Ethics of Science and Technology Assessment | Volume 38

Radioactive Waste

Technical and Normative Aspects of its Disposal

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ISBN: 978-3-642-22924-4 e-ISBN: 978-3-642-22925-1

Ethics of Science and Technology Assessment ISSN: 1860-4803
e-ISSN: 1860-4811

Library of Congress Control Number: 2011935561

Cover design: eStudio Calamar S.L.

Typesetting: Scientific Publishing Services Pvt. Ltd., Chennai, India.

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Introduction

The threat posed to humans and nature by radioactive material is particularly a result of the ionizing radiation released during the radioactive decay of this material. It is therefore necessary to safely store radioactive waste accumulated in research, medicine and technology (particularly high level waste in nuclear facilities). The decisive factor determining the duration of the hazardous state is the characteristic physical half-life time in which the various radionuclides decay, ranging from fractions of seconds to many millions of years. Fuel elements taken from the reactors of nuclear power plants contain radionuclides with very long half-lives. It has therefore been an accepted fact worldwide, since power plants of this type have been in operation, that the radioactive material needs to be confined in isolation from the biosphere, the habitat of humans and all other organisms, for very long periods of time. As waste is also present in Germany, it is seen as necessary to create a final disposal site here too.

The concepts for final disposal which have been discussed most are near-surface disposal, disposal in deep geological formations, and deep sea or sub-seabed disposal (SSK 1987). Internationally, other concepts have also been discussed (e.g. long-term or indefinite storage, disposal in outer space, CoRWM 2006), the majority have, however, chosen disposal in deep geological formations. This is also the case in Germany. Of vital importance for the long-term safety of these disposal facilities is the host rock, which must prevent radioactive materials from escaping from the disposal facility into the biosphere in any significant quantity. Internationally, the host rocks under discussion are crystalline formations (e.g. granite), salt domes and clay. In Germany disposal in salt formations was proposed as early as the 1960s.

In 1977 the German federal government commissioned the national metrology institute, the Physikalisch-Technische Bundesanstalt (PTB) to begin the planning approval procedure for the disposal of radioactive waste in the Gorleben salt dome (Tiggemann 2004).

Originally the disposal facility was intended to be part of a nuclear waste management centre with a reprocessing facility. To clarify the connected safety issues and risks of the waste management centre, and thus of a disposal facility, a "Symposium of the Government of Lower Saxony on the fundamental safety-related feasibility of a nuclear waste management centre" (the "Gorleben Hearing" was held in Hanover from 28 March to 3 April

1979. After matter-of-fact discussions chaired by the physicist Carl Friedrich Freiherr von Weizsäcker, the following conclusion (amongst others) was reached by Ernst Albrecht, the Minister President of Lower Saxony at the time, who hosted and took part in the symposium. He presented his findings to the Parliament of Lower Saxony on 16 May 1979: "Although a nuclear waste management centre […] is in principle feasible in terms of safety, the Government of Lower Saxony recommends that the Federal Government not pursue the reprocessing project. Instead a new waste management concept should be resolved upon immediately, along the following lines:

(1) Immediate establishment of inherently safe long-term storage sites to manage waste from the nuclear power plants […],
(2) Promotion of research and development on the safe disposal of radioactive waste,
(3) Deep drilling in the salt dome and, if the results are positive, mining exploration of the salt dome in Gorleben; if the drilling should have a negative outcome, exploration of other disposal sites; because we do need disposal sites."

The exploration programme in Gorleben began in 1979/1980 – first from the surface, and then, from 1986 on, underground. The programme was interrupted by a moratorium of a maximum of 10 years in 2000. In this period numerous Castor shipments of radioactive waste were made to Gorleben, and deposited in an interim storage site there. The explorations in Gorleben and the shipments of nuclear waste through Germany led to emotionally charged debates, and to extensive, heated, sometimes militant demonstrations by critics of nuclear energy in general and of the Gorleben disposal site in particular. The Federal Government's decision, in October 2010, to resume the exploration of the Gorleben salt dome reignited and strengthened resistance to the nuclear disposal facility. The result is a highly charged atmosphere which makes matter-of-fact dialogue nearly impossible.

In a parallel development in this period, national and international scientific committees have examined safety issues relating to disposal facilities for radioactive waste, and established corresponding criteria. Thus in June 1985 the German Commission on Radiological Protection (Strahlenschutzkommission, SSK) approved a recommendation about "aspects of radiological protection when disposing of radioactive waste in geological formations". The SSK worked on the principle that future generations have to be protected from ionizing radiation to the same extent as people today. For the post-closure phase and thus for long-term safety, it was recommended that the "potential radiation exposure for individual members of the population after the occurrence of improbable events should not exceed the amount of the average range of variation of natural exposure to radiation (effective dose equivalent) in the Federal Republic of Germany" (SSK 1987). This is achieved if the dose constraint of 0.3 mSv per year is observed. The International Commission on Radiological Protection recommended setting a potential radiation exposure of 0.3 mSv per year (effective dose) as the dose constraint for the post-closure phase (ICRP 1999).

In order to look at long-term safety, periods of several tens of thousands of years were initially taken into consideration. A key argument for such a period was that a new ice age can be expected in our region within this time frame. On the basis of geologists' prognostic statements on the timescales of possible changes in the sites of disposal facilities and on the possible migration of material through the geological barriers, assessments of the long-term safety of disposal facilities for radioactive waste have now been expanded to a range between hundreds of thousands and one million years (SSK 2008; ICRP 2011; BMU 2010). More recently a dose constraint of 0.1 mSv per year has been proposed for potential radiation exposure in the post-closure phase (SSK 2008). The various models of disposal facilities for high level waste in deep geological formations with various overlaying rocks, and the experiences with deep geological disposal facilities for chemotoxic materials offer strong evidence for the feasibility of such disposal sites, even with the strict criteria stipulated.

In Germany and other countries deep geological disposal facilities for chemotoxic waste material are already in operation today. They are largely accepted, despite the absence of comparably elaborate safety cases, and the fact that this material possesses "perpetual" chemical stability and can pose a greater potential threat to health than radioactive waste. Nonetheless, it has not yet been possible to achieve social and political acceptance for a consensual concept for the disposal of radioactive waste material. This is particularly the case for Germany, but also for many other countries worldwide. It has been possible in Finland and Sweden, however, to locate sites for such disposal facilities (Finland: Olkiluoto, Sweden: Forsmark, Östhammar municipality). France and Switzerland are evidently progressing well towards this goal, but there has been a serious drawback in the USA.

The reasons for the lack of acceptance for disposal facilities for high level waste are complex. They lie partly in the special perception of the danger of ionizing radiation and thus of radioactive material in the waste. Although humans are permanently exposed to this radiation from natural sources, and incorporate naturally occurring radioactive materials every day with their food, their water, and the air they breathe, and although nearly all humans in industrialized countries are exposed to ionizing radiation in medicine, for diagnostic or therapeutic reasons, and the possible health risks can be reasonably well estimated, many people have serious reservations when it comes to being exposed to ionizing radiation from technical facilities – even if the radiation doses are low. In the case of nuclear power plants there is no doubt that in this context the consequences of possible major accidents play a significant role in the non-acceptance of their hazard potential. The disposal of radioactive waste does not involve any danger of explosions, meltdowns or other sudden accidents, and yet the lack of acceptance of nuclear power impacts on the acceptance of nuclear waste disposal.

It is very obvious that the issue of the appropriate management of radioactive waste is attended by considerable potential for conflict. Yet when it comes to this topic the emotionally charged positions and the passion with which arguments are put forward are only an external indicator. Often the discussion about the nuclear disposal facility masks deeper social debates about the significance of technological developments for the future shape of the economy, energy production and life in society. The acrimony with which this conflict is carried on in public is also doubtlessly characteristic of the debate and is worthy of more careful attention, especially if one is interested not just in the theoretical development of problem-solving strategies, but also in the practical resolution of the conflict. If a decision is to be brought about through the answering of factual questions, the social dimensions of the conflict will also have to be analysed in order to discover how the current polarized positions can be converted into a constructive discourse about rational strategies, i.e. ones which can be understood and tolerated by all parties. This is the only possible way to achieve an effectively legitimized decision on the site issue and modalities of a final disposal facility for high level waste.

Recent decades have shown that planning and dealing with large-scale technological facilities cannot be successfully carried out purely by solving technical problems. It is desirable, if not necessary, and also appropriate in a democratic system to attain the acceptance or at least the tolerance of the people affected. This idea was already expressed in Minister President Albrecht's concluding remarks on the "Gorleben Hearing" in 1979. He said: "[…] that the formation of opinions must occur in a democratic process, that this is not about technocratic decisions, but ultimately about democratic decisions. Democracy, however, requires argumentation, and publicity requires transparency." This plea for information, participation, communication and transparency was clearly not followed closely enough in the years that followed. Minister President Albrecht also said, however, back in 1979, that the final decision "is a typically political decision. The responsibility for this decision lies with the political authorities, and no one can relieve them of it." The need for these sequences of action is elaborated in the present study.

In the decision-making process regarding a disposal facility for high level waste, considerable importance is accorded to the uncertainty of scientific knowledge and models, to possible ambiguity in the evaluation of a condition, and to possible contradictions in the statements of experts. As a consequence, the affected population feels insecure. In Germany this has been reinforced considerably by the events surrounding the "experimental disposal facility" at Asse. It is scarcely possible to explain to the wider public that Asse, being only an "experimental disposal facility", was conceived with quite different standards than the planned geological disposal facility for high level waste will be. Credibility is also undermined when it emerges that there has been misconduct or neglect in the scientific/technical and administrative management of the Asse disposal facility.

Unavoidable uncertainties in knowledge and scientific data, and the way these are presented and dealt with, are without doubt extremely difficult topics and substantial obstacles for the attempt to gain acceptance for disposal facilities of this kind. The very long time spans of the necessary prognoses clearly reinforce these effects considerably. Even in small and everyday technical instruments, the parameters of the system and the external influencing variables are not always fully known. For reasons of principle, this applies even more to singular large-scale technical installations, however thoroughly they may have been examined. The most recent developments in Fukushima, Japan, also show that exceptionally extreme events can occur which cannot be expected even if all available data are used as a basis for planning, but against which precautionary efforts must nonetheless be undertaken because their consequences are so severe.

Clearly this applies particularly to the planning of disposal facilities for high level waste. Statements must be made about long-term safety over periods of time so long that they reach the limits of the human capacity of imagination. Prognostic statements are then only possible by means of model calculations with correspondingly high levels of uncertainty. Reaching an understanding of these matters is no easy task.

Geological processes of evolution occur over considerably longer periods of time than biological or social processes of evolution. These characteristics of possible geological developments and their changes over time mean that prognostic statements about the possible breaching of technical and geological barriers over longer periods of time can be made with sufficiently higher degrees of accuracy than prognoses about how the region of a disposal site will be inhabited over this period, and what the lifestyles of these people will be like. But even such great prognostic uncertainties do not justify ignoring the possible claims of future generations to adequate management of radioactive waste, or dismissing these claims as irrelevant. On the contrary, an adequate waste management strategy must – in keeping with the ethical principle of universalism – give the same consideration to members of future generations as it does to those of the present generation.

The above discussion of the extreme complexity of the conflict is not intended to either accord a special status to the problem of radioactive waste management, or indicate scepticism about the likelihood of resolving this conflict: highly complex controversies, in which the debate over the appropriate or suitable solution to a problem not only throws up questions about the appropriateness and suitability of the problem-solving strategies, but also questions about the appropriateness and suitability of the standards for evaluating these, are established practice in various areas of private and public life. They give rise to the political, judicial and socio-economic institutionalization of conflict resolution. Here procedural rules, neutral evaluation or competition ensure that efficient decisions are made and the capacity to act is maintained, – since responding to ongoing controversy by doing nothing often turns out to be an unfavourable option. The analysis and discussion of highly complex controversies are also established practice in science, however, which can virtually be seen as something brought forth by society for the professionalization, i. e. the delegation, of the systematic and long-lasting engagement with controversies of this type, freed from the pressure to make efficient decisions.

There is no reason, then, to give up in the face of extreme complexity. On the contrary, as long as there is no pressure to reach efficient decisions, the conflict-producing constellations of problems should be registered following the rules of scientific rationality; the questions requiring decisions should be differentiated, analysed and stated more precisely, and the options put in order and examined.

In preparation for a situation in which efficient decision-making will become necessary, care must be given to how the instruments of conflict resolution are chosen or developed so that a lasting resolution of the conflict can be brought about. But the only lasting solution can be one that is accepted or at least tolerated in the long term by a large proportion of those involved. This presupposes that the answers to the technical questions which have influenced the decision do not quickly turn out to be erroneous, and that those involved do not suddenly begin to perceive the process through which the decision came about as "unfair" and disadvantageous to them, and retrospectively deny the legitimacy of the result despite their earlier agreement with the process. Here we should recall the remarks made at the outset about the social dimension of the conflict and the emotionally charged nature of the debates, which may be at least partially due to the fact that not enough attention was paid to this in the early stages, when the "depth" of the conflict could not be foreseen. With this in mind, the present study attempts to point out and propose ways to find a way out of the dilemma of the current situation and devise an acceptable procedure for locating a site and constructing a disposal facility for high level waste.

In part A of the study the texts are available in both English and German. First the key information from the chapters of part B is presented in comprehensive summaries, followed by chapters with conclusions and recommendations. Possible ways to find a site are pointed out.

In part B of the study the strategies and technical concepts for the management of high level waste and its disposal in deep geological foundations are presented in separate chapters, along with the related issues of radiation risk and radiation protection. The aim is to give the reader an overview of the latest state of knowledge. Chapters follow on ethical, normative aspects of long-term responsibility, on legal issues of the disposal of radioactive waste, and on guidelines for a socially sustainable and fair means of selecting a site. In order to make the study accessible to an international readership from a scientific background, these chapters are written in English.

Part C offers supplementary information on the fundamentals of radiobiology and a comparative law overview of the regulations of important states using nuclear energy.

A key conclusion of the study is that the best possible procedure would be for the investigation of Gorleben as a possible site to continue, but with one or two other sites also being considered and surface-based exploration being carried out at these locations. The advantage of this procedure would be that if Gorleben were to fail, little or no time would be lost switching to another site. It can be expected that such an approach would increase acceptance of the site selection process. On the other hand such a procedure would also offer the possibility of submitting an alternative site to a more in-depth, i.e. sub-surface exploration, if the available studies show that the alternative site fulfils the selection criteria much better than Gorleben. In the site-finding process a high level of significance is ascribed to information, communication, participation and transparency. It is made clear, however, that the final decisions must, in accordance with the legal regulations of the Federal Republic of Germany, lie with the responsible institutions.

A Executive summary, conclusions and recommendations

1 Executive summary

1.1 Technical issues of long-term radioactive waste management

A solution to the problem of long-term radioactive waste management (RWM) comprises a technical and social dimension, i.e. it must not only be technically achievable, but also legally and politically feasible and publicly acceptable. The technical solutions have to ensure beyond reasonable doubt safe and secure containment of long-lived highly radioactive waste for the indefinite/distant future and avoidance of undue burdens on future generations. Despite the perceived link between RWM and the controversial debate on nuclear power production the problem of RWM is considered as one which has to be solved no matter which perspectives are foreseen or debated concerning nuclear power production: the additional amount of radioactive waste due operating time extension is small compared to the existing stocks of radioactive waste. The fact that a solution of the RWM problem would disprove a key argument against nuclear power is not a justified reason to hinder such a solution. There is a wide variety of radioactive wastes arising from several activities, the most important one (in Germany) being nuclear power production. For some radioactive materials it is a matter of definition and strategy whether they are considered as resource or waste. In particular, this applies to irradiated spent fuel (SNF).

The types of waste mentioned above show a great variety in terms of radionuclide content, chemical composition, and physical condition. These features have implications w.r.t. all steps of RWM. Waste categorization varies from country to country often linked to the disposal route foreseen. The focus of the report is heat generating waste (called high-level waste, HLW) for which a disposal solution is still lacking in Germany.

Presently we distinguish between "once-through cycle" and "partially closed cycle":

- For the former, any irradiated fuel is considered as HLW and an increase of fuel burn-up would help to reduce the fractions of remain-ing fissile material as well as the amount of highly radioactive cladding and structural material per unit electricity while the amount of long lived, heat-generating minor actinides would slightly increase.
- The latter, involving reprocessing, has been selected by a number of countries, particularly those with large and well-established nuclear power programmes but abandoned by Germany. The infamous CASTOR shippings to Gorleben go back to earlier reprocessing con-tracts, resulting in vitrified HLW to be taken back by the country of origin.

The partially closed cycle concept aims to better utilize the energy content of natural resources by MOX fuel and to reduce the volume and toxicity of the spent fuel and waste to be stored. It leads to an increased number and volume of transports of radioactive materials which are potentially hazardous and subject to strict international regulation but also to public intervention. Separation of fissile and radiotoxic material (in particular plutonium) and its storage on site are considered further disadvantages. Advanced fuel cycles strive for fully closed fuel cycles connected with further developed proliferation-resistant reprocessing technology and various types of advance reactors either with thermal or fast neutron spectrum. Numerous national and international efforts are under way to develop advanced "reactor systems" being commercially deployable between 2030 and 2040.

Partitioning and transmutation of long-lived minor actinides (P&T) could significantly reduce, i.e. a hundred-fold, long-term radiotoxicity inventories of the disposal; the energy content and heat capacity of the final waste could also be reduced dramatically, resulting in potential decrease of the repository size or, in the case of large programmes, number of repositories needed. Regarding potential radiation exposures to the biosphere in the very long run due to a possible migration of radioactive nuclides through the host geology no further signification improvements are to be expected, though.

Subcriticality of irradiated fuel and wastes of all kinds has to be ensured for all steps of the RWM chain, especially for the final repository. Assessments as an element of national RWM programmes show that, if burn-up credits and given uncertainties are accepted, subcriticality can be ensured for "once-through cycles"; for non-open cycles this issue becomes irrelevant. As other wastes, proper radioactive waste management (RWM) requires a strategy ultimately targeted on protecting human health and the environment and ensuring security. It should comprise unloading, processing, transportation, storage and disposal as important steps. The exact sequence of these steps varies for different countries, different waste types and basic decisions and choices made concerning the whole fuel cycle.

Storage is (by IAEA definition) done "with the intent of retrieval" and may be of different purpose (e.g. in order to decrease the content of short-lived radionuclides or transport logistics, but also awaiting a disposal solution). Established technical solutions vary from above or shallow below ground, wet or dray, forced cooling or natural convection. Storage times are in the range of decades up to one century; even several centuries are sometimes discussed or envisaged.

Disposal is (by IAEA definition) done "without the intent of retrieval". This implies that the material is indeed declared as waste and not as resource. A variety of disposal options was discussed in the past, including exotic solutions. Remaining options for HLW/SNF follow the basic decision "concentrate & confine" instead of "dilute & disperse". They are

– those technically comparable to storage and this requiring human activities such as monitoring, control, maintenance, refurbishment etc. over the whole timeframe considered;

– those leading to a state at which no further human intervention or follow-up activity is needed ("passive safety"); deep ("geologic") disposal in mine-type facilities, sometimes also deep borehole disposal are favored.

Lack of confidence in "passive safety" was one of the motivations behind promoting long-term storage solutions or of going for disposal approaches for which waste retrieval, although not intended, is – although only for some time after emplacement – eased by design measures ("retrievable disposal"). International solutions (sometimes also called regional) make in particular sense for countries with smaller waste amounts and/or geographical and/or geological boundary conditions which make national solutions difficult to implement.

To explain how the above mentioned elements of a RWM strategy match and to illustrate associated safety and security challenges, a rather simple strategy is described as reference case in greater detail, based on the "once through" cycle. SNF is declared as waste, no reprocessing takes place, and the waste is to be finally disposed of in a deep (geologic) repository. Not addressing other waste, the SNF-related process comprises the following steps:

– Decay storage for several years in cooling pond at reactor site after discharge from reactor;
– Emplacement in transport casks, short-distance transport to local or long-distance transport to central storage site;
– Interim, buffer, and decay storage (local or central) for several decades (dependent on disposal programme);
– Transport to conditioning facility (short or long distance dependent on location), buffer storage, conditioning for disposal;
– Buffer storage, transport to disposal facility (long or short distance dependent on location);
– Emplacement in disposal facility.

Strategies based on partially or fully closed (advanced) fuel cycles call for reprocessing of SNF and fabrication of mixed fuels and therefore result in differences concerning logistics of pre-disposal material/waste management and waste amount, form, radioactivity content, heat generation, etc.

As to strategic decision on the "end point" of RWM the two most remarkable differences between the options "prolonged storage" and the "disposal in deep geologic formations" are the degree to which

– safety and security in the long run depend on active measures (which involve radiological exposures of workers), and
– emplacement measures are reversible (and, in particular, the waste is retrievable) at different future points in time.

Preferences concerning these issues depend on the confidence one has into the safety and security of the different options and on the consequences one derives from the awareness of the duties to future generations. Potential conflicts of targets become also visible when considering hybrid solutions such as retrievable disposal and/or delayed closure of repositories. Approaches pursued in different countries are, e.g., delayed closure in the UK and staged closure of repository going along with decreasing possibility/increasing effort of reversibility in France. Prolonged storage (potentially for more than one century) is implemented in the Netherlands. The variety clearly demonstrates the inherent ambiguity in the decision on the "end point". In particular, it becomes evident

- that implementing reversibility or retrievability is a complex under-taking,
- that there is no simple answer to the question whether disposed waste is retrievable but rather a varying "degree of retrievability" can be considered, and
- that this degree of retrievability strongly depends on the timeframes considered which, however, are considerably shorter (in the order of decades up to three centuries) compared to the timeframes post-closure safety has to be ensured (up to thundered thousands of years).

The desire for retrievability of the emplaced materials on one hand and for a disposal which is safe and secure in the long run might lead to conflicts of goals or trade-offs. In particular there is an antagonism between retrievable disposal and protection against access (security). The ultimate goal of any disposal and deep geological disposal in particular, is to ensure safety and security in the long run and to balance conflicting aspects, where appropriate. This is the same for all concepts, but there is still room for considerable variations due to different available host rocks and other reasons. But in case of a target conflict measures that allow for retrievability should be subordinated. All concepts presently discussed strive for safety and security in the long run – although the pillars of safety and security (containment, isolation, migration delay, limitation of impacts) are the same, the weight to be put on each of them (depending on the point in time after closure) as well as the ways they are achieved vary. Generally spoken, no host rock will provide only favorable conditions with regard to all of these aspects, designs and (geo-)technical measures have to be adjusted in order to take advantage of the favorable features of the host rock and to compensate for the less favorable ones, taking different time frames into account.

Evidence must be provided that the ultimate goals of RWM have been achieved by long term assessments taking the whole spectrum of undesired events, states and processes into account. The proof of adequate security can focus on human intrusion: Following the decision for the concept of concentrating and isolating the radioactive waste in a repository, the possibility inevitably has to be accepted that radiation exposure limits may be exceeded in the event of intrusion into the repository. In addition, it is not possible to quantify appropriately the consequences associated with human intrusion due to the lack of predictability of the boundary conditions and other parameters to be assumed. However, the radiotoxity of the disposed material may serve as a measure for the hazard involved.

Emphasis on assessing radiological safety in the long run traditionally concentrates on calculating potential exposure for scenarios, but lack of predictability for some components of the systems, especially those close to the surface, lead to high aleatory and epistemic uncertainties. Thus, calculated doses are not measures of real health detriment, but rather indicators of repository performance which mainly depends on the behaviour of better predictable components situated at greater depth. The concept of Safety Case is created by bringing together safety-related elements and arguments from site exploration, research, disposal site development and construction, safety analysis, etc. The Safety Case is evolving over time together with the repository programme and concept. Handling uncertainties is a pivotal element of the safety case.

The evolution of a repository programme, associated site investigation and R&D case can be seen as optimization process over some decades. The target function is composed of short term and long term safety and security issues, feasibility, costs, societal acceptance, legal feasibility and perhaps others. The target function itself can change over time (e.g. the timeframe of concern for long-term safety proof increased by two orders of magnitude over the last two decades); the knowledge base and ability to bound uncertainties also evolve over time. Thus, it does not make sense to revisit past decisions ("retrospective optimization") in order to ask whether these decisions were achieved according to today's standards. Rather the question whether the result of past decisions (site, layout, etc.) is still defensible under today's standards is essential.

In Germany repository operation could start in 2035 at the earliest, provided that every programme step would be fully successful (i.e. acceptance of Gorleben in 2017, planning permit without delay, etc.). Delays caused, e.g., by the rejection of Gorleben, the search for a new site (immediately or after rejection of Gorleben), etc. would lie in the order of magnitude of one or two decades.

Technical implementation of new technologies (e.g. P&T) can be expected in the 2030ies or 2040ies. As long as SNF is not emplaced (i.e. at least until 2030) there is no decrease of flexibility caused by a "fast" disposal programme. This is, however, only valid if a schedule with well-defined decision points exists. Otherwise, the forth-and-back of the past and the present with its strong dependence on the political orientation of governments which might change with each election would continue, the process could become indefinite without obtaining a solution.

1.2 Radiation risk and radiological protection

To evaluate radio-toxicological effects it is necessary to know the dose-effect relationship. In radiological protection two fundamentally different classes of these relationships are used. The fundamental difference consists in whether a dose-effect curve with or without threshold dose is present. The first option applies to *deterministic* effects (acute effects, fibrotic and similar tissue effects, and effects in the area of developmental biology). The threshold doses for these effects lie in a range of over 100 mSv. There is, on the other hand, no threshold dose assumed for *stochastic* effects (genetic effects and cancer); according to this premise, effects may occur even at very low radiation doses. A linear dose-effect relationship without a threshold dose (LNT model) is envisaged for these effects.

The fundamental quantity in radiological protection is the absorbed dose (D) in gray (Gy), it indicates the energy absorbed in an element of mass (m). Since various qualities of radiation (radiation type and radiation energy) lead to different effects from the same absorbed dose, the absorbed dose is weighted, giving the dose equivalent dose (H) in sievert (Sv). The risk of cancer significant for low radiation doses differs from organ to organ at the same equivalent dose. Hence the equivalent doses are multiplied by corresponding tissue weighting factors. The sum of these products gives the effective dose (E) in Sv, which relates to the stochastic radiation risk. The effective dose is a useful instrument for estimating regulatory processes such as optimization. It allows us to measure all pathways of human exposure and show them as a total value.

The dose limits and dose constraints are given as effective doses. The limits for on-site employees during the operational phase of the disposal facility (i.e. the placing of the radioactive material in the repository) are 20 mSv per year, and for members of the public in the immediate vicinity of nuclear facilities during the operational phase 1 mSv per year. For disposal facilities for high level waste various international committees envisage a "dose constraint" of 0.1 to 0.3 mSv per year in the post-operational phase (thousands to millions of years) after the closure of the disposal facility. The BMU (German Ministry for the Environment) recently suggested 10 μSv per year for this dose. The ICRP deems this a "trivial" dose of no significance.

To optimize sources of radiation in radiation protection, the effective collective dose is often cited. The average of the effective individual doses is multiplied by the number of persons exposed, and the dose is then given in "man Sv". To better judge the situation, the areas of the personal doses, the time period in which the relevant doses were considered, and other factors should be mentioned when establishing the collective doses. Collective doses are not suitable for assessing radiation risks, especially in the lower dose range.

The radiotoxicity of the radionuclides is determined by the radiation which occurs during radioactive decay. With regard to the long-term risk, radionuclides with long physical half-lives are of crucial importance, since these radionuclides continue to exist in considerable quantities for more than a million years, in some cases, and undergo radioactive decay over long periods of time. After this material has been incorporated into the human body, radiation exposure can occur over fairly long periods of time, particularly if a long physical half-life is accompanied by a long biological half-life. It then becomes necessary to estimate the "committed dose" over a long period of time (50 years for adults and for children up to the age of 70 years). In these cases the radiation dose is estimated with the help of the committed effective dose coefficient (CED, given in Sv/Bq). This coefficient is a good measure of the radiotoxicity of a radionuclide.

Two factors are of decisive importance for the exposure of humans and the environment through disposal facilities:

(1) The duration of the physical half-life of the relevant radionuclide
(2) The mobility of the radioactive material after it is released from the container in the disposal facility, and the subsequent migration through the technical and eventually the geological barrier into the biosphere.

Model calculations with granite, salt and clay as host rock and overlaying rock have found that, because of their low mobility, it is generally not the poorly soluble oxides of the α-emitting transuranium elements which contribute decisively to human exposure in the late phase of a disposal facility. On the contrary, it is the very mobile radionuclides, often present as ions, such as iodine-129, chlorine-36, carbon-14, selenium-79 and caesium-135. In the available model calculations the highest radiation exposure comes from iodine-129 generally found to occur in the 20,000 to 100,000 year time span. The radiation doses are again given as effective doses. For iodine-129, this means that, for biokinetic and metabolic reasons, it is almost only the thyroid gland which is exposed due to this radionuclide. Thus the radiation dose for radioactive iodine is higher by a factor of around 1,000 in the thyroid gland than in the other organs and tissues. The effective dose is lower than the dose in the thyroid gland by a factor of about 20. The causation of thyroid cancer by radioactive iodine has been thoroughly investigated, especially after the Chernobyl reactor disaster and in studies in the field of nuclear medicine. The release and migration of the mobile radionuclides from the disposal facility into the biosphere and their modification requires further intensive investigations.

Microdosimetric considerations mean that very heterogeneous dose distributions occur with radiation doses less than 1 mSv. As the dose decreases further, fewer and fewer cells of a tissue are exposed. With a dose of 1 μSv, less than 1 cell per 1,000 is exposed, while the dose for each exposed cell remains the same. The significance of this fact for the causation of health effects has not yet been clarified.

For disposal facilities of highly radioactive material, no radiation exposures at the level of the threshold doses for deterministic effects are to be expected in the late phase after the closure of the facility. Hence these effects cannot occur. Only stochastic effects (especially the causation of cancer) can be estimated using extrapolative calculations. Epidemiological studies have found that, for a general population, a significant rise in cancer cases can be observed after a radiation dose of around 100 mSv. Since there are, in an individual cancer case, no specific features to show whether the individual cancer was caused by ionizing radiation or not, it is only possible to give the probability of causation for the disease.

These studies have led to the definition of risk factors, resulting in a value of 5×10^{-2} per Sv. This means that, given a dose of 1 mSv, the cancer risk is 5×10^{-5}, and given a dose of 0.1 mSv, it is 5×10^{-6}. This risk should be compared with the general lifetime risk of about 0.4, the rate at which people in Germany develop cancer. The potential cancer risks which may arise through a disposal facility lie far below a "measurement range" in which possible, additional cancer cases might be recognized.

All living beings have always been exposed to ionizing radiation from natural sources. In Germany this exposure is about 2.3 mSv per year (effective dose) for every citizen. About 50 % of this dose is caused by the inhalation of radon with its radioactive progeny. The other components of the exposure are external cosmic radiation through the sun, external terrestrial radiation from radioactive material in the earth, and internal radiation exposure through the incorporation of radioactive material with food and drinking water. Every human being in Germany is carrying around, on average, about 9000 Bq of natural radioactive material in his or her tissues (mainly potassium-40 and carbon-14). Radiation exposure from natural sources differs greatly from region to region. In Germany the external exposure can be 5 to 8 times greater than the average value, even more with radon.

As well as exposure from natural sources, humans, particularly in the industrialized countries, are also exposed to other kinds of man-made radiation. Medicine, particularly diagnostic radiology, delivers the greatest proportion. The average value per head of population in Germany now lies roughly in the range of the median exposure from natural sources, and continues to rise.

There is no scientific doubt that radiation exposure from natural sources can cause the same biological/health effects as exposure to man-made radiation. A comparison of radiation doses from the various sources with the ensuing effects is thus completely justified.

In the low-dose range of 1 mSv and below, estimations of doses and risks are attended by great uncertainty. Since the possible radiation doses related to disposal facilities are mainly produced by the incorporation of radioactive material, this uncertainty becomes even greater, since the dose can only be estimated using model calculations. On the other hand there are relatively good data for the radioecological pathways of iodine and caesium, from experiences after the reactor disaster in Chernobyl and the fallout from tests of nuclear weapons.

Estimations of doses and risks are carried out with the aid of reference models and reference persons. Hence individual variability within the human population is not taken into consideration. On the other hand it can be assumed that metabolism, and thus the biokinetics of radioactive material in the human organism, will not change as dramatically, even after thousands to millions of years, as lifestyles and general human rules of conduct. It is also scarcely possible to make statements about the size of human populations and other conditions of human life at the location of the disposal facility over a time span reaching much further into the future than our knowledge of human history reaches into the past.

1.3 Management of high level waste with reference to long-term responsibility

The appeal to "ethics" in conflict situations is often based on an inappropriate understanding of this discipline, as is the idea that it is necessary to take one's bearings from "ethical standards" when making decisions of importance to society. Ethics cannot formulate higher principles, timelessly valid imperatives or values from which appropriate directives for action for the situation in question might be deduced from the top down. On the contrary, the domain of ethics is the development of promising strategies for conflict resolution. After all, the conflict is often caused by following the rules ("morals") which determine action within a culture and serve to legitimate the actions of the individual, but which are established differently in different cultures and in their subcultures. The critical analysis of morals and their scope is thus a prominent object of ethics.

In the conflict over the management of high level waste we can expect not just divergent opinions about the effects and side effects of the means to be employed, but also divergent aims, divergent ideas of morality, and ultimately different understandings of what requires legitimation and what constitutes acceptable grounds for legitimation. A rational solution to this conflict thus presupposes not only agreement on the cause-effect relations, but also critical reflection on the desired ends and on the grounds for legitimation put forward for the choice of means ("waste management strategies").

In cross-generational problems such as the management of high level waste it would be a category mistake to take for granted, without further testing, criteria taken from established "life-world" moral practices – at least as long as the requirements for action still leave (temporal) resources available to develop suggestions which are as rational as possible, while neutrally considering as many aspects as possible, and if need be to change the conditions of action and decision-making in such a way that optimal conflict resolution becomes possible.

Three category mistakes of this kind pervade the debate on the management of high level waste:

(1) The demand for an immediate solution to the problem bears a considerable burden of justification which can only be lifted if the situative conditions of action are interpreted according to the model of an emergency situation. Emergency situations often justify impositions on third parties which would otherwise be unacceptable in longer-term planning.
(2) In view of the decision-making situation for issues of the just distribution of burdens (costs, risks), where there is no urgent need to act, it is not simply a matter of applying the established principles of justice to a fixed situation of distribution with a fixed "volume to be distributed". On the contrary it is necessary to devise a plan which – working on the principle that exceptions to the rule of equality must be justified – is suited to bringing about the strategic optimization of the situation of distribution and of the "volume to be distributed". The conflicts over claims, put forward with an appeal to moral principles, can thus be transformed into deliberations (or negotiations) about conflict-pacifying allocations of all possible burdens and commodities.
(3) In the light of the many people who will be affected by the risks in the future, fairness may dictate – contrary to the moral intuition expressed in the "polluter pays" principle – that the producer of waste not be given the task of disposing of it. If others are, because of greater expertise or more favourable conditions, in a better position to provide a form of waste management which will do justice to the claims of future generations, then it could even be advisable, from an ethical point of view, to transfer the task of waste management to them, in return for freely accepted compensation.

Considering the far-reaching consequences of a decision about strategies for high level waste management, reflection about the possible conflicts with members of future generations must be an essential part of the preparation for decision-making. Given the irrelevance of all reasons for setting limits, a restriction of scope to those people who interact with us, or to a fixed time span (e.g. n generations) is not sustainable for ethical, i. e. rational, conflict resolution.

With regard to concrete actions, an obligation thus exists for exactly as long as the consequences of these actions produce potential for conflict. The obligations attendant on the management of high level waste therefore exist for as long as the hazard potential of the radiotoxic and chemotoxic substances.

For *ethical* reasons it is necessary to distinguish between on the one hand the universalistic, i.e. indefinitely existing *obligation* and on the other hand the degree of its *binding force*, which diminishes with spatial, social and temporal distance. When, in the framework of our moral praxis, we ascribe a higher degree of binding force to the obligation towards the generations closely following ours (and ascribe to these generations an obligation towards those which closely follow them), we are organizing our long-term obligations and making them practically manageable. The extent to which binding force diminishes, however, is not firmly correlated with temporal distance, but with our potential to fulfil obligation in a tactical and controlled manner. Moral agents have an influence on how far-reaching this potential is – and it is part of their obligation to make use of these opportunities for influence, within the bounds of proportionality of means. Thus, if we want to act in a technological way, there is also an obligation to procure knowledge about the consequences and the conflict these may cause. In the same way the increase in the scope of our actions through technologisation and collectivization comes with the obligation to form organizations and equip them with the requisite resources so that they can, on the basis of the knowledge gained, or of rationally founded suppositions, organize society's long-term obligations, without being dependent on the resource constraints of the individual actors. In particular, advocacy for future claims requires a mandate which is legitimized by procedural organization, anchored in institutions, and controlled by society – rights of representation cannot simply be claimed by declaring oneself to be competent, responsible, or personally affected. The actors thus create "responsibility", but do not relinquish their obligation – on the contrary, they still have the task of ensuring in the long term that their obligations are fulfilled responsibly.

In optimizing complex plans with high potential for conflict, the participation of all those with local or technical expertise, regardless of actual certification or profession, is in principle desirable, for purposes of plan optimization and process control. The inclusion of those directly affected in complex planning can, by dispelling mistrust and fears, help to create the social prerequisites for a rational discourse aimed at conflict resolution. Participatory processes must be designed in such a way that the decision-making behaviour of those responsible for making decisions is not distorted (biased) by implicit or explicit lobbying by the present generation, but that it remains focused on the claims of all, including the non-participating members of future generations.

The expectation that participation might also help to legitimize decisions, as expressed by parts of the public and of the specialist community, should be met with scepticism. In particular, the incorporation of participatory processes into the preparations for decision-making should not lead to a situation where the responsibility delegated to institutions by the citizens as bearers of long-term obligations is then transferred back to the citizens by the institutions ("circle of allocation of powers"). The view put forward in justification, that the individual is ultimately the one who knows most about his own needs and interests and is thus best able to represent them ("thesis of self-competence") overlooks the fact that this is all about creating a balance between a disparate mass of interests for which no subgroup can be representative, and which can therefore not be representatively replaced by individual stakeholders. Models which seek to transfer decision-making powers back to the citizen are often based on an image of social decision-making as an antagonistic negotiation between social sub-systems, with "politics", "science" and "the public", as tribes of equal standing amongst others, each representing its own interests ("tribalisation thesis"). This, however, confuses the methodically organized discourse of knowledge in the sciences, and the institutionally organized discourse of decision-making in politics, which are actually intended to counteract the centrifugal processes involved in the subjective formation of opinions and interests, with the mere representation of opinions and interests on the part of the individuals involved. And yet it is precisely in decision-making questions in which the claims of some parties to the conflict (such as those of the members of future generations) can only be reasonably imputed and represented by means of advocacy, that the legitimating power of procedures takes on great significance. It is desirable that procedures be changed or expanded to increase participation and respond more precisely and in a more differentiated way to the claims (insofar as they are relevant to the conflict) and to the local and technical expertise of the present generation. This must, however, be weighed up against the obligation towards the members of future generations.

1.4 Legal questions of managing high level radioactive waste

The final disposal of high level radioactive waste raises difficult legal questions. Of primary importance are the shaping of the responsibility of the state, the avoidance of institutional conflicts, the principles of radioactive waste management and the – constitutionally required or politically desirable – degree of legalisation. Within this framework a number of complex legal questions of detail is addressed. At international level the Joint Convention on the Safety of Spent Nuclear Fuel Management and on the Safety of Radioactive Waste Management of 1997 (International Atomic Energy Agency – IAEA) is most important as regards the development of principles of nuclear waste management and the institutional framework of regulation. Besides, there are a number of relevant recommendations adopted by IAEA and other organisations such a, in particular, the International Commission for Radiological Protection (ICRP).

The European Union has regulated in the field of radioactive waste disposal only to a limited extent. To be noted are the basic health standards laid down in the Directive 96/29/Euratom and the Directive relating to the safety of interim storage and treatment of spent fuel. A Commission proposal sub-mitted in 2010 also provides for the introduction of regulation in the field radioactive waste disposal which will require certain adjustments of German law.

The present study compares the regulation of high level waste disposal in major nuclear countries such as the United States, France, the United Kingdom, Switzerland, Sweden, Finland, Spain, and Japan (a summary is presented in the main text, the details are contained in the Annex). The comparison reveals a number of common features but also important differences that can be attributed to a number of factors. This variety rules it out that one could draw generally valid conclusions from the foreign experience. However, the experience of foreign countries can give important impulses to the discussion. It is to be noted that as a response to widespread, albeit differently strong, lack of public acceptance of previous site selection attempts, there has been a clear tendency to introduce new forms of participation relating to the development of strategies and in particular site selection. For various reasons, the good experience made in Finland and Sweden in this respect cannot be generalized. In the other countries under review, the new decision-making model still is on probation.

Under German law, the responsibility of the state for radioactive waste disposal has strong roots in the Constitution. Article 20a of the Federal Constitution explicitly obliges the state to protect the natural bases of life of future generations. The Atomic Energy Act contains demanding requirements for the authorization of radioactive waste repositories. According to case law best possible prevention of significant risks and precaution against low risks according to practical reason are the standards that govern the state duty to protect. However, the German courts recognise that the ultimate responsibility for determining and evaluating the relevant (potential) risks and deciding on their tolerability is vested in the legislature and – in the framework of the Atomic Energy Act – to the executive.

The Atomic Energy Act provides that the Federal State is responsible for establishing and operating a high level radioactive waste repository, either on its own or through a federal agency such as the Federal Radiation Protection Agency. The State can charge third persons with performing these obligations or even confer the sovereign powers necessary for performing them to third persons. In view of the very long-term nature of the relevant tasks the model of assignment is not without problems. The Atomic Energy Act concentrates management and supervisory functions regarding the operation of high level radioactive waste repositories in the Federal Radiation Protection Agency which in principle is subject to directions from the Government. This institutional set-up is still consistent with the principle of effective independence of waste management and regulation as laid down in the Joint Convention and IAEA recommendations. The reason for this assessment is that the supervisory function within the Agency is vested in a separate department that is independent. However, a reform of the relevant competences appears advisable.

The basic strategic options of high level radioactive waste management in Germany are set out in the Atomic Energy Act (partly, as regarding the principle of geological disposal, not explicitly). By contrast many important elements are left to decision by the executive which has to observe the principle of best possible prevention and precaution. As regards groundwater protection, the principle of "no concern" under the Water Resources Management Act is applicable. In autumn 2010 the Federal Ministry for the Environment published safety requirements for the final disposal of high level radioactive wastes. These requirements are to be further developed during the ongoing underground investigations at Gorleben. Problematic from a legal perspective are in particular the timeframe of precaution in the post-operation phase and associated to it the requirements for the demonstration of safety. A practical exclusion of any risk of future harm does not need to be ensured until the (almost) complete decay of radio-activity of the wastes disposed of, but only for such a period of time as possible according to the present state of science and technology, including prognostic feasibility. Beyond, the relevant risks must be reduced to a reasonable extent. This constitutes best possible prevention of risk and precaution against significant risk in the meaning of the Atomic Energy Act.

The selection process for the site of a repository for radioactive waste in Germany has been characterised by a low degree of legalisation. In response to the selection of Gorleben as the site for a final repository in the 1980s that was considered as technocratic, various proposals have been made to reopen the site selection process. Although the German Government in the meantime decided to resume the underground investigations at Gorleben without considering alternatives, it appears reasonable to discuss site selection anew because the suitability of Gorleben is not yet established and it is not known either whether there is no alternative that is better suited than Gorleben.

For various reasons a site selection procedure cannot be based on the planning permission procedure under the Atomic Energy Act or on general spatial planning at federal level. However, following the pattern of the waste management plan under the Life Cycle Economy and Waste Act, it would make sense and be legally feasible to introduce a sectoral planning procedure that would precede the planning permission: It is to be noted that such a site selection procedure is not mandated by the Constitution since the legislature and executive have the ultimate responsibility for deciding on tolerability of risk. In shaping the proposed procedure the legislature should orient itself at the requirement of optimisation which is derived from the principle of best possible prevention of risk and precaution against potential risk However, the safety of a repository is a product of a combination of geological and engineered barriers at a particular site. Therefore, optimisation cannot be pursued in an isolated manner in relation to a particular host rock and site.

Although considerations of legitimacy and acceptance may militate for the complete reopening of the site selection process, the decision of the Federal Government to continue the underground investigation of Gorleben is in keeping with the ultimate responsibility of the executive and can also justified by pragmatic reasons. However, it appears reasonable to investigate, in parallel to Gorleben, alternative sites and introduce, for that end, a modern site selection procedure that is linked to the progress of investigations carried out at Gorleben. This mode of action counteracts further postponing of site selection should Gorleben fail. Moreover, on the grounds of good governance and legitimacy, it makes it possible that even in the case of suitability of Gorleben an intensive investigation and eventually selection of an alternative site can be carried out where it can be demonstrated that this site may fulfil the site selection criteria evidently better than Gorleben. The site selection could proceed in eight or nine steps and should be based on selection criteria that the executive, with the participation of an independent expert commission and the public, would prescribe. The procedure should be transparent and allow for a comprehensive participation of all affected persons and stakeholders.

For improving the legitimacy and acceptance of the relevant decisions, the traditional rules on public participation should be enriched. The major elements of such enrichment should in particular be the establishment of an independent expert commission, an opportunity of affected persons and stakeholders to exert an early influence on the shaping and planning of the finding process, the establishment of a permanent dialogue forum at local-regional level and access of affected persons and stakeholders to a pool of independent experts.

Apart from reviewing the suitability of the site of the repository, the planning permission procedure is designed to ensure that the construction and operation of the repository is consistent with the legal requirements. In particular it must be ensured that during normal operations the requirements of the Radiation Protection Regulation are complied with. Furthermore a demonstration of safety and groundwater protection, which is governed by the principle of "no concern", is required. The relevant statutory requirements are in principle, that is, subject to modifications mandated by the long-term nature of the regulatory task, also applicable to the post-operation phase of the facility. The Radiation Protection Regulation that is geared to current operations of nuclear facilities can at least serve as a guideline for radiation protection in the post-closure phase.

The Atomic Energy Act places the financial responsibility for final disposal of radioactive waste on the operators of nuclear power plants. They are obliged to make financial contributions for covering the necessary expenses for waste disposal, among others also for the planning of the disposal facilities. Since site selection aims at creating the prerequisites for the construction of a repository and the repository confers advantages on the operators, it is submitted that the expenses of site selection are necessary insofar as mandated in accordance with the relevant statutory site selection procedure – as opposed to a purely political procedure.

A weakness of existing law is that the obligations of operators relating to future financial burdens are limited to establishing reserves in their balance sheets. In view of the very long-term nature of final disposal of high level radioactive waste, this financing model raises some problems in case of insolvency or dissolution of waste generators insofar as these are subsidiaries of the public utilities. In case of termination of the existing enterprise contract between the parent company and its subsidiary due to insolvency or dissolution of the latter the liability of the parent company is limited to obligations that have already arisen. It is doubtful whether the abstract statutory obligation to cover the future, not yet foreseeable costs of waste management can be deemed to be an obligation that already has "arisen". These doubts could be solved by a joint and several liability of the parent company independent from the validity of the enterprise contract, in particular when operations are not continued. Of course, the existing statutory liability of the parent company for the debts of the subsidiary in case of a contract to transfer the profits would remain unaffected. Fund solutions are not recommended.

1.5 Guidelines for a socially acceptable and fair site selection

Nuclear waste disposal mobilises people, not only in Germany, but all around the globe. The question of final disposal is symbolically charged: it is no longer primarily about technological viability, or even about long-term safety, but rather about fundamental perspectives of societal development. As a society, do we wish to continue pursuing technologies in power generation that are central, highly efficient and energy-dense, but risky? Or should we opt for decentralized technologies, which are often not very efficient, low in energy density, and, while not necessarily low-risk, are locally restricted with respect to disaster impact?

This starting position defines the terms for a future solution to the question of how to dispose of high-level radioactive waste. According to some empirical results:

- In all existing surveys, solutions to final nuclear waste disposal rank very highly in the public perception of what poses a threat. This is the case throughout the world, even, interestingly enough, in Finland, where the problem of final waste disposal has been largely resolved on a political level despite these public concerns.
- The complexity of this situation becomes apparent when considering the results of a German representative survey from 2001 and 2002: at the time of the survey, roughly 65 % of those interviewed assumed that over the next decade a final nuclear waste repository would be established,

while 81 % objected to such a repository being created in their vicinity. This classic *NIMBY* ("Not in my backyard!") syndrome is typical in site selection processes for large-scale technological and risk-related facilities. In principle, the public endorses the need for such technology, but on condition that it is as far removed as possible from their domicile.

– Surveys on stakeholder mobilisation show differences worldwide, from which much can be learned. Some countries, such as Finland, Sweden and Switzerland, have made progress with regard to finding solutions for final nuclear waste disposal. It is not impossible to reach an institutionally satisfactory solution that is tolerable for the majority of the population if the right approach is taken. However, it is not easy to find an approach that will gain acceptance. And success is never guaranteed. If the wrong approach is chosen, however, failure is certain.

Why is the risk perception of final nuclear waste disposal so emotionally charged? From a psychological perspective, the risks of nuclear power generation in general, as well as those of final nuclear waste disposal, are associated in the eyes of the public with the semantic pattern of "the sword of Damocles". In the way they function, semantic patterns are not unlike drawers in a filing cabinet. If confronted with a new risk, or taking in new information regarding risk, people, in general, will try to file away this information into one of the existing drawers.

The "sword of Damocles" is such a pattern. This is to do with technological risks where, irrespective of whether or not such attributions are justified, a high potential for damage is combined with a very low probability of occurrence. The stochastic nature of such an event makes it impossible to predict the time of its occurrence. Subsequently, the event may theoretically occur at any point in time, even though the probability for each of these points is extremely low. However, when in the realm of the perception of rare random events, probability plays but a minor role: the randomness of the event is the actual risk factor. The idea that an event could hit the affected population at any random point in time generates a feeling of threat and loss of control. Instinctively, most people can mentally (in real life this may be questionable) cope much better with danger if they are prepared for and attuned to it.

Another factor is the nature of radioactivity, which defies sensory perception. This takes us to a second semantic pattern that can often trigger fear and is called "insidious or creeping danger". In the context of this risk pattern, people rightly assume that scientific studies can detect creeping dangers in good time and discover causal relationships between activities or events and their latent effects.

In the case of the semantic pattern of "creeping danger", the people affected must rely on information provided by third parties. In general, they can neither perceive the hazards sensorially nor verify the claims of various experts, which tend to be contradictory. When laypeople evaluate such risks they are faced with a key question: can I, or can I not, trust the institutions that provide me with the necessary information? If the subjective evaluation is negative, then there will be an uncompromised call for zero risk. This is because a person who relies on third-party information for risk assessments, but does not trust the third party, will not accept any cost-benefit balance, but rather call for zero risk. In contrast, if that person is undecided as to whether or not he can trust the third party, then peripheral aspects assume particular importance, aspects that factually have no connection to the circumstances of the decision. A layperson has no option but to distribute trust according to peripheral aspects, because she/he is not able to assess the risk of being harmed by radiation. She/he must trust either one side, or none at all. These patterns are deeply embedded in unconscious processes for evaluating reality. They can only be overcome when people learn to understand these perception patterns and recognize the impact they have as unconscious evaluation benchmarks when forming judgements. Risk communication cannot, therefore, merely be confined to relaying scientific insights about risks, but must also vividly communicate the mechanisms of risk perception.

Even if the parties involved engage in an intensive risk dialogue, as has occurred to an increasing extent in recent times, this certainly does not mean a resolution of the conflictual situation. Rather, the establishment of a basis of communication is the prerequisite, but by no means sufficient condition for reaching a universally acceptable solution. In principle, three main approaches to the final disposal of high-level radioactive waste can be outlined based on current conditions:

In the *Top-Down Approach,* the representatives elected within the democratic system have the sole right of decision-making. By virtue of their office they act in the best interests of the people. Any active participation by the population, if envisaged at all, would be within a very narrow scope. However, this solution is also based on transparent risk communication involving the population. Citizens may voice their opinions during hearings or discussions, but without having any guaranteed say in the final decision-making process. The decision-makers must also prove that all objections have been duly dealt with. Then, however, it is in the hands of the decision-makers to come to a decision, while being obliged to disclose all arguments in favour and against.

The *Muddling-Through Strategy*, a pragmatic mixture of the top-down and bottom-up approaches, relies on minimum consensus (muddling through), which emerges from the political opinion process. The only options to be considered legitimate are those that induce the least amount of opposition within society. In this form of management, societal groups may influence the process of political decision-making in the extent to which they provide proposals that offer connectivity, i.e., that are adapted to the language code and processing style of the political control systems, and mobilise public pressure. In politics, the proposal that will then be accepted will be the one that best holds its ground in the competition of proposals, i.e., the proposal that entails the least loss of support among interest groups for the political decision-makers. Previous debates on final waste disposal seem to conform most closely to this form of muddling through.

The third variety – *the bottom-up approach* – is based on a discursive solution and an attempt at fair negotiation of the site selection between the different groups involved. Discursive methods claim to enable more rational (in the sense of a discursive understanding of reason), just (in the sense of an understanding of justice based on negotiation) and competent solutions to existing problems. No matter which specific claims we associate with discursive processes: They must be structured according to certain rules in order to ensure their effectiveness, for instance to provide constructive solutions to problems in an appropriate and fair manner keeping open more than one possible decision, and to prevent, as far as possible, strategic behaviour amongst the participants. In principle, the legitimisation of collectively binding norms depends upon three conditions: the agreement of all parties involved, a substantial justification of the statements delivered within the discourse as well as suitable compensation for negatively affected interests and values.

How could a meaningful combination of bottom up and top down be implemented? The entire selection procedure must be transparent and comprehensible (effective risk communication criterion). The selection procedure must appear fair (all shared value and interest groups involved have a say), competent (the problem is treated appropriately and with the necessary expertise) and efficient (the means or costs of the decision must be proportionate to the objective) to non-participants. The selection itself must be comprehensible and inter-subjectively justifiable whilst reflecting the plurality of moral concepts of the affected population in the sense of a fair consensus or compromise. If we seriously aimed at fulfilling all these demands for legitimising the site selection process, a single political regulatory instrument would certainly not suffice. Rather, such wide-reaching decisions call for a sequence of different regulatory instruments, each of which would cover a different aspect of these criteria.

Adhering to the principles mentioned requires a combination of several steps and elements. First, it requires scientific-technological agreement over the suitability of site location plans and criteria in the form of threshold values that would have to be obtained for a site to count as suitable in terms of long-term responsibility. These criteria would have to be established before the results of the suitability test were presented. This should be based on consensus-oriented methods of scientific tests, which must be conducted in an independent, factual and transparent fashion. Institutionalizing it would require a professionally led, neutral platform, which would bring together scientists on a national level, and include international experts (thus increasing essential credibility), with the goal of arriving at the knowledge consensus demanded here. Also, in order to demonstrate to the general public that the experts are not making a one-sided selection, provision can be made for giving the stakeholders the right of nomination.

Second, fair compensation for accepting uncertainty is needed. The goal here is to find a robust solution that is acceptable to all concerned, in order to anticipate and deal with uncertainty. Methods such as mediation or establishing a round table with stakeholders can lead to compensation for the consequences of uncertainties in a way perceived of as fair. Here it is particularly important to not conceal insecurities, particularly regarding long-term effects, but to address them openly and to ensure compensation by promoting economic or location development. We are not referring here to the "sale of indulgences" or the corrupting practice of paying people to carry the risk, but rather about types of social compensation common to other areas of life: Those who will in future bear the uncertain consequences and burdens for the general public should in return receive recognition and support from society. This procedure would show that accepting uncertainty is respected and honoured. We cannot expect people to silently "swallow" the uncertainty. To this end, unbiased dialogue forums with the groups affected by the consequences would be preferable. We can learn from Sweden in this respect, where such forums are staffed locally. In some cases, experts are involved as sources of knowledge and information.

Here follows the third and final component of a discursive solution: a forum for societal orientation about future energy supply and post-industrial lifestyles. The debate about final disposal is about more than waste managment, rather it involves the question of how we want our lives to be in the future. How can the subject of final disposal be integrated into a constructive blueprint for future lifestyles and living conditions? This could involve discourse-oriented methods, such as citizens' forums, round tables or consensus conferences, which have shown a degree of success in other countries.

At the beginning of any new initiative for resolving the question of how to dispose of high-level radioactive waste we must concentrate on such keywords as: reducing complexity by means of a scientific consensus as to the best selection procedure, coping with uncertainty through fair offers to those who will have to live with the consequences of this uncertainty, and treatment of ambiguity through an open and sincere discourse on objectives regarding the future of our energy supply. Not least, it requires discourse in society about how Germany as a country with few natural resources can remain successful in the future.

2 Conclusions and recommendations

2.1 Ethical framework

(1) Obligations to future generations are generally valid indefinitely. Management strategies for radioactive waste must nonetheless be developed for limited time spans.

Obligations which commit the stakeholders to prudent management of radioactive waste are in principle valid indefinitely and continue to exist towards the members of distant generations – though their binding force gradually decreases over time. The complex sequences (the "sequence spaces") which must be included in the development of waste management strategies must nonetheless have time limits set, to meet the rational requirements of planning and for reasons of efficiency. Such a time limit should be based on the foreseeable future effect of the consequences, and thus on the relative hazard potential of the contents of the disposal facility and of possible exposure in the biosphere, which vary with the phases of the decay process and the chosen waste management strategy.

(2) The present generation as the primary beneficiary of nuclear energy has the obligation to initiate the solution of the disposal problem. The demand for *immediate* disposal of high level waste, however, imposes an unjustifiable burden on the present generation.

From an ethical point of view, the utilization of moral principles which impose the entire burden of disposal on the present generation as a community of originators and beneficiaries is by no means self-evident. As long as – based on authoritative forecasts – reliable relations of exchange could be organized across generational or communal boundaries, without detriment to third parties, there could be no ethical objection to, for example, transferring the "responsibility for disposal" in exchange for freely accepted compensation. The demand for an immediate solution to the problem is not self-evident and requires justification. If it is probable that a future generation with which we are in verifiable interaction has access to "better" waste management strategies, then it may even be advisable to take this option. Considerations of justice do however impose a duty on the originator to offer adequate compensation. This also applies, mutatis mutandis, to international relations of exchange: for an adequate perception of long-term obligations, the relevant factors are not national borders – which in any case seem rather historically contingent in view of the time spans in question – but the availability of skills and resources.

(3) Processes of legitimisation to solve the question of disposal facilities must be designed in such a way that they do justice to everyone equally, and in particular give adequate consideration to the claims of future generations.

It is desirable that the legitimising procedures should be designed to respond to the claims and the local and technical knowledge of those alive today, where these are relevant to the conflict, but this must be weighed up against obligations towards those who are not involved in the consultations, in particular members of future generations. Thus the criterion for the decision must not be solely the agreement of members of the present generation, achieved through procedures. On the contrary, the decision must also be acceptable in the sense of a rationally presented justification based on universalist arguments. In the public debate, there must be advocacy for those who cannot participate, or who have no incentives to stand up for their requirements. This responsibility cannot simply be claimed by individual stakeholders or groups of stakeholders; the transfer of this responsibility must be legitimated.

(4) A categorical rejection of all proposed solutions for the disposal of high level waste is incompatible with our obligations towards future generations.

The management of radioactive waste is a collective duty shared by society as a whole. This gives rise not only to the duty of care, which dictates that proposals should be tested to see whether they fulfil this obligation, but also to the obligation to participate constructively in the development of suitable proposals, and/or to create or support structures which make this kind of participation possible. The right of veto held by those who base their arguments on the unsuitability of a proposed site or of the disposal concept per se is linked with the expectation that they will participate constructively in the development of alternative proposals. Promising projects and processes which aim at the development of alternative proposals must be supported with the necessary resources. A categorical rejection of all proposals ignores our obligations towards future generations.

(5) The instrumentalisation of future generations for arguments against longer operating lives of nuclear power plants is unacceptable.

There is an obligation towards the members of future generations to dispose of already existing radioactive waste. The additional quantities which would accumulate if the operating life of nuclear power plants were extended would be too small to have any substantial impact on the choice of disposal strategies. In the light of the long delays to be expected for disposal, the extension periods in question are insignificant. It would therefore be unacceptable to instrumentalise the interests of future generations to exert a controlling influence on decisions about the operating life of nuclear power plants.

2.2 Safety requirements and goals

(6) The prudent disposal/management of radioactive waste presupposes the development of an appropriate overall strategy with regard to safety, health protection, and environmental protection. The German Constitution and the Atomic Energy Act give a clear legal framework for the best possible prevention of significant risks and precaution against low risks.

The prudent disposal/management of radioactive waste presupposes the development of an appropriate overall strategy which considers all relevant technical factors and options and, taking into account previously made decisions, meets the requirements of technical, social and political feasibility. Both the German Constitution and the Atomic Energy Act establish a clear normative framework for this by linking each solution to the legal requirement of best possible prevention of significant risks and precaution against low risks. The legislature and executive are, however, accorded a broad margin of discretion in this matter.

The safety of a repository is a product of a combination of geological and engineered barriers at a particular site. Based on the international consensus as to the particular importance of geological barriers, one could indeed assert that one should select the best possible geological barrier and couple it with the best engineered barriers. However, this combination does not necessarily provide the best possible safety since the nature of the host rock and the local geophysical conditions may place limits on the additional safety that can be provided by the engineered barriers. What ultimately counts is the safety of the whole system.

(7) For evaluating long-term safety, it is necessary to work from scenarios based on the evaluation of natural developments with regard to the potential for the transport of contaminants through host rocks and overlaying formations, and for the potential release of radiation into the biosphere.

The evaluation of strategies must be carried out on the basis of criteria which take into account short and long term environmental impact and which meet the safety and protection needs of the present generation just as much as those of members of future generations. The assessment of long-term safety must be based on scenarios about naturally induced processes. It is necessary to investigate to what extent these can lead to a gradual transport of radioactive substances through geological host rocks and overlaying formations, and to what extent they are therefore connected to the risk of a release of radiation into the biosphere and to the corresponding risks for humans when exposed to radiation on the surface or in the case of inadvertent intrusion. Furthermore, subcriticality needs to be ensured for the irradiated fuel and radioactive material brought into the disposal facility; the corresponding proofs seem to be unproblematic.

(8) Humans have a limited ability to develop prognoses about future developments of geological or anthropogenic systems over extremely long time spans.

One of the ethical principles is the insight that, due to planning requirements, a time limit must be set on the consideration of distant hazard potentials, especially of the risks for humans connected with a possible release of radioactive substances. In discussions held so far, such time limits are often justified by the decrease in radiotoxicity over time. The orders of magnitude cited in these discussions, ranging from 100,000 to one million years, are usually based on the radiotoxicity of natural uranium ore bodies. The basis for the comparison is the fact that, for this time frame, the buried radioactive waste will fall short of this measurement. The human ability to predict the evolution of geogenic or anthropogenic systems over extremely long time periods is limited, however. Models describing e. g. the confinement of waste or radionuclide migration to the biosphere become increasingly meaningless since the underlying assumptions lose their justification as the forecast periods increase. It is possible in principle to derive clues for the subsequent development of charted data by extrapolating the possible course beyond the end of the foreseeable time frame. This must be weighed, however, against the increasing unreliability of the information which can be gained by such calculations.

(9) The time frame of one million years for the evaluation of the long-term safety of high level waste seems an appropriate compromise between the ethical requirements for long-term responsibility and the limits of practical reason.

The rationale behind the often quoted time frame of one million years proposed by the German Ministry for the Environment (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, BMU) is the ability to find sites in a geological environment which is, according to current geo-scientific knowledge, believed to conserve its favourable features for a period of that order of magnitude. This approach appears to be a reasonable compromise between the requirements coming from ethical considerations on the one hand and the realization of the limits of practical capabilities on the other.

(10) The proposal to set the reference dose in Germany at 10 μSv (0.01 mSv) should be rejected from a radiobiological point of view; it also diverges considerably from the international consensus of 100 μSv (0.1 mSv) per year.

The annual reference effective dose of 10 μSv (0.01 mSv) proposed for disposal facilities with heat-generating radioactive waste in the post-closure phase should be reconsidered. Such a radiation dose is less than one per cent of the average radiation dose which originates from natural sources (in Germany and many other regions worldwide) and thus lies within the range of variation for exposure from natural sources. This radiation dose is lower by a factor of 10 than the customary international value of 100 μSv (0.1 mSv) for unlikely situations in the post-closure phase. The ICRP calls a dose of 10 μSv (0.01 mSv) a trivial dose.

(11) Investigations of long-term safety should mainly concentrate on radionuclides which are of particular relevance for potential radiation exposure in humans.

It is possible to estimate by means of models that there are certain radionuclides, present as ions readily soluble in water, which are particularly relevant for human exposure to radiation. Subsequent investigations should focus on how ^{129}I, ^{14}C and ^{36}Cl can be kept immobile in the disposal facility, and examine how the migration of these radionuclides can be better understood and modelled.

2.3 Waste management programme and timescale

(12) There is a high degree of evidence for the technical feasibility of some concepts for disposal which have already been developed.

The concepts developed for the disposal of HLW, meeting the safety and security needs of both present and future generations, seem in principle to be technically feasible. The strategies for implementation have to include the following aspects:

(1) distinctions between radioactive material which is to be treated as waste and that which is to be treated as a resource;
(2) a decision to concentrate the radioactive waste, confine it properly and deposit it in deep geological formations;
(3) independence from active measures after closure of the disposal facilities;
(4) an explicit, well-coordinated schedule for the execution of a waste management programme.

(13) The development of a general programme and a schedule for Germany is recommended. The programme should be designed in such way that there is a realistic chance of it surviving changes in government.

As Germany particularly lacks a coordinated general programme and schedule, it is recommended that a schedule be developed which explicitly lists the principles upon which the concept is built, covers all the options for implementing these principles, and establishes a sequence defining what time periods must be allowed for research and when a binding choice must be made between alternative options, and structuring the site selection process in the framework of the existing legal regulations (cf. the decision-making pathways in section A 2.8). Such a schedule would be in line with the proposed EU Directive on the management of spent fuel and radioactive waste.

A comprehensive national programme would provide an incentive for developing a systematic and coordinated approach to radioactive waste management. It could also help to make political decision-making more transparent, facilitate public participation in the preparation for decisions, and thereby help to improve actual acceptance and ethical acceptability.

(14) It must be made clear on which scientific/technical and factual basis, by which procedure and by which institutions the decisions are to be made.

For each decision to be taken according to the programme it is necessary to clarify on which scientific/technical and factual basis (e. g. site investigation results, outcomes of conceptual/technical developments, safety assessment results, content of license application), by which procedure and by whom the decision is to be taken.

(15) The general programme should contain the waste management strategy, the procedure and the schedule for the site selection. It should also make clear which decisions have already been made and which measures have already been taken, and which of these can be considered reversible if need be.

The general programme should explicitly list the measures already taken and decisions already made, and indicate which of these can be considered potentially open to revision, and in which circumstances a revision might be possible. In the view of the authors, decisions previously taken in Germany result in well-defined amounts of radioactive waste awaiting disposal. The changing policy on the reprocessing of spent nuclear fuel (SNF) in the past has led to a situation in which both vitrified high level waste from reprocessing and SNF are awaiting disposal. SNF is stored partly at reactor sites, and partly in central facilities, while the vitrified waste is stored in the latter facilities. SNF is considered as waste and it is thus intended that it will be disposed of in deep geological formations without relying on active controls after the closure of the facility. Further disposal measures are subject to the following political parameters:

- the principles and requirements stated in the most recent BMU Safety Requirements, in particular those concerning the confinement of the waste in a "rock zone", the measures for recovery, as well as the development and optimization processes to be followed when commissioning the facility;
- the strategy of favouring steep rock salt formations for disposal.

(16) A waste management strategy should be open to possible positive adaptations. This also applies to possible advances in research and development.

There are various options for influencing the capacity of a disposal facility with a given set of geological conditions. Such possibilities include changing the burn-up rate, the decay time in the storage facility, or the disposal facility design, allowing for better utilization of the available host rock. A waste management strategy should be developed which does not assume the availability of these options, but remains open for potential positive adaptations. This applies equally to possible advances in research and development, such as partitioning and transmutation, which may significantly reduce the safety and security requirements to be met by a disposal facility.

(17) With regard to site selection and the construction of a disposal facility, the general programme should be focused on bringing about a solution as fast as is reasonably achievable.

The recommended programme for site selection and construction of a disposal facility should be focused on bringing about a solution as fast as is reasonably viable given the relevant technical, legal and planning-related aspects and the social and political concerns.

New scientific developments which might change the requirements for a disposal facility should also be incorporated. The programme should remain open for unforeseen events and should include the possibility that Gorleben might turn out to be unsuitable.

Sufficient reserves of time should be built in for legal decisions, participation and communication. Time spans for each section of the participation process should be agreed on in advance with those involved, to make it more difficult for individual stakeholders to pursue a strategy of perpetually delaying decisions.

There always is the theoretical possibility of finding a better site. However, for practical reasons, an infinite continuation of site investigations is not possible. Therefore, optimisation through siting arguably cannot be pursued absolutely but only in the form of a planning directive – as in its classical area of application (radiation protection) the minimisation principle is not absolute.

2.4 Selection process, criteria

(18) The conflicts emerging in the discussion in Germany demand a decision-making process focused on legitimation and conflict mitigation, one which also makes it possible to take into consideration more deep-seated conflicts.

The choice of Gorleben as site of a disposal facility is highly controversial in the public discussion. One argument is that this preliminary selection was made largely on the basis of political, not scientific/technical criteria, another criticism is that carrying out a test of suitability on only one site is not a reliable means of finding a suitable site. Reaching a decision is fraught with conflict: restricting the test of suitability to Gorleben fuels the suspicion that no objective search for the (relatively) best site is taking place, but extending the search to other sites will in all probability provoke equally great protests there. This dilemma does not seem soluble in the short term, which makes it all the more urgent that a decision-making process focused on legitimation and conflict mitigation be devised. Decision-making processes must, moreover, take into consideration the deeper-seated conflicts over modernization and lifestyles, the general direction of energy policy, and questions about the legitimation of collective decision-making.

(19) Decisions must be as transparent and comprehensible as possible, offering opportunities for direct public participation, but without restricting the responsibility of the state.

In the framework of the decision-making and the selection process it is important that the individual steps in the process be made as transparent and comprehensible as possible, and that civil society be constructively involved, without limiting the clear responsibility of the institutions legitimated by the German Constitution and the Atomic Energy Act in the framework of the representative and federal system of the Federal Republic of Germany. The integration of structured forms in which groups in society and the local population can participate in building a consensus and preparing for decision-making is not incompatible with representative democracy, which it can supplement and even enhance if a suitable approach is taken.

(20) Various options for the process of seeking a site should be discussed and weighed up against one another.

In principle the problem-solving options, particularly for the site selection, are as follows:

(a) exploration of a joint European solution,
(b) continuation of sub-surface exploration and testing of the Gorleben site following recognized target values for suitability,
(c) as in (b), but with further sites to be found and explored immediately in parallel, and
(d) beginning a completely new search process to explore several possibly suitable sites at the same time (including or excluding Gorleben) and evaluate them in relation to each other (cf. for further details the remarks in section A 2.8).

(21) A joint European solution is only plausible if Germany also contributes a possible site.

A joint European solution can only be put forward convincingly and fairly if Germany also contributes a site in its own country. Thus this solution would also require the selection of a site in Germany. This reduces the number of options to be considered to three.

(22) It would not be sensible to insist on the site investigation in Gorleben without testing alternatives.

Since the Federal Government of Germany has already decided to resume underground investigations at Gorleben without considering alternatives, proposals to initiate a new search seem politically questionable. However, in view of wide-spread acceptance problems, and the aspiration to find a site particularly suitable for Germany, it seems reasonable to integrate further site options into the search. Furthermore, the considerations about spatial and regional development that determined the selection of the Gorleben site at the end of the 1970s have lost much of their persuasiveness in the meantime. This means that it is once again necessary to seek a solution which is appropriate in terms of land-use planning and environmentally acceptable. For these reasons, the selection among the three remaining options (b), (c) and (d) should be reopened and become subject to broad public participation. Only after an organized national debate, which could also be supplemented by forms of Internet participation, should the Federal Government decide anew which option is to be pursued.

(23) The project group recommends a hybrid approach allowing for the continued exploration of the Gorleben site while at the same time carrying out surface investigations of alternative sites.

The working group recommends a hybrid approach ("Gorleben plus") which comprises the following components:

(a) further exploration of the Gorleben site, development and assessment of waste management strategies for this site in order to clarify whether it is suitable and fulfils the safety and planning requirements.
(b) at the same time: investigation of alternative sites as additional disposal options, and beginning of above-ground investigations of these sites, building especially upon the German "Arbeitskreis Auswahlverfahren Endlagerstandorte" (AKEnd) proposals and the regions and sites identified as "promising" by the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe).
(c) a well-defined point in time for taking a decision in principle about whether and how to pursue the exploration of the Gorleben site and/or the alternative sites; the decision should be prepared and taken in a manner that makes it as robust as possible in the face of political changes.
(d) a concept for communicating all previously obtained results and arguments as well as the scientific and technical constraints to all stakeholders so that they can participate appropriately in the debate and – as far as the legal provisions allow for this – in the decision-making process.

(24) The recommendation to explore the Gorleben site and determine additional site options is aimed at maximizing the chances of having a disposal facility available in the next few decades.

Recommending both further investigation of the Gorleben site and the identification of additional waste management options primarily aims to maximize chances of having a disposal facility for radioactive waste available within the next few decades. Excluding Gorleben would result in losing a potentially suitable site without any guarantee that an alternative would be found within a reasonable time period. Excluding alternative site options while the site search is still underway would result in a considerable loss of time (in the order of several decades) if the Gorleben project should fail at a late stage in the investigation. From a safety point of view it is quite reasonable to stagger the exploration over time, if the storage facilities are upgraded accordingly (for more on this cf. the remarks in section A 2.8).

(25) The parallel search not only saves time if the Gorleben project fails, but also increases the credibility of the selection process.

The parallel search increases the overall credibility of the testing procedure. However, it must be admitted that there are, even then, certain shortcomings in terms of public acceptance, especially at local and regional level, compared to an entirely open site selection process. Nevertheless, "Gorleben plus" offers the prospect of a solution that is timely, conserves resources, and is sensitive towards public opinion and stakeholder engagement.

(26) The establishment of the criteria for the sites should be carried out in a transparent process incorporating an international "peer review".

The establishment of the criteria for determining the suitability or non-suitability of the sites will be carried out in a transparent procedure incorporating an international "peer review". As in the Swiss procedure for selecting a site, safety-related, geological and land-use planning criteria will be developed in parallel. Criteria and threshold values must be defined in such a way that they are not just applicable to Gorleben but to all sites.

(27) It should be stipulated that sub-surface explorations will be carried out at another site if the surface explorations give rise to the expectation that this site might fulfil the selection criteria considerably better than Gorleben.

For pragmatic reasons the focus should be on finding a site which is, according to the criteria developed, suitable for the safe burial of high level waste. Aspects of optimization should be brought to the fore, particularly when examining the reserve sites. Arrangements should be made for sub-surface exploration to be carried out at one of the alternative sites if and when the surface exploration finds that this alternative site (with salt or another host rock) fulfils the selection criteria demonstrably better than Gorleben.

(28) Programmes for research and development should be designed to meet requirements and monitored regularly, but should be set up with sufficient breadth and flexibility that any revisions of decisions are not excluded.

Programmes for research and development should be designed in coordination with the requirements derivable from the schedule in the general programme, and should be monitored regularly. They should be focused on supporting the programme options determined by resolution, but at the same time be sufficiently broad and flexible that they do not impede a revision of earlier decisions. In particular, the ongoing investigation of burial in reinforced clay should be continued, in order to keep all eligible additional options open.

2.5 Transparency, communication of risks, participation

(29) A comprehensive supply of information to the public must be ensured. To support the required transparency, an information centre should be set up.

Transparency is of particular importance for the successful completion of the process. Comprehensive information and communication with the public and all involved parties about the safety and security standards which have been laid down for the disposal facility are essential. All decision-making activities should be accompanied by a proactive and dialogue-based communication programme. Persons (yet to be specified) will be offered the necessary information to be able to form a well-founded judgement for decision-making. In particular, information about the following aspects should be made available in a way which is easily understandable for non-experts. This should be supported by an information centre (communication centre), which has yet to be set up. Public information should include:

- The geological setting of the site and its interplay with the technical design of the disposal facility and the different barriers;
- The relevant processes and their time frames;
- The reference doses (dose constraints and dose limits) for the various phases of the disposal facility and their position and justification within the overall system of radiological protection;
- Models and methods for estimating doses for the selected release scenarios, and their results;
- Research and development undertaken in Germany and abroad, waste management options discussed internationally, and solutions implemented in other countries in the past and present.

(30) Effective participation should take place in the selection of the site, without calling into question the ultimate responsibility of parliament and executive.

The site selection process should allow for effective participation, while not calling into question the ultimate responsibility of parliament and the executive. In order to avoid paralysing the process by excessive complexity, overly cumbersome procedural structures, e. g. ones entailing several levels of discourse and a multitude of formal institutions, should be avoided.

(31) An organized public debate should be provided for all questions of national significance.

At the national level, a public debate on questions of national importance, supplemented by new forms of participation, should be initiated and organized, for example by the German Nuclear Waste Management Commission (Entsorgungskommission), the German Commission for Radiological Protection (Strahlenschutzkommission), and the Federal Agency for Radiation Protection (Bundesamt für Strahlenschutz). Items for debate should include the decision about options for the site selection process, the site selection criteria, and the selection of sites for further (sub-surface) characterization, as well as issues of retrievability.

(32) Closer involvement of local representatives of civil society only makes sense when issues of local importance are at stake.

Closer involvement of local civil society groups only makes sense when issues of local importance are at stake. This applies to the ongoing evaluation of the investigation results for Gorleben, the evaluation of the results of the exploration of alternative sites, and the decision about whether Gorleben is suitable as a site or not. If a decision is made in favour of Gorleben, public participation should also take place around the local and regional implementation (regarding the "how"). The relevant proposals made by AK-End could be taken up here.

(33) In the site selection process taking place in parallel to the exploration of the Gorleben site, voluntary alternative candidates who appear suitable should be considered first.

Voluntarism on the part of a potential host community or region would be desirable, in analogy to the procedure in Finland and Sweden. Thus during the selection process for alternative sites which is to be conducted in parallel to the investigation of the Gorleben site voluntary alternative candidates should be considered first, provided they fulfil the selection criteria in the relevant stage of the procedure.

2.6 Institutions in the procedure, expert groups

(34) A committee of experts with proven scientific or technical expertise should be formed.

The working group recommends convening a group of experts whose main task is to establish the criteria for the test of suitability, and to make a recommendation at the end of the exploration as to whether the criteria are fulfilled or not. Since this committee will have a high level of responsibility, and will be reliant on a high degree of legitimation in such a conflict-laden situation, the focus should be on proven scientific or technical expertise, independence and balance. To ensure this, the working group recommends:

- The committee should be attached to an independent institution, e.g. the National Academy of Science.
- Members can be nominated by the relevant scientific organizations, by civil society groups, and by the companies operating nuclear power plants.
- The meetings of the committee are public.
- The committee will be given the right and the necessary resources to request expert advice, and to hold hearings if it sees these as necessary.
- The recommendations of the committee are not binding. However, the responsible decision-maker would have to be able to demonstrate cogent and publicly comprehensible arguments in order to diverge from the committee's vote.

(35) At the local level a dialogue forum should be set up for every site under consideration for selection as an institutional point of contact for the regional population.

A further institution of public participation at the local level should be a dialogue forum for each site still under consideration for selection (including Gorleben). The local dialogue forums should function as an institutional point of contact to facilitate effective participation of the regional population and provide access to independent knowledge on the state of the proceedings in the various stages of the selection process. To this end, the forums could instigate public debates, organize public panel discussions and allow access to pools of experts.

2.7 Administrative structure

(36) The division of responsibilities of the government agencies and other organizations dealing with the management of HLW should be improved.

A streamlined distribution of responsibilities between organisations involved in waste management would considerably increase the chances of implementing the proposed radioactive waste management programme.

This would also comply with the Joint Convention as well as with the proposed EU Directive on radioactive waste management. A clear and visible distinction and the observance of the necessary organizational distance between the applicant and the regulatory agencies should contribute to a greater acceptance of, and trust in, the process and those involved in it. The supporting research should be organised in a manner that boosts the effectiveness of these altered structures as much as possible. In this respect, the presently established distinction between site-specific and basic research may turn out to be inappropriate.

(37) As part of the reform of the institutional framework, the Federal Agency for Radiation Protection (Bundesamt für Strahlenschutz) should be turned into an independent regulatory agency.

One major objective of reforms of the institutional framework for the regulation and execution of high level radioactive waste management should be the transformation of the Federal Agency for Radiation Protection into a genuinely independent regulatory agency that can assume core responsibilities in the field of radioactive waste management, especially for regulation, siting and supervision. To this end, the present commingling of its various duties in regulation and execution should be abandoned in favour of a clear separation of functions.

(38) The operation of the disposal facility could be transferred to a new higher federal authority, a public body, or a private-law corporation vested with public powers.

The management of the disposal facility could be transferred to a new federal agency or, in the framework envisaged by the Atomic Energy Act, to a public corporation or a private law corporation that is vested with corresponding public powers. Shares could be held in this corporation by both the companies that directly or indirectly (through subsidiaries or joint ventures) operate the nuclear power plants in Germany and – in the interests of creating public trust – the Federal Government. In any case, however, the majority of shares should be held by the public authorities.

2.8 Decision-diagrammes

2.8.1 Preliminary Remarks

In order to illustrate the boundary conditions concerning the development of the proposed radioactive waste management programme (cf. conclusions and recommendations, section A 2.3), a decision tree was developed which aims at visualising (i) decisions already made in the past which might or might not be subject to revision and (ii) options for decisions to be made in the future. The time estimates shown in the tree are based upon the considerations of section B 1.5 "Timescales and potential roadmap".

The decision tree has been derived using ideas developed in the EU COMPAS project (Dutton et al. 2004) but taking issues specific for the situation in Germany into account. Although the logic of the COMPAS project was in principle adhered to, a major deviation was introduced with regard to encapsulation. This has been done because encapsulation for disposal only can take place adequately if the disposal solution is already known.

The decision tree focuses on the management of Spent Nuclear Fuel (SNF). The following assumptions concerning the German programme were anticipated:

- No new nuclear power plants will be built in Germany. As explained in the Part B of this book, the lifetimes of existing nuclear power plants will have no principal impact on the decisions to be made.
- The safe disposal of radioactive waste in deep geologic formations is technically feasible.

Decisions which were already taken in the past and/or are technically determined are indicated by darker grey panels. Bold arrow lines indicate the recommendations given in the present study – which decisions taken in the past better should not be revised and which decisions should be taken in the future, if maximizing the chances of having a disposal facility available in the next few decades is the aim.

In the following, some of the decisions shown in diagramme I (Fig. A.1) are further explained. The numbers correspond to the ones in the decision nodes of the diagramme I.

⟨1⟩ According to the German Atomic Energy Act, since 2005 no further transports to reprocessing plants in France and in the UK are taking place. Thus, the decision "no reprocessing" has been marked as "taken in the past". Nevertheless, waste from earlier reprocessing exists and has to be managed as well.

⟨2⟩ The reprocessing plant at Wackersdorf went never into operation. Before 2005, SNF was sent to reprocessing plants in France and the UK. Before 1989, all SNF arising form nuclear power operation in Eastern Germany was sent back to the Soviet Union.

⟨3⟩ While the waste arising from reprocessing in France and the UK was or will be taken back to Germany, no waste resulting from the reprocessing of SNF which arose in Eastern Germany was or will be returned. Remaining SNF from Eastern German nuclear power plants is being stored in the "Zwischenlager Nord" storage facility near Lubmin/Greifswald. According to international treaties, SNF from Eastern German research reactors has to be returned to Russia.

⟨4⟩ Presently, the policy in Germany is to store SNF locally close to reactor sites. However, in the past some SNF was already transported to central storage facilities at Ahaus and Gorleben and is being stored at these facilities. At Gorleben, also vitrified high-level reprocessing waste is being stored and it is planned to also ship the remaining waste from reprocessing to Gorleben. All storage facilities are licensed for 40 years, starting with the emplacement of the first cask. The licenses are linked to the lifetime for which the CASTOR casks are licensed. Therefore, a lifetime extension of storage facilities would require new licenses.

⟨5⟩ Here, it will only be distinguished between those options for waste management endpoints for which waste retrieval is impossible due to the nature of these options on one hand and those for which retrieval is in principle possible (regardless whether retrievability will actually be implemented or not). The decision tree does only consider the *option* of retrievability; in contrast, decisions connected to *actual retrieval* are not considered.

⟨6⟩ Practically, Germany has taken the decision in favour of deep geological disposal. This is in accordance with the recommendations made here.

⟨7⟩ For the implications of considering international solutions cf. Conclusions and Recommendations, § 21: A joint European solution is only plausible if Germany also contributes a possible site.

⟨8⟩ The decision for a host rock has to be made accounting for a number of boundary conditions and criteria, including availability in geologically stable regions and safety evaluations based on the disposal concept as a whole (including technical components). Note that there is an interplay with the decision <9> on retrievability. The bold arrow indicates the preference for rock salt as a host rock in Germany which is manifested not only by the Gorleben investigations but also by numerous R&D activities. The AKEnd proposal attempted at a site selection process without determining the host rock *a priori*. Nevertheless, the concept of a "confining rock zone" which was first mentioned by the AKEnd and now found its way into the BMU Safety Requirements (2010a: "Sicherheitsanforderungen an die Endlagerung wärmeentwickelnder radioaktiver Abfälle") results in a focus on salt and clay as host formations while it is unlikely that crystalline formations in Germany can offer such a confining rock zone.

⟨9⟩ The BMU Safety Requirements (BMU 2010a) require retrievability during the operational phase and containers remaining for 500 years in a condition allowing recovery (§ 8.6). It is likely that future discussions on the waste management programme will re-open the issue. Note the interdependence of the issue with the choice of the host rock.

⟨10⟩ Decision to be taken in the near future. The bold arrow indicates the preference of the working group for a hybride approach ("Gorleben plus") for a number of reasons (cf. Conclusions and Recommendations, §§ 23, 24, 25). The subsequent part of the diagram will indicate the time when and in dependence of which outcomes central targets of waste management presumably will be reached. The vertical distance between the tree elements give a rough idea of the timeframes to be anticipated.

Diagramme II (Fig. A.2) describes in greater detail the phases and various possible outcomes of the site selection process under the hybrid model "Gorleben plus" advocated by the group.

2.8.2 Decision diagramme I

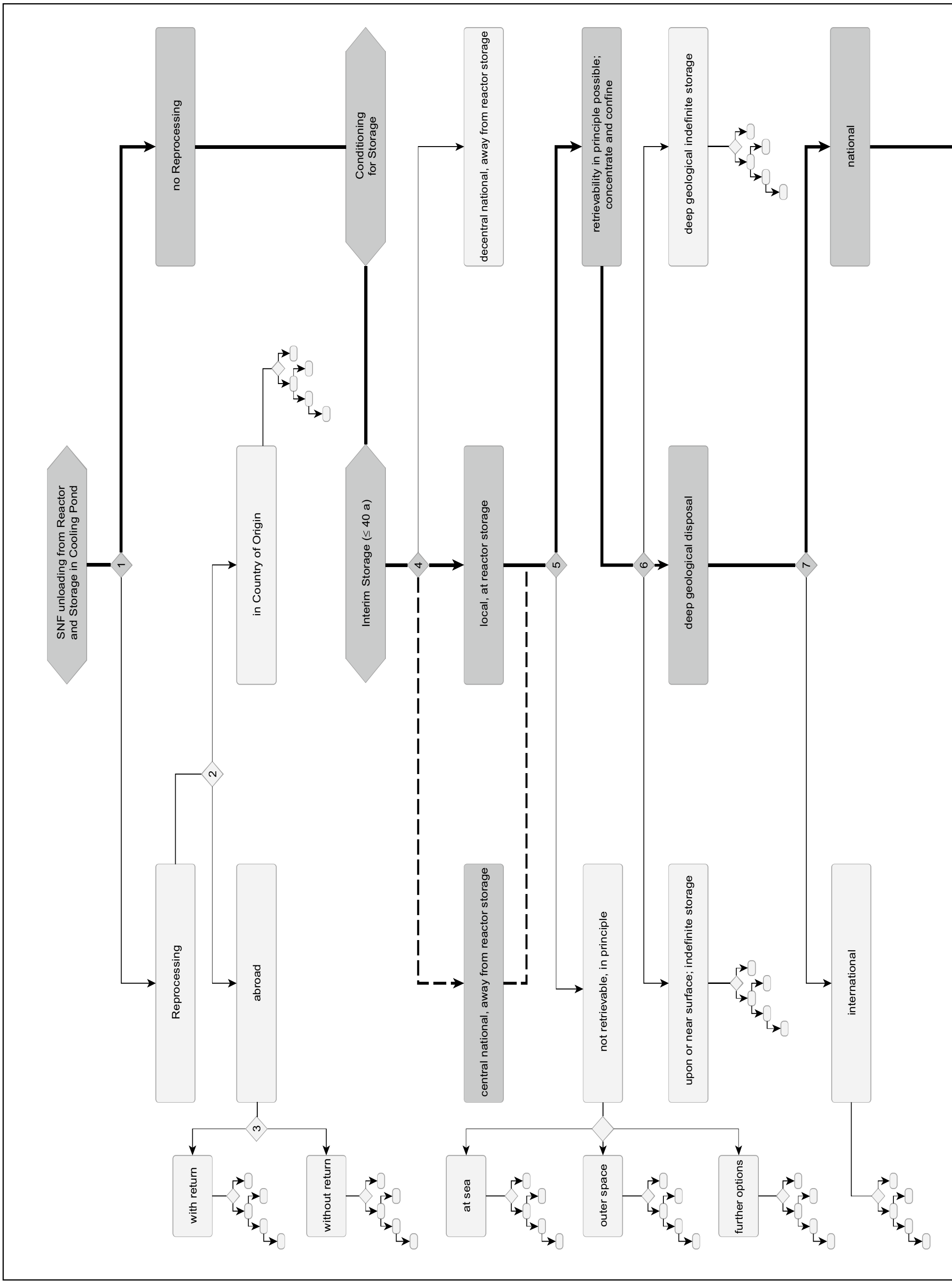
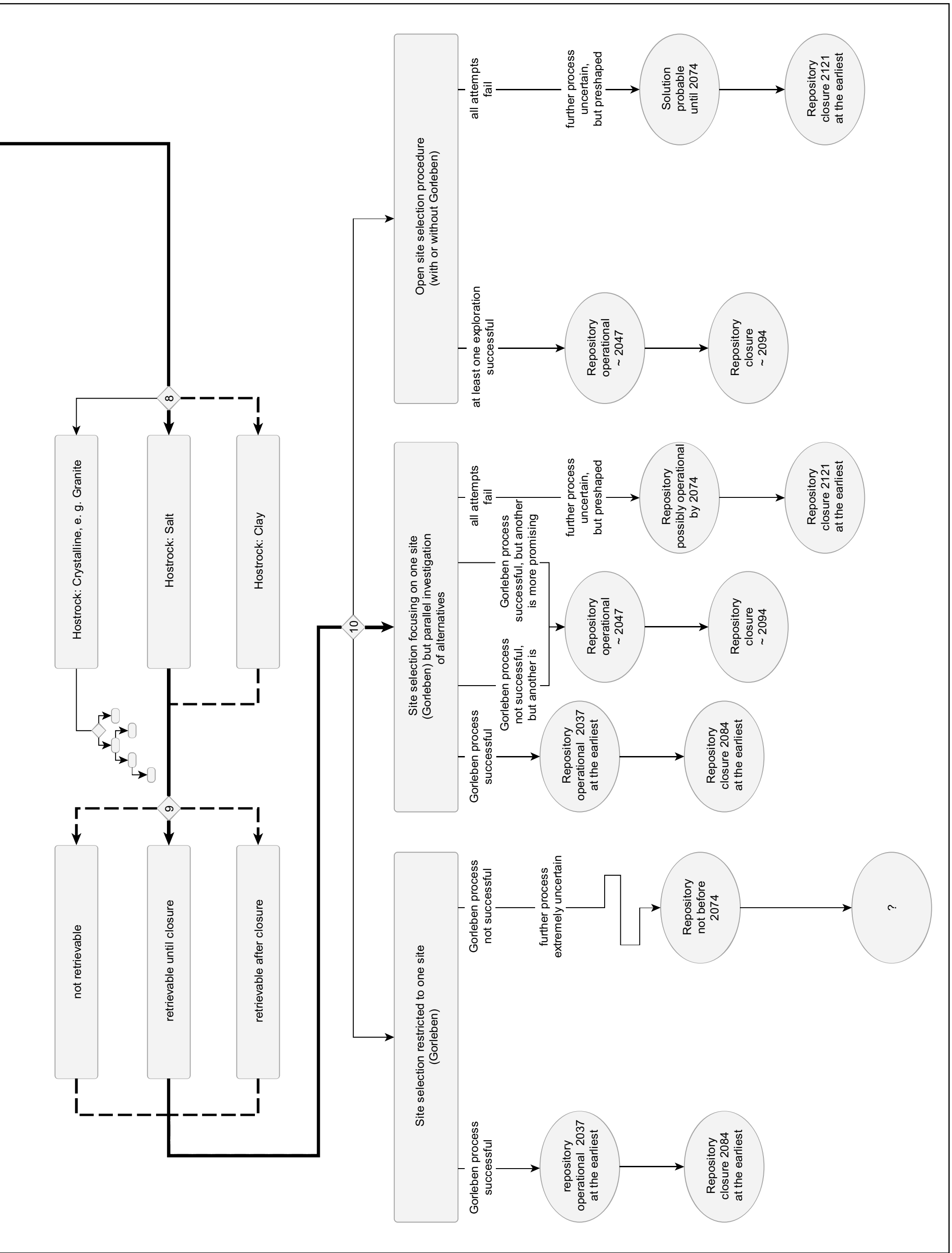


Fig. A.1: Decision diagramme I: Boundary conditions concerning the development of the proposed radioactive waste management programme (cf. conclusions and recommendations, section A. 2.3)


8
Hostrock: Crystalline, e. g. Granite
Hostrock: Salt
Hostrock: Clay
9
not retrievable
retrievable until closure
retrievable after closure
10
Site selection restricted to one site (Gorleben)
Gorleben process successful
repository operational 2037 at the earliest
Repository closure 2084 at the earliest
Gorleben process not successful
further process extremely uncertain
Repository not before 2074
?
Site selection focusing on one site (Gorleben) but parallel investigation of alternatives
Gorleben process successful
Repository operational 2037 at the earliest
Repository closure 2084 at the earliest
Gorleben process not successful, but another is
Gorleben process successful, but another is more promising
Repository operational ~ 2047
Repository closure ~ 2094
all attempts fail
further process uncertain, but preshaped
Repository possibly operational by 2074
Repository closure 2121 at the earliest
Open site selection procedure (with or without Gorleben)
at least one exploration successful
Repository operational ~ 2047
Repository closure ~ 2094
all attempts fail
further process uncertain, but preshaped
Solution probable until 2074
Repository closure 2121 at the earliest

2.8.3 Decision diagramme II

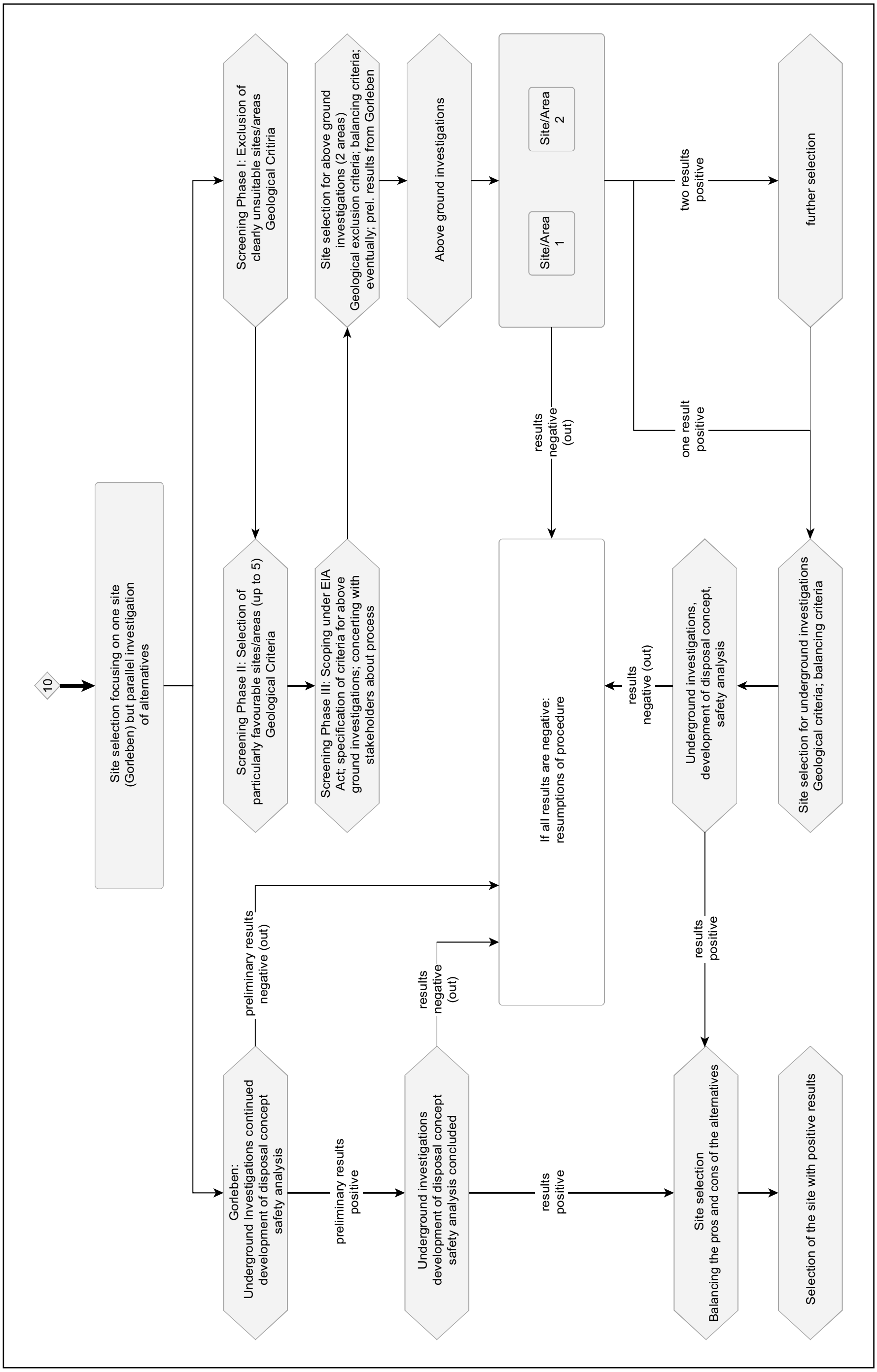


Fig. A.2: Decision diagramme II: Phases and various possible outcomes of the site selection process under the model "Gorleben plus" (cf. section B 4.5.5)

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Acknowledgement

The project "Radioactive Waste. Technical and Normative Aspects of its Disposal" was supported by the VGB PowerTech e.V. The content of the book is only the authors' responsibility.

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Ethics of Science and Technology Assessment
Volume 38

C. Streffer · C. F. Gethmann · G. Kamp · W. Kröger · E. Rehbinder · O. Renn · K.-J. Röhlig

Radioactive Waste

Technical and Normative Aspects of its Disposal

Waste caused by the use of radioactive material in research, medicine and technologies, above all high level waste from nuclear power plants, must be disposed of safely. However, the strategies discussed for the disposal of radioactive waste as well as proposals for choosing a proper site for final waste disposal are strongly debated.

An appropriate disposal must satisfy complex technical requirements and must meet stringent conditions to appropriately protect man and nature from risks of radioactivity over very long periods. Ethical, legal and social conditions must be considered as well. An interdisciplinary team of experts from relevant fields compiled the current status and developed criteria as well as strategies which meet the requirements of safety and security for present and future generations. The study also provides specific recommendations that will improve and optimize the chances for the selection of a repository site implementing the participation of stakeholders including the general public and not neglecting the responsibility of the legal institutions.

The study provides an advanced and, due to its interdisciplinary approach, novel contribution to the corresponding scientific debates including normative and social aspects of acceptability and acceptance. At the same time it serves as a contribution to public and political debates presenting an easily comprehensible executive summary and describing practicable recommendations.

ISBN 978-3-642-22924-4

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