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PERFORMANCE OF A TYPE IP-2 PACKAGING SYSTEM IN ACCIDENT CONDITIONS OF TRANSPORT

Lo Frano R.*, Pugliese G., Forasassi G.
*Author for correspondence
Department of Civil and Industrial Engineering,
University of Pisa,
Pisa, 56126,
Italy,
E-mail: rosa.lofrano@ing.unipi.it

ABSTRACT

A package to be used for the transport of hazardous /radioactive materials must demonstrate to fulfil the International standards requirements in order to provide protection to the human being and environment even under accident conditions, such as rigorous fire events. In these conditions, the system (package or cask), constituted, in general, by a massive sealed steel vessel, must thus demonstrate to be robust, safe and reliable so to guarantee both structural strength and radiation shielding.

The present study deals with the evaluation of the thermo-structural response and performance of an Italian design type IP-2 packaging system, provided by Sogin, that should be adopted for the transportation of low and intermediate level radioactive solid/solidified wastes.

To evaluate its performance, a FEM model has been set up and implemented in a rather refined way taking into account all the packaging system components.

Numerical simulations addressed fire scenarios as specified in the IAEA regulations: packaging subjected to an engulfing fire of 800 °C for 30 minutes.

All the heat transfer mechanisms, inside the system and between the system itself and the environment, have been considered in the thermal analyses performed.

The results of the thermal analyses are presented and discussed. Analysing the results obtained it is possible to conclude that although any potential damage the integrity of IP2 packaging system is assured.

NOMENCLATURE

E	[Pa]	Young modulus
ρ	[kg/m^3]	Density
ν	[-]	Poisson coefficient
σ_y	[m]	Yielding stress

INTRODUCTION

About 20 million consignments of radioactive material take place around the world each year, of which only about 5% are fuel cycle related [1]. An essential component for any safe shipment is thus a robust safe and reliable system (package or cask) constituted in general by a relatively massive sealed steel vessel able to provide both structural strength and radiation shielding.

The design requirements set forth by the National Safety Authority and, in general, International Atomic Energy Agency (IAEA) in [2] and/or relevant national regulations (in Italy [1], [3] and [4] must be considered) cover inspections, both prior to the first shipment and prior to each shipment, shielding, containment, heat transfer and criticality safety (confinement system effectiveness) of specific packagings.

Moreover, according to the activity, physical state and fissile nature of the radioactive material, the types of package (Figure 1) prescribed by IAEA regulations are:

- Unpackaged;
- Excepted packages;
- Industrial packages: types IP-1, IP-2, IP-3;
- Type A packages;
- Type B packages;
- Type C packages;
- Other.

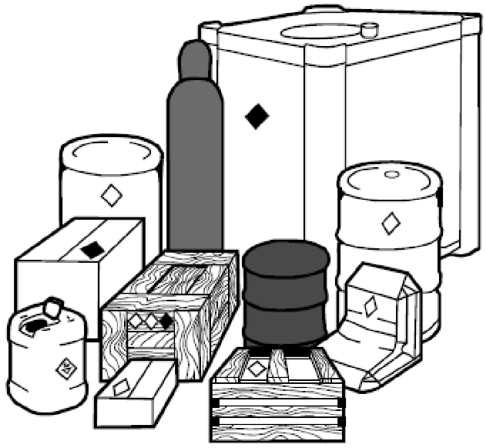


Figure 1- Overview of package types

The main purpose of the regulations [2] that guide the radioactive material transportation is to protect the people, property and environmental protection from the effects of the irradiation. It is required the containment of the radioactive contents, the control of external levels of the radiation (Table 1) from the cask inside, the prevention of criticality, and the prevention of damage caused by heat, under normal and accident conditions [2, 5].

Table 1- Permitted package dose rates [2]

Package type	Dose rates		
	Surface**	2m	3m*
Excepted	5μSv/h [s]		
IP-I, II, II		≤0.1 mSv/h	≤10 mSv/h
Type A	≤2 mSv/h	≤0.1 mSv/h	
Type B	≤2 mSv/h	≤0.1 mSv/h	
Type C	≤2 mSv/h	≤0.1 mSv/h	

*unshielded radioactive contents
** 10 mSv/h for packages under exclusive use (except by air which is limited to ≤2 mSv/h).

The integrity of packages is thus crucial for a safe disposal, storage and transport of RAM/RW: to certify the packages the manufactures or "applicant for approval" are required to demonstrate that they can withstand loads, that could occur under normal operation and accident conditions [5-6], and meet the safety requirements in terms of performances of containment, radiation protection and criticality-safety (if necessary).

REQUIREMENTS FOR PACKAGINGS AND PACKAGES

Before packages were firstly used, qualification tests or corresponding validated numerical simulations, covering normal and accident situations, which can be realistically envisaged in order to guarantee safety throughout the package lifetime, must be done to demonstrate their ability to withstand such conditions of transport. In particular the accident ones are:

1. Mechanical test consists of three different drop tests:
   1.1. horizontal, slap down, vertical, oblique drop tests onto a flat and unyielding surface (Figure 2): the order in which the specimen is subjected to the drops shall be such that, on completion of the mechanical test, the specimen shall have suffered such damage as will lead to maximum damage in the thermal test. The free drop distance shall be 9 m measured from the lowest point of the specimen to the upper surface of the target.
   1.2. puncture test: the specimen shall drop onto a bar (of solid mild steel of circular section, 15.0 ± 0.5 cm in diameter and 20 cm long) rigidly mounted perpendicularly on the target so as to suffer maximum damage. The height of the drop shall be 1 m.
   1.3. dynamic crush test: the specimen is positioned on the target so as to suffer maximum damage by the drop of a 500 kg mass from 9 m onto the specimen. The mass shall consist of a solid mild steel plate 1×1 m and shall fall in a horizontal attitude.
2. Thermal test consists of 2.1 followed by 2.2:
   2.1. exposure of a specimen for a period of 30 min to a thermal environment that provides a heat flux at least equivalent to that of a hydrocarbon fuel-air fire in sufficiently quiescent ambient conditions to give a minimum average flame emissivity coefficient of 0.9 and an average temperature of at least 800°C, fully engulfing the specimen, with a surface absorptivity coefficient of 0.8 or that value the package demonstrated to possess if exposed to the fire specified.
   2.2. exposure of the specimen to an ambient temperature of 38°C, subject to the solar insulation conditions, as specified in Table 12 of [2], and to the design maximum rate of internal heat generation within the package by the radioactive contents for a sufficient period to ensure that temperatures in the specimen are everywhere decreasing and/or are approaching initial steady state conditions.
   Alternatively, any of these parameters may have different values following cessation of heating, provided due account is taken of them in the subsequent assessment of package response. During and following the test, the specimen shall not be artificially cooled and any combustion of materials of the specimen shall be permitted to proceed naturally.
3. Water immersion test: Following mechanical and thermal tests, either the same specimen or a separate one shall be subjected to the effect(s) of the water immersion test(s). The specimen shall be immersed under a head of water of

at least 15 m for a period of not less than 8 h in the attitude that will lead to maximum damage. For demonstration purposes, an external gauge pressure of 150 kPa shall be considered to meet these conditions.

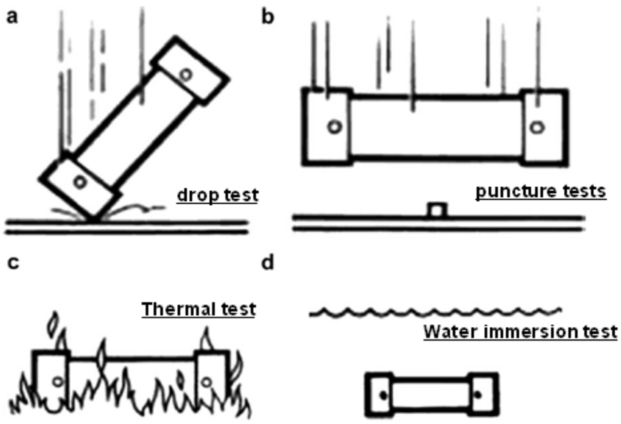


Figure 2 - Sequence of possible accident conditions according to IAEA requirements

The present paper describes the evaluation of the thermo-structural response and performance, in transport accident conditions, of an Italian design type IP-2 packaging system, provided by Sogin, which should be adopted for the transportation of low and intermediate level radioactive solid/solidified wastes. This package will be referred to as CC-440 in what follows.

To evaluate the package performance, a FEM model has been set up and implemented in a rather refined way taking into account all the packaging system components. The proposed approach for the thermal test numerical simulation is showed without any comparison to experimental results.

The numerical simulations (by ANSYS© code [7]) carried out to evaluate of the structural response of the packaging system and effects/damages caused by the fire scenarios as specified in the IAEA regulations, are presented and discussed.

THE IP2 PACKAGE MODEL DESIGN DESCRIPTION

The CC-440 is a cylindrical packaging system designed to stow solid/solidified RAMs inside a concrete matrix in which they are uniformly distributed throughout. According to [2], since the radioactive content is of LSA II material type, the CC-440 packaging system is classified as industrial package type 2 (IP-2).

The main design characteristics, the geometrical and material properties of this package type are defined in [8], which represents the Italian reference standard for packaging National requirements.

The packaging system (Figure 3) consists of an inner carbon steel package, a solidified waste, simulated though an inert content, and a primary lid with gasket and closure lid.

Figure 3 - CC-440 packaging system

The packaging system is about 1.2 m in height and 0.8 m in diameter. The primary closure lid is guaranteed by means of M12x25 bolts [9, 10].

The package can be made of S235 steel (also known as Fe360) and/or X2CrNiMo17-12-2 stainless steel (AISI 316L). This latter, despite the higher cost, is preferred in relation to the container lifespan (and in vision of its interim storage) as it has higher mechanical strength and better corrosion resistance.

The overpack, on the other hand, is 1.5 m in height, 95 mm thick and has an external diameter of about 1 m.

CC-440 materials properties are instead summarized in Table 2.

Table 2- Material properties

Material	Young modulus E [Pa]	Poisson's ratio υ [-]	Yield stress σ_y [Pa]	Density ρ [kg/m^3]
A316L	$2{\cdot}10^{11}$	0.3	$2.75{\cdot}10^8$	7800
A 304	$2{\cdot}10^{11}$	0.3	$2.1{\cdot}10^8$	7800
Concrete	$3{\cdot}10^{10}$	0.2	-	2400

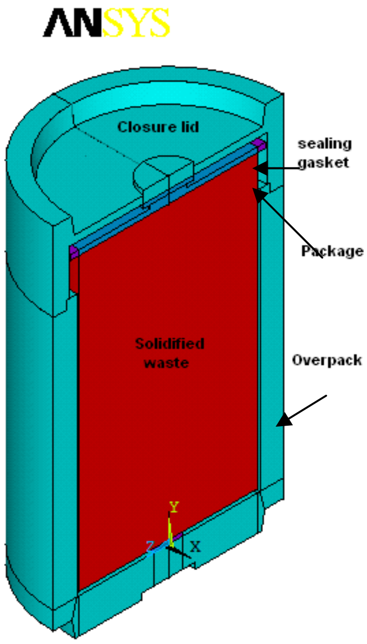
NUMERICAL METHOD

To simulate the model behaviour and determine the thermal performance of package CC-440 a numerical model (by ANSYS©) of the packaging system plus the external overpack was set up and implemented in a rather refined way, taking into account material properties and constitutive laws [6, 11, 12].

To this aim both steady-state and transient thermal analyses have been performed dry storage/transport condition has been considered in order to determine the temperature distribution which might arise in the event of fire.

In doing that, the first step of the adopted methodology was to set up and implement a suitable 3-D finite element model, representing, in as much detailed as possible, the real geometry of the CC-440 packaging system (Figure 4).

Structural parts as lifting trunnions, bolts and threads were not modeled once these parts have little influence on the temperature distribution.



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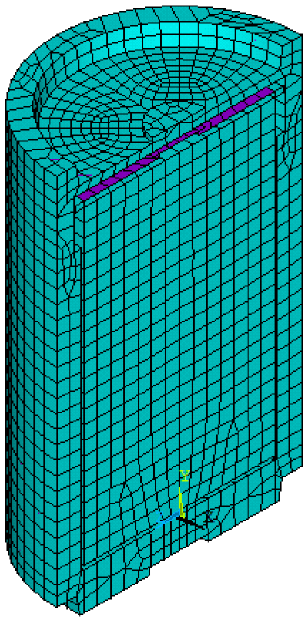


(b)

Figure 4 – CC-440 packaging system enclosed in the outer overpack (a) and its FEM model (b)

The 3-D FEM model, shown in previous Figure 4, includes more than 100.000 solid elements representing the package, the "solidified waste" mass, the overpack with its closure lid, the filtering system, the gasket resting between the cylindrical package body and the primary lid/flange, etc.

The SOLID90 element with 20 nodes [7] and the SHELL57 element along with thermal contacts elements were used in order to simulate all heat transfer mechanisms inside the package and between the package and the environment.
The contacting walls among the packaging system have been considered as continuous material (conservative hypothesis). All surfaces in contact were modeled with a thermal contact conductance value defined through a specific constant value. All other structural surfaces with some theoretical gap between them were modeled independently with no contact but with radiation and/or a convection coefficient between them.

Validation of numerical model

Since the safety margin on temperature results obtained from numerical calculation, is commensurate with the uncertainty associated to the numerical model a validation analysis has been also carried out. Therefore, the influence of the number of element/mesh has been checked.

The results obtained indicated that when the number of element is doubled, the difference in the calculated temperature solutions resulted less than 5%, quite similar results have been obtained evaluating the influence of the type of element. Therefore it is possible to state that these factor seem to not influence the thermal analyses performance.

THERMAL ANALYSIS

All the heat transfer modes (conductive, convective and radiation) were taken into account, in the thermal analyses performed, by means of adequate values and hypotheses.

The conductive coefficient values were consistent with the package material properties and temperature while the convective heat input must be included on the basis of still ambient air at 800 °C, in the accident condition, assuming also the absence of artificial cooling after the end of external heat input.

The convection, between a body surface and a fluid in motion, depends, mainly, on the (bulk) fluid and the surface temperature difference as well as the fluid properties and velocity: heat convection coefficients (h) are obtained from experimental correlations, available in the literature as, for instance, in [5].

Radiation is another heat transfer process that depends on the component emissivity and the rate at which the (heat) energy would radiate from them if they were a perfect black body when the heat energy 'travels' through the vacuum.
Each radiating surface pair is defined by means of its emissivity. In addition the 'Radiation Matrix Method' was adopted: a radiation matrix was created using a routine, defining the geometry, emissivity, the Stefan-Boltzmann constant (5.67e-8 W/m^2K^4) and the temperature offset (273 ºC).
The radiation mode has been assumed characterized by an emissivity values equal to 0.5 and 0.8, respectively for normal and accident transport conditions, for the CC-440 components.

The heat flux values have been conservatively determined assuming that the solar irradiation on the external surface of the packaging (in agreement with IAEA rules) is maximum, for duration period equal to 12 h.

In the (transient) analysis beginning these surfaces are cold and isothermal (20 ºC) and after some time there is a temperature difference among them and as this difference becomes greater the heat flow by thermal radiation among them becomes more important. This type of heat transfer (radiation) makes the analysis strongly non-linear which adds to the inherent material non-linearities due to the temperature (as the change phase of the lead and the thermal conductivity).
In addition, for calculation purposes, the surface absorptivity must be either the value that the packaging system may be expected to possess if exposed to a fire or 0.8; the greater of these two values is used.
Finally a schematic diagram for the problem description including the initial and boundary condition is represented in

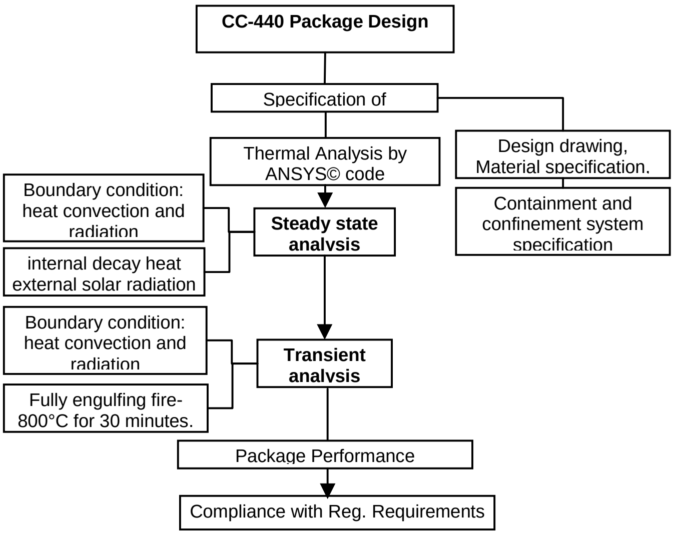
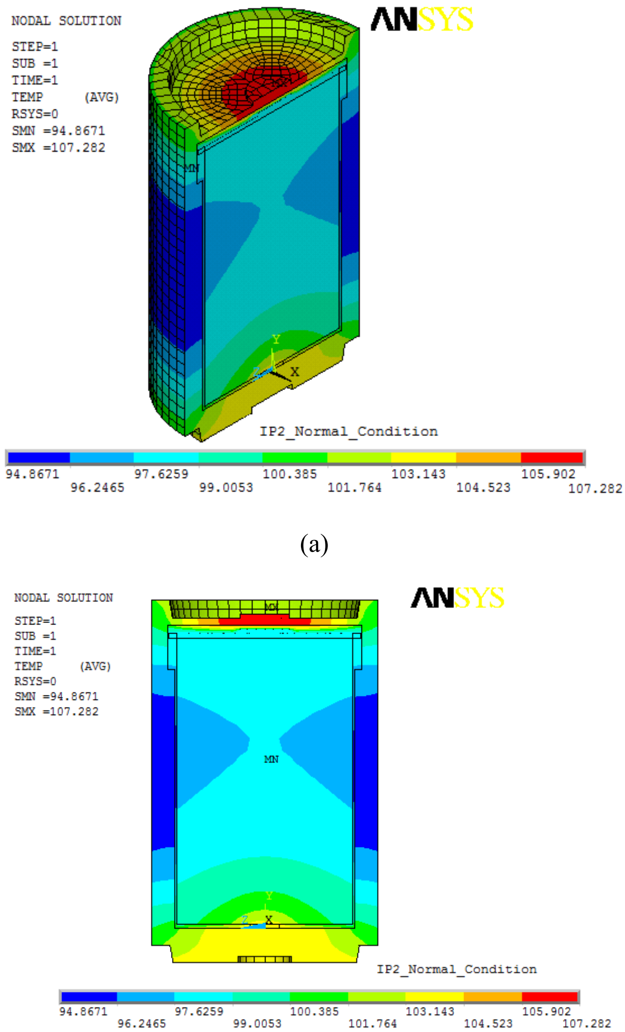


Figure 5 – Schematic diagram for the problem description

TRENDS AND RESULTS

The implemented packaging FEM model, representative of the cask configurations, was firstly analyzed assuming a steady-state thermal condition. In particular, the structural integrity for normal condition of transport was evaluated considering the thermal boundary conditions due to environment temperature of 38 °C. The thermal response of package has been evaluated considering it subjected to full solar heat input.
In Figure 6 are shown the temperature distributions inside the packaging for dry transportation, obtained from the steady state analysis considering it exposed only to the environmental temperature. The maximum and minimum outer surface temperatures resulted 94.8 °C and 107.3°C respectively; in particular the maximum temperature was observed on the overpack closure lid.

It is worthy to note that the steady-state temperature field, was used in turn as initial condition in the transient analyses simulating engulfing fire effects (Figure 6÷Figure 10).

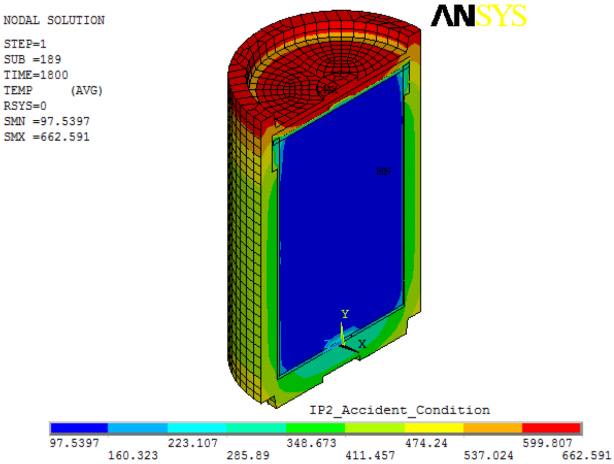


(a)

(b)

Figure 6 –Temperature distribution at the beginning of the accident condition

As shown, the fire leads to the rapid increase of the temperature of the internal components (gasket, package, closure lid, etc.), but it only influences the inner of the cask slightly. This implies that the external heat cannot reach the internal space in such short time; the CC-440 can absorb a lot of heat without much increase in temperature. Moreover the temperature at the closure lid is higher than the other overpack surfaces due to the assumed related to the full solar heat input (indicated in the Thermal analysis sect.).
Figure 7 and Figure 8 show the temperature distributions respectively at 0 and 30 min (beginning and end of the heating period): they represent respectively the distribution of the temperature in the full model and in the solidified RWs, without the surrounding package.
Particularly, in this latter case, it can be noticed the hot spot due to the inward propagation of the heat, enhanced at the connections between the waste and the cylindrical container.



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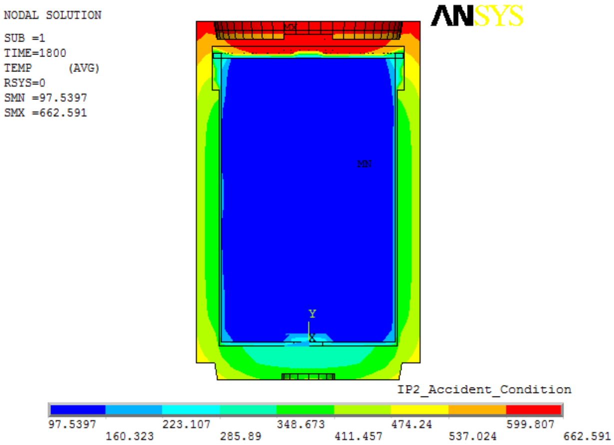

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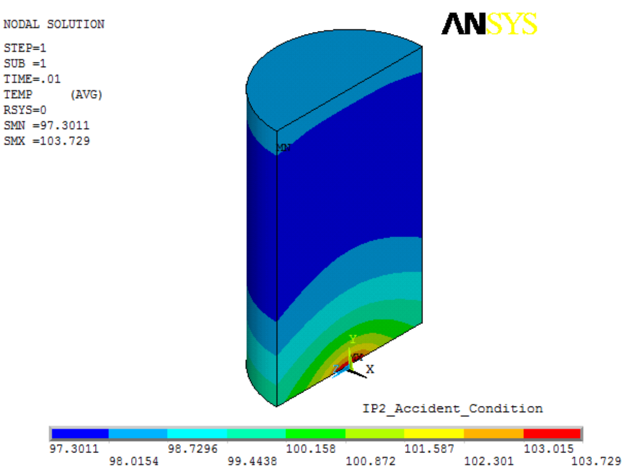
Figure 7 – Temperature distribution at the end of the accident condition



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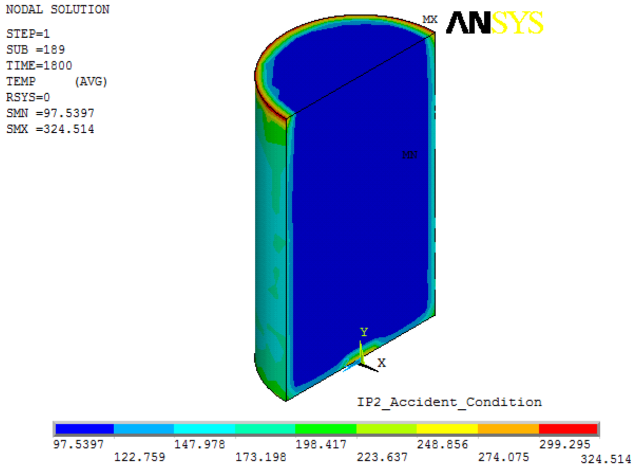

(b)

Figure 8 – Temperature distribution in the solidified RWs (a) at the beginning and end (b) of the fire accident condition

In Figure 9 and Figure 10, are shown the temperature behaviours vs. time calculated respectively in the solidified RWs and in the outer packaging surface (blue curve) and inside the package (violet curve).

Analysing the obtained temperature values, it is possible to note that, after half an hour of fire exposure at 800 °C, the temperature distribution in the package was about 4 times lower than the external ones and therefore not sufficient to determine severe structural damages. Moreover the temperature in correspondence of the sealing was about 200 °C and no sufficient to attain a reduction of bearing and sealing capability.

Finally it is possible to conclude that, since the maximum temperatures were lower than the allowable limits, i.e. for solidified wastes generally below 400 °C [13], the integrity of the CC-440 packaging system was therefore ensured.

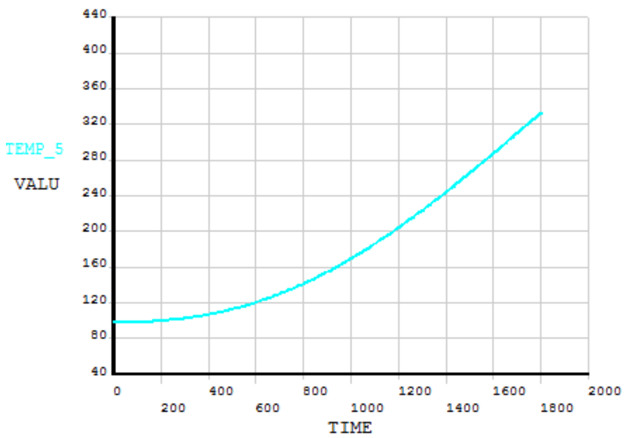

Figure 9 – Temperature vs. time in the solidified RWs

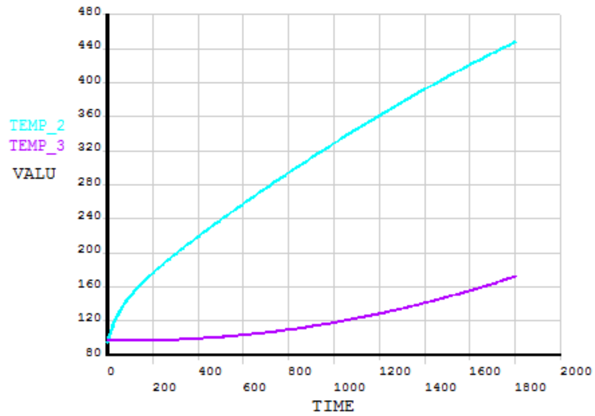

Figure 10 - Temperature vs. time at the outer packaging surface (blue curve) and inside the package (violet curve)

CONCLUSION

This paper showed the evaluation of the thermo-structural performance of an Italian design type IP-2 packaging system, provided by Sogin, to be adopted for the transportation of low and intermediate level radioactive solid/solidified wastes.

A brief description of the packaging model has been also presented.

The numerical model using finite elements and the hypothesis to build it were detailed and discussed. To the purpose of this study all the heat transfer mechanisms, inside the system and between the system itself and the environment, have been considered in the thermal analyses performed.

Numerical simulations of the fire scenario as specified in the IAEA regulations consisted in an engulfing fire of 800 °C for 30 minutes.

The results of the thermal analyses are presented and discussed highlighting that after half an hour of fire exposure at 800 °C, the temperature distribution in the package was about 4 times lower than the external ones, while, as an example, in the sealing was about 200 °C.

These temperature values were not sufficient to attain a reduction of bearing and sealing capability or to determine severe structural damages.

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