

Repository for low- and intermediate-level waste: the planning of a complex scientific and technical challenge

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1 Introduction

First of all, I would like to thank the Ministry of Science and Research for inviting me to give this lecture. In view of the short time available for the discussion of such a complex topic, I would like to dive into media res. As we already explained 20 years ago on the occasion of the review of the global disposal concepts within the framework of the Swiss Commission for Radioactive Waste Disposal Concepts (EKRA), an analysis of the disposal options leads to a clear conclusion: according to current knowledge, no other option than the deep geological disposal of radioactive waste is emerging for the long-term management of radioactive waste. This conclusion has not changed fundamentally to date, and this is significant in view of the many negative experiences gained in the concrete implementation of this strategy. The difficulties involved in nuclear disposal had been recognized from the earliest times, and by none other than Enrico Fermi, who warned his fellow physicists as early as 1944 not to underestimate the large quantities of artificially produced radioactive materials and their effect on social acceptance. Other heavyweights of the time, such as James Conant, chemist, president of Harvard University, director of the National Defense Research Committee during the Second World War, expressed similar opinions. And these early doubts have not changed significantly to this day, as we will see in a moment.

2. A look back

Within the framework of the following remarks on the disposal programs for radioactive waste, I would like to try to give you an very short overview from a relatively high altitude of the status of nuclear disposal, with special attention to the repositories for low- and intermediate-level waste. These are statements that essentially deal with two perspectives: a retrospective view into the past, which is intended to answer the question why in almost 80 years not a single storage concept has been successfully implemented worldwide - at least for high-level waste, and at least for most repositories for low- and intermediate-level waste. And then, secondly, to look ahead into the future, which should show what we might have learned at best, or at least what could be derived from it, how to proceed in the future, especially in answering fundamental planning questions and in strategically setting up waste management programs. It is precisely this second question that cannot usefully be answered without having taken a self-critical look at the past. Nevertheless, I would like to make it quite clear that this review is not intended to make accusations of any kind against those responsible. It is, in fact, primarily about understanding from which context which decisions and actions were taken, which later turned out to be errors and mistakes. In other words, it is about learning from the mistakes of the past and developing better processes, decisions and programs that should not lead to such intergenerational effects and damage. So much for the objectives of this presentation.

2.1 Images in the context of time

So let us begin with a brief review: The next pictures - it is a selection of a few in a wealth of similar testimonies - show a small part of what was common practice in handling radioactive materials and waste almost 80, 70, 60 years ago and even later. The first picture you see is one of the plutonium-breeding reactors of the Hanford atomic bomb factory in Washington, which were built and operated from 1943 onwards as part of the US atomic bomb program. The cooling water for such reactors was taken directly from the Columbia River and returned to the river after decantation in a sedimentation basin. You can also see in this picture the contaminant plume in the river and the dilution effects of this disposal strategy desired by the operators. Liquid and solid waste was placed in tanks, in swamps, trenches for infiltration and gradually dilution in the Columbia Basin groundwater stream. Enclosed is an interpretation of the sorption effects of this infiltration practice, with cascading gradual retention of individual radionuclides - a figure that was used for decades to ensure that the disposal practices of the time would not cause further harm. In the meantime, the site is being completely remediated, the time needed to complete the work is well beyond 2070, and the cost of the total remediation of the site, which will be completed towards the end of the century, is estimated to be between 320 and 680 billion US dollars. (DOE, 2019, p. ES-3/ES-4)

Given such images and the demonstrable damage caused by such practices, one may well ask how it was possible to dump and dilute such obviously hazardous waste in this way directly into rivers or via regional groundwater sources. The explanation lies in the obviousness of such patterns of action in the context of the time. We must always remember that nuclear energy was a child of the war and was still at the center of political conflict between West and East after the end of the World War. The money flowed into the rearmament spiral, disposal was an annoying and at best expensive by-product, which should cost as little as possible. This also applies to the civil, i.e. so-called peaceful, use of nuclear energy. It was not until the protests of civil society that nuclear waste disposal became the focus of public attention. Little by little, questions arose as to why the many repository projects that had been started were repeatedly faced with problems or crashed.

2.2 Some examples of failed projects

From the following brief overview of a number of different projects of low and intermediate level waste, reasons for the problems and the failure of the projects can be identified. The text manuscript for this presentation contains references for further, scientifically verified information on these cases.

The basic strategies for final disposal in geological strata were already developed in the early 1950s, as shown, for example, by the 1957 report of the National Academy of Sciences.¹ Clay, salt and crystalline rocks were set as host rocks at an early stage, as a large number of publications from this period prove.² The first repository projects to be implemented in concrete terms focused on salt rocks for the simple reason that the infrastructure in the form of mines already existed. From the perspective of the time, dry salt in often huge salt deposits seemed to guarantee the safe confinement of radioactive waste. Erroneous assessments or decisions in the concepts or the procedures that were set in motion led to the projects crashing or to extremely difficult situations. Some examples of repositories for low and intermediate level waste:

Carey Salt Mine - Project Salt Vault, Lyons-Kansas (ORNL, 1965-1972): various field studies and experiments were carried out in the mine between 1965 and 1968, the project had to be abandoned

¹ NAS, National Academy of Sciences, 1957a, *The Disposal of Radioactive Wastes on Land*. Report of the Committee on Waste Disposal of the Division of the Earth Sciences, National Research Council

² EKRA, 2000, *Disposal Concepts for Radioactive Waste*, Final report, Federal Office of Energy, 31st January 2000

because of hydrogeological risks that could have led to the flooding of the mine (e.g. dozens of prospecting boreholes were simply overlooked as possible paths for groundwater ingress).³

Asse experimental repository (1965-1979): emplacement of 126,000 waste drums containing long-lived low-level radioactive waste and 16,000 casks (originally indicated only 1300) containing also long-lived intermediate-level radioactive waste. The increasing instability of the caverns and possible water inflows from the salt face had already been feared and predicted by the responsible senior mining office in 1965 and later by independent experts. From 1988 onwards, the water inflow from the salt flank increased and could no longer be dammed. This development was concealed by the operators for 20 years until it became public in 2008 and caused a storm of indignation. The repository was then placed under the control of the Federal Office for Radiation Protection (in the meantime, the Federal Company for Radioactive Waste Disposal [Bundesgesellschaft für Endlagerung]). The Asse experimental repository is now regarded as a remediation case par excellence, and the success or failure of retrieval of the waste will have a decisive impact on the social acceptance of deep geological repositories.⁴

Felsenau Mine (1969 - mid-1980s): The Felsenau gypsum mine in the gypsum and anhydrite layers of the Middle Muschelkalk of the Germanic Triassic was initially to receive low and intermediate level wastes from the neighbouring Beznau NPP. It was later even named as a site for high-level waste. However, the heterogeneous anhydrite layers, which are no more than 40 m thick, are permeable to water, especially via various karstified doline systems that cut the mine tunnels. Due to the unsuitability of the site, the project was abandoned in the 1980s. Today the mine is flooded.⁵

WIPP (Waste Isolation Pilot Plant) : I am attaching some important bibliographical references here, which deal with the safety culture and governance of programmes, both key concepts that explain the problems in WIPP.⁶ The crucial weakness in the WIPP project was - besides conceptual shortcomings - above all the dismantling of the safety culture. The accident on 14 February 2014 involving the explosion of a 50-gallon drum, as well as the extensive contamination of the deep repository itself and the release of small quantities of radioactivity into the environment, was due to obvious errors in the conditioning of the waste at the supplier's site (Los Alamos Laboratory). In the cask, nitrate salts reacted with an added organic sorbent (organic kitty litter). This accident, like the

³ Walker, Samuel Jr., 2006/2007, *An Atomic Garbage Dump for Kansas, The Controversy over the Lyons Radioactive Waste Repository, 1970-1972*, Kansas History: A Journal of the Central Plains 27 (Winter 2006–2007): 266–285, https://www.kshs.org/publicat/history/2006winter_walker.pdf (27.02.2020); Alley, William / Alley, Rosemarie (2013): *Too Hot To Touch. The Problem of High-Level Nuclear Waste*, Cambridge University Press

⁴ Möller, Detlev (2007): *Endlagerung radioaktiver Abfälle in der Bundesrepublik*, Studien zur Technik-, Wirtschafts- und Sozialgeschichte, Vol. 15, Peter Lang, Internationaler Verlag der Wissenschaften

⁵ Buser, M., 2017, Short-term and Long-term governance als Spannungsfeld bei der Entsorgung chemo-toxischer Abfälle, ITAS / Entria Arbeitsbericht 2017-02, <http://www.itas.kit.edu/pub/v/2017/buse17a.pdf> (29.01.2020)

⁶ Augustine N., Mies R. et al, 2014, *A New Foundation for the Nuclear Enterprise*, Report of the Congressional Advisory Panel on the Governance of the Nuclear Security Enterprise, November 2014; DOE, 2014a, *Accident Investigation Report, Underground Salt Haul Truck Fire at the Waste Isolation Pilot Plant on February 5, 2014*, Department of Energy (DOE), Office of Environmental Management, March 2014 ; DOE, 2014b, *Accident Investigation Report, Phase 1, Radiological Release Event at the Waste Isolation Pilot Plant on February 14, 2014*, Department of Energy (DOE), Office of Environmental Management, April 2014; Ialenti, Vincent, 2018, *Waste makes haste. How a campaign to speed up nuclear waste shipments shut down the WIPP long-term repository*, in: Bulletin of the Atomic Scientists, 74.; Klaus, David M., 2019, *What really went wrong at WIPP: an insider's view of two accidents at the only US underground nuclear waste repository*, in: Bulletin of the Atomic Scientists, 75, 4.; Mora, Carl J., 1999, *Sandia and the Waste Isolation Pilot Plant 1974 – 1999*, Sandia National Laboratories Albuquerque SAND99-1482

fire of a vehicle underground nine days before, showed the weaknesses in the safety culture and led to an interruption of the operation of the plant for about 3 years and remediation costs of 2 billion dollars in total. In 2017, part of a ceiling fell off, a type of accident that could pose another safety-related problem for the waste stored underneath. The series of accidents and problems at the WIPP is significant because the repository was praised worldwide as the lighthouse project of final disposal.

There are dozens of other case examples that show the same cause of malfunctioning over and over again. Like many other countries, Switzerland has so far faced the same problems in project development for low- and intermediate-level waste, which finally led to the abandonment of the repository project at Wellenberg in the Canton of Nidwalden in 2002.⁷

2.3 Reasons for problems and failure of concrete waste management projects

The reasons for failure can be traced back primarily to deficits in the organization and management of projects and the concrete handling of processes. The four examples considered show the same pattern again and again: incomplete clarifications of the geological siting process, belief in certain models of how the underground could be structured or how the transport of pollutants underground could work, insufficient system and risk clarifications, as the example of the 29 "forgotten" prospecting wells in the Lyons project shows, failure to comply with standardized procedures, the dismantling of independent supervision, authoritarian management structures, failure to listen to criticism, competence asymmetries between operators and supervision, etc. causes mainly based on governance deficiencies. This explanatory pattern has been recognized for decades and was explained in the works of sociologists such as Charles Perrow ("Normal Accidents")⁸ and Ullrich Beck (Risk Society)⁹ published in the early 1980s. Perrow also recognized the historical character of the problems, which were related to the military structures and the warlike development of the atomic bomb programs. At this point it should also be remembered that the safety culture in nuclear energy was actually only developed after the Chernobyl catastrophe and to this day has proved to be primarily the domain of the social sciences and psychology. The classical natural sciences still find it more difficult until today to incorporate questions of governance and process management into their programs than their colleagues in sociology or psychology. We will return to these questions in connection with the outlook at the end of the lecture.

3. Challenges of a planning process for an underground repository

The planning of a long-term safe and functioning deep geological repository poses enormous challenges for science and technology, for the organization of such a task and for the management of the programs. I would like to give you a number of examples to illustrate the complexity of the issues that need to be addressed and how they can be tackled at best. Some of them are:

Incorporation of previous experience in previous projects: In the first part of this presentation, problems and the failure of previous programs were briefly discussed. It would therefore be interesting to evaluate these experiences systematically and to explore the reasons for the problems and the failure. Interestingly, there is no such approach to systematically work through the problems of previous projects and plans for final disposal and learn from them - despite the large number of failures. To my knowledge, there is not a single international project - not even on the part of the International Atomic Energy Agency - that pursues such an approach. In a forward-looking learning process, it would be very useful to examine the factors that led to projects getting into difficulties

⁷ Scholz, R., Stauffacher, M. et al., 2006, *Entscheidungsprozesse Wellenberg*, Verlag Rüegger

⁸ Perrow, Charles, 1999, *Normal Accidents, Living with Risk Technologies - Updated Edition*, Princeton Paperbacks

⁹ Beck, Ullrich, 1992, *Risk Society, Towards a New Modernity*, Sage Publications

and having to be abandoned. Extremely important corrective measures are needed here, and I myself am currently working on a project to close this knowledge gap, at least in part. The enclosed table gives a first indication of how a comparative analysis of such projects could be carried out (Table 1). In my view, this basis is essential for future planning, especially with regard to the management of these highly complex projects and the development of a fault and safety culture. Following the Chernobyl accident, the International Atomic Energy Agency has laid down authoritative standards for the safety culture of nuclear power plants. Interestingly, however, many of these standards were not applied to the planning and implementation or operation of geological repositories, i.e. they were not included for whatever reasons. WIPP is a classic example of how a good safety concept that had previously been implemented can be undermined by cost savings and so-called "efficiency measures".

Planning security and follow-up problems: It is important to ensure greater planning security. So far, the planning institutions have managed to simply extend the implementation timetables in the event of difficulties. All project planning for radioactive repositories worldwide to date has been out of hand for decades. A good example of the consequences of this can be drawn from developments in Switzerland. The ongoing postponement of waste management planning into the future has meant that the operators of nuclear power plants, as the producers of the waste and thus as organizations responsible under the law (polluter pays principle), have had to construct three additional external interim storage facilities, including a central interim storage facility in Würenlingen (ZWILAG), in order to stack the growing volume of waste that has accumulated because it could not be transferred to a definitive storage facility in a timely manner. This shifted the problems to interim storage, which is now increasingly becoming a "*Providurium*" (extended storage).¹⁰ These interim storage facilities were designed for an operating time of originally 40 years. Now the responsible safety authorities must extend the operating periods of these interim storage facilities until a deep geological repository is ready for filling. This not only leads to additional costs (the operation of the ZWILAG, for example, costs about 50 million euros per year), but also raises security-related questions with regard to the ageing of the facility and the security systems, or protection against the current threat of terrorism or violent conflicts. The pressure on the various institutions is therefore growing strongly, especially with regard to the long-term interim storage of the highly radioactive waste, for example for maintenance costs, and with regard to the ageing of the existing unconditioned or conditioned waste and the associated problems with its repackaging. In the case of spent fuel elements, it is to be assumed, for example, that the cladding tubes made of zirconium alloys oxidize during cooling by air, as occurs during dry storage in transport and storage casks, and gradually lose their strength. The barrier function of the cladding would be impaired during longer storage periods and would possibly be lost, as investigations suggest.¹¹ Other processes to be considered include general or stress-related corrosion, material fatigue, and then, of course, cross-cutting effects, such as relationships between temperature profiles, chemical and radiochemical reactions, and the damage patterns and damage development over time (corrosion, stress cracks, deformations, etc.). Such developments would in turn have direct consequences on the repackaging process and the planning of the facilities required for the final conditioning of the waste for the repository, e.g. the provision of hot cells, of further conditioning facilities for such aged residues with fragments or remnants, which in turn would have to be repackaged. In addition, in the case of dry storage, there are also uncertainties regarding the condition of fuel element baskets, where corrosion damage and damage to weld seams may be present after a longer storage period, which could lead to serious

¹⁰ The World Nuclear Waste Report 2019, Focus Europe, https://www.boell.de/sites/default/files/2019-11/World_Nuclear_Waste_Report_2019_Focus_Europe_0.pdf (10.02.2020).

¹¹ Steinbrück, M., Böttcher, M., 2011, *Air oxidation of Zircaloy-4, M5® and ZIRLO™ cladding alloys at high temperatures*, Journal of nuclear materials, Vol. 414, Issue 2, 15. Juli 2011

problems during removal from transport and storage containers.¹² In the case of intermediate-level waste, such as the bituminization of intermediate-level radioactive sludges, the question of possible exothermic reactions arises, especially if such waste is stored in a closed environment. In the meantime, the phenomena of exothermic reactions (self-ignition) are somewhat better understood and there has been a certain all-clear for bituminized waste, provided that the temperatures in the waste are below 150°C, as recent studies suggest.¹³ But: such studies always show that new surprises can arise during the ageing of materials, which have an immediate effect on the planning process. The same applies to the corrosion of copper canisters in the Swedish and Finnish projects and, more recently, to reactions between the steel containers and the vitrified high-level waste, which also suggests a significantly reduced lifetime of these barriers. As these examples show, the task is extremely complex and presents the planners with incredible problems. So how can increased planning security be created so that project planning can be implemented over reasonable periods of time and at reasonably acceptable and budgetable costs?

In the case of low- and intermediate-level waste - and in contrast to high-level waste - not only the wider range of different types of waste must be considered, but also the different materials used for conditioning in deep geological disposal: metals in particular pose a problem in underground storage because of the expected gas formation caused by metal corrosion and bacterial consumption of organic matter (bituminous waste, plastic waste etc.). The inventory to be stored in the LLW/ILW is comparatively small compared to the HLW. Nevertheless, even in this case, long-lived isotopes ensure that the isolation time of the waste, 100,000 years, covers enormously long periods of time. The gas problem poses a particular challenge because such a repository must be watertight but gas-permeable. The extent to which such a requirement can be implemented at all is uncertain today.

Status of the geological concepts and storage designs: As in the rest of the world, Switzerland has based its search program for deep geological repositories on sediments such as marl, clay (and formerly salt rock) and crystalline rock. In the meantime, clays and their closest relatives have been given priority. However, Switzerland is a geologically hardly suitable country for nuclear waste disposal, which is why the search - after initial programs in the Alpine region (Wellenberg) - is concentrated in the north-western part of the country furthest from the Alps, where a so-called Opalinus Clay is located at an interesting depth of several hundred meters. The site search program is now in the third and final stage of the selection procedure. However, it is highly controversial. Not only external experts, but above all the cantons concerned are expressing their doubts about the direction being taken. In addition to certain geological issues, the most controversial aspects are the design of the repositories, namely the size of the caverns, the emplacement and backfilling concepts, but also the models for the discharge of substances. It is an exciting debate, not only from a scientific but also from a societal point of view.

The next figures show the design of the deep repository for low and intermediate level waste, with the eight large storage caverns for different types of waste, the test section and the pilot facility.¹⁴ In a ductile rock, such caverns must be naturally secured, with concrete and steel structures. How the rock will react to such an intervention is of course the subject of fierce debate, especially since a relatively wide excavated damaged zone (EDZ) is created around such a large cavern.

In the next figure you can see a compilation of the organic waste components, which include a wide range of organic matter. A number of experiments have been carried out in the Mont-Terri laboratory to study the gas formation of organic matter in the Opalinus Clay repository and to

¹² GRS, 2010, Sicherheitstechnische Aspekte der langfristigen Zwischenlagerung von bestrahlten Brennelementen und verglastem HAW, GRS-A-3597, S. 47-48, 122.ff.

¹³ ASN, 2019, Revue externe sur la gestion des déchets bituminés, Rapport final, Autorité de sûreté nucléaire, 28 juin 2019

¹⁴ see the different Reports of Nagra, 2008, 2014 and others on the Web-Site of Nagra (www.nagra.ch).

understand the reactions - especially potential sinks - and the reaction kinetics.¹⁵ The final products are mostly simple: H₂, CH₄ and CO₂. An attempt has been made to model the different reactions over time. These are actually good developments which are now trying to clarify important transport processes for radioactive substances from the repository by means of concrete experiments. The forecasts of the Swiss repository organization Nagra are promising, since it is postulated that the bacteria population can use the gas as a metabolic product and precipitate it again. However, it should be critically noted that these experiments were carried out on its own scale and that up-scaling of the results on a repository scale can bring unpleasant surprises. The same applies, of course, to the hydraulic hazard of the entire plant.

In addition, many techniques are not yet up to date that would guarantee successful application. This applies in particular to placement and sealing techniques, which pose a particular challenge, especially in the case of high-level waste and the confined conditions in the storage galleries. However, standards will also have to be set for deep geological repositories for low- and intermediate-level waste with caverns of over 120 m² cross-section in order to achieve industrial maturity in the construction and operation of such facilities. In Switzerland too, therefore, there is still a great deal to be done before it can even be assessed whether the chosen direction of underground exploration can provide a permanent solution for the existing radioactive waste.

4. Outlook: Resulting framework conditions of a planning process

I would like to briefly summarize the conclusions from the above in four points. If we want to minimize the risks of bad planning and failures, as we have seen again and again in the past, I believe that we should take four important elements into account:

Acknowledge the central role of a farsighted program management and safety culture: The governance of projects must be fundamentally improved. This concerns the role of the leading institution, as well as that of the supervisor (authorities), who should be given other means and competences to intervene in a process. It concerns the governance of processes, which would also need to be accompanied by other bodies in an independent manner (I am thinking here of the "National Monitoring Committee" set up in the Federal Republic of Germany or the "Regional Conferences" operating in various countries, which are even increasingly involved in the safety debate). Above all, governance requires a high level of scientific, technical and social competence on the part of those involved and an open culture in the handling of processes.

Recognizing and acknowledging the complexity of planning processes and the need to react openly and flexibly to new findings: The quality of planning (was in the past and) still is in most projects known to me insufficient. I repeat, this is not about criticism of institutions and people, but rather about an insight that should be put to good use. The complexity of such projects, the large number of disciplines that should interact, makes it necessary to develop other instruments in dealing with such complex tasks. To reflect these challenges, I have recently introduced the term "too big to manage" to show that even good governance is not enough to start and finish such a project successfully, and that other instruments must be developed accordingly, which must also allow for a reversal or regression of the strategies pursued so far.

The need to correct errors and make decisions reversible: It is clear from the above that a comprehensive error and safety culture is absolutely essential and that listening to and taking seriously both scientific objections and criticism from siting regions must be taken seriously. Decisions must be reversible, and setbacks must be possible. It is true that some highly contaminated sites are now being remediated, particularly those from the early days of atomic the age. With enormous effort, at enormous cost, and with risks for personnel that cannot be ignored. On the

¹⁵ Leupin, O. et al., 2016, *An assessment of the possible fate of gas generated in a repository for low- and intermediate level waste*, Technical Report 16-05, December 2016

other hand, the success in retrieving waste from deep underground repositories is limited, as the experience at the Asse repository or the underground storage site for chemo-toxic waste at Stocamine in Alsace shows. Without such evidence that waste can actually be safely retrieved without too much effort, it will hardly be possible to gain acceptance from the civil society concerned at specific new sites for the storage of radioactive waste.

Outlook on the further planning procedure for deep geological repositories: To conclude, I would like to draw a basic conclusion regarding the further planning procedure for deep geological repositories. Today we must go further than the Swiss EKRA Commission did in the years up to 2002, and not just consider long-term monitoring of deep geological repository planning and implementation. In view of the storage periods that are barely comprehensible from a human perspective - cited as between 100,000 and 1 million years - it makes sense not to define such a process from the outset as a definitive project that can be successfully implemented in a single planning and implementation step. All experience to date in the implementation of such programs has shown us that we should formulate our expectations much more cautiously, and that a step-by-step process that aims for and implements goals in stages and allows for ongoing corrections could take us much further than the hack programs implemented to date. This will, of course, trigger a new social debate on radioactive waste and nuclear technology, and will also raise fundamental questions about the global architecture of the future and a profound transformation of technology. Also in the sense that beneficial generations cannot simply dump their unpleasant and dangerous remnants underground and leave them for future generations. This also means starting from the most realistic contexts possible, however inadequate they may be.¹⁶ Above all, however, it is always important to ensure that strategies and projects are actually feasible in principle.

Thank you for your attention.

¹⁶ Georg Kreisler, Alles ist zulänglich, <https://www.youtube.com/watch?v=p8pH1Mmd2Ns>

Area	Repository	Asse	DMS	Stocamine	WIPP
Legal context					
• Legal Situation		Amalgam of laws, grey areas in application	Legal basis available	Legal basis available	Legal basis available
• site conformity		Originally yes, today no longer	Not legally compliant	Originally yes, today questionable	Yes, with reservations
• Conformity of operation		Not legally compliant	Not legally compliant	Not legally compliant	Not legally compliant
• Reversibility		No requirement	For interim storage facilities as a condition in the operating permit. Not respected	For interim storage facilities as a condition in the operating permit. Not respected	Provided à priori
Location, Geology					
• Choice of location		No site selection procedure	Site selection procedure overlooks exclusion criteria	No site selection procedure	Site selection procedure with shifts
• Host rock		rock salt, water-permeable in places	Reef limestone, permeable to water (karst)	rock salt, partly open along the old mine	rock salt, brine and gas inclusions
• Hydrogeology		Inflows for decades, slow flooding in progress	Inflows flow off again at the bottom of the mine	Inflows for decades, flooding in progress	Desert climate, de facto no flooding expected today
• Stability of the underground repository		No, strong convergences	Yes, but a lot of roof collapses	No, strong convergences	No, strong convergences
Waste and plant					
• Type of waste		Radioactive mixed waste	Chemo-toxic wastes, type residual landfill	Chemo-toxic waste, type UTD DK IV	TRU wastes (durable ATA)
• Conditioning		Partially, e.g. concrete shielding	Cement consolidation	Mostly not (waste loose in drums/big-bags)	Partly, in different containers
• Backfilling (inclusion)		No	Intended	No	No
• Recovery of waste		Required and foreseen	Is done (completely)	Restricted, in progress	Potentially possible
• Closures, shaft custody		After dismantling: planned	Mine filled with excavated material, no closure	Special closures provided, effect unknown	Special closures are required, effect unknown
Economic efficiency					
• Cost factor		Central for selected disposal path and operation	Central for selected disposal path and operation	Central for selected disposal path and operation	Important for selected disposal path, central for operation
Structures and cultures					
• Operating structures		Not Adequate	Not Adequate	Not Adequate	No (more) adequate
• Supervision		Not Adequate	Not Adequate	Not Adequate	Available (EEG), then rationalized away and overstrained
• Safety culture		None or not implemented	None or not implemented	None or not implemented	Existing, not systematically implemented

Table 1: An example of a comparative analysis