Major results and lessons learned for performance assessments of spent fuel geological disposal: the SPA project

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Abstract:

This paper presents a summary of the results obtained in the framework of the *SPA* (*S*pent fuel disposal *P*erformance *A*ssessment) project. The project was undertaken by ENRESA, E; GRS, D; IPSN, F; NRG, NL; SCK.CEN, B and VTT, FIN between May 1996 and April 1999. Devoted to the study of spent fuel disposal in various host rock formations (clay, crystalline rocks and salt formation), it notably had the objective to evaluate the long-term performance of different repository systems and to identify the most influential elements.

The variety of concepts, sites and scenarios considered in the framework of this project provides a wide range of information from which some general conclusions can be drawn. Focusing on the work done in the case of granite host rock formations, this paper describes the various approaches adopted and states the main sources of differences. It particularly stresses the differences related to the geosphere and biosphere modelling. For the geosphere modelling, ENRESA, GRS and VTT use one dimensional discrete approaches to model the migration of contaminants through the geosphere taking into account for matrix diffusion, whereas IPSN uses a three dimensional continuum approach based on a single porosity model. The comparison of the biosphere conversion factors shows the high influence on the calculated radionuclide dose contributions that can results from biosphere modelling assumptions. It notably points out the differences existing between a simplified “water drinking” approach as implemented by VTT and a more classical one in which a wider range of exposure pathways are taken into account.

With regards to the results obtained, several common trends can be identified. Among the fission and activation products, ^{129}I is found to play a leading role in most of the calculation cases. The contribution of ^{14}C, ^{36}Cl, ^{79}Se, ^{126}Sn and ^{135}Cs also appears to be potentially high but the variability from one participant to another or from one calculation to another may be sometimes large. Among heavy nuclides, ^{226}Ra is commonly recognised as one of the most important dose contributor. Among the others heavy nuclides, daughter nuclides in the tail of the decay chains (notably ^{229}Th, ^{230}Th and ^{231}Pa) are also of relative importance.

1. INTRODUCTION

The SPA project [1] is a direct continuation of the efforts made by the European Community since 1982 to build a common understanding of the methods applicable to performance assessment of a deep geological disposal. Devoted to the case of spent fuel, SPA is a follow-up to the PAGIS [2], PACOMA [3] and EVEREST [4] projects that dealt with the disposal of intermediate level long lived wastes and high level vitrified wastes.

One of the particular interests of these successive projects is to constitute a “practical” framework to develop and implement methods and tools for integrated performance assessment. They also enable to draw preliminary conclusions on the respective importance of the radionuclides present in the different types of waste, on the influence of some of the main assumptions used in the modelling and help to specify the role that can be expected from the various disposal system components.

In addition, international participation gives an opportunity to share experiences and practices. Different approaches can be compared and their particular interest can be better understood, their justification can be debated and strengthened and eventual complementarities can be identified.

In the case of SPA, six national research institutions representing implementing as well as regulating organisations in six member countries of EU (ENRESA for Spain, GRS for Germany, IPSN for France, NRG for The Netherlands, SCK.CEN for Belgium and VTT for Finland) worked together from 1996 to 1999. The project comprised assessments of four different granite sites (by ENRESA, GRS, IPSN and VTT), three different clay sites (by IPSN, NRG and SCK.CEN) and two different rock salt formations (by GRS and NRG). In each assessment, in addition to a « normal evolution » scenario, 2 to 3 altered evolution scenarios were envisaged.

This paper only addresses the assessments made for granitic formations studied by ENRESA, GRS, IPSN and VTT. It focuses on the case of a normal evolution scenario for which an overview of the results is proposed.

Though the performance assessments undertaken within the project are only methodological exercises, they require the definition of a general framework on which the different assumptions used in the studies can ground. This general framework comprises the definition of the amount and nature of the wastes to be disposed of, the characteristics of the sites and the characteristics of the different engineered barriers. Choices are generally made in agreement with the national contexts but do not intend to precisely reflect every technical option prevailing on projects actually developed in each country.

Performance assessment entails the modelling of five distinct components: the container, the waste form, a clayey engineered barrier surrounding the container – also called “buffer”–, the geological medium – sometimes comprising a Damaged Rock Zone (DRZ) – and the biosphere. The first three components as well as the possible DRZ are usually referred to as "the Near-Field", whereas the geological medium is called "Far-Field".

2. NEAR-FIELD MODELLING

2.1 Containers

Container performance is usually dealt with through the definition of a mean failure time: before that time, all the containers are considered to be perfectly tight, after they are not assumed to ensure any role. Typical values for failure times are in the range of some thousands years. In the case of VTT, due to the choice of an iron-copper container, packaging integrity is expected to last much longer and only a few defective containers are assumed to leak within the period considered in the assessment.

2.2 Waste form as a source-term

The performance assessment of the waste form is dealt with by the definition of a "source-term model". Because the distribution of radionuclides in spent fuel is heterogeneous, two distinct parts of a fuel assembly are distinguished. The first part is associated with the metallic parts (the claddings and the structural parts of the fuel assembly); it notably contains the major part of C, Ni, Zr and Nb inventories. The second part is associated with the fuel matrix in which the activity is bounded to the UO_2 matrix except for a fraction of some fission and activation products located in the gaps or to the grain boundaries (see Figure 1). This fraction is essentially constituted of some % of C, Cl or I.

In relation to this distribution of activity in the fuel assembly, a common source term model is defined by the participants and used in the assessments. It distinguishes three different contributions. The first contribution is associated with the inventory fraction located in fuel gaps; it is instantaneously released when water comes into contact with the waste form. The second is governed by the progressive degradation of claddings, structural parts and grain boundaries of fuel pellets; it leads to a continuous release over 1,000 years. The third is governed by the UO_2 matrix degradation; it leads to a continuous release over one million years.

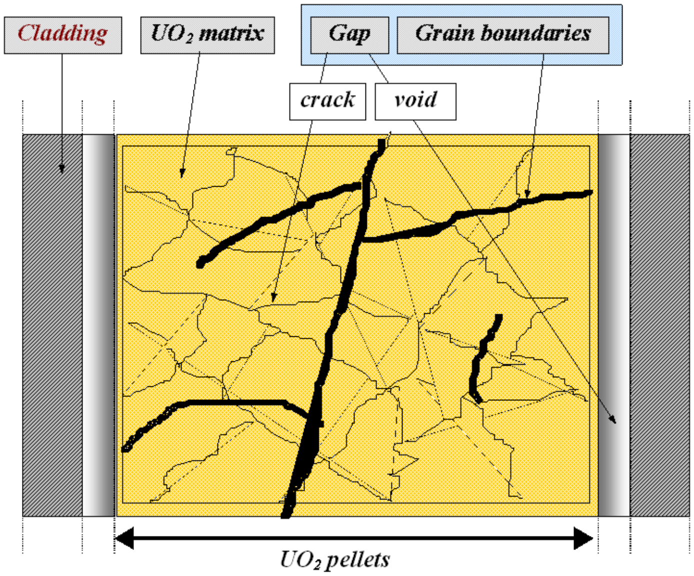


Figure 1: **Schematic section of an irradiated fuel element**

2.3 Clayey buffer and Near-field modelling

Performance assessment of buffer and geological medium is based on radionuclides groundwater transport modelling and involves processes such as diffusion, advection, sorption and dissolution / precipitation.

In granite, the clayey buffer and geosphere are separately modelled by ENRESA, GRS and VTT. It is considered as two media with distinct properties within one single model by IPSN. In the first case, simplified 1-D radial (ENRESA, GRS) or compartments (VTT) diffusion models are used for buffer. Separate 1-D discrete models are then used to simulate transport in single fractures. In IPSN granite modelling, a single 3-D code is used to model the transport of radionuclides from the waste package up to the natural outlets, integrating both the Near-Field and Far-Field. A Disturbed Rock Zone (DRZ) at the buffer/geosphere interface is considered for all the participants. IPSN models explicitly the transport of radionuclides across the DRZ by considering that hydraulic conductivity is increased as compared to the rock mass, whereas the other participants deal the DRZ through a “mixing tank” boundary condition at the interface buffer/DRZ.

Main assumptions for the Near-Field modelling are summarised in Table 1.

Table 1: Comparison of the main features, processes and assumptions for Near-Field models in granite.

	ENRESA	**GRS**	**IPSN**	**VTT**	
				"Disappearing container"	***"Hole in container"***
Code	RIP	GRAPOS	MELODIE	REPCOM	
Geometry	1-D radial	1-D radial	3-D	Compartment	
Solution method	Finite difference	Finite difference	Finite element	Matrix exponent	
Near-Field representation	Explicit representation of container and engineered barriers	Explicit representation of container and engineered barriers	Full representation of the repository in geosphere Explicit representation of engineered barriers and DRZ	Explicit representation of container and engineered barriers	
Contaminant transport in buffer	Diffusion to DRZ (advection neglected)	Diffusion to DRZ (advection neglected)	Diffusion/advection to host rock (equivalent porous medium)	Diffusion	
Contaminant transport in backfill	Not considered	Neglected	Not considered	Advection and diffusion	Not considered
Transport out of repository	Instantaneously along DRZ to major conducting features	Instantaneously along DRZ to major conducting features	Advection/diffusion in equivalent porous medium (DRZ and geosphere)	Into rock fissures, DRZ and via tunnel backfill	Into rock fissures
Source term for transport	Solubility applied in container (1 m^3 of water/container)	Solubility applied in container (0.3 m^3 of water/container)	Solubility applied in buffer ($\approx$8 m^3 of water/container)	Solubility applied in container (0.4 to 0.7 m^3 of water/container.)	
Outer boundary condition(s)	"Mixing tank" advective flux = diffusive flux (buffer/DRZ interface)	"Mixing tank" advective flux = diffusive flux (buffer/DRZ interface)	Diffusive flux = 0 at the outlets (geosphere / biosphere interface)	Transfer coefficients host rock/engineered barrier interface	

3. FAR-FIELD MODELLING

3.1 Main features of the sites

Among the four assessments carried out for granite, three are based on hypothetical sites. Only VTT considers a real existing site.

In ENRESA assessment, the generic site studied is developed from the data available for different granites already investigated in Spain.

In GRS assessment, the work achieved within the national project GEISHA [5] is used as a basis to define the generic site used for the assessment. Within the GEISHA project, the possible German granite sites were compiled and roughly characterised.

In IPSN assessment, the hypothetical generic site is the same as the one defined within the framework of EVEREST. The topography and general geological and structural context are derived from investigation data available at a granitic site in the Western part of France. These data are complemented by additional data judged to be representative of a granitic context.

In the case of VTT, the assessment is based on the four candidate sites for a spent fuel repository currently investigated in Finland: the Hästholmen nuclear power plant (NPP) site in Loviisa, Kivetty in Äänekoski, the Olkiluoto NPP site in Eurajoki, and Romuvaara in Kuhmo.

Two categories arise from these sites characterisations : sites for which fractures are considered as lowly conductive and rather regularly distributed and connected, and sites for which some identified major fractures are expected to be preferential pathways.

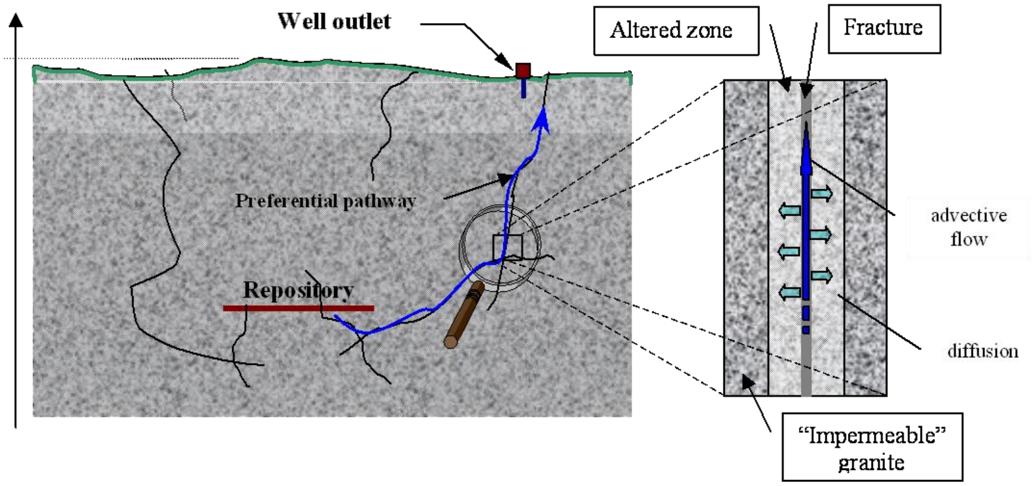
3.2 Conceptual modelling of radionuclides transport in the geological barrier

ENRESA, GRS and VTT use one dimensional discrete approach to model the migration of contaminants through a single fracture taking into account matrix diffusion. These calculations are complemented with dedicated aquifer modelling. IPSN uses a three dimensional continuum approach based on a single porosity modelling transport up to the natural outlets. No complementary aquifer calculations are thus required. A schematic description is shown in Figure 2.

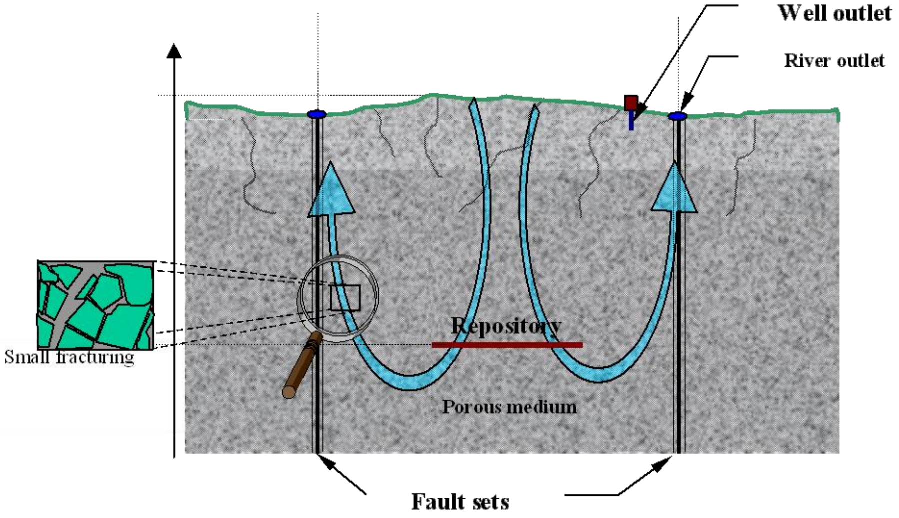
IPSN models the groundwater flow as well as Near-Field and Far-Field transport of radionuclides with the same 3 D code based on a continuum approach (single porosity). The IPSN modelling assumes that small and intermediate scales of discontinuities may be homogenised with a generic cubic cell of about 100 m × 100 m × 100 m. The larger faulted zones are explicitly represented as continuous 2 D planes included in the 3 D finite element mesh. The main structures outlined by the regional geology and taken into account in the modelling are grouped into three porous media: the faulted zones (described as continuous plane), the swamps associated with the faulted zones and the rock mass. In each of the three entities, the nature of the migration phenomena is the same and differences simply result from differences in hydrogeological properties. Sorption phenomena are dealt with through the use of a retardation factor. Retardation is assumed to be essentially due to sorption on clay minerals filling the fractures, clay particle being considered to represent $\approx 1\%$ of the rock mass. Migration of radionuclides is performed from the entire set of galleries.

In ENRESA's modelling approach, effective 1 D pathways are quantified from 3 D flow modelling. Migration of radionuclides is performed through these pathways from different parts of the repository to the outlets. The mathematical modelling is based on a 1 D discrete approach to simulate transport in a fracture taking account for matrix diffusion in the rock mass adjacent to the fracture plane. In addition to diffusion, sorption in the matrix is also taken into account. Both processes are not explicitly modelled but they are dealt with by means of effective retardation factors.

Figure 2: Schematic representation of geosphere modelling used in the assessments.



(a) Discrete approach: matrix diffusion model



(b) Continuum approach: single porosity model

A specificity of the assessments done by ENRESA and IPSN is to account for every possible flowpaths. Assessments thus reflect a range of transit times that can realistically be associated with the heterogeneity of a crystalline rock at the scale of a potential repository (several km^2).

VTT and GRS consider that the radiological impact is dominated by one container or part of containers affected by the highest flow rates and fastest flow channels in the geosphere. The complexity of the hydraulic patterns of the geosphere is reduced to one preferential pathway and the behaviour of the repository system is assessed with respect to this route. The modelling of the radionuclides migration is based on a 1 D discrete approach. The retardation is only caused by diffusion from the water-conducting fracture into the adjacent rock matrix and sorption into the matrix (sorption on fracture surface and infills is conservatively neglected). A dispersion related to the heterogeneity of the pathways has not been considered: the shortest pathway to the biosphere is only considered and delay and dispersion of the solute is related to matrix diffusion.

Transit times differ drastically from one calculation to the other. The shortest travel times from the repository to the biosphere performed by IPSN and ENRESA are in the order of some 1,000 years whereas they are of some years for GRS and VTT.

4. BIOSPHERE MODELLING

Geosphere calculation outputs give activity fluxes or concentrations at the groundwater outlets. They are converted in dose values using biosphere modelling.

To go further into details, two different kinds of *sources* are distinguished depending on the nature of the interface between geosphere and biosphere:

- In the first case, the contaminated water is directly abstracted from the ground through a well. The source is then expressed as a radionuclide concentration in the abstracted water. Biospheres of this kind are called « well type biosphere »,
- In the second case, the contaminated water enters the biosphere at a natural outlet for groundwater flow and eventually dilutes in a river. In this case, the source is expressed as the amount of radionuclides annually pouring in the considered river. Biospheres of this kind are called « river type biosphere ».

In both cases, the relevant input data needed for biosphere calculations is the activity concentration in water. In the case of a natural outlet, this data is derived from the annual amount of radionuclides reaching the considered outlet using a volume of dilution corresponding to the annual river flow (in $m^3.year^{-1}$).

Choices made by each participant in terms of source type are shown in table 2.

Table 2: Source type for biosphere modelling

	ENRESA	GRS	IPSN	VTT
River Type Biosphere			✓	
annual river flow			$10^8\ m^3.year^{-1}$	
Well Type Biosphere	✓	✓	✓	✓

As regards the transfer pathways considered by the SPA participants, they all belong to the following list:

1. direct intake of contaminated water
2. intake of vegetables irrigated with contaminated water
3. intake of animal produce from cattle fed on an area contaminated by irrigation
4. intake of fish bred in contaminated water (river or artificial pond)
5. external exposure due to a contaminated soil
6. inhalation of contaminated soil particles

Two distinct approaches can however be distinguished. For VTT, transfer pathways are conventionally limited to direct ingestion of contaminated water (pathway 1) in order to minimise the number of parameter values to be set and thus limit to the maximum the sources of uncertainties. Under these conditions, the only parameter values used are the ICRP dose coefficients for ingestion and the annual intake of contaminated water by a member of the hypothetical critical group. All the other participants consider a more thorough contamination of the environment leading to multiple exposure pathways. Every pathway is thus taken into account unless they are considered not relevant to the characteristics of the source and more precisely to the amount and the availability of water at the considered outlet. For instance, in the case of IPSN well type biosphere, pathways 3 and 4 are not taken into account because the large volume of water they required is not considered compatible with the relatively low productivity of the aquifer. In the case of ENRESA well type biosphere, the well is considered to be located at a relatively great depth. Because of the relatively high financial cost likely to be associated to water abstraction under these conditions, the use of water is assumed to be limited to drinking purpose only.

Table 3 shows the list of transfer pathways selected for each biospheres used in the SPA calculations.

Table 3: Transfer pathways selected

	ENRESA	***GRS***	***IPSN***		***VTT***
	well	well	river	well	well
Drink. Water	✓	✓	✓	✓	✓
Vegetable	✓	✓	✓	✓	
Farm animal	✓	✓	✓		
Fish		✓	✓		
External	✓	✓	✓	✓	
Inhalation	✓	✓	✓	✓	

Calculation of dose still requires the definition of man diet (annual intake of drinking water, vegetables, farm animal products, fish) and behaviour (agricultural practices, time annually spent on site, volume of air annually breathed) and of transfer parameter values. For each modelling, the precise list of required parameters of course widely varies notably depending on the list of transfer pathways involved. However, from a general point of view, choices made by the different participants are rather similar in the sense they all relied on the same general assumptions: they are notably all defined in relevance with the current agricultural practices in developed countries, under the assumption of a temperate climate and according to a relatively high level of self-subsistence for food.

4.1 Comparison of biosphere conversion factors

4.1.1 Definition and use of biosphere conversion factors

For the purpose of a geological disposal performance assessment, biospheric transfers can be taken into account either through the use of a set of biosphere conversion factors or by coupling geosphere model with a dynamic biosphere model.

Definition of biosphere conversion factors enable to run independently biosphere and geosphere calculations. They are used to convert any geosphere modelling output into a dose value. Their use relies on the assumption that the different compartments of the biosphere have a quasi-static behaviour.

The comparison made within SPA is based on the biosphere conversion factors derived by each participants from dedicated biosphere modelling calculations using a constant unit source-term (1 Bq.l^{-1}). In the case of VTT, biosphere conversion factors are directly calculated as the product of the ICRP dose coefficients for ingestion by the volume of contaminated water annually drunk by a member of the critical group (0.5 m^{3}.year^{-1}).

4.1.2 Comparison of values

Table 4 shows the biosphere conversion factors for every participant and for a set of radionuclides considered important when assessing the long-term performance of a deep geological disposal. Values are expressed in (Sv.year^{-1})/(Bq.m^{-3}).

Table 4: Biosphere coefficient factors [in (Sv.year^{-1})/(Bq.m^{-3})]
N. C.: not considered in the calculations

	VTT	***ENRESA***	***GRS***	***IPSN***	
	well	***well***	***well***	***well***	***river***
^{14}C	2.9E-10	3.1E-8	9.7E-8	2.8E-9	2.1E-8
^{36}Cl	4.7E-10	1.8E-8	2.6E-8	7.1E-9	1.2E-8
^{59}Ni	3.2E-11	6.7E-10	1.7E-9	2.6E-10	3.9E-8
^{79}Se	1.5E-9	6.9E-7	2.3E-7	8.9E-9	4.2E-8
^{93}Zr	6.1E-10	2.7E-8	8.2E-9	1.8E-9	1.8E-9
^{94}Nb	8.5E-10	2.1E-6	9.2E-8	1.4E-7	9.0E-8
^{99}Tc	3.2E-10	2.4E-9	4.9E-9	5.9E-9	9.5E-9
^{107}Pd	1.9E-11	1.2E-8	3.0E-10	1.7E-10	4.0E-9
^{126}Sn	2.5E-9	1.8E-6	8.7E-6	2.2E-7	3.2E-7
^{129}I	5.5E-8	3.8E-7	3.7E-7	3.5E-7	4.8E-7
^{135}Cs	1.0E-9	1.6E-8	8.6E-8	6.6E-9	2.8E-8
^{240}Pu	1.3E-7	9.6E-7	2.2E-06	7.4E-7	9.0E-7
^{236}U	2.4E-8	1.2E-7	2.2E-07	1.4E-7	1.8E-7
^{232}Th	5.3E-7	1.2E-4	1.6E-05	3.4E-6	9.8E-6
^{245}Cm	1.1E-7	4.1E-6	3.0E-6	1.6E-6	2.1E-6
^{241}Pu	2.4E-9	1.2E-8	5.6E-8	N.C.	N.C.
^{241}Am	1.0E-7	1.0E-6	2.7E-6	N.C.	N.C.
^{237}Np	5.5E-8	3.1E-7	6.2E-6	3.4E-7	4.4E-7
^{233}U	2.6E-8	1.3E-7	3.0E-7	1.5E-7	2.0E-7
^{229}Th	3.1E-7	1.9E-5	5.4E-6	1.9E-6	3.5E-6
^{246}Cm	1.1E-7	2.5E-6	N.C.	8.2E-7	1.0E-6
^{242}Pu	1.2E-7	9.4E-7	N.C.	7.1E-7	8.6E-7
^{238}U	2.4E-8	1.4E-7	3.1E-7	1.5E-7	1.9E-7
^{234}U	2.5E-8	1.3E-7	2.4E-7	1.5E-7	2.0E-7
^{230}Th	1.1E-7	4.0E-6	2.8E-6	6.6E-7	1.1E-6
^{226}Ra	1.1E-6	1.2E-4	1.5E-5	3.9E-6	1.6E-5
^{243}Am	1.0E-7	4.9E-6	3.5E-6	8.3E-7	1.2E-6
^{239}Pu	1.3E-7	9.8E-7	2.2E-6	7.4E-7	9.0E-7
^{235}U	2.4E-8	1.6E-7	9.5E-7	1.5E-7	1.9E-7
^{231}Pa	9.6E-7	4.9E-5	1.4E-5	5.9E-6	9.6E-6

From the previous biosphere conversion factors, ratios between the biosphere conversion factor defined by an institute and the VTT one are derived. As VTT dose conversion factors give the contribution from water ingestion only, the ratio value can be considered as a measure of dose « amplification » resulting from the transfer and accumulation in environmental compartments and from a multiple pathway exposure. A value of 100 roughly means that the dose incurred by an individual that directly drinks contaminated water is 100 times higher if the contaminated food products are ingested (the water also contaminates soil, fish, plants or farm animals) and if external exposure occurs.

The comparison of ratio values shows that discrepancies exist from one participant to another but that the values usually remain within the same order of magnitude when the same approach is adopted. They are usually sufficiently homogeneous to define three broad classes of radionuclides: those for which dose calculations are highly influenced by biosphere transfer (ratio greater than 100), those of medium influence (ratio between 10 and 100) and those for which dose calculations are lowly influenced (ratio lower than 10). This classification is shown in table 5. When the discrepancies between participants make the classification difficult, a « ? » is indicated.

Table 5: Classification of the radionuclides according to the influence of environmental transfer on their biosphere conversion factors

Influence	***Fission Products***	***Actinides***
High *(ratio > 100)*	^{14}C, ^{79}Se, ^{94}Nb, ^{107}Pd (?), ^{126}Sn	^{226}Ra (?), ^{232}Th (?), ^{237}Np (?)
Medium *(10< ratio < 100)*	^{36}Cl, ^{59}Ni, ^{93}Zr, ^{99}Tc, ^{135}Cs	^{245}Cm, ^{241}Pu, ^{241}Am, ^{229}Th, ^{246}Cm, ^{230}Th, ^{243}Am, ^{235}U, ^{231}Pa
Low *(ratio < 10)*	^{63}Ni, ^{90}Sr, ^{129}I	^{240}Pu, ^{236}U, ^{233}U, ^{242}Pu, ^{238}U, ^{234}U, ^{239}Pu

5. RESULTS

Figure 3 shows the time evolution of effective dose rates obtained by the different participants in the case of normal evolution scenario.

5.1 Time of arrival and main contributors

From the results obtained, it can be concluded that (1) calculated doses are usually very low (order of µSv); (2) the contribution from fission and activation products to doses clearly differentiates from that of transuranic isotopes in terms of time occurrence; (3) only a few radionuclides significantly contribute to the total radiological impact.

Looking at the time dependent dose rates resulting from the different calculations, a relatively clear distinction between three successive periods can be made: the first one is characterised by the absence of radiological impact, the second is dominated by the contribution of fission and activation products and the third by the contribution of heavy nuclides. The starting times for these successive periods vary from one site to another and from one calculation case to another.

According to the calculations performed, total dose rates are predominantly caused, in the first step, by the contributions of activation and fission products (^{14}C, ^{36}Cl, ^{129}I, ^{79}Se and ^{126}Sn essentially), then by the contributions of heavy nuclides (the most important ones being ^{226}Ra, ^{230}Th and ^{229}Th). For the fission and activation products considered to be non-sorbed or weakly-sorbed (notably ^{14}C, ^{36}Cl and ^{129}I), arrival in the biosphere occurs relatively early in time. For all the participants but GRS, the major dose contributor in the first 10^5 years is ^{129}I.

The release of fission and activation products begins shortly after container failure for GRS and VTT and only after some 10,000 years for ENRESA and IPSN. Transuranic elements reach the biosphere only after some 100,000 years in the case of IPSN and beyond one million years in the case of ENRESA, GRS and VTT.

Whereas a total of 28 fission and activation products and 37 isotopes of transuranic elements are dealt with, screening out radionuclides with the lowest individual contributions whatever the time and the calculation considered, brings to the following short-list: ^{14}C, ^{36}Cl, ^{79}Se, ^{107}Pd, ^{126}Sn, ^{129}I, ^{135}Cs, ^{236}U, ^{232}Th, ^{237}Np, ^{233}U, ^{229}Th, ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{235}U, ^{231}Pa.

Within the first million years, ^{129}I is usually found to be responsible for more than ¾ of the maximum dose and often dominates the impact over the whole period. In granite, some nuance must however be observed. For GRS, maximum dose is mostly due to ^{14}C and ^{129}I is only one of the successive leading contributors along with ^{36}Cl and ^{135}Cs. For ENRESA and VTT, ^{129}I governs the maximum dose over the considered period but at some points in time, ^{36}Cl and

^{126}Sn respectively, are found to lead the impact. Lastly, for IPSN, after some 100,000 years, isotopes of transuranic elements (mainly ^{226}Ra and ^{230}Th) become predominant and even cause the maximum dose level. Participants who pursue calculations beyond one million years also observe a relative predominance of transuranic elements isotopes in the very long-term. Thus, for GRS, the very-long term dose is dominated by ^{229}Th.

5.2 Interpretation of the shape of the breakthrough curves

Beside these quantitative descriptions of the results, more qualitative lessons concerning the main mechanisms governing radionuclides contributions to the radiological impact can be drawn from the curves presented in Figures 3 and 4.

With regard to the capacity of the different barriers to lower the released flux, a distinction is done between the two components of the source-term, namely the instantaneous release from the gaps and the continuous release from the fuel matrix. As suggested by the shape of ^{129}I curves in Fig. 3, the activity flux that reaches the outlet is remarkably steady for most of the participants. This suggests a predominant influence of the fuel matrix degradation.

To go further in details, the instantaneously released fraction is usually efficiently smoothed during its transfer through the successive barriers and does eventually not contribute significantly to the total dose (see Fig.3). One exception however exists for VTT, because of the relatively high conductive properties of the fracture constituting the preferential pathway and the resultantly very short transfer time through the geosphere ($\approx$ 10 years). The pulse associated to the instant released fraction is then only weakly spread in time when reaching the outlet and thus significantly contributes to the total dose.

Contrarily to the case of instant release fraction, the second component of the source term (the continuous release from the spent fuel matrix) is usually not affected by the transfer through the successive barriers. The flux of ^{129}I reaches a plateau equal to the flux released at the considered outlet. Because of the long half-life of ^{129}I and the matrix degradation time on the one hand, the transfer time through the disposal system on the other hand, a steady state is usually reached. The transfer through the disposal system does not enable to reduce the flux level. The efficiency of the system to control the activity release then relies on the fuel matrix performance. The geological barrier only delays the release. The delay is more or less important depending on the hydrogeological properties of the barrier.

Because of their high sorption onto geological medium, heavy nuclides are notably delayed before reaching the biosphere. This delay that depends on modelling assumptions made by each participants, is always strong but differs from one assessment to the other. Relative dose contribution varies over a relatively large range mainly as a result from differences in solubility limit values. In some cases, they are of similar importance as contribution for fission and activation products.

5.3 Importance of dilution

In addition to the normal evolution scenario, complementary radiological calculations have been performed by focusing on the exploitation of a deep pumping well to supply the water requirements (drinking and irrigation of a vegetable garden) of a family. The well is assumed to be located at a depth of about 200 m in a major conductive fault in the vicinity of the repository. The situation considered in this altered scenario (a partial short-cut of the geological barrier and exploitation right in the center of the radioactive plume) can therefore be considered as one of the most unfavourable possible configurations.

Figure 4 shows the time evolution of the effective dose rates for this scenario. According to these results, the radiological impact associated with the deep well altered evolution scenario appears similar in shape with the radiological impact associated with the normal evolution scenario. The hierarchy of the radionuclides as well as the time of occurrence of the maximum effective doses obtained for the various radionuclides are roughly identical for both scenarios. The main difference in fact lies in the effective dose rates obtained; they are roughly four orders of magnitude higher than those corresponding to the normal evolution scenario (a few mSv to a few 10mSv).

As suggested by the similar times of occurrence of the maximum effective doses obtained for the normal evolution and the deep well scenarios, migration times from the repository into the surface outlets or into the deep well are rather similar and the influence of radioactive decay is accordingly low. In particular, it cannot explain the existing differences in dose values. Most of the dose increase is in fact due to a dilution of the plume much lower at the well location than at the natural outlets or in the river: the deep well leads to an exposure by a water about 500 times more concentrated than the water that would naturally reach the surface if not pumped. In the river, because of a further dilution by surface water, the concentration is another 100 times lower.

The effective dose rates calculated for this scenario are significant but would always require detailed interpretations and complementary informations in a real site specific study for judging if the level of protection of health and environment provided by the repository is adequately optimised. Representativeness of the assumptions done in the modelling but also likelihood of the situation would in particular need to be more precisely questioned. In order to adequately analyse this scenario, the dose results obtained would require to be complemented by other types of information such as the importance of exploitable water resources contaminated by the radioactive wastes and the resulting expected number of people likely to be exposed.

6. CONCLUSION

Although the various assessments made within the SPA project involved a relatively wide range of assumptions (different geological sites, different conceptual modelling and mathematical approaches), common lessons have been drawn from this study.

Calculations undertaken confirm that the spent fuel geological disposal would result in a low radiological impact at least in a case of a normal evolution scenario. Results also confirm the dominant contribution of long-lived soluble, weakly sorbed fission and activation products (^{129}I in particular) at least within a first period of time. A high contribution of heavy nuclides in the long term is also possible. For ^{129}I, activity flux is likely to be controlled by the degradation rate of the spent fuel matrix, the geological barrier providing only a delay in the arrival of the flux at the outlet. In this case, dilution is a key parameter governing the radiological impact. As a consequence, adequate identification and characterisation of the water resources potentially affected by the radioactive plume seems to be of primary importance.

The geological system appears to be an efficient filter that levels down contribution of radionuclides with half-lives smaller or in the order of magnitude of the transit times through the geosphere (correlation between groundwater transit times and radionuclides retardation) by the way of radioactive decay.

The influence of biosphere can be very high. The level of dose incurred by an individual because of direct ingestion of water can be greatly amplified if the water can also be transferred to other environmental compartments. For some of the considered radionuclides, value of the ratio can be as high as 3 orders of magnitudes. In addition, the level of influence is specific of a radionuclide. Effects of biospheric transfer on the level of dose incurred vary greatly from one radionuclide to another.

The SPA project also shows that, in spite of a nearly 20 years of experience now achieved in the field of performance assessment, relatively large discrepancies still exist for some of the key parameters.

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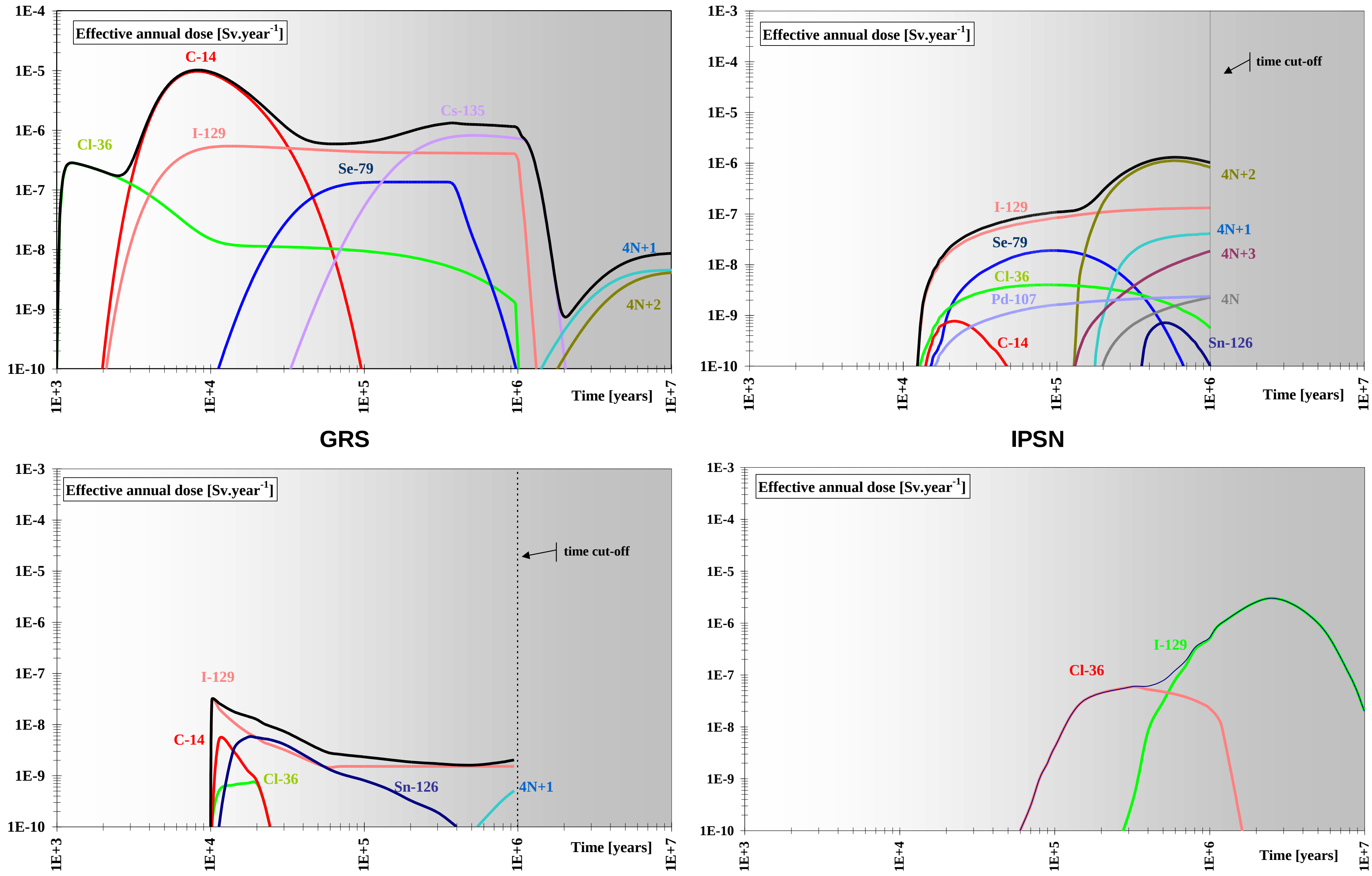

GRS **IPSN**

VTT **ENRESA**

Figure 3: annual dose rates results in the case of normal evolution scenario – Granite formations

(4N: ^{236}U → ^{232}Th; 4N+1: ^{237}Np → 233U → ^{229}Th → ^{225}Ra; 4N+2: ^{238}U → ^{234}U → ^{230}Th → ^{226}Ra; 4N+3: ^{235}U → ^{231}Pa)

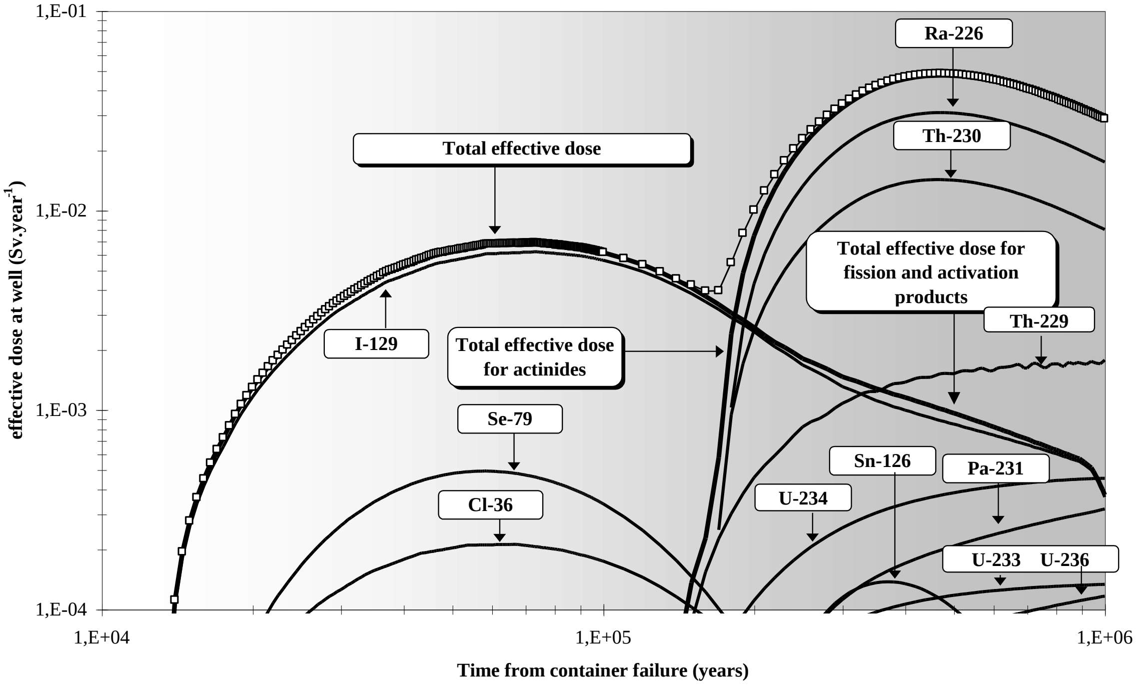

Figure 4: Total effective dose rates for the deep production well scenario and main contributors (IPSN case).