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Deep Geological Radioactive and Chemical Waste Disposal: Where We Stand and Where We Go

Marcos Buser, André Lambert and Walter Wildi

Introduction A recognized waste disposal concept and its troubles

For about 40 years, deep geological disposal of radioactive and chemical waste has become the most widely recognized strategy for eliminating waste. However, this pole position in the ranking of concepts contrasts with the daily lived situation in the field, as exposed here.

In 1976, the International Atomic Energy Agency published a brochure entitled “Radioactive Waste – Where from – Where to”; its cover picture showed a schematic cross-section of the Asse II repository for low and intermediate level waste in Wolfenbüttel (Germany). The contents of the brochure revealed that the nuclear industry and international organisations were confident about the feasibility and long-term safety of repositories for radioactive waste. This confidence persisted until after the turn of the millennium, despite all the difficulties and problems that were persistent and became apparent in the selection of sites for deep disposal infrastructures or the implementation of concrete projects. In 2002, a fire broke out in the Stocamine (Alsace, France) underground storage facility for chemo-toxic waste, which signalled the end of the project, and for the first questioned the long-term safety of geological repositories[1]. If this event could be attributed to the lack of safety culture in the final disposal of non-radioactive waste, this could not explain the water inflow from the overlying strata into the former Asse II experimental repository mine, which became known by the public in 2008. This was when the responsible operators publicly admitted for the first time that there was an inflow of water into the repositories and also the existence of potential hydrogeological hazards. This is a fact that was known by the monitoring staff since 1988 (or even before)[2]. Another German repository for radioactive waste in Morsleben (ERAM) showed similar stability problems and indications of leachate intrusion. These needed extensive stabilisation measures which cost billions of Euros[3].

Finally, between 2014 and 2017, various incidents and accidents occurred at the Waste Isolation Pilot Plant (WIPP, New Mexico), the repository for trans-uranium radioactive waste, which above all put into question the safety culture and governance of the facility[4]. The conditions for a safe implementation of a repository in the WIPP model project seemed to be particularly favorable, as the framework conditions for comprehensive, safety-oriented management of the project were clearly set. “Fifteen years of smooth, uneventful operations had lulled these sites into routines and practices inconsistent with the discipline and order that is in the centre of a ‘nuclear culture’”[5], as described by an insider about the loss of safety culture. Another observer regretted that the investigating authorities failed to identify the real causes of the event[6]. Lessons were, of course, learned from these incidents. Also, numerous investigations have been carried out on the incidents and accidents, and several reports have been published. However, the question regarding the effectiveness and sustainability of this learning process remains open.

“Lessons Learned” As a Basis to Establish a New Safety Culture

At least since the publication of Charles Perrow’s book on “Normal Accidents” in 1984 [7], planners, builders and operators of high-risk technologies and facilities have increasingly perceived the need to protect their large-scale technological projects and facilities from avoidable errors and from crashes that are very costly and can damage their image. This led to the development of methodological instruments in a wide variety of government and economy sectors, which were designed to detect and correct sources of errors at an early stage of a technological development and production process. A number of these methods are briefly mentioned below.

“Lessons learned” is the most frequently used term when it comes to evaluating running or future projects and programs. The term originally comes from the Anglo-Saxon industrial world and has subsequently spread and established itself in project and knowledge management[8]. What makes “lessons learned” so attractive as a term is a fact that it can be used in any field and it conveys a fundamentally positive message. Errors do not necessarily have to be understood in every detail; what is more important is how to eliminate them. With “lessons learned” one wants to show that a certain project and program is under control and that one is able and willing to learn and thus to correct errors. However, the term has weaknesses in the universal claims to accomplish projects and in its applicability. As a rule, “lessons learned” do not lay claim to standardization, and does not guarantee a more comprehensive quality assurance process; particularly it does not promise that a process can be reflected and reviewed in its entirety.

Over the last decades, a large number of different methods have been developed and used to evaluate and

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optimise processes, all of which follow the so-called "top-down" approach, i.e. the hierarchically prescribed decision paths. The range of methods developed is broad and extends from benchmarking in the field of economic comparability of processes and projects[9], through best practice in business administration[10], auditing and quality assurance programmes in the monitoring of companies and industrial processes[11], to risk management in the application of risky projects or risk technologies. The latter, in particular, is characterised by a strong standardisation of process sequences and contents, whereby this also includes organisational references. As a rule, the method of risk management differs fundamentally from that of "lessons learned" in terms of stringency and quality level of its procedure. As for other quality assessment processes, risk management is also defined by guidelines of the International Organization for Standardization (ISO), and in particular by (ISO 31000).

A method specially adapted to risk issues is the so-called safety culture, which is applied in high-risk areas such as nuclear energy, and also in medical fields[12]. The safety culture focuses not only on standardised procedures for determining risks (e.g. event and fault tree analyses, safety analysis) but also on the safety management of an organisation and therefore strongly addresses questions of the organisation of a company and the relationship between the company and its employees. This also includes the processes of supervision and control, the documentation of process sequences and establishment of chains of errors, the management of processes and conflict management, and the methods used for their correction. What makes safety culture fundamentally different from other processes is the emphasis on the term "culture", which implies that the people involved in a system actively shape a process. In this way, safety culture transcends the purely technical-scientific level and elevates to issues of organisational structures and the behaviour and behavioural interplay of organisations, their staff and collaborators. The safety culture in the field of nuclear energy was introduced after the Chernobyl reactor accident[13].

Of all these methods the one to be used to improve processes in a particular project depends on the preferences of the institutions and organisations doing the project. In our context, we will mainly apply terms that are characterised by standardised and well-defined methods.

A Review of Concepts and Failures in Nuclear Waste Management

A review of nuclear waste management over the past 75 years can be focussed on both the concepts proposed and the success of the strategies and projects implemented to date. The concepts of nuclear waste management developed over decades can be found in a large number of publications. It is worth remembering the writings of Bürgisser et al. (1979)[14], Milnes et al. (1980)[15], Milnes (1986)[16], the Swiss expert group EKRA (2000)[17], or the recently published research reports in the German Entria-Project (Appel et al. 2014/2015)[18]. They describe most of the concepts that have been put forward or implemented by different authors and institutions since the late 1940s (see **Table 1**). If we examine the maturity of these concepts, it is striking that most of the ideas for dealing with radioactive waste were not technically mature, were not considered, or could not be considered with respect to risk considerations. Also, most of these concepts were based on ideas that originated from university institutions or military agencies and whose technical implementation had not been tested adequately and deeply. An example of how quickly ideas are caught up by reality can be seen in the concept of final storage in polar ice shields, an idea that was widely discussed by scientists in the 1950s and that was then considered as completely obsolete a few decades later.

The situation was quite different, however, for the two concepts of dilution and containment, which emerged in the late 1940s. Dilution was implemented in the early days of nuclear energy use, mainly for cost reasons. It was done by sea dumping, dilution in rivers or dumping of solid, liquid or slurry materials in landfills or percolation ponds, as is also explained in many early publications[19]. At the military plutonium factory in Hanford (Washington), for example, the cooling water for the plutonium-breeding reactors was fed directly into the Columbia River via a settling basin. Other large research laboratories, such as the Oak Ridge National Laboratory (Tennessee), similarly handled their liquid waste. At the Windscale/Sellafield reprocessing plant, the conviction prevailed until well into the 1960s, when there were serious discussions about diluting the entire global inventory of highly active fission products in the oceans[20]. It was not until the end of the 1950s that the concerns of the radiation protection authorities became increasingly widespread and led to the gradual reduction and abandonment of the dilution principle. However, sea dumping of L / ILW waste continued into the 1980s[21]. In the 1970s, the increasing social discussion and questioning of the dilution and dumping strategies finally led to the specification of a strategy for the containment of radioactive substances, which is essentially covered by the multiple-barrier concept still valid today. The idea of containment, which can be traced back to the late 1940s[22] and early 1950s[23] received decisive impetus in the 1970s from the American programmes (ERDA/DOE), the "sub-seabed-disposal" project and the Swedish disposal programme (SKB)[24]. The concept of various barriers connected in series according to the principle of the Russian doll ("Multi-barriers") has

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Waste Management Concepts	Specification	Comment	Author and Year	Publication	Status of Implementation	Result and Success
HLW: immobilization in clay / ceramics	smectites (montmorillonites)		Hatch 1953; Ginell et al. 1954,	Amer. Scientist 41/3 Nucleonics 12/12	no direct disposal	laboratory-tested
HLW: vitrification & ceramics	borosilicate glasses and ceramics	proposed since 1951	Herrington et al. 1953; Rodger 1954	Nucleonics 11/9 Nucl. Engineering 50/	current application (vitrification)	laboratory-tested
HLW & LILW: disposal in near-surface strata	dump or land burial	as part of the nuclear fuel chain	Goodman 1949	Nucleonics 4/2	widely implemented	basically failed, wide pollutions
LILW (& HLW?): dilution & seepage	ventilation of gases / drainage of fluids		Beers 1949 ; Browder 1951, de Laguna et al. 1958	Nucleonics 4/4 & 6/1 Nucleonics 6/1	widely implemented	basically failed, wide pollutions
LILW: injection	in boreholes or wells		Herrington et al. 1953	Nucleonics 11/9	widely implemented (UdSSR, USA)	effects not known, DSP-principle
LILW (& HLW): sea dumping	dumping / dilution in sea water	regulated after 1972 by London Convent.	Claus 1955	IAEA 1955 P/848	widely implemented	basically failed, DSP-principle
HLW: subsea bed disposal	final disposal in marine sediments	from 1977 as “sub-seabed”-project	Evans 1952	NSA 8, 1954: 4929	project abandoned	not achieved
LILW & HLW: geological disposal	diverse host-rocks in mines	mostly in disused mines	Theis 1955 NAS 1957	IAEA 1955 P/564 Report	widely implemented	mostly damaged or under observation
HLW: disposal in subduction zones	submarine repository in subducting plate		Bostrom et al. 1979	Nature 1970, 228	idea abandoned	not developed
HLW: disposal in fault zones	deep-sea trenches		Renn 1955; Bogorov et al. 1959	IAEA P/569 IAEA 1958, P/2058	idea abandoned	not developed
HLW: disposal in ice	Antarctic repository	meltdown in ice	Philbert 1959	Atomkernenergie 4/3	idea abandoned	not developed
HLW: meltdown in the deep underground	deep underground melting	melting in atomically generated cavern	Gilmore 1977	NDC-Publication	idea abandoned	not developed
HLW: Disposal in space			Hollocher 1975	MIT Press	idea actually abandoned	not feasible (costs, risks)
HLW: partitioning and transmutation	long-lived species conversion	reduction of disposal time	Cecille et al. 1977 Hage, W., 1978	IAEA 1977 36/366 EUR-5897	research still in progress	uncertain (costs, success, risks)
Cost-based implementation of disp. practices	reduction of costs		Scott 1950	Nucleonics 6/1	still central	cost-related practice has consistently failed

Tab. 1.
Historical management concepts.

remained more or less unchanged even after several decades; it speaks for the great acceptance and the almost unchallenged conceptual stringency of this approach. However, the concrete success of this concept can only be “proven” more or less reliably after its implementation, the emplacement of the waste in the storage media and the longer-term monitoring of the repositories in the deep geological underground.

Two conclusions can be drawn at that stage from the compilation of the concepts for nuclear disposal:

- On the one hand, all relevant ideas and concepts of nuclear disposal were already formulated at a time when industrial use by nuclear power plants was beginning to emerge. Indeed, important scientific representatives of the nuclear community – first and foremost Enrico Fermi and James Conant – had pointed out the challenges and risks of radioactive residues and their disposal[25]. But the implementation of nuclear waste management was considered feasible a priori by the majority of involved institutions and scientists. This way of thinking has remained unchanged until today.
- On the other hand, it became clear from the very beginning which concepts of disposal were based solely on ideas that – published in scientific journals – were noticed by the scientific community and caused discussions at congresses and conferences. With the exception of the Sub-Seabed Disposal Project, which was led by the Woods-Hole Oceanographic Institute, Massachusetts, and Sandia Laboratories, Albuquerque,[26] none of the numerous ideas outside of continental disposal reached a conceptual technical and economic maturity that would have given reasons to trust and use them for a successful implementation of a project.

As early work on the topic shows, the implementation of long-term safe disposal was strongly influenced by the cost pressure on the various national reactor programmes[27]. A large part of the difficulties that arose in the actual disposal process is due to the lack of finance and implementation of better programmes. The idea of the chairman of the American Atomic Energy Commission, Lewis Strauss, that nuclear energy is “too cheap to meter”[28], reflected the prevailing opinion that nuclear disposal was not only feasible but also practically at zero cost. This misconception that economic criteria should take precedence over safety considerations is probably the main reason for the misguided developments in waste management policy to date. And so, it is not surprising that under such conditions, one waste management project after the other ran into difficulties and the list of initiated but failed projects is constantly growing **(Table 2)**. Contrary to the requirements of a comprehensive safety culture, the required practices have not been dealt systematically, which led to serious reservations in the acceptance of disposal programmes to this day, as we shall see later[29].

Trouble Shooting in Waste Management and Improving of Geological Waste Disposal Projects

The lessons learned by repository planners worldwide from past failures consisted primarily in adapting the concept for geological repositories. This adaptation was nothing more than a further development of the old

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[28] Strauss, Lewis, 1954, Remarks For The Delivery At The Founder’s Day Dinner, National Association of Science Writers, New York, 16. September 1954, Atomic Energy Commission, p. 9
[29] The cases of Asse and WIPP may be exceptions.

mining concept with one major difference: Disused mines should no longer be converted into repositories. New facilities were now planned which were to serve the sole purpose of final disposal. The first country to present a detailed concept for such a geological repository was Sweden. As mentioned in chapter 3, almost all newer nuclear waste disposal projects around the world followed this KBS – multi-barrier concept developed by the Swedish company SKB (Svensk Kärnbränslehantering AB) in the 1970ties. After that, many countries developed their specific design variants with regard to the importance of the individual barriers, to the access structures (ramp/shaft) or the positioning of the canisters in the disposal galleries. But these minor changes lastly did not deviate from the original concept, which still assumes a geological repository at depths of several hundred meters in a system of galleries. With this adaptation, the main conceptual flaw seemed to be resolved and the requirement to identify and correct the main planning flaw was satisfied. Further analyses, which sought answers to possible risk or break-points in the concepts and the procedure for implementing the programmes, were not required. The responsible institutions were satisfied with the results achieved and no longer questioned the emerging developments. Even before the turn of the millennium, it became clear that there was a need for action, as can be briefly illustrated by three aspects:

Public implication and responsibility

On the one hand, the official institutions entrusted with the project development have underestimated for a long time the problems concerning the social acceptance of repositories for long-lived highly toxic waste. If waste management projects are ever to be realized, they must be supported by the public opinion and the affected population. After decades of debate, this insight seems to be more or less accepted by all stakeholders. But the degree of involvement of concerned regions and people is still disputed. A fundamental question in this context is, how far can the rights and responsibilities of affected communities go? Is it a simple participation right, that makes discussions possible but does not go beyond them or that leaves decisions in the hands of the repository designers and authorities? Or do these latter want to leave some of the key decisions to those affected? If yes, how many? How much can and should be decided jointly? Is the blockage caused by "NIMBY" due to these questions? One can answer them partly from experience, but only partly. Today's projects are planned still exclusively based on scientific and technical expert knowledge. In contrast, the ethical, political, but also technical concerns of the public on questions of nuclear safety, public health and environmental impact are still treated negligently, as the Swiss case of the "sectoral plan for deep geological repositories" shows very clearly. These projects institutionalize "participation" and even public forums – so-called "regional conferences" – and claim to remedy these deficiencies. They do not, however, give the concerned population any real responsibility, i.e. no voice for co-decision, which ultimately strengthens the resistance against such projects. "Safety is not negotiable", as the Federal Office of Energy (SFOE) repeatedly stated. From the Office's point of view, the so-called "licence holder" or "operator" and his experts are responsible for safety, which is monitored by the authorities. However, how can it be explained that with the continuous

Repository, Owner	Waste-Type	Host Rock	Operation Period	Status of Implementation	Result and Success	Author and Year
Hutchinson-Mine, Kansas (USA), ORNL	HLW	salt	test-phase 1959 - 1961	tests with non-radioactive liquids and heaters	"encouraging but not conclusive"	Walker, S. jr., 2006
Lyons Kansas (USA), ORNL	HLW	salt	test-phase 1965 - 1968 Project 1970 - 1972	tests with fuel elements Site selection	site selection, abandoned (vulnerable site)	Boffey 1975, Walker, S.jr. 2009, Alley et al. 2013
Asse II Mine (FRG), (Test Disposal Site), several owners	LILW with TRU-wastes, CTW	salt	1967 - 1978 from 2008 onwards	in operation, remediation project	site abandoned (vulnerable site), remediation in planning	Möller 2008 BGE 2020
ERAM Morsleben GDR/FRG, several owners	LILW, CTW	salt	1971 -1998	in operation, remediation project	site abandoned (vulnerable site), remediation under way	Documentation of BGE
WIPP DOE	TRU-Wastes	salt	1999 - 2014, from 2017 onwards	in operation, remediation project completed	site still in operation, although seriously questioned	DOE 2014a, 2014b, 2015, Ialenti 2018, Klaus 2019
Olkiluoto (FI), Posiva	LILW	crystalline	since 1992	in operation	site in operation, long-term safety questioned	Buser 2019, WNWR 2019
Forsmark (SE), SKB	LILW	crystalline	since 1988	in operation	site in operation, long-term safety questioned	Buser 2019, WNWR 2019
Examples of shallow subsurface mines						
Hostim (HU), several owners	Research wastes	limestone	1959 - 1964, closure 1997	final repository	vulnerable site (limestone), long-term safety questioned	WNWR 2019
Mina Beta (ES) JEN/CIEMAT	LILW	crystalline	1961 - 1980	remediated	remediation successfully achieved	Lopez Perez et al 1976, Estratos 1987
Bratrstvi (CZ), Súrao	LILW (MIR)	pegmatites	since 1974	in operation	vulnerable site (uranium mine), long-term safety open	Woller 2008, WNWR 2019
Alcazar (CZ)	LILW, CTW	limestone	1959 - 1964, 1991	final repository, reopened 1991, higher toxic rad-waste and CTW removed	potentially vulnerable site, long-term safety open	Woller 2008
Richard II (CZ), Súrao	LILW ((MIR)	limestone	since 1964	in operation, refurbishment 2005-2007	potentially vulnerable site, long-term safety open	Woller 2008, WNWR 2019
ORNL (USA), injection in boreholes or wells	LILW/TRU-wastes	LILW/TRU-wastes	1950 - 1980ies	completed	monitoring data show remobilisation, results only partially available	ERDA 1977; ORNL, 1985; Stow et al. 1986
Russian sites, injection in boreholes or wells (USSR)	LILW (HLW)	LILW (HLW)	since 1957 (Tomsk-7, Krasnoyarsk-26, Dimitrovgrad etc.)	completed?	unknown	Spytsin et al. 1975; NDC 1977; Schneider et al. 2011

Tab. 2.
Implementation, result and success of geologic repositories for nuclear wastes (sources in bibliography).

occurrences of serious problems and accidents none – and really none – of the deep geological repository projects implemented to date have been able to meet the required quality standards **(Table 2)**. This is because failure to plan waste disposal as well as project to date puts the quality of expertise and control into question, which is a heavy burden on the acceptance of new projects. And this leads to a second fundamental weakness of nuclear waste management: Organization and safety culture.

Safety culture: "Desiring to promote an effective nuclear safety culture worldwide"

It is at the top of the list of objectives, as can be seen from the preamble (V) of the IAEA Joint Convention[30]. But if you then look for the concrete regulations, you will hardly find anything regarding safety culture in the field of geological waste repository planning processes. The conception and planning seem to have escaped the attention of a comprehensive supervisory process. Yet it is precisely the concepts that are the fundamental guard rails for safety, as the entire history of waste management of highly toxic waste shows. The fact that not a single formal overall review of the planning and implementation of repositories to date has been carried out **(Table 2)** clearly shows this deficit.

Industrial maturity

In this context, the questions relating to the long-term safety of deep geological repositories can be asked in a far more stringent manner. The statements made to date on the long-term safety of these planned repositories over periods of up to one million years are based exclusively on calculations from a safety analysis known as a safety case[31]. However, industrial experience and feasibility are rarely included in these considerations. The reason is understandable, as the IAEA correctly states in a publication from 2012: "While the maturity criterion can be applied to disposal facilities for radioactive waste, it has to be recognized that data on the actual long term performance of disposal facilities are not available"[32]. However, the question of the industrial maturity of a plant is the determining factor for the assessment of long-term safety. This maturity process can only be achieved by a step-by-step procedure and by knowledge and approach, based on experiments and experience. As with any industrial process, the development of a deep geological repository requires a step-by-step approach that is divided into clear stages and characterized by experimental validation. The success of the planning process is therefore largely determined by the quality and time dedicated to the implementation of this process, which has a decisive influence not only on the design of a deep geological repository itself but also on the possibilities for corrective action, as demonstrated, for example, by the current difficulties encountered in retrieving the emplaced waste from the Asse II experimental mine. It goes without saying that such a planning process, until industrial maturity is reached, also has an impact on the duration of interim waste storage.

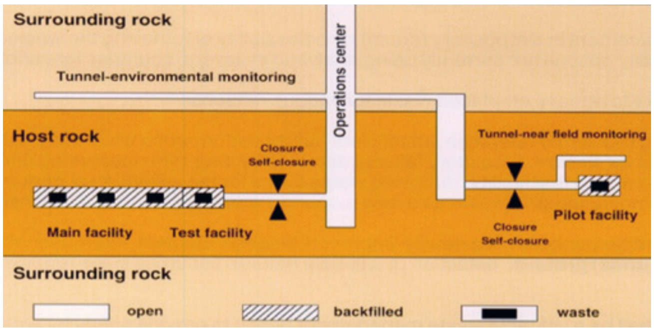

Fig. 1.
EKRA-Concept.

An Inclusive Planning Approach

As seen above, the strategy for deep geological disposal of radioactive waste is considered to be largely uncontested. However, it is also undisputed that solutions for a deep geological repository must be implemented at the highest possible quality level and on a socially acceptable basis over a long term. The first planning group to give these basic principles the necessary comprehensive consideration was the Expert Group on Disposal Concepts for Radioactive Waste (EKRA), which was set up by the competent Swiss ministry. In their first report published in 2000, they proposed a procedure that not only followed this step-by-step philosophy but also provided for the appropriate facilities to systematically monitor the planning and implementation process[33]. For this purpose, a phase of intensive experimental verification of the site is planned as well as the construction of a so-called pilot plant **(Figure 1)**; the entire emplacement and storage process is to be implemented and monitored with a representative waste quantity, as long as there is a social consensus on it. In a second report, EKRA later defined the guidelines for the structural monitoring and governance of the project[34]. EKRA was celebrated as a model of an acceptance-building approach and was more or less fully anchored in Switzerland's new nuclear energy legislation.

The developments observed since then, with a steady stream of new accidents, show that the current planning for deep geological repositories does not meet the requirements for a long-term safe planning process and needs to be fundamentally improved. If one wants to avoid similar developments as in the past, an inclusive planning approach is required that considers the findings from previous errors and problems:

- Without any doubt, the first improvement that is needed is a **safety culture** that deserves this name, as mentioned above, and which has to be a key element during the most important phase of the process – the conceptual design and planning phase.
- One has to recognize, that a **top-down approach,** as it has been followed in all previous planning processes for deep geological repositories, **must be supplemented by a bottom-up approach,** which ensures that the concerns of the regions and people directly affected are considered. A simple right of co-determination in the sense of consultation processes, as practiced in the Swiss sectoral plan procedure, is by no means sufficient to ensure the necessary acceptance by the population. Trust must also be established by subjecting security issues to an assessment process by the population directly

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affected. This is also a central element in ensuring the contemporary governance of such a long-term risk project.

- **The site selection and implementation process must be carried out in clearly defined steps and must be completed to industrial maturity.** Even the best project ideas are not sufficient and have to be complemented by an experiment based process that can be implemented on an industrial scale. This applies, for example, not only to the disposal of radioactive waste at depth but also to industrial retrieval in the case of undesirable developments, incidents or accidents. Of course, the safety culture in these phases is again a key process variable, as the recent example of the aviation industry (Boing 737 MAX 8) impressively shows.
- The last of the central elements of the process is the possible **step back option:** this is an essential condition in this process of site selection and in the realization of a deep geological repository. Corrections and returns must always be possible in a process that promises safety over 1 million years. The project must be managed in a way that it can actually maintain this extraordinarily high long-term safety benchmark.

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