Proceedings of the 19th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2019
August 4-9, 2019, New Orleans, LA, USA

THERMAL ANALYSIS IN SPENT NUCLEAR FUEL CASK

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ABSTRACT

Currently, to prevent unacceptable degradation during storage, spent nuclear fuel temperature calculations are focused on maximum temperatures in compliance with the limits specified in the Interim Staff Guidance of the NRC ISG-11 rev.3. These calculations can be extremely conservative in some cases and non-realistic in others, especially when material ductility is an important factor.

Therefore, a long-term collaboration project between ENUSA Industrias Avanzadas S.A., S.M.E and Universidad Politécnica de Madrid (UPM) has been launched in order to obtain more realistic cladding temperature results during transport and storage, and its evolution with time.

Thermal analysis have been developed for the TN-24P storage cask configured for PWR with helium backfill gas. The main reason to choose the TN-24P cask is that experimental data are available and simulation results can be compared to measured test data.

Two computer codes, COBRA-SFS and STAR-CCM+, have been used. This paper is focused in COBRA-SFS, a thermal-hydraulic analysis code developed by PNNL specific for spent fuel storage and transportation casks.

Considering the following parameters (velocity, enthalpy, temperatures, mass flux …), good agreement between the experimental thermocouple data and COBRA-SFS code predictions are obtained. Additionally, different sensitivity analysis for key parameters have been performed:

(1) Gaps between the basket and the inside wall of the cask. Results show an important impact in the simulations.
(2) Helium flow rate distribution. The analysis show a negligible effect by this factor due to the low velocity and low pressure the helium has inside this cask.

Additionally, several scripts that process COBRA-SFS input and output data have been set. As a consequence, the results are shown as heat map or as a graphic. The user can choose the parameters and/or the assembly from which to show the results.

Creating different simulation cask models and developing a methodology to obtain useful understanding of thermal behaviour of spent fuel storage and transportation systems is one of the main objectives of this project, therefore in future works other storage casks designs are going to be analysed.

1. INTRODUCTION

The COBRA-SFS (Spent Fuel Storage) code [1] provides the capability for thermal modeling of the entire storage module (including fuel assemblies, canister internals and overpack). This code performs thermal-hydraulic analyses of multi-assembly spent fuel storage and transportation systems. It uses a finite difference approach to predict flow and temperature distributions in spent fuel storage systems and fuel assemblies, under forced and natural convection heat transfer conditions, in both steady-state and transients.

The TN-24P cask has been chosen to be modeled due to the extensive literature available and the published testing results performed by EPRI [2].

1.1 COBRA-SFS basic structure

COBRA-SFS code calculates the fuel temperature evolution in a container. This input is highly structured and organised into five basic categories or groups:

1. The physical properties of the solid materials and working fluid
2. The flow channel geometry and solid node structure
3. The constitutive models for the flow and heat transfer solutions
4. The boundary conditions
5. Solution control parameters and output options

The COBRA-SFS model is constructed by dividing the cask into a set of finite volumes or nodes, consisting of assemblies which are made up of channels that represent the fluid flow paths and rods that represent the fuel. The channels are bounded by solid conduction nodes (slabs) which represent the solid structure of the cask (canisters, support baskets, shield yielding and structure shells).

Figure 1 is a scheme of the TN-24P storage cask container, meanwhile Figure 2 represents the cross-section of the node map resulting of 365 solid nodes and 44 assemblies, 24 with fuel assemblies inside meanwhile 20 are empty channels for coolant (helium) recirculation.

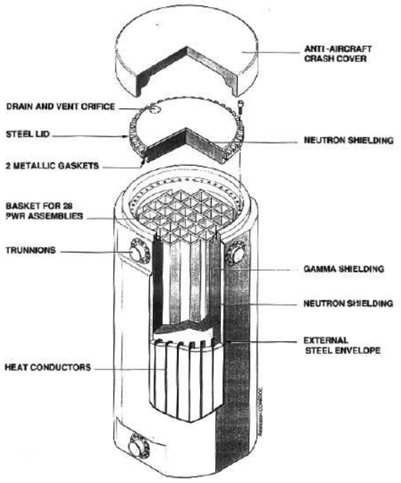

Figure 1. TN-24P cask structure

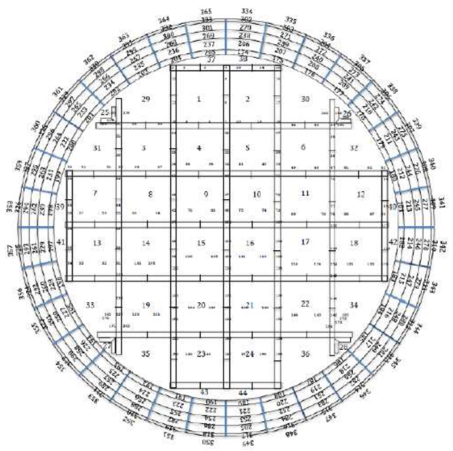

Figure 2. Cross-section of the COBRA-SFS model

1.2 Conservation equations

The governing equations for flow of a single-component mixture can be formulated on an arbitrary fixed Eulerian control volume [1]. This approach is used to develop the conservation equations solved in the COBRA-SFS code. Integral balances for mass, energy, and linear momentum are formed on the arbitrary Eulerian control volume, then applied to subchannel modeling with appropriate definitions and simplifications (see [1]), and converted to partial differential equations over the subchannel control volume.

2. TN-24P MODEL

2.1 Test conditions

The test consisted of loading the TN-24P cask with 24 PWR spent fuel assemblies from Virginia Power´s Surry reactor. Testing was performed with vacuum, nitrogen and helium backfill environment in horizontal and vertical cask orientation. In this paper only the vertical orientation cask with helium backfill is analysed with an ambient temperature of 20ºC.

The Surry spent fuel assemblies used during testing are of a standard Westinghouse 15x15 rod design with fuel assembly decay heat generation rates totalled 20.6kW at the start of testing and 20.3 kW at the end of testing for an average of 850 W per assembly. Figure 3 shows the predicted axial decay heat profile assumed for each fuel assembly.

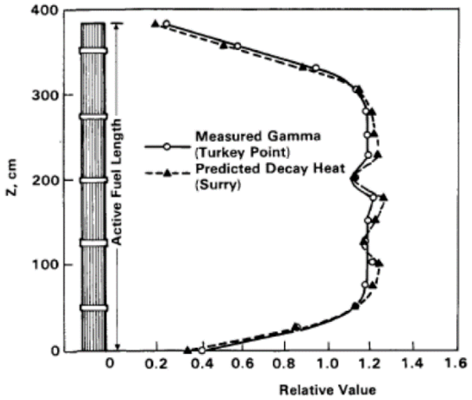

Figure 3. Axial decay heat profile [2]

2.2 Input Python scripts

Due to the non-user friendly interface COBRA-SFS code has, Python scripts have been developed to help the user create the input files and to post-process the results so they can be analysed easily.

Therefore, each group described in section 1.1 has a script to create that part of the input code. This is done by writing a matrix using an Excel file that defines each group of the input:

- Channel: specifies flow field geometry.
- Rods: defines fuel rod geometry and thermal connections between fluid channels and rods.

- Slabs: specifies slab node geometry, defines slab thermal connection types, assemblies and the map of solid conduction nodes.
- Radgen: specifies the thermal radiation exchange factors for rod arrays and slab nodes.

The rest of the input must be written directly by the user, but since these input groups are the most tedious, having these scripts makes work much easier and reduces user errors.

Figure 4 is an example of the process followed to create the input file needed for COBRA-SFS. First, the user has to create different node maps in Excel to define all the contacts between slabs and each assembly, then the user runs the script and finally the script process the Excel data and provides a .txt file with the input needed for each group defined previously.

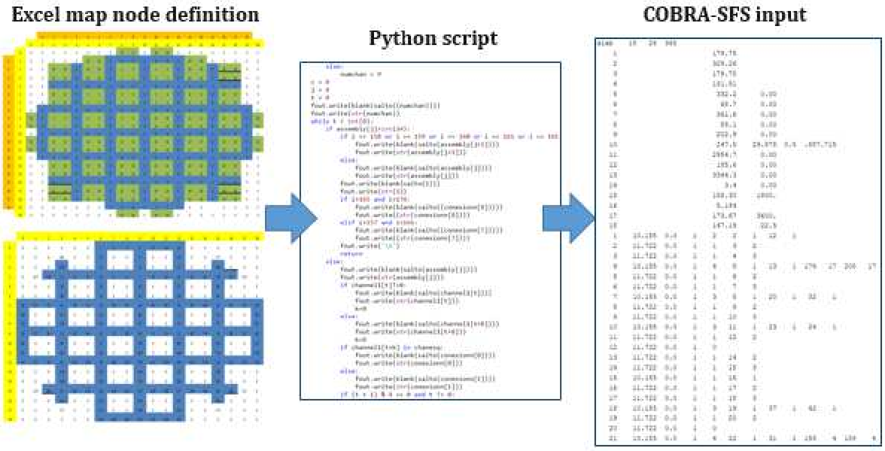

Figure 4. Input generation using Python scripts

To calculate the exchange factors of assemblies with rods inside, COBRA-SFS has an additional code RADGEN where defining the geometry of the assembly, emissivity and number of rods inside, provides the thermal radiation heat transfer coefficients in a new .txt file called tape10 that can be read directly by COBRA-SFS.

Whereas for assemblies with no rods inside, the exchange factors must be calculated by hand using the cross-string correlation approach (Hottel 1967). Depending on the cask model, these calculations can become quite tedious. To solve this, a Python script has been created. It consists of different geometries depending on the assembly geometry definition and with an option for the user to introduce any geometry not pre-defined in the script, as well as the option to introduce a curve segment correction in each pre-defined geometry, very useful as most peripheral assemblies have curved sections (Figure 2).

2.3 Output Python scripts

Processing the output file is not simple nor user friendly. The user has to import the data to a post-processing tool (Excel, Matlab,…) region by region. Therefore, Python scripts have been developed to process these results easily and represent the data of interest as a profile plot or coloured map. These scripts allow the user to see the main variables such as pressure, enthalpy, temperature, density, mass flux, volume flux and velocity at different heights.

Figure 5 shows temperature values in the assemblies and solid structures of the canister, using Python post-processing scripts and temperature in assembly 9 (assembly with the highest temperature in the cask).

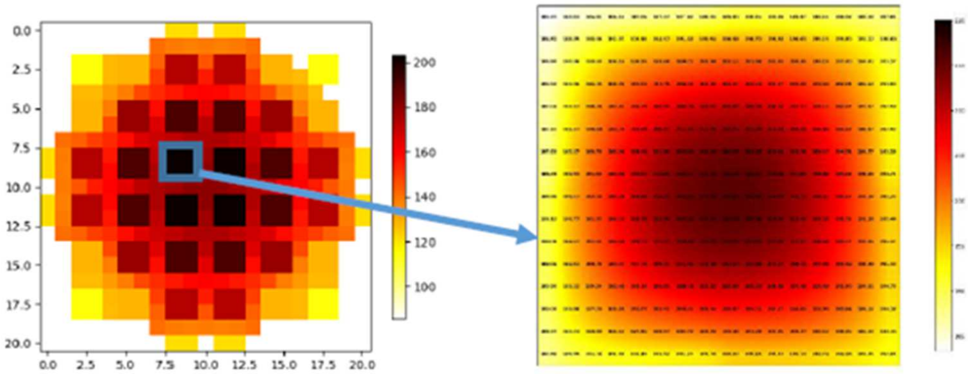

Figure 5. Post-processing of temperature results using Python scripts

3. TN-24P RESULTS

Figure 6 shows the peak temperature results on the hottest assembly (assembly 9, in the center location in the basket, in the hottest rod, number 173) obtained with COBRA-SFS code, compared to the measurements of the thermocouple (TC) in this assembly. The code predicts very good results regarding maximum temperatures located in the center of the axial height of the rod (220ºC), but in the upper and lower height of the rod these temperatures have some differences compared with the measurements of the TC. This could be a result of several possibilities, one the boundary conditions of the experiment, there is no precise information about where the cask was located when the experiment was performed in the warm shop, and the other option is due to how COBRA-SFS models the upper and lower plenum (a single node where the gas pressure and temperature is instantly mixed), this might explain the difference between temperatures at the bottom of the cask and the upper parts of the assembly.

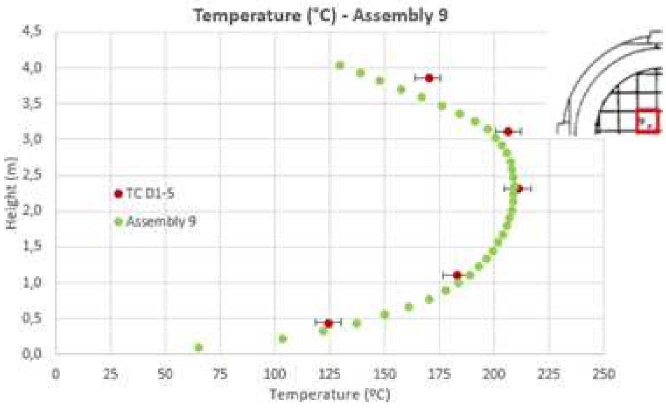

Figure 6. Temperature (ºC) vs TC (interior assembly)

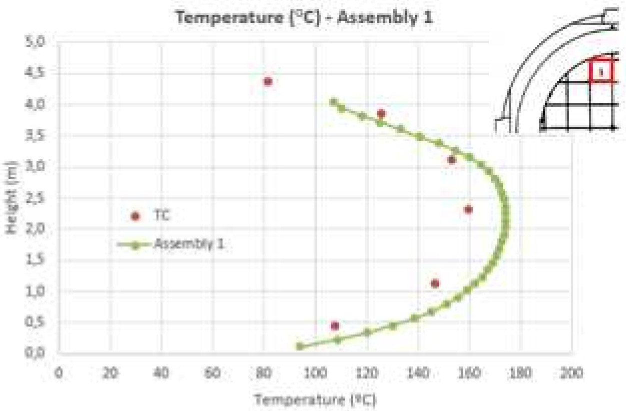

Figure 7. Temperature (ºC) vs TC (peripheral assembly)

For the peripheral assemblies, predicted temperatures are slightly different compared to TC. In Figure 7, temperature results for assembly 1 are represented compared to TC measurements where COBRA-SFS predicted results have a difference of 10-15 ºC in temperature.

3.1 Helium flow rate distribution sensitivity analysis

Trying to find the reasons for such difference, the helium flux behaviour inside the canister was analysed in detail, it was found that all the helium flux comes down only through two specific assemblies as shown in Figure 8. This is not a realistic solution due to the symmetrical initial and boundary conditions in the system, so the helium flux behaviour should be symmetrical too. It was expected that all outside assemblies (assemblies without rods) would act as channels for the thermo-syphon closing the helium loop. This effect has been proven to appear only using helium as coolant, other simulations with nitrogen and vacuum have been studied with no unusual behaviour in the flux.

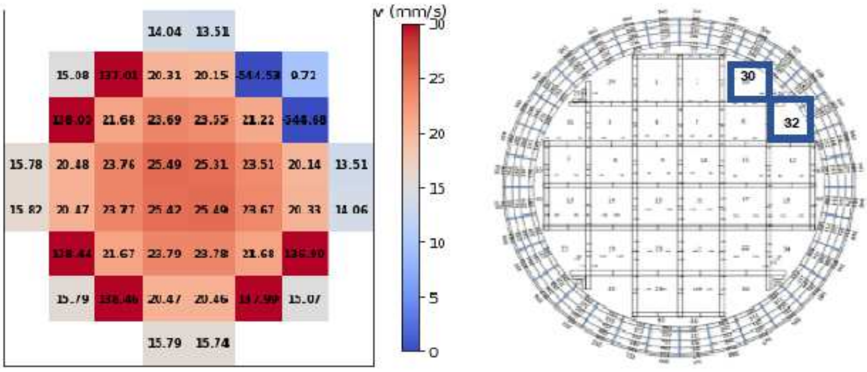

Figure 8. Helium flux velocity (mm/s)

Therefore sensitivity studies have been done concerning this unusual flux behaviour. To do this, the same simulation has been simulated in STAR-CCM+ where the flux distribution is obtained and introduced in COBRA-SFS. Figure 9 represents the new symmetric helium flux distribution in different planes of the cask.

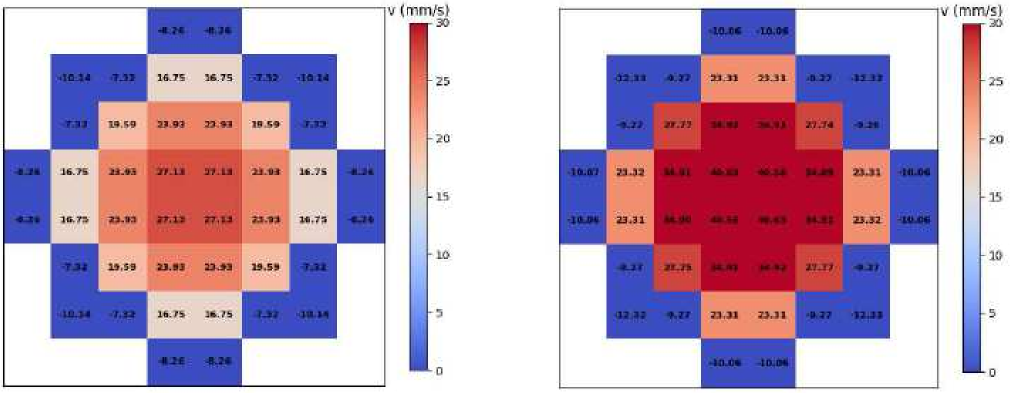

Figure 9. Helium flux velocity (mm/s) lower plane (left) and upper planes (right)

Figure 10 shows the results obtained with COBRA-SFS with the new helium flux distribution compared with the case with the unusual flux behaviour where the maximum differences are 3ºC.

It can be concluded that this unusual flux behaviour hasn't shown an important effect on temperature, main parameter of interest in these simulations, due to the low velocity the helium flux has inside the TN-24P cask.

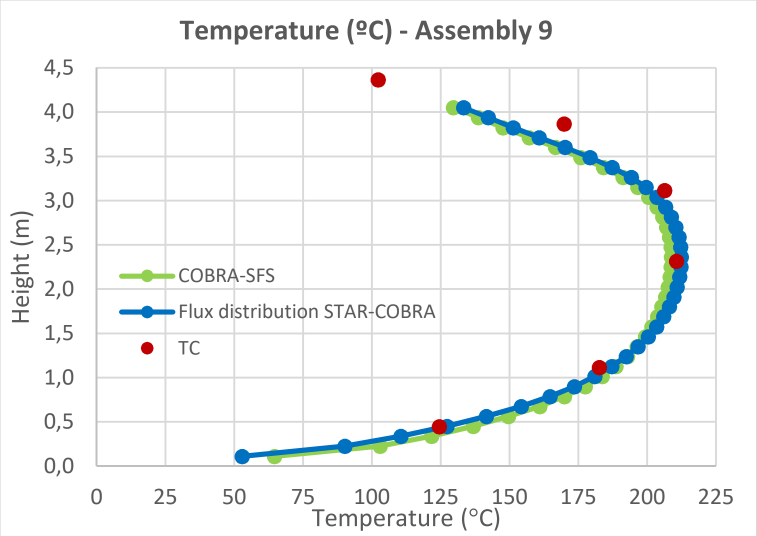

Figure 10. Temperature comparisons results with STAR flux distribution in COBRA-SFS

3.2 Gap effect

To estimate the temperature impact of the contacts between the canister and the inside wall of the cask (Figure 11) sensitivity analysis considering different gap values have been developed for the TN-24P model.

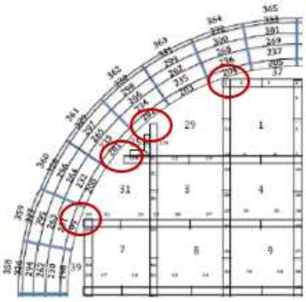

Figure 11. Gaps in TN-24P

Since no information regarding tolerances for these gaps are included in [2], three main cases have been analysed: a full contact case, an adiabatic case and finally a half contact case. Although the full contact and the adiabatic cases are non-realistic, they give the results on both edges. These results give a temperature range where thermal expansions are going to be produced, therefore a half gap contact has also been included due to the symmetry of the cask.

Table 1 represents the Minimum Cladding Temperature (MCT) and Peak Cladding Temperature (PCT) impact for these three cases, where the difference between the full contact case and the adiabatic case is 20ºC in PCT. Regarding MCT, temperature differences are not so high, with 5ºC of difference between the two extreme cases.

	Full contact	**Half contact**	**Adiabatic**
PCT (°C)	215.7	225.9	234.8
MCT (°C)	75.4	78.5	80.3

Table 1. PCT and MCT (ºC)

In Figures 12 and 13 temperature profiles compared to TC measurements are shown in an interior assembly (9) and in a peripheral assembly (1). Results show the adiabatic case increases a maximum temperature of 20ºC compared to the TC in Figure 12, and 30ºC compared to TC measurements in Figure 13 where the differences between the full contact case and the adiabatic case are 18ºC.

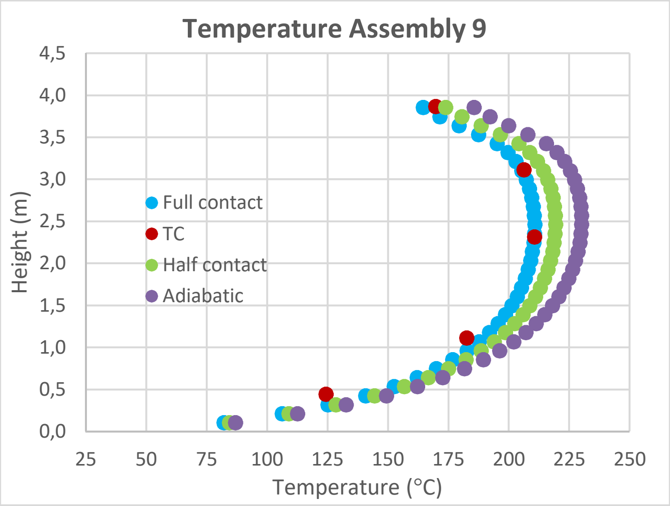

Figure 12. Temperature in assembly 9

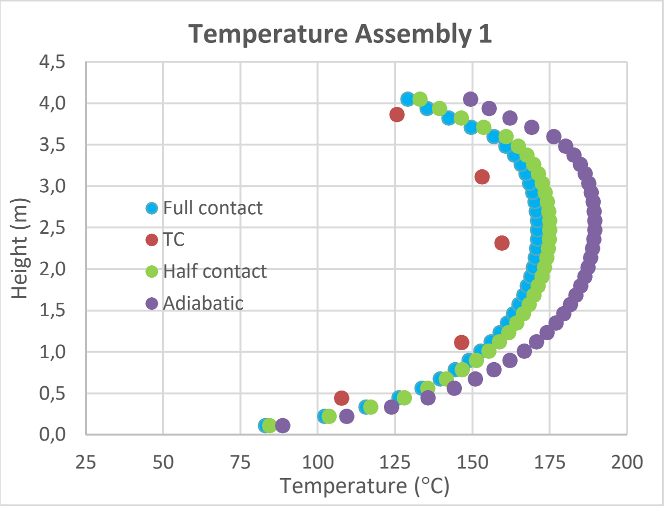

Figure 13. Temperature in assembly 1

Gap sensitivity studies show high differences in temperature results for the small regions the gaps represent, therefore two cases should be analysed (adiabatic and full contact) to obtain a temperature limit range. As a best practice, if the cask is symmetric, establishing half contact gaps can be a solution for COBRA-SFS temperature results.

4. CONCLUSIONS

COBRA-SFS code has very low computational time and provides good results for fuel temperature during dry storage. However, building detailed thermal models with COBRA-SFS is not a trivial process but can be extremely useful, in terms of obtaining deeper understanding of thermal behaviour of spent fuel storage and transportation systems. To help the user generate the input file and post-process the results, several Python scripts have been developed at

ENUSA-UPM, these scripts save time and avoid user errors that can be easy to make while writing the input file.

The results obtained for the TN-24P cask filled up with helium, compared to measured temperature data shown accurate temperature results (Figure 6) and have particularly good agreement in the center of the assembly, where the maximum temperature is located, with maximum differences of 15ºC in peripheral assemblies.

The post-process scripts make the results lecture easier with graphics and coloured maps, thank to these scripts, parameters such as helium flux can be analysed. This lead to the unusual behaviour that the helium flux showed (Figure 8). To analyse this impact, sensitivity studies have been made, coming to the conclusion that temperatures are not affected by this unusual flux distribution due to the low helium velocity inside the cask.

To complete the simulations, the effect of the gap between the canister and the inside wall of the cask has been analysed, proving the high impact these parameters have in temperature results, as shown in Figures 12 and 13. To obtain realistic temperature solutions, analysing an adiabatic case and a full contact case should be a best practice to do in any thermal calculation.

Creating different simulation cask models and developing a methodology with the aim of obtaining useful understanding of thermal behaviour of spent fuel storage and transportation systems is one of the main objectives of this project, therefore currently other storage casks are being developed at ENUSA using COBRA-SFS as well as STAR-CCM+.

5. REFERENCES

[1] TE Michener, JM Cuta; COBRA-SFS: A THERMAL-HYDRAULIC ANALYSIS CODE FOR APENT FUEL STORAGE AND TRANSPORTATION CASKS.

[2] "THE TN-24P PWR SPENT-FUEL STORAGE CASK: TESTING AND ANALYSES", EPRI J.M. Creer, T.E Michener, M.A McKinnon, J.E. Tanner, E.R. Gilbert, R.L Goodman. April 1987. (EPRI NP-5128).