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Summary

While the use of nuclear energy is set to be phased out in Germany by April 2023, the management of high-level radioactive material remains a long-term task that will also concern future generations. With the Site Selection Act (StandAG), legislators have defined the regulatory framework for the site selection procedure currently under way for a deep geological repository[1] in Germany. The aim of the procedure is to ensure the best possible safety for a period of one million years in order to provide lasting protection for humans and the environment from possible harmful effects of high-level radioactive material. On the basis of current knowledge, disposal of the waste in a geological deep repository is the best option. Less consideration is usually given in this context to the time horizon until the deep repository is closed, which in all likelihood will extend into the next century. Assuming a delay of some 10 to 35 years in site selection, as estimated by the Bundesgesellschaft für Endlagerung mbH (BGE), the deep geological repository may not be closed until the middle of the 22nd century. A maintenance-free condition of the repository is only achieved after closure. This means that StandAG is merely a starting point for a process which science and society will have to actively address for some generations to come.

This long-term nature of the project, its great relevance to society and the legislators' demand for a learning process give rise to special requirements for the design of research programmes and the scientific research landscape. The assembled interdisciplinary group of experts has worked intensively on this subject and on future developments. The authors are aware that research programmes of the organisations involved in the procedure are currently evolving dynamically which means that a detailed analysis of this evolution is beyond the scope of this paper. Instead, the focus is on the medium- and long-term design of independent research as well as on overarching aspects which are summarised in the following key themes:

1. Establishing a long-term strategy and governance for the learning process

Considering the long period of time until a deep repository is completed and closed, it is vital to implement the project with determination so that high-level radioactive waste can be transferred as promptly as possible from the interim storage facilities designed for a limited period of time into the passively safe and maintenance-free state of a closed and sealed final repository. Care must nevertheless be taken to ensure that sufficient time is available both for the consideration of safety-relevant scientific and technical aspects and for the participatory design of the procedure. It is therefore important for the stakeholders involved to implement the learning process required by the Site Selection Act (StandAG) constructively and in the long term over a number of decades.

Research in a learning process must be open to new scientific findings, permanently monitoring and assessing such insights and incorporating them into the current state of knowledge. Successfully shaping the overall "nuclear waste management" project and the learning process organisationally over a number of generations requires a long-term strategy and governance, i. e. organisational structures and processes. This includes developing a waste management strategy, a future-oriented approach to research, and a research landscape which is sufficiently flexible to be capable of responding to unforeseen and, from today's perspective unforeseeable, developments. This is relevant not only to science and technology but also to the social sciences and thus requires an interdisciplinary approach.

In line with the recommendations of the Commission on the Storage of High-level Radioactive Waste (or Final Repository Commission for short), this research landscape should also include independent scientific involvement. This differs from the project-related research commissioned by the final repository project organisations the Bundesgesellschaft für Endlagerung mbH (BGE) and the Federal Office for the Safety of Nuclear Waste Management (BASE). Independent scientific involvement is intended to counteract the development of any "tunnel vision" which might arise from an excessively strong focus on the specific deep disposal project at hand. However, recent decades have seen much less interdisciplinary nuclear disposal and final repository research being initiated at universities and institutions of higher education. Putting such research back on a firm footing, considering appropriate research funding, will play a crucial role in the success of the final repository project in Germany. In this context, instruments for promoting and training young talent are also important in order to create attractive (study) opportunities and employment prospects for the specialists of future generations. Two examples of this are the integration of interdisciplinary modules including nuclear waste management into degree programmes in relevant disciplines, such as the geosciences, and the creation of interdisciplinary post-graduate research

1 | See information box in section 1 regarding the interchangeable use of the terms final repository and deep repository.

training groups. There will be a need in future for researchers and experts from diverse backgrounds with an understanding of the overall system not only for site selection as well as for the construction and operation of a deep repository, but also to provide independent and critical monitoring for the overall project.

2. Developing research infrastructure, methods and technologies with foresight

With regard to the entire course of the procedure, foresight will be essential when it comes to identifying research infrastructure, methods and technologies necessary at specific points in the procedure. Long lead times are frequently required to provide research infrastructure, such as underground research laboratories, data platforms, virtual and specialised experimental laboratories, which, among other things, enable research on radioactive materials. The development of repository containers and new technologies, such as exploration methods for characterising sites and sensors for repository monitoring, are further long-term projects. A technology forum which involves relevant industrial companies in the research programmes at an early stage would appear to be helpful in order to optimise costs and timing.

3. Strengthening exchange between society and research

As in previous decades, societal attention and concern regarding nuclear waste management will vary regionally and over time. Against this background, it is particularly important to develop and expand integrative research models which involve non-specialists and non-scientific stakeholders as initiators and questioners in transdisciplinary research projects relating to nuclear waste management and so sensitise them to the scientific aspects of final disposal. In doing so, it is important to maintain the motivation of all stakeholders to participate in the process over an extended period of time. Among other things, this also requires appropriate communication of complex scientific interrelationships. Such projects ideally lead to collective learning processes among all participants.

4. Intensifying and integrating social science research

The discussion of waste management plans should increasingly also take account of conceivable major changes to society as whole over the coming decades and further into the future. On this basis, conclusions can be drawn as to how a waste management project can be designed to be as robust as possible in the face of political, economic and societal change which might impede or even prevent safe emplacement of high-level radioactive waste in a deep repository and the transformation of the repository into a passive and maintenance-free state. Social science and humanities research must be correspondingly intensified and integrated into final repository research in order to address how issues around different societal futures can be incorporated into the ongoing procedure. The current war in Ukraine clearly shows that political developments which were considered improbable in Europe only a short time ago must also be taken into account.

5. Consolidating technically appropriate handling of major uncertainty

In comparison with alternative disposal routes, the concept of deep geological disposal offers the highest level of passive safety for the containment of high-level radioactive waste. At the same time, the safety assessments for a deep repository have to be carried out on the basis of assumptions that, given a time horizon of one million years, are sometimes inevitably associated with considerable uncertainty. There is accordingly still a need for further research projects which address the uncertainty associated, for example, with coupled long-term processes in deep repository systems and host rocks over such long time periods. However, uncertainty may also arise in the nearer future, including from sociotechnical and societal systems. Dealing with such uncertainty requires powerful methods, for example multi-criteria decision analyses, which permit transparent decision-making under uncertain circumstances.

6. Regularly evaluating research results against the current international state of knowledge

While safety assessments for deep repository projects worldwide are usually subjected to international review by the IAEA or OECD/NEA, there is no corresponding process for independently evaluating research on nuclear waste management issues. However, regular quality control and assurance of research programmes and results in the form of reviews by national and international experts (peer review) makes sense in order to achieve ongoing improvement. In Germany, this evaluation could for example be carried out by the Science and Humanities Council in cooperation with the National Citizens' Oversight Committee (NBG). A basic requirement here is for all relevant national reports and publications also to be published in English, which has not always been the case in the past. In view of the sometimes highly controversial discussion of scientific results and their significance for the safety of the disposal project, contact points should also be provided for dealing with cases of scientific dissent.

Internationally, some deep repository projects are already at a very advanced stage, for example in Finland, Sweden, Switzerland and France. An ongoing comparison with the international state of knowledge about deep repository systems in different host rocks will help to identify knowledge gaps and so define research projects which are to be carried out as a priority. The specificities of the German situation, for example the need for a comparative assessment in the selection procedure of repository concepts in three host rock formations over a number of procedural steps, must also be worked out for this purpose.

Project

Projektpartner

- acatech – German Academy of Science and Engineering (principal)
- Deutsche Akademie der Naturforscher Leopoldina e. V. – German National Academy of Sciences Leopoldina
- The Union of the German Academies of Sciences and Humanities

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Workshops and authors of "Long-term societal aspects" information box

The working group asked a panel of experts in social sciences and the humanities to consider the issue of "long-term societal aspects". Relevant considerations, which are presented in the information box in section 3.1.5, were discussed in two workshops. This text was written between October 2021 and early March 2022.

Invited participants
- Prof. Dr. Thomas G. Kirsch, University of Konstanz
- Prof. Dr. Frank Nullmeier, University of Bremen
- Prof. Dr. Andreas Reckwitz, Humboldt University of Berlin
- Prof. Dr. Hartmut Rosa, University of Jena
- Prof. Dr. Uwe Schimank, University of Bremen
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- Dr. Johannes Simböck, acatech Office – coordination

Experts in the working group workshop on 24 October 2019

- Steffen Kanitz, Bundesgesellschaft für Endlagerung mbH (BGE)
- Dr. Axel Liebscher, formerly Federal Office for the Safety of Nuclear Waste Management (BASE, formerly Federal Office for the Safety of Nuclear Waste Management, BfE); currently Bundesgesellschaft für Endlagerung mbH (BGE)
- Prof. Dr. Ralph Watzel, Federal Institute for Geosciences and Natural Resources (BGR)

Consultation and comment

- Dr. Andreas Gautschi, Independent consultant and formerly National Cooperative for the Disposal of Radioactive Waste (Nagra), Switzerland
- Prof. Dr. -Ing. Kurt Kugeler, RWTH Aachen University
- Prof. Dr. President (ret.) Hans-Joachim Kümpel, formerly Federal Institute for Geosciences and Natural Resources (BGR)
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- Prof. Dr. Miranda Schreurs, Technical University of Munich/ National Citizens' Oversight Committee

Project duration

04/2019–03/2023

1 Introduction

According to the current state of scientific knowledge, disposal[2] in deep geological strata is the best choice for the safe long-term disposal of high-level radioactive material. Given careful selection of an optimised technical disposal concept and suitable geological strata in which conditions have been shown to change only over extremely long periods of time, this option can provide the highest degree of long-term safe containment for high-level radioactive material in comparison with other disposal routes. For other disposal options on the Earth's surface, the impact of long-term changes due to humans, climate change or natural developments are much less readily forecast. Most countries which use nuclear energy are therefore pursuing the strategy of managing high-level radioactive substances by disposal in deep geological strata. Well advanced projects in Finland or Sweden, where repository facilities will be commissioned in the near future, show that it would appear to be possible to achieve deep geological disposal using currently available means, but that this will take decades due to the wide range of technical and societal challenges.

Terminology: final repository or deep repository?

This acatech DISCUSSION deals with research in connection with the emplacement of radioactive, in particular high-level radioactive, waste in the geological subsurface at a depth of at least several hundred metres. In German-speaking countries, there is some variation in the use of the terms "final disposal" and "deep disposal", a distinction which is also made in the English-speaking world: the International Atomic Energy Authority (IAEA) uses the term "deep geological disposal", while the Nuclear Energy Agency (NEA), an intergovernmental institution within the Organisation for Economic Co-operation and Development (OECD), uses the term "final disposal" for all types of repositories, including those in deep geological formations.

In the opinion of some stakeholders, the term "final disposal" is very much loaded due to value judgements made in connection with debates in society and politics, not least because it inherently includes an idea of finality. It was for this reason that the "Waste Management Concepts for Radioactive Waste" expert group recommended using the term "deep geological repository" in Switzerland's sectoral plan process. In terms of content, considerations regarding finality led to strategic decisions regarding the reversibility of procedural steps. The German procedure outlined in the report of the Final Repository Commission and defined in StandAG also provides various elements of reversibility. It contains the following key points:

- The procedure in its entirety is reversible, it permits a "change of direction while the process is under way to allow errors to be corrected".[3]
- During the operational phase, retrievability of the emplaced waste must be ensured. This means that the procedures for any retrieval must be planned technically, evaluated in safety terms and the necessary technical facilities kept in place, with the limitation that "the technical costs and time required for this purpose do not disproportionately exceed the costs required for emplacement".[4] As understood by the NEA, retrievability is a special case of reversibility, the technical process of emplacement being reversible.[5]
- The possibility of recovery must be provided for a period of 500 years after decommissioning (closure) of the final repository. Such recovery would be an unplanned emergency measure, for which "adequate provision" must be made.[6] Requirements regarding mechanical stability and traceability of the

2 | See adjacent information box regarding the choice of terminology.
3 | See StandAG 2017, § 2.
4 | See EndlSiAnfV 2020, § 13.
5 | See Wildi 2012.
6 | See EndlSiAnfV 2017, § 26, paragraph 2, clause 3.

containers and regarding documentation have been set out in this context.[7] In comparison with the planning for retrieval, this is a requirement of a distinctly lesser and different nature. Since the constraints for any emergency are unknown, it would accordingly make no sense to speak of "recoverability".

- Decommissioning (closure) is intended to create a state in which "passive and maintenance-free" safety is achieved[8] – no intervention or maintenance work should be necessary".[9] This is frequently also referred to as freedom from post-closure care. This also makes it clear that the primary intention is not to get the waste back out. The notion of passive and maintenance-free safety has no effect on surveillance and monitoring measures, for which no time limits are set, but safety is not intended to be dependent on such measures.

The Final Repository Commission describes the approach outlined in this way as "final disposal with reversibility" and speaks of "placement in a final repository mined in a deep geological formation"[10] (as opposed to the likewise discussed option of placement in boreholes some thousands of metres deep).

There are thus well-founded reasons for the use of both terms – "deep disposal" and "final disposal". The authors have therefore decided to use both terms interchangeably in this paper.

In Germany, the Site Selection Act (StandAG)[11] of 2017 defined a new legislative framework for the currently ongoing search for a final repository site. Historically, the search for a site has taken place in the context of the controversial debate in society around the use of nuclear energy (see section 2.1). After Gorleben had been the reference site for several decades and had been hotly disputed as a possible final repository site, StandAG set a new direction for the search for a site. The legislative provisions reflect the consensus reached by the "Commission on the Storage of High-level Radioactive Waste" (commonly known as the "Final Repository Commission"), which represented the spectrum of a broad range of societal groups, and provide a roadmap for the search for the final repository site with the greatest possible safety. In September 2020, the German waste management organisation appointed to conduct the site selection, Bundesgesellschaft für Endlagerung mbH (BGE), published an initial spatial delimitation of suitable areas in the "Interim Report on Sub-areas pursuant to § 13 StandAG".[12] This selection was discussed with the public in the relevant committees of the principal stakeholders in nuclear waste management (see information box) and in public participation symposia. This is the first milestone in the reorganised site selection procedure, which is to identify a site by 2031. This will be followed by the construction and commissioning of the final repository and, according to the National Waste Management Programme (NaPro), the emplacement of high-level radioactive waste around 2050.[13] Only after further decades of emplacement operation will the repository then be closed with subsequent monitoring (see section 2.2.1). It is becoming apparent that this timeline is likely to be subject to significant delay.[14] The BGE recently came to the same conclusion and estimated that the site selection process may be delayed by about 10 to 35 years.[15, 16]

Due to the long time horizon and the considerations involved, StandAG requires the institutions involved in the procedure – in particular, in addition to BGE, the Federal Office for the Safety of Nuclear Waste Management (BASE)[17] as the supervisory authority and the German National Citizens' Oversight Committee (NBG) – to form a "self-questioning" system which prevents a blinkered approach and fosters a culture which welcomes criticism. This requirement includes the organisational and procedural structure, the decisions to be taken in this structure, their scientific basis and the technologies used. Particular importance is attached to the task of

7 | See EndlSiAnfV 2020, § 14, paragraph 2, clause 1.
8 | See ibid., § 4, paragraph 2.
9 | See EndlSiAnfV 2017, § 26, paragraph 4.
10 | See Endlagerkommission 2016, 31.
11 | See VkENOG 2017.
12 | See BGE 2020.
13 | See BMUB 2015.
14 | See Thomauske/Kudla 2016.
15 | BGE 2022a.
16 | BGE 2022b.
17 | Formerly Federal Office for the Safety of Nuclear Waste Management (BfE).

continuously monitoring and taking account of the evolving state of knowledge in the relevant disciplines, maintaining data accordingly and, where necessary, promoting research and development. Building on this foundation, it is important to take account of the intertwined nature of the various disciplines in the site selection procedure and the construction of a deep geological repository.

Principal stakeholders in nuclear waste management

The principal stakeholders in nuclear waste management report to the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). Legislators have appointed BGE as the project administrator for the construction of a safe final repository for radioactive waste and established BASE, the specialist authority for nuclear safety issues, as the responsible supervisory and licensing authority. BASE is also responsible for public participation in the site selection procedure. NBG's mission is to oversee the project as a mediating and independent body and, in addition to the lead scientists, its members include citizens and public figures. Bundesgesellschaft für Zwischenlagerung mbH (BGZ) is additionally responsible for aspects of interim storage of radioactive waste.

Research institutions are involved in various ways in the site selection procedure as well as in the construction and operation of the deep repository. In addition to project-related research commissioned by BGE and BASE, the Final Repository Commission recommends that independent, basic scientific research across a broad range of disciplines, as well as research for civil society stakeholders, be included in the final repository project.[18] This will place particular demands on Germany's research landscape. The former federal government pointed out that it will remain necessary for Germany to continue maintaining and developing skills and expertise in nuclear technology and nuclear waste management as well as radiation protection, and so placed an emphasis on the importance of sustainably promoting young talent.[19] There is also a need for a pathway to develop skills and young talent because many of the currently available experts in the relevant disciplines are already institutionally involved at various points in work and processes for implementing site selection for a deep repository. This means that experts who are not yet involved could become rare, at least in Germany. Independent assessment is, however, vital not only for the quality and robustness of the solutions but also for the public's long-term trust in the procedure and its outcome.

This paper begins by identifying the particular challenges facing researchers in nuclear waste management which will extend many decades into the future, while safety aspects have to be considered over geological time periods. In addition, technical and fundamental scientific issues are associated with high levels of societal interest and concern.

A wide range of interdisciplinary research will be required to fully address and interconnect both the sociotechnical and societal levels of the project (see section 3.1) and the scientific and technical aspects of site selection and of deep geological disposal (see section 3.2). Some of the key themes listed as examples in the paper are already receiving attention in existing research agendas (BGE, BASE, research programmes funded by the ministries) and are set to be implemented in the near future so that they can take effect in the medium to long term. Research programmes directly relating to the final repository project are under development by BGE and BASE, the institutions driving and overseeing the procedure. The aim of this publication is therefore not to provide a detailed analysis of ongoing or past research activities.

Instead, its focus is on "independent" research, i.e. research whose direction must be defined with academic independence which requires, among other things, that research funding be structured accordingly. The authors of the paper aim to inspire a discussion of the design of research and the research landscape and to set out areas of activity concerning the necessary regulatory framework and structures for the best possible research strategy and the required research landscape (see sections 3.1 and 3.3). As recommended by the Final Repository Commission, these should enable not only the research commissioned by BGE and BASE, but also the stated independent basic research as well as research involving various social groups. The research strategy and research landscape should also pay attention to training young specialists who will be urgently needed in the coming years and decades, and to creating and maintaining the necessary research infrastructure. In addition, examples are provided of specific areas of technical development in which industry must also be involved at an early stage. These considerations are stated with the hope of stimulating resilient solutions over the course of the overall, decades-long procedure.

18 | See Endlagerkommission 2016.
19 | See BMWi 2020.

This publication gives no consideration to alternative or complementary technologies, for example partitioning and transmutation,[20] or disposal in very deep boreholes.[21, 22] There is also no discussion of joint transnational, multinational deep repository concepts. Although such ideas are certainly being explored and debated,[23] the current consensus is that, for ethical, moral, and legal reasons, each country is responsible for managing its own radioactive waste. In Germany, this principle is laid down in the Nuclear Energy Act.

20 | See acatech 2014.
21 | See Sandia 2012.
22 | See GRS 2017.
23 | See World Nuclear Association 2020.

2 Site selection and final disposal of high-level radioactive materials in Germany

2.1 A brief history of the site selection procedure

Germany has been tackling issues around the management and deep disposal of high-level radioactive materials for decades. As part of this, political decisions led to the discussion of a Nuclear Waste Management Centre including both a complex for reprocessing nuclear fuel and interim storage and final disposal facilities. In 1977, a possible site for the final disposal of high-level radioactive materials was selected in the salt dome near the town of Gorleben in Lower Saxony, and its suitability as a deep geological repository site was investigated in the course of exploratory work over the following decades. From today's perspective, the decision in favour of the Gorleben site was made with insufficient societal discussion and public participation. The selection and assessment of suitability criteria were not made transparent in the procedure. Resistance to the possible Gorleben site quickly grew among the public. The procedure did not involve a detailed comparison of sites, the search instead essentially being limited to Lower Saxony and salt domes as the host rock.[24] Moreover, some of the site selection criteria used at the time related to above-ground characteristics of the initially planned Nuclear Waste Management Centre with interim storage facility, reprocessing plant, conditioning plant and final repository. Due to public opposition, construction of a reprocessing plant was abandoned in 1979 while the procedure was ongoing. The idea of retaining Gorleben as a final repository site, on the other hand, has remained the subject of much controversy in politics, society and the scientific community.[25] The reorganisation of the site selection procedure in the first version of StandAG in 2013 led to the cessation of exploratory work and Gorleben entered the new procedure on an equal footing to other sites.

In 1999, while the Gorleben site was still being explored, the interdisciplinary "Working Group on the Selection Procedure for Final Repository Sites (AkEnd)" began its work on behalf of the Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) with the aim of establishing comprehensive scientific criteria for selecting a final repository site. In its final report in 2002, AkEnd emphasised not only the importance to the overall procedure of public participation, setting out, among other things, a procedural structure for a site selection without prior assumptions in terms of location, a "blank map" so to speak, but also the necessity for underground exploration of at least two sites to ensure a proper comparison.[26] However, the following years saw no restructuring of the site selection procedure and it was not until 2011 that an interdisciplinary project group presented an analysis,[27] which set out the "Gorleben plus" proposal that, while the Gorleben site should continue to be examined, alternative options should also be developed in parallel.[28]

In 2011, the reactor accident in Fukushima (Japan) occurred, as a result of which Germany decided to phase out the use of nuclear energy by mid-April 2023. This also gave new impetus to the search for a deep repository site, which ultimately resulted in a reorganisation of the site selection procedure by the first version of StandAG dating from 2013. Exploratory work in Gorleben was stopped. StandAG set out the aim of ensuring a transparent and science-based site selection procedure and outlined the stages of the site search. According to § 3 StandAG, the German Federal Parliament and Federal Council established the Final Repository Commission in 2014, whose final report from 2016 was incorporated into the 2017 amendment to the currently valid StandAG, which defines the starting point for the site selection as a blank map of Germany. A comprehensive comparative assessment of different host rocks and deep repository concepts is planned, with intensive involvement by the public and societal groups (for details, see section 2.2).

Provided that the federal government's decision to phase out the use of nuclear energy for power generation in April 2023 is maintained, the nature and quantity of high- and medium-level radioactive waste, which generates heat due to its high radioactivity, is well known: according to BGE, 10,500 tonnes of high-level radioactive waste from fuel assemblies will have accumulated by 2080.[29]

24 | See Endlagerkommission 2016.
25 | See ibid.
26 | See AkEnd 2002.
27 | This was carried out as part of a project by Europäische Akademie zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen Bad Neuenahr-Ahrweiler GmbH (now IQIB GmbH).
28 | See Streffer et al. 2011.
29 | See BGE 2021.

BMU similarly assumes a volume of approximately 10,100 tonnes of spent fuel assemblies plus around 8,000 stainless steel canisters holding vitrified waste. The latter originate from the reprocessing of German fuel assemblies in France and Great Britain, which was carried out under cooperation agreements until 2005.[30] Depending on the type of packaging and container used, the total volume of such waste could be around 27,000 cubic metres. Stacked to a height of three metres, they would then occupy an area roughly the size of a football pitch. However, due to the evolution of heat by the waste, an area of approximately 3 to 10 square kilometres is required in a deep geological repository, depending on the nature of the host rock and emplacement.[31, 32, 33] Although the volume of these types of waste is relatively small compared to low- and medium-level radioactive waste, they contain over 99 per cent of the total radioactivity of all waste.

Approximately 300,000 cubic metres of low- and medium-level radioactive waste, which generates negligible heat, from research, operation and dismantling of nuclear power plants are set to be emplaced in the approved Konrad shaft repository from 2027. It is estimated that up to an additional approximately 320,000 cubic metres of low- and medium-level radioactive waste will arise during waste retrieval from the Asse II salt mine and from uranium enrichment. The current plan is for this waste to be emplaced in a separate mined final repository on the same site as the high-level radioactive waste.[34, 35] According to StandAG, this is permissible providing that it does not compromise the safety of the high-level radioactive waste repository. However, nothing has been determined in this regard. Thanks to the comparatively low evolution of heat, the repository area required for this waste will be significantly smaller than that for high-level radioactive waste despite the higher volumes.

Deep geological disposal worldwide

High-level radioactive waste is generally managed at national level. As a result, management projects are many and varied worldwide, with all existing national procedures providing for management in deep geological strata. To date, however, no deep repository has yet been completed or commissioned, and only a few countries have begun construction of a deep repository or are set to commission one in the medium term. The construction of a deep repository is most advanced in Finland, where commissioning is expected in 2025, and in France, Sweden and Switzerland, where a deep repository site has already been identified. Elsewhere, site options have been shortlisted before the final siting decision is made, for example in the Czech Republic and Canada. In the USA, the procedure is currently at a standstill for political reasons following a long examination of the Yucca Mountain site. Sites have been selected in Russia and China where underground research laboratories are being set up for further exploration and research. In the past, many projects have experienced delays, interruptions and sometimes even restarts due to a lack of public acceptance.[36] One special feature of site selection in Sweden is that communities were willing to apply voluntarily.[37] In Sweden and Finland, the choice ultimately fell on sites where there were already nuclear power plants. The positive attitude of the local population towards the use of nuclear energy and nuclear facilities would thus appear to have had an impact on the acceptance of a future deep geological repository. In both countries, the local authorities concerned had a right of veto but chose not to exercise it. Differences and effects in relation to the inclusion in the Finnish and Swedish procedures of the local communities of possible sites are described in detail in the literature.[38]

The timelines of the procedures in different countries reflect differing societal viewpoints on nuclear power and deep disposal. In Sweden, because communities could apply to host deep geological repositories, there was no need to compare sites on the basis of a white map, as

30 | See BMUB 2015.
31 | See DBE TEC 2016.
32 | See Bundestagsdrucksache 18/11398 2017.
33 | See BGE 2020.
34 | See BMUB 2015.
35 | See EndlSiAnfV 2020.
36 | See NWTRB 2016.
37 | See Kari et al. 2021.
38 | See ibid.

in Germany, since the corresponding scientific investigations also showed suitability. Geological conditions also differ significantly internationally and have an impact on the site selection procedure. In Scandinavian countries, for instance, virtually all suitable formations occur in crystalline rock while in other countries potential sites primarily occur in claystone.

By way of example, figure 1 shows the timeline of the procedure for deep repository construction in Sweden. It is apparent that even a comparatively rapid process, where the majority of the local population had a positive opinion and only one type of host rock was considered, is an intergenerational undertaking.

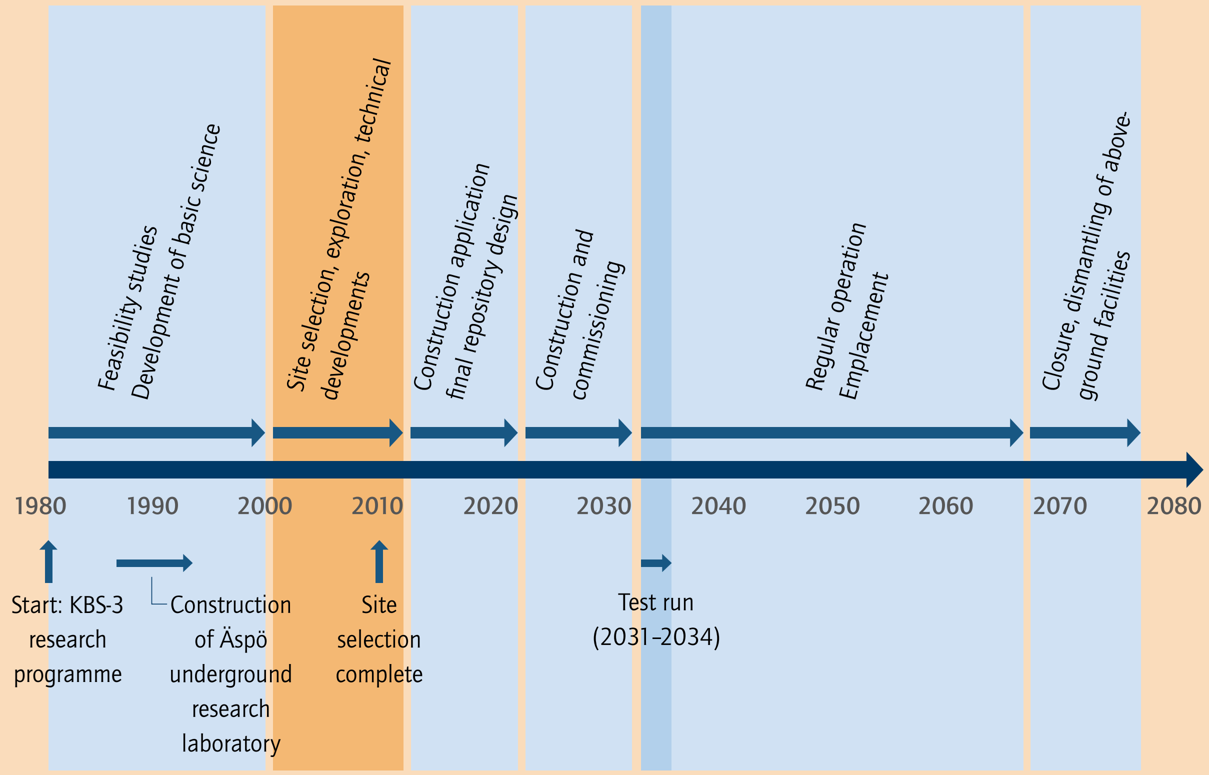

Figure 1: Timeline of a deep repository project with Sweden as the example (source: own presentation after SKB 2013, 2019). Note: “KBS-3” is the name of the Swedish repository concept for spent fuel assemblies.

2.2 Site selection procedure and final disposal

2.2.1 Planned stages of the disposal project

It is possible to identify various stages in Germany's ongoing site selection procedure and in the operation of a deep repository (figure 2), site selection being only the first stage. In September 2020, BGE published its "Interim Report on Sub-areas", an initial narrowing down of potential site areas on the basis of statutorily defined exclusion criteria, minimum requirements and consideration criteria.[39] These sub-areas cover more than half of Germany's total area. The interim report was publicly discussed at the sub-area symposium, the first statutorily required participation format in the search for a site for the deep geological disposal of high-level radioactive waste. The suggestions made and objections raised will be taken into account in the remainder of the procedure.

After application of further criteria and provisional safety assessments, StandAG provides that BGE should propose site regions for above-ground exploration. These proposals are reviewed by BASE and publicly discussed in "regional conferences" in the individual proposed regions. Finally, the Federal Parliament should decide in which regions the above-ground exploration should proceed. The further narrowing down of possible sites on the basis of the above-ground exploration should provide at least two sites which, again after public participation, review by BASE and a Federal Parliament decision, will be subject to underground exploration in the further course of the procedure. Once the underground exploration is complete, StandAG specifies that the Federal Parliament should make a definitive site selection, if possible by 2031.

Considerable doubt has, however, repeatedly been cast on the achievability of this ambitious goal; this selection process may possibly take years or even decades longer.[40] The BGE recently concurred and estimated that the site selection process will likely be delayed by 10 to 35 years.[41, 42] The authors consider a moderate delay in the timetable to be justified in order to meet the public's expectations of the procedure. At the same time, however, due to the limited duration of the operating licences for the interim storage facilities and also in the interest of intergenerational justice, there is an urgent need to implement the procedure as quickly as possible.

The second stage, which is intended via the licensing procedure to lead to commissioning of the mined final repository in 2051, would then begin correspondingly later and possibly extend to the end of the century or beyond. If the third stage, operation of the repository with emplacement of the waste, is assumed to last 30 years, as is officially the case, the fourth stage of monitoring, proposed by the Final Repository Commission but not yet laid down in law, would be able to begin in 2080 at the earliest, but possibly not until the 22nd century. During this phase, the waste must still continue to be retrievable. This requires that, in the event of waste retrieval, infrastructure and specialised personnel must be provided to enable safe handling of the waste. Subsequently, after an as yet undefined period of time, closure of the facility will be started. All in all, the time of decommissioning, which is intended to render the repository "passive and maintenance-free",[43] would be reached at the earliest at the end of the 21st century, but possibly also distinctly later depending on the course of the procedure. From this point on, recovery of the waste should remain possible for another 500 years.[44] However, unlike retrieval, while recovery must be possible in principle, technical infrastructure does not have to be put in place for this purpose. In summary, it can be stated that, depending on the stage, it is necessary to take account of very different time horizons which, when viewing the deep repository project as a whole, are extremely long by human planning standards.

2.2.2 Consequences of the long-term nature of the disposal project

The timing of the repository project already has short- and medium-term consequences for the interim storage of high-level radioactive waste. Until a repository is commissioned, this will remain in transport and storage containers in the interim storage facilities, some of which are centralised facilities, for example in Ahaus, Gorleben and Lubmin, while others are located at nuclear power plant sites. In the light of the site selection and repository construction procedure, it is to be anticipated that the provided licence period of forty years for the storage of high-level radioactive waste in CASTOR containers will be significantly

39 | See BGE 2020.
40 | See Thomauske/Kudla 2016.
41 | BGE 2022a.
42 | BGE 2022b.
43 | See EndlSiAnfV 2020, § 4, paragraph 2.
44 | See StandAG 2017.

exceeded for a large proportion of them. The high-level radioactive waste may possibly have to be kept in interim storage in its respective local authority areas for decades longer than originally agreed. This harbours the potential for social conflict and makes it necessary to maintain protective measures, for example against terrorist attack, in the long term. In addition, technical questions remain unanswered regarding the safety and handling characteristics of the spent fuel assemblies after extended interim storage.

Current plans for the long-term deep repository project are based on the tacit assumption that relatively stable political, economic and social structures will remain in place in Germany over this period. In view of the periods of time outlined above, however, it is not necessarily possible to assume that the situation will remain stable in the long term (see information box "Long-term societal aspects", section 3.1.5). Possible changes in the political, economic and social framework must therefore be taken into account. For instance, a major crisis or (natural) disaster which causes politicians and society to set priorities other than continuing a nuclear waste management project cannot be ruled out in the future. The armed conflict in Ukraine clearly shows that political developments which were considered improbable in Europe only a short time ago must also be taken into account. However, a look at Europe's eventful history over the past century with its armed conflicts and severe economic crises also provides further proof. It therefore makes sense to consider how the "nuclear waste management" project can be made sufficiently robust that it does not, for example, break down before a largely passive safe state, i. e. reliable containment of the waste without the necessity for continuous human guarding or maintenance, is achieved.

The described consequences of the long-term nature of the deep repository project underline the urgency of the search for a site and the construction of a repository, as well as the importance of foresighted, accompanying research on sociotechnical, societal and scientific/technical aspects. The procedure must be pursued with determination, it being vital to ensure public participation as well as to exercise the utmost care regarding safety-related measures.

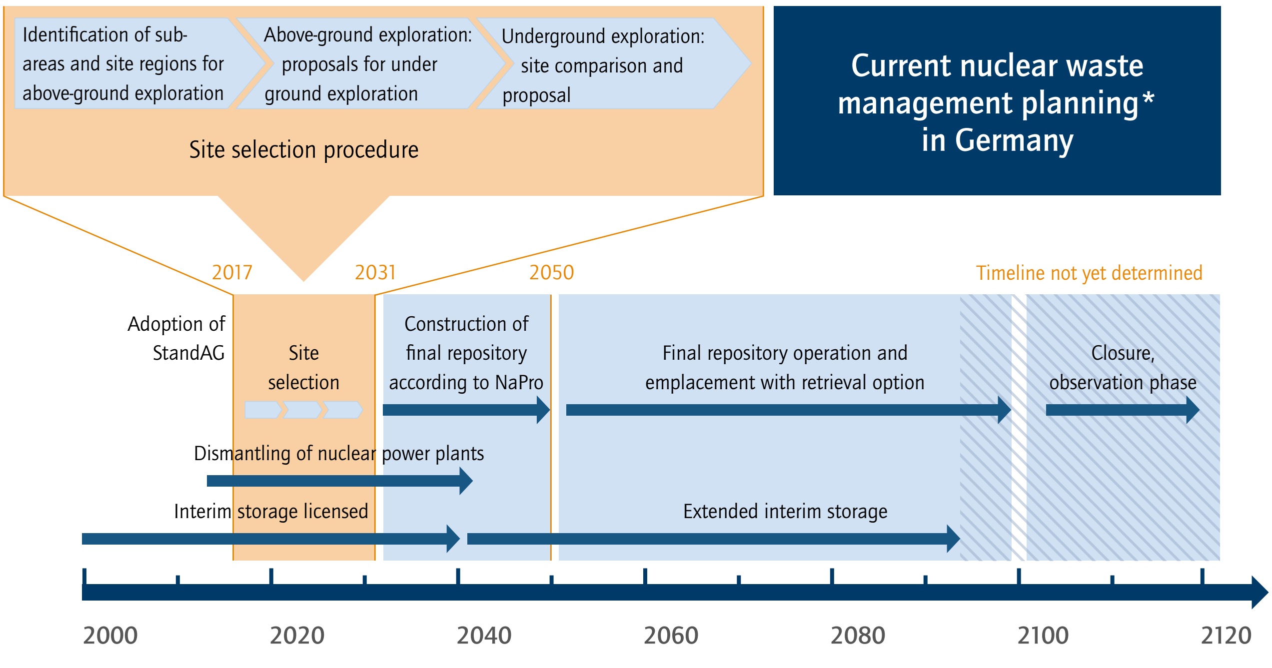

Figure 2: Time scale of current plans for the final disposal of high-level radioactive waste in Germany according to StandAG and National Waste Management Programme. The figure describes the planning objectives defined in the procedure. The likely delay of 10 to 35 years, as assessed by the BGE, pushes back the time horizon correspondingly (source: own presentation after BMUB 2015, BGE 2020).

2.2.3 Geological timescales as the basis and motivation for deep geological disposal

The timescales with which the safety assessments for a repository for high-level radioactive waste are concerned are of a different order of magnitude. StandAG requires the best possible safety for humans and the environment for a period of one million years. The public perception is that the levels of unpredictability and uncertainty associated with such time frames often appear too great and that statements regarding safety are largely implausible.

Over the course of decades of research into the safe management of radioactive waste, the concept of deep disposal of radioactive waste at depths of several hundred metres in very old geological formations such as crystalline rock, claystone and rock salt has ultimately prevailed. This is based on the idea of taking advantage of the long-term stability of these geological formations: changes in the deep subsurface often occur very slowly and with only minor changes over many millions of years. These are also referred to as "geological timescales" which permit safety statements and forecasts on the long-term development of the system to be made. Moreover, deep geological storage offers the highest level of passive safety. Other technologies which have been discussed, such as disposal in space or emplacement in deep-sea sediments, subduction zones, or polar glacial ice, have failed to gain acceptance in part because it is less possible to provide an accurate forecast of how reliably the high-level radioactive material can be kept away from the biosphere than it is for the geological formations mentioned above.

On the basis of the criteria and requirements set out for a final repository in StandAG, the only formations which will be approved are those for which, according to the current state of knowledge, no developments detrimental to safety are to be anticipated over a period of one million years. Safety assessments deal in detail with the effects of plausibly occurring scenarios in which various events and processes act upon a deep repository system. Even processes with very low probability of occurrence can be relevant over this extremely long timescale. A "good" repository concept must prove to be robust and resilient should such factors materialise and must meet statutory safety objectives even under unfavourable conditions. This applies, for example, to the barrier effect, i. e. obstruction or prevention of fluid access to the waste or the retention of radioactive substances which might be released from the waste packages. In general, safety assessments with a time horizon of one million years do not provide absolute predictions, but rather safety indicators for evaluating scenarios which are subject to uncertainty. In their entirety, these scenarios are intended to cover the entire range of evolutions which the deep repository system can actually take.[45] The extremely long-term assessment of some aspects is subject to clear limitations. For instance, radiological dose calculations which assume present-day dietary habits and climatic conditions cannot be used to infer the future hundreds or thousands of years from now. The results should here instead be regarded as safety indicators, without any claim to be able actually to predict the real dietary habits of human societies in the distant future.

The selection of the best possible site for a deep geological repository is thus still subject to uncertainty and unpredictability, factors which have to be taken into account and presented in a generally understandable way in the safety assessment documentation.[46] In general, the reliability of a forecast declines with the length of the time period considered. At the same time, however, it must be borne in mind that the inventory of various radionuclides and the radiotoxicity of the waste will decrease to the level of naturally occurring uranium ore deposits within several hundred thousand years due to radioactive decay. In other words, while the uncertainty of safety assessments increases with an increasing time horizon, the radiological hazard potential of the high-level radioactive material declines at the same time. Nevertheless, the assessment period of hundreds of thousands of years also requires consideration of events which are considered improbable, such as the future inadvertent intrusion of humans into a deep repository constructed in the distant past.

45 | See NEA 2009.
46 | See ibid.

2.3 Final repository research in Germany

2.3.1 Germany's research landscape

Compared with the situation in other countries, Germany's research landscape on deep disposal issues is complex. At the federal level, until 2022 three ministries were responsible for nuclear waste management research. Figure 3 outlines the allocation of nuclear safety research tasks which applied until then. The principal stakeholders in nuclear waste management (see information box "Principal stakeholders in nuclear waste management") were and still are associated with BMU (now BMUV) and, to fulfil their mission, develop research programmes directly related to their specific area of responsibility, some of which they implement themselves and others they commission. In addition, NBG (not shown in figure 3) initiates studies but is not a research funding institution. On the basis of the decisions of the current federal government, this structure will continue to remain in place.

As part of the federal government's 7th Energy Research Programme, the Federal Ministry for Economic Affairs and Energy (BMWi) funded research projects on topics relating to nuclear waste management which were organised by the project administrator it appointed.[47] These projects related to application-oriented basic research, but were also explicitly directed towards promoting young talent in the light of the federal government's stated objective of developing skills in matters of nuclear safety.[48] Thematically, there are overlaps with research topics of the institutions BGE, BGZ and BASE which are associated with BMU. The projects are handled by universities, non-university research institutions and/or companies. In addition, repository research took place within the framework of BMWi departmental research in subordinate federal agencies: the Federal Institute for Geosciences and Natural Resources (BGR) conducts research in the field of geosciences and the Federal Institute for Materials Research and Testing (BAM) on materials science topics.

In late 2021, the federal government modified some responsibilities. It was accordingly decided to transfer nuclear safety and waste management research from BMWi (now: Federal Ministry for Economic Affairs and Climate Action; BMWK) to the new Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). The associated implementation and changes are not yet foreseeable at the time of completion of this paper in December 2022.

The Federal Ministry of Education and Research (BMBF) is funding research and development for nuclear waste management primarily via its partial funding of the Helmholtz Association's "Nuclear Waste Management, Safety and Radiation Research (NUSAFE)"[49] research programme. In addition, again as part of the federal government's 7th Energy Research Programme, BMBF is funding other research projects on topics relating to nuclear safety and waste management, radiation research and the dismantling of nuclear facilities (FORKA).[50, 51] The projects range from very basic scientific topics directed towards maintaining skills to highly applied technical developments for dismantling technologies. In this case too, companies are involved alongside university and non-university research institutions. Many of the institutions involved in final repository research in Germany have come together in the German Association for Repository Research (DAEF) where they regularly exchange information. Many of the stated stakeholders cooperate with partner organisations from other European countries within the framework of the "European Joint Programme on Radioactive Waste Management (EURAD)"[52] (see also section 3.2). Further international collaborative research is taking place in connection with underground rock laboratories and under the umbrella of the "Implementing Geological Disposal of Radioactive Waste (IGD-TP)"[53] technology platform, the NEA/OECD and the IAEA.

Even if the three ministries involved (see figure 3) have so far focused on different sub-areas of research and development and their research programmes have differed in terms of funding types and potential funding recipients, the boundaries were not sharply defined. For example, BMWi-funded research projects were not solely restricted to application-oriented basic research (see figure 3). In addition, contract research for final repository organisations can also take place in universities and institutions of higher education, while research institutes in government agencies or the Helmholtz Association likewise have the opportunity to work to a limited extent on research topics outside their respective research programmes.

47 | See BMWi 2021.
48 | See BMWi 2020.
49 | See Helmholtz-Gemeinschaft 2022.
50 | See BMBF 2017.
51 | See BMBF 2021.
52 | See European Commission 2021.
53 | See IGD-TP 2021.

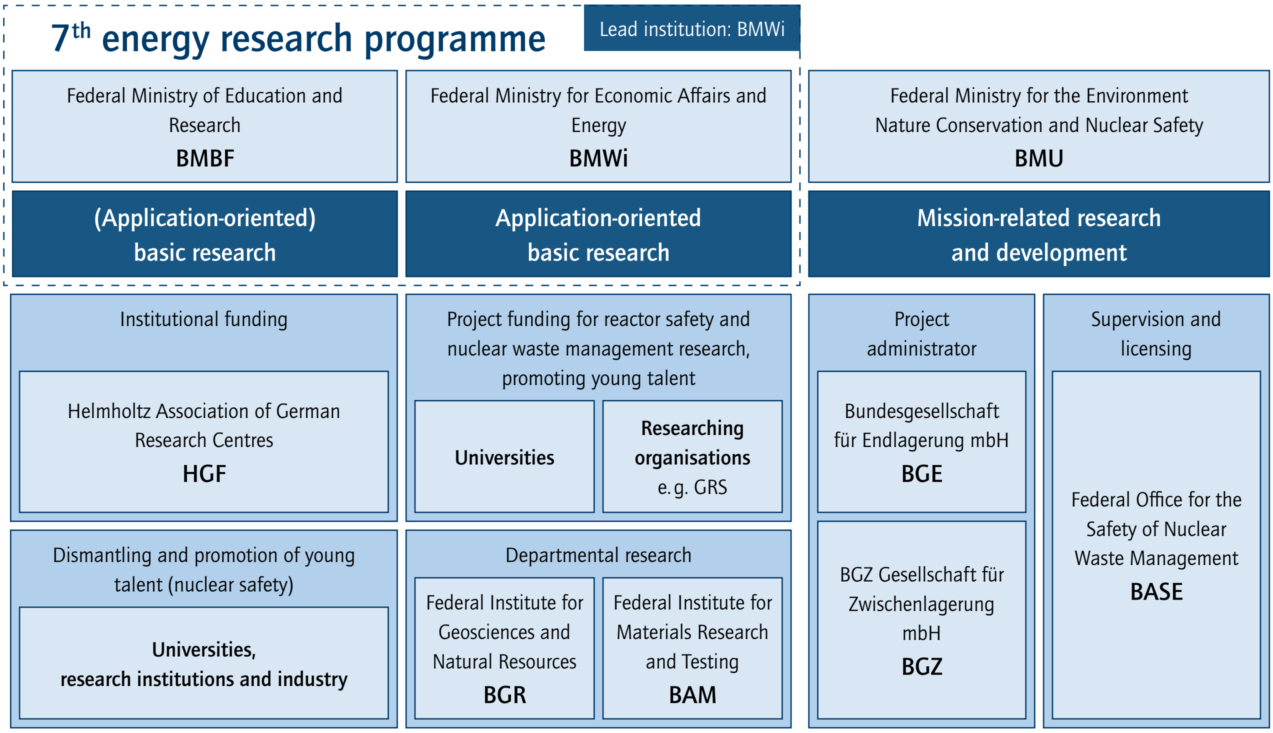

Figure 3: Allocation of nuclear safety research tasks in Germany until 2022. The changes to some responsibilities made by the new federal government in late 2021 are not shown here. For instance, the project funding for reactor safety and nuclear waste management research and for promoting young talent have now been transferred from BMWi (now BMWK) to BMUV's area of responsibility (source: own presentation after BMWi 2021).

The individual institutions – BGE, BGZ and BASE – are in the process of establishing or developing their research agendas and plans. As far as research funding is concerned, interministerial talks have so far been held for assigning research topics so as to avoid overlaps and duplication of funding wherever possible. Expert panels have also been convened to compile relevant research topics for funding programmes. Furthermore, BASE has laid claim to a coordinating role in nuclear waste management research[54] but it is unclear quite how this is to be put into practice. In addition, it is not always apparent how to assign topics clearly in the research funding landscape, which contributes to a certain lack of transparency. It remains to be seen what changes the reorganisation of the ministries' responsibilities will bring.

54 | See BASE 2019.

Research categories

"Research" can be broken down into a number of areas. In the context of deep repository research, these can be described as follows:

- The primary purpose of **basic research** is to gain new knowledge and an improved understanding of nature and its laws, without having an immediate application in mind.[55]
- **Application-oriented research** relates to the implementation and use of findings from basic research, here specifically with regard to issues relevant and directly related to nuclear waste management. This research does not, however, focus on short-term use. The boundary between basic and application-oriented research is fluid, as indicated, for example, by the concept of application-oriented basic research in figure 3.
- **Methodological and technical developments** building upon the findings gained from application-oriented and basic research will be necessary for implementing a deep repository. Large-scale technical developments (e. g. the development of containers or technologies for deep repository mining, retrieval, monitoring etc.) require the involvement of relevant companies in research and development programmes.
- **Demonstration** experiments, for example carried out in underground research laboratories, are required for trialling the application of concepts and technologies in the implementation of a deep repository.

In research practice, there is overlap between the sub-areas of research, development and demonstration

2.3.2 Interdisciplinarity of research for safe waste management

Research into the deep disposal of high-level radioactive materials is also challenging because it involves a variety of different scientific fields. The expertise required for addressing the task of deep disposal of high-level radioactive material, which is extremely demanding both from a scientific and technical and from a sociopolitical standpoint, ranges from mathematics via the natural sciences (including geosciences, physics, chemistry and biology), the engineering sciences (for example mining and civil engineering, nuclear engineering) to the humanities (social sciences and economics).

The geosciences, with their various specialist fields, provide the fundamentals and methods for assessing the geological barriers of a deep repository and thus site selection: geology and geophysics provide insights into the structure, stratification and physical nature of the substrate and into tectonic features and geomechanical properties of the barriers. Hydrogeology and hydrochemistry make statements about the mobility of water in geological formations and, in conjunction with radiochemistry, the behaviour of radionuclides in rock strata, while biogeochemistry considers, among other things, the effect of corrosion-promoting processes of a biological and chemical nature on containers. The totality of the information obtained in this way gives rise to a compilation (synthesis) of the geoscientific knowledge and model concepts of relevance to deep disposal for the region or site, as well as a long-term forecast in geoscientific terms of the future evolution of the region or site.

Furthermore, radiation and radiation protection research and radioecology address possible radiological effects on personnel during repository operation as well as on the population once the repository has closed due to the potential escape of radionuclides and so provide a further important basis for enabling a repository safety assessment.

The construction of a deep-mined repository, the design of containers for high-level radioactive material and of engineered barriers are the subject of engineering studies as well as materials science research. In turn, handling of the material for disposal in containers is based on detailed knowledge from nuclear science about how forms of radioactive waste and nuclide mixtures behave over time in deep repository systems with regard to criticality, radiation intensity, evolution of heat and their chemical properties. A safety assessment of a disposal concept requires input from many scientific sub-areas in order to achieve a systemic and interdisciplinary approach. For instance, construction of the repository and the repository itself will have repercussions on the

55 | See Wissenschaftsrat 2020.

host rock (including mechanical effects of tunnelling, heat generation), which means that geoscientific as well as engineering and material science aspects must be taken into account.

Equally important are the fields of science which consider the social dimensions of the deep repository project and offer scientific insight into them. Research in communication science, didactics, social science, psychology and law is required for dialogue with society, public participation in the procedure and the design of decision-making processes. Expertise from these fields creates the basis for scientific communication and collaboration between science and society on equal terms. Dealing with uncertainty, unpredictability and different levels of knowledge, as are in the nature of a site selection procedure, are essential themes at the interfaces between the natural sciences and humanities.

The diversity of issues relating to the deep disposal of high-level radioactive waste which have been outlined here underlines the need for interdisciplinary scientific research in order to do justice to the stated requirements placed on the site selection procedure. Prospects for the success of a deep repository project also depend on effective collaboration between all these scientific disciplines and fields.

3 Key themes for the safe management and deep disposal of high-level radioactive material

As described in section 2.3, research into nuclear waste management requires a strongly interdisciplinary approach. The following discussion addresses key themes not only from scientific and technical aspects but also from sociotechnical and societal areas. This publication does not intend to provide a comprehensive analysis, but focuses on key themes in repository research which, in the view of the authors, will be of particular relevance in the future. In view of the sometimes extremely long timeframes, it is considered very important to set up research and the research landscape in such a way that the learning process called for by legislators is supported and that no "tunnel vision" of the tasks and problems arising develops. The design of the research landscape, for example with regard to interdisciplinarity, is thus essential in order to ensure that problems, risks or opportunities in the deep repository project can be appropriately addressed.

3.1 Sociotechnical and societal aspects

Sociotechnical aspects of deep disposal are characterised by the fact that technical and social components are closely intertwined with regard to problem description, research, methods and potential solutions. A strict separation into technical and social science issues would miss the core of the challenge and thus lead to misdirected research and inappropriate solutions. Societal aspects are here taken to mean developments and dynamics in society which are of significance for ensuring deep disposal is as safe as possible in the long term and supported by society. The term "acceptance" is deliberately avoided here because it often gives the false impression that societal consent could be obtained merely by putting a particularly positive spin on the situation. If society is to accept the mission of deep disposal and this mission is to be tackled and solved responsibly for society as a whole and for future generations, more than "passive" acceptance will be required in the long term.

The approach to the safe management of high-level radioactive waste is an extremely long-term project which has been highly controversial in Germany for decades (see sections 2.1 and 2.2) and can only succeed if the procedure and solution to the mission are supported by society in general, but in particular by the population in the region of the site. Building such a common consensus in a democratic society is a major challenge, especially in Germany with its long history of resistance to the use of nuclear energy, and a collective learning process and careful collaborative balancing of diverse demands will be key to doing so. This is only feasible if the decision-making process is transparent and the geological and technical requirements are understandable to broad sections of society. Transparent information and honest communication are therefore vital. As StandAG also provides in part, new ways of involving and communicating with those directly affected as well as with society as a whole must be developed. This means more than simply explaining study results after the fact. Instead, working together with NBG and other institutions, the public should be informed and involved in the decision-making processes from the outset of the investigations. The impression must also not be created that decisions have already been made and that there are no longer any opportunities for participation.

Different time horizons for the tasks at hand also bring different challenges. The key themes are listed below according to these time horizons starting from acute problems and issues arising in the short term and moving on to long-term considerations.

3.1.1 Multi-criteria decision-making processes under uncertainty

The ongoing site selection procedure is intended to be "participatory, science-based, transparent, self-questioning and learning".[56] This combination of requirements is more than challenging methodologically. Even for apparently quite simple decisions such as the depth from which sufficient protection from erosion processes can be assumed, it is necessary to carefully weigh up the question: how safe is safe enough? It is almost impossible to address this question in a sufficiently precise and well-founded way to be able to transparently dispel any doubts about the answer.

56 | See EndlSiAnfV 2017, § 1, paragraph 2.

It will be significantly more difficult to apply the geoscientific consideration criteria according to § 24 StandAG because they are in some cases not comparable with each other or overlap and no weighting factors are specified.[57] This applies in particular to the provisional safety assessments which have to be carried out pursuant to StandAG and the Final Repository Safety Assessment Ordinance (EndlSiUntV) in each phase of the site selection procedure for the regions or sites under consideration. They contribute to the decision-making process by providing an assessment of the extent to which the relevant safety requirements can be expected to be met. In addition, statements regarding the relevance of the consideration criteria have to be provided for each specific case.

Independent scientific oversight of how consideration criteria are applied in specific cases is therefore likewise required. The complexity of the site selection procedure and the processes involved must be presented in a way that the public can understand. As is clear from a glance at the list of consideration criteria, many such considerations in part demand geoscientific expertise and geotechnical knowledge of barriers. However, the weighting of the various criteria on a qualitative basis, drawing on social and ethical issues, must also be clarified. One example is the distribution of possible damage scenarios on a time axis which illustrates that different generations could be affected differently by a damage event. Particular scientific and communicative attention needs to be paid to achieving technically appropriate and ethically responsible handling of the sometimes great uncertainty or even lack of knowledge as well as of disagreement between experts if a transparent discussion is to be enabled. The need for research and development in this area is confirmed by the feedback from the symposia with interested members of the public on the "Interim Report on Sub-areas"[58] published by BGE in September 2020. In the feedback, the procedures used are described and criticised as being in many respects difficult to understand, in particular for non-scientists.[59, 60]

There is therefore a need to promote independent method development in preparation for future requirements in the site selection procedure. One essential point is that decisions should be made on the basis of the consideration criteria in such a transparent manner that any suspicion of political influence or abuse of power can be ruled out as completely as possible. This requires a dedicated methodology which goes beyond the existing assessment procedures, takes account of different criteria and includes in particular a trade-off methodology where there are conflicts of values and highly uncertain circumstances. Also included are presentation methods for complex trade-off procedures and their conceptual foundations or basic rationale. These must not only be transparent, but also comprehensible so there is a good chance they can be used with success in participatory processes. In any event, participation is already subject to the particular conditions of the deep repository project: existing social conflict, the high degree of interdisciplinarity, as well as varying familiarity with scientific language and handling of uncertainty.

New methodology can be developed on the basis of current scientific knowledge. Multi-criteria decision analysis (MCDA), i. e. analysis which takes multiple criteria into consideration, including the widely documented knowledge of its shortcomings (see section 3.2), may be mentioned here as the state of the art for making trade-offs. It can be used to assess not only a candidate site's geotechnical suitability but also its socio-political resonance. Integrative sustainability assessment methods, in which there is similar experience in dealing with trade-offs as well as weighting conflicts, may also be mentioned. Weighting conflicts often arise not only from different values or different ideas about the weighting of criteria, but also from different, diverging assessments of the state of knowledge as well as diverging assumptions about possible damage scenarios. Integrative methods are frequently embedded in participatory processes. In particular, when it comes to defining the weighting factors, there is a need for participatory safeguards involving the affected societal groups.

In the development of a trade-off methodology, different scientific fields must work together, for instance geosciences and geotechnical engineering, sustainability research, safety analysis, decision theory and ethics, conflict research, sociology of science, communication science, computer science (e. g. for visualising complex processes) and technology assessment. BGE is already planning contract research on subsidiary issues relating to the presented challenges.

57 | StandAG lists eleven geoscientific criteria, but does not explain how they are to be weighed relative to one another. For example, one investigation area A has less favourable characteristics with regard to the radionuclide retention capacity criterion in comparison with another investigation area B. On the other hand, investigation area A has more favourable characteristics with regard to the water supply and groundwater movement criterion. These two criteria are directly related in terms of an assessment but no trade-off instructions are provided (see Entsorgungskommission 2021 for further information).

58 | See BGE 2020.

59 | See NBG 2020.

60 | See NBG 2021.

3.1.2 Public participation in the implementation of major projects

Public participation is a key requirement in the site selection process. BASE accordingly lists public participation under point 6.1 in its research agenda[61] but it is not apparent whether there is any intention to include case studies from the non-nuclear sector. It is well known that there are numerous infrastructure projects, such as airports, open-cast mines, power transmission lines and power plants, which have had to struggle with acceptance problems and for which there are also reports and studies about participation projects. Public participation in technical projects has been widely practised and researched over the last twenty years or so, often motivated by bad experiences in planning without special participation, such as the Stuttgart 21 project. Such experience and previous public participation in the site selection procedure should be built upon in order to upgrade models of participation in such a way that they are capable of overcoming the serious loss of trust from the past (see section 2.1).

The framework for public participation has changed significantly in the era of the coronavirus pandemic and the latter's impact on public participation needs to be considered in detail. It is already apparent that the largely exclusive use of digital formats brought about by the pandemic resulted in difficulties of adaptation which made it more difficult to maintain a genuine dialogue. At the same time, digital participation formats lower the threshold for access since participation is possible without travel and the corresponding costs. When it comes to developing and evaluating pandemic-proof participation processes, there is a particular need for input not only from the social and communication sciences and psychology but also from technical sciences which can contribute, for example, to the user-friendliness of digital participation platforms.

3.1.3 Promoting interdisciplinary and intra-societal dialogue

In its 2019 research agenda, BASE lists as important research topics "handling uncertainty, unpredictability and lack of knowledge" as well as "didactics and formats […] of target audience-oriented knowledge transfer".[62] If the required public participation is to be achieved, it is essential to ensure comprehensible communication with laypeople on equal terms, but this is yet still far from always the case. Reportedly, there was criticism following the publication and presentation of the interim report which took place in the course of the kick-off event for the symposium for all interested citizens in autumn 2020. Despite the "best will in the world", some content was hardly comprehensible to "ordinary" citizens.[63, 64] If a debate is to take place on equal terms, the subject matter and findings from the various disciplines must also be communicated to laypeople. The goal must be to make content comprehensible to a sufficient depth that laypeople can discuss key points on equal terms with the experts and actually participate in decision-making. The interdisciplinary and, to a certain extent, intercultural culture of discussion must be organised and shaped in such a way that a democratic consensus can truly be achieved. Given differing levels of prior knowledge and varying interests, this is no simple task.

It is therefore advisable to research this theme of interdisciplinary and intra-societal dialogue in the broadest possible terms, and preferably also outside BASE, and to network the relevant stakeholders with each other. Ultimately, the significance of this approach in our science-driven world extends far beyond nuclear engineering – just think of the many debates which raged during the coronavirus pandemic. This would also provide an opportunity to independently assess BASE's research in this field. A particular focus is on developing suitable programmes for training specialists and for imparting knowledge to laypeople when dealing with and communicating risk, uncertainty, unpredictability and lack of knowledge. There is an increasing need for such communication skills which will be of benefit to our entire modern knowledge society.

3.1.4 Self-questioning system

According to StandAG, the parties involved in the site selection procedure should form a self-questioning system,[65] which will operate over many decades to foster the emergence of a culture which welcomes criticism. This is also intended to prevent a blinkered approach from hindering the procedure: the long-time horizons of a deep repository project can contribute to the development of unintentionally compartmentalised thinking in the participating institutions. Meeting this challenge will entail developing and researching mechanisms which ensure that the stakeholders concerned continually question their actions internally and among one other. In addition, questioning must be enabled and

61 | See BASE 2019.
62 | See ibid., pp. 63 & 66.
63 | See NBG 2020.
64 | See NBG 2021.
65 | See StandAG 2017.

encouraged by policy makers and civil society. Self-questioning must also include technologies which are already in use and investigate their suitability in comparison with competing and possibly newly emerging alternatives without preconceptions. Moreover, interactions between technical developments and human actions must be considered in order to identify any possible resultant counterproductive system effects at an early stage. Psychological factors, both individual and organisational, must also be borne in mind, in particular with regard to the development and maintenance of a "culture which welcomes criticism". The need for self-questioning and openness to objective criticism can be assisted by technology: for example, it would be conceivable to have a platform anonymised by encryption which would enable internal critics to have their concerns discussed without having to fear negative repercussions on themselves. An independent institution could, for example, fund and moderate the platform as part of a "participatory peer review" and then also carry out an assessment and initiate responses to the criticism expressed.

Particular attention must be paid to the emergence of possible path dependencies, not only technical but also political or intellectual. On the one hand, these may prove necessary as the procedure progresses, but on the other they may also lead to firm decisions which may make self-questioning more difficult. It would be psychologically challenging and possibly also very costly if, after years of effort, the operators of the site selection procedure had to consider backtracking in the procedure or even making a complete change of direction due to trade-offs arising from a change in circumstances.

A distinction must be drawn between the fundamental and long-term safeguarding of institutional learning on the one hand and dealing with urgent issues that arise in the procedure in the short term on the other. Just the design of the procedure in the Final Repository Commission required lessons to be learned in many areas. In particular, it was important to draw on the experience gained from previous attempts and processes in connection with the planned Gorleben repository. Specific questions are constantly arising during the ongoing procedure, for example due to the unforeseen situation of BGE's interim report unexpectedly identifying as much as 54 per cent of the area of Germany as sub-areas which will have to be further considered in the course of the search for a final repository for high-level radioactive waste. Some of these are suitable multiple times over due to the presence of several potential host rock formations.[66] The necessity of replacing all face-to-face events with online formats due to the coronavirus pandemic also resulted in direct learning processes (see key theme "Public participation in the implementation of major projects").

There is also a difference between whether spontaneously occurring changes in situations result in "learning taking place in the procedure" or in "the procedure itself learning". It would not be possible to handle the requirement for reversibility or to address other options which may emerge in future for dealing with the waste, and similar scenarios in the short term. This highlights the need for preparatory, foresighted and, above all, independent research which has no need to take existing paths into account. This research should also identify ways of transparently dealing with conflicting goals in a self-questioning system. On the one hand, legal certainty and procedural reliability must be ensured which necessitates defined rules while on the other hand, in view of the time horizon in question, rule changes must be possible and indeed required on the basis of lessons learned. If rules are changed as a result of learning and self-questioning, this must be done with transparency, communication and participation to avoid suspicion of underhandedness or abuse of power. One possible approach could be to define breakpoints at certain times at which decisions about changes must be made on the basis of safety-oriented criteria which are yet to be defined.

This key theme deals with interdisciplinary issues for which existing knowledge from individual and organisational psychology from other safety-relevant fields, such as aerospace or occupational safety, is of relevance. At the same time, there is a need for methods for decision support (operations research), systems engineering, systems research, organisational sociology, psychology, social sciences, and complexity research, often in cooperation with technical disciplines. This is because self-questioning also affects the technical and scientific decisions, trade-offs between alternative options in the event of setbacks in the procedure, or the further development of criteria initially set out in StandAG which are intended to lead to the site with the best possible safety. In the event of new scientific findings, there may be a need for adjustment which conflicts with the stability of the current set of criteria desired for reasons of confidence and equal treatment. The learning and self-questioning process must also include regular comparison with the international state of knowledge.

66 | See BGE 2020.

3.1.5 Long-term strategy and governance

As explained in section 2.2, the search for a site for a deep repository and its construction, operation and proper decommissioning is a process which will take many decades. It is a challenge for any society to shape such long-term processes successfully and stably while at the same time remaining capable of learning and acting appropriately. This applies in general to other long-term processes such as the energy transition. Particular challenges in the management of high-level radioactive material arise from the problem of interim storage beyond previously approved time periods and the possibility of setbacks in the procedure which might require a partial restart from a certain stage. These particular challenges require an appropriate long-term strategy and governance, i.e. certain organisational structures and processes which allow for learning, backtracking and taking a new direction without losing sight of the goal (see section 3.1.4). This process involves technical issues (such as research and development needs, time requirements for developments), scientific issues (such as data requirements, development of new and rapid survey methods, modelling) and societal issues (such as determining the criteria for backtracking and changes in direction and their funding) which are all intertwined. The motivation for the in-depth treatment of an appropriate long-term strategy and governance is complicated by the particular challenge that the best possible safe deep disposal is only associated with minimising possible damage but not with a positive vision as is the case for processes of transformation like the energy transition or digitalisation. In other words, dealing with contaminated sites is not a very attractive proposition, all the more so if the process drags on for decades. On the other hand, the challenge of dealing with a previously unsolved social problem can also have a motivating effect. Greater emphasis should be placed on this aspect in communication.

The issue of knowledge transfer in a broader sense is another factor in the long-term strategy. Conventional methods for storing knowledge are out of the question over the required periods of time. Since BASE's research agenda includes "information management and long-term documentation",[67] which would essentially appear to deal with these issues, we will not pursue this theme any further in this document.

The development of long-term strategies and appropriate governance is not an established field of research. It is common practice in radioactive waste disposal projects to work with plans which work out timewise only if certain assumptions prove correct, for instance that site selection will be complete in 2031. In contrast, flexible long-term strategy and governance includes dealing with unforeseen developments and new findings, as well as any resultant opportunities and necessities for learning (see key theme "Self-questioning system"). Findings and methods from sustainable development research can be adopted here.[68] There are also some approaches in other areas, such as conceptual approaches for the energy transition from the Kopernikus project, Energy Transition Navigation System.[69] At the same time, there is an initial need to review other long-term projects so that strategies and control mechanisms for stabilising the project can be developed appropriately to fit with the site selection. These will be able to balance the necessary stability and reliability of the procedure against the desired flexibility requirements for learning purposes. It will accordingly be possible to identify and avoid any unwanted path dependencies at an early stage. Psychosocial support for long-term motivation, the establishment of a methodology for anticipating research and development needs, and the development of "risk literacy"[70] among stakeholders and the general population are further necessary elements of long-term strategy and governance.

A long-term strategy in the broad sense also includes consideration of general societal conditions which could shape the project after a number of decades or even further into the future. Since there has been little research in this field and it is not possible to predict developments, the working group asked a panel of experts in social science and the humanities to consider this issue. The panel's considerations are set out in the following information box.

67 | See BASE 2019, p. 65.
68 | See Voß et al. 2011.
69 | See KIT 2021.
70 | See Gigerenzer 2013.

Long-term societal aspects

This text was drawn up between October 2021 and January 2022 and slightly amended in early March 2022.

At the invitation of the working group, an external discussion panel of experts in social sciences and the humanities[71] discussed the question of what, if anything, can be said today from a scientific perspective about the possible range of variation in societal conditions in the medium and more distant future. This was carried out against the background that, in view of the long-term nature of a deep geological repository project (see section 2.2), different societal developments may have an impact on the deep repository plans, on the search for a suitable site and on the deep geological repository itself. The discussion panel offers the following for consideration:

Societies are characterised by an interplay of permanent structural change on the one hand and the reproduction of certain structural characteristics on the other. Modern societies are fundamentally distinguished by the fact that societal change, at every level, is considered inevitable or even desirable. At the same time, certain basic patterns, such as those of capitalist economic activity or of modern statehood, have persisted over longer phases and then appear as basic features of "modernity". It is fundamentally impossible to predict how continuities and discontinuities will be configured in the future and how stable or changeable these social configurations will be over which periods of time. It is therefore not possible to subscribe to the continuity assumption, which has long been cultivated even in the social sciences and according to which certain basic patterns, such as parliamentarism, individual self-control or functional differentiation, are regarded as inviolable or unchangeable in the long run and that here a kind of ratchet effect would make it impossible to go "backwards". Instead, societies are too complex, and the unintentional effects of seemingly limited interdependencies can be too incalculable, for future societal structures, orders or developments to be reliably predicted even in the medium term. We know this not least from the history of forecasting the future: we live in societies whose social structures, ways of thinking, forms of communication, normativities, interpretations of the world and much else were entirely unimaginable 100 or 500 years ago and could not have been predicted. The coronavirus pandemic since 2020 and, most recently, the "turning point in history" brought about since late February 2022 by the brutal Russian war waged against Ukraine, which has abruptly and profoundly changed the defence and energy situation, demonstrate how quickly and unexpectedly conditions can change. Even if we cannot (yet) speak of fundamental societal change, the consequences are unlikely to be foreseeable.

Nevertheless, it will be understood that institutions and individuals in the social world necessarily harbour expectations about the future which they use to guide their actions. Even complicated technical systems for handling long-lasting high-level radioactive material such as the deep repository project are inevitably based, implicitly or explicitly, on certain ideas about the future. The great challenge, then, is to think about futures and plan future action, even though we know that no reliable statements can be made about societal futures.

The social sciences and humanities thus have substantive reasons to be sceptical about any expectation that they will be able to make reliable statements of this kind about future societies. However, from a social theory standpoint, it must be assumed that there can be no "purely technical" solutions to problems faced by society, which also includes the problem of long-term radioactive waste repositories, because every technology is produced, used and maintained under certain social conditions, i. e. it is socially institutionalised. When it comes to the long-term disposal of high-level radioactive material, this means that a disposal site must not only be technically sealed, but that at the same time any unsealing must be socially prevented and warnings provided of the dangers it presents. How this can be achieved in the medium and long term is an open question.

71 | The following were invited and participated: Prof. Dr. Thomas Kirsch, Konstanz; Prof. Dr. Frank Nullmeier, Bremen; Prof. Dr. Andreas Reckwitz, Berlin; Prof. Dr. Hartmut Rosa, Jena; Prof. Dr. Uwe Schimank, Bremen and Prof. Dr. Peter Strohschneider, Munich.

The following thought experiment shows how every currently conceivable course of action is socially conditioned. On the assumption of complete uncertainty about future social continuities and discontinuities, the experiment is based on two opposing approaches: social exclusion or inclusion of a deep repository.

Exclusion:
The first line of thought relies on decoupling the disposal site from possible societal changes by hermetically "encapsulating" it. On the one hand, this could be attempted by politically initiated isolation, i.e. by erecting physical and legal barriers to access. The disposal site would be drawn up under unchangeable rules and behaviours and protected from any kind of attempt to access it. On the other hand, the attempt could be made to exclude the disposal site by cultural isolation or "repulsion" on the basis of a societal reflex having the nature and force of a taboo. Access to the disposal site would have to be regarded as completely ruled out; the very desire to gain access should not even arise. In this way, the special position of the deep geological repository would be secured over extended periods of time, possibly even in the absence of political or legal isolation, by cultural transmission of a taboo.

Inclusion:
The alternative line of thought expects, and willingly permits, the repository for high-level radioactive material to remain exposed to unforeseeable societal changes. Technological innovations, like societal and political restructuring, could influence the future design of the deep repository; the idea of irreversible closure of the repository could even be abandoned. Central to such an approach is that society is always capable of distinguishing between potential useful learning progress and risky social regression ("unlearning"). However, can we expect future societies to be able to recognise their own regression as such and not mistakenly take it to be learning progress? In any event, this line of thought assumes that such an expectation is justifiable.

This hypothetical sketch shows that, whether the approach is of social exclusion or inclusion, very strong, but at the same time highly uncertain, assumptions have to be made about governmental/political and cultural/normative continuities if a disposal site for high-level radioactive material is to remain functional over the long term. Inevitably, certain assumptions about future social structures (for example in terms of the validity of constitutions or taboos, the possibility of progress in societal learning etc.) are always involved, even if only implicitly in the background, when medium- and long-term technical solutions are considered. These continuity assumptions must themselves be questioned, although no scenario can manage entirely without assuming continuity: any strategy would be undermined if societies of the future were to be structured completely differently from those of the present. In order to be able to proceed strategically in any way at all in this situation, the (difficult to justify) assumption must be made that future societies will not be structured completely and in every respect differently from those of the present.

Although it is not possible to make any reliable statements about societal futures, it is essential to take potential scenarios into consideration in order to avoid unrecognised and problematic continuity assumptions. It is here that there is considerable need for social science and research in the humanities. Greater depth of knowledge of the relevant key themes could help to hold continuity bias in check as far as possible reflexively and to identify methods for making long-term projects more resilient to societal upheaval by means of appropriate stress tests and corresponding adjustments.

3.2 Scientific and technical aspects

While there is only little existing prior research experience in relation to nuclear waste management to build upon with regard to key sociotechnical and societal themes, the situation is quite different in science and technology. In many fields, it is possible to draw on findings and data from around sixty years of research. At the same time, however, new questions are arising. The need for further research in the natural and engineering sciences results, on the one hand, from the constant influx of new scientific methods and findings and, on the other, from changing societal and legal parameters. Examples of legal changes of relevance to research over recent decades include the requirements to consider three potential host rocks, to select the best possible site in terms of safety, and to ensure retrievability during the operational phase of a final repository.

Germany's directly involved institutions and research funding organisations have therefore identified areas of activity and set out their research concepts[72] in a number of publications. This includes BMUV which has taken over research responsibilities from BMWi (now: BMWK) in the reorganisation by the current federal government, BMBF and various research organisations.[73]

Corresponding strategic research plans are also being drawn up and updated at a higher European level, for example within the EURAD[74] research programme. The research planning agenda covers a variety of subject areas ranging from aspects of basic science to applied issues of management, knowledge integration, and safety analysis. In addition, activities are taking place to document the internationally available state of science and technology in the individual relevant subject areas in a wiki format, and as well to organise education and training events. In view of the intergenerational timeframes involved, such measures are considered essential by all European partners. IAEA and NEA programmes are also addressing such research topics at an international level.

Specific issues do, however, also arise for Germany's particular situation due to the differences in circumstances, concepts and degrees of implementation of the respective waste management projects in Germany and elsewhere. For example, in Germany, three host rocks and thus also different disposal concepts involving distinctly different engineered and natural barriers have to be compared in parallel (see sections 2.1 and 2.2). The investigations into deep disposal in rock salt can build on earlier comprehensive programmes,[75] while Germany has a less thorough understanding of other host rocks, in particular crystalline rock. Although research in Germany has increasingly also focused in recent decades on disposal in claystone and crystalline rock, in part within the framework of international collaborative projects in underground research laboratories, knowledge regarding rock salt as a host rock remains comparatively more detailed and in-depth. Looking across borders is helpful for reviewing the international state of knowledge regarding deep repository projects and for carrying out a detailed analysis of research needs identified outside Germany precisely for these other host rocks. This is particularly the case, for example, for planned research in Finland, Sweden and Canada within already well advanced projects for deep disposal in crystalline rock[76, 77] and in Switzerland and France in consolidated claystone.[78] Local geological circumstances have led these countries to focus on their respective host rocks. A detailed analysis of the findings obtained in other countries should be able to clarify and highlight what internationally available knowledge, data and scientific questions can be transferred to Germany's situation.

To illustrate the complexity and diversity of issues facing scientists and technologists, some topics which are of particular relevance to the situation in Germany are listed below by way of example. These topics are also reflected in the previously mentioned research programmes and strategies of German funding organisations and research institutions. Discussing them at this point is intended to make clear that technical problems, emerging fundamental issues, and societal implications are closely intertwined. Accordingly, decisions in the site selection procedure will not be possible solely on the basis of the criteria listed in StandAG and a scientific consensus will indeed not always be achievable. It is for this reason that procedures are required for systematically handling and transparently communicating uncertainty. This in turn underscores the need to dovetail scientific and technical research with research in the social sciences, as well as the urgency of establishing long-term arrangements for ensuring the effectiveness of scientific research and the research

72 | Vgl. BGR 2022; vgl. BGE 2019; vgl. BASE 2019; vgl. BMBF 2021; vgl. Helmholtz-Gemeinschaft 2022; vgl. BMWi 2021.
73 | Among others Gesellschaft für Anlagen- und Reaktorsicherheit GmbH (GRS), BGR, BAM and the Helmholtz Association.
74 | See EURAD 2020.
75 | See GRS 2013.
76 | See SKB 2019.
77 | See NWMO 2019.
78 | See Nagra 2016.

landscape (see also sections 3.1 and 3.3). With regard to the technical implementation of a repository, industry must also be involved early enough for the necessary technologies (for example disposal containers) to be available in good time in a quality which meets licensing requirements and enables proper use (see information box "Forward planning of research programmes and industrial cooperation", section 3.3.3).

3.2.1 Aspects of the first phase of site selection

In September 2020, BGE published its "Interim Report on Sub-areas", an initial narrowing down of potential sites on the basis of statutorily defined exclusion criteria, minimum requirements and consideration criteria for site selection (see section 2.2). Accordingly, sub-areas of the order of magnitude of more than half the area of Germany continue to be eligible for further investigation. The requirement for a self-learning procedure demands that it be questioned to what extent the previous steps and formalities were selected and defined in the best possible way. Criticism of the content of the "Interim Report on Sub-areas" was voiced by various professional organisations[79] and the public at symposia.

One example of different expert assessments with far-reaching consequences was the debate around the exclusion of the Gorleben site for a final repository, this exclusion being made by BGE in its interim report on the basis of the geoscientific consideration criteria according to § 24 StandAG. The different assessments relate in particular to the use of reference datasets and the evaluation of the criterion "protection of the effective containment-providing rock zone by the overburden".[80] In its provisional safety analysis[81], GRS assessed the overburden covering the salt dome as being of relatively little relevance in safety terms, which also implies that this issue would not be particularly relevant in a siting decision. BGR,[82] LBEG[83] and DAEF[84] have also criticised BGE's line of argument regarding the application of this criterion. In its response to this criticism, BGE has explained its approach and defended its point of view.[85]

The emergence of such different assessments should be scientifically reviewed because the resultant insights could be instructive in dealing with differing expert assessments in future, in particular with regard to transparent communication with all stakeholders.[86] This will also determine the trust of the interested public, which is currently organising itself in the form of the Final Repository Search Technical Forum and is closely monitoring site selection progress, in the procedure.

Scientifically well-founded but conflicting assessments on various issues may also continue to arise at any time during the procedure. The example mentioned here shows that the criteria set out in StandAG cannot always be interpreted unambiguously and that applying them does not always necessarily lead to a clearly science-based decision. This makes it all the more important to set up committees to deal with cases of scientific disagreement and to develop a methodology which nevertheless allows decisions to be presented and justified in a comprehensible manner.

The procedure itself and the role of the institutions involved should also be scientifically reviewed now at the beginning of the site selection procedure. One question which is already relevant today and will recur as the procedure progresses is: should the supervisory authority provide detailed specifications regarding scientific and technical methods, data collection and processes or should it primarily define the goals of each step and leave it largely up to BGE as the implementing institution to decide how to achieve them? Another issue relates to the detailed definition of criteria in StandAG, in part with numerical values. This can lead to conflicting goals. While, on the one hand, the reliability of the procedure is increased since a precise goal is stated, on the other, new findings which suggest an adjustment to the value in the course of the procedure cannot be incorporated into the process, or only with difficulty. This consequently limits the capability of the procedure to learn, which is also statutorily required (see also section 3.1.4).

79 | Among others, the Saxony State Office for the Environment, Agriculture and Geology, BGR, the Lower Saxony State Geological Survey, the Lower Saxony State Office for Mining, Energy and Geology (LBEG), DAEF.
80 | See EndlSiAnfV 2017, appendix 11 to § 24, paragraph 5.
81 | See GRS 2013.
82 | See BGR 2021.
83 | See LBEG 2021.
84 | See DAEF 2020.
85 | See Grube et al. 2021.
86 | See Kahneman et al. 2021.

3.2.2 Extended interim storage of irradiated nuclear fuel rods

In view of the timetable for the final repository project, it is foreseeable that the interim storage of irradiated nuclear fuel rods in centralised and decentralised storage will exceed the licence period of forty years, in some cases by several decades.[87] Quite apart from questions of container tightness, ageing management of interim storage facilities and licensing procedures, the safe transfer of nuclear fuel rods to a deep repository requires knowing whether the fuel rods and cladding tubes will still be intact after extended storage or whether further protection and conditioning measures will be required. However, knowledge regarding the embrittlement and corrosion processes of such materials under interim storage conditions over time periods until transfer to a deep repository of possibly one hundred years or more is still very limited. Fundamental scientific investigations are still required to allow for reliable statements regarding material behaviour under elevated temperatures in conjunction with radiochemical processes. Transfer of the interim storage containers complete with contents directly to the final repository is currently also under discussion. Repackaging or conditioning of irradiated nuclear fuel rods could be avoided as a consequence. However, since these containers are developed specifically for transport and interim storage, it must first be checked whether their shape and composition are actually also suitable for the requirements of deep geological disposal.

In addition to the technical issues associated with extending the operation of interim storage facilities for a number of decades, there is also potential for social conflict because the communities in which the interim storage facilities are located might have to host them for significantly longer than originally agreed. Among other things, this raises further questions about securing such storage facilities over the extended period of operation. The war in Ukraine vividly demonstrates that security considerations for interim storage facilities over extended periods of time cannot rule out the possibility of armed conflict.

3.2.3 Retrievability and monitoring

New concepts that have been introduced into repository projects in recent years involve possible provisions for facilitating retrieval of waste from a repository. Legislators have specified that a final repository in Germany must include technical retrieval provisions up until the repository is finally closed. Although ideas for achieving this for various deep repository concepts have already been proposed internationally, measures for concrete technical implementation still require considerable development. It is further required that recovery of the waste after closure of the repository be possible. Deciding to proceed with retrieval or recovery is a serious matter and requires a solid foundation, to which comprehensive monitoring can contribute in order to allow conclusions to be drawn as to unwanted evolutions of the repository and its surroundings. Numerous aspects of monitoring are addressed by past and ongoing research projects:[88] major technical challenges remain, for example in the development of instruments whose reliability must be guaranteed over extended periods of time under difficult environmental conditions. One fundamental task will be to clarify which data are required and on what scale in order to provide reliable statements about the safety status of the repository, which criteria must be met in order to justify retrieval or recovery and how potentially corrupted monitoring measurements should be handled. At the same time, in the event that retrieval or recovery is necessary, it must be borne in mind that technical facilities for storing and further processing the retrieved waste will be required and may have to be developed, and that their construction must have public support. Last but not least, account must be taken of the risks posed by retrieval and recovery to personnel, the population and the environment.

3.2.4 Role of the container concept for deep geological disposal

The urgency of development work for a suitable final repository container is due, on the one hand, to the long lead times required for developing and licensing a container. On the other hand, the preliminary safety assessments of the site selection procedure also include the development of provisional safety concepts and repository layouts and thus also of container concepts. The reason for this is that, depending on the disposal concept, the container for high-level radioactive waste has to fulfil different barrier functions.[89]

In Germany, EndlSiAnf[90] specifies that the "essential barrier" must reliably contain the waste over the entire evaluation period.[91] In the case of final disposal in crystalline rock, the container in conjunction with the planned geotechnical barrier, for

87 | See Entsorgungskommission 2015.
88 | For example the MoDeRn project at EU level, see ANDRA 2021.
89 | See Entsorgungskommission 2016.
90 | See EndlSiAnfV 2020.
91 | See ibid.

example swellable clay, can be classified as an essential barrier. Corrosion-resistant containers based on a coating with copper are provided for deep repository concepts in crystalline rock, for example in Sweden or Finland. Repository concepts in claystone and rock salt place lower demands on the container and use carbon steel as reference material. The essential barrier in this case is the host rock in conjunction with the geotechnical barriers which jointly retain pollutants or minimise their transport. Nevertheless, alternatives such as copper cladding or coating with ceramic materials, for example silicon carbide, are also being considered here due to possible negative effects caused by the evolution of hydrogen during corrosion.[92] Requirements to guarantee safe repository operation and possible retrieval and to enable recovery must furthermore be applied to the containers. Different host rocks and concepts thus result in different requirements on the containers, in particular in terms of their behaviour after closure of the repository. It remains to be verified how far findings on container materials obtained outside Germany can be transferred to German conditions.[93]

The difficulties in this area are obvious. Due to the long time periods required for the development, industrial qualification and licensing of a container, a concept must be submitted as soon as possible if it is to be ready for service at the latest when emplacement begins (see information box "Planning research programmes and industrial cooperation with foresight", section 3.3.3). On the other hand, a decision in favour of a specific host rock is unlikely in the next few years. If a concept is selected which requires a corrosion-resistant container with long-term stability, it will be a scientific challenge also to sufficiently prove its containment function over a period of one million years pursuant to StandAG. In this case, the main burden of the isolation effect of the deep repository system for this long period of time would fall upon a human-manufactured engineered barrier concept which, despite industrial quality assurance procedures, may also be defective. It differs significantly from concepts in which the containment effect is primarily provided by a geological barrier which has proven long-term stability. This example also shows an ideal site cannot be selected solely on the basis of the criteria listed in StandAG. In due course, decisions will also have to be made as to which deep repository and container concept will be given preference. Such decisions must then be justified in a comprehensible and transparent manner.

3.2.5 Consideration of extremely long time periods

As mentioned in section 2.2, a safety assessment for a deep repository extending over hundreds of thousands of years is often met with incomprehension not only from the public but also from scientists who are not involved. While geological developments can undoubtedly be realistically predicted over much longer periods than can societal change, this being the main argument in favour of deep disposal, forecasts over one million years sometimes seem very "daring". The effects of comparatively slow, but nevertheless dynamic, processes in geological strata have to be taken into account here. Geologically, Germany is located in a moderately inactive zone and more active regions (Alps, Tertiary rifts) have already been ruled out by the "Interim Report on Sub-areas". It is precisely because the extremely long time periods in safety assessments are difficult to comprehend that scientists place great emphasis on long-term developments in deep repository systems. The aim is to identify possible developments of relevance to safety and to describe and evaluate them as quantitatively as possible. In addition to geological processes, long-term climatic processes in the far field of the deep repository, i. e. in the overburden, which can have an impact on the near field must also be taken into account, for example deep erosion processes brought about by glaciers passing over following climate change. Such processes may be natural or anthropogenic in nature and are already the subject of safety assessments.[94, 95] New and improved methods, for example for dating sediments, can make an important contribution, as may progress in the numerical modelling of complex processes such as climate-driven erosion. A high level of geoscientific research is a prerequisite for successful deep disposal.

The uncertainty involved in investigating extremely long time periods is countered by using a standard international approach to develop scenarios which describe developments, including unfavourable ones, as comprehensively as possible, even if not all processes are yet understood in detail.[96] One scenario which is particularly difficult to evaluate is possible unintentional human intrusion into the repository zone at some time in the distant future where there is extreme uncertainty regarding the nature of a possible intrusion and the extent of the impact on humans and the environment. It will therefore be difficult to optimise a deep repository system with regard to such scenarios.

92 | See Nagra 2014.
93 | See BGE TEC et al. 2020.
94 | See Mrugalla 2020.
95 | See GRS 2013.
96 | See NEA/OECD 2016.

Other scenarios relate to the near field of the deep repository, where different materials adjoin one another and where chemical reactions with evolution of gas and the involvement of microbes may occur which may have an impact on the stability of radioactive waste forms and the dispersion of radionuclides. A more thorough, in-depth understanding of the complex, combined interactions over extended periods of time in deep repository systems can help to further increase confidence in safety assessments. This knowledge can be used to develop concepts for which such uncertainty is of little relevance. The National Waste Management Programme[97] proposes joint storage of high-level radioactive and low- to medium-level radioactive waste on a single site. As a result of the huge diversity of substances present in low- and medium-level waste, this concept can involve even greater interaction complexity.[98] Safety assessments must demonstrate here that such a concept meets the StandAG requirement for the best possible safety.

The complex processes which take place in a deep repository over extended periods of time therefore require research which takes a holistic view of the entire system. This includes investigating the dispersion behaviour of radioactive substances and the complex reactions of radionuclides in the geosphere and biosphere, and thus the possible long-term impact of a deep geological repository on humans and the environment. Linking experimental work with environmental simulations and systems analysis has the potential to enable an improved evaluation of the impact of combined processes (thermal, hydraulic, mechanical, chemical and biological (THMCB)) on the living environment and on the long-term development of a repository. Although major progress has been made in this respect in recent years, taking all relevant processes in such combined systems into account remains a challenge which pushes even computational models and computing capacity to their limits.

3.2.6 Dealing with uncertainty

Dealing with uncertainty is also directly related to the problem of long periods of time. Uncertainty relates to long-term safety statements and decisions on the siting, construction, operation and closure of a deep repository and, if necessary, on retrieval. Dealing with uncertainty likewise plays an important role in debates in society and communication with the public (see section 3.1). All the institutions involved in the site selection procedure therefore address this aspect in their research plans.

The natural and engineering sciences have developed a wide range of concepts and tools for dealing with uncertainty. A fundamental distinction is drawn between aleatory uncertainty, which involves random or natural fluctuations, and epistemic uncertainty which arises from a lack of knowledge. In the former case, it is not generally possible to reduce the uncertainty (e.g. the natural variation in permeability in the rock mass) but merely to describe it statistically, provided that a sufficient volume of data is available. In the second case, uncertainty (e.g. the question: how will the geology in the environment of the repository develop in future?) may possibly be reduced by additional research. Epistemic uncertainty is studied, for example in the probabilistic evaluation of the safety of nuclear power plants, using logical trees whose branches represent the different effects of different model assumptions.[99] This method has also already been used for investigating repository safety in some cases.[100] This approach is, however, not uncontroversial and has not yet been adopted in other repository projects. Another approach often applied in long-term safety assessments distinguishes between scenario, model, and parameter uncertainty. Well-established methods are available for dealing with each of the stated types of uncertainty, for example scenario methods, model qualification methods, as well as deterministic and probabilistic uncertainty analyses.

The "what if" concept moreover provides one possible way for investigating and demonstrating the robustness of the deep repository system. This involves considering the possible impact of specific hypothetical, possibly also highly improbable or even impossible events on deep repository development. One example of this is omitting individual barriers from analyses and calculations in order to hypothetically push the remaining system to its limits. Results from such analyses provide important information about the robustness of a deep repository system even in the event of unfavourable and highly improbable events and thus indicate whether the system would be capable of coping with unforeseeable events. This characteristic of a final repository is also referred to as "resilience" (see information box).

97 | See BMUB 2015.
98 | See also ongoing GemEnd project commissioned by BASE.
99 | See NEA/CSNI 2013.
100 | See Rechard et al. 2014 regarding Yucca Mountain Project.

Resilience[101]

The term resilience is used with different meanings in a number of scientific disciplines,[102] including materials science, psychology, ecology and engineering.[103, 104] Today, it is additionally used in relation to sociotechnical systems.[105] According to E. Hollnagel:

"A system is resilient if it can adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions."[106]

According to Hollnagel, the term thus refers to the ability of a system to "heal itself" after being impaired. It would not appear necessary for a deep geological repository which, once closed, is intended to assume a passively safe state and the functionality of which is to be at most only slightly limited by disturbances, to fulfil such a characteristic.

Another definition describes "resilience" as "the ability of technical systems not to fail completely in the event of disturbance or partial failure, but instead to maintain vital system functions".[107] This ability of a deep repository system is examined in safety considerations insofar as the robustness of the system is also tested for highly improbable events or "what if" scenarios. In other words, it is investigated whether the system maintains essential safety functions even in the event of very unfavourable developments.

As the concept of resilience has proven fruitful in the context of sociotechnical systems, it would make sense also to apply it systematically to the overall nuclear waste management system. The entire sociotechnical process of site selection and the overall nuclear waste management framework must be included here. Such considerations underlie the concept of long-term governance (section 3.1) and are discussed in the context of regulatory and legal aspects of site selection.[108]

There remains a need for further research into the uncertainty arising from human actions, for example in the development and construction of deep repositories or in safety assessment. The aim is to provide appropriate safety management in order to avoid misjudgements, deliberate or unintentional ignoring of safety-relevant facts or even incorrect implementation of safety-relevant specifications. Knowledge management poses a particular challenge for an intergenerational task such as nuclear waste management.

The key will be to decide which uncertainties society is willing to accept and which ones can and should be mitigated or avoided. Relevant decision-making criteria are for example the nature and extent of the effects on safety aspects of the deep repository, the costs involved in limiting the uncertainties or the associated potential effects, as well as the associated prospect of success.[109, 110]

Until now, however, there has been no systematic methodology for dealing with safety-relevant uncertainty, for example in the context of provisional safety assessments which can be modelled on stress testing methods in other fields such as flight safety or banking stability. Policy recommendations for dealing with uncertainty should address, among other things, the appropriate combination of deterministic and probabilistic methods and the impact of highly improbable cases.

101 | This text on resilience was written at the suggestion of Prof. Ortwin Renn.
102 | See Hollnagel 2014.
103 | See Holling 1996.
104 | See Holling 1973.
105 | See Taysom/Crilly 2017.
106 | See Hollnagel et al. 2006.
107 | See Pregenzer 2011.
108 | See Smeddinck 2016.
109 | See Eckhardt 2021.
110 | See Röhlig 2021.

As already described in section 3.1.1, decisions have to be made at various points in the procedure despite ongoing uncertainty. Methods for complex decision-making problems such as MCDA and multi-attribute utility theory (MAUT)[111] have been developed for handling conflicting goals. Some of these methods take account of uncertainty both in the input parameters and in evaluation of the weighting of criteria and the impact of decisions. Such methods may possibly also be useful in the context of repository issues. They do not generate decisions but make the decision-making process and its basis comprehensible and transparent. It must, however, also be borne in mind that the individual weighting of separate factors decisively determines the result of such analyses. Furthermore, new methods of artificial intelligence (AI) and for decision support (operations research (OR)) should also be kept in mind in the field of decision-making. The methods to be developed in the field of decision-making naturally do not relate solely to the search for a site, but also to all other questions, for example relating to the construction and closure of a deep repository or to retrieval or recovery.

3.2.7 Information technology

It is clear from the above explanations that information technology is of great significance when it comes to dealing with uncertainty and further developing decision-making methods. Given the long-term nature and complexity of deep repository projects, enormous volumes of data will be generated. From a regulatory perspective, long-term data backup is indispensable, for example for data on construction, operation, closure and possible retrieval as well as site identification. Comprehensible data structures are crucial for quality control and transparency reasons. The dynamic development of data management plans is still in its infancy. A roadmap emerged in 2019 in the course of NEA projects which addresses the issues of safety demonstration (what data and knowledge are necessary, how are they structured?), knowledge management (how must knowledge be documented across generations?), archive storage (how can data and knowledge be preserved without suffering a loss of reliability and readability?) and awareness (how can knowledge and the memory of it be preserved in changing societies?).[112] Building on this, another key theme is dedicated to the further development and application of modern information technology concepts, in particular the development of what is known as an electronic safety case.[113] The importance of powerful simulations and computational decision-making tools has already been emphasised above. In other areas, the comprehensive digitalisation of industrial processes by networking modern information and communication technologies is already being pursued, for example as part of the federal government's "Industry 4.0" strategy.[114] The development and application of AI methods, virtual or augmented reality and the creation of "digital twins" of complex facilities play a central role here. Such developments from other fields should be put to use and further developed for the nuclear waste management project where they are urgently needed. Virtual representations can also assist with visualising deep repository systems and the processes which take place within them and so make them more comprehensible. They can also be valuable tools for communicating with different stakeholders and with the public.[115]

3.3 Research and training landscape

As already described in section 2.3, Germany has a truly diverse but sometimes also confusingly intertwined research landscape, consisting of university and non-university institutions, organised and funded by various ministries. Research needs in project funding programmes and research plans and agendas published by the various institutions currently still cover topics which are in large part identical or similar. Future developments in terms of clearly defined thematic boundaries and responsibilities would help to significantly improve the transparency of the system. At present, geoscientific research into final disposal is predominantly funded through calls for proposals by BGE and BASE, neither of which are independent research funding institutions but

111 | MAUT addresses the overall benefits of various alternative courses of action that differ with regard to various criteria and dimensions. Unlike MCDA, which frequently takes criteria as given, MAUT, which is grounded in psychological decision theory, attaches great emphasis to the discursive derivation of attributes by the individuals and groups carrying out the evaluation. The attributes obtained in this manner are then reformulated as criteria for the procedure.

112 | See NEA 2021.

113 | A safety case is a compilation of safety-relevant information. It includes, for example, exploration results, scientific and technical fundamentals, final repository concept and design, scenario analyses, model calculations and safety assessments. The safety case serves as the basis for decisions on how to proceed in a final repository programme, for example, when deciding on siting and at the start of construction or emplacement. Such a compilation is traditionally provided in a conventional report form. More recent developments, however, are directed towards exploiting the possibilities of modern information technology solutions. These include structuring, ranking, linking and the analysis and visualisation of information, see Röhlig 2021.

114 | See BMWK 2022.

115 | See Rink et al. 2014.

instead stakeholders involved in the procedure. Supplementary assessments by the NBG's expert panel, being carried out on a random sampling basis, are not necessarily sufficient for objectively clarifying controversial issues. This raises the question of independent research funding to ensure unbiased independent research and support self-learning in the procedure.

A look at the European countries whose deep repository projects are already well advanced shows that research into nuclear waste management is very much steered by energy industry companies or by the waste management organisations which they at least partially fund (SKB, Sweden; Posiva Oy, Finland; ANDRA, France; Nagra, Switzerland). In addition, the respective supervisory authorities initiate projects as part of their supervisory mission. The responsibilities of research funding organisations are clearly defined in Sweden, Finland, France and Switzerland and research activities would appear to be distinctly better targeted than in Germany. However, this very high level of control by the waste management organisations means that there is little or no discernible "independent" research which is not directly connected to the particular waste management project. Whether justified or not, however, it is precisely independent research that is often considered more trustworthy by civil society groups.

Since nuclear waste management research touches on numerous disciplines and fields of science, waste management projects extend over long periods of time, and the topic of final disposal is perceived by the public to be of considerable importance, particular requirements must be applied to the research landscape and its organisation.

1. Despite Germany's decision to phase out the use of nuclear energy, there is a need to develop or retain the expertise of a sufficient number of stakeholders in all those fields of science which are required for comprehensive waste management research. In this context, exchange, education and training programmes must work towards developing not only disciplinary excellence but also an overall interdisciplinary view of the deep repository system and also of the overall nuclear waste management system (see also section 3.1).

2. Waste management research must be embedded in scientific institutions in a future-proof manner so that, as knowledge develops further and new developments and findings are made, they can be fed into ongoing projects as part of a learning process.

3. The knowledge, expectations and fears of laypeople and non-scientific stakeholders must be taken into account. Consideration must therefore be given to integrative research models which can involve interested members of the public in nuclear waste management research as initiators and questioners (see information box "Transdisciplinary research"). In its final report, the Final Repository Commission explicitly recommended that appropriate concepts be developed.

4. In view of the intergenerational nature of this issue, it is important to arouse the interest of young scientists, engineers and technicians in nuclear waste management matters.

5. At the same time, an attractive offer must be developed not only to train the next generation of specialists, including attractive courses of study, interesting interdisciplinary research projects and modern research infrastructure in an international context, but also to draw on the innovation potential of industry (see information box in section 3.3.3).

3.3.1 Diversity and interdisciplinary collaboration

As already described in section 2.3, a wide variety of scientific disciplines and key themes are involved in deep repository research and interdisciplinary links must be created between them. Despite Germany's decision to phase out the use of nuclear energy and related technologies, research into the further development of nuclear technologies internationally remains relevant. The country must also have the expertise available to be able to classify new developments and make a fact-based assessment of advantages and drawbacks against the background of the specific German situation. Not only scientific and technical but also societal aspects must be taken into account. A corresponding research landscape must be set up in such a way that it can respond flexibly to social change and different trends without losing sight of a focus on waste management safety (see also section 2.3).

It is for these very reasons that it is advisable to create opportunities from the outset which enable researchers from different disciplines to collaborate and interact with one another. Projects such as ENTRIA[116] are a good example of such interdisciplinary collaboration. The Swedish National Council for Nuclear Waste (SNC) also recommends the development of interdisciplinary lines of research.[117] Although the Swedish waste management programme is one of the most advanced in the world, it

116 | See ENTRIA 2019.
117 | See SNC 2020.

is anticipated that even there it will take around seventy years until the deep repository for spent nuclear fuel is closed. The SNC justifies its proposal by stating that, in view of dynamic developments in society, politics and the economy, it cannot be assumed that the project will progress "linearly" over this period. A "robust" waste management project, like the research landscape required for it, must bear these interconnected developments in mind (see sections 3.1 and 3.2).

The current phase in the site selection process is largely concerned with methodological and geoscientific questions, the science-based answers to which will determine where the final repository will be located. Given this level of significance, the proportion of independent geoscientific research is surprisingly low. Geoscientific aspects have also so far been insufficiently linked to transdisciplinary research projects. It is therefore advisable to develop appropriate research programmes.

The research needs directly related to the actual deep repository project are determined by the progress made over time in terms of site selection and repository construction. At the beginning, fundamental topics and techniques, such as the development and application of exploration techniques, will dominate while, towards the end, technical implementation and facility construction will take precedence. The overall duration of the project is expected to extend into the next century (see section 2.2). Foresighted research planning should therefore provide a line of research which, as outlined in the fields of activity in sections 3.1 and 3.2, lies outside the time-limited, project-based work and is designed for the long term. This line of research will broaden the field of view by also allowing consideration of possible alternatives to the ongoing project. Radioactive waste from medicine, research, natural deposits of radioactive materials and other areas will continue to be produced beyond the period of currently ongoing projects making use of nuclear energy including the management of the corresponding waste (see time scales, section 2.2), and must be handled safely. While developments in the technical monitoring of a deep geological repository, the retrievability of waste and the like do indeed have to be taken into account today, they will also continue to develop over the coming decades until they will be implemented. Further developments in fields such as digitalisation, robotics or materials science are already taking clear shape. Possible applications in the field of nuclear waste management should be continuously reviewed and evaluated so that appropriate solutions can be provided when they are needed.

3.3.2 Involvement of societal groups

In its final report, the Final Repository Commission recommends creating opportunities for social groups to develop and maintain "critical, but factually objective capacity".[118] However, it provides no clear description of what it means by this. Capacity building could, on the one hand, be achieved by financially enabling such groups to commission independent studies and expert opinions, for example on certain aspects of site selection. On the other hand, developing research projects which directly involve civil society organisations opens up opportunities for building capacity and developing trust. Research can gain in transparency and comprehensibility if societal stakeholders can understand it by being directly involved. Transdisciplinary models are conceivable here, which also offer interested members of the public an opportunity to contribute aspects and lines of argument which have not previously been considered to research projects. There are examples of such projects not only in the area of research into the energy transition,[119] but also already in deep repository research (see information box "Transdisciplinary research"). Corresponding projects are not in any way capable of replacing disciplinary research projects, for example on scientific and technical aspects of repository safety. However, among other things, they can introduce society's perception of the risks associated with deep disposal and its assessment of safety aspects into the considerations. Meeting on equal terms and mutual trust between the parties involved are vital to the success of such projects.

118 | See Endlagerkommission 2016, p. 371.
119 | See Gölz et al. 2019.

Transdisciplinary research

In its final report, the Final Repository Commission recommended the creation of an transdisciplinary research consortium. This leaves some room for interpretation in view of different and sometimes diverging definitions of the term "transdisciplinarity"[120] A central feature of the TRANSENS[121] project is the inclusion of laypeople and people active in practice in research processes in order to be able to take account of non-specialist knowledge, values and expectations.

Such transdisciplinary projects may include "citizen science" projects, which are carried out with the direct assistance of interested citizens in ongoing research projects. Projects in which user-friendly computer programs enabling laypeople to understand simulation results are developed jointly with interested parties are one conceivable example. Other projects could involve laypeople in data collection with easy-to-use measuring instruments.

3.3.3 Attractiveness of research and training

It is obvious that there will be a need for skilled personnel and expertise for many decades to come.[122] The intergenerational nature of nuclear waste management projects means that the deep disposal of high-level radioactive material will have to maintain a long-term presence in research and teaching across a broad range of disciplines and in interdisciplinary teams at universities and other research institutions. Scientific engagement with nuclear waste management issues makes an essential contribution to addressing a socially relevant problem. Such engagement will be necessary and a moral imperative for decades to come and must therefore remain scientifically attractive. The process for selecting a site for a final repository with the best possible safety, which has been restarted with a broad political and social consensus, underscores the great importance of scientific research. It follows that there is a need for attractive training opportunities as well as degree programmes and modules, a good proportion of which should be interdisciplinary. Only by promoting young scientists, engineers and technicians will it be possible to create the basis for responding flexibly to change and transformation. It must be about more than just obtaining the skills to "get the job done" in waste management projects. The state of knowledge and technology must be further developed in such a way that the StandAG requirement of achieving the best possible safety can be met.

University research is therefore of particular significance. German universities, however, currently have only three chairs explicitly dedicated to nuclear waste management and final repository research: the Professorship of Final Repository Systems at Clausthal University of Technology, the Chair of Final Repository Safety at RWTH Aachen University and a Chair of Nuclear Waste Management, also at RWTH Aachen University. Further professorships at university and non-university research institutions also address sub-areas of final repository and waste management research among their areas of expertise. Creating additional endowed professorships and establishing Master's degree programmes, as well as integrating interdisciplinary modules into existing degree programmes in relevant disciplines and creating interdisciplinary post-graduate research training groups can pave the way to increasing the profile of nuclear waste management in research and teaching. For instance, a broad-based Master's programme on "geosystem management" or "geo-resources"[123] could, in addition to deep repository matters, address further socially important topics such as water, raw materials or sustainability from the fields of environmental sciences, geoenergy and economic geology. Such a programme would be attractive to students in many fields and would help train a new cohort of researchers who combine detailed knowledge with an understanding of the overall system. Strengthening appropriate conference formats and platforms (research networks) also promotes exchange between research groups with a differing scientific focus in universities, institutions of higher education and non-university institutions. In this way, synergies between deep repository research and related fields, such as geoenergy, can be created and intensified. The development of transdisciplinary research formats in nuclear waste management could also be accelerated more generally in the university sector.

120 | See Klein 2013.
121 | See TU Clausthal 2022.
122 | See BMWi 2020.
123 | See by way of example the Bachelor's and Master's geo-resources management programmes at RWTH Aachen University and similar offerings.

Planning research programmes and industry cooperation with foresight

The search for sites suitable for a deep repository is progressing from broad-brush to increasingly small-scale investigations, the depth of detail of which is increasing in parallel. This means that investigatory methods and technologies which need to be available at a certain point in time of the site selection procedure and deep repository project must be developed as early as possible and with foresight in research programmes.

Industry cooperation is also a high priority if mature technologies are to be provided when they are required. Industry involvement provides a broader social footing for the project and mobilises the innovative capacity of various branches of industry for the final disposal process. Some examples of technical development are briefly outlined below.

Comparing siting regions and sites as the site selection procedure progresses entails increasingly detailed knowledge of the geological conditions and physico-chemical properties of possible host rocks. A comparative evaluation therefore requires region- and site-specific characteristic values for rocks. However, these values vary not only by a factor but also by orders of magnitude, which makes a statistical analysis necessary. Such an analysis is currently available for only a few regions and for selected properties in Germany.[124, 125] FGeophysical measurements and, possibly, new exploratory drilling will be required for surface exploration for the second phase of the site selection procedure which, according to StandAG, is set to begin in a few years. It will be difficult to develop innovative technologies for this purpose within the short time available. In the third phase, however, identified sites will have to be subjected to highly detailed comparative exploration. For example, innovative minimally invasive drilling technologies could be helpful for obtaining the highest possible information density but they would have to be developed today in cooperation with industry. The number and location of such drilling operations can be determined, among other ways, using optimal experimental design methods.[126, 127] Since industry generally only becomes actively involved when there is commercial potential, it must be encouraged at an early stage to develop less expensive and minimally invasive drilling technology. The same applies to the further development of above-ground exploration, for example the use of potential field measurements (gravity, magnetics, electromagnetics, magnetotellurics) which can be applied effectively in particular in the exploration of crystalline rocks, as well as techniques for non-destructive mine exploration from underground.

Another example of the importance of research cooperation with industry in the shortest possible term is the development not only of optimised waste containers and emplacement techniques but also of sensors for deep repository monitoring. The development of new data evaluation methods, for instance using artificial intelligence (AI), or of simulation methods should also be mentioned. More direct forms of collaboration with the relevant industries should be considered for this purpose, for example a technology forum encompassing anything relating to industry participation.

124 | See Bär et al. 2020.
125 | See Jorand et al. 2015.
126 | See Curtis/Maurer 2000.
127 | See Seidler et al. 2016.

3.3.4 Research infrastructure

Nuclear waste management research requires the provision of dedicated research infrastructure, in particular underground research laboratories (URLs) for the relevant host rocks as well as nuclear chemistry laboratories in which research can be conducted into the behaviour of high-level radioactive waste forms and radiotoxic radionuclides.

Close cooperation with operators of generic URLs in neighbouring countries is already under way and will also be of benefit for future URL planning in Germany. Which findings from generic URLs can be transferred to the ultimately selected sites will have to be checked on a case-by-case basis. Site-specific URLs are often used for in-depth underground exploration, technology demonstration, as well as for testing repository design and operation and for developing trust.[128] URL experiments require long-term planning because their results will only be robust if they have a long run time. Key long-term safety characteristics, such as the self-healing properties of claystones or the compaction behaviour of crushed salt[129] as a geotechnical barrier have been well studied in the laboratory but much less thoroughly so on the far larger scale of a URL with consideration of various stress fields and different temperature conditions.

Establishing URLs requires many years of preparatory planning and therefore Germany must also give consideration to such infrastructure as early as possible. This is in particular the case if URLs are to be constructed in types of host rock which are not covered by existing international URLs, as is the case for rock salt, or which differ greatly from them, which is the case for the claystone formations of the North German Basin.

Nuclear chemistry laboratories allow in particular high-level radioactive waste forms and their radiotoxic components to be handled. Such laboratories thus enable scientific studies of the behaviour of relevant radionuclides and high-level radioactive waste in interim storage facilities and deep geological repositories but are costly and largely unavailable in Germany. Virtual laboratories will increasingly be used in research for the digital simulation of processes during the dismantling of nuclear facilities and of geophysical and geochemical processes in repositories. There will additionally be a need for large-scale facilities for the development and testing of dismantling technologies as well as test facilities for the emplacement and possible retrieval of radioactive waste and the safe closure of deep repository structures. Such demanding research and development infrastructure requires long-term advance planning which must start at an early stage in the procedure. These facilities should be set up organisationally in such a way that, irrespective of their location, they are accessible to and usable by research projects and researchers, including those from the international research community.

3.3.5 International networking and additional quality assurance

While nuclear waste management projects are generally the responsibility of individual countries, research is already under way in an internationally networked environment (see also section 3.2). Joint projects, including with countries outside Europe such as China or the USA which are pursuing national deep repository projects, are essential and are already being funded by the organisations responsible for final repository research. International collaborative efforts allow synergies to be exploited and different technical and procedural concepts to be compared and possibly adapted. In any event, the international dimension of research must be maintained and further developed. Pronounced internationality also helps to make the research more attractive to students and researchers.

How science management is designed will be of crucial significance to the organisation and efficiency of the research. Critical reflection is essential to science and external peer review provides additional quality control. This is achieved in basic research by scientific papers being published in peer-reviewed journals. This is also already the case in programmatic, application-oriented basic research on nuclear waste disposal projects. It is furthermore usual to submit safety assessments for deep repository projects for international review by the IAEA or NEA. Instruments for independent review should also be expanded for research directly related to a waste management or deep repository project. In particular for site-specific final repository research, it must be borne in mind that quality control and assurance have to meet the most stringent legal requirements. Independent review will be easier if the relevant reports are also available in English so that not only German-speaking experts can be involved. Switzerland's and Sweden's practice of making all project reports publicly available online in English is certainly exemplary and ensures transparency of science-based

128 | See NEA/OECD 2013.
129 | Crushed salt is a fine-grained salt rock material.

decision-making. A formalised review process is standard practice, for example, in evaluating the site safety of nuclear power plants.[130] Here too, research questions which have not been covered or only insufficiently so are identified and it is checked whether and to what extent the societal context has changed.

Not only the design of quality assurance and data backup but also the provision of data can be left to the organisations in question. Nonetheless, it would appear reasonable to set up an overarching scientific advisory board to sift through and evaluate the available scientific results from all the stated areas of research and make recommendations. Such an advisory board could help to avoid duplication and possibly bring together projects which are under way at different locations. Further missions for such an advisory board could be to make suggestions for better coordination of research funding on the part of the institutions involved (see section 2.3) and evaluate the findings from non-programmatic research and so possibly feed them into the process. This board could likewise address cases of scientific dissent. Entrusted with these functions, such an advisory board could provide complementary support to NBG, which oversees the overall process and is intended to provide an interface with civil society. One possible option for providing such an advisory board would be to refer repository research regularly to the German Science and Humanities Council for review.

130 | See USNRC 2018.

Appendix

Glossary

Recovery	Possible extraction of high-level radioactive material after decommissioning of the deep geological repository. In contrast to the concept of retrievability, the repository is then no longer in active operation but in a closed and sealed state. A further difference is that recovery operations are not specifically planned in safety terms and technical facilities are not kept in place in the mined final repository. Recovery is taken into consideration in the safety concept to the extent that the plan permits recovery in principle. Among other things, this means that final repository containers must remain stable for a certain period of time, for example at least 500 years, after the deep repository has been closed in order to enable recovery.
Operation	Phase between the start of emplacement and decommissioning of the deep repository
CASTOR(R) containers	Specialised containers for the interim storage and transport of high-level radioactive materials. Their design varies depending on the material to be accommodated, for instance fuel assemblies or vitrified reprocessing waste. The name is derived from *"**Ca**sk for **S**torage and **T**ransport **o**f **R**adioactive Material".* In everyday language, often incorrectly used as a generic term for containers for radioactive material.
Geological and engineered barriers	Facilities in the mined repository intended to enclose and shield waste in the deep repository. A distinction is drawn between the natural geological barriers of the host rock and engineered barriers, such as containers and mine installations.
Conditioning	Treatment and packaging of high-level radioactive materials for transport, interim storage or deep disposal.
Near and far field	The near spatial region around a radiation source, which in particular also includes the container, the geotechnical barriers or the transition to the geological barrier, and the far region of the geological barrier.
Partitioning and transmutation	Methods for dividing ("partitioning") the radioactive material into radionuclides and selectively converting ("transmuting") some of them into nuclides which have a distinctly shorter half-life or are not radioactive. As a result, the hazard potential of the waste could fall significantly faster to the level of naturally occurring uranium deposits. The main problem which arises here, however, is the need for complex chemical processing and irradiation of the high-level radioactive waste. This entails the construction of complex above-ground nuclear facilities which may well not be accepted by the public. Another acatech publication provides a detailed analysis.[131]
Passive safety	State of a closed repository containing emplaced waste which is beyond easy human access. This safety must not be dependent on access control and maintenance.
Radionuclide	Unstable, radioactive nuclide (type of atom). An individual (radio)nuclide is characterised by the number of protons and neutrons in the atomic nucleus. Different elements are defined by having a different number of protons. Isotopes of a single element are defined by having a different number of neutrons with a constant number of protons. As a result of nuclear fission, "spent" fuel rods contain a broad mixture of stable nuclides and radionuclides.
Radiotoxicity	The adverse health effects of radiation emitted by radioactive material on the human body in the event not only of external exposure but also of incorporation by ingestion or inhalation
Retrievability	In Germany, according to the provisions of StandAG, the retrieval of high-level radioactive waste only has to be possible prior to closure of the mined final repository. Subsequently, the term recovery is used. The procedures for any retrieval must be planned technically, evaluated in safety terms and the necessary technical facilities kept in place, providing that "the technical costs and time required for this purpose do not disproportionately exceed the costs required for emplacement".[132] Outside Germany, however, the possibility of retrieval beyond the period up until the deep repository is closed is also being discussed
Decommissioning and closure of the deep repository	After emplacement of the high-level radioactive material, underground cavities are backfilled as completely as possible with suitable materials, the deep-mined repository is closed, and technical facilities that could impair the long-term safety of the deep repository are dismantled.
Preliminary safety assessment	Assessments to be carried out in each phase of the site selection procedure for regions or sites to be considered, in accordance with the Site Selection Act and Final Repository Safety Assessment Ordinance. The aim is to verify that the safety requirements and criteria according to StandAG are met on the basis of an overall view of the available information and to create a basis for comparison between regions or sites.
Host rock	Deep subsurface rock formation in which the deep repository for high-level radioactive materials is to be constructed. The host rock has properties which prevent the propagation of radionuclides for the longest possible period. In general, a distinction is drawn between three superordinate types of host rock: (crystalline) bedrock, claystone and salt rock. These have different properties, for example in terms of deformability and water permeability, which complicates any comparison of suitability for a deep repository.
Interim storage	Time-limited storage of radioactive waste materials at various sites, both central and decentralised, prior to transfer to a deep repository.

131 | See acatech 2014.
132 | See EndlSiAnfV 2020, § 13.

Abbreviations

AkEnd	Working Group on the Selection Procedure for Final Repository Sites
ANDRA	French National Agency for Radioactive Waste Management
BAM	Federal Institute for Materials Research and Testing
BASE	Federal Office for the Safety of Nuclear Waste Management
BGE	Bundesgesellschaft für Endlagerung mbH [German federal government-owned company for radioactive waste disposal]
BGR	Federal Institute for Geosciences and Natural Resources
BGZ	Bundesgesellschaft für Zwischenlagerung mbH [German federal government-owned interim storage company]
BMBF	Federal Ministry of Education and Research
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (2018-2021)
BMUB	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (2013-2018)
BMUV	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (since 2021)
BMWi	Federal Ministry for Economic Affairs and Energy (2013-2021)
BMWK	Federal Ministry for Economic Affairs and Climate Action (since 2021)
DAEF	German Working Group on Final Repository Research
DFG	German Research Foundation
EndlSiAnfV	German Ordinance on Safety Requirements for the Final Disposal of High-level Radioactive Waste (Final Repository Safety Requirements Ordinance)
EndlSiUntV	German Ordinance on Requirements for the Performance of Preliminary Safety Assessments in the Site Selection Procedure for the Final Disposal of High-level Radioactive Waste (Final Repository Safety Assessment Ordinance)
EURAD	European Joint Programme on Radioactive Waste Management
FORKA	Research into the dismantling of nuclear facilities
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit GmbH [company for facility and reactor safety]
IAEA	International Atomic Energy Agency
AI	Artificial intelligence
LBEG	Lower Saxony State Office for Mining, Energy and Geology
MAUT	Multi-attribute utility theory
MCDA	Multi-criteria decision analysis
NagraAGRA	Swiss National Cooperative for the Disposal of Radioactive Waste
NaPro	German National Waste Management Programme
NUSAFE	Nuclear Waste Management, Safety and Radiation Research
NBG	National Citizens' Oversight Committee (Germany)
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
SKB	Swedish Nuclear Fuel and Waste Management Company
SNC	Swedish National Council for Nuclear Waste
StandAG	German Act on the Search for and Selection of a Site for a Final Repository for High-level Radioactive Waste (Site Selection Act)
URL	Underground research laboratory
VkENOG	German Act on Reorganising Responsibilities in Nuclear Waste Management

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While the use of nuclear energy is set to be phased out in Germany by mid-April 2023, the management of high-level radioactive material remains a long-term task that will also concern future generations. With the Site Selection Act (StandAG), legislators have defined the regulatory framework for the site selection procedure currently under way for a deep geological repository in Germany. The aim of the procedure is to ensure the greatest possible safety for a period of one million years. The time horizon until the deep repository is closed will in all likelihood extend into the next century. The long-term nature of the project, its great relevance to society and the legislators' demand for a learning process give rise to special requirements for the design of research programmes and the scientific research landscape.