# TEMPERATURE CALCULATIONS IN SPENT NUCLEAR FUEL CASK USING COBRA-SFS

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## ABSTRACT

Currently, 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 for cladding, 400ºC for normal conditions of storage and short-term loading operations, to prevent unacceptable clad degradation during storage. These calculations can be extremely conservative in some cases, and non-realistic in others, especially when material ductility is an important factor.

Therefore, the need to develop new capabilities arises in ENUSA in order to obtain more realistic results of spent fuel temperature distribution during transport and storage. As a result, a long-term collaboration project between ENUSA and Universidad Politécnica de Madrid (UPM) has been launched.

In the first phase of the project, COBRA-SFS, a computer code developed by Pacific Northwest Laboratory is being used. This is a thermal-hydraulic analysis code specific for spent fuel storage and transportation casks. The TN-24P storage cask configured for PWR spent fuel with helium backfill gas has been chosen. 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. Additionally, several scripts that process COBRA-SFS input and output data have been developed.

## 1. Introduction

This collaboration project between ENUSA Industrias Avanzadas S.A., S.M.E, and Universidad Politécnica de Madrid, is focused on developing realistic thermal calculations of spent fuel during dry storage and transportation. Therefore, two codes are being used: COBRA-SFS and the CFD code STAR-CCM+.

In this paper, COBRA-SFS code is described and the results are shown for the TN-24P cask.

## 2. COBRA-SFS code

The COBRA-SFS (Spent Fuel Storage) code provides the capability for thermal modelling 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.

## 2.1 Basic Structure of COBRA-SFS Modeling

To be capable of analysing fuel temperature evolution in a cask container, the COBRA-SFS code needs an input where the container is described by parts.

The input is highly structured, it is organized 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

A COBRA-SFS cask model is constructed by dividing the cask into a set of finite volumes or nodes, consisting of assemblies which are made up of channels to represent the fluid flow paths and rods to represent the fuel. The channels are bounded by solid conduction nodes (slabs) that represent the solid material of the cask, such as assembly canisters, support baskets, shielding layers, and inner and outer structural shells.

Figure 1 is a schedule of the TN-24P storage cask container simulated in this project with 24 PWR spent fuel assemblies each with a 15x15 rod configuration.

Figure 2 represents the model needed to run COBRA-SFS code. The assemblies numbered from 1 to 24 have spent fuel rods inside while the assemblies numbered from 25 to 44 are empty channels for coolant (helium) recirculation.
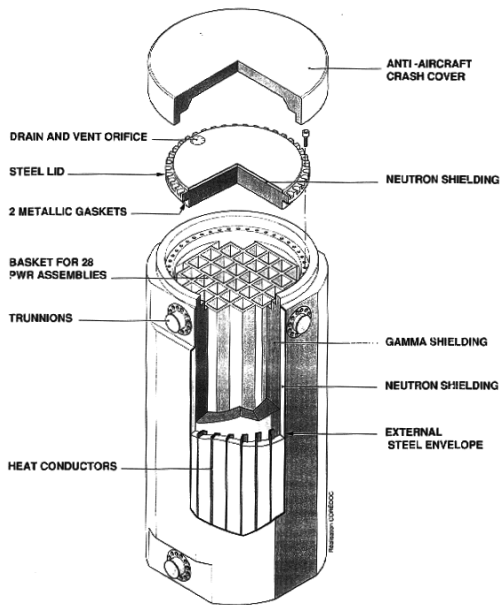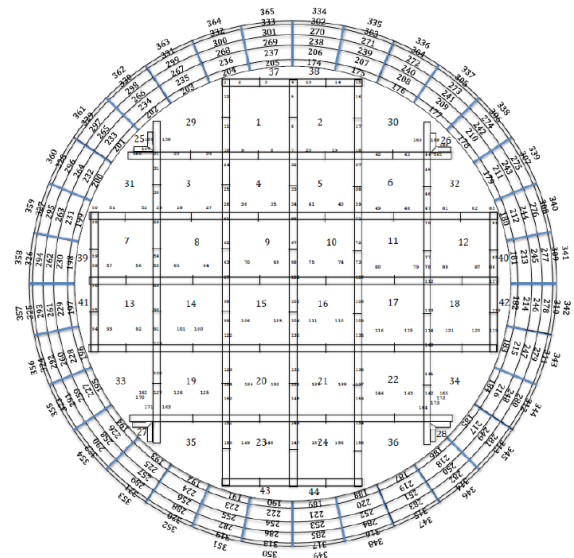


**Figure 1. TN-24P Cask structure**



**Figure 2. COBRA-SFS TN-24P cask model**

## 2.2 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 modelling with appropriate definitions and simplifications, and converted to partial differential equations over the subchannel control volume. In figure 3 subchannel definition is described for COBRA-SFS code.
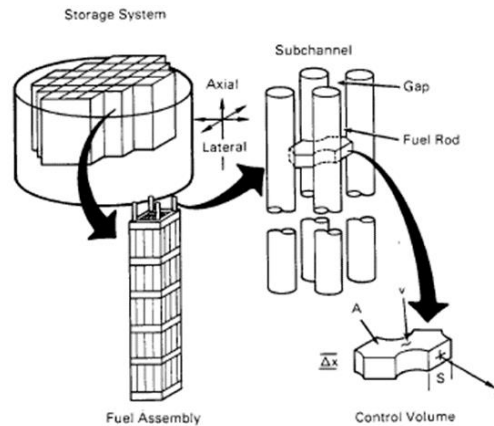
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*Figure 3. Subchannel definition*

A number of simplifying assumptions are applied to these integral balance laws, consistent with the intended application of the code, such as:

1. The flow is at sufficiently low velocity so that kinetic and potential energy are negligible compared to internal thermal energy.
2. Work done by body forces and shear stresses is small compared to surface heat transfer and convective energy transport in the energy equation.
3. Gravity is the only significant body force in the momentum equation.
4. The fluid is incompressible but thermally expandable, so that density and transport properties vary only with the local temperature.
5. The radioactive energy source in the fuel is sufficiently decayed so that direct energy deposition in the fluid is negligible, and there is no significant gamma heating.
6. There is normally no lateral cross-coupling for momentum.

For more details about the COBRA-SFS code, structure and equations see [1].

## 3. The TN-24P test

### 3.1 Test conditions

In the first part of the project, 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].

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 4 shows the predicted axial decay heat profile assumed for each of the fuel assemblies.
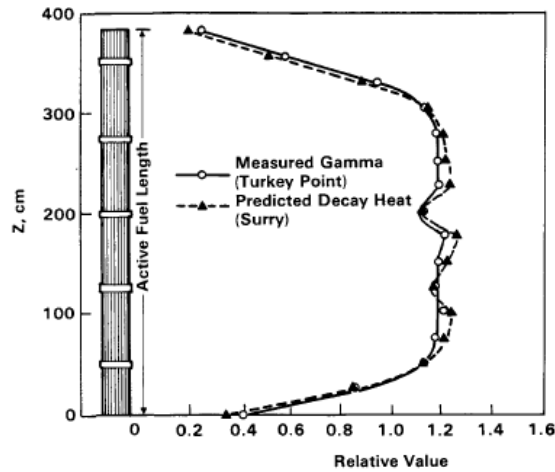
**Figure 4. TN-24P test predicted axial decay heat profile [2]**

For more details about the TN-24P test see [2].

### 3.2 Results

Once the COBRA-SFS input has been prepared based in data contained in [2] and with the help of Python scripts developed for this container in particular (described in section 4), the code only takes a few minutes to generate the output data.

Figure 5 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.
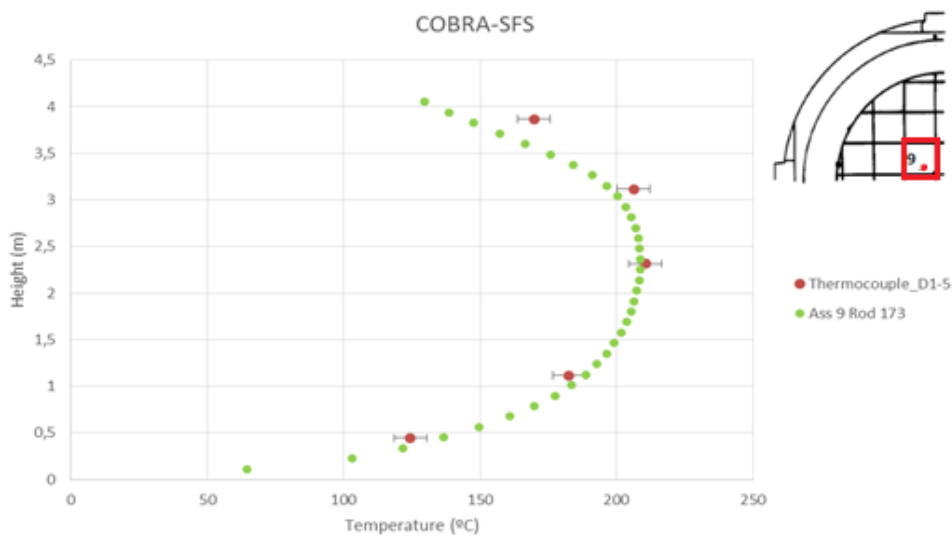


**Figure 5. COBRA calculated Temperature (ºC) vs TC measured results**

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COBRA-SFS code has very good agreement regarding temperature results especially in assemblies located in the center of the container as shown in Figures 5 and 6.
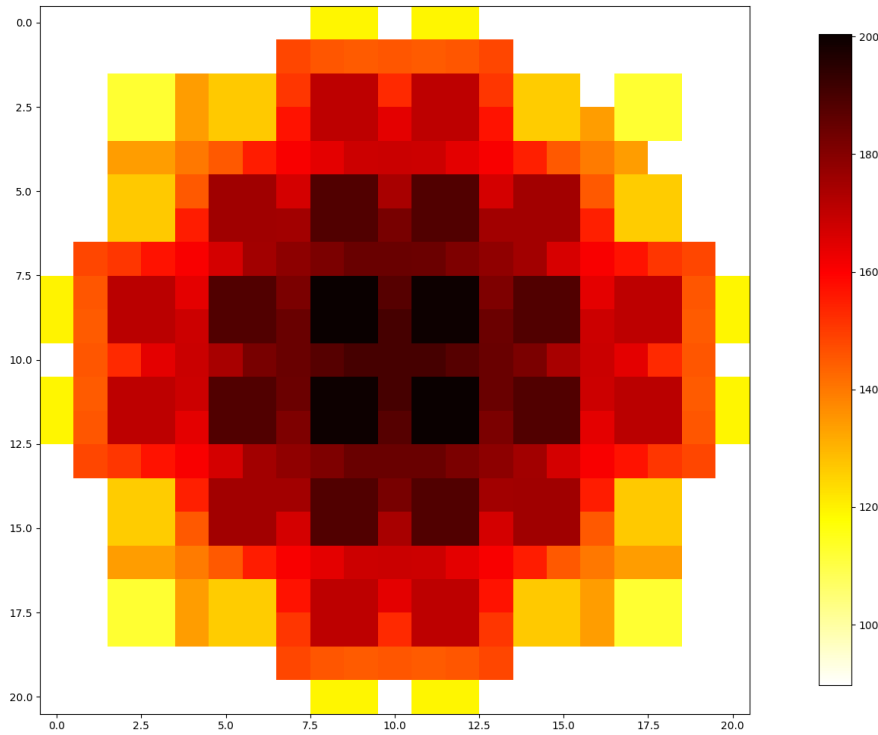


***Figure 6. Temperature (ºC) in canister and assemblies***

For the peripheral assemblies, predicted temperatures are slightly different compared to measurements. In Figure 7, temperature results of two of the peripherals assemblies are represented compared with the measured TC located in the assembly. In the graphic, COBRA-SFS predicted results are approximately 10-20ºC above the TC measurements. The TC measurement out of the profile at 4,4m height, is the temperature measured at the top of the cask lid.
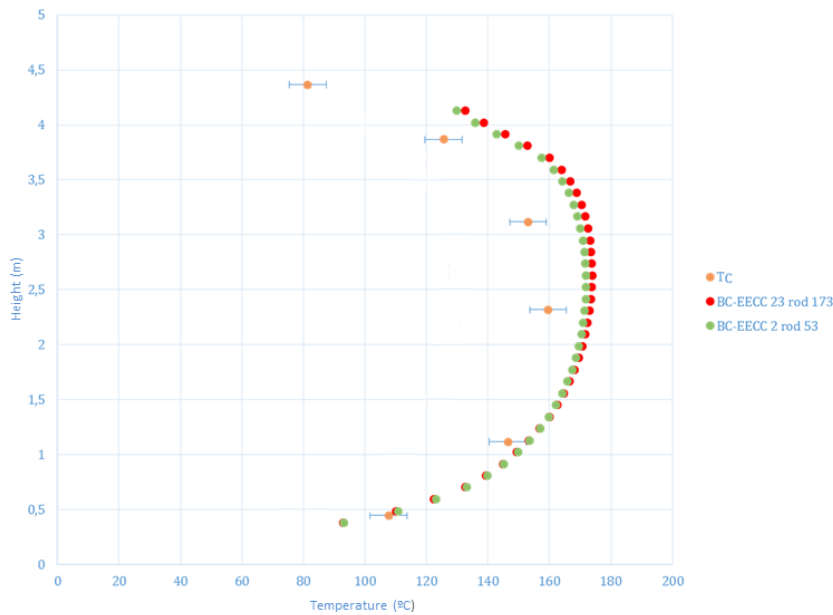


***Figure 7. Peripheral assemblies temperature (ºC)***

Trying to find the reasons for such difference, the helium flux behaviour inside the canister was analysed in detail, coming up to the conclusion that the helium flux inside the cask in COBRA-SFS code was not calculated properly, as 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 because initial and boundary conditions in the system are symmetrical, 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.
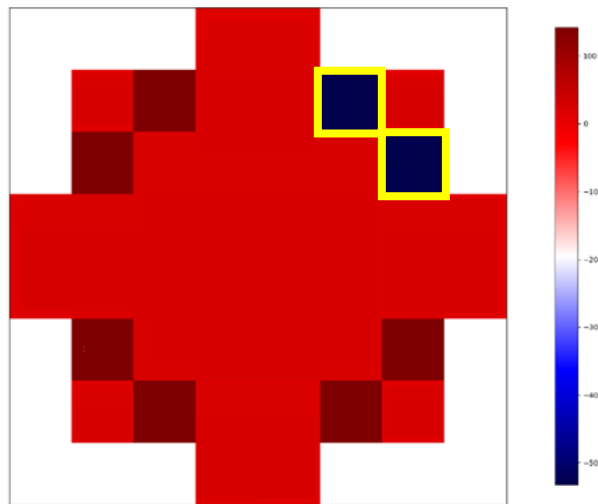


***Figure 8. Flux velocity (mm/s) results per assembly***

Therefore, one of the main goals in this part of the project is to solve this COBRA-SFS distribution of helium flux inside the cask. In order to do this, parameter studies of sensitivity are being performed and a new methodology is being developed due to this flux disagreement in the code. Simulations with CFD code STAR-CCM+ are being developed, with the aim of introducing STAR-CCM+ predicted flux results in the COBRA-SFS input and analyse how this affects the results. The main issue CFD codes have is the high computational cost to obtain the results, compared to using other codes such as COBRA-SFS, therefore developing new capacities and methodology using mainly COBRA-SFS code supported by STAR-CCM+ when necessary, is one of the goals regarding this project.

## 4. COBRA-SFS: Python scripts

As described in section 1 of this paper, the COBRA-SFS input and output interface is neither graphical nor particularly user friendly, therefore the need to develop scripts in Python, that process COBRA-SFS input and output data in this project.

### 4.1 Input

To simplify the process of typing the entire input (a txt file), the first step is to create an Excel matrix that represents the geometry of the model. The main input is defined by three different matrix:

- SLABS: this group represents the solid structure of the cask container and thermal connections between them and the fluid.
- CHAN: the fluid geometry is specified in this group.

- RODS: rod geometry and thermal connections between them and the fluid are defined.

Once these matrices are defined, a Python script processes the information and the main input groups are automatically generated.

## 4.2 Output

The COBRA-SFS code output is a txt file, this file is structured very similar to the input file, the results are shown by regions (subchannels, rods, solid structure and fluid) depending on the height.

Processing this output is not simple or user friendly. In order to work with it, the user has to import to a post-processing tool region by region (Excel, Matlab …). The scripts built in Python 3.6 help the user process the output file 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. All these values can be seen at different heights.

In Figure 9 temperature values in the assemblies and solid structures of the canister, using Python post processing scripts, are shown. Figure 10 shows the velocities in the channels of an assembly.
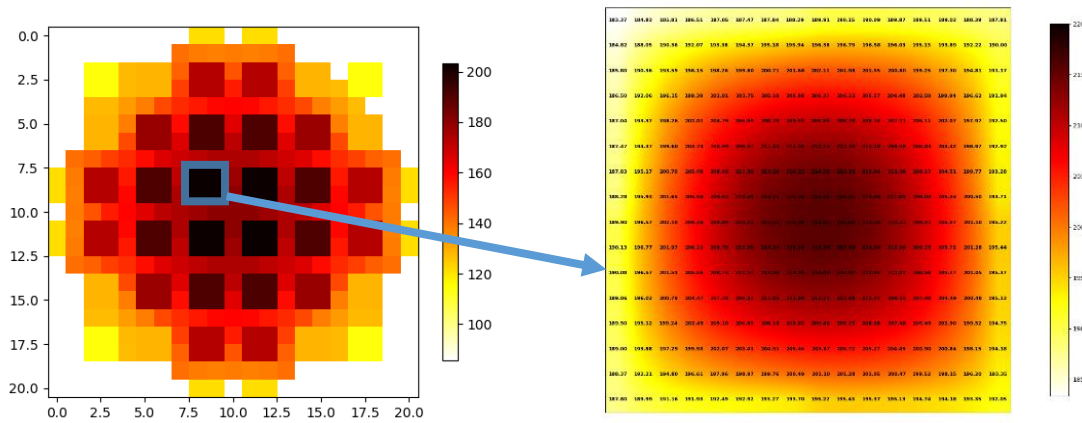


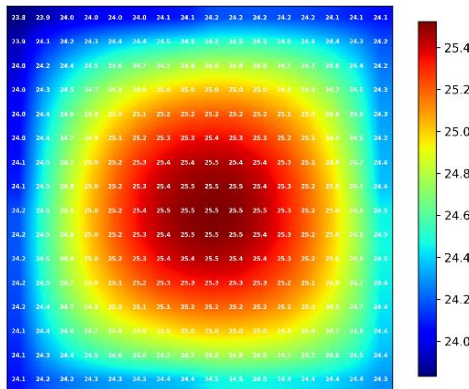*Figure 9. Temperatures (ºC) in canister and assembly*



*Figure 10. Velocities (mm/s) in assembly*

These scripts have been developed for the TN-24P cask model, for another type of cask a few modifications have to be done in these scripts, but the main structure is the same.

Additionally, graphic results can be illustrated with these scripts, they are very useful to compare different results in a simple way. Figure 11 shows average temperatures per fuel assembly, each line in the graphic represents the temperature profile in different assemblies in the canister.
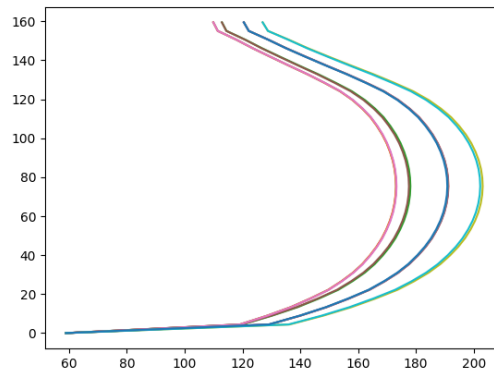


*Figure 11. Average Temperatures (ºC) per assembly vs. Height (inch)*

## 5. Conclusions

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.

The results obtained for the TN-24P cask filled up with Helium, compared to measured temperature data shown in Figure 5, have particularly good agreement in the center of the assembly, where the maximum temperature is located. These temperatures are way below the 400ºC established in the Interim Staff Guidance of the NRC ISG-11 rev.3.

In the next phase of this collaboration project, other storage casks are going to be modelled with COBRA-SFS and STAR-CCM+ code. Currently parameter sensitivity analysis are being developed due to the importance of these parameters for realistic temperature calculations.

## 6. References

[1] "COBRA-SFS: A THERMAL-HYDRAULIC ANALYSIS CODE FOR SPENT FUEL STORAGE AND TRANSPORTATION CASKS, CYCLE 4", Michener, Thomas E, J.M. Cuta, DR Rector, and H. E. Adkins. October 2015.

[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).