Modeling of radionuclide migration through the geologic media. Application to the Meuse/Haute-Marne site in France

A.K. de Hoyos, G. Mathieu
IRSN (Institut de Radioprotection et de Sûreté Nucléaire)
DSU/SSD/BECS, B.P.17, 92262 Fontenay-aux-Roses Cedex
France

P.P. Viennot
Ecole des Mines de Paris
Centre de Géosciences, 35 rue Saint Honoré, 77305 Fontainebleau Cedex
France

ABSTRACT

In order to review ANDRA’s modeling of a deep geological disposal of HLW in a clay formation located in the Meuse/Haute Marne area, IRSN has developed its own modeling methodology, based on three numerical models. A first “host rock model”, including a simplified repository design, is used to simulate the activity transport throughout the repository and the argillite host layer. The model aims at evaluating the role of components of the repository design, together with the host formation, on the activity transport. Then, a second “hydrogeological model”, set on hydrodynamic parameters measured in situ, allows the determination of possible water pathways, outlets and associated transfer times taking into account the possible hydraulic role of identified or postulated tectonic structures in the vicinity of the site. Several possible combinations for the hydraulic parameters (hydraulic conductivities and transmissivities) allow to fit the in situ measured hydraulic heads. The “hydrogeological model” is finally coupled with a radionuclide “transport model”, devoted to simulate the transport of radionuclides out of the host rock to the outlets. Considering the uncertainties related to both advection and diffusion processes in the aquifers, a sensitivity analysis is carried out in order to assess its influence on the activity transport through the different layers above the host formation. Two specific outlets are considered: at the ground surface, a “natural” outlet above the location of the repository system, and in the host rock’s overlying aquifer, in a “well drilling” zone. It is shown that the activity reaching the “natural” outlet is mainly governed by diffusive fluxes whereas the activity reaching the “well drilling” zone depends on the advective properties of the fault zones. The lesson learnt from this modeling is that the diffusion regime needs to be better quantified in order to discriminate the respective influence of both outlets.

INTRODUCTION

The French Institute for Radioprotection and Nuclear Safety (IRSN) has assessed the elements relating to the feasibility of a repository for high-level and long-lived radioactive waste in the

deep geological formation of the "Meuse/Haute-Marne" site presented by ANDRA[1] in the "*Dossier 2005 Clay*". This site, that comprises the Callovo-Oxfordian clay formation, studied by means of the Bure underground research laboratory, is located in the Eastern part of the parisian sedimentary basin. IRSN has in particular analysed the assumptions and models used by ANDRA to estimate the release and migration of the radionuclides contained in the waste packages. This analysis was performed on the basis of IRSN's own models devoted to simulate the transfer of radionuclides from the repository to the surface outlets. IRSN has specially developed a groundwater flow model, fitting the hydrodynamic parameters measured in situ, in order to localise the potential radionuclide outlets and estimate the transfer times to these outlets. This hydrogeological model is coupled with a radionuclide transport model allowing the evaluation of activity release of radionuclides at the outlets.
The first section presents the base data and construction of the flow and transport models. The second section deals with the assumptions used to calibrate the groundwater flow model and the third section presents the results of the radionuclide transport simulation. Conclusions and perspectives are drawn in the last section.

Model data and construction

The simulations of groundwater flow and radionuclide transport are based on three separate but inter-related models.

Radionuclide transport model in the host formation

The groundwater flows within the homogeneous host formation at the laboratory scale are mainly diffusive, because the upward vertical hydraulic gradient (0.2 m/m) and the average hydraulic conductivity are too low to constitute a dominant advective flow throughout the clayey formation.
Radionuclide transfer within the host formation was modelled using the MELODIE[2] code [1], developed by IRSN in cooperation with the Paris School of Mines and the University of Pau. MELODIE is a computer code aiming at modeling the transfer of radionuclides in geological formations, from the waste packages to the biosphere outlets.
A numerical model of the repository itself has been developed. It represents the repository components in the Callovo-Oxfordian host formation, and allows an estimation of the molar flow rates throughout these components, to the main transfer paths considered (host formation and access shaft). In the design presented by ANDRA, each main category of waste package (cemented waste packages, vitrified waste packages and spent fuel) is disposed of in a dedicated area. Each area is independent of the other. In the present study, only the spent fuel (UOX)

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[1] National radioactive waste management agency

[2] The mathematical model is based on the assumption of an equivalent continuous porous medium. The physical processes modelled are: water flow according to Darcy's law, convective/diffusive transport of radionuclides taking account of radioactive decay and filtration, and transport delay due to the sorption of radionuclides. IRSN has also developed in the MELODIE code a method of parallelisation based on "domain decomposition" to allow the code to be used for large-scale grids.

disposal area is modelled. Radionuclide releases from this area are assumed to be envelope of those from other waste packages, considering in particular the amount of I-129 activity, and that a part of the radioactive inventory is instantaneously released when the canister is breached. The inventory has also been maximised by assuming that processing of spent fuel will stop as from 2010.

Repository design

The numerical model incorporates ANDRA’s main assumptions [2] (radiological inventories, activity release kinetics, chemical and hydraulic properties of the different components and of the host formation) and the general principles of repository architecture defined by ANDRA for the disposal of spent fuel [3] (dimensions of the repository components, dead-end disposal tunnels, grouping of tunnels in modules, sealing of access drifts between the disposal tunnels and the access shaft). The tunnels hold 3 or 4 spent fuel containers. The repository is located in the middle of the Callovo-Oxfordian formation, on a single level to maintain an approximately 65 m thickness of undisturbed argillite above and below.

The drilling of the tunnels mechanically damages the rock around the excavations: this zone is called EDZ (Excavation Damaged Zone). The radial extent of the EDZ is assumed to be proportional to the excavation diameter and depends on the stress field in the geological layer. It constitutes a more permeable and diffusive medium than the originally "undisturbed" rock. Potentially favourable to water flowing, this zone is locally interrupted by the mean of seals in order to prevent flow, and to maintain a mainly diffusive radionuclide transport mechanism in the vicinity of the tunnels. Preliminary calculations focused on flow and radionuclide transport modeling in the vicinity of disposal tunnels (not presented here) have shown that the radionuclide migration regime out of the tunnels is dominated by diffusion, even when tunnels and drifts are not properly sealed [4]. It is the reason why the computer model of the spent fuel disposal area has been simplified, considering all the disposal tunnels as a homogeneous medium without representing all the different components. An engineered barrier made of rings is placed around the waste packages in the disposal tunnel. The disposal tunnels are linked by handling drifts and grouped into disposal modules. The bentonite seals are placed in the handling drifts and in the access drifts. Finally, the access drift is connected to the surface via an access shaft. The disposal area modelled represents a surface area of 5.2 km^2 within the Callovo-Oxfordian formation which has a constant thickness of 130 m. The mesh representing the spent fuel repository consists of 6.75 million tetrahedrons, 1.25 million computational nodes and 9 computation domains (multi-domain approach used to calculate flow and transport).

Repository evolution scenarios

The repository evolution scenarios have been defined in order to estimate the confinement capacities of the repository under different operational and environmental conditions. Two scenarios are thus considered in the present study. One, the so-called normal evolution scenario (NES), considers that components perform as they have been specified. The second scenario named "altered" evolution scenario (AES) assumes that drifts are not properly sealed. The aim of this scenario is to assess the influence, on radionuclide transfer, of the failure of the narrow bentonite-filled trench[3] supposed to interrupt the damaged zone.

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[3] The filled-trench is a part of the bentonite sealing and replaces locally the EDZ for hydraulically isolating the EDZ.

Radionuclides considered in the spent fuel release model

The radionuclides considered for the simulations are I-129, Se-79 and Cl-36 because of their high amount of activity in the waste packages. They are not sorbed in clayey materials and their half-life is sufficiently long compared to the transfer times through the Callovo-Oxfordian[4]. However, Se-79 may be solubility limited. The waste package release model for these radionuclides comprises an "IRF"[5] fraction that is instantly released (approximately 10 % of the inventory) and two other fractions of the inventory that are gradually released as both Uranium oxide pellets and the metallic parts in contact with water dissolve.

Hydrogeological model

In order to simulate the transfer of radionuclides from the Callovo-Oxfordian host formation to the outlets, a groundwater flow model, including the various sedimentary layers surrounding the host formation, was first built. This model is the result of a seven-year collaboration between IRSN and the *Geosciences Center* of the *Paris School of Mines*. The computer code used, called NEWSAM, was developed by the *Paris School of Mines*, and has incorporated the knowledge developed by the site characterisation as well as the remaining questions raised by the long term safety assessment. NEWSAM is a computer code for simulating groundwater flow in sedimentary hydrogeological systems, consisting of alternating aquifers[6] and semi-permeable layers[7].

Model Extension and hydrodynamic parameters used

This hydrogeological model was produced using a multi-layer 3D model designed to simulate the underground water flow throughout the Paris sedimentary basin. The hydraulic properties[8] introduced in the model are essentially found in literature as well as in a hydrodynamic database of the Paris basin (called BPDATA[9] [5]), established by IRSN since 1998. These hydrodynamic parameters were then re-evaluated during the model calibration phase, which consisted in matching the computed hydraulic heads as closely as possible with those measured in the boreholes by ANDRA [6]. This was done by selecting the parameters of each layer of the model consistently with the on site measurements as well as the available literature data or the litho-stratigraphic nature of the formations.

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[4] The transfer time for the anions is 1 300 000 years and for the cations 100 000 years.

[5] Instantaneously Released Fraction. Part of the inventory released immediately upon arrival of water after corrosion of the container

[6] Permeable water-bearing formation capable of yielding exploitable quantities of water.

[7] Geological stratum of low hydraulic conductivity (=aptitude of a medium to allow a fluid to pass), in which large volumes of water cannot be collected, but through which significant transfers of water from adjacent aquifers can occur by leakage.

[8] Physical parameters quantitatively defining the behaviour of a conducting medium or body with respect to the fluid.

[9] Data from petrol or gas wells, geothermal wells and water supply wells, springs, ANDRA test bores, theses, as well as water sample analyses (chemical and isotopic compositions).

Uncertainty concerning fracturing

The repository area will be located some kilometers away from major faults (multi-kilometric). However, uncertainties remain concerning both the presence and the hydraulic role of tectonic structures in the vicinity of the repository. The influence of tectonic structures is a key question of the safety evaluation because they may have potential for locally leading to a channelling of flows through the different sedimentary beds and govern the outlet positions, transfer times and dilution of the radionuclides. The tectonic structures taken into account in the model have been identified from a map of the main faults in the Paris basin [7]. Detailed mapping has also been carried out by ANDRA near the Bure laboratory in order to better understand the tectonics of the Meuse/Haute-Marne site. IRSN has in addition carried out its own study by producing a map of the different fracturing scales based on data obtained from DEM[10], investigations by 2D seismic profiles, boreholes and a field tectonic analysis of the site.

Radionuclide transport model from the host formation to the biosphere

The model of transport in the sedimentary layers overlying the Callovo-Oxfordian at the Meuse/Haute-Marne site incorporates parts of the hydrogeological model presented in the previous chapter (see Table II). Based on the MELODIE code, it aims at simulating the radionuclide transfer times and concentrations from the top of the host formation to the surface outlets.

For these calculations, the extension of the model has been reduced compared to the hydrogeological model which covers the entire Paris basin. It is centred on the Meuse/Haute-Marne site and provides more detailed results in that area.

The hydraulic boundary conditions and the hydrodynamic parameters used for the transport model are consistent with the data and the results of the hydrogeological model calibration. Horizontally, the model is discretised with cells of 1 km length, the grid extending approximately 90 km from East to West and from North to South. This extension aims to integrate the possible groundwater outlets (faults/rivers), as well as the main aquifers’ recharge zones (outcrops of the different formations to the East and the South of the site). The thicknesses of the different geological layers of this model have been assigned using ANDRA’s borehole data [6]. Vertically, the model is made of 23 layers (see Table I).

Table I. Vertical discretisation of the transport model

	FORMATION		**TYPE**	
Transport Model extension	Layer 1	PORTLANDIAN (1 layer)	Aquifer	**Hydrogeological Model extension**
	Layers 2 to 6	KIMMERIDGIAN (5 layers)	Alternation of aquifers and semi-permeable layers	

[10] Digital Elevation Model

	Layers 7 to 23	OXFORDIAN (17 layers)		Alternation of aquifers and semi-permeable layers	
Host Formation Model		CALLOVO-OXFORDIAN		Semi-permeable	
		DOGGER	BATHONIAN	Aquifer	
			M.A.O.	Semi-permeable	
			BAJOCIAN	Aquifer	
		LIAS		Semi-permeable	
		RHETIAN		Aquifer	
		KEUPER		Semi-permeable	
		MUSCHELKALK		Aquifer	
		BUNTSANDSTEIN		Aquifer	

Hydrogeological model flow calibration

The calibrated hydrogeological model yields a correct representation of the various hydraulic heads and geochemical measurements (in particular the salinity of the water) obtained throughout the Paris basin [6].

However, only a few hydraulic head measurements for calibrating the model at the Meuse/Haute-Marne site are available. Hence, several flow models, with comparable calibration accuracy (in terms of average error between measured and simulated hydraulic heads) are able to correctly reproduce the measured values. Therefore, in order to discriminate between the proposed models, an additional analysis is required. Among these various models, some give the tectonic structures a hydraulic role[11] while others do not.

When no structure plays a hydraulic role, calibrating the heads (piezometric level) in the Oxfordian and Dogger formations requires a limitation of flow exchanges between these two aquifers through the Callovo-Oxfordian formation. This in turn requires to consider significantly increased hydraulic conductivity values for the Dogger formation in the vicinity of the Meuse/Haute-Marne site. While this hypothesis allows for calculating hydraulic levels that are consistent with the measured values, the hydrodynamic parameters used are not plausible, as the low hydraulic conductivity values measured by ANDRA [6] are not consistent with the high values introduced into the model. A different approach has thus been adopted that aimed at assigning a hydraulic role to the structures that were explicitly mapped or suspected within the repository area.

According to this approach, several new hydraulic models can still be proposed. Two models in particular, which use different hypotheses but are geologically plausible and give a satisfactory fitting of measured data, are discussed below. The faults transmissivities applied to the Oxfordian and the Callovo-Oxfordian formations are identical in both models. The difference

[11] In the model, these structures are either large faults at the Parisian Basin scale, or less extensive faults in the repository area.

lies in the underlying Dogger aquifer. In case no. 1, a very low matrix hydraulic conductivity is imposed within the formation. Associated with this overall hydraulic conductivity is a network of local faults of high fracture transmissivity (in particular a fault located NW-SE along the axis of a river called Saulx), and relatively high hydraulic transfers through the major structural discontinuities in the sector. Case no. 2 assumes a different arrangement of transmissivity values for the smaller faults (few kilometres or less), in particular a lower transmissivity in the Dogger formation beneath the Saulx river. This calibration then requires an extent of the transmissive zone in lower Dogger outcrops, and the definition of an area of lower hydraulic conductivity within the East part of the repository area. For IRSN, the modification of the lower Dogger outcrop area is consistent with field observations that show this formation to be more karstified[12] where it outcrops than does the rest of Dogger formation.

Case no. 1 and case no. 2 satisfactorily reproduce the hydraulic heads measured in the Oxfordian and the Dogger aquifers using parameters that are consistent with those obtained from site investigations. Fig. 1 shows the computed and measured hydraulic heads for the Oxfordian and Dogger aquifers, for both cases. In the repository area, the average fitting accuracy is less than 2 m in the Oxfordian for both models. In the Dogger formation (Bathonian), the difference between the computed and the measured values is 0.2 m for the first case and 2.4 m for the second one.

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[12] When they outcrop, limestone formations are often subject to karstification. This is due to limestone weathering in contact with the air that makes it much more permeable.

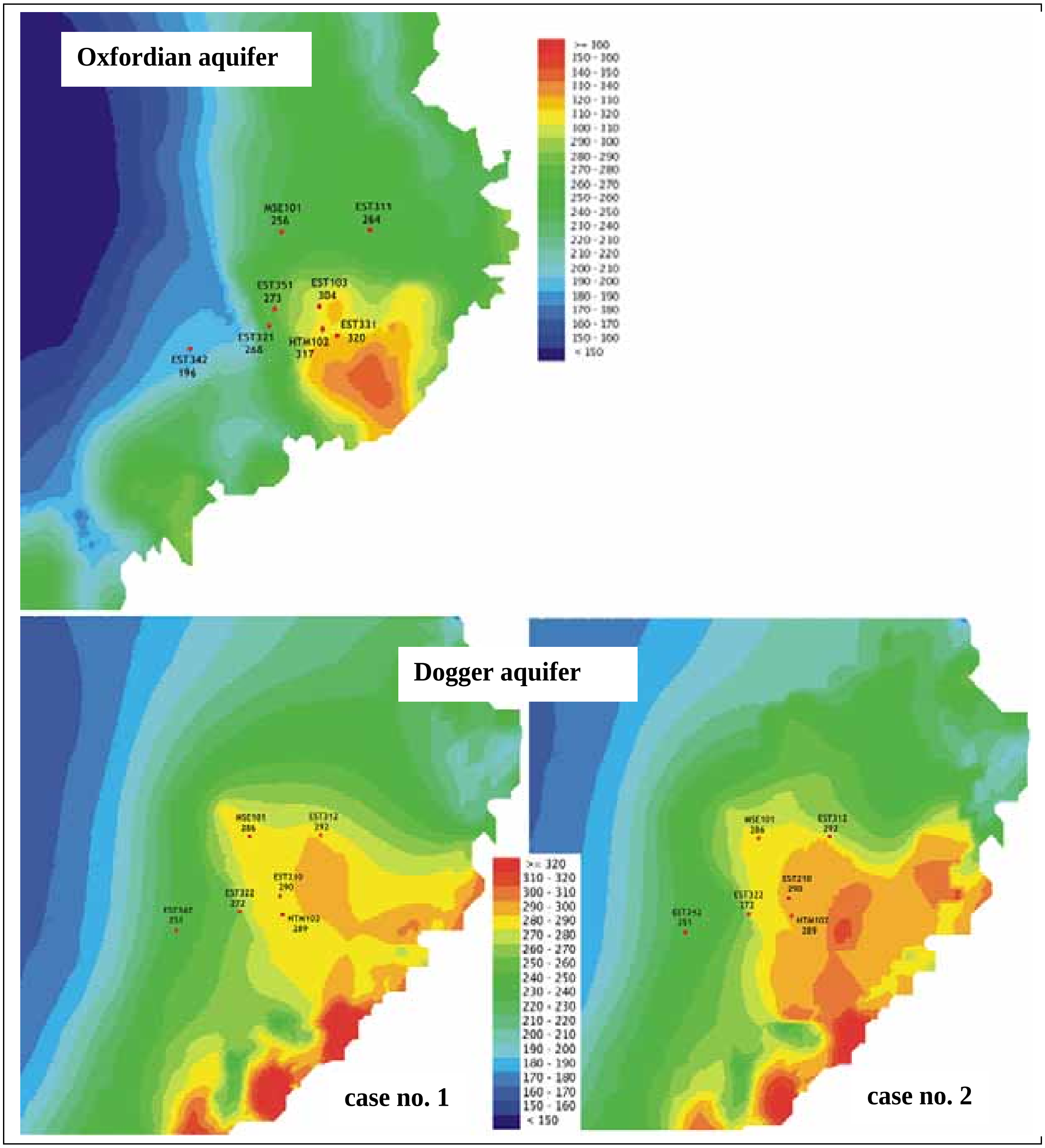

Fig. 1. Computed head values (colors) and measured head values (red dots) for the Oxfordian and the Bathonian aquifer, in case no. 1 and case no. 2.

Case no. 1, which is in theory more pessimistic (the faults are more transmissive), has been chosen to simulate the transport of radionuclides from the top of the host Callovo-Oxfordian formation to the biosphere outlets.

Results of radionuclide transport simulations

Radionuclide transfer through the host formation and the repository system

Given that the values of flow rate in the host formation are extremely low (0.4 µm/year) due to the very low hydraulic conductivity of the Callovo-Oxfordian formation (hydraulic conductivity between 5×10^{-13} and 5×10^{-14} m/s), the dominant radionuclide transfer regime through the homogeneous host formation is diffusion. Within the drifts, flow rates are by one or two orders of magnitude higher depending on seal performance. In the unfavourable case of a not properly sealed repository (AES), the flow rate values in the tunnels still remain low (of the order of 5 mm/a). These low flow rates are notably due to the limited amount of water inflow due to the low hydraulic conductivity of the Callovo-Oxfordian formation and the dead-end disposal tunnel architecture. The significant length of the connecting drifts also contributes to the reduction of hydraulic gradients between the disposal tunnels and the shaft, and the diffusion of activity plumes to the clay layer through the contact surfaces between the drifts and the host formation. These features thus limit the flows of radionuclides towards the access shaft. Fig. 2 shows the molar flow rate out of the shaft and the Callovo-Oxfordian formation (top and bottom[13]), for the I-129. For both scenarios (NES and AES), the upward gradient is set at 0.2 m/m.

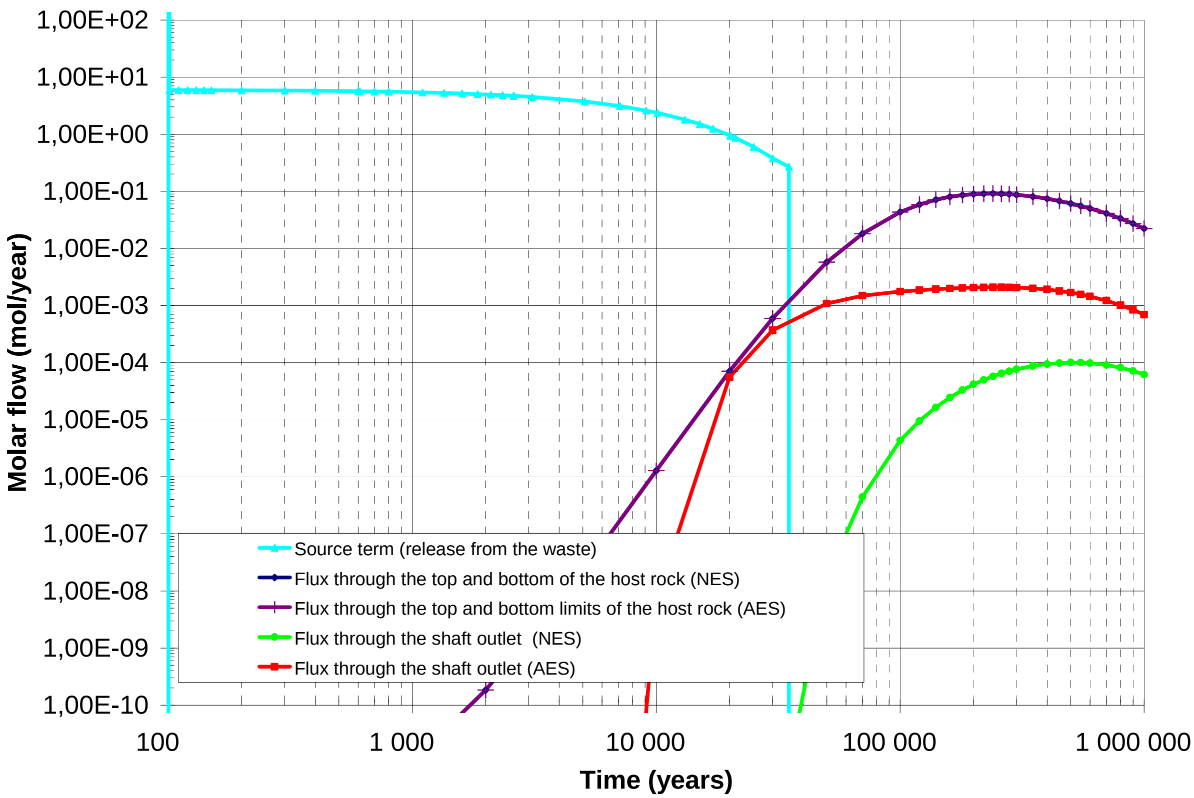

Fig. 2. Molar flow rate of I-129 out of a shaft and the Callovo-Oxfordian formation.

[13] The bottom (wall) corresponds to the lower extent of the formation, the top (roof) to its upper extent

Comparing the calculated molar flow rates at the top and bottom of the Callovo-Oxfordian formation with those calculated at the shaft outlet (which gives an estimate of transfers through the drifts) shows that the host formation is the main radionuclide transfer pathway whatever the seal performance scenario considered (see Fig. 2. and Table II).

Table II. Summary of the results obtained for the shaft and the Callovo-Oxfordian formation

	Maximum molar flow rate value (mol/year)		Time to achieve maximum molar flow rate (years)		Activity out of the Callovo-Oxfordian (COX) formation and shaft as a percentage of the total activity released (%)	
	Shaft	COX	Shaft	COX	Shaft	COX
I-129 (NES)	1.02 E-04	9.24 E-02	520 000	240 000	0.07	77.6
Cl-36 (NES)	-	6.19 E-04	-	180 000	-	32.1
Se-79 (NES)	-	1.39 E-06	-	1 000 000	-	0.04
I-129 (AES)	2.09 E-03	9.13 E-02	260 000	240 000	2.1	75

When considering the three different radionuclides (I-129, Se-79 and Cl-36 as shown in Fig. 3), reaching the boundaries of the Callovo-Oxfordian formation, it is shown that I-129 is the radionuclide having the highest molar flow rate (0.1 mol/year), two orders of magnitude higher than Cl-36 and five orders of magnitude higher than Se-79. The half-life of Cl-36 is of the same order of magnitude as the transfer time through the Callovo-Oxfordian formation, therefore the maximum estimated molar flow rate of Cl-36 is reached earlier than for I-129. The release of Se-79 is controlled by its low solubility in clay as can be observed from the shape of the curve (characteristic plateau controlled by precipitation around the waste packages). The curves of I-129 and Cl-36, on the other hand, are characteristic of a diffusive transfer controlled by the host formation properties considering that the spent fuel matrix releases its activity rapidly with respect of the diffusive transport time through the host formation.

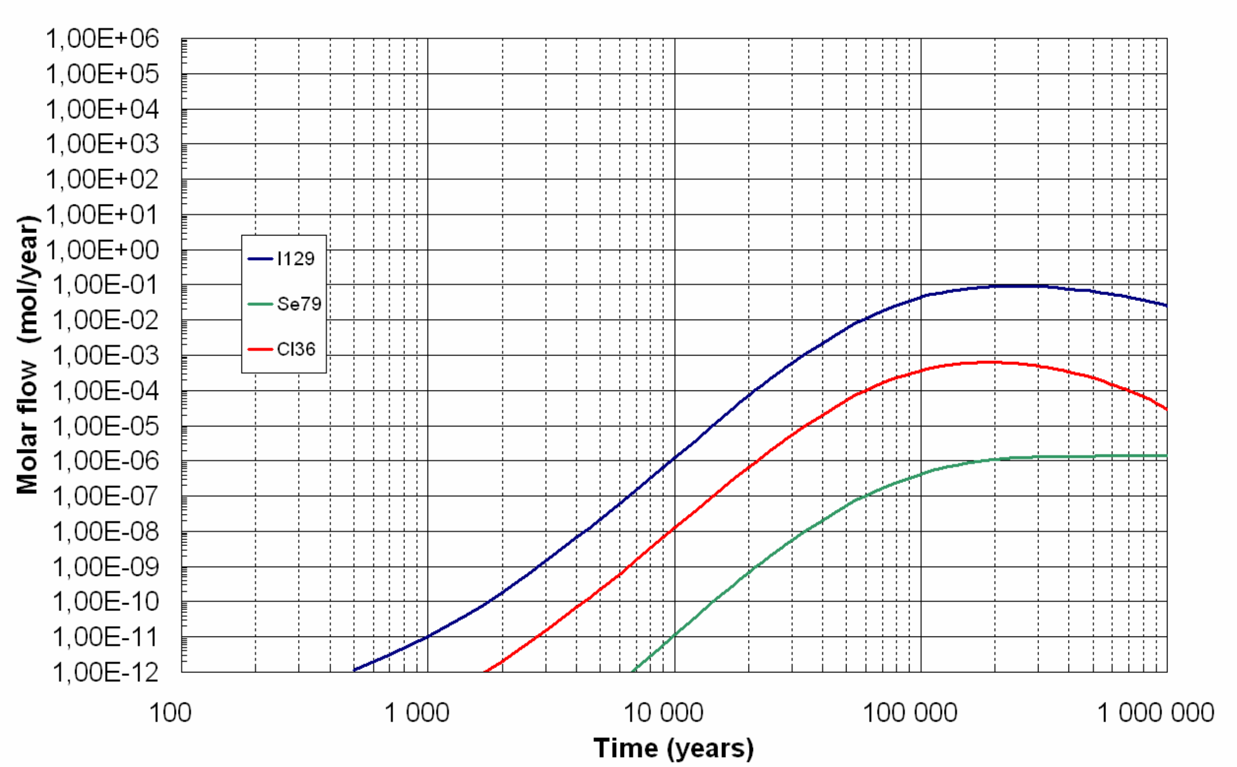

Fig. 3. Molar flow rate of I-129, Se-79 and Cl-36 out of the Callovo-Oxfordian formation.

The molar flow rate throughout the shaft increases by a factor of 20 when the seals are not effective. Despite this increase, the maximum molar flow rate out of the shaft remains more than one order of magnitude lower than the molar flow rate throughout the Callovo-oxfordian formation (Fig.2).

Radionuclide transfer from the Callovo-Oxfordian formation to the biosphere outlets

The hydrogeological model used to build the radionuclide transport model from the top of the host formation to the surface via the aquifers of the Oxfordian and Portlandian formations assumes the presence of conductive faults in the Oxfordian and a low hydraulic conductivity matrix of the Dogger formation (case no. 1 presented above). But, given the lack of knowledge regarding the value of the diffusion coefficient (Dp) in the aquifers, a sensitivity study is conducted for this parameter in order to estimate its influence on the radionuclide transport regime. The tested values are 10^{-9}, 10^{-10} and 10^{-12} m^2/s.

The radioactive plume entering the formations overlying the Callovo-Oxfordian formation is the molar flow rate of I-129 calculated at the top of the Callovo-Oxfordian host formation, upright of the repository. During transfer, the radioactive plume is diluted and dispersed by water circulating in the aquifers of the Oxfordian formation. Diffusion into the semi-permeable layers of the Oxfordian and the Kimmeridgian formations also contributes to the plume spreading as it progresses. The pathways and associated transfer times thus depend on the relative influence of diffusion (through the semi-permeable layers) and advection (in particular in structural heterogeneities).

The computation of I-129 transfer through the Oxfordian/Portlandian overlying formations displays a "natural" outlet located at the surface (Portlandian aquifer) and a second "well drilling" outlet that is assumed to be suitable for drilling a deep water supply borehole located in a fractured zone of high transmissivity in the Oxfordian (major fault zone 5 km to the West of the repository site). The results in Table III show that the maximum molar flow rate of I-129 in the “well drilling” outlet is obtained between 400 000 and 500 000 years. The transfer regime towards this zone being predominantly convection through the aquifers of the Oxfordian and through the fault zone, the concentration is significantly reduced during I-129 transfer (a factor of 400 between the top of the Callovo-Oxfordian and the maximum concentrations at the borehole) but the total activity released at this outlet is relatively high (approximately 10 % of the released mass at the top of the Callovo-Oxfordian). The sensitivity analysis conducted shows that this outlet is hardly influenced by the diffusion coefficients characterising the geological layers crossed. The molar flow values (Fig. 4) remain of the same order of magnitude regardless of the diffusion value.

For the "natural" outlet, located directly upright of the repository, the maximum molar flow rate is obtained (depending on the diffusion coefficients chosen) between 350 000 and 550 000 years (after the release from the waste packages has started). The transfer of radionuclides towards this outlet is controlled by diffusion through the semi-permeable formations and by diffusion/dispersion through the aquifers. As shown by the results in Fig. 4, the molar flow rate increases proportionally with the diffusion coefficient of the sedimentary layers and can reach a level that is not negligible compared to the molar flow rate at the “well drilling” outlet. It can be noted on Fig. 4, that, when the maximum diffusion value of 10^{-9} m²/s is computed, both outlets are of similar level. This result, even if such high value is an upper bound in aqueous medium, highlights therefore that diffusion may play a significant role on mass transfer in the overlying aquifers.

Table III. Summary of the results at the « natural » and « well drilling » outlets for I-129

	Maximum molar flow rate value (mol/year)		Time to achieve maximum molar flow rate (years)		Activity exiting as a percentage of the total activity released at the COX outlet (%)	
	« natural » outlet	« well drilling » outlet	« natural » outlet	« well drilling » outlet	« natural » outlet	« well drilling » outlet
Dp = 10^{-9}m²/s	1.80 E-03	3.28 E-03	350 000	400 000	3.9	7.3
Dp = 10^{-10}m²/s	4.83 E-03	9.57 E-05	500 000	500 000	0.2	11.2
Dp = 10^{-12}m²/s	4.93 E-03	7.88 E-07	550 000	500 000	0.002	11.8

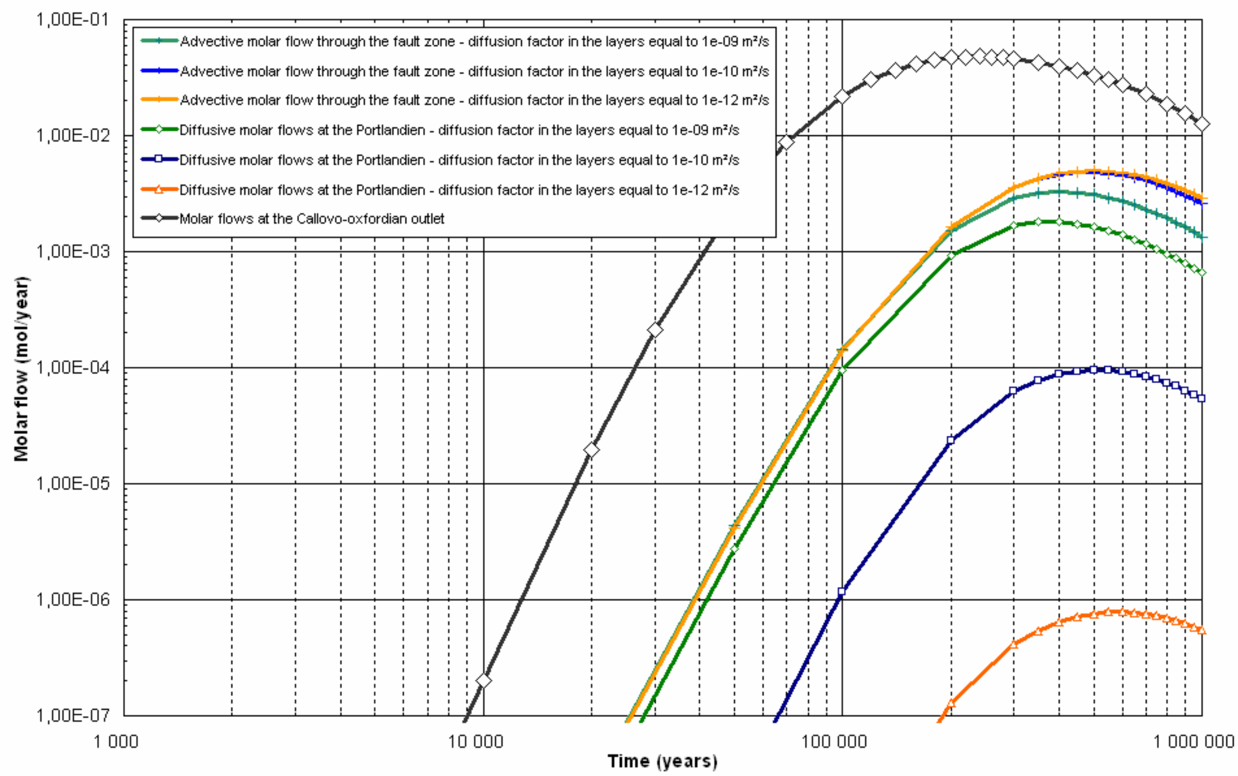

Fig. 4. I-129 Molar flow rates at the outlets of the overlying layers.

Conclusions and perspectives

Beside the waste matrix and package (of which influenceon radionuclide release are not assed herein), the molar flow rates released by canisters are controlled by two essential elements of the repository design, namely the host formation and the sealing systems intending to prevent water movement.

The host rock is the main diffusive pathway. The clay acts as a "sink" for the radionuclide plume, then spreads the amount of activity as long as its confinement properties remain unchanged.

When the seals are effective (NES), the handling drift and shaft do not act as major pathways for radionuclides and a diffusive transport regime occurs through the facility to the host rock. When the seals are bypassed by EDZ (AES), on the light of calculations not presented in the present study [4], the repository design (dead-end tunnels) is efficient to preserve diffusive conditions in the vicinity of the tunnels whereas advection in the drifts increases. In this altered situation, activity released by the tunnels is trapped by advective flow occurring in the drifts. As a consequence, enhanced transport of activity through the drifts to the access shaft provides an increased molar flow rate at the shaft outlet combined with a shorter transfer time than in the NES. So the seals are essential to ensure a diffusive regime in the drifts and shaft and avoid comparatively rapid release of radionuclides to the outlets through the aquifers. As it is shown in the present study, the definition of the outlets (artificial "well drilling" zone or at the ground surface), requires the characterisation of groundwater flow regimes based on advective movement of water in the aquifers and possible conductive discontinuities.

The results obtained for the different flow simulations have highlighted the fact that the computed hydraulic heads in the different layers could be calibrated using different groundwater flow patterns where the identified or suspected structures within the studied area either play a hydraulic role or not. Additional hydrogeological field studies would be necessary in order to reduce the number of flow models that could be considered in the repository area. Influence of remaining groundwater flow schemes on the transfer times and concentrations of the radionuclide plumes at the outlets should be assessed (by the mean of a sensitivity study) to select the flow scheme leading to major release of activity at the outlets.
But the simulation of radionuclide transport through the permeable and semi-permeable formations also requires the quantification of the diffusive transfer process. While this phenomenon is recognised as being dominant through the homogeneous Callovo-Oxfordian formation and has given rise to studies aimed at specifying it, the present modeling exercise has shown that such phenomenon must also be more accurately characterised in the aquifers in order to discriminate the importance of more widely scattered outlets (in areas which might be potential water resources) away from hydraulic discontinuities. Else, the uncertainties resulting from a lack of knowledge regarding this process must at least be taken into account by means of a sensitivity study.

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