Water boiling time in a spent fuel pool with adiabatic and non-adiabatic boundary conditions

Tempo de ebulição da água em uma piscina de combustível usado com condições adiabáticas e nãoadiabáticas

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ABSTRACT
The Spent Fuel Pool (SFP) of Angra II, from Brazil, has received standard spent fuel (SF) assemblies of Uranium dioxide (UO2) discharged from Pressurized Water Reactors (PWR) of the Nuclear Power Plants (NPP) of Angra since the beginning of its operation. However, in case of using Mixed Oxide (MOX) or Thorium-based fuels, it would require further thermal studies of wet storage. It includes the determination of the water boiling time (Tb) of the SFP in case of breakdown of its external cooling system (ECS). This work presents studies of Tb of a simulated SFP storing mixed SF discharged from PWRs. The types of mixed SF studied include MOX plus UO2, oxide of thorium/uranium (U-Th)O2 plus UO2, and oxide of Thorium/transuranic (TRU-Th)O2 plus UO2. The simulations were implemented in CFX Ansys considering the top of the SFP as either adiabatic or non-adiabatic wall. Tb is considerably higher when the non-adiabatic boundary condition is used.

Keywords: Spent fuel pool, computational fluid dynamic, CFX Ansys.

RESUMO
O Pool de Combustível Irradiado (SFP) de Angra II, do Brasil, recebeu desde o início de sua operação conjuntos padrão de combustível queimado (SF) de dióxido de urânio (UO2) descarregado de Reatores de Água Pressurizada (PWR) das Usinas Nucleares (PNPP) de Angra. Entretanto, em caso de utilização de combustíveis à base de óxido misto (MOX) ou de tório, seriam necessários mais estudos térmicos de armazenamento úmido. Inclui a determinação do tempo de ebulição da água (Tb) do SFP em caso de falha de seu sistema de resfriamento externo (ECS). Este trabalho apresenta estudos de Tb de um SFP simulado que armazena SF misturado descarregado de PWRs. Os tipos de SF mistos estudados incluem MOX mais UO2, óxido de tório/urânio (U-Th)O2 mais UO2, e óxido de tório/transurânico (TRU-Th)O2 mais UO2. As simulações foram implementadas no CFX Ansys considerando o topo do SFP como adiabático ou parede nãoadiabática. Tb é consideravelmente maior quando a condição de limite não-adiabático é utilizada.

Palavras-chave: piscina de combustível gasto, dinâmica do fluido computacional, CFX Ansys.

1 INTRODUCTION

Spent fuels discharged from nuclear reactors must remain under wet storage into pools awaiting their temperature and radioactivity emission to reach safety values for transportation to the final repository. The temperature and radioactivity levels vary according to each country regulation [1]. The water temperature between 298 K and 310

K in SFP is maintained by an ECS. Thermal studies must consider hypothetical scenarios of ECS breakdown that would provoke overheating and structural damage in the spent fuels SF stored.

Based on the idea of using reprocessed nuclear fuels in conjunction with UO_2 in a PWR [2-4], this work evaluates the water boiling time in the ECS collapse scenario. UO_2, (TRU-Th)O_2, (U-Th)O_2, and MOX spent fuels were assumed discharged from PWR. Two loading patterns of these kinds of SF assemblies were considered: a single-type loading of UO_2, and mixed loadings containing a quarter of reprocessed fuels. The modelled SFP consists on the smallest arrangement of assemblies (unit of repetition, UR) that represents each loading pattern of a PWR's SFP. The aim is to determine the influence on T_b of setting the top of the SFP either as adiabatic or non-adiabatic wall. This work is an extension of preliminary studies developed by our research group, which determined T_b for different SF types under wet storage considering all the SFP walls as an adiabatic boundary [5].

The simulations were implemented in CFX Ansys, and the results were highly dependent on the boundary condition. Simulations considering the top of the SFP as a non-adiabatic wall yielded higher T_b values, which varies from 6.2 h for the loading containing UO_2 together with (TRU-Th)O_2 to 9.04 h for the loading containing UO_2 together with MOX.

2 MATERIALS AND METHODS

2.1 SPENT FUEL PROPERTIES

The heat sources in simulations are the SF and were derived from previous studies [6]. The main characteristics of SFs of interest in the present work, including the final amount of fissile material, the burnup and the operation time of the reactor were obtained from [6], and are listed in following:

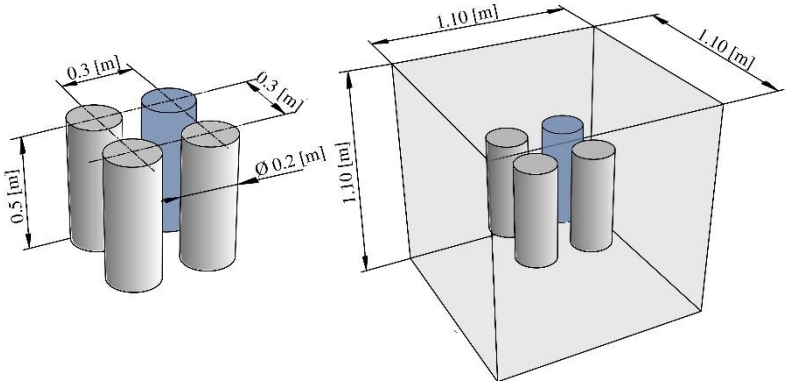
- UO_2: enriched to 4.3 w/o $^{235}U/U$; burnup of 48 GWd/tHM during 3.61 years and 1.634% of final amount of fissile material.
- (TRU-Th)O_2: fuel composed of 10 % of Th and 90 % of reprocessed fuel by UREX+, with 9.53 % of fissile material; burnup of 48 GWd/tHM during 3.61 years and 6.657 % of final amount of fissile material.
- MOX: enriched to 0.25 w/o $^{235}U/U$; burn-up of 48 GWd/tHM during 3.61 years and 3.375 % of final amount of fissile material.

- (U-Th) O_2: Enriched to 4.869 w/o $^{235}U/U$; burn-up of 48 GWd/tHM during 3.61 years and of 2.084 % of final amount of fissile material.

2.2 GEOMETRY

Figure 1 shows the minor UR for an arrangement of four elements of SF. In the mixed storage, one of the four elements (blue cylinder) is either (Th,TRU)O_2, or (U-Th)O_2, or MOX, while the remaining are UO_2.

Figure 1: Dimensions of the simulated SFP. Blue cylinders represent the SF from reprocessed fuel. The designs are not to scale.

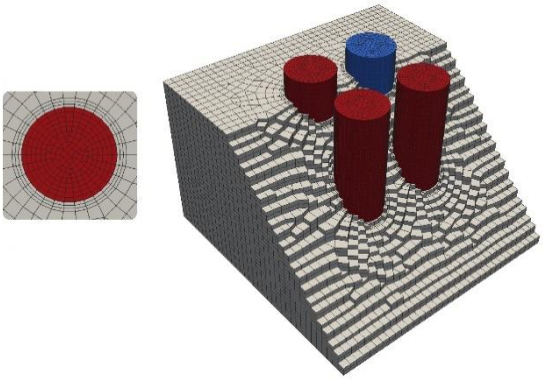


Each assembly of SF was modelled as a solid cylinder, and only a single UR is represented. To determine the volume of water in the model, the proportion SF/water in the real pool of the PWR from Angra II-Brazil fully filled with assemblies was adopted, i.e., 0.0508 [7], considering that the real pool has approximately 1,298 m^3.

2.3 MESH OF THE GEOMETRY

The meshes were performed with Ansys CFX meshing tool. The domains were meshed in different element sizes, depending on their dimensions. Figure 2 shows the mesh of the geometry. The domains were meshed in different element sizes depending on their dimensions. Studies of spatial grid convergence were carried out following the Roche's method that is based on the Richardson's extrapolation (ER) [8].

Figure 2 : An illustration of the meshing. The figure is not to scale.



The number of elements was 24960 in each cylinder of SF and 86720 in the pool. The pool element size was set up at 3.7 x 10^{-2} m.

2.4 THERMOPHYSICAL PROPERTIES OF MATERIALS

The water properties are from [9], at 298 K. The UO_2 properties, at 673 K, are from [9,10]. The molar mass of MOX, (U-Th)O_2, (TRU-Th)O_2 and (U-Th)O_2 were estimated from their chemical compositions from [6], at 298 K.

The remaining MOX properties are arithmetic means of values between 600 K and 700 K from [10]. The density, specific heat and thermal conductivity of (U-Th)O_2, at 673 K, are from [11], while its thermal expansivity is from [12] at this temperature.

The (TRU-Th)O_2 properties were estimated considering the most significant dioxides present in its composition, which are ThO_2, PuO_2 and UO_2 [6]. The density, specific heat, conductivity, and thermal expansivity are represented by Q, and were estimated by the following expression:

$$Q_{(TRU-Th)O_2} = \frac{xQ_{(ThO_2)} + yQ_{(PuO_2)} + zQ_{(UO_2)}}{x+y+z} \quad (1)$$

where x, y and k are the fractions of ThO_2, PuO_2 and UO_2, respectively. These fractions were obtained from [6], whose values are 0.74, 0.093, 0.013, respectively. The dioxides properties were derived from [9, 11], and are arithmetic means in the temperature range from 600 K to 700 K. The properties values are summarized in Table 1.

2.5 BOUNDARY AND INITIAL CONDITIONS

The k-epsilon turbulence and the buoyancy models were adopted. The pressure in water was set at 1 atm. The initial temperatures were 298 K for water and 673 K for SF, which is the temperature of an assembly of SF at the nuclear reactor shutdown. First class of simulations adopted all the walls of the SFP as adiabatic. Second class adopted all the walls of the SFP, except its top, as adiabatic. In this case, two heat transfer coefficient (h) values (h=20 and h=100), in W/m^2K unit, were simulated, and the outside temperature was set at 298 K.

T_b is the mean temperature of the water, being averaged over the whole water volume. Figure 3 shows the main boundary and initial conditions of the model.

Table 1: Thermophysical properties of materials.

SF type	**Density [kg/m^3]**	**Molar mass [kg/kmol]**	**Specific heat [J/(kg.K)]**
Water	997.1	18.02	4183
UO_2	10830	270	297
(TRU-Th)O_2	11400	265	276.5
(U-Th)O_2	9510	202.83	362.4
MOX	10873	207	297.9
SF type	**λ [W/(m.K)]**	**Thermal expansivity x10^{-6} [K^{-1}]**	
Water	0.5948	259.4	
UO_2	4.74	10	
(TRU-Th)O_2	3.065	8.604	
(U-Th)O_2	5.2	8.0	
MOX	2.48	9.9	

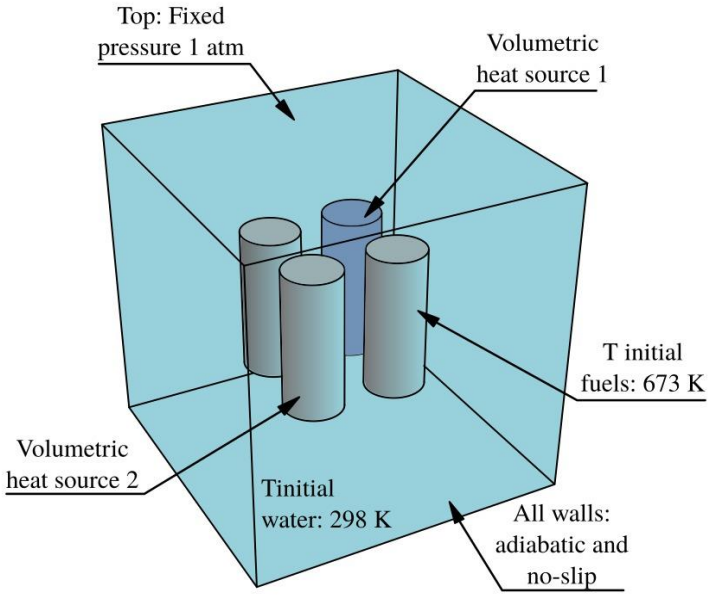
2.6 HEAT SOURCES

The heat sources were derived from the decay heat profiles of the SF, at time t=0 year after reactor discharge [6]. To convert from [W/tHM] to [W/m^3], the values were multiplied by the SF densities. Table 2 shows the heat sources values and their densities.

Table 2: The heat sources values. (a) Only UO_2; (b) UO_2 together with SF from reprocessed fuels.

SF type	**Density (kg/m^3)**	**Heat sources-2 x10^5 (W/m^3)**
[a] UO_2	10830	3.24537
[b] UO_2		2.37162
(TRU-Th)O_2	11400	6.07654
(U-Th)O_2	9510	3.49903
MOX	10873	3.15659

Figure 3: The boundary and initial conditions of the model. All the simulated cases were also carried out setting the top of the SFP as non-adiabatic.



3 RESULTS AND DISCUSSION

3.1 INCREASING OF THE WATER TEMPERATURE

Figure 4 shows the behavior of the water temperature along the time for the loading containing only UO_2 (left), and a mixed loading containing $(TRU\text{-}Th)O_2$ together with UO_2 (right).

Both situations were simulated considering the top of the SFP as either adiabatic or non-adiabatic boundary, with h=20 and h=100, in W/m^2K unit. Note that the higher is the parameter h (tending to forced convection regime), the temporal behavior of the water temperature becomes non-linear, which occurs due to the heat transfer from the SFP to the external environment. Such behavior described above is observed for all SF types.

3.2 COMPARISON OF T_B – SFP WITH THE TOP SET AS ADIABATIC AND NON-ADIABATIC

Table 3 summarizes the data for h = 100 W/m^2K. Note that when the top of the SFP is left free to exchange heat with outside (non-adiabatic boundary), T_b is greater. The enhancement on T_b is dependent on the SF type.

Figure 4: Water temperature behavior along the time.

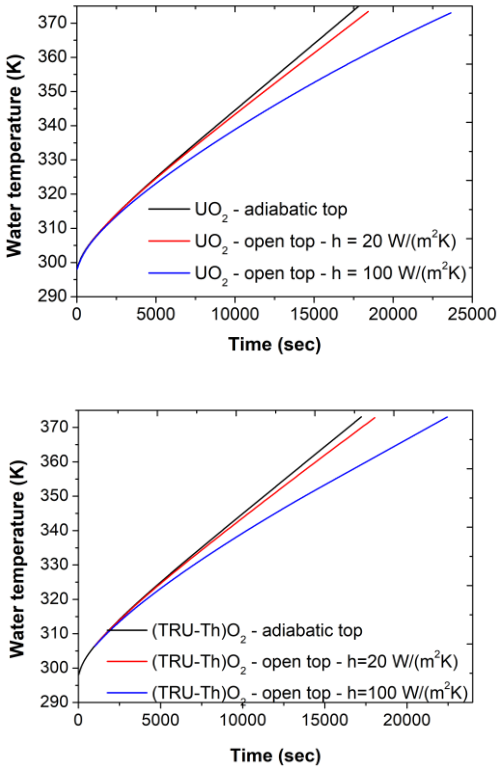


Table 3: T_b – SFP with the top set as adiabatic and non-adiabatic.
*One cylinder together with three cylinders of UO_2. See Figure 1.

SF type	**T_b (h)**	
	Top of the SFP - adiabatic	Top of the SFP – non-adiabatic
*(TRU-Th)O_2	4.78	6.20
*(U-Th)O_2	5.79	8.07
*MOX	5.97	9.04
UO_2	4.81	6.57

4 CONCLUSION

T_b is highly dependent on the boundary condition of the SFP's top. The adiabatic condition is more conservative, yielding lower T_b values, since the heat is confined to the SFP environment. In view of this dependence, the non-adiabatic boundary condition would be the appropriate option for future heat transfer simulations. This boundary condition is closer to the real operation of a spent fuel pool.

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