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THERMAL ANALYSES FOR OPTIMISATION WAYS OF THE REPOSITORY CONCEPT FOR HIGH LEVEL LONG LIVED WASTE GLASS PACKAGES.

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ABSTRACT

This paper is devoted to the thermal and economic aspects involved in the design and conception of a repository for High Level long-lived (HLLL) radioactive waste. The design under consideration is a deep geological disposal in argillite. The French National Radioactive Waste Management Agency (ANDRA) is in charge of the design and building of the repository. The dimensioning repository design has to meet a thermal criterion to prevent any damage on the argillite and account for the compactness of the disposal underground installation to limit the cost. In the first stage, a description of the ANDRA design, followed by the development of its 3D modelling are presented. Then, a methodology to optimise the repository design is carried out in order to determine the best concept dimensioning. Afterwards, an additional investigation of a further optimisation focuses on the reduction of the container steel thickness, the associated analyses show that two antagonist effects (geometrical and thermal effects) compete with respect to the economical optimisation of the concept.

INTRODUCTION

The purpose of ANDRA was to demonstrate the feasibility of a geological disposal of waste packages in argillite [1]. The related concept is based on the existence of technical solutions but may evolve along the successive stages. The proposed options, which are described hereafter, represent the technical concept of what a repository installation may look, it will be named the « *reference concept* ».

However, the architecture set out by ANDRA should not be regarded as a definitive optimised solution either on a technical or an economical point of view. Therefore, in this context, EDF, which is responsible of its unloaded waste from nuclear reactors, has undertaken to further analyse and optimise the ANDRA “reference concept” under various technical aspects such as chemical, mechanical, etc …. fields.

This paper only focuses on the thermal modelling of the HLLL waste glass packages, which aims in increasing both (i) the reliability of forecast phenomena, and (ii) repository compactness to minimise the cost construction. These thermal analyses are devoted to the impact of the package heat release, which is dissipated by passive conduction in the geological formation and by radiation through closed space clearances; they account for a 90°C thermal criterion to prevent the argillite from any damage.

NOMENCLATURE

Φ	[W/m^2]	Heat density flux
T	[°C]	Temperature
N	[-]	Number (of package)
Cp	[J/(kg.K)]	Specific heat
Px	[m]	Inter axial distance between 2 adjacent cells (of the same drift)
Dy	[m]	Distance between 2 opposite disposal cells end
Luc	[m]	Useable Length of cell (for packages and buffers)
Lb	[m]	Length of glass buffer
Lp	[m]	Length of disposal package
$Vexc/p$	[m^3]	Excavated Volume by disposal package
Special characters		
Δt	[s]	Time step
λ	[W/(mK)]	Thermal conductivity
ρ	[Kg/m^3]	Density
ε	[-]	Emissivity
β, γ	[-]	Radioactivity radiation types
Subscripts		
max		Maximum
BG		Geologic Barrier or argillite or rock
p		Disposal package

THE REPOSITORY CONCEPT

The deep underground disposal concept [1] is planned to be built in the east of France (in Bure site) where the permeability of the argillite is very low (a few centimeters per hundred thousand years) and suitable to confine the disposal nuclear packages.

Architecture of repository concept

The repository installation would include surface facilities connected to the underground structures. The underground disposal concept is a single horizontal level laid out in the middle of a Callovo-Oxfordian layer at a 500 m depth (Figure 1).

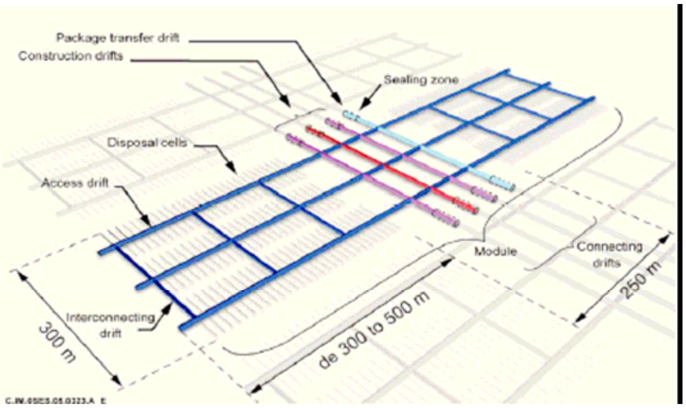

Figure 1 Underground disposal concept at a 500 m depth for (C) glass packages zone

Specialised access drifts connect shafts to repository zones. The "disposal cells" in which the waste packages are placed are dead-end horizontal tunnels of 40 m length and 0.7m diameter, laid out perpendicular to the access drifts (Figure 2). They have a 25 mm thickness metal sleeve as ground support, which enables packages to be placed in, and if necessary, withdrawn.

In the cell, the highly exothermic packages are separated by spacing buffers (dummy glass packages) to decrease the diffused heat in a larger argillite volume. The head part of the cell is blocked by a thick steel plug, to provide radiological protection. When it is decided to close the cell, i.e. after 30 years of management, swelling low permeability clay and concrete plugs tightly seal the cell head, and the access drift is back- filled by concrete.

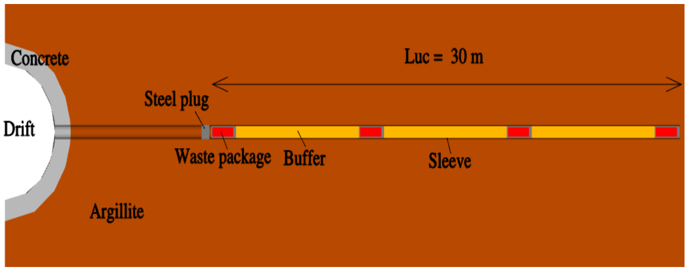

Figure 2 Repository disposal cell and drift concept

Glass Packages

The HLLL waste glass packages (Figure 3) concern unrecoverable nuclear material as fission products, minor actinides and activation products. Their high β and γ radiation level generate considerable heat, which decays fairly quickly over time as illustrated on Figure 4. Presently, these products are incorporated in a borosilicate glass matrix with a particularly high and long lasting containment capacity (several hundreds of thousand years) under favourable conditions. The radionuclides are spread uniformly in the glass matrix to constitute the C primary package. This primary package needs an over-pack to (i) ensure a reliable water tightness on the package glass during a long thermal phase (defined by a package temperature greater than 50°C, about thousand years scale) and (ii) allow the ability to with-draw packages (at least for a century) ensu-ring "reversibility" in the repository management. We study here only one variety of these disposal glass waste packages, the so-called C2 ones (PWR UOX enriched recycled uranium). For this kind of package, ANDRA suggests to install them in the cell after a preliminary storage of 60 years, when initial thermal power of the package has decreased to 489 W [2].

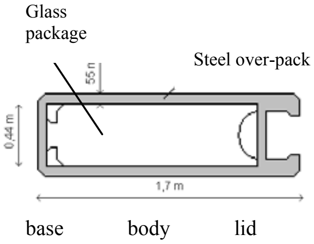

Figure 3 Disposal glass waste package (C)

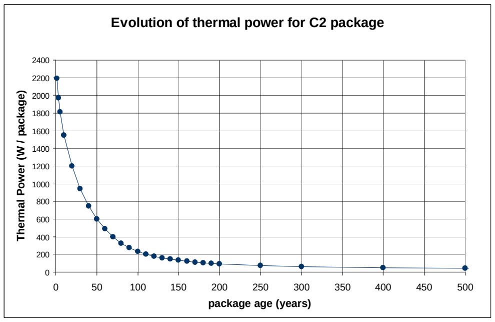

Figure 4 Thermal power of C2 package

COMPUTATIONAL MODELLING OF THE REPOSITORY

To assess and quantify the evolution of the installation modelling and simultion tools are required.

Computational tool

To model the heat transfer processes in the repository concept, the SYRTHES software is selected. This 3D numerical code can solve the conjugate heat transfer by conduction and radiation for transient process. It has been developed at EDF/R&D [3] for industrial applications.

The conduction equations are solved by a finite-element method on unstructured grids. All material characteristics are allowed to vary with space, time, and temperature, as it is needed for thermal properties of disposal materials. Anisotropy is handle for the conductivity of the different layers of argillite.

The heat transfer by radiation is solved by a radiosity approach. Accurate and efficient algorithms based on a mixing of analytical/numerical integration, and ray-tracing techniques are used to compute the view factors. The main assumption is that emitting and reflecting surfaces are supposed to be grey and characterised by an emissivity.

To couple the different phenomena, SYRTHES relies on an explicit numerical scheme, and to provide flexibility the heat transfer phenomena are solved on two independent grids.

For the 3D conduction meshing and the 2D surface radiation meshes, the SIMAIL mesh generator is used for its known relevance capacity to parameterise the grid in terms of modelling needs.

Modelling and simulation approach

The main issue with thermal repository modelling lies in the space domain (about 500 ha for C waste packages) and time scale (about thousand years).

In term of space and to limit the number of meshes and the simulation duration, only a symmetric model of a single cell is considered. This is equivalent to the modelling of an infinite lateral disposal site (of several identical cells), taking into account symmetry conditions ($\Phi = 0$) on delimited planes. In this type of approach, the lateral diffusion term in the host formation is neglected. This assumption leads to evaluate a bounding envelope of the highest rock temperature.

In term of time scale, we successively consider :

- a "*short term*" modelling which aims at simulating the heat transfer in the rock for the first thousand years after the waste disposal in the cell. During this short time, the heat is released in close field;
- a "*long term*" modelling which allows to calculate more precisely the temperature evolution on long time (over ten thousands years) and on close as well as far vertical domains.

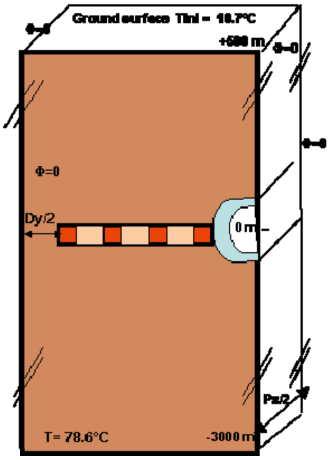

Figure 5 Representative « Long term » modelling

"Long term" modelling consists in considering a half-cell and drift with 500 m of rock above the cell and 3000 m under. It represents a slice of rock (Figure 5) delimited by four vertical symmetry planes. At one side, two planes delimit : a half drift, a whole length cell and a half distance between disposal cells end (Dy/2); at the other side, the two planes delimit half vertical cell and drift to half inter-axial distance between 2 adjacent cells (Px/2).

Boundary Conditions are:

- at ground surface : Tair = 10.7 °C, with a heat convection coefficient of 10 $W/(m^2.K)$,
- at a 3500 m depth : imposed T = 78.6 °C,
- on the 4 vertical symmetry planes, heat density flux = 0.

Initial Conditions :

- ground geothermal axial temperature gradient equal to 2.3°C/100 m with a 10.7°C ground surface [4]. This results in 22 and 78.6 °C at respectively 500 and 3500 m depths,
- Thermal power in a primary package = 489 W.

"Short term" modelling is basically similar to the "*long term*" one, but the simulation domain is reduced considering that the horizontal mid-plane of the cell and drift is a symmetry one (it represents an upper quarter cell and drift with only 500 m of rock above the cell). This modelling is use to optimise the repository dimensioning duration up to 5 years after the peak temperature on the argillite is reached (it is generally less than one hundred years after the disposal of the packages in the underground cells).

Thermal characteristics of material

These characteristics are provided in Table 1 (argillite) and Table 2 (cell). The argillite presents various anisotropy thermal conductivities for each stratified layer. The thermal conductivities and specific heat depend moreover on the temperature. These data are based on various measurements carried out on Bure underground argillite [4].

Layer in the rock	*Depth (m)*	*λ (W/m.K)*	*Cp (J/kg.K)*	*ρ (kg/m^3)*
Kimmeridgian	0 to 125	1,3	1024	2450
Oxfordien	125 to 418	2,3	925	2470
Cox 1	418 to 473,5	// : 2,2.(1-0,0009.(T-20)) ⊥: 1,6.(1-0,0009.(T-20))	1,3.T+908	2460
Cox 2	473,5 to 516	// : 1,9.(1-0,0009.(T-20)) ⊥ : 1,3.(1-0,0009.(T-20))	1,5.T+974	2390
Cox 3	516 to 548	// : 2,7.(1-0,0009.(T-20)) ⊥ : 1,9.(1-0,0009.(T-20))	2,7.T+1023	2420
Dogger	< 548	2,3	925	2470

Table 1 Physical properties of argillite

Materials	λ ($W.m^{-1}.K^{-1}$)	Cp ($J.kg^{-1}.K^{-1}$)	ρ ($kg.m^{-3}$)	ε (-)
Glass	1,3	982	2750	0.9
Concrete	1,35	1505	1600	0.9
Steel	35	500	7850	0.9
Argillite Cox	See above			0.9

Table 2 Physical properties of built material [5] + argillite emissivity

Heat transfer modelling related assumptions

The thermal power source provided in Figure 4 is considered uniformly spread over each primary glass package. The main involved **heat transfer is by conduction** in the solid built materials and in the argillite.

Heat transfer by radiation takes place in all functional clearances, and in cell head and drift before its back-filling by concrete. Two functional thin clearances appear : (i) a 15 mm thickness one between the disposal package and the sleeve and (ii) between the sleeve and the argillite a 12.5 mm one. The thin steel sleeve thickness (25 mm) would require a tiny refinement solid grid which, with the modelling of the

Figure 6 Simplified modelling

two thin clearances, would penalize the computing time. In order to simplify the modelling, a single clearance is taken into account, it represents the thickness of the clearances plus the sleeve one; this single equivalent clearance of 52.5 mm provides the same heat transfer surface and, consequently, results in the same heat flux as in the actual configuration (Figure 6). The reliability of this assumption has been proved by simulation tests. Other thin clearances are the seat of radiation heat transfer, at cell head between the first package and the plug steel (20 mm), at cell end between the last disposal package and the argillite (110 mm).

Else, it has been shown, in prior simulations, that heat transfer by convection could be neglected in these closed clearance and in the vacuum drift.

Improvement of numerical parameters

Before trying to optimise the dimensioning of the reference concept, sensitivity studies have been carried out to define the adequate numerical parameters [6].

The refinement of the different **solid meshes** (buffers, over-pack, cell, drift, rocks…) is function of primary package size in order to have regular grid. The size of the rock meshes increases as they are farther and farther from the heat packages (Figure 7). For the volumetric meshes linked to the conduction heat transfer, a reliable refinement of grid has been obtained with 5 longitudinal meshes for the 1.7 m primary package length.

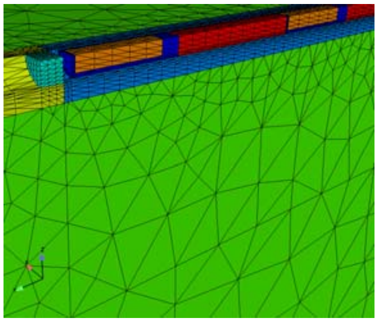

Figure 7 Solid meshes refinement

For the **radiation surface meshes**, the first test was done with 4 meshes for a disposal package and a buffer whole length. Two other tests with a refined meshing were carried out. The results, described in Table 3, show that this parameter has a significant impact on the maximum temperature of geological barrier (T_{maxGB}); thus the same refinement as solid meshes has been selected.

Variation/ Meshes	T_{maxGB} Variation	Year of T_{maxGB} Variation
4 to 20 meshes	8°C	- 3.5 years
4 to same as solid meshes (~30 meshes)	9°C	- 4.5 years

Table 3 Sensitivity on radiation meshes

The **time step** is named "multiple" in the SYRTHES code, meaning that for each successive given duration, the time step is constant. In this context, the chosen time steps are very short at the beginning of the simulation, when the thermal power and the decreasing slope are strong and after 30 years when the drift is back-filled (modelling modification). Then, the time step increases gradually with the disposal time. It is about 6 h for the first 20 days, then 2 days for the next 9 months, 3 days for the following 2 months, etc.., and 2 years from 50 years to the end of the simulation. Two refinement time tests are done. The first one consists in dividing by 2 all the time steps and the second one using an automatic time step calculated by SYRTHES code, in order directly to match on the temperature slope variation. This latter option is interesting but very computer time consuming. This is why, for the further simulations, a time step divided by 2 which gives good results, is selected.

Variation/ test time step	T_{maxBG} variation	Year of T_{maxBG} variation
Δt to Δt/2	+1.5°C	-6 years
Δt/2 to automatic Δt	-1°C	-1 year

Table 4 Sensitivity on time step

REPOSITORY DIMENSIONING OPTIMISATION

The dimensioning of the repository is conducted with the aim of controlling the T_{maxGB} and the excavated volume by disposal package (Vexc/p).

Methodology

To carry out an optimised dimensioning of the repository, a three step methodology is required, based on essential dimensional design parameters : the Number of package by useable cell length and the inter-axial distance between two adjacent cells ($N_{p/Luc}$ and Px).

The first step just consists in determining the length of the buffer (Lb) for a given number $N_{p/Luc}$, knowing the useable cell (Luc) and package lengths (Lp).

The second step is a heat optimisation control done with the "short term" modelling. The simulation is carried out with a given ($N_{p/Luc}$) and various inter-axial distance between two cells (Px) (between 3.5 m and 25 m for reference case to satisfy geo-technical laws) in order to adjust the thermal power to meet (without exceeding) the 90°C thermal criterion on the argillite.

Then, *the third step* is linked to economical needs; it consists in evaluating the necessary Vexc/p for the parameters couple ($N_{p/Luc}$, Px) which meets the thermal criterion.

These 3 steps are repeated several times in order to minimise Vexc/p, which is directly linked to the construction cost of the repository.

Finally, the optimised repository dimensioning is the couple *which results in the lowest excavated volume per package*. For this retained couple, which presents the highest possible thermal load along with the best-estimate repository from an economical point of view, a new simulation with "long term" modelling is carried out in order to have the thermal behaviour of the repository over a 1700 years duration.

Optimised dimensioning of repository

The thermal and compactness optimised dimensioning is obtained for the parameters couple (Np/Luc = 4, Px = 5.3 m) and the associated Vexc/p

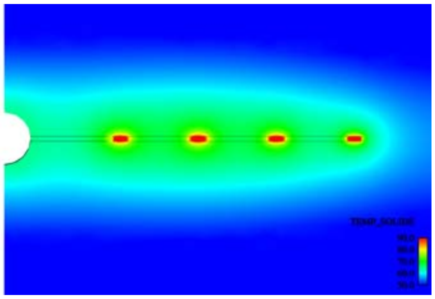

Figure 8 Thermal field close to disposal cell

is about 60 m^3 per package. The thermal pattern at peak time on the argillite is illustrated in Figure 8. The thermal optimisation resulting for tested (Np/Luc, Px) parameter couples is providing in Table 5 and visualised in Figure 9 (reference over-pack curve).

Table 5 provides a comparison between short and long term (ST and LT) modelling results obtained on the same optimised dimensioning; the difference is about 0.5 °C on the temperature peaks and 3 years on the peak of disposal time.

Configuration	Np/Luc	Px	L_B	Tmax BG	Year of TmaxBG	Tmax-p	Year of Tmax_p	Vexc	Model	Comment
Reference concept	(-)	(m)	(m)	(°C)	(years)	(°C)	(years)	(m3/ package)		
Over-pack = 55mm; Sleeve = 25mm	2	3,5	26,8	88,9	30	99,3	12	77,8	ST	limited Px > or = 3,5 m
	3	4,1	12,6	89,7	19	100,0	14	59,9		
	4	5,3	7,85	89,1	23	99,5	16	57,2		
	4	5,3	7,85	89,4	26	99,4	16	57,2	LT	
	5	6,7	5,5	89,9	27	100,1	14	57,2	ST	
	6	8,4	4,05	90,0	18	100,3	14	59		
	7	10,3	3,1	89,4	18	100,1	13	61,6		
	8	12	2,45	90,0	19	100,9	13	62,6		
	9	14,6	1,95	90,0	17	101,4	10	67,4		
	10	18,5	1,55	89,9	12	102,2	8	76,5		

Table 5 Optimised dimensioning results for reference concept

INVESTIGATION OF AN ADDITIONAL POSSIBLE OPTIMISATION WAY

The corrosion of the steel used in the repository concept release hydrogen gas and the involved overpressure is likely to impact materials and geological medium confinement. Even if this impact is still a questionable issue, investigations related to a reduction of the steel thickness, used essentially in the over-pack and sleeve are carried on at EDF with respect to thermal, mechanical, hydraulic, chemical, economical and long term safety points of view. Below, only the thermal and financial consequences on the repository concept of such steel thickness reductions, are presented.

Three package/sleeve thickness configurations are studied (see Table 6) :

- the reference configuration of ANDRA concept, in which the steel thickness has been determined in a conservative way,
- two "alternate" configurations defined further to EDF/R&D corrosion studies [7], in order to ensure that the packages can be removed for at least a century, as required for the ANDRA concept. However, the last one (steel over-pack suppression) is to be considered rather as an extreme case that could be justified only in the total absence of water in the cell, to avoid early package glass alteration.

Reference over-pack configuration Retrieved period = 4000 years	Over-pack thickness. : body = 55 mm, base : 77mm, lid : 177 mm Clearance thickness : 55 mm Interval of Px : 3,5 m< Px <25 m
Reduced over-pack configuration Retrieved period = 300 years	Over-pack thickness. :body = 20 mm, base : 50mm, lid 150 mm Clearance thickness : 55 mm Interval of Px : 3 m< Px <25 m
Suppressed over-pack configuration Retrieved period = 100 years	Over-pack thickness. : body = 0 mm, base : 0 mm, lid : 0 mm Clearance thickness : 20.5 mm Interval of Px : 2.5 m< Px <25 m

Table 6 : Studied configurations of reduction steel thickness

Simulation assumptions

In order to keep the useable 30 m cell length (Luc), the over-pack lid (used to handle the package, Figure 3) and base thickness reductions, are compensated by an equal lateral increase of the buffer lengths introduced between the packages for both "alternate" configurations.

Optimised dimensioning results

The thermal optimised dimensioning parameters for these three configurations are plotted in Figure 9. The Vexc/p values increase with steel thickness reduction, for any fixed Np/Luc value.

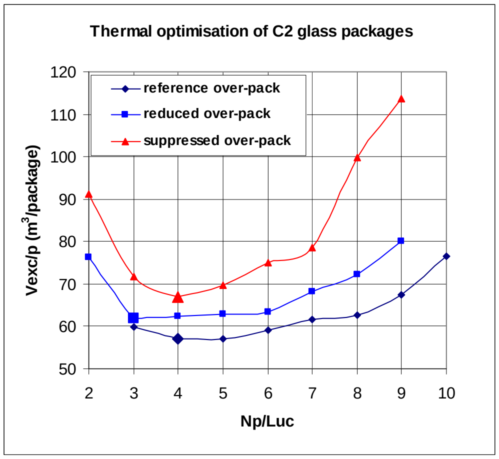

Figure 9 Thermal optimisation dimensioning

As compared to the reference configuration, Table 7 additionally shows that configurations with a reduced or suppressed over-pack results in an increase of respectively about 8 and 17% for the parameter of interest, Vexc/p.

Configuration	Over-pack thickness	Np/Luc	Px	Lb	TmaxBG	Year of TmaxBG	Tmax_p	Year of Tmax_p	Vexc/p	Relative variation of Vexc/p (reference)
(-)	(mm)	(-)	(m)	(m)	(°C)	(years)	(°C)	(years)	(m^3)	%
Reference over-pack	55	4	5,3	7,85	89,4	26	99,4	16	57,2	
Reduced over-pack	20	3	4,33	12,7	89,8	17	103,3	12	62,0	-8
Suppressed over-pack	0	4	6,4	8,2	89,6	14	111,1	7	67,0	-17

Table 7 Optimised dimensioning results

A refined physical analysis shows that two opposite effects are competing for the repository excavated volume behaviour when the steel radial thickness is reduced :

- the direct geometrical effect which results in a Vexc/p decrease;
- the indirect thermal effect associated with the reduction of the heat transfer surface of the geological barrier; it causes an increase of T_{maxBG} above the criterion (90°C). This requires to decrease the heat flux thanks to variations of influent parameters, i.e. Np/Luc decrease or Px increase which both result in a Vexc/p increase.

Evolution over time of the maximum temperatures

The behavior of the maximum temperatures on package and rock (T_{maxBG}, T_{max-p}) is characterized by a quick increase up to a peak (due to exothermal package installation in the cell) followed by gradual drop further to the transient decay of the radioactive waste.

The up and down temperatures (Figure 10) are faster with a steel thickness reduction (same findings for package temperature), this is consistent with the second afore mentioned effect.

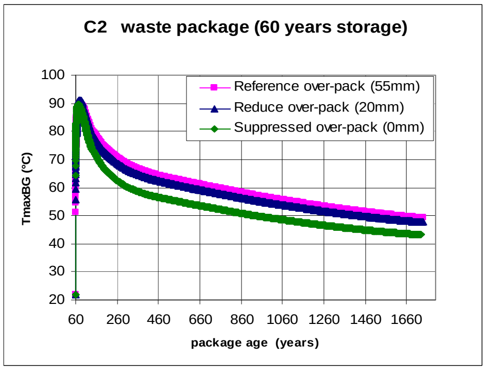

Figure 10 Temperature evolution over time

Spatial temperature profiles

On Figure 11, transverse profiles of temperature are provided at different heights (time is when highest temperature is reached at each height); as expected, they show that : (i) the oscillations, due to the succession of heat package and colder buffer, are attenuated and (ii) the temperature decreases, as the axial distance from the package increases (pink, dark blue, yellow and light blue). For the reference configuration, the peak of T_{maxBG} is located at the middle of the second package.

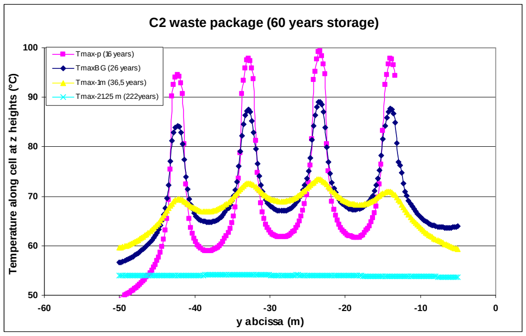

Figure 11 Temperature evolution over spatial horizontal /vertical axis

The thermal behaviour of the repository versus time as well as over local and large medium fields, affects other processes and is often an input data for chemical, hydraulic and mechanical studies.

CONCLUSION

This study aimed at determining the best repository concept dimensioning which meets the afore mentioned thermal criterion on the argillite and the compactness of excavated volume limiting the construction cost. This dimensioning results from numerical simulations of the repository thermal behaviour.

A first stage is devoted to the 3D finite element modelling with SYRTHES software for both conduction and radiation heat transfer processes that take place in the repository concept. The modelling assumptions and the numerical parameters are improved by further sensitivity simulation tests.

Then, the methodology for dimensioning optimisation with respect to two different aspects, the thermal one (result of thermal modelling which respect of a 90°C criterion on the argillite) and the economical one (minimisation of excavated volume linked to construction repository cost) is drawn up. The application to C2 glass package disposal in ANDRA reference concept, highlights the two influent optimisation dimensioning parameters : in this frame, 4 waste packages per cell separated by buffers and an inter-axial distance of 5.3 m between adjacent cells should be adopted.

Eventually, the investigation of an additional way of technical optimisation is related to the reduction of the steel thickness of the package over-pack and cell sleeve. The reference thickness questions about possible confinement alteration by chemical and mechanical processes. The thermal analysis shows that two opposite physical effects compete by increasing and decreasing the excavated volume per package. The dominating effect leads to an increase of the excavated volume and then of the repository built cost for the studied 60 years storage glass packages prior to disposal.

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