Treatment of Human Intrusion into a Repository for Radioactive Waste in Deep Geological Formations - #10010

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ABSTRACT

The disposal of high-active and long-lived radioactive waste in deep geological formations is the worldwide favored option as a durable protection against ionizing radiation. The safety of disposal systems for radioactive waste has to be proven in the so-called safety case. For this, potential developments (scenarios) of the disposal system are studied regarding their effects on safety. In this context, potential adverse effects on the isolation capacity of the disposal system through future human actions, such as human intrusion into the repository, and the resulting consequences have to be discussed. However, any prediction of human actions over an extensive demonstration period is speculative. As a consequence, regulations and guidelines are necessary for dealing with the problem in the safety case. The present work focuses on the development of conditions and recommendations for the treatment of human intrusion in order to provide the groundwork for envisaged guidelines in Germany. In this regard, the discussed main issues refer to basic assumptions and conditions, stylized human intrusion scenarios, measures against human intrusion, scope of the analysis and consequences.

INTRODUCTION

The option favored worldwide is to isolate high-active and long-lived radioactive waste in disposal systems located in deep geological formations. The safety of such disposal systems has to be proven in the so-called safety case. Although the intrinsic hazard of radioactive wastes decreases with time, a significant hazard remains for a considerable period of time. Safety cases therefore usually consider demonstration periods ranging from thousands to millions of years. All events and processes that might affect the performance of the disposal system during those time frames have to be considered.

For this reason, a safety case has to investigate potential developments of the disposal system with regard to their impact on safety. Potential developments, which are usually referred to as scenarios, can be driven by natural or human events or by processes connected to the waste or the disposal system. These scenarios will be usually derived in a systematic scenario development except for those driving events and processes that are not amenable to quantification. This especially applies to the events caused by human intrusion into the disposal system. Although, difficult or impossible to quantify, human intrusion has to be taken into account in the safety case.

To some extent, future human actions involved in safety considerations in the different national approaches differ considerably from each other. This mainly attributes to differences in the disposal concepts, sites, regulations and country-specific perceptions. In recent years, the focus has shifted from drastic human intrusion scenarios to scenarios which are aligned towards the resilience or robustness of the disposal system in case of an unintended human intrusion. An example for a drastic human intrusion is the former widely considered core examination scenario. In this scenario it was assumed that a geological exploration drilling crosses the disposal system and that borehole cores, containing fragments of the disposed high active waste, are examined by geotechnical staff.

For this example, it is obvious that the drilling staff and geotechnical staff might be exposed by the contaminated borehole core. The consequences can range widely depending on the assumed frame conditions for this scenario, e.g. fraction of high active waste in the core, duration of the exposure, and number of concerned people. Since the scenarios and their frame conditions cannot be determined on a scientific basis there is a common opinion in the international community that human intrusion should be regulated by the respective responsible authorities.

In Germany there has been a discussion on a common view on the treatment of future human actions in the safety case. Herein, potential impairments of the isolation capacity of the disposal system through human actions, such as human intrusion into the repository, and the resulting consequences have also to be discussed. However, any prediction of human actions over a demanded demonstration period of a million years will be speculative. As a consequence, regulatory procedures and guidance are necessary for dealing with the problem.

GENERAL OUTLINE

Regulations and recommendations

According to the Atomic Energy Act [1], the German Federal Government has to ensure the safe disposal of radioactive waste by providing repositories. The legal basis for licensing of federal installations for the safekeeping and final disposal of radioactive waste is the "Plan Approval Procedure" required by the Atomic Energy Act. Radioactive waste disposal policy in Germany is based on the decision that all types of radioactive waste are to be disposed of in deep geological formations. The „Federal Ministry of the Environment, Nature Conservation and Nuclear Safety" (BMU) published in 2009 the "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste"[2] which includes inter alia requirements that directly and indirectly relates to the issue of human intrusion. These requirements replaced the former safety criteria for the final disposal of radioactive waste in a mine from 1983 [3].

In addition, a working group on scenario development, composed of various German waste management organizations including a regulatory support organization, has developed and issued a joint position and recommendations on the treatment of human intrusion in the safety case [4].

For this work, a number of expectations and tasks for both the implementer and regulator were described on the basis of stylized human intrusion scenarios. The above mentioned recommendations of the working group and the requirements from the BMU were also taken into account. The study addresses human intrusion scenarios with regard to the general framework and conditions for their treatment and different technical aspects. Technical aspects relate primarily to the initiating action and the time of intrusion, the view of occurrence probabilities, likelihood of such actions and how to deal with assessed consequences as well as the group of exposed individuals affected. Further, it was discussed whether anomalies or noticeable characteristics induced by the disposed waste and disposal system - e.g. by means of temperature anomalies due to the heat generating waste or the mechanical resistance of the waste casks to drilling - can be detected by future generations before, during and after an intrusion. In addition, a number of passive and active measures against human intrusion were considered and evaluated with respect to their possible effectiveness.

Definition and classification of human intrusion

The evolution of the disposal system is in principle affected by the following three groups of phenomena:

- natural phenomena,
- anthropogenic phenomena and
- repository and waste induced phenomena.

In the following the group of anthropogenic phenomena is of primary interest. This group can be divided in “human activities which alter the effectiveness of the barriers or the site situation” and in “human activities which compromise or bypass the barriers of the disposal systems”.

The former activities will be considered in the common component of “Scenario development” and might be finally treated as variant scenarios. Examples for those activities are the construction of a dam at the surface or the construction of a tunnel near to the surface as well as the drilling of a well also near to the surface.

The latter activities are known as human intrusion. Human intrusion is understood as [4]:

“…any human activity after the closure of the repository mine that will immediately damage the barriers within the backfilled and sealed mine workings and the isolating rock zone.”

These activities can be divided in intentional human intrusion and unintended human intrusion. There is a general consensus that the intentional intrusion into a repository, i.e. in knowledge of the site and its hazard potential, does not have to be considered in the safety analyses since it is not possible to protect future societies against their own decisions. Such intrusions have to be placed in the responsibility of the respective acting society. The same applies to acts of war and terrorism.

The unintended human intrusion in turn should be analyzed on the basis of stylized scenarios. The term unintended implies that the repository location is unknown, its purpose is forgotten, or the consequences of an intrusion are unknown [5]. It is only the unintended human intrusion that will be considered in the following.

Assumptions and frame conditions

There is a general consensus that the evolution of human society and human actions inclusive human intrusion cannot be predicted over timescales which are relevant or of interest for the disposal of high active waste [5, 6, 7, 8]. This has significant consequences for the further consideration of human intrusion from a safety point of view. At first, human intrusion has to be treated in the safety case since those actions cannot be fully excluded in the future. When analyzing human intrusion in the safety case it is recommended to take current actions and technologies into account, since it is not possible to forecast applied techniques and taken actions for the future.

Another aspect concerns the favored option of high active waste disposal in deep geological formations. This option based on the waste management strategy of concentrating and isolating the radioactive waste. Against the background of this strategy, there is an increased risk of radiation exposure in the event of human intrusion that can only be reduced to a limited extent.

In addition, a systematic scenario development, like for natural phenomena, is impossible for human intrusion events due to their unpredictability. Therefore, it is recommended to analyze human intrusion scenarios separately from the other scenarios. In fact, human intrusion should be already considered in the site selection process and in the design phase of a repository.

Furthermore, the consideration of occurrence probabilities regarding human intrusion derived, e.g., from former drilling and mining activities in the site region or from the projection of the future need for resources and the perception of raw and valuable materials on the basis of the current situation is not a reliable approach due to the lack of predictability.

RECOMMENDATIONS FOR THE TREATMENT OF HUMAN INTRUSION

The following discussion and recommendations comprise the subjects of measures against human intrusion, kind and type of stylized scenarios, detection of anomalies and calculated consequences.

Measures

Regarding the measures to be taken against human intrusion into a repository, the view is held that potential precautions against human intrusion are limited and that measures cannot finally prevent intrusion into a repository [4]. Measures and precautions, e.g. active, passive, concept-based and structural ones, can - at the most - hinder, impede or delay unintended human intrusion into a repository.

Moreover, measures have to fulfill the following general requirements:

- Measures must not impair the effect of repository-related safety concepts.
- Measures must not lead to other hazard to man and the environment.
- Measures have to follow the principle of proportionality regarding benefits, efforts and costs.

For the measures to be taken with regard to delay or retardation, the hindrance or impediment, etc., of human intrusion, the potentially most unfavorable events are to be taken into account for the selection of a disposal site, planning and design of a repository. However, kind and scope of the measures are to be defined under consideration of concrete concept-specific planning and site-specific conditions while adhering to the regulatory requirements. In addition, the appropriateness and effectiveness of measures have to be evaluated.

An effective measure is connected with the depth of the repository. The envisaged depth in Germany is about several hundred meters. This design option limits from a today´s perspective the number of

- kinds of actions e.g. drilling, leaching and excavation;
- motivations e.g. exploration, exploitation, mining, disposal;
- individual groups of persons which have the intention, means and resources for such an endeavor.

A sufficient depth of the repository is one of the most appropriate measures against human intrusion [4].

Another effective measure is seen in the preservation of information and maintenance knowledge. The main intention of preserving information and taking precautionary measures to preserve the knowledge for future generations is to maintain the awareness of existing disposal sites and of the potential hazard posed by the respective repository. As a result, the risk of unintended human intrusion into the disposal system can be excluded or at least reduced. However, from a safety point of view this can only be assumed for a limited period of time which is relatively short compared to the demanded demonstration period. Actually, both the required timeframe and the earliest possible intrusion time cannot be determined on a scientific basis and should be therefore fixed in regulations. A common approach is to equate the earliest possible intrusion time with the time of loss of information. The preservation of information on the other hand should be carried out as long as possible. Since this is an undefined specification, some countries take into account historical documents e.g. maintained by archives, registers or national libraries. The experience in Germany shows that information could be preserved for some hundreds of years. This experience can be derived from German mining archives that are still in use and preserved to this day. It should be noted that there are other examples from the history in form of symbols, inscriptions and ancient writings which cannot be interpreted for sure. One of those unexplained mysteries is the Nazca Lines in Peru. In fact, it is unknown what these geoglyphs mean and who has created them. It is believed that the Nazca Lines were created by the Nazca culture between 800 BC and 200 BC.

It is recommended that inadvertent human intrusion should only be assumed to take place after at least 500 years.

In conjunction with information preservation it is also essential to decide, what kind of information and in which form the information should be conserved. There are lots of recommendations from national and international studies that relate to these issues [9, 10, 11]. Therefore this subject will not be further discussed here but it should be noted that suitable arrangements have to be met in order to establish a sustainable basis to preserve the necessary information. This includes e.g. sophisticated technical solutions, methodologically sound concepts, secured funding, and stable organizational structures.

Information preservation is basically a passive control measure and involves the necessary condition for preventing unintended human intrusion. However, the sufficient condition is, that the future generations keep aware of the preserved information and that they interpret them appropriately. The latter condition is often discussed in connection with active institutional control. An active institutional control contravenes the principle of not having to take active measures in the future in order to avoid undue burdens on future generations. Therefore active institutional control has to be discussed as a measure within the framework of regulatory requirements.

The same applies to the measure of markers, monuments or other symbols with the intention to alert future generations and keep them away from the disposal site. There are some doubts that markers will work as intended. History has shown that warnings to successive generations were neglected, e.g. rune stones in Norway [11] and pyramids in Egypt. Furthermore, the lifetime of markers are also limited and will be presumably much lower than the demanded demonstration period. On the other hand, markers may be an important element, depending on the repository, disposal concept, and the type of waste. In Germany, however, markers at the repository site are currently not part of the safety concept since it is intended to dispose of all categories of waste in deep geological formations. Thus, human intrusion is only possible by activities in the deep underground, such as drilling or mining activities. For near-surface repositories, planned or operated by some nations, markers may possibly play a much greater role.

If, however, markers are planned for a site, a standardized form, design, size, etc., should be used globally. The reason is that in case of an intrusion with radiological consequences the societies at other marked places are warned and may react accordingly.

Another measure refers to reducing the likelihood of human intrusion by avoiding sites with valuable resources. This issue is discussed both on an international and national level. Some nations require the exclusion of disposal sites with exploitable resources. However, there are some reservations as to whether the likelihood can be really reduced over timeframes considered in safety assessments [12]. Reducing the likelihood of human intrusion by avoiding sites with valuable resources includes the assumption that future generations have the same requirements about needs and resources, as the present generation. This may not necessarily be the case given the long timescale for the isolation period of high active waste. However, the real situation at a specific time cannot be predicted, and secondly it can be assumed with sufficient reliability that habits and needs will not change dramatically in the near-term. Therefore, the assumption of reducing the likelihood in this matter seems to be valid for a certain period of time shortly after repository closure. On the other hand, a geology that mainly consists of materials occurring in large amounts near the surface can be expected to make intrusions less attractive over long time periods.

There are some other kinds of measures which make it difficult to intrude, e.g. an increased wall thickness of waste casks as a barrier against drill bits. Other measures might reduce the amount of affected waste in case of an intrusion, e.g. the construction of compartments in the emplacement area.

However, the most appropriate measures seem to be the disposal of the waste in deep geological formations and for a limited period the information preservation.

Stylized scenarios

As mentioned before, human intrusion has to be treated on the basis of stylized scenarios, in the following referred to as reference scenarios. The reference scenarios shall be used for site selection and repository design, both being an inherent part within the framework of the safety case. This means that the investigation of human intrusion has to be performed already in advance to the long-term safety assessment.

A reference scenario comprises a set of assumptions and definitions that reduce the speculative character of the treatment of human intrusion into a repository in a deep geological formation to an acceptable degree. The sequence and the initiating process for a reference scenario have to be oriented towards today's social environment which comprises the current techniques and work processes as well as human behavior. The reference scenarios do not have the character to be covering or conservative and are not consciously directed to robustness or the integral destruction of the repository system. The reference scenarios only reflect potential future scenarios presenting an evolution that is possible, comprehensible and plausible.

The spectrum of reference scenarios should be limited to the exploratory drilling, the construction of a mine, the extraction of geothermal energy, and the mining of caverns as storage medium (e.g. crude oil, natural gas). Here, special importance is attached to the reference scenario "exploratory drilling" since drilling is principally regarded as initiating process for all other reference scenarios mentioned above. The above-mentioned reference scenarios are the result of considerations related to current practices and techniques, mirrored on the properties of the host rock salt, national mineral deposits and conceptual requirements such as the depth of the repository [13, 14].

As already mentioned, the contents of the reference scenarios shall be based on the state of the art in science and technology. This means, taking drilling as an example, the current methods, techniques and processes before during and after drilling of a borehole that are to be considered in the treatment and assessment of the respective reference scenarios. Further, case distinctions are to be considered in the analyses of the reference scenarios that take into account the regional and local conditions, such as different drilling locations and excavation zones. Some examples for case distinctions relating to the reference scenario "exploratory drilling" are:

- Exploratory drilling through
    - a waste container holding spent fuel assemblies located in a backfilled emplacement drift,
    - a backfilled emplacement drift between spent fuel containers,
    - a backfilled drift without radioactive waste, and
    - the isolating rock zone outside the emplacement area.

Detection of anomalies

Although the construction of a repository in deep geological formations does not leave any visible structures once all surface work has been completed, there will still be some traces left for posterity that indicate certain abnormal or unexpected characteristics of the surrounding area. Such repository-related anomalies are for example [13, 14]:

- porosity, permeability and density differences caused by mining, opening and backfilling work,
- temperature differences for the area of heat-generating waste, and
- emplacement of dissimilar material such as containers, casks, concrete, radioactive waste, etc.

The analysis of reference scenarios has taken into account potential anomalies induced by the repository design (e.g. using of dissimilar material like concrete) and the waste emplaced (e.g. heat generation, radioactivity) that can be detected before, during and after a specific action takes place. Here, potential time spans are to be considered or identified in which the possibility of detection is given or is particularly high.

An example is the temperature development around the emplacement area resulting from the heat-generating waste. Its anomaly could, under certain conditions, be detected in the geological formation by temperature measurement carried out during drilling. The prerequisites are, e.g., that the borehole is drilled through a zone that may be affected by a corresponding temperature impact and that the temperature deviation, compared to the expected or normal rock temperature at the respective depth, is sufficiently large at the time of drilling for interpreting an anomaly. Calculations of the temperature development for a repository in a salt formation show that the temperature in the disposal area of high active waste is for several thousand years (approx. 330 K – 400 K) still noticeable higher than the normal rock temperature in the respective depth (approx. 300 K) [15, 16]. However, the temperature anomaly is detectable only for a short time compared to other features like dissimilar material or the radioactivity.

Further, discussions with exploration companies have shown that in case of drilling a metal waste cask the drill bit would be either destroyed or deflected if the wall thickness of the canister is approx. 0, 03 m or more. Therefore, it is very unlikely that a thick-walled metallic canister like the German POLLUX canister for spent fuel can be hit without being detected or noticed by the drilling team. In case of the normal evolution of a repository in salt the lifetime of the canisters for spent fuel are probable pretty long, e.g. several 10.000 years. Furthermore, there are many accompanying geophysical measurements during the borehole drilling, e.g. gamma log, temperature, density log, sonic log and resistance log. All these measurements can contribute to the detection of anomalies or unexpected characteristics.

Barriers made of concrete can also have characteristics that strongly contrast with those of the host formation. However, whether these materials will be recognized as exotic materials by the drilling team will strongly depend on the type of host formation and its characteristics.

Depending on the reference scenario, case distinction, time and applied technique, there are many possibilities that reveal anomalies or irregularities. The detection of anomalies and irregularities will possibly not always be directly associated with a repository and the hazard emanating from it, but it may lead to increased attention or sensitization for the implementation of the respective activity or give the impetus for investigating the cause.

Along with the analysis of the respective reference scenario, it shall be shown, on principle, which chain of processes, features and control mechanisms would have to remain unnoticed, ignored, undetected, misinterpreted, etc., due to human and/or technical circumstances so that the repository or the irregularity will not be identified. In other words, with the number of identified detection possibilities, the confidence increases that the repository will not remain undetected during the sequence of the respective reference scenario and thus the necessary knowledge for the taking of measures will be available.

Exposure and calculated consequences

With the decision for the concept of concentrating and isolating the radioactive waste in a disposal system, there is an inevitable risk on radiation exposure in the event of human intrusion. In principle, two main concerned person groups can be considered:

- Active person group (A) that executes a corresponding activity at the site or is involved in the process, such as drillers, miners, landfill operators and laboratory personnel.
- Passive person group (P) that is affected during or following a corresponding activity, such as people sojourn in the vicinity at the disposal site or residents living in the region of the disposal site.

For the active person group (A) it is assumed that they get in direct contact with contaminated material. An example of this type of exposure is the handling and possible the examination of a drilling core containing fragments of the disposed waste.

The passive person group (P) can be further subdivided into a subgroup (P1) that comes directly in contact with contaminated material, e.g. by radioactive substances which were brought to the surface, and a subgroup (P2) that might be indirectly affected. An example for the latter subgroup can be that groundwater comes in contact with the radioactive waste through a borehole. Then the radionuclides are dissolved by the groundwater and transported to an aquifer which is connected to the biosphere. Consequently, several exposure paths to the subgroup (P2) are possible.

For scenarios on the basis of natural phenomena and waste induced or repository induced phenomena the common procedure will be to determine the consequences in form of dose and risk and then to compare the results with regulatory limits. In the case of human intrusion, there are recommendations from international organizations that calculated doses and risks should not be compared with thresholds but the resilience of the disposal system to such events should be evaluated [6, 7]. Similarly, the National Academy of Science (NAS) [8] recommended, that the robustness of the disposal system in terms of human intrusion should be appraised.

The following quotation from NAS [8] relates to the above mentioned person group (A) and the subgroup (P1):

- "This consequence assessment is to be done separately from the calculation of compliance with the risk limit from other events and processes, and is to exclude exposures to drillers or to members of the public due to cuttings."

In addition, the Swedish Radiation Safety Authority (SSI) stated the following [17]:

- "The consequences for the individuals performing the intrusion need not be assessed."

The German safety requirements [2] state that no risk limit will be defined for developments on the basis of unintended human intrusion into the isolated rock zone.

In addition, the working group on scenario development holds the view [4]:

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. Therefore, it is not reasonable to evaluate consequences of human intrusion by means of radiological limit values.

Finally, it is recommended that human intrusion scenarios should be investigated in a more qualitative manner. For the assessment of the impact, calculated doses or risks should be seen as indicators which can provide information about the resilience and robustness of the disposal system.

CONCLUSION

In this work, specific aspects, e.g. classification, measures, stylized scenarios, of human intrusion were discussed and recommendations for their treatment in the safety case were given. The current regulatory basis for the issue human intrusion in Germany was described.

Human intrusion can be understood as actions which have the potential to directly compromise the isolating capacity of the barriers of the disposal system and therefore might have radiological consequences. It is only the unintended human intrusion that has to be considered. Intentional human intrusion, i.e. human actions with knowledge of the disposal site and the hazardous waste, cannot be prevented. The respective society taking that action is therefore responsible for its own decision.

There is consensus that human actions over timescales which are relevant or of interest for the disposal of high active waste are unpredictable. In addition, it is not possible to derive human intrusion scenarios in a systematic way like for the other scenarios. The same applies to the derivation of the occurrence probabilities for human intrusion events. As a consequence, the human intrusion scenarios should be determined on a stylized basis whereas current technology and social behavior have to be taken into account.

The treatment of human intrusion should be addressed in regulations and guidelines provided by the respective responsible authorities. Regulations and guidelines should include e.g. the framework for the analysis of human intrusion scenarios, scope of the investigations, constraints and conditions. In addition, the scenarios should be determined on a stylized basis. However, it should be acknowledged that stylized human intrusion scenarios can never be complete or comprehensive. Furthermore, the topic of human intrusion should be already considered in the site selection process and in the design phase of a repository.

The consideration of appropriate measures against human intrusion is an essential task in the scope of investigations, whereas measures themselves must not compromise other safety aspects of the repository. Albeit potential measures against human intrusion are limited, a sufficient depth of the repository and information preservation, are considered as appropriate measures against human intrusion. Another aspect refers to the selection of sites without valuable resources in order to reduce the likelihood of human intrusion. There are some reservations as to whether the likelihood can be really reduced over the long timeframes that are considered in safety assessments.

The main type of action is drilling and mining associated with exploration of the site, exploitation and extraction of natural resources and injection of substances and/ or resources for storage and disposal. Herein, the exploratory drilling indicates actually the initial event for all the other actions like mining and exploitation.

The investigation of human intrusion scenarios should also consider if the anomalies induced by the waste and the repository could be detected based on today´s knowledge and applied technology. These investigations can serve as potential additional arguments in terms of repository safety.

It is further recommended to examine case distinctions of stylized human intrusion scenarios that take into account the regional and local conditions, such as different drilling locations and excavation zones.

Finally, the investigation of human intrusion scenarios should be done in a more qualitative manner. Respective calculated consequences in form of doses or risks should be seen as indicators for the resilience and robustness of the disposal system.

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