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Risk assessment associated to possible concrete degradation of a near surface disposal facility

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Abstract. This article outlines a risk analysis of possible concrete degradation performed in the framework of the preparation of the Safety Report of ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials, for the construction and operation of a near surface disposal facility of category A waste – short-lived low and intermediate level waste – in Dessel. The main degradation mechanism considered is the carbonation of different concrete components over different periods (from the building phase up to 2000 years), which induces corrosion of the rebars. A dedicated methodology mixing risk analysis and numerical modeling of concrete carbonation has been developed to assess the critical risks of the disposal facility at different periods. According to the results obtained, risk mapping was used to assess the impact of carbonation of concrete on the different components at the different stages. The most important risk is related to an extreme situation with complete removal of the earth cover and side embankment.

1 introduction

ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials, is developing a safety concept and a design to dispose category A nuclear wastes (low activity and short-lived medium activity).

The disposal structure is composed of structurally independent concrete modules, in which the disposal waste packages, i.e. the monoliths, will be placed (Fig. 1). In a later stage (phase Ib, cf. Fig. 2), the modules will be covered by a multi-layer cover that aims at minimizing the percolation rate of water to the underneath concrete structure. This multi-layer cover is composed of an impervious top slab and an earth cover.

Several periods and phases are distinguished in the lifetime of the waste disposal facility. The operational phase, named phase I is divided into two sub-phases:

- Phase Ia : the radioactive waste is emplaced in the disposal facility and a steel roof is present to protect the modules from weather conditions (expected duration of 50 years);
- Phase Ib: the steel roof structure is removed and a multi-layer cover is emplaced.

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The closure phase, called phase II, consists of the backfilling and sealing of the inspection rooms and galleries. The post closure control phase is the period following the operational period and consisting of the nuclear regulatory control phase (phase III) and the post nuclear regulatory control phase (phases IV to VI):

- Phase III: during this phase the active monitoring and surveillance of the site will continue.
- Phase IV: during this phase a high degree of isolation of the waste against human intrusion and water infiltration is obtained. This phase will end after about 800 years after the beginning of the operation.
- Phase V: the phase corresponds to the retardation by chemical retention only.
- Phase VI: the phase corresponds to the time frame after the time-horizon "predictability".

The illustration of the different phases and their postulated durations are illustrated in Figure 2.

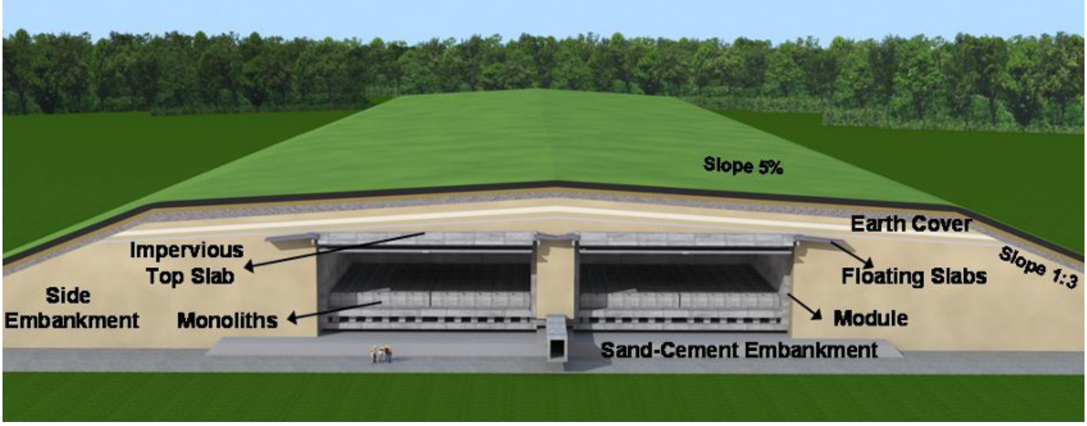

Fig. 1. Disposal facility components after multi-layer cover emplacement.

Operation Phase		**Closure Phase**	**Nuclear Regulatory Control Phase**	**Post-Nuclear Regulatory Control Phase**		
Ia. Operation Phase (Steel Roof)	**Ib. Operation Phase** (Multi Layer Cover)	**II. Closure Phase** (Backfilling)	**III. Nuclear Regulatory Control Phase**	**IV. Isolation Phase** (Water Flow & Human intrusion)	**V. Chemical Containment Phase**	**VI. Post Containment Phase**

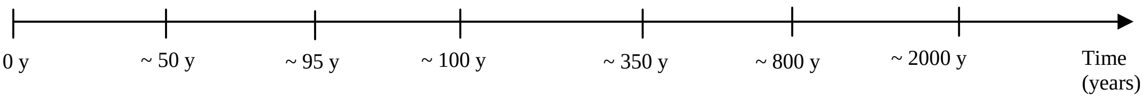

Fig. 2. Postulated time duration of the different phases

This risk analysis will only focus on the safety function "limitation of water through the system (due to the engineered barriers)".

2 Ageing of the different components

The main degradation mechanism of concrete structures which may impact the service life of the different components is considered to be carbonation. Other degradation processes have been discarded by ONDRAF/NIRAS based on a specific formulation of the concrete composition taking into account site environment conditions. Some assumptions are also considered: a sound concrete was assumed (i.e. cracking effects are not considered from the carbonation process itself); a very conservative value of the average humidity of 60% was considered to maximise the carbonation process; and a multi-layer cover staying in a good state for 350 years (to the end of the Nuclear regulatory Control Phase repair can be made if necessary).

Subjects and postulated failure modes associated to ageing have been defined to represent the main phenomena likely to occur. The subjects and associated ageing failure modes considered in this study are summarized in the table 1. They have been defined after a functional analysis of the system and the possible impact of different ageing mechanisms.

Table 1. Subjects and postulated failure modes associated.

Component	Subject	Ageing Failure Mode description	
Monolith	Steel rebars in 6 cm thick areas (localised)	M1	1
	Environmental conditions impact / pouring (Temp. from 5 to 30°C)	M2	2
		M3	3
Module Wall	Removing of formwork at the corner after one day	MW1	2
	Environmental conditions impact / pouring (Temp. + Humidity)	MW2	2
		MW3	3
	No more side embankment after 351 years	MW4	1
Module Foundation Slab	Environmental conditions impact / pouring (Temp. + Humidity)	MFS1	2
		MFS2	3
Module Support Slab	Environmental conditions impact (Temp. + Humidity)	MSS1	2
		MSS2	3
Impervious Top Slab	Reinforced vs. fibrous concrete	ITS1	2
	No more earth cover after 351 years	ITS2	1

1 - Cracking caused by carbonation-induced corrosion
2 - Cracking caused by carbonation-induced corrosion and influenced by shrinkage-induced cracking
3 - Cracking caused by carbonation-induced corrosion and influenced by internal sulfatic reactions cracking

With regards to initial cracking of concrete that can affect the carbonation process, only early age cracking due to autogenous shrinkage is likely to occur considering the design. Internal sulfatic reaction will however also be considered in the calculations.

Autogenous shrinkage, due to structural effects, could lead to crack opening that can locally exceed the limit generally recognised for self-healing (200-300 μm) but which is not uniformly distributed on the structure. On the other hand, internal sulfatic reaction by the means of DEF (Delayed Ettringite Formation), could create more uniformly distributed cracking with openings higher than the limit generally recognised for self-healing. The impact on carbonation would then be more important because it would not be localized.

These considerations of the impact of initial cracking on carbonation-induced corrosion are included in the risk analysis performed in the following paragraphs by the means of a correcting factor F_B.

3 Modelling and parameters

Modules and monoliths rebars and concrete parameters considered in this study are summarized in the table below.

Table 2. Monoliths and modules rebars and concrete parameters considered in the study.

		Monolith	Monolith (localised: corner, ext side)	Module
Rebars	Minimal cover thickness (mm)	40	30	40
	Maximal cover thickness (mm)	45	32	45
	Average cover thickness (mm)	42	31	42
	Steel rebars diameter (mm)	14	8	20
Concrete	Cement content (kg/m^3)	350		
	Characteristic compressive strength fc_{28} (MPa)	40 (design value)		
	Porosity (%)	9,7		

The modeling work performed in this study takes into account the variation of the environmental conditions with time and for the different subjects. The main environmental parameters considered to affect concrete carbonation are temperature, relative humidity and carbon dioxide content.

Table 3 show the minimal, maximal and mean value considered for each parameter and each ageing postulated failure mode (M1, M2, M3 only in this table but the same work has been done for all other components, see Table 1)).

Table 3. Environmental parameters associated to the monolith's ageing failure modes (M1, M2 and M3)

			Distrib. laws Serie 1	Temperature	Distrib. laws Serie 2	Relative Humidity	Distrib. laws Serie 3	CO_2 partial pressure
M1	Steel rebars in 6 cm thick areas	0 - 4 years Module not closed	A1	T_{min} : -5 T_{max} : 30 T_{mean} : 10	A2	HR_{min}: 30% HR_{max}: 80 % HR_{mean} : 60%	A3	$PCO_{2\,min}$: 35 Pa $PCO_{2\,max}$: 44 Pa $PCO_{2\,mean}$: 39 Pa
		4 -2000 years Module closed	No simulation. Carbonation driven by CO_2 amount available in the module.					
M2	Environmental conditions impact (Temp. from 5 to 30°C)	0 - 4 years Module not closed	A1	T_{min} : -5 T_{max} : 30 T_{mean} : 10	A2	HR_{min}: 30% HR_{max}: 80 % HR_{mean} : 60%	A3	$PCO_{2\,min}$: 35 Pa $PCO_{2\,max}$: 44 Pa $PCO_{2\,mean}$: 39 Pa
		4 -2000 years Module closed	No simulation. Carbonation driven by CO_2 amount available in the module.					
M3		0 - 4 years Module not closed	A1	T_{min} : -5 T_{max} : 30 T_{mean} : 10	A2	HR_{min}: 30% HR_{max}: 80 % HR_{mean} : 60%	A3	$PCO_{2\,min}$: 35 Pa $PCO_{2\,max}$: 44 Pa $PCO_{2\,mean}$: 39 Pa
		4-2000 years Module closed	No simulation. Carbonation driven by CO_2 amount available in the module.					

As there are some uncertainties in the different environmental parameters used, a beta distribution law has been associated to every parameter in order to limit its range of variation to physically representative values. The different laws are identified by their names (A1, B1, A2…). The different distributions used are summarized in table 4.

Temperature and humidity values are derived from ONDRAF/NIRAS data or additional assumptions. CO_2 partial pressures values were chosen according to IPCC (Intergovernmental Panel on Climate Change) forecasts and ONDRAF/NIRAS data.

Table 4. Probabilistic distribution law

		Distribution law	Mean	Standard deviation	Coefficient of variation	Maximal value	Minimal value
Temperature [°C]	A1	Beta	10	5	50%	30	-5
	B1	Beta	10	2	20%	19	2.5
	C1	Beta	10	1.5	15%	15	5
Relative Humidity [%]	A2	Beta	60	7	20%	80	30
	B2	Beta	95	3	3%	100	80
CO_2 partial pressure [Pa]	A3	Beta	39	2	5%	44	35
	B3	Beta	49.5	3	6%	57	44
	C3	Beta	500	50	10%	600	400
	D3	Beta	160	20	10%	200	120

4 Calculation cases and modelling

Regarding Tables 3 and 4, it can be noticed that for the different time periods considered, several combinations of temperature, humidity and CO_2 content are the same. Therefore, only four combinations of these parameters (named “Calculation cases”) are necessary to describe every postulated failure mode environment. These different cases are described in Table 5.

Table 5. Calculation cases definitions with temperature, relative humidity and CO_2 partial pressure

Cases	Temperature	Relative Humidity	CO_2 partial pressure
Case 1	A1	A2	A3
Case 2	B1	A2	B3
Case 3	C1	B2	C3
Case 4	B1	A2	D3

To determine concrete carbonation considering the different ageing failure modes with time, the calculation cases corresponding to the environmental conditions are combined. The modeling of the different failures modes related to ageing (see Table 1) can be represented by 7 different models. Table 6 synthesizes these models, the corresponding postulated failure modes and the time sequence of the different cases involved.

Table 6. Definition of modelling and associated failure modes and cases

	Ageing failure modes	0 – 4 y	4 – 50 y	50 – 80 y	80 – 350 y	350 – 2000 y
Mod1	M1	Case 1	No more CO_2			
Mod2	M2, M3, MSS1, MSS2	Case 1	No more CO_2			
Mod3	MW1, MW2, MW3	Case 2		Case 3		
Mod4	MW4	Case 2		Case 3		Case 5
Mod5	MFS1, MFS2	No more CO_2				
Mod6	ITS1	Before construction		Case 3		
Mod7	ITS2	Before construction		Case 3		Case 5

5 Modelling results

A probabilistic approach has been used to assess the time evolution of the carbonation front in concrete elements by Monte Carlo simulations. The probability for the carbonation front to be greater than the concrete cover represents the end of the initiation period and the possible start of corrosion along rebars. The results obtained for the model Mod7 is illustrated in the following figure:

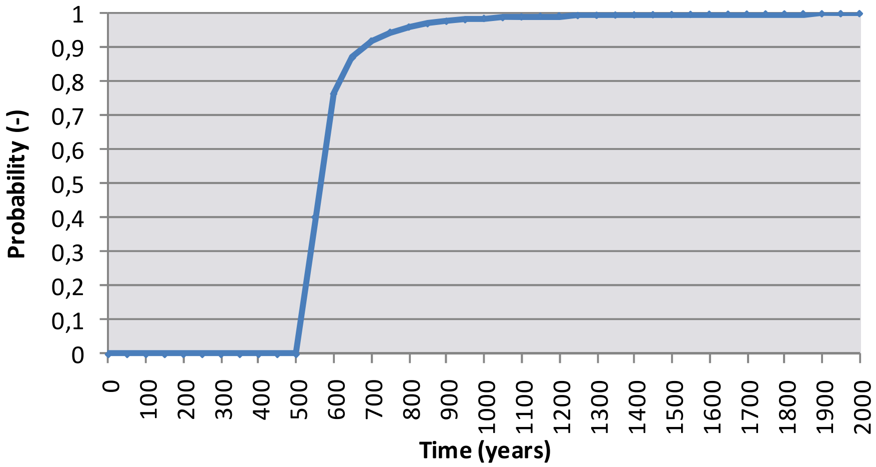

Fig. 3. Probability of corrosion initiation vs. time for modeling Mod 7

The model used for the simulations has been developed by Hyvert et al. (1) and (2). This model has been chosen as it allows the effect of environmental parameters such as CO_2 partial pressure to be considered in an analytical model allowing Monte Carlo simulations over the required timeframe.

6 Risk analysis

A risk analysis framework provides consistent, comparable and reliable results of risk assessment as a result of a transparent and structured methodology. The results allow highlighting the most critical failure modes of the system according to different criteria and the prioritization of the recommendations likely to decrease the risk (risk management). The risks are estimated by means of the following parameters:

- Severity of a thread on the components in respect of their safety function (limitation of water flow)
- Frequency of a thread (probability of occurrence).

Risk estimation results in the establishment of a risk mapping. Each risk is plotted by means of its criticality value, representing the severity level of a threat vs. the frequency of this threat.

6.1 Frequency

The frequency scale is qualitative and helps to compare the different threads on the same reference. The frequency F is defined by:

- The frequency of occurrence F_A of the failure modes subject,
- The frequency F_B representing the early age cracking effect,
- The frequency F_C of carbonation induced corrosion initiation.

$$F = 2 (F_A + F_C) + F_B \tag{1}$$

Considering the fact that the early age cracking will be very low (to be further investigated by phenomenological studies) and followed by quality control during the building phase, it has been chosen to decrease its frequency influence F_B on the global frequency compared to F_A and F_C.
The following paragraphs present the indexes levels and the assessment methodology.

Frequency level of occurrence from the failure modes subjects - F_A

F_A levels represent the level of occurrence from each subject (cf. Table 1). Frequency levels F_A are defined by 4 levels as described in table 7. For example, high pouring temperature on a 12 cm thick monolith concrete wall is less probable than high pouring temperature on module concrete that are 70 cm thick. These factors are identified for each failure modes subject of table 1.

Table 7. F_A Frequency grid

Description	**F_A**
Very improbable, never observed	1
Improbable, never observed but dreaded	2
Probable, already observed	3
Almost certain	4

Table 8. F_B grid

Initial cracking considered	**F_B**
No initial cracking	0
Initial cracking due to shrinkage	1
Initial cracking due to internal sulfatic reaction	2

Frequency level of the initial cracking – F_B

The frequency F_B represents the level of occurrence of an initial cracking, caused by shrinkage and internal sulfatic reaction. It is really hard to compare cracking caused by shrinkage and internal sulfatic attack because those phenomena have very different origins and effects. However, to define the F_B indexes, the assumption is made that internal sulfatic reaction cracking is more critical than initial shrinkage cracking (in most cases, crack opening is higher when caused by internal sulfatic attack). This is a very conservative assumption because, as already mentioned, the internal sulfatic reaction is not expected to occur due to the design choices. Table 8 represents the different FB values considered for the different failure modes.

Frequency level of carbonation-induced corrosion initiation – F_C

F_C level represents the level of occurrence of carbonation-induced corrosion initiation considering the different modelling. For each time period considered (350, 500, 800 and 2000 years) during the risk analysis, a frequency level F_C is estimated for each model. Then, each risk is characterized by 4 frequency notes: F_C 350y, F_C 500y, F_C 800y and F_C 2000y. Frequency levels $F_C(t)$ are defined by 4 levels as described on Table 9 and Figure 4.

Table 9. FC Frequency grid (at time t)

Description	F_C
Probability that carbonation depth reaches the rebars lower than 0.10	1
Probability that carbonation depth reaches the rebars between 0.10 and 0.30	2
Probability that carbonation depth reaches the rebars between 0.30 and 0.50	3
Probability that carbonation depth reaches the rebars higher than 0.50	4

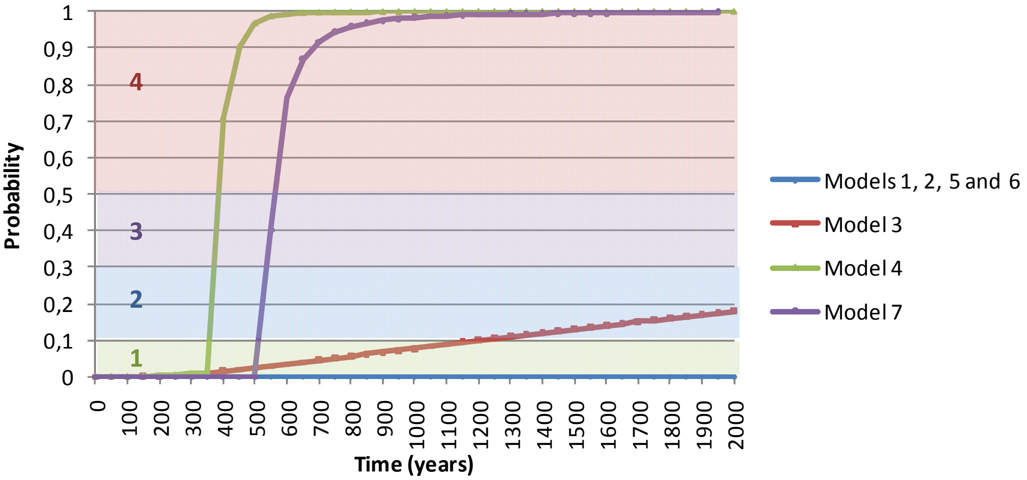

Fig. 4. F_C levels definition

6.2 Severity

Severity levels are defined by 4 levels, as described in Table 10, and are related to the safety function “limitation of the water flow”. The severity levels take into account the component considered and its role into the system regarding this safety function (low or high consequences if a failure occurs). The maximum severity according to different stakes (localized, extended or global impact on the safety function) is considered.

Table 10. Severity grid for the safety function “limitation of water flow”

	Localized impact	**Extended impact**	**Global impact**
Monolith	1	2	2
Module wall	2	3	4
Module support slab	1	1	1
Module foundation slab	2	3	4
Impervious Top Slab	2	3	4

6.3 Criticality

The frequency and severity ratings are combined to give a global score for each risk (i.e. criticality level) that is able to compare the relative importance of each risk. The global frequency indexes (given by equation (1)) are ranged between 4 and 18. The severity indexes are ranged between 1 and 4. To give the same weight to frequency and severity, it has been chosen to weight by 4 the severity indexes. So the criticality index is given by the following relation:

$$C = F * 4S=[2*(F_A + F_C) + F_B] * 4S \qquad (2)$$

The possible criticality values are between 16 and 288. Those values have no signification by themselves; they just help to compare the criticality of the different failures modes through the same reference system. In order to make a relative and not absolute comparison, the criticality domain is split in 4 levels, from the less to the most critical.

7 Results

This methodology of criticality calculation has been applied to each component for each ageing failure mode and each time period according to the previous results for F_A, F_B and F_C. According to the calculations and all the conservative assumptions made, the results show that there is no critical risk (i.e. ranked 4) related to the safety function of limiting the water flow whatever the time period considered. After 350 years, there are only two risks ranked 3. They are related to:

- the module wall in the case of complete removal of side embankment after 350 years (no risk related to carbonation-induced corrosion before this date);
- the impervious top slab in case of complete removal of the earth cover: no risk related to corrosion-induced corrosion before 800 years.

Some minor risks (ranked 2) are related to module wall and module foundation slab in the case of early age cracking related to internal sulfatic attack. Another minor risk is evaluated to be the removal of the formwork resulting in early age cracking related to concrete shrinkage.

Finally, the following synthesis regarding the impact of cracking on the risk of corrosion induced by carbonation can be made:

- for all components: no critical risk detected during the period 0-2000 years; minor risk before 350 years related to the removal of the formwork for the module wall (localized cracking due to concrete shrinkage): this risk can be avoided by an appropriate quality control during building and visual inspection of the disposal facility;

- minor risk before 350 years related to environmental conditions for module wall and foundation slab (extended cracking due to internal sulfatic attack): this risk is avoided by the concrete formulation (this was confirmed by a large-scale demonstration test performed by ONDRAF/NIRAS);
- lower risks related to embankment or earth cover removal are not present before 350 years. This risk can be avoided by an appropriate survey of the disposal facility.

8 Conclusions

The methodology of risk analysis performed on the facility design made by ONDRAF/NIRAS to dispose category A nuclear wastes (low activity and short-lived medium activity) showed that there is no critical risk arising from carbonation-induced corrosion considering possible early age cracking induced by concrete shrinkage and internal sulfate attack. Moreover, appropriate measures can be taken to manage the remaining lower severity risks. The use in this study of a risk analysis methodology coupled with an aging approach showed that it is possible to assess the risk evolution on a common framework for the different components at the most important periods of the system considered.

References

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