2013 International Nuclear Atlantic Conference - INAC 2013
Recife, PE, Brazil, November 24-29, 2013
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: 978-85-99141-05-2

ANALYSIS FRAMEWORK TO CALIBRATE A NUMERICAL MODEL TO SIMULATE THE THERMAL TEST OF A 1:2 SCALE DUAL PURPOSE CASK UNDER ACCIDENT CONDITIONS

Carlos A. J. Miranda[1], Rosani M. P. Libardi[2], Sergio Marcelino[3], Carlos Alberto de Oliveira[4] and Miguel Mattar Neto[5]

Centro de Engenharia Nuclear
Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
[1]cmiranda@ipen.br
[2]rmpenha@ipen.br
[3]sergio.marcelino@gmail.com
[4]calberto@ipen.br
[5]mmattar@ipen.br

ABSTRACT

This work describes thermal analysis framework including a 3D model and some 2D models to be performed in a 1:2 scale model of a dual-purpose cask to transport and to store spent fuel elements from research reactors to assess the behavior of the cask structure and materials when submitted to heating and drop tests. The analyses should consider all non-linearities involved like the lead phase change and thermal contacts, beside the variation of material properties with the temperature, the air inside it and the heat transfer phenomena (conduction, convection and irradiation) to reproduce the experimental results already obtained in a 1:2 model. A full 3D finite element model takes several hours to run just one analysis. To speed up the analyses to evaluate the significance of some parameters like the emissivity, contact resistance and heat transfer phenomena, among others, two 2D models are planned: one simulating a vertical cut by a diametral plane and another one simulating a horizontal cut by a plane at the cask half height. These 2D models are predicted to run fast enough to allow several analyses in a short period of time and to define options and the best parameters values to match the already obtained experimental results. As this thermal test can not be extrapolated to an 1:1 scale, these parameter values will be used in the final 3D model analysis and also in the full scale model.

1. INTRODUCTION

This is a tri-national IAEA project whose participant countries, Argentina, Brazil and Chile, operate research reactors (TRIGA and MTR) since the 50's, that aims to improve the regional capability to manage the spent fuel elements produced by the reactors.

By international standards, the casks to transport spent fuel elements from research reactors should be submitted to rigorous tests like the 9m free drop onto a rigid surface and the 800 ºC fire for 30 minutes, among others, to be qualified for use. Among the acceptance criteria it can be mentioned: assurance against criticality, structural integrity and biological shielding. One of these criteria can be translated in an equivalent Helium leak rate whose value should be verified after each set of tests simulating the accidental conditions.

All the ‘mechanical’ qualification should be carried out experimentally, but numerical analyses are used to verify and estimate the cask behavior before the tests. It is allowed to use scaled models (1:2 until 1:4 are common). When using scaled model, some mechanical parameters can be adequately scaled to predict the behavior of the actual cask (prototype or 1:1 scale). This is valid for ´mechanical´ tests as the free drop tests and their numerical simulation. However, the thermal results from a scaled model can not be scaled to the actual (1:1) cask. Even so, thermal tests are done in scaled models to allow parameters be obtained to calibrate numerical models.

Once the thermal model is calibrated and reproduces the experimental results it can be used to analyze the 1:1 scale cask. The internal temperatures should be limited to values established in the standards depending on the fuel elements material. Specifically, the thermal analysis should consider all nonlinearities from the design like the lead phase change and thermal contacts, besides the material properties varying with the temperature, the air inside it and the heat transfer phenomena. The mass of the fuel elements, formed by Aluminum parallel plates, will be simulated by solid Aluminum bars with orthotropic properties. This work describes the planned analysis framework including a 3D model and some 2D models, all of them considering the non-linearities mentioned above, to reproduce the experimental results already obtained in a 1:2 model.

A 3D model that takes several hours to run just one analysis was already developed. To speed up the analyses, at least two 2D models are planned: one simulating a vertical cut by a diametral plane and another one simulating a horizontal cut by a plane at the cask half height. These models are planned to evaluate the significance of each heat transfer phenomena (radiation, convection and conduction) in the results, as well as the specific parameter values to be adopted in the analysis as emissivity and contact resistance, for instance. The 2D models are predicted to run fast enough to allow several analyses in a short period of time and to define options and parameters to be used in the final 3D model analysis.

2. CASK DESCRIPTION

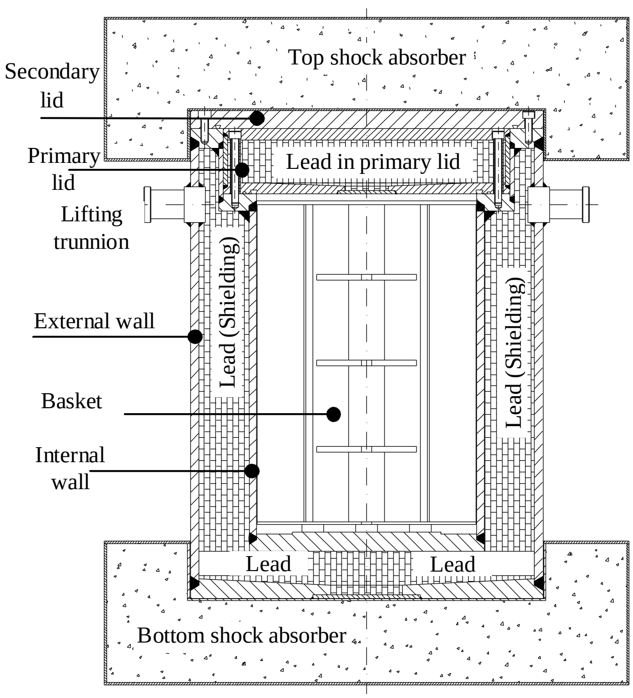
The cask is classified [1] as Type B package carrying fissile materials. Its design should meet the transportation criteria established by the IAEA that postulates some accidents during transportations as the 9m free drop onto a rigid surface and a 800 ^{o}C fire for 30 minutes fire. Beside these, there are other criteria that the cask should resist: submersion in 15m deep water, punction test (one-meter drop onto a flat pin), etc.

The 9 m free drop, the 800 ^{o}C fire and the 15 m depth water submersion are the postulated accident scenario during transportation. Therefore, the cask has to be sturdy enough to resist these postulated transport accidents.

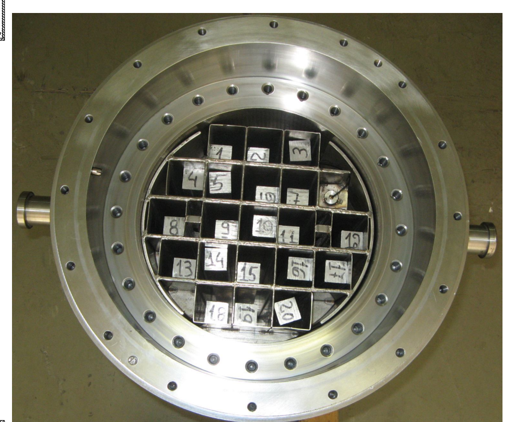
The designed cask has a cylindrical main body (one internal and the other external connected by an outer and an inner flange, with lead in-between), an inner lid formed by two plates also full of lead, one external lid and two shock absorbers connected by four round bars. Internally, to hold the fuel elements, there is a basked which should be adapted for each type of fuel (from TRIGA or MTR reactor). To allow the cask handling there are also four lifting trunnions in the external cylinder. To assure the cask closure there is a double sealing system in all openings (the drain port and the inner lid) with metallic O-rings. There are 24 bolts to connect the inner lid to the main body and 16 bolts to connect the external lid whose main function is to give protection to the inner lid during transportation. The external lid has no function and can be removed during storage and, so, there is an elastomeric gasket between this lid and the cask outer flange.

The shock absorbers are, basically, cylindrical devices with a thin stainless steel skin and are filled with polyurethane foam with density ~160 kg/m^3. They are sacrificing devices protecting the cask in case of accident whose main function is to reduce the acceleration level in the basket containment. To improve the cask thermal behavior, a fire retardant is added in the foam composition.

The main dimensions, diameter, ϕ, and height, for the 1:2 scale cask model are, respectively: ~0.50m and 0.70m. When the shock absorbers are in place the overall dimensions become: ~1.20m and 1.00m. Figure 1 shows a schematic view with the main parts described above.



(a) Cask main parts



(b) Internal view
(basket and dummy masses)

Figure 1: Schematic dual purpose cask view with main parts.

2.1. Mechanical Tests Already Performed

The 1:2 scale model was already tested for the so-called normal conditions of transportation and operation (free drop from 1.0 m height in several orientations and penetration test). Stacking and water spray tests were not performed due to its irrelevancy or because the cask is not stackable. Also, the postulated accident scenario which includes the water immersion test, punch tests onto a vertical bar, free drop tests from 9 m height, and thermal test, were performed. The latter one, as already mentioned, was performed to give information to the numerical simulations. The penetration test (a 6 kg bar drop from 1 m height) produced only a small dent very localized in the external cylinder with no influence in the cask overall performance verified after each set of tests. The 1.0 m drop test onto a rigid vertical bar and the 9m free drop test onto a rigid surface were performed in several positions and/or orientations to look for the worst result in terms of Helium leak rate.

Before each set of tests, an initial He leak rate test was performed to verify if the cask leak is below the established limit (in this situation the cask is said to be leak tight). So, after the tests, the cask should be leak tested again to assure that its tightness was not affected by the test. Typically, for the 9 m drop tests three positions were tested: the vertical (as in Fig. 1 but upside down), the horizontal (Fig. 1 turned 90º) and inclined (the cask center gravity, with impact limiters, is aligned with the impact limiter corner). Due to the suffered damage, the shock absorbers, as well as some connecting bars, should be replaced after each 9 m drop.

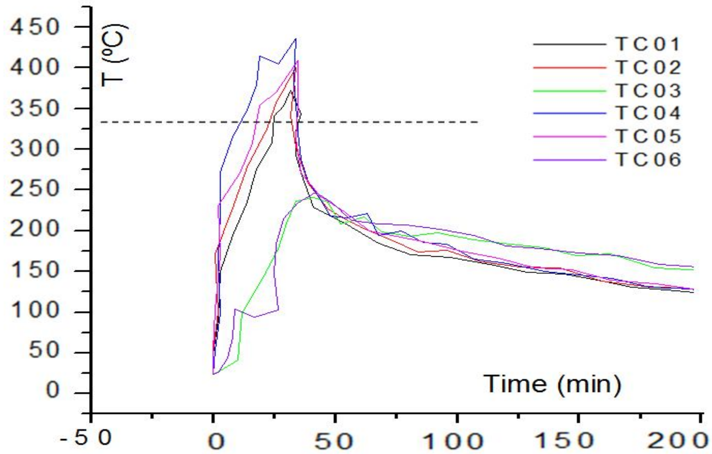
In all three test campaigns the cask was not found to be leak tight after the 9 m drop. The other mechanical tests, not involving the 9 m drop, the cask performed OK. Ref. [2] presents details about these test campaigns, main tests performed and the respective results, as well as the small design modifications meant to improve the cask performance among tests and campaigns.

2.2. Thermal Tests Already Performed

In previous two test campaigns the thermal test was performed with the cask instrumented with thermocouples and temperature indicating labels (templabels). In the first test campaign the cask was put in the furnace with no shock absorber and in the second one two thermal tests were done: with and without shock absorbers. The cask was introduced in an industrial furnace pre-heated at 800 ºC and left there for 30 minutes. After this soaking period the cask was allowed one full day for cool down. The templabels were positioned in several locations (in both radial and vertical positions) inside the cask. In the first test, six thermocouples (TC1 to TC6) were positioned as indicated in Fig. 2a with the furnace lifting device visible. There are two positions through the cask body wall at 1/3 and 2/3 deep on the cask+lead thickness (TC4 and TC5, respectively), and two others inside the cask cavity (TC3 and TC6). The collected data from the thermal tests (maximum temperatures, from the templabels, and the temperature x time, from the thermocouples) will be used to calibrate the finite element 3D model developed for the thermal numerical simulation. The typical thermal tests results from the thermocouples are shown in Fig. 2b (adapted from [7]). As one can see, the lead was partially melted during the 30min in-furnace period (> 327 ºC) and, also, there was some instability in the TC3 and TC6 in the first 30min period.

3. THERMAL ANALYSES

The thermal model should consider all heat transfer phenomena (conduction, convection and irradiation) and all non-linearities involved (the lead phase change, the thermal contacts and the material properties varying with the temperature) as described below.



(a) Thermocouples positioning and identification

(b) Temperature x Time curves

Figure 2: Typical Thermal Experimental Results.

3.1. Heat Transfer Basics

The basics of the heat transfer phenomena of the conduction, convection and radiation will be present.

3.1.1. Conduction

When the heat is transferred by the molecular movement (with no motion of the material as a whole) it is said we have the (heat) conduction. In one dimensional body like a bar, with one end hotter than the other one, the heat (the energy) will flow from the hotter to the colder extremity. So, the heat flows through the body material.

In one-dimensional form, let's say, in the x-direction, thermal conduction in steady-state condition can be expressed as

$$q_x = -K_x \frac{dT}{dx} \tag{1}$$

Where T is the temperature (K or ºC), K_x is the material thermal conductivity coefficient ($W.m^{-1}.K^{-1}$ or $W.m^{-1}.{}^{o}C^{-1}$) and q_x is the heat flux ($W.m^{-2}$).

3.1.2. Convection

Convection occurs when a fluid is flowing on a body surface (area A, in m^2), with both at different temperatures. The transferred energy from the hotter to the colder depends on (a) the difference between the average fluid temperature (bulk) and the body surface temperature, (b) the fluid properties and (c) the fluid velocity. The fluid velocity allows the convection to be classified as natural or forced. If the fluid flows fast as when there is a pump action, for instance, it is said ‘forced’. By other side, it is said ‘natural’ if it’s due to the buoyancy forces, caused by the difference in the fluid density due to the temperature differences in the fluid mass. Also, the heat exchange due to convection depends on the geometry and the (relative) dimensions of the channel used by the fluid to flow as well as if it is a closed or an open space.

Specific experimental correlations are obtained for each situation (forced or natural) and geometry to define the heat convection coefficient (h, in W/m^2 K) and are available, for instance, in [3].

Considering a constant heat transfer coefficient, h, the transferred thermal energy, Q (joules, J), is given by:

$$\frac{dQ}{dt} = h\,A\,\Delta T \tag{2}$$

where ΔT is the Temperature difference between the body surface (T) and the fluid (T_{bulk}) far from the surface, also called ‘bulk temperature’.

3.1.3. Radiation

When the heat energy is transferred with no physical medium, in the form of electromagnetic waves, the process is called radiation. If a body has a temperature above zero degree (absolute, 0 K or -273 ºC) it radiates energy which depends on the surface emissivity. The net heat flux $\dot{Q}$ (Watts, W or J/s) transferred from a body at temperature T_1 with surface emissivity ε to another body at temperature T_2 is expressed by

$$\dot{Q} = \varepsilon\,A\,\sigma\,(T_1^4 - T_2^4) \tag{3}$$

where A is the body radiating area (m^2), σ is the Stefan-Boltzmann constant (= 5.669 x 10^{-8} $W/m^2\,K^4$), T_1 and T_2 are absolute temperatures (K).

As shown in Eq. (3), the net heat flux exchanged by two bodies depends on their nature (emissivity), and temperature difference. In fact it depends, also, on the geometry form (not only area) and relative position. For instance, two concentric shells or two parallel plates will exchange heat by radiation in different ways (amounts) as well as if the exchange is between a flat and a curved surface. In the proposed model and thermal analyses heat flow by radiation will occur only between those surface pairs close to each other, but not physically in contact, and one in front of the other. In the considered cases, a non-zero emissivity value is defined for each surface pair, as indicated in table 1. Section 3.3 will describe how radiation is treated by ANSYS. In those surface pairs in contact it will be defined a thermal contact as described in section 3.2.

3.2. Thermal Contact

The heat conduction between solid bodies in physical contact is treated by the Thermal contact conductance. The thermal contact resistance is responsible for the temperature drop observed at the interface between two surfaces in contact as shown schematically in Fig. 3.

The observed temperature drop depends on several factors. The main ones are the contact pressure and the surface roughness. As the contact pressure increases the contact conductance also increases or, changing words, the contact resistance is reduced. By other side, as the surfaces' roughness increase also does the thermal contact resistance once the average distance among the surfaces becomes bigger. In the limit of this situation the contact occurs at discrete points and the actual contact area is less than the nominal area of the surfaces [3].

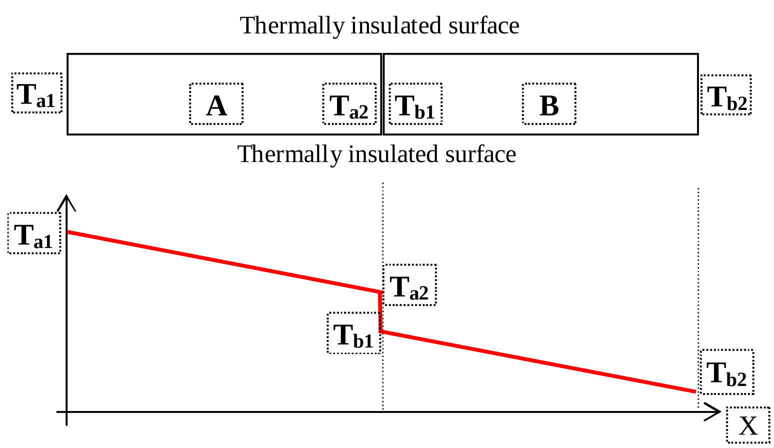


Figure 3. Temperature distribution at the interface between two bodies in contact.

The ANSYS program uses the Thermal Contact Conductance, TCC, as the parameter associated with this phenomenon. In the initial analyses it will be considered perfect thermal continuity between contact surfaces (i.e.: no thermal resistance). Once the model is running OK the thermal contact resistance will be allowed to vary (it will be 'calibrated' together with other parameters using the experimental results from the cask thermal tests).

3.3. Modeling Radiation Among Internal Surfaces

There are different methods in the ANSYS program [6] to consider radiation. Among them, the 'Radiation Matrix Method' option was the adopted one. In this method, for each surface pair, a radiation matrix (like a superelement matrix) is created. A previous run should be done using the ANSYS AUX12 routine, defining the geometry (3D), the emissivity, the Stefan-Boltzmann Constant, and the temperature offset (273 ºC). The created superelement is used in the thermal analysis. The offset is necessary to allow the temperature be used in Celsius degree.

Each radiating surface pair is defined to the program, by the same 'Real Constant' value with the associated parameters (basically the emissivity). By hypothesis, only two internal and ‘parallel’ surface pairs can exchange heat by radiation: (a) the circular plates in the basket lateral side (shown in Fig. 5) and the internal cylinder whose nominal gap is 1mm (in the model this value is constant along all the circular plate area), (b) the circular plate with holes in the basked base (shown in Fig. 7b), and the bottom of the internal cylinder. There is a nominal gap of less than 1cm between them.

The analysis has two main parts. The first one starts with an isothermal situation (20 ºC) and lasts for 30min, simulating the period inside the furnace at 800 ºC irradiating heat to the cask. As a continuation, the second one starts after the initial period with no hot source (the furnace) and considering natural convection outside the cask. So, when the (transient) analysis starts all 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 is in addition to the inherent material non-linearities due to the temperature (as the changing phase of the lead and the thermal conductivity).

3.4. Considering Convection in the Model

External Surfaces. In the second part of the analysis, when the cask is outside the furnace, heat convection coefficient (HF) is defined in the external cask surfaces to simulate the situation during the cooling phase (simulated for only two hours) in an environment (air) at 20 ºC under natural convection. The ANSYS program needs two parameters: HF and TF (the bulk temperature, the fluid temperature far from the surface): TF = 20 ºC, HF = 30 W/m^2.ºC.

Internal Surfaces. By hypothesis, only those internal surface pairs close to each other, but not physically in contact, and one in front of the other, can exchange heat by thermal convection. To consider this, a heat (natural) convection coefficient (HF), took from the literature, is defined between each pair. As the internal environment is at rest and the spaces are small the influence of this kind of heat exchange is expected to be small. So, an average value for the estimated bulk temperature is considered.

3.5. Symmetries

In the very preliminary and exploratory analyses, and aiming to reduce the cpu time spent in each one, two artificial hypothesis will be done: (a) the radiation oven environment will be simulated by forced thermal convection and, (b) the model size will be reduced by adopting double symmetry (null heat flow) in the surfaces at X = 0 and Y = 0. The actual geometry is not precisely symmetrical, nor does the presence/ consideration of thermal radiation allow this, however this model option seems reasonable once these are exploratory analyses. Besides, the cask stainless steel will be considered with constant thermal conductivity coefficient. With these hypotheses some non-linearities will be eliminated in the beginning. Once the model is considered as working well the actual material properties will be input, the oven environment will be simulated by radiation and the model will be doubled to allow the analyses whose results will be compared with the experimental ones.

4. THERMAL CASK MODELS

There are two main objectives in these thermal analyses. As they run fast, the 2D models will allow to evaluate the significance and the best numerical values of some parameters, for which there are some uncertainties, like the emissivity, the internally heat transfer by irradiation, contact resistance, the importance of the air conduction and convection inside the cask, among others. Once these parameters are established, the 3D thermal model will be calibrated to reproduce the experimental thermal results (temperature x time curves and maximum temperatures in some internal places).

This calibrated 1:2 scale 3D model will be used to analyze the 1:1 scale cask. To do so, and roughly speaking, the model will be doubled (all dimensions will be multiplied by 2) with some minor adjustments, for instance some internal and small pieces will not have their dimension doubled in the 1:1 cask, and the final thermal analysis will be performed for licensing purposes. One major change, however, have to be done: the spent fuel elements as mentioned below.

The cask steel walls, the lead and the air inside it will be always considered. To verify the influence of the shock absorbers in the temperatures inside the cask, other two analyses will be performed: one with and the other without them. To model the shock absorbers, the foam and its steel skin will be modeled. As an approximation, once the foam can get fire in the involved temperatures, average foam thermal property values will be considered.

In both 2D and 3D models, some structural parts as the lifting trunnions, the bolts and threads, were not modeled because these parts have none or very little influence on the temperature distribution. The ANSYS program [6] was and will be used in the modeling and in the analyses. The contacting walls among the square tubes and among tubes and the plates that form the basket are considered as continuous material (this is a conservative hypothesis). Also, the lead-steel interfaces are considered having continuous heat conduction. All other contacting parts were modeled separately and a contact was defined between each pair of surfaces. At each interface pair among the square solid bars, representing the dummy fuel element masses, and the basket walls the same modeling hypothesis was adopted: there are two independent surfaces in each contact.

All surfaces in contact were modeled independently, with a thermal contact conductance value defined with a specific Real Constant number to identify each surface pair. In the ANSYS, a contact can have up to 26 real constant values to model it. One of them is the PINBALL parameter (PINB) defined with a 3mm value for all contacts. This parameter tells the program the extension around a given node were it should search for contact. In the 3D model there are about 30 contact pairs. The other important contact parameter is the TCC value already defined.

The actual fuel elements are formed by parallel aluminum plates. For the prototype analyses (1:1 scale) each fuel element will be modeled as one block with an equivalent anisotropic material which has its thermal conductivity in the aluminum plate's plane greater than the conductivity perpendicular to the plates. A study should be conducted to establish these values once each plate is a 'sandwich' of aluminum and uranium oxide and between two plates there is a gap. The spent fuel elements have, also, a residual internal heat generation that should be considered (once the cask can be used for storage) and this value depends on the time the spent fuel elements stays in the decaying pool.

All other structural paired surfaces with some theoretical gap between them were modeled independently with no contact but modeling the air between them to consider the conduction and, also, with radiation and/or a convection coefficient among them.

4.1. 2D Thermal Models

The 'vertical' 2D thermal model is presented in Fig. 4. Referring to Fig. 1a, and from top to bottom, one can identify the secondary (upper) lid, the flanges, the primary lid resting on the internal flange, the external wall, the lead and the internal wall cylinders. Also, the internal basket, the dummy masses representing the fuel elements as well as the air, are modeled.

The other 2D Thermal Model, the 'horizontal' one, is partially shown in Fig. 5 (only the 'structural' parts of the internal basket and the attached cylindrical shells are shown). The cylinders representing the external and the internal cask walls as well the one representing the lead between them are not shown in Fig. 5 but they will be present in the numerical model. The same applies for the air inside the cask as was done for the 'horizontal' model (Fig. 4).

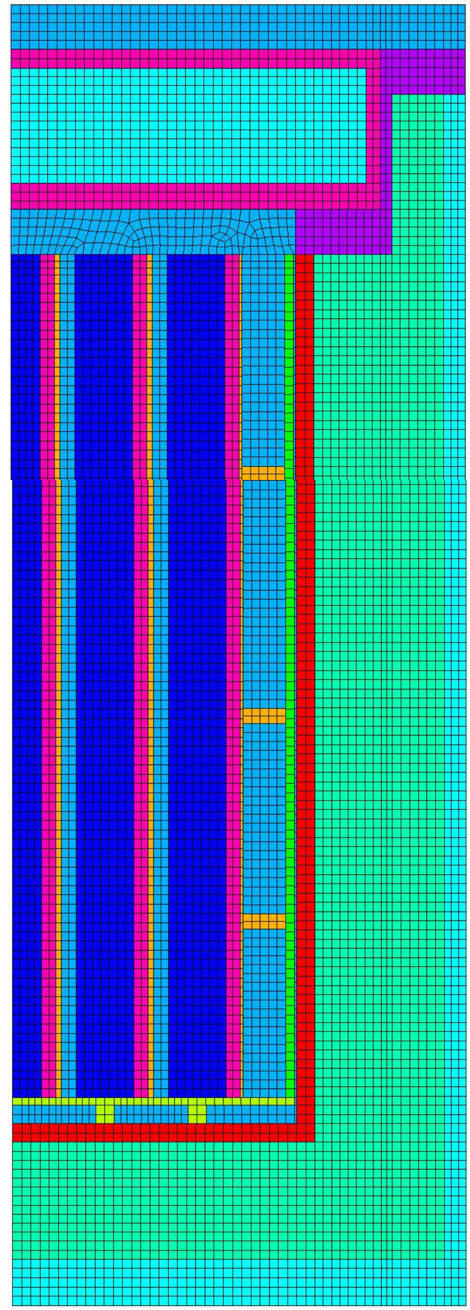


Figure 4: 2D Thermal Model – Vertical.

4.2. 3D Thermal Model

The 3D Finite Element model uses mostly the ANSYS isoparametric solid elements SOLID90 with 20 nodes each. In a first step, for fast processing in the preliminary analyses, the model has two symmetries as shown in Fig. 6 and 7, which is an approximation once considering the thermal radiation does not allow symmetry. For thermal radiation, a radiation matrix Superelement is previously created using the SHELL57 element with unit thickness, null density and emissivity as defined in Table 1. For the 'regular' thermal analysis these shell elements are deleted.

The contacting surface pairs are defined by two element types: TARGE170 and CONTA174 (with quadrilateral shape) used to consider and model the thermal contacts. In thermal analysis, the contacts should be defined with the TEMP (temperature) degree of freedom.

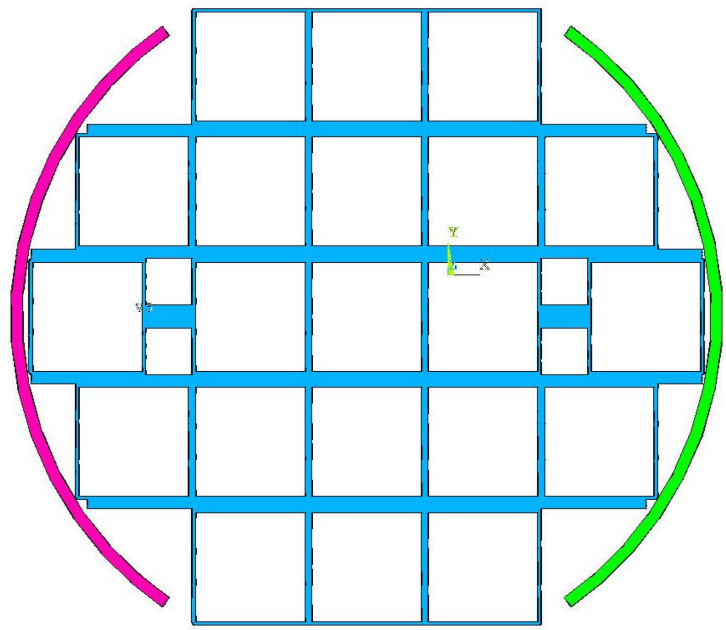


Figure 5: 2D Thermal Model – Horizontal (only the internal basket structure is shown).

4.3. Materials Properties

The main material property values **[3, 4, 5]** that will be used in the analyses (E – Young modulus, ν - Poisson's ratio, ρ - density, K_{xx} – thermal conductivity and C – specific heat) are presented in Table 1. The Emissivity in all internal surfaces was considered as 0.5.

Table 1: Material properties adopted in the analysis

Property	Stainless Steel	Lead	Aluminum	Unit
E	200e9	14e9	70e9	N/m^2
ν	0.30	0.42	0.34	---
ρ	7500	11500	2700	Kg/m^3
Kxx	20.0	30.0	230	W/m ºC
C	500	150	1000	J/Kg ºC

To consider the phase changing of the lead from solid to liquid at 327.1 ºC, the specific enthalpy X temperature curve [6] shown in Fig. 8 was adopted. For the program, the curve was defined as in Fig. 8, with temperatures in Celsius degree. Internally the ANSYS program adjusts all input temperatures to the Kelvin scale by a defined offset value (273).

5. CONCLUSIONS

The present work described the planned framework thermal analysis which includes a 3D model and two 2D models to be performed in a 1:2 scale model of a dual-purpose cask of spent fuel elements from research reactors. The analyses will be transient ones considering the material properties varying with the temperature and the involved non-linearities (mainly the lead phase change, thermal contacts and radiation).

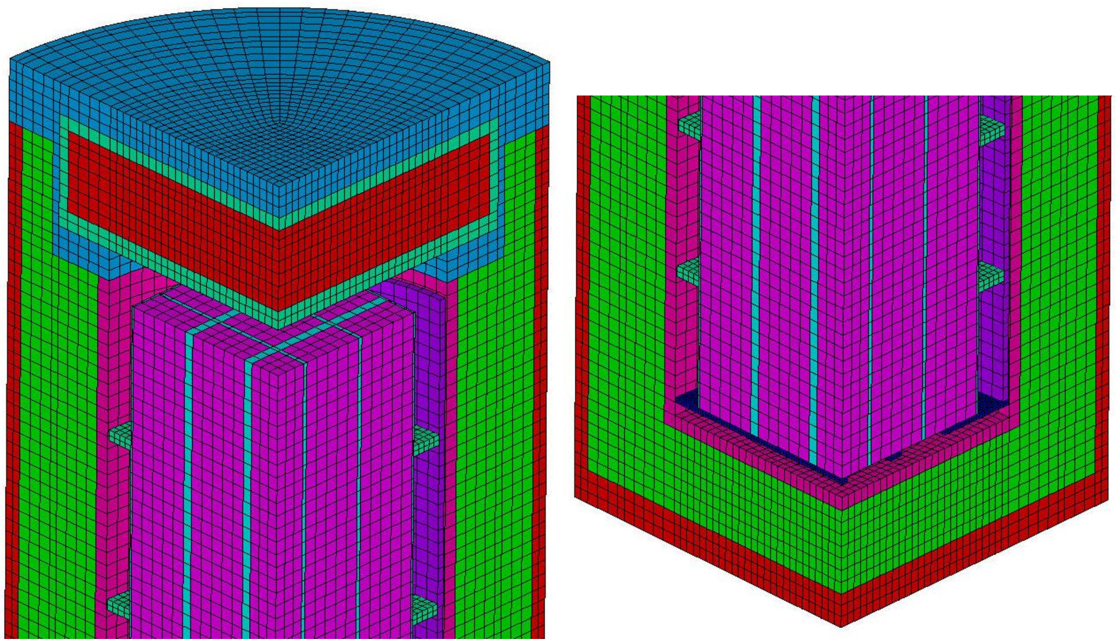
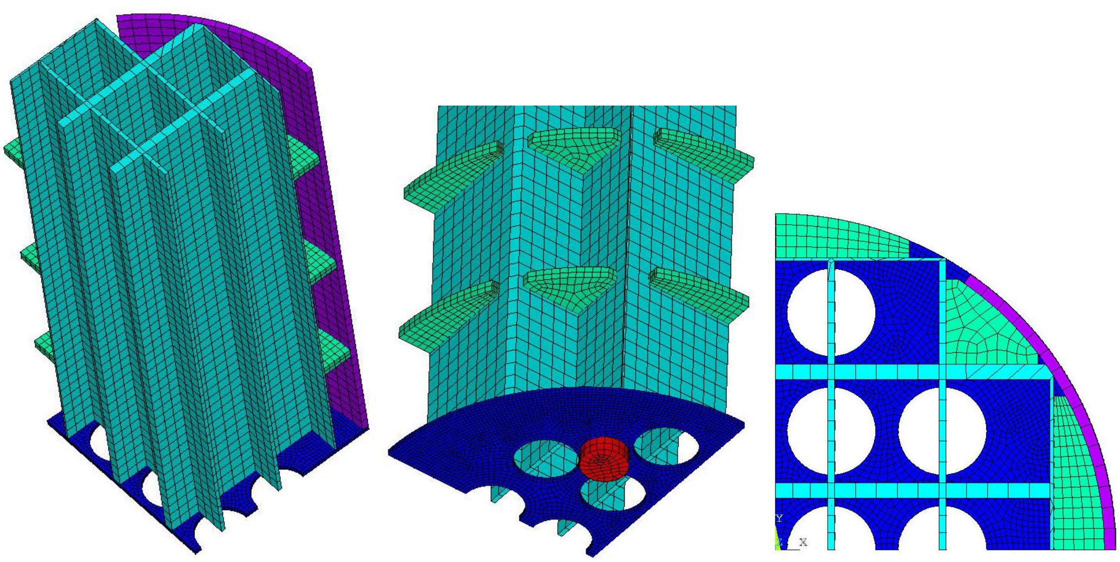


Figure 6: 3D Thermal Model (air not shown).



(a) with lateral circular plate (b) bottom view (no lateral circular plate) (c) Upper view

Figure 7: 3D Thermal Model – Internal Parts (air not shown).

The 3D model takes several hours to run just one analysis. As the 2D models will run faster than the 3D model, they will be used to evaluate the significance of each heat transfer phenomena (radiation, convection and conduction) in the results, as well as some specific parameter values as emissivity and contact resistance. The final goal is to use the 3D model to reproduce the experimental thermal results already obtained in the cask 1:2 scale model.

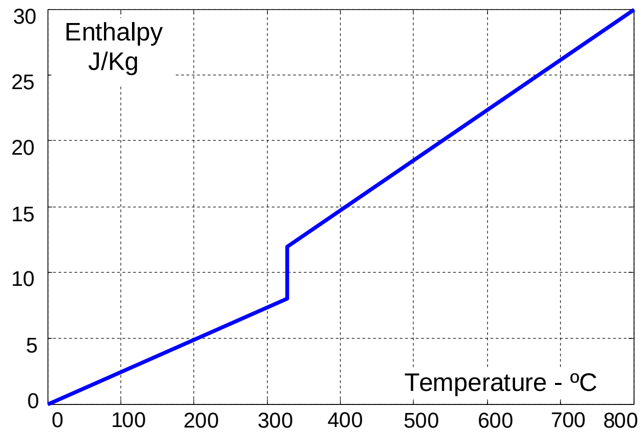


Figure 8. Specific Enthalpy X Temperature – Lead [6]

ACKNOWLEDGMENTS

The authors are grateful to their institution, Nuclear and Energy Research Institute, IPEN-CNEN/SP, for the support given for this specific work as well as to the IAEA for the general project funding support and to the technicians who made possible the 1:2 scale cask model itself and all experiments.

REFERENCES

1. International Atomic Energy Agency. *Regulations for the Safe Transport of Radioactive Material*, IAEA Safety Standards Series No. TS-R-1, Vienna, (2009).
2. Testing of a Transport Cask for Research Reactor Spent Fuel, Rogério P. Mourão, Luiz Leite da Silva, Carlos A. Miranda, Miguel Mattar Neto, José F. A. Quintana, Roberto O. Saliba, Oscar E. Novara. *WM2013 Conference*, Phoenix, Arizona, USA, pp. 24 – 28 (2013).
3. Fletcher, L. S., "Recent Developments in Contact Conductance Heat Transfer". *Journal of Heat Transfer*, November 1988.
4. NEA – Nuclear Energy Agency. *Handbook on Lead-Bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-Hydraulics and Technologies*. http://www.nea.fr/html/science/reports/2007/nea6195-handbook.html (2007).
5. Frank P. Incropera, David P. DeWitt, *Fundamentals of Heat And Mass Transfer*, 5th ed., John Willey Sons, Inc. (2002).
6. ANSYS v11.0 ANSYS Structural Analysis Guide & Theory Reference Manual.
7. Rogério P. Mourão, Project RLA/4/020, Test report - *Test for design validation of a research reactor spent fuel transport cask*, CDTN – Belo Horizonte, Brazil, 02 – 13 June, 2008.