Cask thermal analysis to assess spent fuel safety: from the CFD modelling to the engineering approach

Jaime Penalva, Francisco Feria, Luis E. Herranz

CIEMAT, Unit of Nuclear Safety Research, Avda. Complutense, 40 Madrid 28040 Spain

Abstract

Dry interim storage of spent fuel has expanded significantly, being a major option in today's fuel cycle. The ability of storage systems to meet safety functions must be assured. One of the main aims to achieve is to guarantee fuel rod integrity. The main interest is focused on cladding degrading mechanisms like creep and hydrogen related phenomena (i.e. hydrides embrittlement), which are strongly influenced by temperature. Therefore, the thermal response of the storage system is a key aspect to assess fuel safety under normal and accident conditions. To address that, the Computational Fluid Dynamics (CFD) modelling provides a robust support; however, the calculations are time consuming so the derivation of reliable engineering correlations would be an enabling feature.

The present work shows an engineering approach to assess the integrity of dry stored fuel through thermal predictions. Three scenarios have been studied based on vertical cask storage: normal conditions, total blockage of air cooling and pressure loss of the canister that stores the fuel. In each case a 3D model has been developed with ANSYS-FLUENT 16.0 code. Based on that, the maximum fuel temperature has been estimated under the conditions simulated at different heat loads; from this supporting database, the temperature has been well correlated in each scenario as a power function of the heat load. Thus, the engineering equation derived is simple, supported by CFD calculations and valid under different conditions of cask storage.

1. INTRODUCTION

A dry storage cask is a system for storing spent fuel. As other options, it has to guarantee cooling of fuel assemblies under normal, off-normal and accident conditions. This requirement is of primary importance to ensure fuel rod integrity during dry storage, due to the fact that major degrading mechanisms of cladding mechanical behaviour (e.g. creep, hydride embrittlement) are strongly influenced by temperature (USNRC, 2003). Therefore, thermal modeling in dry storage is a key aspect to predict cladding mechanical performance.

The cask thermal analyses are often carried out with Computational Fluid Dynamics (CFD) codes, so that an accurate insight into the thermal response of the cask is achieved (Heng et al., 2002; Lee et al. 2008; Zigh and Solis, 2008, Holtec International, 2010, Tseng et al. 2011, Herranz, et al., 2015). The CFD main downside is the high computational cost. Given the importance of knowing the fuel thermal performance during the cask service life, an engineering approach capable of providing reliable predictions would be valuable and particularly suitable to be implemented in fuel performance codes.

Simplified models of fuel thermal evolution under normal conditions of dry storage were developed for low burnup fuel (around 30 GWd/tU) stored in vertical and horizontal casks (Levy et al., 1987); the correlations derived were based on COBRA-SFS calculations (Rector, 1986). In order to cover high burnup fuels, a correlation of fuel maximum temperature with time was derived based on FALCON calculations for a high burnup fuel rod (60 GWd/tU) subjected to normal in-cask conditions (Rashid and Dunham, 2001). Direct use of these models would not be appropriate: on one side, they are burnup independent; on the other, their time domain is restricted to a maximum of 50 years, while longer extensions are under discussion (Hanson, 2012).

Feria et al. (2015) derived a more comprehensive fuel temperature correlation, which takes into account the burnup dependence and spans up to 300 years of cask storage. In this case, a simplified equation was obtained based on CFD calculations under normal conditions of cask storage. Nonetheless an easier use of such an equation would be accomplished by encapsulating burnup and time dependences within a primary variable like the decay heat. If, in addition, the equation could be extended from normal to off-normal and accident conditions, that would be a substantial step forward towards a thermal characterization of spent fuel in dry casks without requiring sophisticate codes running.

Inspired by the potential of such an engineering approach, the goal of this work is to derive specific correlations between fuel maximum temperature and decay heat under different conditions that might occur in a vertical dry storage cask, from nominal to accidents. To do so databases from CFD simulations have been built for three specific cases: normal conditions, total blockage of air cooling and pressure loss of the canister that stores the fuel.

2. SYSTEM DESCRIPTION

The cask considered in this work is the HI-STORM 100S developed by Holtec International, which is a vertical storage system. It arranges the spent fuel assemblies in a multi-purpose canister (MPC), which is placed inside a concrete overpack. A thorough description of the system can be found in Holtec International (2010).

Fig. 1 shows the longitudinal section of the HI-STORM cask conceptual model, where the air (blue line), helium (green line) and heat flows (red arrows) are described. As it is shown, the HI-STORM has to reject the decay heat emitted by the spent nuclear fuel, q. A great bulk is rejected to the environment by natural convective action, q_1 (chimney effect). Nevertheless, a small quantity of the total heat rejection happens by natural convection and radiation from the surface of the module, q_2.

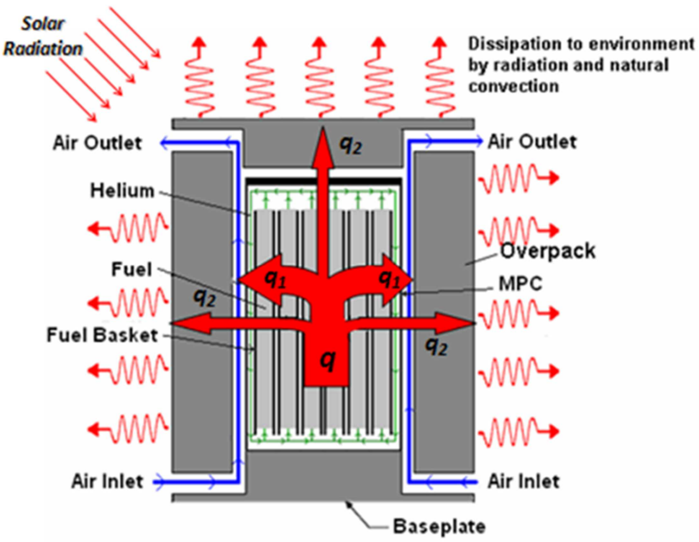

Fig.1 Cask conceptual model

For storage systems with internal air flow passages, blockage of inlet flow is a situation that should be evaluated (UNSRC, 2010a). Total blockage of all inlets may result in fuel heat up that may affect the cladding integrity. Furthermore, this casks design relies on helium (He) over normal pressure to provide effective convective cooling to fuel during dry storage; as it is mentioned in the ISG-25 (USNRC, 2010b), the pressure loss of the canister housing the spent fuel could degrade the cooling capacity of the system, so it is other situation to be aware of.

3. CFD MODELLING

As said above, the engineering approach intended required to build-up a database built from CFD simulations. The calculations have been carried out with ANSYS-FLUENT 16.0 code and a thorough description of the modelling done is given by Herranz et al. (2015). The main hypotheses and approximations considered in this study are the following:

- The computational domain has been restricted to 1/8 of the whole circular cross section of the storage cask (symmetry based).
- The fuel assemblies have been approximated as porous rectangular parallelepipeds with internal heat generation. An effective thermal conductivity and ad-hoc pressure drop have been derived, which consistency was previously demonstrated (Herranz et al., 2015).
- All fuel assemblies are PWR 17x17 and with same power (0.94 kW).
- A ‘‘plateau-shaped’’ axial heat distribution has been imposed following the common practices (Holtec International, 2010).
- The baseplate has been considered adiabatic.

The simulations performed with ANSYS-FLUENT followed the CFD Best Practice Guidelines (BPGs) of the US Nuclear Regulatory commission (USNRC, 2014).

4. ENGINEERING APPROACH

The approach proposed in this work is based on an engineering equation that correlates the fuel maximum temperature with the decay heat. In order to have a supporting database to derive the equation, steady state CFD simulations have been performed at different decay heats for each of the scenarios studied: normal conditions, total blockage of air cooling and pressure loss of the canister (in this case, the simulations have been carried out under atmospheric inner pressure).

Fig.1 shows the temperature estimations as a function of the decay heat (between 0 and 30 kW) for the different conditions simulated. In all the cases, an increasing trend with progressively decreasing slope describes the temperature evolution with the decay heat. Thus, based on the fundamental convective nature of the cask system and the role that radiative heat transfer may play at high fuel temperatures, an equation of the form

$$T_{max} = \mathcal{K} q^{\beta} + T_{\infty} \tag{1}$$

has been proposed, with T_{∞} standing for the environment temperature (300 K). In case of a pure natural convection system, decay heat (q) should be raised to a 0.8 power; in this case, though, a variable power (β) has been chosen to provide the equation with some flexibility to accommodate variable contributions of convection and radiation depending on decay heat and the scenarios addressed. Table 1 shows the fitting parameters for each scenario considered, as well as the fitting goodness through the correlation coefficient R^2 (fitting curves shown in Fig. 3). The maximum relative error obtained with respect CFD calculations is less than 0.5%.

Table 1. Fitting parameters and correlation coefficient.

	K(K/kW$^{\beta}$)	**β**	**R^2**
Normal condition	20.985	0.8	0.9998
Total blockage	45.056	0.727	0.9992
Pressure loss	69.526	0.556	0.9979

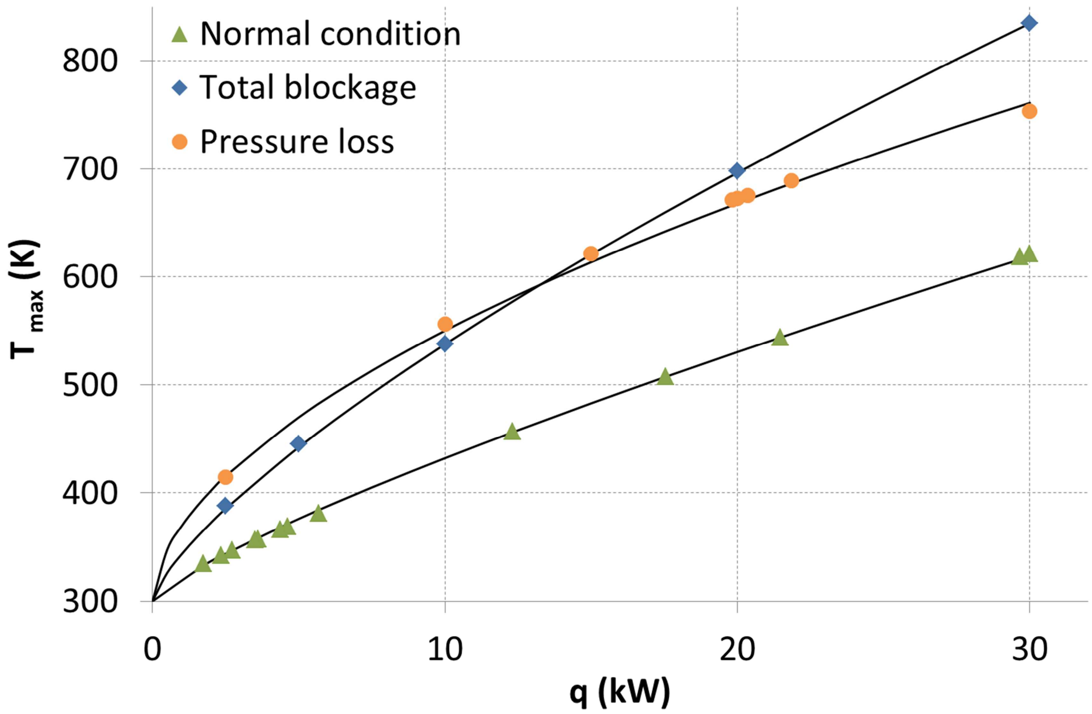

Fig.1. T_{max} vs q for each scenario studied.

Therefore, the excellent match of the CFD results by the correlation proposed allows stating that the so called engineering approach intended in this work would be reliably applicable for the type of dry storage studied under any circumstance.

By using such an equation to assess safety aspects of nuclear fuel, one might conclude that even at the highest heat load anticipated in these dry casks (30 kW), the maximum fuel temperature would never exceed the regulatory thresholds (673 K for normal conditions and 843 K for off-normal and accident conditions, respectively; USNRC, 2003). Whether a conservative 673 K limit was applied regardless the nature of the scenario, the correlation derived would indicate that spent fuels stored in dry casks with heat loads under 18.3 kW and 20.5 kW in case of total blockage and pressure loss, respectively, would undergo no damage.

5. CONCLUSIONS

The results shown above can be wrapped up in the following conclusions:

- No matter the prevailing conditions fuel is exposed to, the engineering approach intended for thermal characterization of spent fuel stored in dry vertical casks is feasible and reliable.
- An analytical correlation of fuel maximum temperature as a function of decay heat has been derived; the expression has been developed based on sound physical foundations and a database built up from CFD calculations.
- A straightforward use of the proposed equation can provide meaningful insights into safety aspects of spent fuel that might help in the management of fuel under any circumstance.

The specific application to vertical dry storage casks shown in this work is to be extended to other type of casks since the generic structure of the equation proposed is foreseen to can accommodate even further diversity of heat transfer scenarios in passive cooled dry casks.

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NOMENCLATURE

β	coefficient beta
K	coefficient kappa
q	decay heat (kW)
q_1	heat rejected to the environment by natural convective action (kW)
q_2	heat rejected to the environment by natural convection and radiation action (kW)
T_∞	environment temperature (K)
T_{max}	maximum temperature (K)

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