gravel, sand or clay pits or in quarries above groundwater-rich layers. Planners and operators of such facilities were initially not particularly concerned about the effects of such disposal sites, given the great dilution of the pollutants in the groundwater or the sorption properties of the subsoil. Only the increasing, sometimes severe, pollution of groundwater and watercourses (NEA 2014) led to a gradual rethinking and a stepwise move away from such practices. Attempts to secure such waste storage sites at groundwater-rich locations using sequential barriers such as base and surface seals failed, as did measures to filter or immobilize contaminants on site. Finally, over the course of a few decades, many of these properties gradually had to be partially or completely excavated and remediated. These developments show that the perception of such projects and their impacts can change and shift fundamentally over time.

The extent of consequential damage can be exemplified by early disposal practices at U.S. nuclear complexes, such as that at Hanford, Washington. The liquid wastes, some of which were treated and placed in steel tanks or in trenches and leach pits from the 1940s onward **(Figure 1)**, have resulted in widespread contamination of ground and stream waters that now require complete cleanup of the vast site over the next half century. Costs, originally one of the key variables in the choice of disposal measures, are now growing immeasurably at this site. For Hanford, worst-case estimates for continued cleanup expenditures suggest additional funding needs of up to $680 billion until 2079 (DOE 2019), with upward tendency. Thus, restoring reasonably adequate protected lands is an extremely complex, costly, and protracted undertaking.

Whether we consider storage sites for radioactive waste or landfills for chemo-toxic waste (NEA 2014), the development of the problems always follow the pattern mentioned above, where the original storage concepts are reflected and re-evaluated according to the knowledge at the time. This rethinking also led to the search for possible solutions for long-term safe disposal of radioactive waste. To be sure, starting in the early 1950s, a variety of concepts were considered on how to deal with highly toxic wastes. The spectrum of these project ideas was broad, ranging from disposal of highly radioactive waste in the ocean subsurface, in oceanic trenches, or (later) in subduction zones of oceanic plates, to sinking in the ice caps of the poles or,

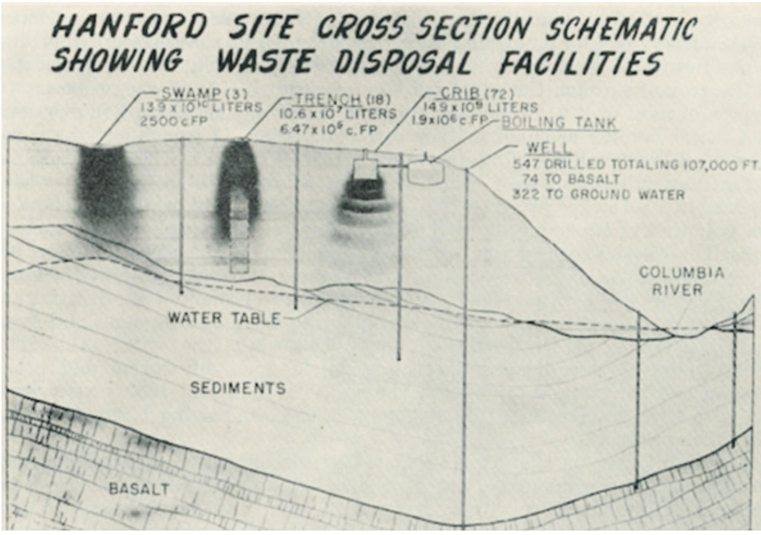

Figure 1
Type of disposal facilities used in Hanford, Washington, according to Pearce, D. W., et. al. (1959). The amounts of deposited fission products (FP) in the figure are given in Ci (c). (1 Ci = 37 GBq).

starting in 1957, disposal in space (Hatch 1953, Bürgisser et al. 1079, Milnes 1985, EKRA 2000, Appel et al. 2015). But all these concepts, with one exception, can be characterized as academic pipe dreams that could not be reconciled with practical reality. In 1957, the National Academy of Sciences finally brought a preliminary decision in the search for repositories of radioactive waste on land and in the sea in two reports that were remarkable for that time (NAS 1957a, 1957b). These analyses were to open the way for the strategy of disposal in underground repositories and for the sub-seabed disposal project (see later: Anderson 1979). Initially, the search for repositories focused on old salt mines, which were pursued mainly in the USA and Germany and which would lead to the projects at Lyons, Kansas, and those at Asse II near Wolfenbüttel and at Morsleben, Ingersleben, in Western and Eastern Germany respectively. Their difficulties and eventual failure required a rethinking of the path taken. Above all, the failure of the Lyons project (Walker 2006/2007) was to prove extremely consequential. Thus, a number of fundamental insights and changes in the specification of nuclear waste management concepts can be attributed to the 1970s. They relate to five areas in particular:

- **The planning and the research:** Especially from the mid-1970s, the responsible authorities began to structure the search for repositories for radioactive waste. Significant preliminary work was done by the relevant U.S. administrations. In the winter of 1976, the Energy Research and Development Administration (ERDA), which had taken over the reins of nuclear programs from the Atomic Energy Commission (AEC) the year before, announced a broad new program for the disposal of radioactive waste from both civilian and military facilities (Hofmann 1980). After a restructuring in 1977, this task fell to the newly formed Department of Energy (DOE), which thus took over the fate of the National Waste Terminal Storage (NWTS) Program. This period saw two fundamental changes: first, the search for repositories in disused mines was abandoned and the focus shifted to underground facilities specifically designed for the disposal of radioactive waste. Second, systematically structured research programs were launched, as documented by the Earth Science Technical Plan for Mined Geologic Disposal developed by DOE and the associated U.S. Geological Survey in 1979 (DOE&USGS 1979). It is the first research program to set out to find geologic repositories with clear objectives and process methods. Significant foundational work on site selection and repository design emerges in this context.

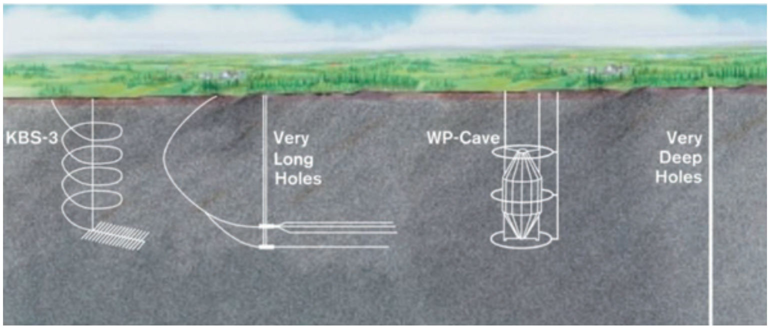

Figure 2
Investigated repository configurations and connection systems for the final disposal of high-level radioactive waste in the geological subsurface in the Swedish program. Finally, the KBS-3 system was selected (SKB 2000).

- **Site selection:** The planning of repositories specifically for radioactive waste also required a process of site selection. The failure of the repository project at the Carey Salt Mine in Lyons in the early 1970s was a major factor in restarting a site research program (Walker 2006/2007). Beginning in the mid-1970s, the U.S. Department of Energy published extensive studies on the specific site selection and narrowing process envisioned in the United States (DOE 1979), which defined the governing process stages in the search for and determination of suitable sites for repositories for high-level radioactive and transuranic waste, which anticipated the search processes initiated in Switzerland in 2008 (Sectoral Plan for Deep Geological Repositories) or in the Federal Republic in 2017 (Site Selection Act). The first repository that was sought according to such process specifications was the Waste Isolation Pilot Plant (WIPP) in the Permian Delaware Salt Basin in the south-central United States. The adventurous history of this site search is traced in Mora (1999) and Alley et al. (2013).
- **The repository concept:** Beginning in the 1970s, two competing concepts begin to gain acceptance: the geologic repository at depths of a few hundred meters and the deep borehole concept, which pursues emplacement of canister-packed high-level radioactive waste even at greater depths of a few kilometers. Both concepts persist to the present day, although today there is a clear preference among most countries for the repository mine option at depths of 500 meters to a maximum of 1,000 meters. An important role in shaping the repository concept was played by the Swedish KBS program, which developed various repository variants starting in the mid-1970s and presented more concrete projects for high-level reprocessed or non-reprocessed waste (KBS 1979a, 1979b, see **Figures 2 and 3**). This layout of repositories at a depth of a few hundred meters will be followed by most of the later developed repository programs of other countries, as we will see soon.

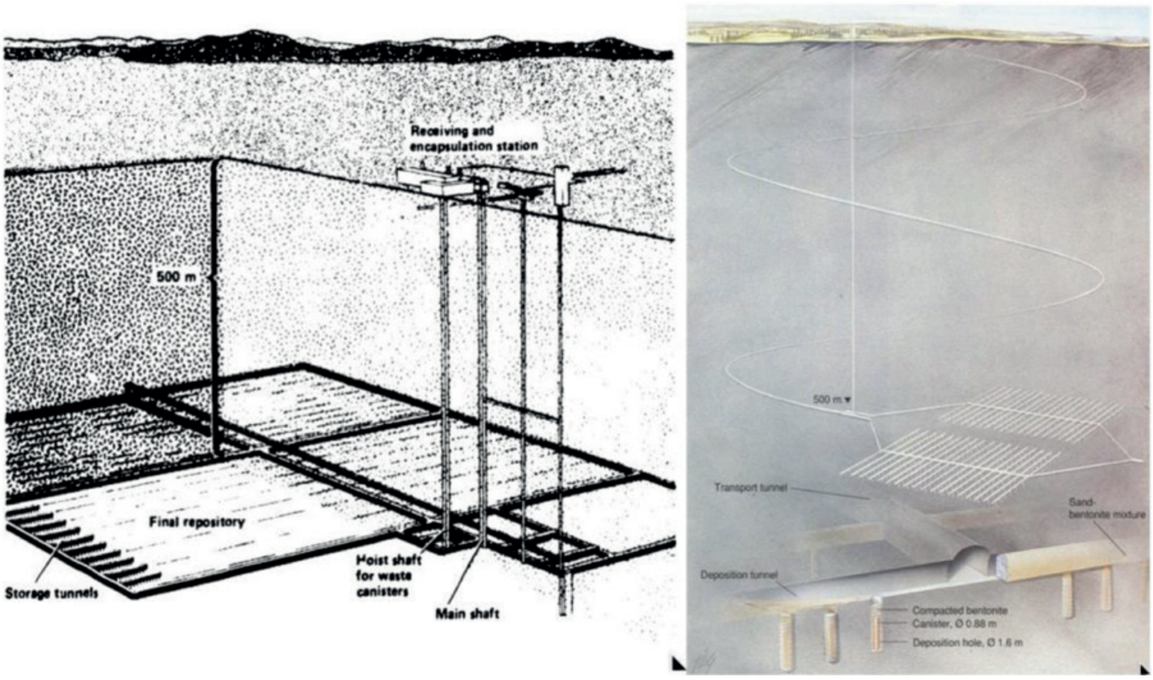

Figure 3
SKB concepts for high-level waste with connection options by shaft or ramp. On the left, according to the original concept with shafts (Ministry of Industry, n.d.), on the right with ramp and shafts from the mid-1990s (SKB, 1993).

- **Long-term effects and monitoring:** The uncertainties in the development of a repository were also recognized at an early stage, which led to the fact that not only different operating phases were envisaged over the closure of a repository, but also the monitoring of these phases by means of suitable monitoring programs were addressed (LBL 1978). Even if concrete monitoring programs were only developed at a later time, it is evident that the basic idea of long-term monitoring found its way into the concrete repository concepts at a relatively early stage.
- **Structures:** Finally, it should be pointed out that the question of structures was also the subject of fundamental discussions as early as the 1970s. The U.S. Energy Reorganization Act of 1974 introduced clear functional divisions between executive and supervisory roles in a program. A not inconsiderable contribution for this development was certainly also made by the realization that clear separations of roles and functions and further a clean definition of terms of reference were able, if not to prevent, then to control in the broadest sense possible deficits in the management of specific programs, as had occurred at the American Atomic Energy Commission (AEC). Structural issues again played a role in the 1990s, although certain basic questions regarding the governance of waste management programs remained unanswered.

Finally, it is important to note the changing social context during this decade. The 1970s, still characterized by a strong expansion of nuclear energy, also witnessed the emergence of an strong opposition that addressed the unresolved issues of nuclear waste management (Buser 2019). As the longtime director of Oak Ridge National Laboratory, Alvin Weinberg, himself later acknowledged, nuclear energy-friendly institutions had underestimated the problem of radioactive waste management and its effect on society (Weinberg 1994, p. 277). The 1970s were therefore a decade in which, under the watchful eye of a society that was becoming critical, the appropriate corrective measures were introduced to the disposal programs.

Brief overview of the international development of actual disposal concepts

As mentioned above, the Swedish concepts for specially excavated and equipped underground radioactive waste repositories published in the late 1970s and early 1980s represented a turning point in efforts to find concrete solutions for the final disposal of radioactive waste in the geological subsurface. For the first time, a fully developed concept for the permanent safe confinement of this waste over geological periods of hundreds of thousands of years and more was presented. It was essentially based on the further development of early ideas and was now oriented towards a model of series-connected barriers (multi-barrier concept), which could delay the dispersion of radioactive materials by a system of immobilization and packaging measures and suitable geological site characteristics to such an extent that the amount of radiation released to the environment by the repository was far below legally defined limits. This concept was de facto adopted by all countries using nuclear energy. Over the next two decades, in addition to the Nordic countries Sweden and Finland also France, Switzerland, Belgium, USA, Canada and Japan developed similar concepts. Other countries, such as Great Britain, Spain or Holland, followed the same concepts, but postponed the concrete programs for political or social reasons. The election of Ronald Reagan as U.S. president and the strong protests at the time against disposing of radioactive waste in the ocean or seafloor led to the abandonment of the sub-seabed disposal project, which – regardless of its debatable objectives – had been pursued as an international project conducted with great scientific care. Although the option of disposing of high-level waste in deep boreholes remained as a reserve option, and solution approaches such as partitioning and transmutation or long-term interim storage over periods of several hundred years were repeatedly evaluated and discussed, the concept of a geological repository at hundreds of meters in depth has largely prevailed – at least until today. It should be noted that certain countries, such as Russia, have their own disposal practices, such as injecting radioactive liquids in deep underground formations.

Basically, all projects pursued today assume similar designs of the repository **(Table 1)**. With a few exceptions – for example Belgium, which wants to place its high-level waste in a shallow marine clay formation (Argiles de Boom) – the vast majority of concepts and projects assume repositories at depths of 500 meters and more in crystalline rocks or salt or clay formations. There are also exotics in the host rocks, for example in the programs pursued so far in the USA (tuff, Yucca Mountain Nevada). But the range of variations in the relevant planning framework conditions are small. The most visible differences are the proposed transport routes to the subsurface, which are via ramps in the French and Nordic projects. While the storage configurations may vary slightly, the differences are limited to, for example, the horizontal or vertical emplacement of the storage canisters. The chosen canister or backfill materials were adapted to specific geochemical characteristics of the subsurface (e.g., copper canisters in crystalline rocks or OPC cement over-canisters in the Belgian concept). Thus, all these projects are no longer concerned with fundamental conceptual issues, but with specific optimizations that are now to be clarified within the framework of in-depth research programs.

The lower part of Table 1 lists further planning requirements that are currently under discussion in various programs. One example is the question of monitoring a high-level repository. In this context, Switzerland is pursuing a concept developed by the expert group “Disposal Concepts for Radioactive Waste” around the year 2000 (EKRA 2000), which ties in with the ideas of isolation and monitoring phases developed 20 years earlier (e.g. LBL 1978). It is the concept of the pilot repository, which is intended to hold a representative waste fraction of the main repository and should be monitored over an extended period of time (Buser et al. 2020). EKRA pursued two goals with the idea of the pilot repository: on the one hand, the understanding of uncertainties in repository development was to be increased by monitoring programs and, if necessary, to be able to intervene in the repository process at an early stage should the decisive development parameters in the repository develop differently. On the other hand, the pilot repository concept was an essential element in building confidence with the local communities. The EKRA concept became an integral part of the Swiss Nuclear Energy legislation, which was enacted in 2003. So far, no other country has joined this concept, although the issue of long-term monitoring has been in the focus of attention for almost 20 years (e.g., “Modern“ program of the EU, see Bertrand et al. 2019). However, direct underground

	Sweden	Finland	France	Switzerland	Belgium	Germany	Canada	Japan
Depth of repository	≥ 500m	≥ 400m	≥ 500m	≥ 500m	≥ 220m	≥ 500m	≥ 500m	??
Rock type	crystalline	crystalline	claystone	claystone	clay	not defined	crystalline	sediments
Disposal galleries	✓	✓	✓	✓	✓	✓	✓	✓
Acess shafts (infrastructure)	✓	✓	✓	✓	✓	✓	✓	✓
Acces shaft (waste transport)				✓	✓	✓ ?	✓	✓
Ramps (waste transport)	✓	✓	✓					
Wastes								
▪ Vitrified HLW			✓	✓	✓	✓		??
▪ Spent fuel (PWR, BWR, Candu, …)	✓	✓	✓	✓	✓	✓	✓	✓
▪ Others (TRU-wastes)	✓	✓	✓	✓	✓	✓	✓	✓
Storage canister (e.g. steel, copper)	✓	✓	✓	✓	✓	✓	✓	✓
Canister position: Vertical	✓	✓					✓	✓
Canister position: Horizontal	✓	✓	✓	✓	✓	✓	✓	
Backfill / buffer (e.g. bentonite, OPC based concrete)	✓	✓	no	✓	✓	✓	✓	✓
Special monitoring facilities	no	no	no	pilot facility	no	no	no	no
Retrievability after closure (years)	??	no	possible	no	??	500y	??	??
Marker programs	possible	no	possible	✓	??	not defined	??	??

Table 1
Overview of some nuclear Waste Disposal programs, compilation based on the published documents of the different companies.

monitoring beyond the closure of the main repository is not envisaged at the moment.

Nonetheless, it is evident in other areas that there is a need for further fundamental clarification and innovation. In the course of the past two decades, the discussion therefore shifted to other topics. First, on the possibilities of using specific computational models to simulate the development of material flows or the resulting dose loads in the environment on the basis of realistic assumptions. Today, this aggregate method is the main computational model-based tool on which decisions for licensing a repository by regulators and political authorities are based. The key variable on which these decisions are based is confidence. This is the essence of the so-called 'safety case': "When it comes to long-term predictions we get out from the narrow scientific domain. A mixture of quantitative and qualitative analyses and arguments (still science-based) will have to be provided to engender confidence of both the provider and the reviewer" (Pescatore 2008). The 'safety case' is a good example of what Alvin Weinberg understood by trans-science (Weinberg 1972): a project between science and politics that can no longer provide definitive scientific answers to the questions posed, such as safety or long-term safety, and leaves or must leave the decisions to politics – or to society (Buser 2002). In this sense, disposal programs for radioactive waste with their long lifetimes transcend the limits of exact scientific research and, in this sense, necessarily lead to social decisions.

Two fields closely linked to these questions are the social participation in such programs and the question of reversibility of decisions. While in the first decades of nuclear technology scientists and experts, respectively the political and technical authorities in which they worked, were the unchallenged and definitive bearers of decisions, the decision-making processes have increasingly shifted in the direction of societal participation. This is evidenced not least by the efforts that have been underway for about two decades to create so-called forums of stakeholder confidence (NEA 2000, 2004, Kaiserfeld et al. 2020). The creation of such exchange platforms follows the realization that undertakings such as nuclear waste management require the approval of the affected population (Di Nucci et al. 2017). In recent years, two major site selection processes have been launched in Switzerland and Germany that institutionalize the participation of affected populations. However, the forms of this participation differ greatly from country to country. Nevertheless, it can be assumed that forms of discussion and decision-making will increasingly shift toward the affected communities in the future.

The reversibility of decisions plays a special role in questions of social trust-building. The principle of reversibility of decisions and retrievability of waste from a geological repository was already under discussion in the late 1970s (Zen 1980), but it was not until the French legislation of 1991 (loi Bataille) that it acquired the corresponding legal significance (Buser 2014). Meanwhile, the principle of reversibility has been widely accepted as a component of waste management programs (IAEA 1999, NEA 2012). Due to the numerous failures in the disposal of highly toxic wastes, the participation of affected populations as well as the willingness to fundamentally reverse decisions represent essential tools for creating acceptance. This is a development that is undoubtedly in the spirit of the time.

Setbacks

Nevertheless, the successful conceptual, methodological and practical developments of the various disposal programs in the last decades should not obscure the problems that repeatedly appear on the way to concrete implementation. For about 20 years, various setbacks, some of them severe, have had to be accepted on this path of implementation of deep geological repositories. This concerns in particular four underground facilities. Fundamental problems, however, are likely to arise in the future in further underground projects and through the development of technology. At two of these facilities – the experimental repository for low- and intermediate-level waste at Asse II near Wolfenbüttel (Lower Saxony) and its sister project Morsleben (Ingersleben, Saxony-Anhalt) – conceptual weaknesses from the early days of nuclear waste disposal can be blamed for the problems (see Buser et al. 2020). However, disclosure of water inflows into mines has been kept under wraps for decades, unnecessarily straining social acceptance and likely placing entirely new demands on the transparency and quality insurance of underground projects. In the case of the chemo-toxic Stocamine underground waste disposal site (Wittelsheim, Alsace), it was the operating and control system set up that did not work, and ultimately led to the definitive abandonment of the project via an underground fire in 2002. The social and political consequences of this case continue to this day. The last serious accident to date occurred at the Waste Isolation Pilot Plant (WIPP, Carlsbad, New Mexico) and shut down the repository for several years starting in February 2014. In this case, again, serious failures in operational management were responsible for the problems (Klaus 2019). The trigger was an incorrectly conditioned 50 gallon drum that reacted chemically and blew up. This incident highlights the challenges of conditioning and manufacturing storable waste containers and the complexity of managing a storage system during its operational life. A basic problem about this incident is the fact that other drums conditioned in this manner remained underground, fundamentally reopening the question of the reversibility of such a backfilled facility.

If we consider the disposal of highly toxic waste in the deep underground as a whole, the disposal of highly toxic radioactive waste or chemo-toxic waste cannot be separated. Both types of repositories are based on similar concepts, although, with the exception of Stocamine, none of the repositories for chemo-toxic waste have been constructed in specially excavated mines. Notwithstanding this undoubtedly relevant difference, similar phenomena are evident in operational risks (e.g., fire and explosion scenarios), transport of materials, and transport phenomena into and out of the deep geological subsurface. Social resistance at the specific repository sites are currently growing in view of the problems encountered (water inflows in the old salt mines, gas leaks of stored pollutants). Science and official institutions are facing the same challenges as with the disposal of radioactive waste – misconceptions and wrong decisions from the past are becoming visible and are catching up with the debate on permanent and safe disposal and final storage of highly toxic waste.

But future radioactive or other waste projects face similar challenges. Licenses or facility construction say nothing about the long-term success of a repository project. The techniques and models developed must be tested and implemented on an industrial scale. Here, too, enormous challenges await the planners and operators of such facilities. In addition, new challenges arise, for example, from technical developments, environmental changes or social reorientations. Above all, technical development not only has the potential to support processes better or to show new approaches to solutions. Technology can also create new problems, as the example of the development of drilling technology in the last decade shows. If the intrusion risks into a repository at a depth of a few hundred meters seemed to be somewhat manageable – despite the severe accident in Lake Peigneur (Louisiana) in 1980 (see Perrow 2011)[1] – the vulnerability of a deep geological repository will increase massively due to the revolutionization of drilling technology. The originally envisioned marking programs for repositories will not be able to meet this challenge in the future and will likely be replaced by a system with active monitoring measures at the surface. It is one of many examples that show that the search for definitive sites for repositories will become even more complicated in the future, and new answers to new questions will emerge. At the same time, the rapid pace of technological development should also enable new approaches to solving the complex tasks of nuclear waste disposal.

Outlook

So how should all these challenges and uncertainties be dealt with in the future? As stated at the beginning of this paper, ideas as well as concepts change in the course and according to the contexts of time. Reliable medium-term forecasts about the development of technical systems and alternatives are hardly possible today. In particular, the enormous potential for technical development could become one of the key variables in the future direction of solutions for the disposal of the accumulated radioactive inventory. In addition, there are the great challenges associated with the governance of complex, socially demanding programs (see EKRA 2002), which can only be successfully implemented in a questioning and learning step-by-step process. Be that as it may: at present, planning for geological repositories at depths of 500 m is likely to continue.

However, it makes sense to look for other options. In the foreground is the second storage option for waste in deep boreholes of more than 5km depth. From a technical point of view, the prerequisites for the further development of such a solution are probably available. But in this case, too, similar questions arise as in the case of a repository project at a depth of 500m. The geology and hydrogeology must be explorable with sufficient certainty. The entire barrier system must be made fit for much larger physical and chemical stresses before any thought can be given to actually implementing such an option. The inventory, with potentially weapons-grade plutonium and americium isotopes, will also determine the storage life of this solution attempt in this case. The safety case for such a project is likely to place even higher demands on the reliability of the transport and dispersion models developed than is already the case for the "shallow" repository option.

Furthermore, there are still the options of a longer – but underground – interim storage (over 100 to 300 years), which would give more time to follow developments in science and technology and to pursue new treatment or immobilization techniques. In addition, there is still the question of the feasibility of developing transmutation technologies on industrial scale. We can therefore be curious to see what developments will take place in the next one or two generations and to what extent society is finally prepared to follow more sustainable paths of a real prevention or genuine circular economy in the waste sector as well. We can only hope that our institutions will make use of the opportunities to react flexibly to new situations and to fundamentally adapt disposal programs in a forward-looking manner.

1 https://www.youtube.com/watch?v=3cXnxGIDhOA

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