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

ANALYSIS OF 3-DIMENSIONAL TEMPERATURE FIELDS OF LOADED DRY STORAGE CASKS

M. Péridis[1, 2], N.-F. Sentuc[3], M. Sonnenkalb[3], J. Stewering[3], M. Stuke[1]
[1] GRS gGmbH, Forschungszentrum, Boltzmannstr. 14, 85748 Garching, Germany
[2] Technische Universität München, Boltzmannstr. 15, 85748 Garching, Germany
[3] GRS gGmbH, Schwertnergasse 1, 50667 Cologne, Germany

ABSTRACT

Spent fuel dry cask storage facilities are proven part of many nuclear waste management concepts. The recent German strategy foresees an interim dry storage duration of a maximum of 40 years. However, the lack of a final disposal will lead to prolongations of the storage time beyond this limit. This requires detailed investigation of the long-term degradation mechanisms to ensure the safety functions to be fulfilled. Further important aspects are transportability and manageability of the fuel assemblies after the dry storage. This requires integrity of fuel rods and especially the exclusion of systematic fuel rod failures.

A key variable to predict the integrity of the fuel rod cladding is the temperature. Almost all degeneration mechanisms are temperature dependent. A realistic prediction of the time dependent temperature field inside the cask is needed to investigate long-term degradation mechanisms properly. Overly conservative temperature estimates with the purpose to assure peak cladding temperatures to be within technical specifications might lead to non-justified conclusions.

In this work we discuss the 3-dimensional temperature fields in a generic Castor-like cask generated with the COBRA-SFS code. We verify the model by comparison with similar analyses performed by the codes ANSYS CFX and COCOSYS. Assuming a homogeneous loading of the cask, we found comparably large temperature gradients within one fuel assembly and over the fuel rod height. Our detailed temperature fields build the basis for more reliable predictions of the cladding behavior during long-term interim storage.

INTRODUCTION

The German strategy for waste management includes long-term dry storage of spent nuclear fuel. After being unloaded from the reactor, fuel assemblies are initially stored for a few years on-site, in cooling pools. After the decay heat decreased sufficiently the fuel assemblies are loaded and dried in transportation and storage casks, and subsequently placed in interim storage facilities. Currently, those facilities have a license for 40 years, starting with the emplacement of the first cask. Within these 40 years it was foreseen, that a deep geological final repository becomes available. However, it is now clear that no final repository will be available in time, and the interim storage has to be prolongated. This requires a new authorization based on further investigations to understand and describe the long-term behavior and degradation effects to ensure continual safe operations.

Almost all long-term effects are temperature dependent. Thus, a detailed knowledge of the temperature - especially the cladding temperature - is desirable throughout the entire storage period. The temperature fields in casks are particularly problematic, as there are few experimental data publicly available to validate the calculational models. Furthermore, the storage casks have a containment function and re-opening a cask for experimental purposes is not straightforward. For this reason, model validation remains challenging.

This work describes first the development and validation of a generic cask model using the thermohydraulic code COBRA-SFS [1] and presents the resulting temperature fields. As a second step, the results of a comparison of the model, with results from two other models, built with COCOSYS [2] and ANSYS CFX [3] are presented.

MODELLING WORK WITH COBRA-SFS

COBRA-SFS thermohydraulic code

We performed the temperature calculations using COBRA-SFS, a thermohydraulic code derived from the COBRA code family. It is developed and validated at Pacific Northwest National Laboratory (PNNL), Richland, USA. COBRA-SFS was specially developed to model spent-fuel storage and transportation systems, in steady-state and transients. It uses finite-difference approach to predict flow and temperature distributions in the spent fuel storage systems and fuel assemblies. Heat exchanges include two-dimensional radiative and three-dimensional conductive heat transfers, as well as natural or forced convection [1].

The software does not provide any graphical user interface, either for the input nor for the output processing. The input is highly structured, with detailed format requirements, which can be hostile to the uninitiated.

Cask model

We modelled a generic Castor-like cask, inspired by the CASTOR® V/19, a transport and storage cask designed by GNS GmbH [4]. The cask is composed of a cask body (stainless steel and shielding materials) with external cooling fins, fuel basket structures which can receive up to 19 fuel assemblies, and a lid system to close the cask. The cask is about 6 m in height, 2.5 m in diameter and weights about 108 t empty. The loaded cask is filled with helium, to ensure an inert atmosphere while enabling good heat removal. The cask has a license for a maximum total thermal power of 39 kW. Concerning the fuel, we modelled 18×18-24 PWR fuel assemblies.

For the COBRA-SFS model, the middle part of the cask (including helium channels, fuel assemblies, and cask body), was represented using 568 “slabs” in COBRA-SFS. The numbering of those slabs can be seen on Figure 1. This numbering is used throughout the input file, to describe the geometry and all the connections between the different elements of the cask (solid parts and fluid channels), and with the environment. There are 19 fuel elements (red numbers 1 to 19 in Figure 1) and 28 “un-rodded assemblies”[1] (red numbers 19 to 47 in Figure 1) corresponding to the helium filled channels. On the axial axis, the model is divided into 36 zones of equal length enabling us to implement axial power profiles and to generate axial temperature profiles in output. Finally, for the uppermost and lowest parts of the cask, the user can define “plenum regions”, to describe the axial boundary conditions in a more realistic way. Yet the modelling is not straightforward, and the impact is limited to the lowest and uppermost tens of centimeters of the fuel assemblies. As an alternative, adiabatic boundary conditions are thus commonly used.

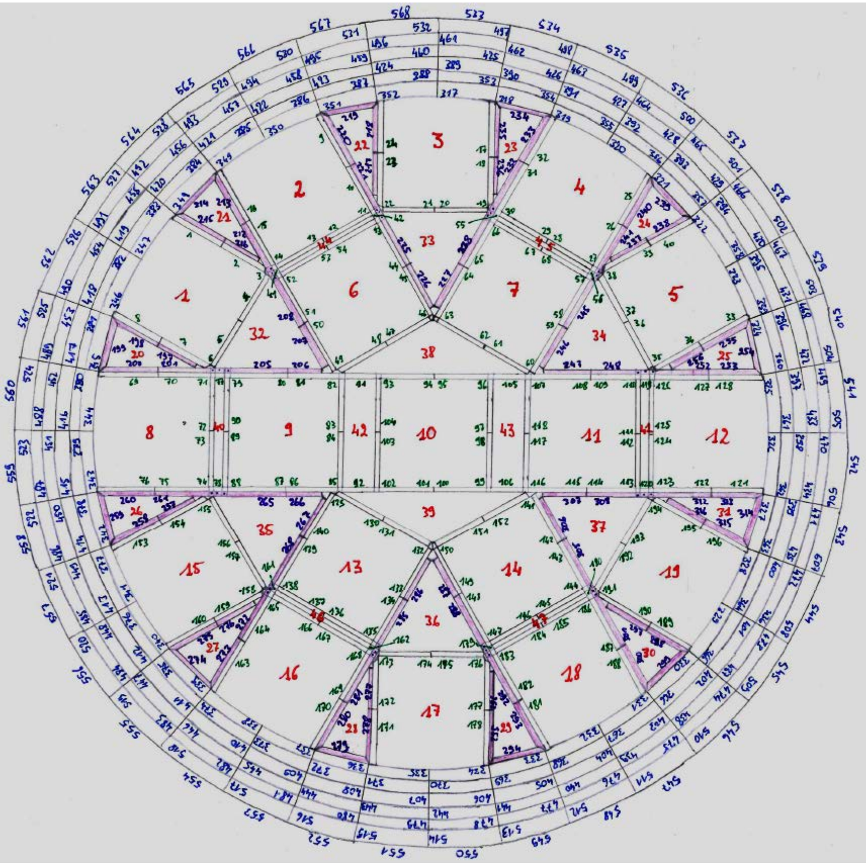

Figure 1. Diagram of the cask model used in COBRA-SFS with node and assembly numbering.

VERIFICATION OF THE COBRA-SFS MODEL

To process COBRA-SFS results, we use ParaView [5]. After building the corresponding geometrical cask model, it enables a 3-dimensional visualization of the results and provides a variety of visualization and analysis tools, including 2-dimensional cross-sections, specific plots, and data analysis functions. Figure 2 shows a cut of the fuel assemblies inside the cask, for a homogeneous load of 39 kW (6.8 W per rod) with a typical axial power profile. As a first

---

[1] COBRA-SFS consider any group of fluid (helium) channels as an *assembly*, whether it includes fuel rods or not. Thus, the helium filled channels are also referred as *assemblies*, labelled as *un-rodded* in this case.

verification, we checked the symmetry of the cask: for a symmetric power load, the resulting temperature field should be symmetrical. This enables to identify input errors, which might occur due to the fact, that the input file consists of thousands of formatted lines, mainly series of numbers.

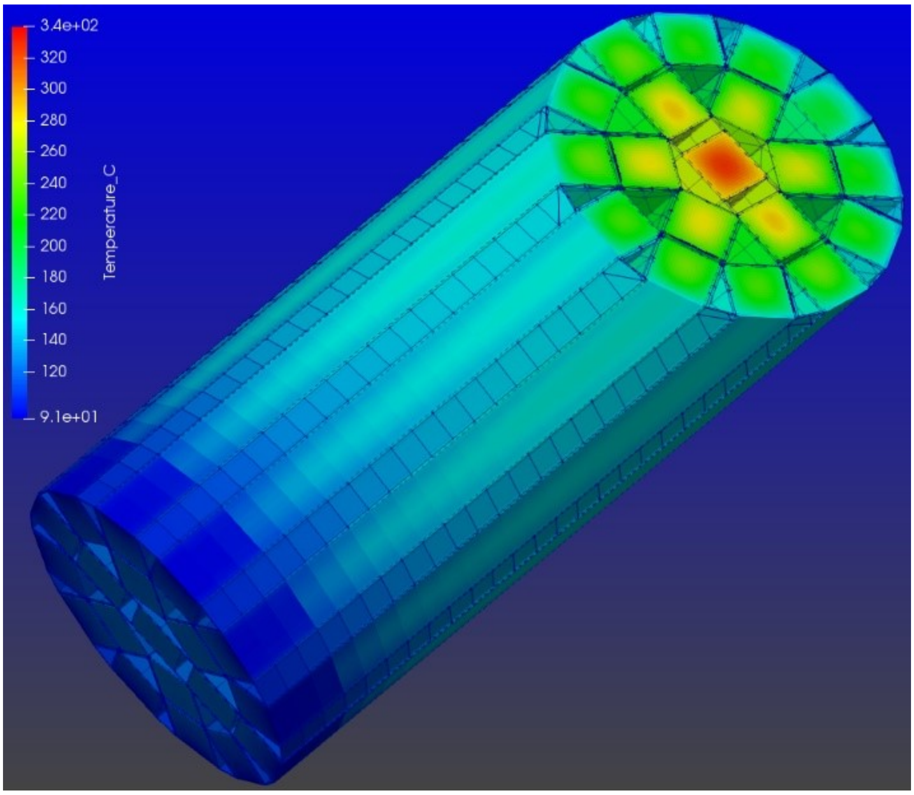

Figure 2. Visualization with ParaView of a cut of the fuel assemblies inside the cask of the COBRA-SFS model (temperature, in °C).

RESULTS OF THE COBRA-SFS MODEL AND OUTLOOK

In the following, results of an application of the model with a typical axial power profile, including fuel-free zones at the top and bottom of the fuel assemblies, and a total power of 39 kW corresponding to 6.8 W per fuel rod are presented. No plenum model was used for the results presented here. The upper and lower boundary conditions are thus adiabatic, which should lead to increased temperatures in the uppermost and lowest zones of the cask but does not impact significantly the middle part.

Temperature profiles over fuel assembly height

Figure 3 shows the temperature domains covered by the assemblies No: 8, 9, and 10 (see diagram on Figure 1 for the numbering) assuming a homogeneously loaded cask with a total power of 39 kW corresponding to 6.8 W per fuel rod. The selected assemblies represent the three main types of assemblies: assembly 10 is the hottest assembly (central position), assembly 9 is in the intermediate area (as well as assemblies 6, 7, 11, 13, and 14) and presents thus intermediate temperatures, and assembly 8 (like assemblies 1 to 5, 12, and 15 to 19) is one of the external assemblies presenting the lowest temperatures.

For the main part (axial location from 50 cm to 350 cm) of the cask, the temperature ranges at a given axial position within an assembly are approximately 45 °C for assembly 10, 65 °C for assembly 9, and 90 °C for assembly 8.

Over the total height of a fuel assembly, the temperature of the rods varies strongly and ranges from approximately 100 °C to 250 °C for assembly 8, from 125 °C to 285 °C for assembly 9, and from 125 °C to 325 °C for assembly 10.

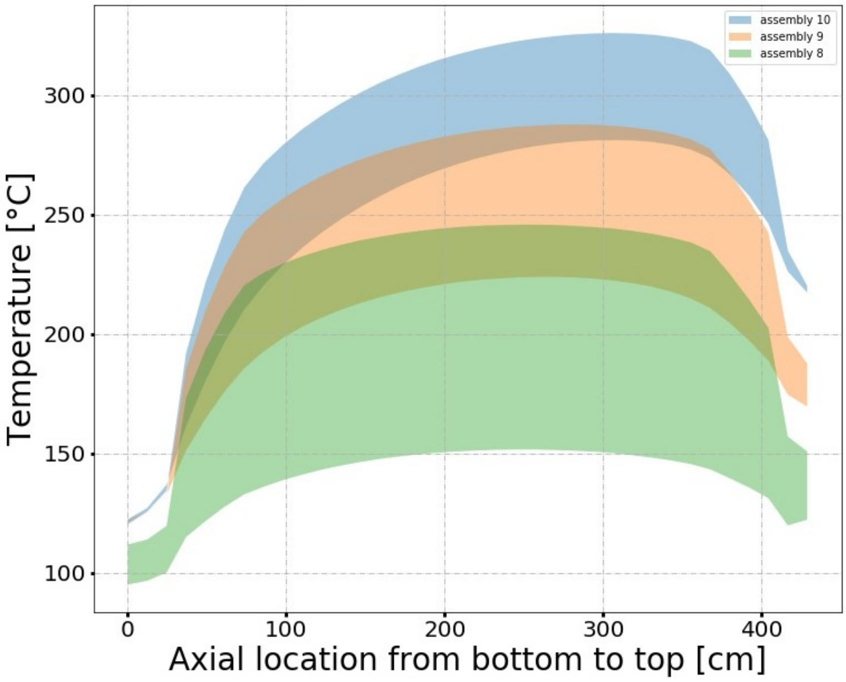

Figure 3: Cladding temperature domains (over the total height of the fuel assemblies) for assemblies 8, 9, and 10, for a homogeneous load and calculated with a typical axial power profile.

Temperature distribution in a horizontal plane

Figure **4. Fuel cladding temperature [°C] at the hottest axial position (294 to 306 cm from the bottom), for a homogeneous load.**4 shows the temperature distribution in the cask for the hottest axial position (from 294 to 306 cm) assuming a homogeneous maximum load and the typical axial power profile. The temperature ranges from 150 °C to 240 °C for the external assemblies, from 220 °C to 285 °C for assembly 9, and from 280 °C to 325 °C for assembly 10. Assembly 9 is slightly hotter than assembly 6 due to the influence of assembly 10. Similarly, assemblies 2 and 8 are hotter than assemblies 1 and 3, due to the influence of assemblies 6 and 9 respectively.

We can also note that, except for the fuel assembly 10, the hottest spots of the assemblies are slightly shifted from the center of each assembly toward the center of the cask.

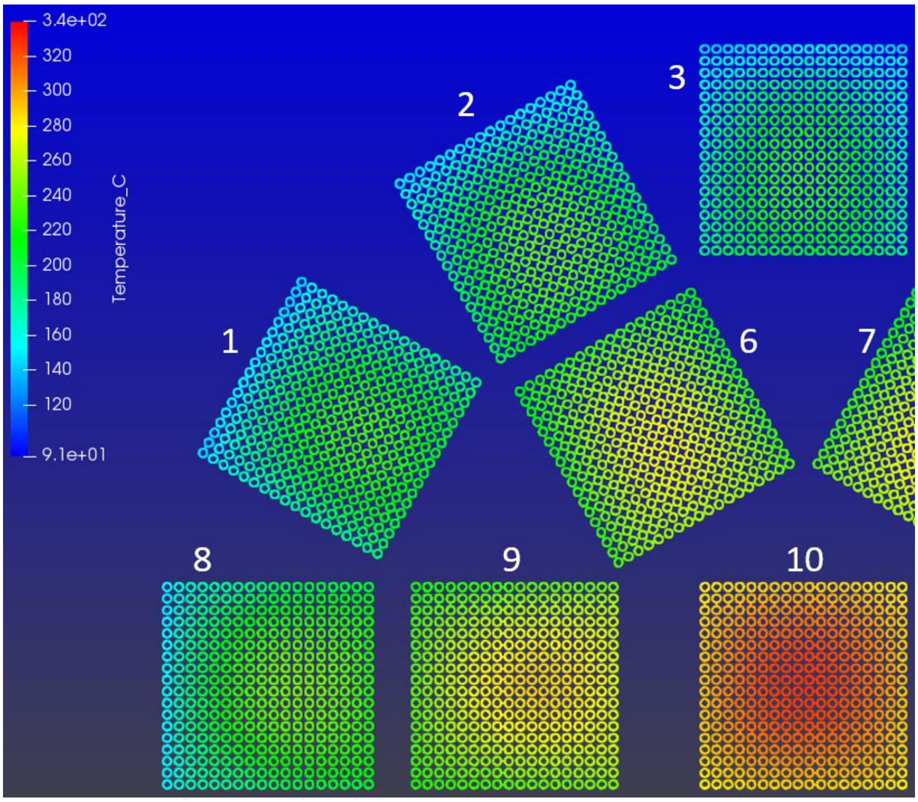

Figure 4. Fuel cladding temperature [°C] at the hottest axial position (294 to 306 cm from the bottom), for a homogeneous load.

Discussion & Outlook

Although the cask modelled has been regularly improved over the last months, there is always room for further improvement. Thus, it would be interesting to work on the plenum modelling. Plenum models would not affect the high temperature domain of the cask (central part), but the coldest regions (lowest and uppermost parts of the cask) would present lower temperatures if paths for heat removal were considered at those boundary regions.

Another major issue is the gap resistances between the basket structures and the cask body: recent calculations performed with our model showed that those thermal resistances have a strong impact on the overall temperature in the cask. Furthermore, for a more improved modelling, it should be taken into account, that those gaps might not be symmetrical within the cask. That would lead to more complex temperature fields, excluding all symmetry even for homogeneous loading schemes.

The model is expected to be applied to transient calculations especially to simulate the drying process. This initial step of the dry storage is necessary to ensure a small amount of residual moisture in the cask, to minimize cladding corrosion and hydrogen content. As it involves strong temperature variations, it is suspected to have important consequences on the cladding properties impacting the mechanical behavior during the whole of the storage period.

Finally, a sensitivity analysis performed using Monte Carlo simulation technique is also desirable, as there are many parameters involved in the model, each of them implying some uncertainty.

COMPARISON OF COBRA-SFS RESULTS VERSUS COCOSYS AND ANSYS CFX

As a second step, we compared the results of our model with results from two other models, built with COCOSYS and ANSYS CFX [6]. There, just an axial section of the inner hottest assembly (18x18-24 PWR) and the surrounding fuel basket structure was modelled and compared.

COCOSYS model

A two-dimensional model was built with COCOSYS (**Co**ntainment **Co**de **Sys**tem) [2], a thermo hydraulic program developed at GRS. An axial section of the central assembly (No. 10 on Figure 1) was modelled. ¼ of the assembly was modelled using 9 different types of fuel rods (B01 to B09 in Figure 5). Heat radiation between these fuel rods is modelled and as well heat transfer to the outer boundary given by the surrounding fuel basket structure. Convection of the helium gas within the cask/assembly is neglected, which might have a significant impact on the temperature: increase of the average temperature. To limit the effect, heat conduction within the helium between the fuel rods and in the gap to the surrounding fuel basket structure is modelled. Still, another simplification remains, to consider all rods in a row (e.g. the outer one B09) similar: according to the other models, the temperature difference between the rods on the outermost row can reach 20 °C.

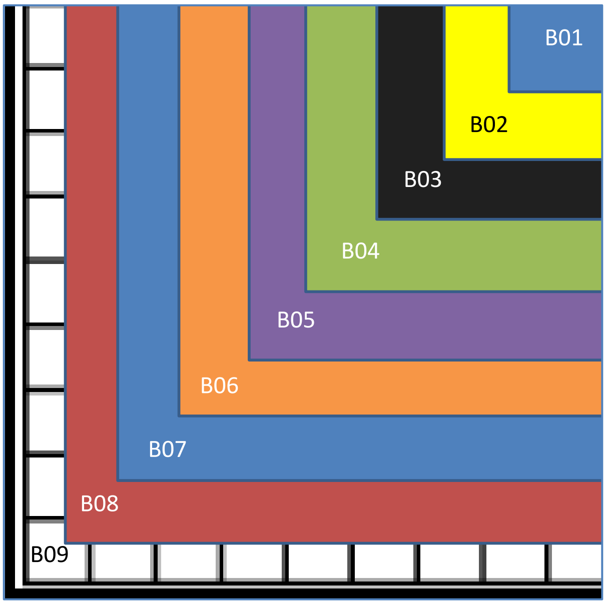

Figure 5. Diagram of 1/4 of the axial section of the central fuel assembly modelled by COCOSYS.

ANSYS CFX model

Using the fluid dynamics program ANSYS CFX [3], again a short (10 cm long) axial segment of ¼ of the central fuel assembly was modelled, but each fuel rod separately. In total nearly 1.5 million elements are used for the meshing as shown in Figure 6. The model takes into account the heat removal by helium as well as through radiative exchanges. A constant temperature (233.6 °C) was taken from the COCOSYS simulation as boundary condition for the fuel assembly basket. With another detailed ANSYS CFX model of the fuel assembly basket it was found, that under the given conditions the temperature would be about 13 °C higher, compared to COCOSYS.

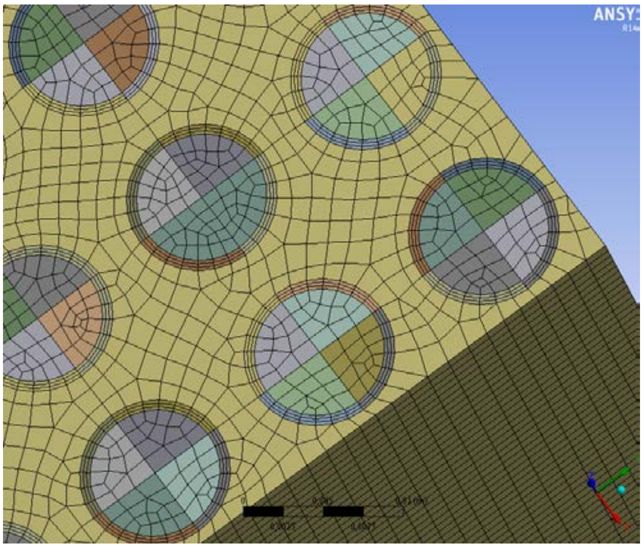

Figure 6. Diagram of 1/4 of the axial section of the central fuel assembly modelled by ANSYS CFX.

Discussion of results

Results yielded by COCOSYS, ANSYS CFX, and COBRA-SFS models are plotted on Figure 7. The cladding temperature is given for two different rows of fuel rods, corresponding to the hottest ("upper" temperatures) and coldest ("lower" temperatures) rods of a row (see diagram on the bottom left-hand corner of Figure). Only one curve corresponds to COCOSYS, as all rods of a row are assumed similar. For the other two models, two curves are plotted.

The COCOSYS model was built using the most conservative assumptions in the fuel assemblies: no helium convection, but heat conduction within the helium, and radiative exchanges, but limited to direct neighboring rods. The ANSYS CFX model also includes some conservatism due to some homogenization, limited consideration of convection, and fixed temperature of the fuel assembly basket based on COCOSYS results.

Even so the results are in general similar, this conservatism could explain the

- small differences in the temperature of the central rod,
- stronger temperature gradients between the inner and the outer rods,
- a greater temperature variation within the assembly: COCOSYS about 70 °C, ANSYS CFX around 65 °C and COBRA-SFS around 45 °C, and
- lower temperature for the outermost rows of fuel rods.

Further, as mentioned a too cold boundary condition for the basket structure enclosing the central assembly was found in the ANSYS CFX calculation. Here the COBRA-SFS model yields the highest temperature of approximately 270 °C at the hottest axial zone. The COBRA-SFS model includes further thermal resistances to take account of the imperfect connection between the basket structures and the cask body.

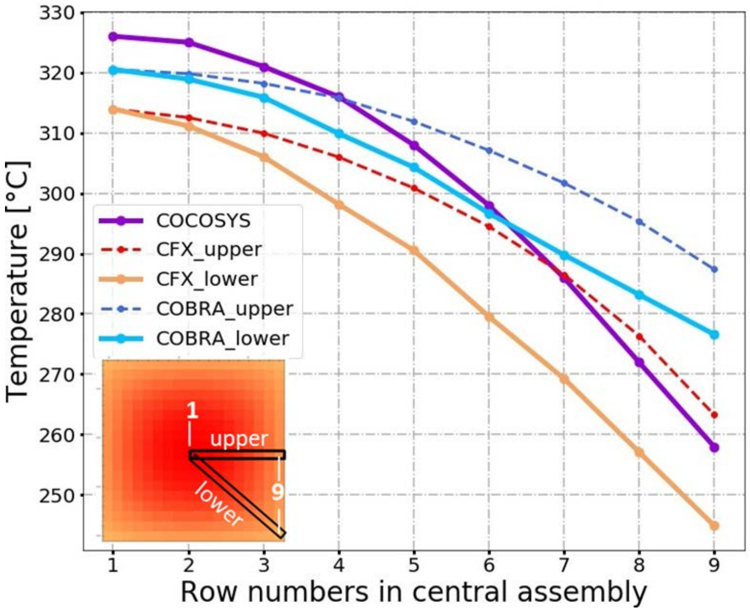

Figure 7. Comparison of cladding temperature in the central assembly with the 3 codes: COCOSYS, ANSYS CFX, and COBRA-SFS.

CONCLUSIONS

A 3-dimensional cask model, similar to the CASTOR® V/19, was built for the COBRA-SFS code. This model takes into account the radiative and conductive heat transfers, as well as the natural convection of helium. The geometrical description includes a detailed representation of the fuel assemblies (all rods and helium channels are processed independently), of the basket structures enclosing the fuel assemblies, and of the cask body. The vertical dimension is divided into 36 zones, which enables to include a typical axial power profile in the model.

Because of their containment function, storage casks cannot be re-opened easily after being loaded. Thus, the temperature inside a cask is not directly accessible which makes a direct validation of a cask model through experimental data difficult. A comparison of the COBRA-SFS results with results from COCOSYS and ANSYS CFX was performed for the hottest inner assembly. As a general observation, the COBRA-SFS model presents smaller temperature gradients than the ANSYS CFX model which has itself a smaller temperature gradient than the COCOSYS model. This might mainly be a consequence of conservatism in the ANSYS CFX and COCOSYS models involving higher thermal resistances within the assemblies and other simplifications as discussed. Despite this conservatism the overall temperature resulting from the COBRA-SFS model is in the same order of magnitude for the central assembly as the temperatures calculated by COCOSYS and ANSYS-CFX. Two factors were identified to explain the relatively high temperature of COBRA-SFS:

- The temperatures used for the comparison of the models correspond to the hottest vertical position in the COBRA-SFS model. The models of COCOSYS and ANSYS-CFX take helium convection only partially into account, if any at all.

- The COBRA-SFS model includes thermal resistances between the internal structures and the cask body to take account of their imperfect connection. Even a small gap leads to an important increase of the overall temperature in the cask.

Eventually, the COBRA-SFS cask model yields detailed 3-dimensional temperature distributions exhibiting a large range of cladding temperatures. Thus, for a homogeneous load with a typical axial power profile, the temperature range within an assembly can reach about 200 °C, over the entire height of the assembly. Considering a given axial position, the temperature range is also large: 45 °C for the central assembly and up to 90 °C for the external assemblies. Because of the numerous parameters involved in the model a sensitivity analysis would be desirable.

The results presented here are a cornerstone for further investigations on fuel cladding mechanics. Indeed, almost all degradation mechanisms are temperature dependent and a detailed knowledge of the time dependent temperature field is required to predict the integrity of the fuel rod cladding. The described model is expected to be applied for transient calculations especially to the drying process.

ACKNOWLEDGMENTS

The work presented is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) under grant number RS1552.

REFERENCES

[1] T. E. Michener et al., COBRA-SFS: A Thermal-Hydraulic Analysis Code for Spent Fuel Storage and Transportation Casks, Cycle 4a, PNNL, October 2017.

[2] S. Arndt et al., “COCOSYS 3.0 User’s Manual “, GRS-P-3/Vol. 1, 2019.

[3] ANSYS Inc., “ANSYS CFX Reference Guide”, Release 15.0, November 2013.

[4] GNS GmbH, CASTOR® V/19 Transport and Storage Cask for Spent Fuel (PWR), Product Information, April 2014.

[5] Ahrens et al., ParaView: An End-User Tool for Large Data Visualization, 2005, ISBN-13: 978-0123875822

[6] J. Stewering et al., Berechnung der Brennstabhüllrohrtemperatur in einem Transport- und Lagerbehälter, Technical Report, GRS gGmbH, April 2014.