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Handling of future human actions in the safety assessment SR-Site

In the earlier distributed report, there are errors that have now been corrected. The corrected pages 7, 43, 45, 57, 62, 75 and 77 are enclosed. The changed text is marked with a vertical line in the page margin. An updated pdf version of the report, dated 2011-10, can be found at www.skb.se/publications.

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Canister penetration by drilling

In the drilling case, it is assumed that technology to drill to great depth is available, that the knowledge of the location and purpose of the repository is lost, that the intruders are incapable of analysing and understanding what they have found and that no societal regulations on drilling exist. It is assumed that an evolution rendering this situation will require some time. Based on this, it is assumed that the drilling will take place 300 years or longer after repository closure. It is also assumed that the purpose of the drilling is to reach great depth. The drilling angle is assumed to be 85° and the cuttings are assumed to be spread on the ground. The site and the borehole are abandoned without further measures. About a month later, a family moves to the site and operates a domestic production farm there. The abandoned borehole is used as a well by the family. The consequences for the repository and the annual effective doses to the family as well as the dose to the drilling personnel are assessed.

The dose rate that a member of the drilling personnel would be exposed to while working in the highly contaminated area 300 years after repository closure is calculated to 130 mSv/hour. If drilling occurs at c 5,000 years after repository closure, the dose rate has decreased to values below 1 mSv/hour. These calculated dose rates are very high and is primarily a result of the cautious assumption regarding the amount of Ag-108m brought to the surface when drilling. In case Ag-108m would not be instantaneously released, 3 percent instead of 100 percent of the inventory of Ag-108m would be brought to the surface when drilling. Due to the total dominance of Ag-108m to the dose rate, this would reduce the dose rate to workers to 3 pecent of the value, i.e. the dose rate 300 years after repository closure would be about 15 mSv/hour. The dose to the family that settles on the site originates from two sources. The total dose from using the borehole as a well 300 years after repository closure is 0.24 mSv/year and is dominated by the contribution from Am-241. The maximum total annual effective dose from the use of the contaminated soil for agricultural purposes is about 7 Sv/year and this dose is obtained 300 years after repository closure. The dose is dominated by ingestion of vegetables contaminated with Tc-99 and there is also a significant dose contribution due to external radiation from Ag-108m. The calculated annual dose is very high, but it should be noted that there are a number of simplified, cautious assumptions made in the calculations.

The impact of an open borehole on the groundwater flow in the repository and the surrounding rock has been studied by introducing boreholes at various locations in the hydrogeological base case model applied for analyses of the temperate period in SR-Site. Although the flow paths are affected by the borehole, the results show only small effects of the borehole, indicating that the flow paths established by the presence of the borehole have similar transport characteristics as the flow paths without a borehole. An open borehole might affect the long-term properties of the backfill in the deposition tunnel in the vicinity of the borehole but the effect on the backfill above neighbouring deposition holes is assessed as negligible.

Rock excavation or tunnel case

A tunnel constructed at 50 metres depth with a cross section of 100 square metres and with a length corresponding to the whole repository footprint along the centre line of the deposition areas is considered. The justification of this assumption is that it is plausible in relation to current practice and does not underestimate the possible impact on the repository. As in the drilling case, it is assumed that the existence of the repository is forgotten and that the technical standards for making underground constructions are similar to those used at the present. Further, it is assumed that the construction of the rock excavation (tunnel) is not initiated before 300 years after repository closure.

At Forsmark, the upper part of the bedrock (down to about 150 metres depth) in the target volume for the repository is much more water conductive than the lower part, especially below 400 metres depth. The assessment indicates that the upper 150 metres of the bedrock above the repository is an unfavourable location for a tunnel from en engineering point of view, due to the exceptionally high water yield in this part of the bedrock. These conditions also imply that a tunnel constructed in this part of the bedrock would not affect the groundwater flow at repository depth such that the presence of the tunnel violates the safety functions of the deep repository. The design consideration to locate the repository to a depth that allows utilisation of the site for generally occurring future human activities should, therefore, be fulfilled at Forsmark.

6 Illustrative cases of future human actions

The aim of this chapter is to illustrate future human action cases. This is required by the regulations to be a part of the safety assessment SR-Site. All analyses of consequences are reported here and are only briefly summarised in the main report of SR-Site. Selection of FHA-cases is discussed in general in sections 6.1 and 6.2.

Prior to SR-Site, the following three FHA-cases were presented and assessed in SR-Can /SKB 2006a/.

- Canister penetrated by drilling at the earliest 300 years after closure and sealing of the repository, including calculation of dose to a family using the borehole as a well in addition to being exposed to external radiation from the drill cuttings left on the ground at the borehole.
- Underground facility near the repository comprising of a tunnel driven above the repository at 50 metres depth, again not earlier than 300 years after closure and sealing.
- A mine at Forsmark, southwest of the selected repository site, outside the tectonic lens associated with the site and into an area containing an iron oxide mineralisation.

In their joint review of SR-Can the authorities SKI and SSI explain the intention with their requirement associated with human intrusion to overview the conceivable consequences /Dverstorp and Strömberg 2008/. To this end examples are needed such as activities that can indirectly lead to deterioration in the repository's protective capacity, damage caused to the barriers in connection to human activity, injuries to people who intrude into the repository and the consequences of an abandoned but not sealed repository.

The first case did not regard exposure of the drillers, nor any consequences of the initial damage to the rest of the repository. In response to the comments made by the authorities in their review, this case has been further evaluated and presented in Section 6.3.

The second and third case were found to be of little or no consequence for the repository. However, the authorities expert group for review of safety assessment methodology in SR-Can commented that supporting arguments were lacking for the claim that rock chambers, tunnels and mining do not affect the repository /Dverstorp and Strömberg 2008, Annex 2/. These two cases are therefore further addressed in the following sections 6.4 and 6.5.

According to the regulations, it is also necessary to define and analyse a case that illustrates the consequences of an unsealed repository /SSM 2008a/. This was not done in SR-Can, but in SR-Site the case of an unsealed, or rather "a not completely sealed repository", has been selected and analysed, see Section 6.6. The name of the case is referring to the fact that deposition tunnels are filled successively, and sealed as soon as they have been filled. Leaving in the middle of such an operation is considered unlikely. It is more plausible that the operation stops and the repository is abandoned after the deposition tunnels have been sealed but the rest of the repository is still open.

6.1 Ambiguities in selection of illustrative cases

Large uncertainties are associated with the development of technology and society. To avoid speculation, the NEA working group on assessment of future human actions /NEA 1995a/ as well as SSI in the general guidelines to their regulations /SSI 2005/ suggest an approach based on present-day knowledge and experience. Another generally accepted premise is to only include unintentional FHA affecting the repository in design and safety assessment.

Analysis of societal factors is not considered meaningful on time perspectives longer than a maximum of 500 years. Not surprisingly this time frame coincides with the maximum time active control of the repository can be assumed to be maintained. The performed analysis of societal conditions concluded that fundamental changes in society are required for unintentional disturbances of the repository to occur. These changes could be the result of some more or less dramatic evolution, or the result of a long time having passed since repository closure. An application of a combination of ongoing current would remain unaffected. Further, such an event implies a nuclear war and the consequences of the war and the blast itself would be much greater than the consequence of the hypothetical leakage from the repository. However, sub-surface testing of nuclear bombs (M6) close to the repository may violate the containment in a similar way to an earthquake. The test would need to be carried out close to the deposited canisters. Testing of bombs could be combined with "The recovery" to form a plausible scenario. However, tests of bombs are carried out below the surface to avoid environmental impact, and also require knowledge of nuclear fission and fission products and the risks associated with them. Since measurements are carried out in connections with the tests, it is plausible that if a detectable leakage from the repository exists, it would be distinguished from the releases from the bomb and handled by a society performing sub-surface weapon tests.

Some of the actions in Table 4-1 can, besides influencing radionuclide transport, indirectly influence the containment of the spent fuel if they affect the capability of the geosphere to provide favourable hydrological or chemical conditions. Such actions would have to be performed directly above or very close to the repository and include drilling and/or construction in the rock (M1, M2). These categories include actions that have to do with heat extraction (T1, T2, T3), well drilling (H1) and disposal of hazardous waste in the rock (C1). Hydropower plants (H5) and open-cast mines and quarries (M3) may also involve drilling or rock works at great depth. Before a rock facility is built, drilling is carried out to investigate the rock. Therefore, if present day technology is applied, all these cases involve drilling in the rock.

Large rock facilities adjacent to the repository are judged to be out of the question in a short time perspective, i.e. within a few hundred years, for several reasons. For example, the repository is itself a large rock facility, the only one of its kind in Sweden, that is very unlikely to be forgotten over such a short time span. Institutional control can be expected to endure on this timescale. The enumerated actions that encompass major rock works are less likely at the repository site, based on current technology and economics. In a slightly longer time perspective, i.e. a few or several hundred years or more, it is difficult to predict how knowledge, technology and society will develop, and thereby how, where and why rock facilities will be built. Based on current practice, rock facilities at depth down to around 50 metres may very well occur and actually exist at Forsmark (the SFR facility, a repository for low- and intermediate level radioactive waste). In the far future, the potential ore resources to the southwest of the investigated area in Forsmark may be exploited.

Of the actions in Table 4-1, "Drill in the rock" is judged to be the only one that can directly lead to penetration of the copper canister and breach of waste containment, while at the same time being inadvertent, technically possible, practically feasible and plausible. "Drill in the rock" is furthermore a conceivable action in the light of the results of the societal analysis. Even if it is possible to build a rock cavern, tunnel or shaft or to excavate an open-cast mine which leads to penetration of the copper canister, doing so without having investigated the rock in such a way that the repository is discovered, i.e. without knowledge of the repository, is not judged to be technically plausible. However, the construction of a rock facility at shallow depth or a mine in the vicinity of the Forsmark site may occur in the future. Therefore, the cases "Canister penetration by drilling" and "Rock facility in the vicinity of the repository" and "Mine in the vicinity of the Forsmark site" have been selected as representative for scenarios related to a sealed repository, and which should be further described and analysed.

6.2.2 Unsealed or incompletely sealed repository

According to regulations, it is also necessary to define and analyse a case that illustrates the consequences of an unsealed repository /SSM 2008a/. Since the repository is gradually excavated and operated, the case selected for analysis represents an incompletely sealed repository rather than an unsealed repository. The strategy for deposition of canisters implies that deposition tunnels are successively filled with canisters and then backfilled and sealed as soon as they are filled. Abandoning the repository in the middle of this process is judged as rather unlikely because this would mean that canisters are left at the surface where they would constitute a larger risk than if emplaced in the repository. It is judged more plausible that the repository is abandoned when all canisters are deposited and all deposition tunnels backfilled and sealed, but all other repository volumes are still open due to, for example, political decisions not to seal the repository completely. Therefore, this is the basic assumption in the case selected as representative for scenarios related to an unsealed or incompletely sealed repository.

Impact of borehole on other parts of the repository

Uncertainties in the analyses of the impact of the borehole on other parts of the repository than the deposition hole directly affected by the borehole is judged as small compared with those associated with the calculations of dose from the canister penetrated by the drilling. The conclusion that a borehole through the backfill above, and buffer in, the deposition hole hit by drilling does not affect the backfill and the buffer in a neighbouring deposition hole, is based on results of analyses reported by /Åkesson et al. 2010, Appendix F/. These analyses addressed loss of backfill above a deposition hole or in the middle between two deposition holes. Although the results reported by /Åkesson et al. 2010/ are associated with uncertainties, their results in combination with the situation in this case, where a potential loss of backfill occurs still further away from a deposition hole, seem firm enough for the conclusion drawn.

The study of the impact of open boreholes on the groundwater flow in and around the repository was performed on a repository block by block basis, i.e. the repository was divided into three blocks and each of the three repository blocks was modelled separately. Potentially a borehole could have an effect on the other parts of the repository which would not be captured in these models. However, it is judged that this would not significantly change the statistical results.

In the hydrogeological models, the boreholes were assigned geometrical and physical (conductivity and porosity) properties that were chosen in order to make a good enough numerical representation of a borehole. The exact values of the parameters are difficult to define, but given the stylized nature of the results obtained the current values are judged sufficiently well established. Also, a freshwater density was assigned to the entire borehole, which should be a pessimistic assumption in terms of hydraulic driving forces.

Particle tracking was only carried out within the repository-scale model, since the effect of boreholes is likely to be local and, consequently, the effects should be most significant at the repository scale.

6.3.5 Conclusions

If a canister is penetrated and the borehole is used as a well for drinking and irrigation, the annual effective doses to representative members of critical groups will exceed the individual limit on annual effective dose for members of the public but not the annual effective dose due to background radiation. Assuming the site-specific median water yield of percussion holes drilled in the repository rock at Forsmark, the dose corresponding to the regulatory risk limit is exceeded if the intrusion occurs during the first c. 35,000 years after repository closure.

If the instant release fraction and crushed material, pieces, and even unbroken fuel rods, from the fuel elements are brought to the surface by drilling, the persons executing the drilling will receive very high doses. After about eight hours of exposure, the limit on 1 Sv for suffering from radiation sickness is exceeded. Further, if the contaminated soil surrounding the borehole is used for agricultural purposes, the exposed persons in the case illustrated may be severely injured. However, as discussed above, the case analysed involves a number of simplified and cautious assumptions and the calculated annual effective doses should be seen as illustrations of possible consequences rather than estimations of what the consequences would be.

An open borehole might affect the long-term properties of the backfill in the deposition tunnel in the vicinity of the borehole but the effect on the backfill above neighbouring deposition holes is assessed as negligible. This implies that the buffer surrounding canisters in neighbouring deposition holes in the deposition tunnel is also unaffected by the borehole. An open borehole through the backfill will also change the pattern of flow paths in the rock beneath the highly transmissive fractures in the upper part of the bedrock. However, the new paths established have similar transport characteristics as those prevailing without an open borehole through the backfill. The change in performance measures generally stays within a factor of four comparing the borehole case with the hydro base case for the SR-Site main scenario. Therefore, it is judged that even if drilling a borehole that penetrates a canister will severely affect the deposition hole hit by drilling, the impact of the borehole on the containment potential of other parts of the repository as well as on the retardation potential of the geosphere is negligible.

6.5.3 Conclusions

The assessment indicates that exploitation of the potential mineral resources in the vicinity of the Forsmark site would not impact the safety functions of the repository. The design consideration to locate the repository at a site without natural resources is, therefore, considered to be fulfilled.

6.6 An incompletely sealed repository

6.6.1 Introduction and specification of the case analysed

According to regulations, it is also necessary to define and analyse a case that illustrates the consequences of an unsealed repository /SSM 2008a/. The basic assumption in the case selected as representative for scenarios related to an unsealed or incompletely sealed repository is that the repository is abandoned when all canisters are deposited and all deposition tunnels backfilled and sealed, but the main and transport tunnels as well as the central area, repository access (ramp and shafts) and the ventilation shafts in the deposition area (see Figure 6-6) are still open due to, for example, political decisions not to seal completely. This assumption is based on the strategy for deposition of canisters, which implies that deposition tunnels are successively filled with canisters and then backfilled and sealed as soon as they are filled. Abandoning the repository in the middle of this process is judged as rather unlikely because this would mean that canisters are left at the surface where they would constitute a larger risk than if emplaced in the repository.

An outline of the case analysed is provided below.

- The central area, tunnel system, ramp and shafts are open to groundwater circulation.
- The plugs at the end of the deposition tunnels rapidly loose their function and the backfill swells out into the water flowing in the main tunnels.
- Water flowing in the main tunnels is saturated with air and oxygen dissolved in the water may be transported to canisters in the deposition holes. In addition, canister corrosion occurs by sulphide dissolved in the groundwater.
- The canisters corrode, and after corrosion breakthrough, nuclides are transported out into the water flowing through the open tunnels and further up to the ground surface.
- Water in the open ramp and shafts is used by humans who are exposed to radionuclides in the water.

6.6.2 Qualitative description of the consequences of a not completely sealed repository

If the repository is abandoned when the main and transport tunnels, central area, repository access and ventilation shafts in the deposition area are still open, these open volumes will successively become water filled. Water will flow through the open volumes with a magnitude and direction dependent on the magnitude and direction of the hydraulic gradient. In addition, the open volumes may affect the groundwater flow pattern in the repository bedrock.

All deposition tunnels will be plugged towards the main tunnels when the repository is abandoned. When the main tunnels have been filled with water, the cement and other components in the concrete plugs may be dissolved in the water and transported away. At some point in time the plugs will lose their function and the backfill in the deposition tunnel will swell out into the main tunnels. This swelling out into the main tunnels will decrease the density of the backfill in the deposition tunnels. How far into the deposition tunnel the decrease in density reaches depends on the amount of backfill material that is lost from the deposition tunnel. If the density in the backfill above a deposition hole is significantly reduced, the buffer in the deposition hole may expand into the backfill above with the consequence that the density of the buffer also decreases. A possible implication of such a reduction in density of the buffer is that advection becomes the dominating process for solute transport in the buffer instead of diffusion.

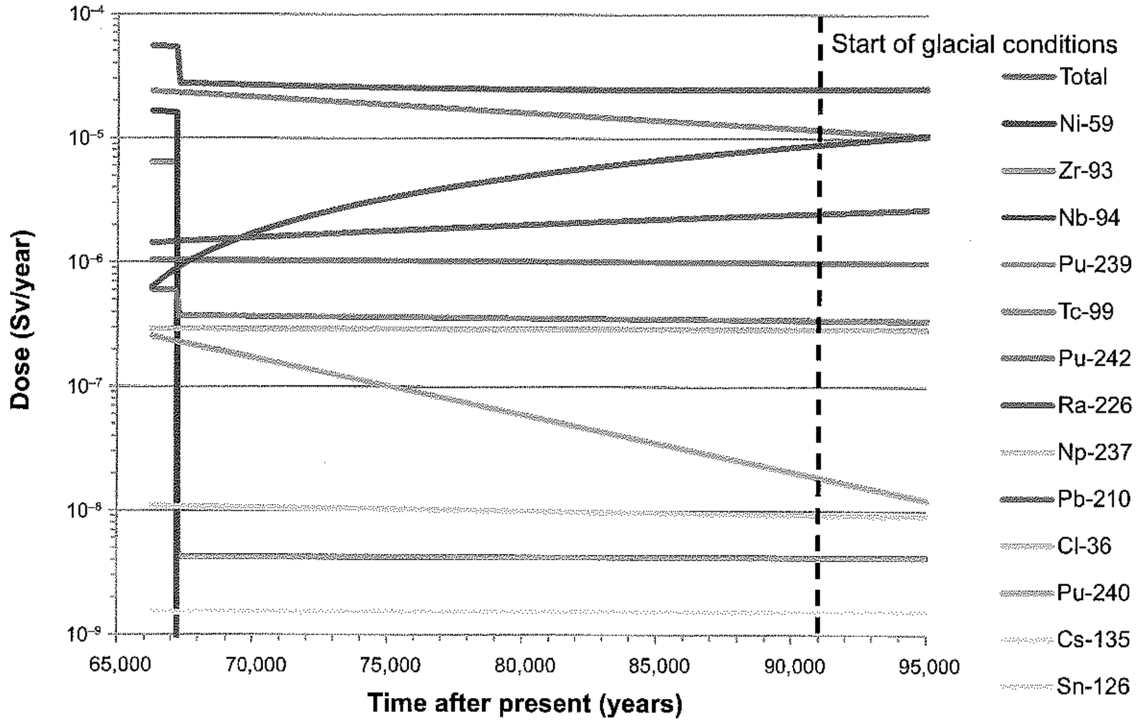

Figure 6-19. *Calculated effective dose from using water in the open shafts and ramp as drinking water and for irrigation.*

The calculated total effective dose during the first 1,000 years after canister failure is 56 μSv/year and the dose is dominated by the intake of food and water contaminated by Pu-239 and by external radiation from Nb-94. Thereafter, the effective dose remains at a fairly constant level of about 25 μSv/year for the remaining period until the start of glacial conditions 90,800 years after present. Over this period, the dose is dominated by the intake of food and water contaminated with Pu-239 and Ra-226.

The calculated effective dose is above the regulatory risk limit of 14 μSv/year during the whole time period analysed, but below the dose of 1 mSv/year from background radiation. The calculated effective dose is obtained for a postulated failure of one canister in the repository during the glacial period prior to 66, 200 years after present. In order to receive an effective dose that is comparable to that received from background radiation, approximately 20 canisters can fail during this period.

6.6.5 Uncertainties

The uncertainties in the analyses of expansion of deposition tunnel backfill are rather large. The friction angle is a function of the swelling pressure and increases with decreasing swelling pressure. The values at low swelling pressure are not well known, but laboratory measurements indicate that the friction angle is higher than 20 degrees at low density and that the lateral stresses (corresponding to the normal stresses towards the rock surface) are higher than the stress in the swelling direction. This means that the resisting force from friction probably is larger than that modelled, which implies that the results probably are pessimistic in the sense that the swelling and thus density loss is smaller than modelled /Åkesson et al. 2010/.

There are a number of uncertainties in the analyses of the impact on groundwater flow of open tunnels in the repository, especially for the simulations with glacial conditions. One important uncertainty relates to the accessibility of water. In reality the flow in an open tunnel below the ice front will probably be limited by the supply of subglacial melt water in the transmissive subglacial layer at the ice-subsurface interface. If the supply of water is insufficient, there will be a drawdown of the pressure and the flow will decrease. In order to give such a high flow as illustrated above, the tunnel entrances have to coincide with a major melt water tunnel under the ice. It should also be noted that the calculations assume a worst case location of the ice front in terms of hydraulic gradient. The

7 Conclusions

This report documents the future human actions, FHA, considered in the long-term safety analysis of a KBS-3 repository. Previous chapters provide an account of general considerations concerning FHA, presents the methodology applied in SR-Site to assess FHA and addresses the aspects of FHA that need to be considered in the evaluation of their impact on a deep geological repository. Finally representative scenarios for illustrative consequence analysis are selected and analysed.

In accordance with ICRP recommendations /ICRP 2000/, intrusion in the post-closure phase of institutional control and beyond is primarily prevented through the design of the repository. In addition to that there will presumably continue to be safeguards measures, preservation of information (record keeping) and possibly some sort of markers placed at the site. Based on generally accepted principles and the Swedish Radiation Safety Authority's, SSM's, regulations concerning safety in connection with the disposal of nuclear material and nuclear waste /SSM 2008a/ and on the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste /SSM 2008b/, the future human actions considered in this part of the safety assessment are restricted to global pollution and actions that:

- are carried out after the sealing of the repository,
- take place at or close to the repository site,
- are unintentional, i.e. are carried out when the location of the repository is unknown, its purpose forgotten or the consequences of the action are unknown,
- impair the safety functions of the repository's barriers.

However, in line with SSM's general guidance /SSM 2008a/, future human actions and their impact on the repository are evaluated separately, and are not included in the main scenario reference evolution or the risk summation.

For the purpose of providing as comprehensive a picture as possible of different human actions that may impact the deep repository as well as their background and purpose, the following systematic approach has been used:

- *Technical analysis:* Identify human actions that may impact the safety functions of the repository and describe and, in technical terms, justify that such actions may occur.
- *Analysis of societal factors:* Identify framework scenarios (framework conditions) that describe feasible societal contexts for future human actions that can affect the radiological safety of a deep repository.
- *Choice of representative cases:* The results of the technical and societal analyses are put together and one or several illustrative cases of future human activities are chosen.
- *Scenario description and consequence analysis of the chosen cases.*

The cases "*Canister penetration by drilling*" and "*Rock facility in the vicinity of the repository*" and "*Mine in the vicinity of the Forsmark site*" were selected as representative cases for scenarios related to a sealed repository. According to regulations, it is also necessary to define and analyse a case that illustrates the consequences of an unsealed repository. Since the repository is gradually excavated and operated, the case selected for analysis is representing an *incompletely sealed repository* rather than an unsealed repository. The following is found:

- The dose rate that a member of the drilling personnel would be exposed to while working in the highly contaminated area can be quite high, but if drilling occurs at c 5,000 years after repository closure, the dose rate has decreased to values below 1 mSv/hour.
- The total dose from using the borehole as a well 300 years after repository closure is below background radiation.