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Thermal Analysis of Spent Nuclear Fuels Repository

Fernando Pereira[a,b]; Jean Salomé[a,b]; Cristiane Viana[a]; Fabiano Cardoso[a,b]; Carlos E. Velasquez[a,b]; G. P. Barros[c]; Claubia Pereira[a,b]*

[a]*Departamento de Engenharia Nuclear – Escola de Engenharia*
Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte MG, CEP 31270-901,Brasil,
[b]*Instituto Nacional de Ciências e Tecnologia de Reatores Nucleares Inovadores/CNPq, Brazil*
[c]*Comissão Nacional de Energia Nuclear-CNEN, Rua Gal Severiano, nº 90 - Botafogo; 22290-901, Rio de Janeiro, RJ, Brasil*

Abstract

In the first part, Pressurized Water Reactor (PWR), Very High-Temperature Reactor (VHTR) and Accelerator-Driven Subcritical Reactor System (ADS) spent fuels (SF) were evaluated to the thermal of the spent fuel pool (SFP) without an external cooling system. The goal is to compare the water boiling time of the pool storing different types of spent nuclear fuels. This study used the software Ansys Workbench 16.2 - student version. For the VHTR, two types of fuel were analyzed: $(Th,TRU)O_2$ and UO_2. This part of the studies were performed for wet storage condition using a single type of SF and decay heat values at times t=0 and t=10 years after the reactor discharge. The Ansys CFX module was used and the results show that the time that water takes to reach the boiling point varies from 2.4 minutes for the case of VHTR-$(Th,TRU)O_2$ SF at time t=0 year after reactor discharge until 32.4 hours for the case of PWR SF at time t=10 years after the discharge reactor.
The second part of this work consists of modeling a geological repository. Firstly, the temperature evaluation of the spent fuel from a PWR was analyzed. A PWR canister was simulated using the Ansys transient thermal module. Then the temperature of canister could be computed during the time spent on a portion of a geological repository. The mean temperature on the canister surface increased during the first nine years, reaching a plateau at 35.5°C between the tenth and twentieth years after the geological disposal. The idea is to extend this study for the other systems analyzed in the first part. The idea is to include in the study, the spent fuels from VHTR and ADS and to compare the canister behavior using different spent fuels.

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Keywords: Thermal analysis; Ansys CFX; Ansys transient thermal; Spent fuels; Spent fuel pool; Geological repository.

* Corresponding author. Phone/Fax: 55-31-34096662
E-mail address: claubia@nuclear.ufmg.br

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1. Introduction

Considering the insertion of different fuels obtained from different reprocessed techniques, and used in different systems of nuclear power generation, it is important to verify how these spent fuels will behave in the spent fuel pool. In the same way, it is important to verify the impact in the final repository. The idea is to compare the temperature behaviour of the spent fuel pool and geological repository for three nuclear systems: ADS, PWR, and VHTR.

For the pool, the external cooling system was not considered and for the geological repository, only the PWR spent fuel was simulated.

1.1. Spent Fuels types considerations

The enrichment, the initial and final amount of fissile material, the burnup and the operation reactor time considered in this work are listed below:

- PWR: UO_2 enriched to 3.2%. The burnup was 33GW/tHM during three years. The final amount of fissile material is 1.46% [1].
- VHTR:
  1 - UO_2 - enriched to 15.5%. The burnup was 90.2 GWd/tHM during three years. The final amount of fissile material is 9.2%.
  2 - $(Th,TRU)O_2$ - this fuel consists mainly of transuranic obtained from UREX+ reprocessed technique containing 15% of the fissile material. The burnup was 97.80 GWd/tHM during three years. The final amount of fissile material is 8.05% [2].
- ADS: $(Th,TRU)O_2$ Fuel consists mainly of transuranic obtained from GANEX reprocessed technique containing 12% of the fissile material. The burnup was 237.6 GWd/tHM during 20 years. The final amount of fissile material is 2.04% [3].

The fuel properties listed above determine the decay heat profiles over the time after the reactor discharge. These profiles are essential for specifying the heat sources in thermal analysis, and they are obtained using the ORIGEN2.1 code [4], using the condition specified above. Figure 1 shows the decay heat profile for the SF types considered.

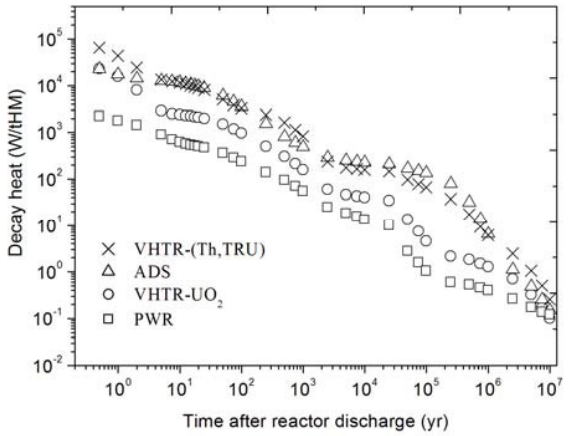

Fig. 1. Decay rate profiles of the SF considered.

2. Description of the models

The Ansys CFX is a fluid dynamics program based on finite elements method [5] and contains powerful geometry tools - the Design Modeler - used to design both SFP and SF. The geometry of SF was performed using the Ansys Cut Material tool, which avoiding SF composition details and their packaging material. This geometrical

technique consists on excluding the water of the regions where SF containers are expected to be. It is a valid approximation since that, in the present analysis, only the heat flux through the SF surfaces is required [6]. The SF containers are detailed in the following.

2.1. SFP geometry, physical properties, and Ansys CFX modeling

Considering the final amount of fissile material in each spent fuel of each reactor system, to design appropriately pool there is an evident need of a criticality study. Nevertheless, for this study and to compare the behaviour of the systems, a standard pool based on a PWR SFP will be modelled. It consists of a parallelepiped which dimensions are 0.56 m x 0.56 m x 5 m. The amount of SF immersed corresponds to one-quarter of its effective volume. Figure 2 shows the simulated SFP. The waste packages containing the SF are simulated as four cylinders of 8.8 cm of radius and 4 m of height, spaced 18.8 cm center-to-center. The distance between the bottom of cylinders and the bottom of SFP is 30 cm. The cylinder dimension is enough to load 1 ton of each spent fuel type with a mean density of 10.2 $g \cdot cm^{-3}$.

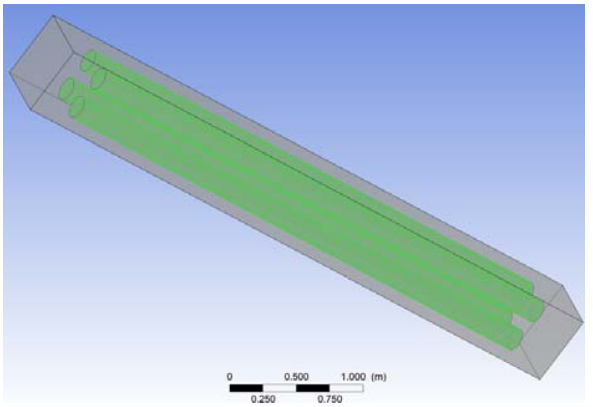

Fig. 2. The SFP simulated. The green cylinders are the SF.

The model was treated with two techniques, which differ essentially in the boundary condition types: 1 –On the top of the SFP was applied the condition called *opening*, allowing only heat transfer between the pool and the environment, but with prohibited mass fluxes and 2 - All the SFP walls were set to adiabatic, and the fraction of water and air were set as 0.95 and 0.05, respectively. The first technique allows the heat transfer between the SFP and the environment while the second one only allows the heat transfer between the SFP and the fraction of air confined inside. The advantage of the latter is the possibility of having a biphasic model, being possible to set physical quantities as, e.g., the Nusselt number and the water-air surface tension.

Table 1. Material properties.

Water | Air Properties	**Values**
Molar mass	18.02 | 28.96 (kg·mol)
Density	992.2907 | 1.185 ($kg \cdot m^{-3}$)
Temperature	40°C | 25°C
Pressure	1 atm
Specific heat capacity	4178.656 | 1004.4 ($J \cdot kg^{-1} \cdot K^{-1}$)
Dynamic viscosity	6.53E-4 | 1.831E-05 ($kg \cdot m^{-1} \cdot s^{-1}$)
Thermal conductivity	0.6286571 | 0.0261 ($W \cdot m^{-1} \cdot K^{-1}$)
Initial water fraction	0.95

Table 2. Boundary conditions.

Boundary Conditions	Values
Heat flux	[a1]1.9865E5; [b1]1.4423E4; [c1]4.03E4; [d1]6.813E4; [a2]5.087E3; [b2]1.057E3; [c2]2.76E2; [d2]5.176E3
Turbulence model	Laminar
Heat transfer	Nusselt Number 1
Water air surface tension	0.074N·m^{-1}
Outer walls heat transfer	Adiabatic

[a,b,c,d] indicate spent fuels from VHTR-(Th,TRU)O_2, VHTR-UO_2, PWR and ADS reactors.[1,2] values at time zero and 10 years after the discharge reactor, respectively. All the heat flux values are in W.m^{-2}.

The meshes were generated using the algorithms provided by the Ansys CFX. Areas near around the structure edges were skilfully divided while the areas where the flow changes smoothly were roughly divided. For both techniques, the Buoyancy model was adopted. To improve the computational simulation time, the symmetry conditions in XZ and YZ planes were applied.

In these thermal simulations were used heat flux values at t=0 and t=10 years, beginning from the fuel discharged. Tables 1 and 2 present the heat fluxes (W·m^{-2}), as well as, the initial conditions and boundary conditions and the material properties.

2.2. Geological disposal, PWR canister, and Ansys thermal transient

The geological disposal taken as reference follows the UK repository idea based on the KBS-3 concept, developed by Swedish Nuclear Fuel and Waste Company for SF in Sweden. According to this concept, the SF is loaded into cooper canisters bonded to a cast iron insert. The canisters are surrounded by bentonite buffer and placed vertically into holes, excavated along parallel tunnels at a depth of 500 m in granitic rock. After emplacement, disposal tunnels is backfilled with a mixture of bentonite and crushed rock. Figure 3 shows a portion of the United Kingdom repository concept [7] and Figure 4 shows the PWR disposal canister design.

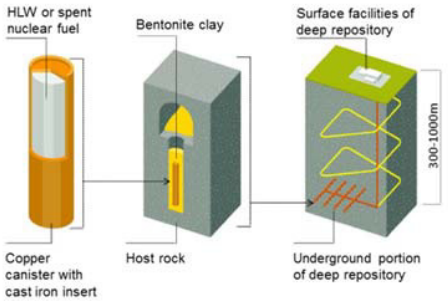

Fig. 3. UK repository concept [7].

The depth and diameter of deposition holes for spent fuel canisters are 7.55 m and 1.75 m, respectively. The diameter of the disposal tunnel is 5.5 m and the distance between the disposal tunnels is 40 m [7].

The geometry consists of a unique PWR canister introduced in a portion of a geological repository, as described before. Some canister dimensions are given in Figure 4 (4.5 m long and 0.9 m in diameter), containing four PWR assemblies. The space between the canister and rock is filled with bentonite. The material properties of the canister, rock and bentonite were obtained from [8]. Figure 5 shows a section of the meshed geometry. From inside to outside, the regions are the fuel, cast iron, cooper, bentonite, and rock.

Symmetry conditions in XZ and YZ planes applied were applied. All the four PWR fuel assemblies are considered as heat sources, which are introduced in the Ansys setup via Internal Heat Generation quantity (W.m^{-3}),

as usual for 3D computations, as can be seen in figure 5. For meshing, different element sizes for each component of the geometry were tested. The sizes were considered suitable when they did not produce difference on the results. The adopted element sizes were: 0.06 m, 0.008 m, 0.05 m, 0.035 m, 0.15 m and 0.25 m for fuel, clad, cast iron, cooper, bentonite, and backfill, respectively. For rock, the regions distant until 2m from the bentonite and backfill, the element size was 0.35 m and in the remaining regions, it was 1.5 m. The layer of rock used was 20 m above and below the holes and 10 m in the horizontal direction. All the external walls were set to adiabatic, including the faces of symmetry. The bottom of the rock was set to 30°C and a vertical thermal gradient of 30°C/km was adopted. In the horizontal direction, it was not considered thermal gradient [8]. The source-term calculation is the PWR SF, disposed of a total storage period of 50 years in the pool. Previous studies show that the temperature at the canister surface reaches a saturation regime at the time lower than 10 years after geological disposal [8]. So, in this work were used decay heat data in the interval of 50 and 250 years for obtaining an adjustment function. Figure 6 shows the fitting using a first-order exponential function by means of the least squares method.

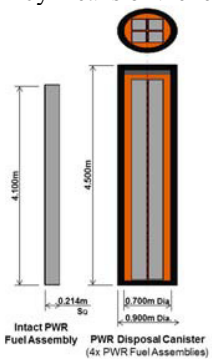

Fig. 4. PWR disposal canister design [7].

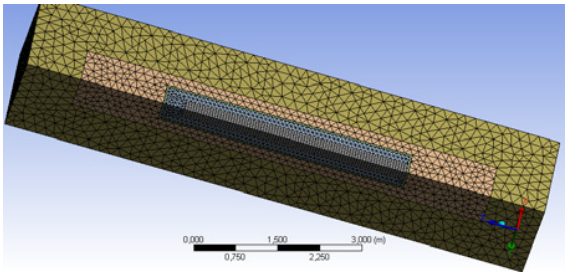

Fig. 5. Portion a meshed geometry of a PWR canister in a portion of a geological repository.

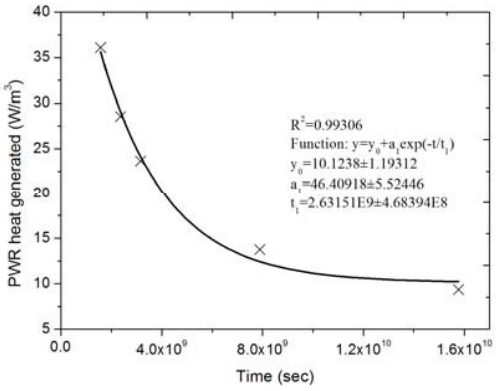

Fig. 6. Fitting of selected data from the PWR decay heat.

3. Results and discussion

3.1. Increasing water temperature rate of the SFP

These results are for SFP analysis using the two different modelling techniques. The first one allowing the heat exchange between the pool and the environment (called as open-top from now) and the second one with all the SFP outer walls adiabatic (called as sealed-walls from now). These studies were carried out supposing the absence of an external cooling system for SFP and considering constant heat flux values at t=0 and t=10 years, beginning at fuel discharged. The quantity evaluated was the mean water temperature during the time. The total time considered in the simulations was 1,000s with time steps of 5s. It was enough to determine the mean water temperature increasing rate, R_T. Figure 7 shows the temporal behaviour of the mean water temperature for each SF type at t=0 year and t=10 years for both techniques

Note that the mean water temperature grows linearly with time. Therefore, R_T was directly obtained by linear fittings of the curves at t=0 and t=10 years. Table 2 presents the results for R_T and the time when the water reaches the boiling point (T_b). All the R_T values are in (°C/s).

The differences in R_T might be due to the amount of minor actinides and plutonium isotopes at the discharge time, which influences on the decay heat. In fact, the higher decay heat values are for the reactors with initial fuel composition based on thorium and transuranic, such as VHTR (Th,TRU)O_2 and the ADS(Th,TRU)O_2, followed by the PWR and VHTR-UO_2, that just use uranium.

Note that the sealed-walls and open-top values differ by less than 16%. Also, as expected the time for reaching the boiling point is directly proportional to the intensity heat source (see Table 1 to checking heat flux values).

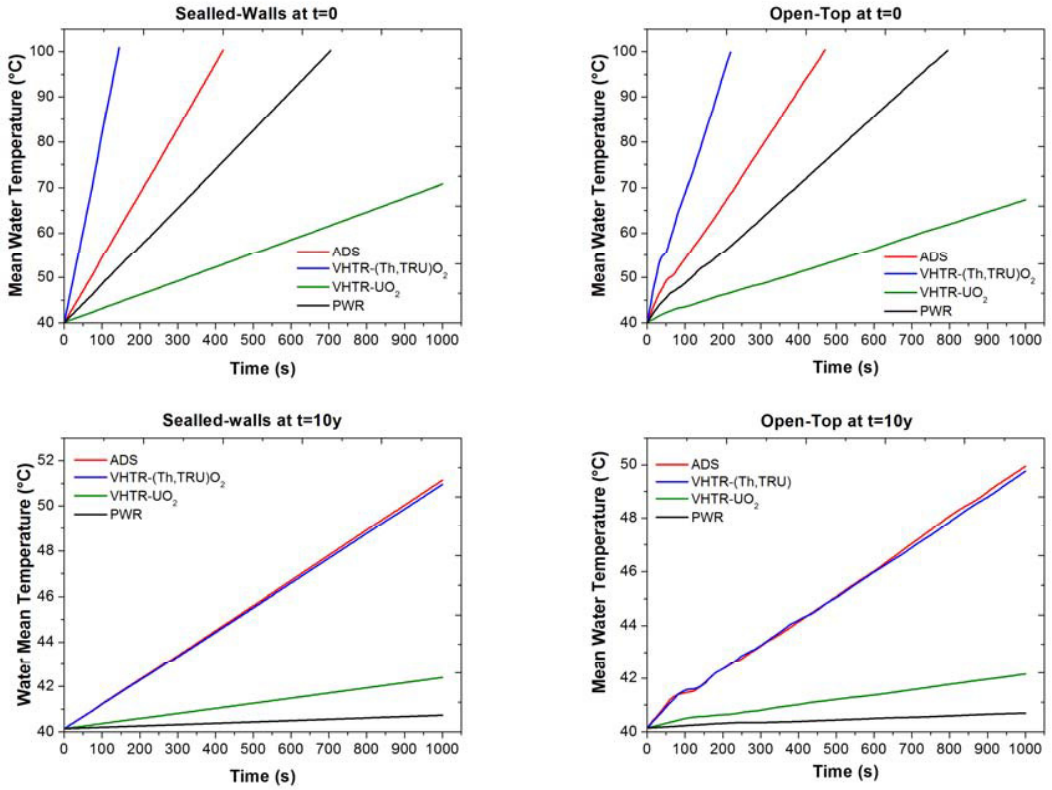

Fig. 7. Mean water temperature behaviour for the two techniques at t=0 and t=10 years after fuel discharge.

Table 2. R_T results for each reactor fuel type. Values are in [°C/s]. R^2>0.999 for all linear fittings.

Spent Fuel types	t = 0 yr sealed-walls R_T; T_b	t = 0 yr open-top R_T; T_b	t = 10 yr sealed-walls R_T; T_b	t = 10 yr open-top R_T; T_b
VHTR-(Th-TRU)O_2	0.422; 2.4 min	0.359; 2.8 min	0.0108; 1.54 h	0.0092; 1.8 h
VHTR-UO_2	0.031; 32.3 min	0.027; 37 min	0.0023; 7.25 h	0.0019; 8.8 h
PWR	0.086; 11.6 min	0.074; 13.5 min	$5.863x10^{-4}$; 28.4h	$5.151 x10^{-4}$; 32.4h
ADS	0.145; 7 min	0.125; 8 min	0.0110; 1.5 h	0.0095; 1.75h

3.2. Temperature behavior on the PWR canister surface

In these studies was adopted uniform initial temperature of 30°C for all the system. The temperature distribution through the canister surface was monitored during the first 20 years after disposal. The first time step was set after 1,000s and then discretized by the automated time step of Ansys. Figure 8 shows the mean temperature for a temporal behaviour on the canister surface. The temporal behaviour of the temperature is as expected, since the heat released by SF decays during the time. This result is in qualitative agreement with previous studies [8].

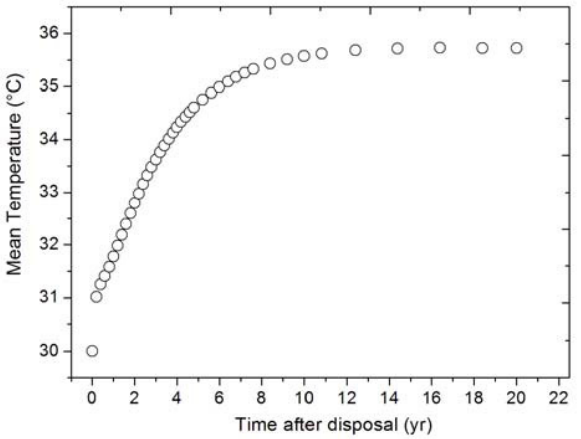

Figure 8. Temperature evolution of the surface of the canister during the time.

4. Conclusion

For both times t=0 and t=10 years after fuel discharged, the increasing rate of mean water temperature was superior to the sealed-walls approximation. For this model pool, the time that water reaches the boiling point varies from 2.4 minutes for VHTR-(Th,TRU)O_2 spent fuel, with a constant heat source value of $1.9865x10^5$ W/m^2 at time t=0 year after the fuel discharged, until 32.4 hours for PWR spent fuel, with a constant heat source value of 276 W/m^2 at time of t=10 years after the fuel discharge. It is evident that the presence of minor actinides and plutonium increases the R_T in the decay heat after discharged. The next step is to design a spent fuel pool considering the criticality analysis for each system and then study the temperature behaviour.

The temperature on the surface of the canister increased during the first nine years, reaching a plateau at 35.5°C between the tenth and twentieth years after the geological disposal. The saturation occurred as expected, considering that the heat released by SF decays during the time. To better determine the behaviour of temperature plateau, the present analysis might consider being also performed by the Ansys steady-state thermal technique in future studies, which would permit to start the transient thermal analysis with the system components in a non-uniform initial temperature.

This work will be extended to include studies of geological disposal of VHTR - (Th,TRU)O_2, VHTR - UO_2, PWR and ADS (Th, TRU)O_2 spent fuels. Further studies will evaluate the SFP dimensions needs for each reactor and their spent fuel composition, as well as, criticality calculation.

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