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ARTICLE

Thermal Behavior of Long-Lived Intermediate-Level Radioactive Waste in ICEDA Storage Unit

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Activated Long-Lived Intermediate-Level metallic radioactive Waste (LL-ILW) from dismantled or in operation French nuclear power plants are conditioned since 2021 in a new EDF facility named ICEDA. After conditioning, packages with LL-ILW are transferred to large halls to be stored during decades before ultimate 500 m underground geological disposal. To control the risk of Delayed Ettringite Formation (DEF) in the packages, core temperature of the packages must stay below 65°C under normal storage conditions. This paper focuses on numerical studies which evaluate the maximum temperature evolution within the packages over time, considering conduction, radiation and convection. Computations show that the core temperature in packages always stays below 65°C, even during the remarkable heatwave that occurred in 2003.

KEYWORDS: nuclear waste, LL-ILW, storage unit, thermal conduction, thermal radiation, thermal convection, numerical simulation, 0D fluid model, Delayed Ettringite Formation, SYRTHES software

I. Introduction

LL-ILW is received, conditioned and stored in ICEDA (**Fig. 1**), a new facility located in the Middle East of France. After a first stage of conditioning,[1)] where LL-ILW is blocked in a cement grout inside long-lasting and confining concrete container, containers are transferred to large halls to be stored for decades, pending disposal in a geological repository. To ensure that the packages retain their confining character, and to limit the risk of DEF, temperature inside packages (depending on mass and residual power of waste and air temperature in the hall), must not exceed 65°C[2)] under normal storage conditions. Numerical models have been developed at EDF R&D in the in-house SYRTHES code[3)] to study predictively thermal behavior of packages all year-round and to show that even in penalizing cases temperatures packages remain below the criteria.

Fig. 1 ICEDA facility

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II. ICEDA Facility

Storage Halls

EDF commissioned a Long-Lived Intermediate-Level metallic radioactive Waste (LL-ILW) conditioning facility in 2020 (**Fig. 2**). Packaging licensing was given by the Nuclear Safety French Authority in 2021. The first radioactive waste package was conditioned in ICEDA in September 2021. After conditioning, the radioactive packages are transferred into two storage halls. Each hall has a capacity of around 1100 packages arranged on three levels (Fig. 2). For a fully packed hall (after 30 years of operation), a different residual power for each package storage level is considered, depending on radioactive decay of waste and consequently on the age of the packages. Even if we know that many packages'residual power will be around a few watts, penalizing assumptions are considered for the oldest packages (those which are at the bottom level), and simulations take into account a residual power of the packages around 40 W. For the intermediate storage level, the residual power of the packages is considered

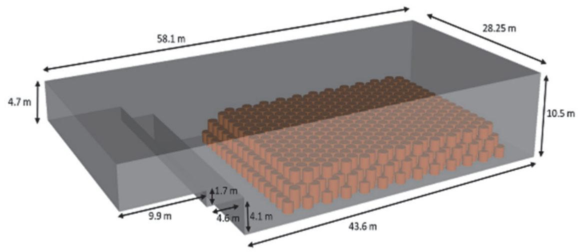

Fig. 2 ICEDA storage hall

around 55 W and finally, on the top level, the residual power of the packages is either 90 W for the older or 170 W for the newest packages. On entering the hall, the study considers that each package has a residual power of 170W even if we know that the activity of a large amont of LL-ILW has already decreased before ICEDA entrance. Under these penalizing hypotheses, the total power in the hall is 80 kW. The hall is equipped with a ventilation system with a flow rate that allows all the air in the hall to be renewed every hour.

C1PG^{SP} Long-lived Intermediate-Level Waste package (LL-ILW)

C1PG^{SP} (**Fig. 3**) is an EDF package of cylindrical shape designed with high performance concrete. The usable inner volume, a steel basket of 0.74 m^3, contains a mix of metallic radioactive waste and grout. The radiological activity of waste

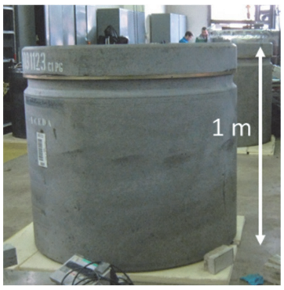

Fig. 3 C1PG^{SP} package

considered for the study is equal to 400 TBq ^{60}Co equivalent, corresponding to the maximum authorized industrial activity for thermal β–γ emitting radionuclides group including ^{108m}Ag. The corresponding residual waste power is equal to 170 W (a penalizing value for every package). Even if the aim is to fill the usable volume of the basket with a large amount of radioactive waste in to limit the number of containers, the penalizing mass chosen for the study is the minimum authorized industrial limit of 400 kg of waste per package. This allows to be in the most penalizing case with a maximum of power contained in a minimum volume (representing 13.7% of the usable volume in the package, **Fig. 4**), which leads to a maximum waste energy density while energy dissipation by conduction is limited by a few amounts of metallic waste in the basket.

III. Numerical Tools: SYRTHES and Code_Saturne

The solid thermal code SYRTHES[3] relies on a finite element technique to solve the general heat equation where all properties can be time, space or temperature dependent. The air in a hall is a non-participating media so SYRTHES radiation from wall-to-wall model is well suited. Surface properties are considered grey (only emissivity must be defined) and the radiation solver is based on a radiosity approach.[4] SYRTHES provides also a 0D fluid model that allows to consider the effect of fluid cavities, each cavity being represented by only one point. Physical properties of fluid and volume of the cavity are attached to the point so we can calculate the energy transfers between the inner boundaries of the hall outer surface of the packages and the air. Flow rates between the different parts of the cavity are given. *Code_Saturne*,[5] developed by EDF is used for thermalhydraulic. The CFD code solves the averaged Navier-Stokes equations for steady or transient, single phase, incompressible, laminar or turbulent flows. Here k-ε turbulent models have been used, but many more turbulence models are available within *Code_Saturne*.

Conjugate heat transfer is used at the fluid/solid interface. Let T_w be the temperature at a node which belongs to the interface, and T_f the fluid temperature within the log layer. At time $t^{(n)}$, the CFD tool *Code_Saturne* provides $h^{(n)}$ the local heat exchange coefficient and $T_f^{(n)}$ the fluid temperature.

Then, in the solid, $\phi_s^{(n+1)}$, the boundary flux at time $t^{(n+1)}$ can be calculated: $\phi_s^{(n+1)} = h^{(n)}(T_w^{(n+1)}-T_f^{(n)})$. Finally, SYRTHES can solve the heat conduction equation inside the solid using this flux as boundary condition. A similar procedure is used in the fluid to update the fluid temperature field.

IV. Methodology

All packages in the stack (with perfect contact between packages), the entire hall frame, the air flowing in the hall and in the gaps between the packages are modeled individually. The three modes of heat transfer i.e. conduction, radiation and convection (**Fig. 5**) must be evaluated and coupled together to obtain the thermal field in the packages.

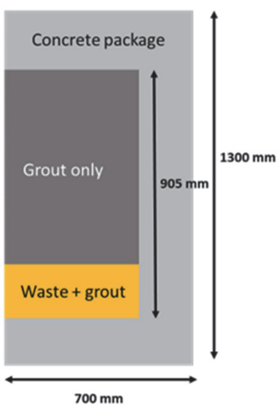

Fig. 4 Penalizing loading case of C1PG^{SP} package

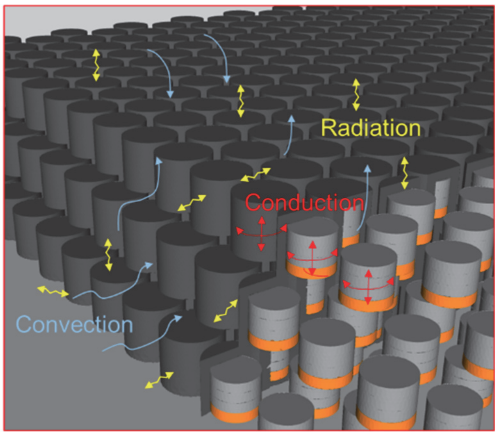

Fig. 5 Conduction, convection and radiation are accounted in the numerical model

Given that year-long transients are required, full 3D computations using a CFD code are not a viable option. This is why we turned to simulations that take into account thermal conduction and radiation in 3D but model the hall's aeraulics using a simpler 0D multi-zonal model. To validate the final numerical model, a step-by-step approach is used:

- Step 1: Full 3D coupled thermal/thermohydraulic calculations with SYRTHES/ *Code_Saturne* for steady states.
- Step 2: SYRTHES 3D thermal calculations (conduction-radiation-0D fluid model) are then performed for the same steady state. Results obtained with that model are compared with the full 3D conjugate heat transfer approach.
- Step 3: long transient studies are done with SYRTHES-3D-0D fluid (1 year and more) and the temperatures at any point of the packages and the frame of the hall at any time are determined.

Numerical models: full 3D and 3D-solid-0D fluid models

To solve the thermal problem, SYRTHES is based on 2 distinct meshes.[6] The first one (**Fig. 6**), volumetric, is dedicated to conduction (42 million elements), while the second one, surface-based, is used to solve radiation equations (**Fig. 7**). SYRTHES uses the classical view factors method

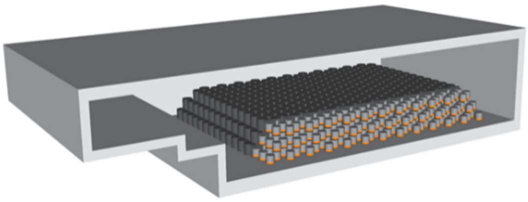

Fig. 6 Conduction mesh (42M cells)

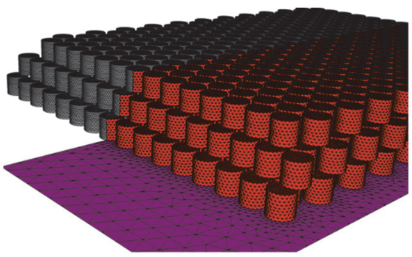

Fig. 7 Part of radiative mesh (Up to 485000 patches leading to 2.3 10^{11} view factors calculation)

and can handle large radiation meshes in complex geometries thanks to ray-tracing powerful algorithms[7] and highly parallel computing procedures. To handle the radiative exchange between the 1093 packages themselves and between stack and walls, different radiation mesh sizes were tested - up to 483 000 patches triangles (leading to the evaluation of 2.3 10^{11} view factors). Computation times remain low: under 10 minutes for 130 000 patches on 48 processors, and around 1 hour for 483 000 patches and 96 processors or 15 minutes for 483 000 patches on 384 processors. View factors are purely geometric quantities and need to be calculated only once for a given simulation. Parametric calculations can then be performed by simply re-reading the view factors. The initial phase of the radiative calculation is then instantaneous.

For full 3D fluid/solid computations, an additional fluid mesh is used by *Code_Saturne* (65 million elements, **Fig. 8**).

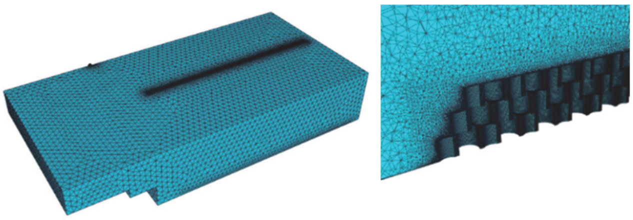

Fig. 8 Fluid mesh (65M cells)

For the 3D solid model combined to a 0D fluid model, previously generated conduction and radiation meshes are used. There is however no need for a 3D fluid mesh, and the *Code_Saturne* CFD code is replaced by a SYRTHES zonal approach.

In this model, the fluid in a cavity is assumed to be well mixed and can be represented by a single temperature. This temperature evolves as a function of time and is determined by calculating energy balances at each time step. On the one hand, we take into account the fluid entering and leaving the cavity, and on the other hand, we take into account the heat exchange between the fluid and the walls surrounding the cavity.

Here the model has been enriched by defining 5 zones, each with a fairly homogeneous temperature. The balances are therefore calculated on the basis of the exchanges with the walls of the zone and the flow entering and leaving the zone. Once the 5 fluid temperatures have been calculated, they are used as boundary conditions for the thermal analysis.

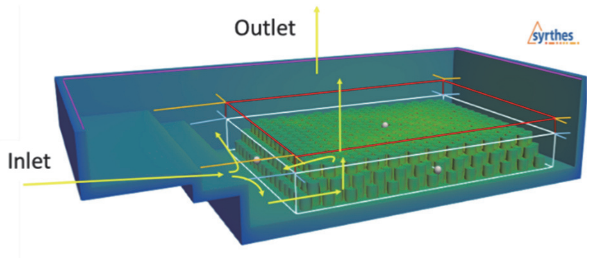

Fig. 9 0D zonal fluid model

Figure 9 shows the 5 defined zones corresponding to the mezzanine air entrance, the stack bottom layer, the stack top layer, the zone surrounding the stack and finally the top of the hall. Flow rates going through the different zones are set using the results of the previous CFD simulations.

V. Results

Results for steady states - steps 1 and 2

The first steps in our methodology are to compute permanent states with SYRTHES/*Code_Saturne* conjugate heat transfer (step 1) as well as with SYRTHES and a 0D fluid model (step 2). The aim is to validate our simplified 0D fluid model before performing long transient calculations. France experienced a remarkable heatwave during the summer of 2003. During that period, in the vicinity of the facility, temperatures rose above 40°C, but the average day-night temperature over the 10 days of the heatwave was 27°C. This value can be considered as a reference point for a hot steady boundary condition for the air outside temperature. However, to validate the model, various calculations have been carried out with outside air temperatures between 10 and 31°C. Results for a case with a constant outside temperature of 27°C are detailed below. **Figure 10** shows good agreement between both approaches: the maximum of temperature reached in side the packages is 55.4°C for the full 3D approach and 55.9°C when using the 0D fluid model for the air flow (3D-0D approach). Regarding the air temperature in the hall, the value reached is 36.1°C for the full 3D approach and 35.8°C for 3D-0D approach. Other steady states, with different outside air temperatures have been calculated and showed again good agreement between both models, with deviations of less than 0.5°C. These results validate the SYRTHES 3D-0D approach, showing that the temperature inside the packages can be well estimated using an averaged model for air flow. Now, this approach can be used to calculate one-year transients.

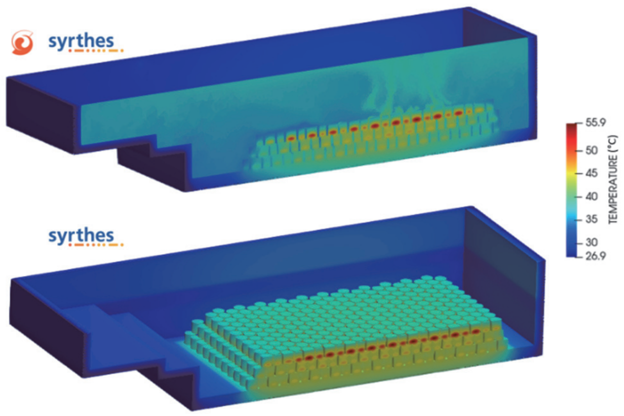

Fig. 10 Steady state with outside temperature of 27°C. Comparison of packages'temperature between the full 3D model (top) and SYRTHES-3D-0D fluid model (bottom)

Results for transient calculations – step 3

When performing transient simulations, weather conditions have an important influence. Wind measurements provide exchange coefficients for outer walls and temperature and solar flux measurements are used as boundary conditions.

Figure 11 shows outdoor temperatures in 2003, with a particular focus on the heat wave in August (red box). **Figure 12** shows the wind velocity and **Fig. 13** the solar flux around the facility during year 2003.

The packages are placed on the hall floor (with perfect contact). A constant 12°C temperature all year round can be considered 10 m deep under the slab. Here, instead of modelling explicitly this layer, an equivalent heat exchange coefficient of 0.1 W/(m^{2}K) has been used direcltly under the slab.

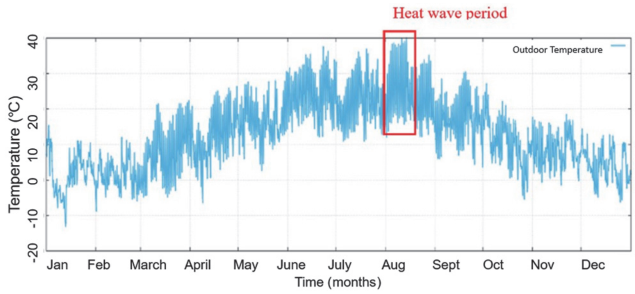

Fig. 11 Outside temperature during year 2003 (heatwave period in the red square)

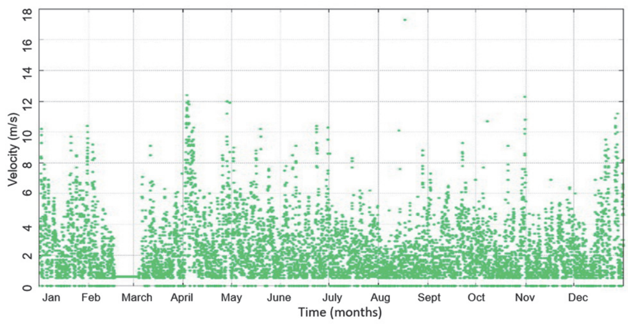

Fig. 12 wind velocity for year 2003

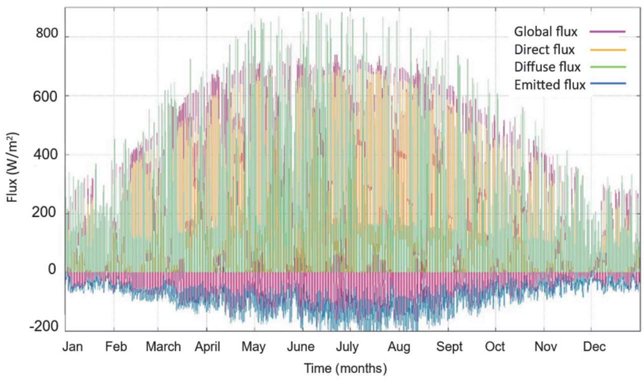

Fig. 13 Solar flux for year 2003 (direct flux in yellow, diffuse flux in green and emitted flux in blue - global flux in pink)

Figure 14 shows the result of the simulation: the evolution of the year-round maximum temperature of packages based on outside temperatures recorded in 2003 near ICEDA unit, for the most unfavorable case i.e. when waste occupies only 13.7% of the usable volume (400 kg of waste, Fig. 4) and for a residual power of 170 W (most unfavorable case i.e. which maximizes the flux density).

The highest temperatures are reached in the upper level packages: even though they are better cooled by ventilation, these are the most recent packages and therefore the ones with the greatest residual power.

Even during heat waves, the packages' temperatures never exceed 59.8°C, and the extraction air temperature (representative of the average air temperature in the storage hall) does not exceed 40°C.

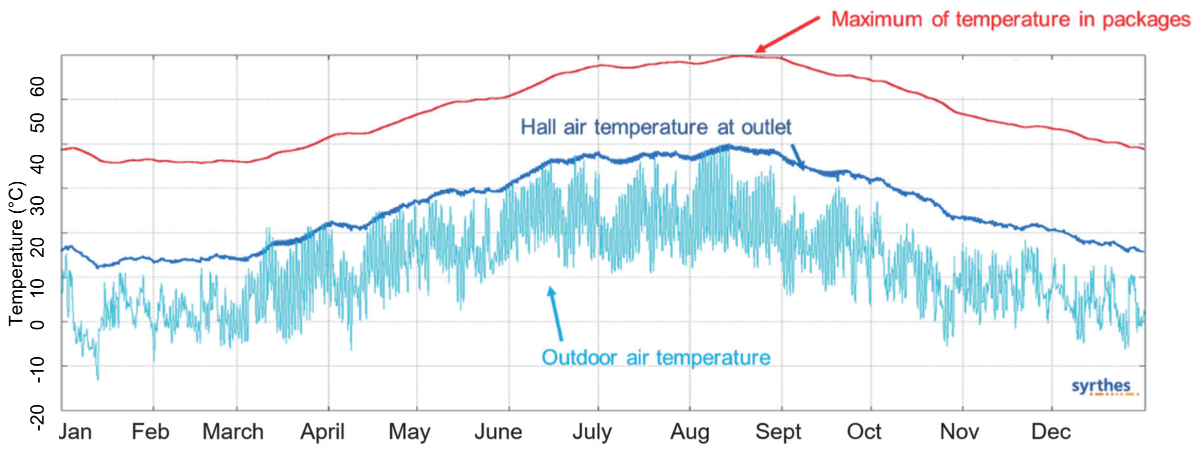

Fig. 14 Maximum temperature in the packages during year 2003

Case of global warming

Based on the remarkable heat-year of 2003, the case of global warming has also been studied. If an increase of +2°C or +4°C in average annual 2003 temperatures is considered, we demonstrate that packages temperatures remain below 65°C even during a summer heatwave. The maximum temperatures reached are shown in **Table 1** for both configurations, while the evolution of maximum temperatures in the packages is plotted in **Fig. 15**.

Table 1 Target thickness and isotopic enrichment

Outside Temp (°C)	Packages Temp (°C)
Year 2003	59.8
+2	61.7
+4	63.6

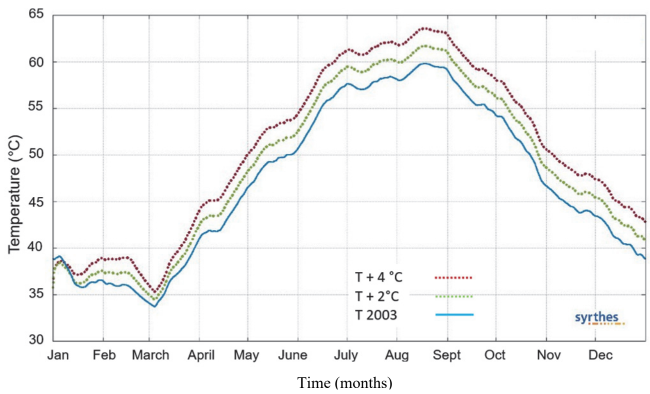

Fig. 15 Maximum temperature in the packages in case of global warming (+2°C or +4°C)

Influence of the quantity of waste in the packages

So far, we have considered the very penalizing case of maximum flux density (in packages where the waste occupies only 13.7% of the volume). In the case of less penalizing waste, i.e. fuller packages, we show that the temperatures reached are even lower. Thus, if the waste occupies 25% of the useful volume of the packages, the maximum temperature reached in the packages under 2003 conditions is 57.6°C. And if the waste occupies 50% of the useful volume of the packages, the maximum temperature reached in the packages under 2003 conditions drops to 54.7°C (**Fig. 16, Fig. 17).**

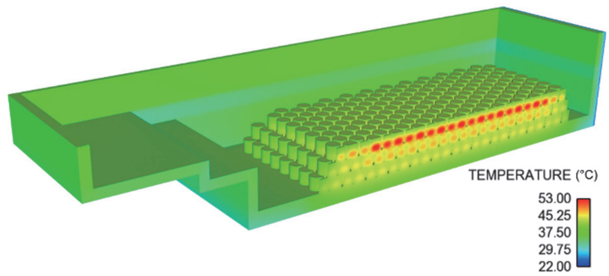

Fig. 16 Temperature in the hall and in the packages when they are 50% full

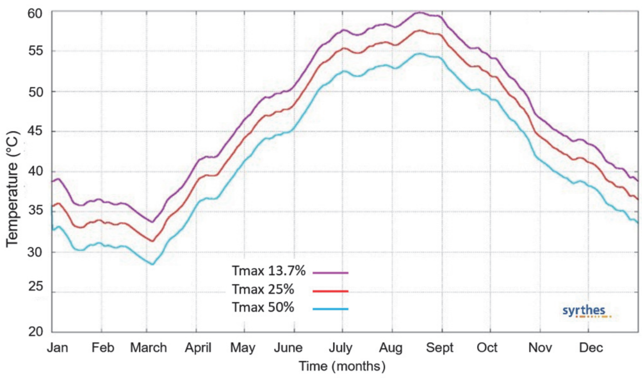

Fig. 17 Maximum temperature in the packages as a function of the fill rate (13.7%, 25% and 50% filling)

VI. Conclusion

A numerical model has been developed to take detailed account of conduction and radiation phenomena in the hall and in the stack of packages. This model has been supplemented by a 0D fluid model to take account of convection during very long transients lasting one year or more This model was validated by performing conjugate heat transfer calculations with a CFD code. Thermal/CFD 3D and thermal/Fluid 0D models predict similar maximum temperatures in the packages. The implementation of a multi-zone 0D fluid model is validated for modeling hall aeraulics over very long transients.

Under unfavorable conditions / penalizing hypotheses, results for the ICEDA facility show that packages filled by 13.7% in volume with waste (400 kg) reach a maximum temperature of 59.8°C over the year.

We also highlight that in the context of global warming (assuming an average temperature increase of +2°C or +4°C compared with the remarkable heat-year 2003), the increase of maximum temperature in the packages is proportional to the increase of the outside air temperature.

Throughout this study we have considered a very penalizing case where all the packages contain only a small volume of waste (13.7%) and we have shown that in cases where the volume of waste is greater, the maximum temperature reached in the packages is then lower.

All the configurations tested in this study show that the temperatures in the packages stay below the acceptable limits to manage Delayed Ettringite Formation risk.

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