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

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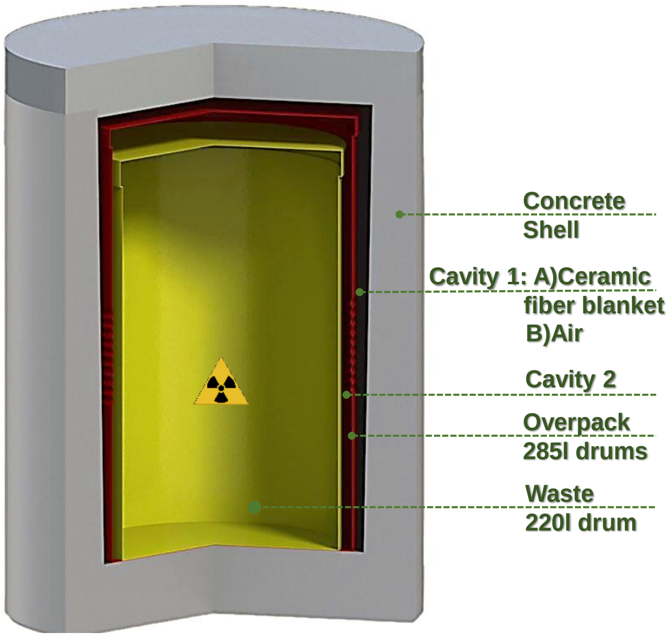
Presentation outline

- Introduction
- Standard's requirements / Experimental set-up
- Numerical model
- Equations and computational domain
- Numerical – Experimental comparison results
- Conclusions

Introduction

For facilities containing radioactive materials, DOE Standard states at least structure's fire resistance for a two hours fire exposure. The aim of this study was to design a Fiber Reinforced Concrete (FRC) overpack that assures thermal insulation and structural integrity of the containment, limiting the release in environment in case of a two hours fire event. A thermo elastic analysis was performed to evaluate the stress field induced in the concrete.
Two prototypes were tested in a certified laboratory to confirm thermal numerical results.



Confinement system is composed by three containment layers:

- A 100mm to 120mm (average 110mm) thickness of concrete shell of 920mm diameter and 1200mm high. The shell material is a polymeric FRC.
- Cavity 1 (CASE A, CASE B)
- Inox steel drum overpack (285l)
- Cavity 2 (filled with air)
- Carbon steel drum (220l-containing waste).

Numerical model

GOVERNING EQUATIONS

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \qquad q = \varepsilon \cdot (G - \sigma \cdot T^4)$$

$$\frac{D\rho \boldsymbol{u}}{Dt} = -\nabla p + \nabla \cdot \boldsymbol{\tau} - \frac{2}{3}\mu \cdot \nabla \cdot \boldsymbol{u})I + \rho \boldsymbol{g} \qquad \nabla \cdot S + F_v = 0$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + (\boldsymbol{u} \cdot \nabla) T \right) = \nabla \cdot (k \nabla T) + \boldsymbol{Q} \qquad \varepsilon_{th} = \alpha \cdot (T - T_{ref})$$

HEAT TRANSFER SIMULATION

COMSOL MODULE: CONJUGATE HEAT TRANSFER

TYPE: TRANSIENT

MODEL: TURBULENT FLOW K-EPS (WALL INTEGRATION)

SOLVER: DIRECT, SEGREGATED, MUMPS

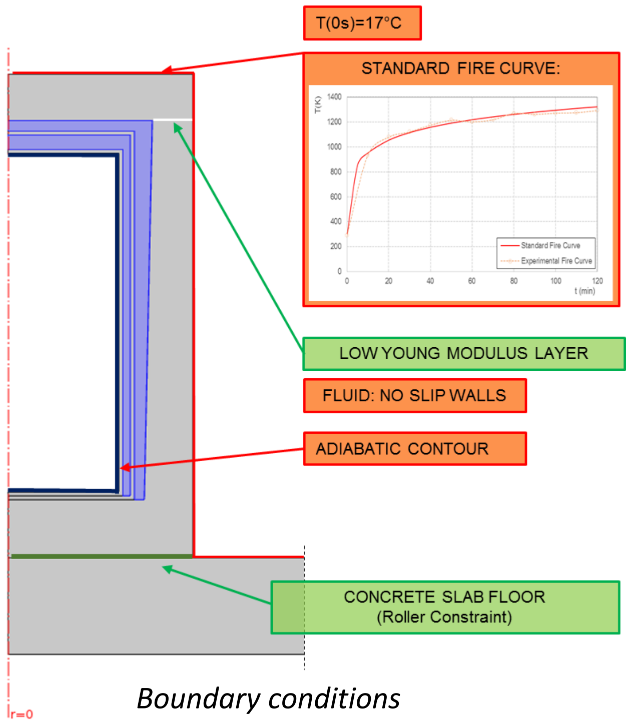
THERMAL STRESS

COMSOL MODULE: STRUCTURAL MECHANICS

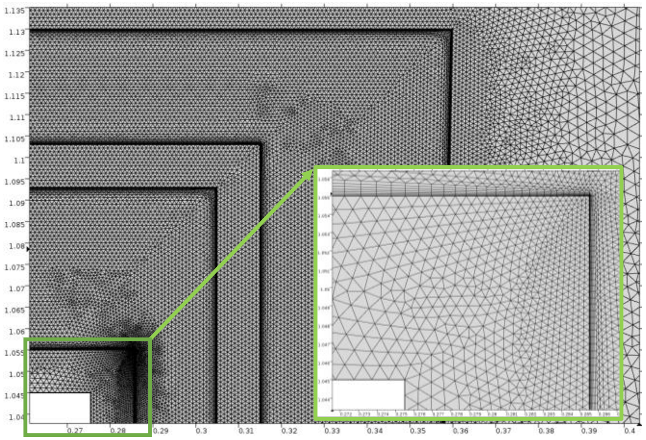
TYPE: STATIONARY

MODEL: LINEAR ELASTIC

SOLVER: DIRECT, MUMPS, FULLY-COUPLED SOLVER



Boundary conditions



Particular of mesh

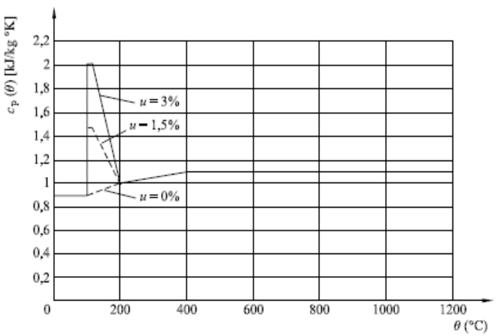
Numerical Model: material properties

Thermal properties

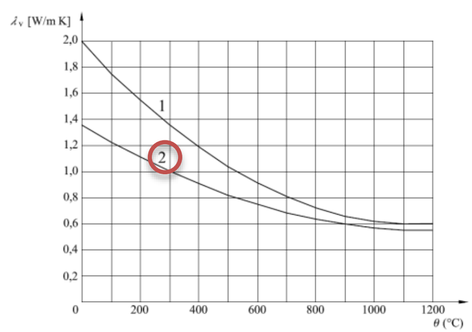
- ρ: loss of mass depending on temperature (UNI EN 1992-1-2:2005)

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

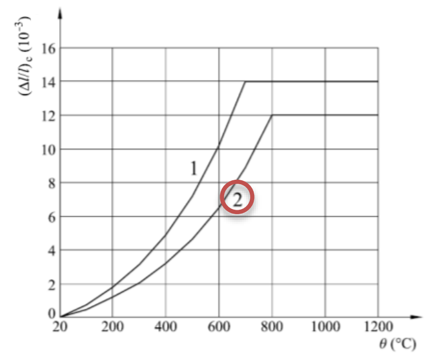
For a temperature of about 1350 K, the loss of mass (that is the water content) is about 12%. Therefore, the cp value has been assumed at 10.000kJ/kg·K



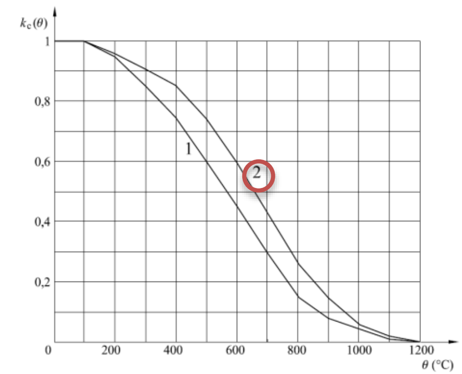
- λ: variation of conducibility depending on temperature (UNI EN 1992-1-2:2005)



Mechanical properties



CONCRETE Thermal deformation depending of temperature (UNI EN 1992-1-2:2005)



Variation of CONCRETE strength properties depending on temperature (UNI EN 1992-1-2:2005)

NOTE: like for concrete, thermal and mechanical properties depending on temperature are taken from Eurocodes:

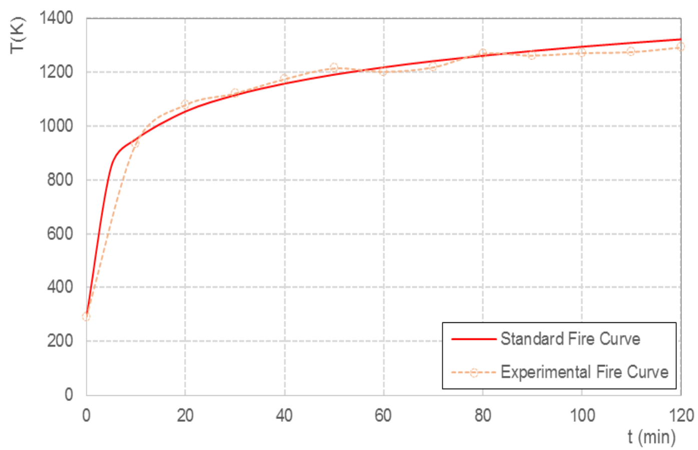
INOX STEEL: UNI EN 1993-1-4_2007

CARBON STEEL: UNI EN 1993-1-2_2005

FIBER CERAMIC BLANKET: λ=0,42 W/m·K (supplier data)

Experimental set-up

Standard requirements (UNI EN 1363-1, 2012):



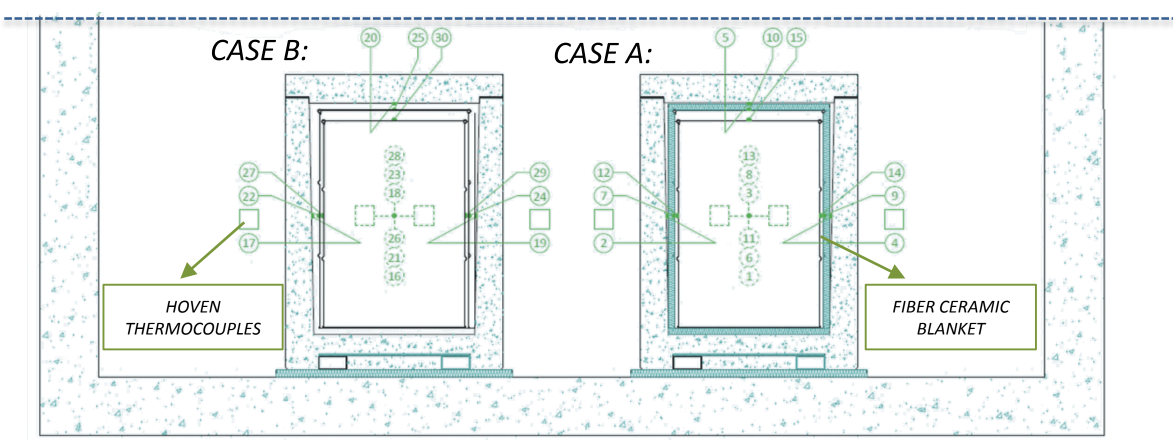
Fire Curve

TEMPERATURE ON UNEXPOSED SIDE FOR STANDARD FIRE CURVE:

$T_{average} < T_{amb} + 140°$ (per $T_{amb} = 20°$, $T_{average} < 160°$)

$T_{max} < T_{amb} + 160°$ (per $T_{amb} = 20°$, $T_{average} < 180°$)

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



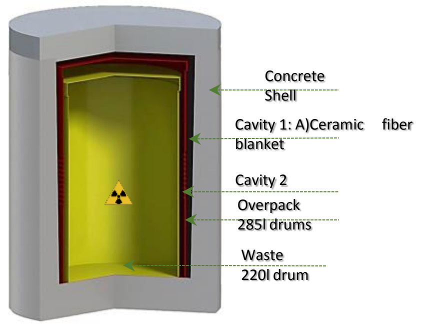
Thermo-couples position

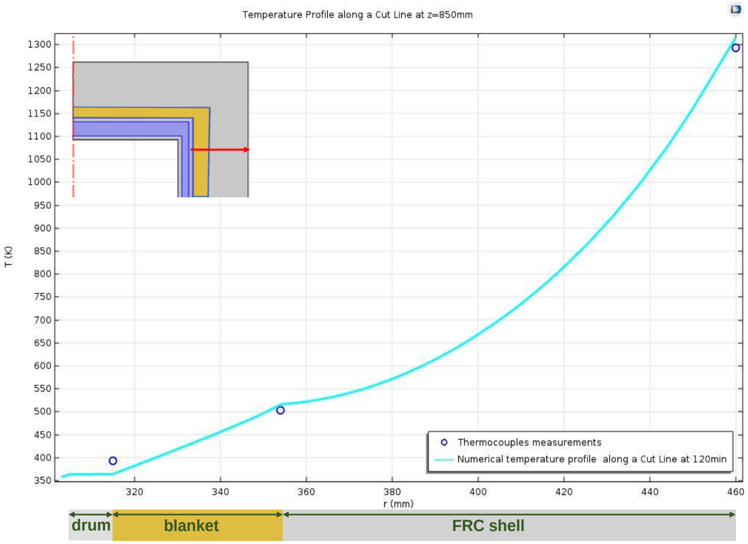
Experimental Set-Up before the test

Numerical Vs Experimental results (1/2)

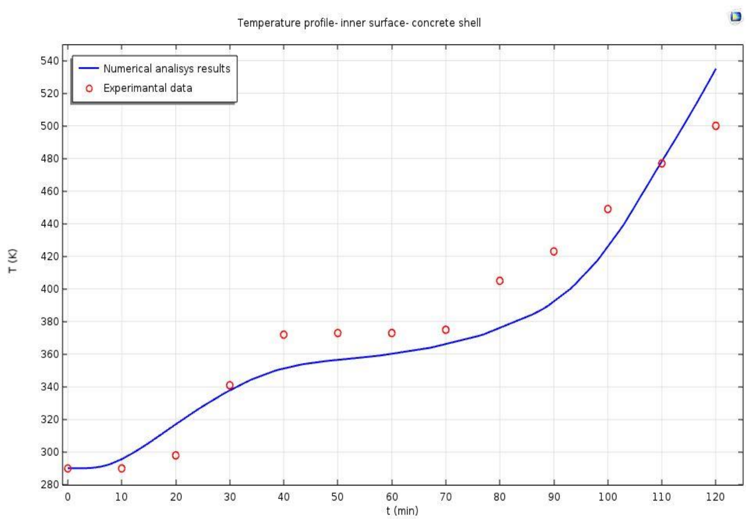
Figures show the comparison between numerical results and experimental data.

CASE A (cavity 1 filled with fiber ceramic blanket)





Temperature profile along a cut-line at z=850mm: Difference between the average of numerical results and experimental data at 120 minutes

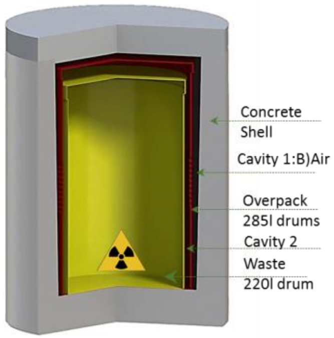


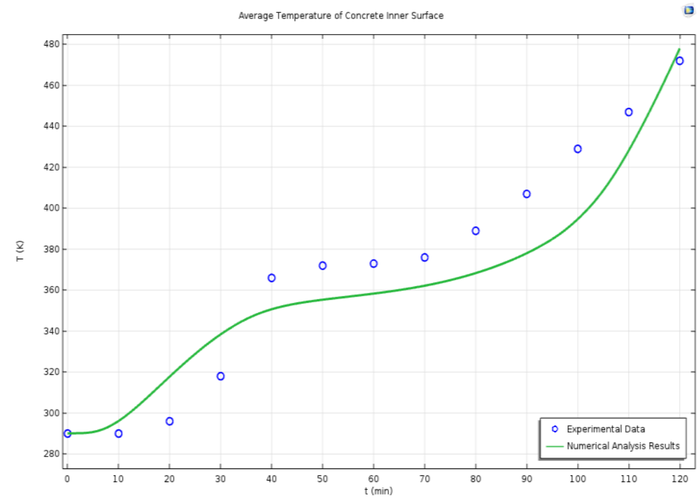
Temperature profile on the inner surface of concrete shell

- THE TEMPERATURE DIFFERENCE BETWEEN NUMERICAL AND TEST DATA IS 35K AT FINAL TIME (120 MINUTES).
- THE DIFFERENCES BETWEEN EXPERIMENTAL DATA AND NUMERICAL RESULTS ARE LESS THAN 10%.

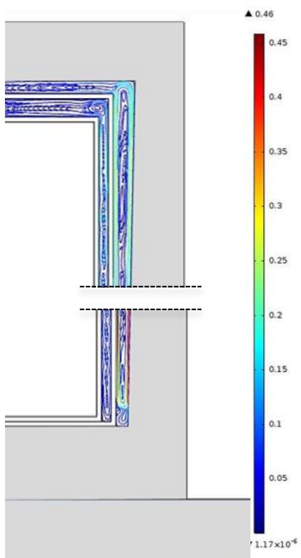
Numerical Vs Experimental results (2/2)

CASE B (cavity 1 filled with air)

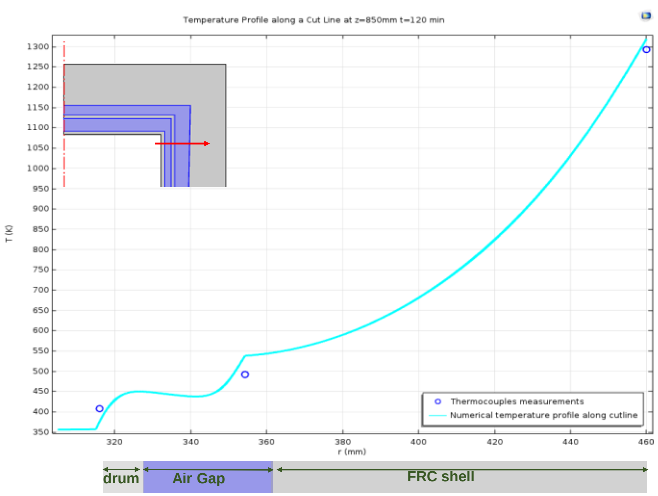




Temperature profile on the inner surface of concrete shell



Natural convection streamlines v=0,45m/s



Temperature profile along a cut-line at z=850mm: Difference between the average of numerical results and experimental data at 120 minutes

- THE TEMPERATURE DIFFERENCE BETWEEN NUMERICAL AND TEST DATA IS 8K AT FINAL TIME (120 MINUTES).
- THE DIFFERENCES BETWEEN EXPERIMENTAL DATA AND NUMERICAL RESULTS ARE LESS THAN 10%.

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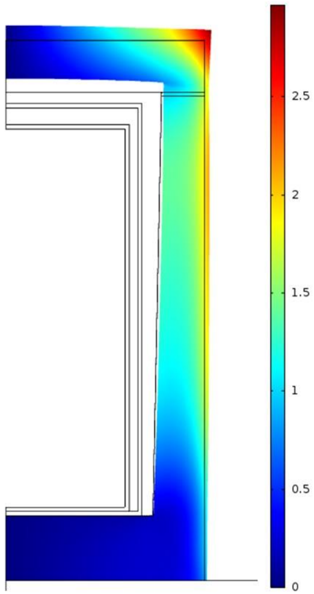
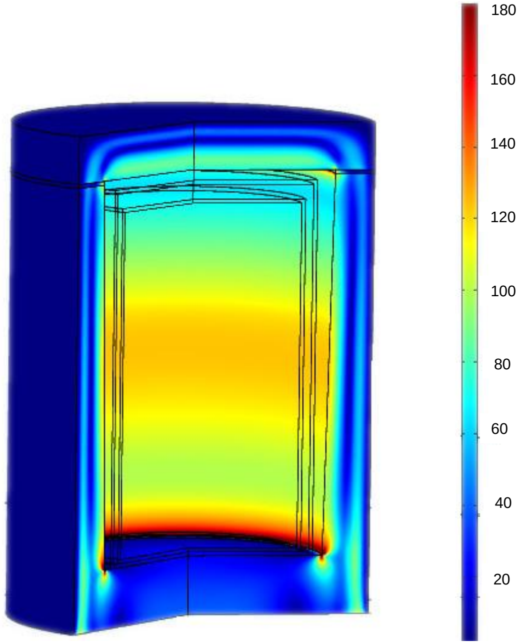
Structural analisys results

STRUCTURAL MECHANICS MODULE RESULTS ARE SHOWN IN TERMS OF THERMAL STRESSES AND DISPLACEMENT FIELD.



Displacement field (mm)



Thermal stress (MPa)

Visual inspection after the test

- 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.
- TENSILE STRESSES ARE DISTRIBUTED ON THE INNER SURFACE WALLS AND REACH MAXIMUM VALUES NEAR TO THE BOTTOM.
- STEEL REINFORCEMENT BARS HAVE BEEN DESIGNED TAKING INTO ACCOUNT THE DISTRIBUTION OF THERMAL STRESSES AND STEEL WORK TEMPERATURE
- A FINAL VISUAL INSPECTION SHOWS STRUCTURAL INTEGRITY OF CONCRETE SHELL

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.

Thank you for your attention!