Numerical Analysis And Experimental Verification of a Fire Resistant Overpack for Nuclear Waste

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Abstract: Confinement systems for nuclear waste are usually designed to perform and ensure safety in view of all the assumed design basis events, including fires. Considering waste typology and radioactivity, the goal of the confinement system design is to protect the content of the steel drums against a two hours fire event. At this aim Sogin has chosen to use Fiber Reinforced Concrete (FRC) shells. Numerical analyses are carried out to evaluate fire performance level of the overpacks in different CASEs. The study has been performed with COMSOL Multiphysics® using Heat Transfer to evaluate the thermal field and Structural Mechanics Modules to compute the stress induced in the concrete. In order to confirm the numerical results, two prototypes were tested in a certified laboratory in the design CASEs. The comparison with the experimental data shows a good match of the numerical results.

Keywords: CFD**,** Conjugate heat transfer, Structural mechanics, Fire resistance, Nuclear.

1. Introduction

In order to reduce radiological release to workers, publics and environment in case of accident, fire hazard analysis (FHA) and safety analysis identify the acceptable damage level for the containment and fire barriers.
This is the case of a non-conditioned alpha-radioactive waste lot that Sogin is going to stock in one of its temporary storage facilities.
For facilities containing radioactive materials, DOE Standard states that structure's fire resistance rating shall be designed for the maximum fire exposure of two hours.
For the specific case, it is also required that confinement system protects the content of the steel drums against a two hours fire event.

At this aim Sogin has chosen to use polymeric fiber-reinforced concrete (FRC) overpacks, assuring the structural integrity of it and limiting the temperature rise inside the drums to exclude any activity release into the environment in case of accident.
Considering the strict geometrical restraints given by the storage space availability (that is an existing building), numerical analyses were carried out to evaluate the fire performance level of the new overpacks.
Two different CASEs are investigated: in the former the inner gap between the concrete overpack and the drum is filled with ceramic fiber blanket, in the latter with air. Standard fire curve and thermo-mechanical properties from literature data have been used considering an axial-symmetric model (see Figure 5).
The study has been performed with COMSOL Multiphysics® (Heat Transfer, Transport of Diluted Species, and Structural Mechanics Modules). The transient heat transfer simulations include conduction, convection and radiation phenomena and moist variation thermodynamic effects. The fluid flow within the air gap due to buoyancy force (natural convection) has been modeled with single phase flow interface.
Finally, a thermo-elastic analysis has been performed using the thermal field computed in the previous study as input, to evaluate the stress field induced in the concrete.
In order to confirm the numerical results, two prototypes of the concrete shells were tested in a certified laboratory in the design CASE.
The development of this work allowed us to obtain detailed information for the design of the new fire resistant overpack.

2. Standard requirements

Fire resistance class of structural elements is the duration of time, two-hours fire event according to DOE 1066-2012, that an assembly can endure the standard fire defined in UNI EN 1363-1:2012 (Figure 5), limiting temperature rise in the unexposed side to 140 K for the average value and 180 K for the maximum value, maintaining its structural functions.
The mechanical strength was preliminarly evaluated using the simplified method according to UNI EN 1992-1-2:2005.

3. Drum's confinement system

Confinement system is composed by three containment layers: on the outside a 100mm to 120mm (average 110mm) thickness of concrete shell, inox steel drum overpack (285l), carbon steel drum (220l-containing waste). The shell is 920mm diameter and 1200mm high. The shell material is a polymeric fiber reinforced concrete. The polymeric fibers (in the concentration of 2% in mass) reduce the spalling phenomena. Furthermore, at a temperature of 440 K, parts of polymeric fibers sublimate leaving free air cavities in the matrix that increase thermal insulation.

Container cap is simply supported on the shell walls. Between cap and walls a high temperature mastic is applied to increase the tightness of the shell.

Thermal field from numerical analysis was used also to evaluate the appropriate concrete cover which protects the reinforcement bars from fire (steel bars work temperature less than 473 K).

Two different cases are investigated: in the CASE A the inner gap between the concrete overpack and the 285l drum (cavity1) is filled with 25mm thickness of ceramic fiber blanket, in the CASE B the gap is filled with air (cavity thickness from 25mm-40mm). The gap between the 220l and 285l drums (cavity2) is about 28mm and is filled with air in both cases.

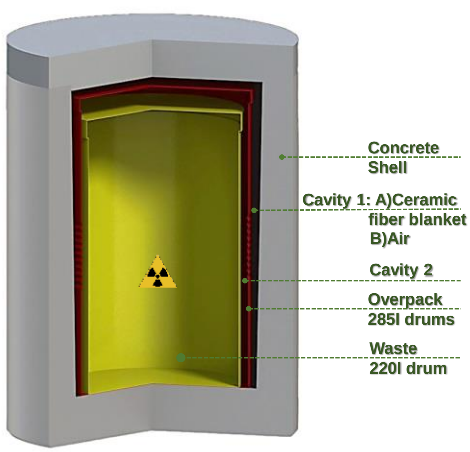

Figure 1. Confinement system

4. Numerical Model

The analysis has been carried out on an axial symmetric model. In this section are described the physical features of the system, the boundary conditions, the material properties and the simplified approach used to take into account the evaporation of the water content in concrete during temperature rise (free and mixed water).

4.1 Governing equations

The heat transfer processes in fluid domains can be described by a system of partial differential equations derived by imposing the conservation of mass (1), Navier-Stockes equation (2), thermal energy (3) within an infinitesimal element of volume. It has been also included the irradiation phenomena on the cavity boundaries (4).

Structural mechanics module is governed by indefinite equilibrium equation (5) and thermal strains (6).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \quad (1)$$

$$\frac{D\rho \boldsymbol{u}}{Dt} = -\nabla p + \nabla \cdot \boldsymbol{\tau} - \frac{2}{3}\mu \cdot \nabla \cdot \boldsymbol{u})I + \rho \boldsymbol{g} \quad (2)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + (\boldsymbol{u} \cdot \nabla)T\right) = \nabla \cdot (k\nabla T) + \boldsymbol{Q} \quad (3)(7)$$

$$q = \varepsilon \cdot (G - \sigma \cdot T^4) \quad (4)$$

$$\nabla \cdot S + F_v = 0 \quad (5)$$

$$\varepsilon_{th} = \alpha \cdot (T - T_{ref}) \quad (6)$$

4.2 Boundary conditions

In both models, the following boundary conditions are applied: the shell is placed on a concrete slab floor, the initial temperature is set to 290 K, standard fire curve on the exposed sides, adiabatic wall on the inner surface of 220l steel drum and on the bottom of slab floor. For what concern the air gap, boundaries are no slip walls, pressure constraints is set on a corner of air cavities.

A material with small elastic modulus is modeled to simulate the high temperature mastic in the space between shell's cup and wall constraint.

The shell is simply placed on the concrete slab (roller constraint).

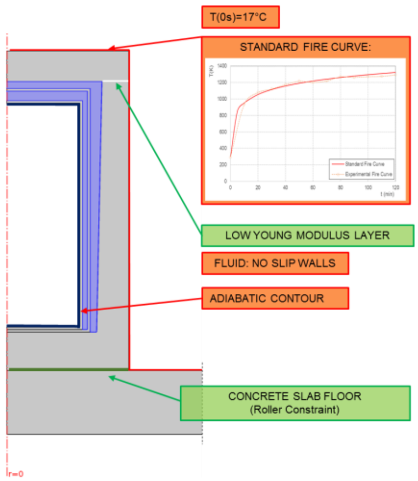

Figure 2. Boundary conditions

4.3 Material Properties

Material properties are temperature dependent, and are modeled according to Eurocodes: UNI EN 1992-1-2:2005 for moist concrete, UNI EN 1993-1-2:2005 for carbon steel, UNI EN 1993-1-4:2015 for stainless steel. Supplier data for ceramic fiber blanket properties are used.

In particular, the c_p in concrete has been computed according to UNI EN 1992-1-2:2005 (see Figure 3). The c_p value has been conveniently increased to take into account the evaporation process of water during the test and the presence of polymeric fibers in the matrix.

The free and mixed water loosed (evaporated) during the test has been determined from the variation in mass computed from the equation below (UNI EN 1992-1-2:2005)

$$\rho(T) = \rho(273K) \cdot \left(0.95 - 0.07 \cdot \left(\frac{T - 673}{1073}\right)\right)$$

For a temperature of about 1350 K, the loss of mass (that is the water content) is about 12%.

Therefore, the c_p value has been assumed at 10’000kJ/kg·K.

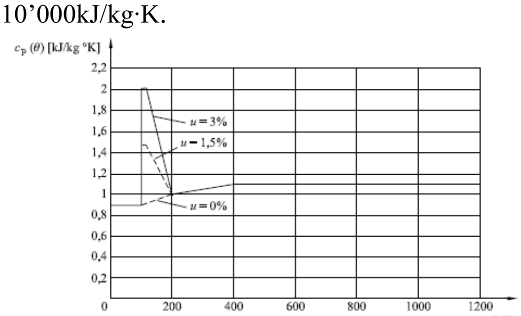

Figure 3.-Example of c_p variation depending on temperature and water content (UNI EN 1992-1-2:2005)

The air in the gaps has been modeled assuming the moist air as an ideal gas.

The thermo-dynamical properties of moist air, such as density and heat capacity, have been computed through the mixture formula.

In particular the air in cavity 1 has been considered at the saturation point from the initial time until the reaching of 368 K.

5. Use of COMSOL Multiphysics® Software

The numerical analysis has been performed with Comsol Multiphysics 5.2a. The Heat Transfer and Structural Mechanics modules have been used in the following steps: 1) Heat Transfer transient study (single-phase compressible flow full Navier-Stokes approach); 2) Stationary Structural Mechanical study to evaluate thermal stresses due to temperature field obtained in the previous study at 120min.

The fluid flow is computed in both cases with turbulent Low Reynolds k-ε closure model (integration up to the wall)

5.1 Mesh

The simulation is carried out using two different mesh for CASE A and CASE B. In the section the main parameter are listed:

CASE A: the mesh consist of roughly 200’000 triangular and quadrilateral elements with 0.925 average element quality (minimum quality 0.061)

CASE B: the mesh is composed by about 400000 triangular and quadrilateral elements with average element quality 0.879 (minimum quality 0.064). A finer mesh near the wall is used to model the boundary layers to accomplice the integration up to the wall approach (see Figure 4).

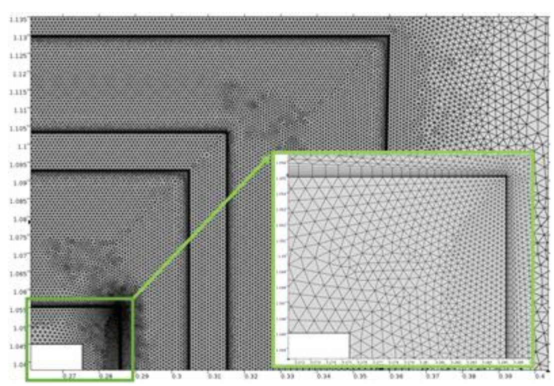

Figure 4. Particular of Mesh for the CASE B

5. Experimental Set-up

The test was carried out in a certified laboratory. The experimental oven is 4000mmx3000mm and provided with four burners and thermocouples to have a good fit with standard fire curve as shown in Figure 5. Four thermocouples to measure temperature on each face of interest are installed (see Figure 6). Internal pressure of the hoven is also monitored. Two prototyped have been tested for CASE A and CASE B.

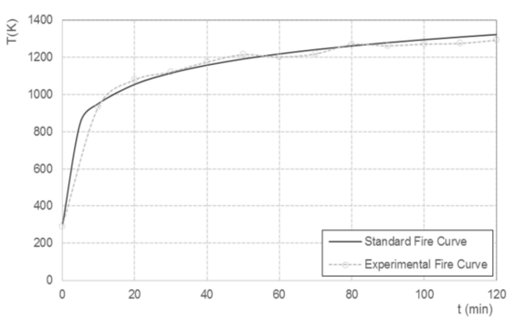

Figure 5. Comparison between standard fire curve and temperature-time curve used in laboratory test

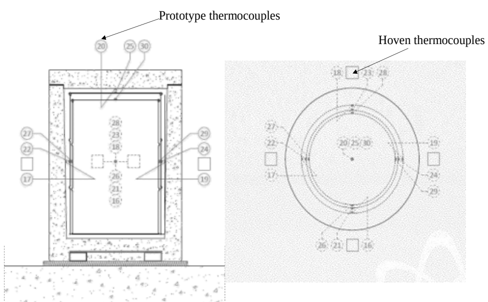

Figure 6. Example of Thermocouples positioning for CASE B

A final visual inspection of the shell assures the structural integrity of concrete (see Figure 7).

Figure 7. Experimental set-up: final inspection

7. Results

In the figures below a comparison between numerical results and experimental data is shown. In Figure 8, for CASE A, the average value of temperature in the inner surface of concrete shell during test is shown. The temperature value between numerical results and experimental data differs of about 35 K at final time, 120 minutes.
In Figure 10, the temperature profile on the cutline at z=850mm and the average temperature measured on the thermocouples at 120min are compared.

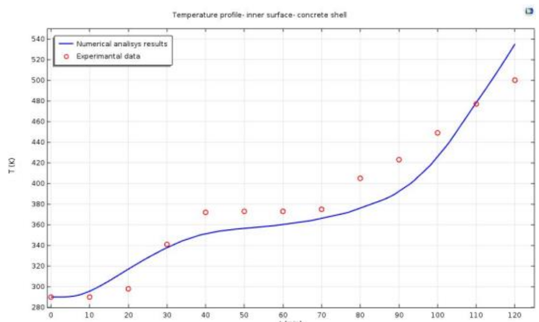

Figure 8. CASE A: Inner surface of concrete shell: Comparison between numerical results and experimental data

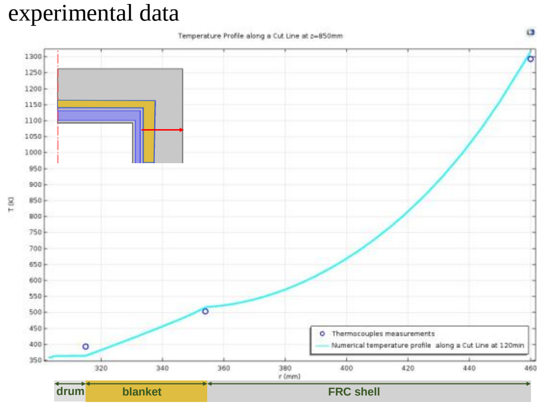

Figure 9. CASE A: Temperature profile for a cut line at z=850mm: Comparison between numerical results and experimental data

In Figure 10, for CASE B, the average value of temperature in the inner surface of concrete shell during test is shown. The temperature value between numerical and test data differs of 8K at final time, 120 minutes.
In Figure 11 the temperature profile on the cutline at z=850mm and the average temperature measured at 120min are compared.
In both cases, the difference between measured and analytical data is less than 10%.

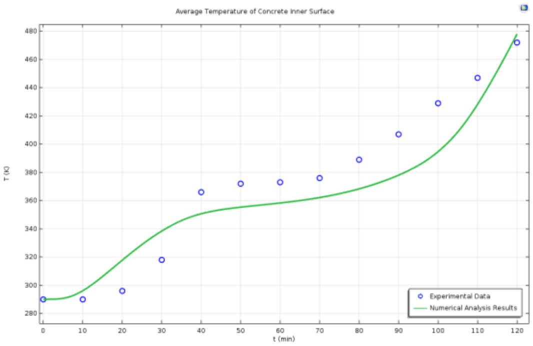

Figure 10. CASE B: Inner surface of concrete shell: Comparison between numerical results and experimental data

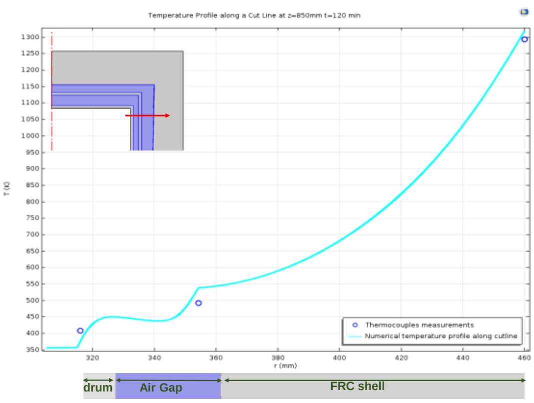

Figure 11. CASE B: Temperature profile for a cut line at z=850mm: Comparison between numerical results and experimental data

In the Figure 12, the streamlines colored by the velocity magnitude are shown. The maximum velocity computed is 0.45m/s in the cavity 1.

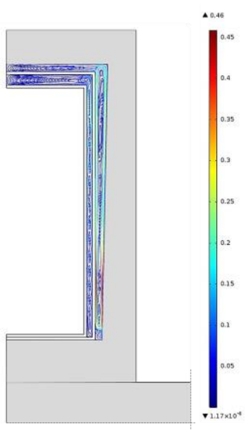

Figure 12. – CASE B: Velocity field in fluid

In Figure 13 and in Figure 14 the structural mechanics module results are shown in terms of thermal stresses and displacement field.

The bottom of the shell, that is less affected by the increase of temperature caused by fire event, works at lowest temperature and represents a constraint for the deformation of the walls (see Figure 14).

Tensile stresses are distributed on the inner surface walls and reach maximum values near to the bottom (see Figure 13). Steel reinforcement bars have been designed taking into account the distribution of thermal stresses and steel temperature.

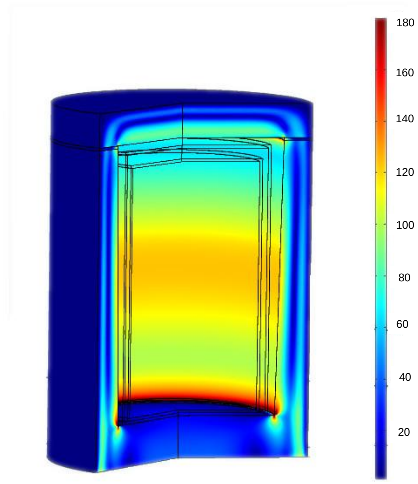

Figure 13. – CASE B: Thermal stresses

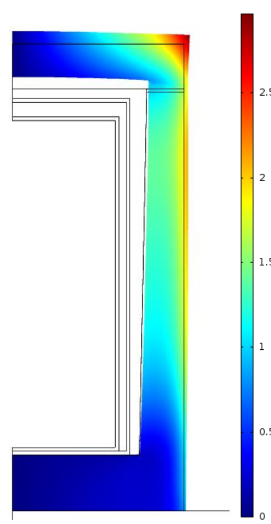

Figure 14. – CASE B: Displacement field

Figures show a good match between analysis and experimental data. The differences are due to: 1) the use of thermal properties suggested by EC2 for standard concrete instead of FRC; 2) the difference between boundary conditions and experimental set up, like for example the relative positions of burner and thermocouples 3) the exact positioning of the thermocouples; 4) the lack of modeling of the water evaporation and consequently moisture diffusion in the porous material and fluid.

8. Conclusions

The comparison with the experimental data shows a good match of the numerical results and confirms the capability of COMSOL Multiphysics® as a multiphysics simulation tool.
The development of this work enable us to optimize the design of the new fire resistant overpack.
Further investigation could be focused on the modeling of moisture transport in porous media and fluid.

9. References

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