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Radiological consequences of accidents during disposal of spent nuclear fuel in a deep borehole

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Summary

In this report, an analysis of the radiological consequences of potential accidents during disposal of spent nuclear fuel in deep boreholes is presented. The results presented should be seen as coarse estimates of possible radiological consequences of a canister being stuck in a borehole during disposal rather than being the results of a full safety analysis.

In the concept for deep borehole disposal of spent nuclear fuel developed by Sandia National Laboratories, the fuel is assumed to be encapsulated in mild steel canisters and stacked between 3 and 5 km depth in boreholes that are cased with perforated mild steel casing tubes. The canisters are joined together by couplings to form strings of 40 canisters and lowered into the borehole. When a canister string has been emplaced in the borehole, a bridge plug is installed above the string and a 10 metres long concrete plug is cast on top of the bridge plug creating a floor for the disposal of the next sting. In total 10 canister strings, in all 400 canisters, are assumed to be disposed of at between 3 and 5 kilometres depth in one borehole.

An analysis of potential accidents during the disposal operations shows that the potentially worst accident would be that a canister string is stuck above the disposal zone of a borehole and cannot be retrieved. In such a case, the borehole may have to be sealed in the best possible way and abandoned. The consequences of this could be that one or more leaking canisters are stuck in a borehole section with mobile groundwater.

In the case of a leaking canister being stuck in a borehole section with mobile groundwater, the potential radiological consequences are likely to be dominated by the release of the so-called Instant Release Fraction (IRF) of the radionuclide inventory, i.e. the fraction of the radionuclides that as a consequence of the in-core conditions are present in the annulus between the fuel pellets and the cladding or on the grain boundaries of the UO_2 matrix.

The estimated maximum annual effective dose from *one* canister containing one PWR element that leaks due to damages created in conjunction with the accident is 5 mSv, primarily from ^{137}Cs and ^{107m}Ag. For *one* canister containing two BWR elements, the corresponding dose will be slightly less than 4 mSv. These doses are higher than the average background exposure of the Swedish population that amounts to about 3 mSv/year. Damage of multiple canisters will increase dose proportionally.

The Swedish Radiation Safety Authority has issued regulations stipulating that the risk for harmful effects in conjunction with radioactive waste disposal should be less than 10^{-6} per year. This corresponds to an annual effective dose of 1.4×10^{-5} Sv. In order for a facility for disposal in deep boreholes to meet this criterion, the probability of an accident in which one canister containing one PWR element is damaged at the time of the accident must be lower than 0.26%, corresponding to 3×10^{-5} per disposal hole.

In accidents involving damaging of a canister, a need to handle contaminated borehole mud may arise. Calculations in the current study indicate that such contaminated mud should be handled in tanks with extra shielding. It is concluded that necessary preparedness for accidents of the type described above is an obvious point of concern in any future planning of a facility for disposal of spent nuclear fuel in deep boreholes.

Sammanfattning

I denna rapport presenteras en analys av radiologiska konsekvenser av potentiella missöden i samband deponering av använt kärnbränsle i djupa borrhål. De presenterade resultaten ska ses som en grov skattning av möjliga radiologiska konsekvenser orsakade av att en kapsel fastnar i borrhålet under deponeringen och inte som resultatet av en regelrätt säkerhetsanalys.

Det koncept för slutförvaring av använt kärnbränsle som utvecklats av Sandia National Laboratories bygger på inkapsling av det använda kärnbränslet i kapslar av kolstål som sedan staplas på 3–5 km djup i borrhål som försetts med perforerade foderrör av kolstål. Kapslarna kopplas ihop till 40 kapslar långa strängar. När en sådan kapselsträng placerats i sin avsedda position monteras en så kallad bridge plug ovanför strängen varefter en 10 m lång betongpropp gjuts ovan på denna bridge plug. Totalt tio kapselsträngar ryms inom deponeringszonen mellan 3 och 5 km djup i hålet.

En genomgång av möjliga missöden under deponeringen visar att den potentiellt allvarligaste olyckan vore att en kapselsträng fastnar i hålet ovanför deponeringszonen och inte kan återtas. Detta kan leda till att hålet måste förseglas och överges varvid en eller flera läckande kapslar kan sitta fast i en del av borrhålet med rörligt grundvatten.

Om en läckande kapsel sitter fast i en borrhålssektion med rörligt grundvatten kommer de radiologiska konsekvenserna sannolikt att domineras av frigörelse av den del av radionukliderna som återfinns i spalten mellan bränslekutsarna och kapslingsrören eller på korngränserna i bränslekutsarna, den så kallade Instant Release Fraction, IRF.

Den beräknade maximala effektiva årsdosen från *en* kapsel som skadas direkt i samband med att den fastnar i hålet och som innehåller ett PWR-element är 5 mSv, främst från ^{137}Cs och ^{107m}Ag. Om kapseln istället innehåller två BWR-element blir den beräknade dosen knappt 4 mSv. Dessa doser är högre en den genomsnittliga exponeringen av den svenska befolkningen som uppgår till cirka 3 mSv/år. Om flera kapslar skadas så ökar den beräknade dosen proportionellt.

Strålsäkerhetsmyndigheten, SSM, har utfärdat föreskrifter som föreskriver att risken för skadeverkningar i samband med slutförvaring av använt kärnbränsle eller kärnavfall ska vara lägre 10^{-6} per år. Detta svarar mot en maximal årsdos av 1.4×10^{-5} Sv. För att en anläggning för slutförvaring i djupa borrhål ska uppfylla detta kriterium krävs att sannolikheten för det ovan beskrivna missödet är lägre än 0,26% motsvarande to 3×10^{-5} per deponeringshål.

Olyckor som medför att kapslar med använt kärnbränsle skadas i samband med deponeringen kan leda till att kontaminerad borrhålsvätska behöver hanteras. Beräkningar i den föreliggande studien visar att sådan kontaminerad borrhålsvätska bör hanteras i tankar som försetts med extra strålningsskärmning. En slutsats är att nödvändig beredskap för missöden av den typ som beskrivits ovan är en uppenbar fråga att hantera i framtida projekteringar av slutförvaring i djupa borrhål.

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1 Background and introduction

This report aims at a preliminary assessment of the radiological consequences of potential accidents during disposal spent nuclear fuel in deep boreholes. The ambition of the analysis has been to give coarse estimates of possible radiological consequences of a canister getting stuck in a borehole during disposal.

SKB has since the second half of the 1980s performed several studies of disposal of spent nuclear fuel in deep boreholes. A design concept for deep borehole disposal was developed and evaluated against other alternative disposal methods in the Pass project (Birgersson et al. 1992, SKB 1992). This concept has been analysed from different perspectives (e.g. Juhlin and Sandstedt 1989, Juhlin et al. 1998, SKB 2000, Harrison 2000, Smellie 2004, Grundfelt and Wiborgh 2006, Marsic et al. 2006, Grundfelt 2010).

The concept developed in the Pass project included disposal of 50 centimetre diameter canisters containing four BWR or one PWR elements. The disposal holes were assumed to have an 80-centimetre diameter and the canisters were assumed to be emplaced in the hole at between two and four kilometres depth. A weak point of the Pass project concept is the wide borehole, which is beyond the experience of the drilling industry. In more recent studies (Beswick 2008, Odén 2013), a consensus has developed that it would be feasible to drill 5 km deep holes with a diameter of 0.5 metre or less in hard rock, although also this would require additional technology development.

Following the cessation of the US Yucca Mountain programme, Sandia National Laboratories, SNL, has engaged into studies of deep borehole disposal. A concept based on disposal of strings of 40 canisters (~200 metres long) between 3 and 5 kilometres depth (Arnold et al. 2011). In the design preferred by SNL, the borehole diameter is assumed to be 17" (about 43 cm). This limits the size of the canister so that it can host only one fuel element without consolidation of the fuel. In a previous report (Brady et al. 2009) an alternative design including 17½" (44.5 cm) diameter holes was presented. Such a hole would allow a canister that could hold two BWR or one PWR elements. Hence, following the results of these later analyses, SKB has decided to base this study on the borehole diameter 44.5 cm to and apply the borehole construction and operation procedures described by Arnold et al. (2011). The design and procedure is described by Odén (2013).

In Chapter 2 of this report, the conceptual borehole design and disposal procedure is described.
In Chapter 3, an analysis of accident risks and consequences of handling accidents is presented.
In Chapter 4 the results of the accident analysis are presented.

2 Borehole design and disposal procedure

The present study is based on a borehole design and procedures for construction, operation and closure originally proposed by Arnold et al. (2011) but with a 44.5 cm (17½”) borehole diameter (Odén 2013). The extra 0.5-inch borehole diameter allows the use of a slightly larger canister that could host one PWR or two BWR fuel elements without fuel element consolidation. The boreholes should be drilled using directional drilling such that they are straight and vertical with only minor deviations from the vertical directions (<0.5°). The facility design and key dimensions are shown in Figure 2-1 and Table 2-1. The table also shows the number of canisters needed for disposal of the spent fuel from the current Swedish nuclear programme.

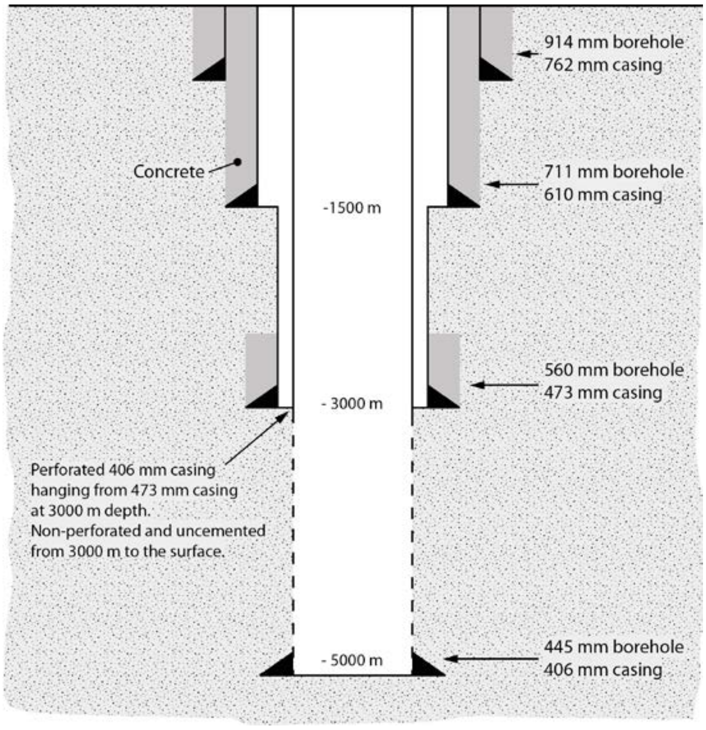

Figure 2-1. *Conceptual design of a facility for disposal of spent nuclear fuel in deep boreholes(not to scale), see Odén (2013).*

Table 2-1. Key dimensions of the deep borehole disposal facility analysed in the current study (Odén 2013).

Design parameter	Value
Borehole diameter in the disposal zone	445 mm
Casing dimensions in the disposal zone	OD=406 mm, ID= 381 mm
Canister outer diameter	340 mm
Canister inner diameter	318 mm
Outer diameter of canister couplings	360 mm
Canister capacity, number of fuel elements	1 PWR or 2 BWR
Number of canisters, BWR fuel+PWR fuel=total	24,010+6,435=30,445

The spent fuel is placed in steel canisters. During disposal strings of 40 canisters are joined together by couplings and lowered to the disposal zone located between three and five kilometres depth using the drilling rig with its drill stem. When a canister string has been emplaced in the hole, a bridge plug is placed above the string and a 10 metres long concrete plug is cast on top of the bridge plug. The concrete plug will then function as the floor of the next canister string. In this way, ten canister strings (400 canisters) can be disposed of in the two kilometres long disposal zone. A facility designed for disposal of all spent fuel from the current Swedish nuclear programme would consist of about 80 deposition holes.

During disposal the borehole is filled with a drilling mud. The casing is perforated in the disposal zone, in order to avoid differential hydrostatic pressure and to ascertain that the drilling mud fills the annulus between the casing and the wall of the borehole. Before each disposal operation, the hole will be monitored with a caliper tool, in order to detect any deformation that might infringe on the possibility for a successful disposal. Also, each canister string will be equipped with a caliper tool at the bottom end so that constrictions in the borehole can be detected.

When all 10 canister strings have been emplaced, a bridge plug is inserted over the last canister string and a 10 metre concrete plug is cast on top of the bridge plug. The borehole is then sealed following a procedure described by Odén (2013). The procedure includes the removal of the portion of the 406 mm casing above the concrete plug and the part of the 473 mm casing above cementation followed by filling the hole with alternating concrete, bentonite, gravel and possibly asphalt plugs (Odén 2013).

3 Potential consequences of handling accidents during disposal

3.1 Accident risks

The construction of the disposal hole involves directional drilling and casing of the hole. This is intended to ascertain that the hole is vertical and without constrictions that would threaten the safety of the disposal operations. In addition, the disposal procedure includes measures for monitoring the conditions of the hole before and during the disposal operations. The borehole design and disposal procedure described in Chapter 2 have been evaluated to be safer than those previously proposed by SKB in the Pass project (Odén 2013). Despite all precautions taken, incidents or accidents cannot be completely ruled out. Table 3-1 presents an analysis of potential events with associated consequences and reasonable mitigating actions (Odén 2013).

The consequences of the event with the potentially most severe radiological consequences, i.e. a canister string gets stuck in the borehole above the disposal zone, can range from completely successful recovery of the canister string without leakage of radioactive material to a complete failure leading to release of radionuclides into the groundwater and subsequent transport to the biosphere, see Figure 3-1.

Table 3-1. Analysis of possible events during disposal of canister strings in deep boreholes. The event that has been judged to potentially have the most severe radiological consequences has been highlighted (Odén 2013).

Event	Consequence, mitigating action	Comment
The canister string is dropped from the drill stem before the canisters have reached their intended position in the hole.	The canisters either continue to their intended position, which would be OK, or get stuck along the route and must be pushed into position.	
An incomplete canister string is dropped before all 40 canisters have been connected.	If the incomplete string reaches the hole bottom, it should be regarded a full string and be locked in by a bridge plug and a concrete plug.	
Failure to release the canister string when it has reached its intended position.	The string should be pulled up to the machine and the coupling between the string and the drill stem be replaced. Alternatively the coupling between the 1st and the 2nd pipe of the drill stem could be replaced by a coupling that could be released.	The alternative including replacement of the coupling between the 1st and the 2nd pipe involves less of a radiation risk as the canister string can be kept in the hole.
The canister string gets stuck above the disposal zone and cannot be released.	Try backing the canisters above the stuck canister and bring them to transportation casks on the surface. Try then to lift the casing with the stuck canister, in order to try to release the canister. Failure to retrieve the stuck canister may necessitate plugging and abandoning the hole.	This is potentially the worst scenario that could require that the hole must be plugged above the stuck canister and abandoned. If the canister is stuck in a borehole section with mobile groundwater, it will result in leakage of radionuclides either because of the canister being damaged during the event or because of canister corrosion.
The canister string is stuck in the disposal zone before reaching its intended position.	Insert a bridge plug and a concrete plug and then continue the disposal in the remaining part of the disposal zone.	This will decrease the capacity of the hole.
Casing displacement.	This should be detected by the caliper tool that is run through the hole before the disposal. If repair fails, the hole should be plugged, sealed and abandoned.	It is very important that the hole is controlled with a caliper tool before each canister string disposal operation.
Deformation of casing due to rock movement or other rock mechanics.	Try opening up the hole with a reamer. If unsuccessful the hole should be plugged, sealed and abandoned.	It is very important that the hole is controlled with a caliper tool before each canister string disposal operation and to utilise the caliper tool at the bottom end of the canister string, in order to avoid stuck canisters.

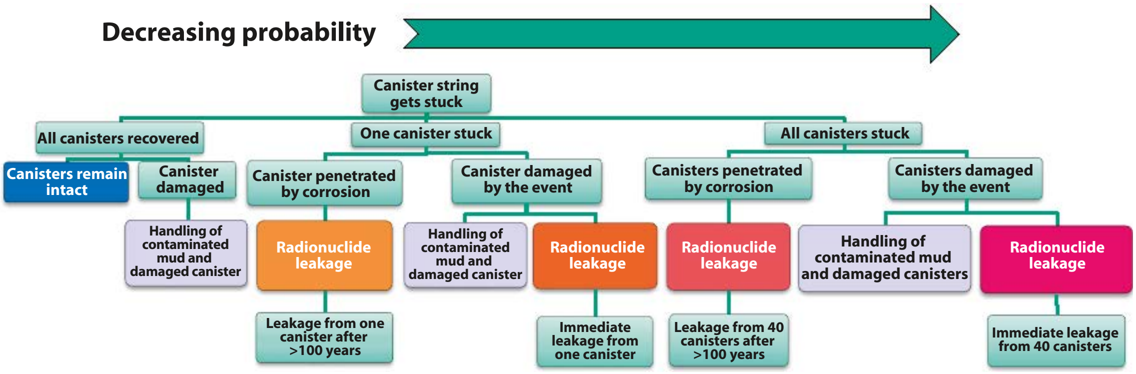

Figure 3-1. *Illustration of the range of consequences from a canister string getting stuck during disposal. The possibility of performing mitigating activities makes more severe consequences less probable.*

3.2 Release of radionuclides from the fuel

When a canister is damaged either direct in a handling accident or because of corrosion, water will enter the canister and there come into contact with the spent fuel. In this study, the consequent release of radionuclides is modelled in the same way as it has been modelled in the safety assessment SR-Site (SKB 2011), which is based on a model developed by Werme et al. (2004). In this model radionuclides contained in the uranium dioxide matrix in the fuel pellets are released at a rate determined by the rate of dissolution or alteration of the uranium dioxide. This process is called fuel conversion. In addition, there is a more rapid dissolution of the portion of the radionuclides that are present in the gap between the fuel pellets and the Zircaloy cladding and of radionuclides that are present on the grain boundaries of the fuel matrix. This portion for each individual nuclide is called the Instant Release Fraction, IRF.

In the SR-Site project as well as in the earlier SR-Can project, a fuel conversion rate of 10^{-7} per year was used. This means that it will take 10,000,000 years to dissolve the fuel matrix. The uncertainty band of this rate was set to one order of magnitude up and one order of magnitude down.

Compared to the time scale considered in safety assessment, the release of the IRF is regarded to be instantaneous. The portion of the nuclide inventory for each nuclide that is present in the IRF varies with the temperature history of the fuel and with the nature of the radionuclides. Thus, volatile radioelements normally have a higher IRF than less volatile elements and the IRF is higher in fuel that has been operated at higher temperature.

For relatively volatile radioelements like iodine, silver and caesium, the IRF is in the order of a few percent of their respective total inventory (SKB 2010a). In PWR fuel, the total inventory of silver is assumed to be included in the IRF as it comes from the control rods disposed together with the fuel (SKB 2010a, c). The fast release of the IRF will for these elements give a much higher release rate to the groundwater than the release by the fuel conversion mechanism. Consequently, for the purpose of this study, it is judged be sufficient to analyse the consequences of the IRF release of radioelements with high IRF inventories. These are primarily caesium, silver, cadmium and iodine. For comparison, also strontium with a significantly lower IRF has been included.

An IRF of 2.5% was used for caesium and iodine for an average canister in the SR-Site study (SKB 2010a). The corresponding value for BWR fuel was 1.9% and for PWR fuel 4.3%. In the current study we have assumed 4% as it cannot be excluded that the stuck canister contains PWR fuel. In a similar way, an IRF of 0.25% has been assigned to strontium. For silver the IRF has been estimated separately for two cases corresponding to a BWR canister and a PWR canister respectively.

In Table 3-2, the inventories of the nuclides ^{90}Sr, ^{108m}Ag, ^{129}I and ^{137}Cs in one canister and their corresponding IRF inventories are shown. For ^{90}Sr, ^{129}I and ^{137}Cs, the canister inventories were calculated as the total inventory in the repository (SKB 2010a) divided by the 30,445 canisters for disposal of the spent fuel from the current Swedish nuclear programme. The uncertainty in these inventory numbers is estimated to be ±15% based on the span of inventories in different canister types assumed in the SR-Site study (SKB 2010a). For ^{108m}Ag, the inventory and the IRF have been given separately for BWR canisters and PWR canisters as they differ significantly between the fuel types.

Table 3-2. Inventory of critical radionuclides in a typical canister and the corresponding IRF inventory.

Nuclide	Inventory year 2045 Bq/canister	IRF Bq/canister
^{90}Sr	5.1×10^{14}	1.3×10^{12}
^{108m}Ag, BWR	4.4×10^{7}	2.1×10^{7}
^{108m}Ag, PWR	3.3×10^{12}	3.3×10^{12}
^{129}I	4.6×10^{8}	1.8×10^{7}
^{137}Cs	$7{,}7\times10^{14}$	3.2×10^{13}

These inventories have been calculated from the average of the inventories of canister types BWR I-III and PWR I-III (SKB 2010a) respectively. When translating the molar inventory of ^{108m}Ag to activity, the half-life was set to 438 years as was recommended for the SR-Site study (SKB 2010a).

In the present study it is assumed that a canister that is stuck in a borehole section will instantaneously release the IRF inventories listed in Table 3-2. This release is judged to represent a predominant part of the total radiation dose from such an event as the release rate from the fuel matrix will be orders of magnitude lower.

3.3 Transport of radionuclides to the surface

If a canister is stuck in a section of the borehole and cannot be retrieved, the borehole section should be isolated to best possible degree. This could include grouting, installation of bentonite plugs, backfilling with asphalt, etc. The optimal design of such measures will be dependent on where in the hole the canister is stuck, how many canisters that have been emplaced in the disposal zone below the stuck canister, geochemical conditions at the site, etc. Although such mitigating measures are likely to retard the radionuclides leached from the fuel in the damaged canister, it is unlikely that they will provide containment of these radionuclides. Hence, it must be assumed that the radionuclides leached from a damaged canister will be transported to the surface by the flowing groundwater. Even if the borehole could be efficiently plugged and sealed, there will still be a transport path through the fractures in the rock.

The transport time to the surface will be completely dependent on the conditions at the site. Based on the experience from site investigations in the past, it is reasonable to assume that the hydraulic conductivity of the rock along the path to the surface will vary in the interval 10^{-9}–10^{-7} m/s and that the hydraulic gradient will be 0.01 or lower. With an effective porosity of the rock of 0.1% this will give transport times between 1 and 1,000 years from a canister at about 300 metres depth to the surface.

Of the radionuclides listed in Table 3-2, ^{108m}Ag and ^{129}I will not decay significantly during the transport to the surface, as their half-lives are longer than the estimated transport times. As the half-lives of ^{90}Sr (28 years) and ^{137}Cs (30 years) are in the same order of magnitude as the transport times, the discharge of these radionuclides to the biosphere may be significantly reduced due to decay during the transport. A transport time of 100 years will reduce the discharge by about a factor of 10 and a transport time of 1,000 years will cause a reduction by a factor 10^{10}–10^{11}.

3.4 Radiological consequences of handling accidents

As described in the previous sections, the consequence of a handling accident in which canisters are stuck in a borehole section with flowing groundwater could be that one or several canisters start to leak radionuclides either directly due to damage caused by the accident or later because the canister is penetrated by corrosion. Moreover, it has been demonstrated above that a predominant part of the radiological consequences will come from fast release of the IRF in the fuel. The radionuclides released in this way will be transported through fractures in the rock surrounding the borehole. The borehole itself may provide an alternative migration path, although the significance of this path could possibly be reduced by appropriate plugging and sealing measures.

As a consequence of the accident, the mud in the borehole and the canister string may become contaminated. As a consequence it may become necessary to handle significant volumes of contaminated mud on the site and to decontaminate canisters.

In the following subsections, simple assessments of the doses to the public resulting from leakage of radionuclides from a damaged canister to the biosphere and estimates of the dose rates on sites from a tank with contaminated mud are presented.

3.4.1 Dose to the public from leaking canisters

In the SR-Site safety assessment, modified Landscape Dose factors (LDF) were estimated for pulse releases (SKB 2010b). Multiplying the modified LDF with the magnitude of the pulse release gives an estimate of the maximum annual dose during the life time of a representative individual in the most exposed group.

Modified LDFs were calculated for ^{108m}Ag and ^{129}I whereas there are no modified LDFs for ^{137}Cs and ^{90}Sr. For the purpose of the present study, modified LDF:s for these nuclides were estimated assuming that the dominant exposure path would be ingestion in direct connection with the discharge, i.e. without significant delay or accumulation in the biosphere compartments contributing most to the dose. The estimates were made by scaling the modified LDF for ^{135}Cs with the committed effective dose per unit intake via ingestion according to Table A in Annex III of the European Basic Safety Standards (Euratom 1996) assuming that the exposed population is adult (>17 years).

Table 3-3 shows the calculated maximum annual effective dose from release of the IRF in a canister that has been stuck in a borehole section with flowing groundwater. The dose has been calculated for a direct release assuming that the canister has been penetrated by damage from the accident and for a delayed release assuming that it takes 100 year to penetrate the canister by corrosion.

It can be seen from the table that ^{137}Cs and ^{108m}Ag are the potentially dose dominant radionuclides. If the stuck canister contains a PWR fuel element and the release is initiated direct at the time of the accident, the calculated dose is about 5 mSv, which is more than the average exposure of the Swedish population of about 3 mSv/year from natural sources, medical examinations and construction material. If the stuck canister contains two BWR fuel elements, the dose from ^{108m}Ag becomes insignificant and, if the release is delayed by 100 years, the calculated dose from ^{137}Cs drops one order of magnitude.

Table 3-3. Calculated annual maximum annual effective dose from a pulse release of the IRF in one canister assuming a groundwater transport time of 100 years.

Nuclide	Scenario	Discharge to the biosphere, Bq	Estimated maximum annual dose, Sv/year
Canister with BWR or PWR fuel			
^{90}Sr	Release direct	1.1×10^{11}	2.8×10^{-4}
	Release after 100 years	9.4×10^{9}	2.4×10^{-5}
^{129}I	Release direct or after 100 years	1.8×10^{7}	1.0×10^{-6}
^{137}Cs	Release direct	3.2×10^{12}	3.7×10^{-3}
	Release after 100 years	3.2×10^{11}	3.7×10^{-4}
In addition for canister with BWR fuel			
^{108m}Ag	Release direct or after 100 years	2.1×10^{7}	1.1×10^{-8}
In addition for canister with PWR fuel			
^{108m}Ag	Release direct or after 100 years	3.3×10^{12}	1.7×10^{-3}

The calculated doses should be compared with the criterion that the risk for harmful effects, i.e. cancer or hereditable effects, should be less than 10^{-6} per year corresponding to an annual effective dose 1.4×10^{-5} Sv (SSM 2008). In order for the facility to meet this risk criterion based on this type of accident only, the probability of an accident in which one PWR canister is damaged in direct connection with the accident must be lower than 0.26% for the whole facility corresponding to about 3×10^{-5} per hole. For an accident in which the PWR canister is penetrated by corrosion, the probability should be less than 0.68% for the whole facility corresponding to 8×10^{-5} per hole. In a similar way the acceptable maximum probability for an accident involving a BWR canister 0.38% if the release is initiated direct at the time of the accident and 3.8% if the canister remains intact for 100 years.

3.4.2 Dose rates from handling contaminated mud

If a canister string gets stuck in the borehole and is damaged in conjunction with this accident, the IRF of the nuclides in the canister will leak into the borehole and contaminate the mud in the hole. The amount of contaminated mud and the distribution of radionuclides in the mud are difficult to estimate as they depend completely on how the accident develops and on the conditions at the site.

In this study it has been assumed that 12 m^3 of mud is contaminated by the IRF of the inventory in one canister and that this mud is collected in a tank on the surface. It has been assumed that the tank is designed to comply with the Swedish regulations for transportation of hazardous goods (MSB 2012). Among other things, this defines the minimum thickness of the tank walls for different tank sizes. For a tank that is wider than 1.8 metres, the wall thickness must be 6 mm or more. In this study, a thickness of 6 mm has been assumed.

The dose rates at different distances from a steel tank containing 12 m^3 mud contaminated with the IRF of the nuclides in one canister has been calculated using the MicroShield® code (version 7, Grove Software Inc.). The resulting dose rates are shown in Figure 3-2. Since the estimate of build-up in this type of calculations normally are somewhat uncertain, the results both with and without the build-up are shown.

The results demonstrate that mud that has been contaminated in an accident of the type analysed here may require handling in extra shielded tanks and/or remote handling. The necessary preparedness for this type of accidents is an obvious point of concern in any future planning of a facility for disposal of spent fuel in deep boreholes.

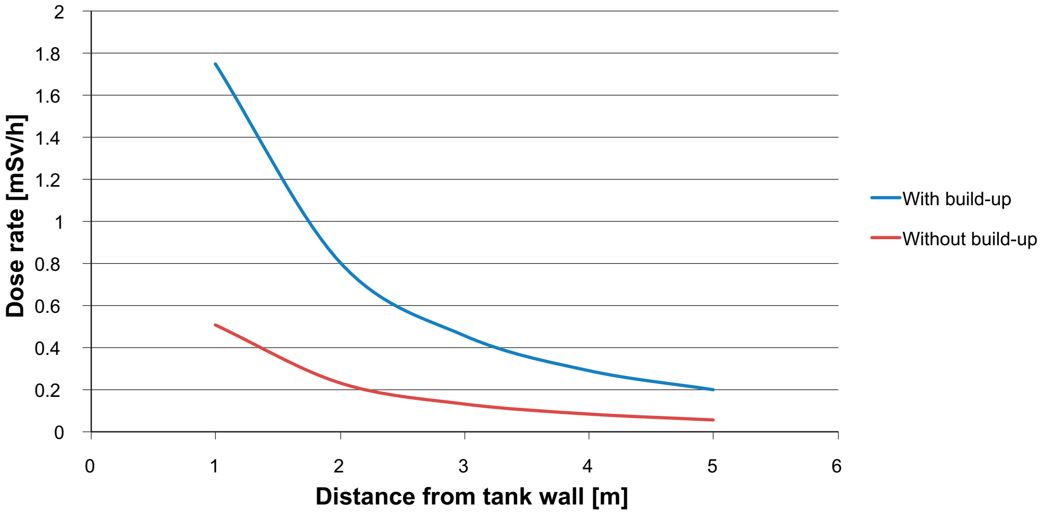

Figure 3-2. *Calculated dose rates as a function of distance from a tank containing 12 m^3 drilling mud contaminated with the IRF of the nuclides in one average canister, see Table 3-2.*

4 Discussion

In this study the potential risks associated with handling accidents during disposal of spent nuclear fuel are analysed. It is concluded that the most severe type of accident is that a canister string is stuck in the borehole before reaching its destination and that one or more canisters are damaged in the accident.

The maximum calculated individual dose is in the order of 5 mSv/year from *one* canister containing one PWR element that is damaged in the accident such that the Instant Release Fraction, IRF, of the radionuclides in the fuel starts to leach directly. This dose is higher than the average dose to a Swedish individual and five times higher than the average dose from natural sources (cosmic radiation, ^{40}K in the body and radionuclides in foodstuff). If the canister is left intact at the time of the accident and corrosion leads to canister penetration after 100 years, this dose is reduced to slightly less than 2 mSv/year. For one stuck canister containing BWR fuel, an accident with direct leaching initiation gives a calculated dose of 3.7 mSv/year. A 100 year delay reduces this dose by a factor of 10. Damage of multiple canisters will increase the calculated dose proportionally.

Although the calculated radiological consequences of a stuck canister accident are not catastrophic, they are significant. In order to meet the risk criterion for disposal of spent fuel set by SSM, the probability for the accident with the highest calculated dose rates must not exceed fractions of a percent for the duration of the site operations. This puts quite stringent requirements on the reliability of the operations.

The accident described may lead to contamination of mud in the borehole, which needs to be handled on the surface and disposed of in a safe mode. Calculated dose rates from the contaminated mud indicate that the mud should be handled in shielded tanks, in order to keep personnel exposure under control.

It can be argued that the modified landscape dose factors are applicable to events in a sealed repository when it remains unknown that a canister has failed, whereas in the present case it is evident that an accident leading to a stuck canister will be known such that mitigating measures can be taken to reduce the dose. It is unlikely that mitigating measures will be such that the radionuclides are contained in the borehole. Instead, the mitigating measures would have to focus on limiting the exposure by administrative means such as prescribing restrictions on the land use in the affected area. Such restrictions would have to be effective over the duration of the potential exposure, which could be several hundred years. It can be concluded that both the potential doses from leaking canisters that are stuck in a borehole section with flowing water, and the radiation field from contaminated borehole mud handled on the site, are of obvious importance in the planning of facilities for disposal of spent nuclear fuel in deep boreholes.

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