Residual heat comparison for stationary campaigns of WWER-1000 and WWER-1200 reactors after preliminary storage in the spent fuel pool

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Abstract. In the presented work the residual heat of spent fuel from WWER-1000 and WWER-1200 reactors after preliminary storage in spent fuel pool is investigated. The selection of nuclides with a significant contribution to the residual heat was made. Their absolute and relative contributions depending on time are considered. Comparison of residual heat generation of spent fuel from a WWER-1000 reactor with a burnup of 40 MW·day/kg and a WWER-1200 reactor with a burnout of 70 MW·day/kg after storage in the spent fuel pool was made.

1. Introduction
Residual heat is one of the most serious problems when dealing with a spent fuel. The magnitude of the residual heat release has a maximum value immediately after the reactor shutdown and decreases at a high rate in initial period of time. During that period of time the most short-living nuclides with the highest activity decay.

In the present work the residual heat of spent fuel from WWER-1000 and WWER-1200 reactors with burnout of 40 MWh/kg and 70 MWh/kg respectively after fuel exposure in the spent fuel pool for more than one year is investigated. In the first year, the majority of nuclides will mostly disintegrate. So the task is reduced to considering a relatively small number of them as was made in current work. Calculations of the activities of fission products are made by the analytical method described in [1]. Data on the activities of actinides was taken from [2]. Based on the activities calculated residual heat was obtained. The calculation and the analysis of the results were conducted.

2. Activity of nuclear fission products
Among all fission products (FP) nuclides with half-lives less than 2 months mostly disintegrate after one year preliminary storage in the spent fuel pool. Hence, they can be excluded from consideration except for the $^{95}\text{Zr} \rightarrow ^{95}\text{Nb}$ chain with half-lives of 64 and 35 days respectively because $^{95}\text{Nb}$ appears with a certain delay and can effect on residual heat amount. Based on this, the following nuclides were selected: $^{85}\text{Kr}$, $^{90}\text{Sr}$, $^{95}\text{Zr}$, $^{95}\text{Nb}$, $^{137}\text{Cs}$, $^{106}\text{Ru}$, $^{144}\text{Ce}$, $^{147}\text{Pm}$.

The calculation of FP activities was performed by the analytical method described in [1]. This method allows to obtain simple analytical expressions for the activities of interest depending on fuel irradiation time. The accuracy of this method does not inferior to numerical calculations (the difference is up to 3% [3–5]). As a result, activity values were obtained at the end of WWER-1000 and WWER-1200 reactors fuel campaigns. The data obtained is presented in table 1. Table 1 also shows the data on the average
heat release per decay $Q_{\beta,\gamma}$ [6], which takes into account not only the direct decay of this element but also subsequent chains. The information on this chains can be found for example in [7].

**Table 1.** Initial values of activities and important characteristics of FP in spent fuel of stationary campaigns of WWER-1000 and WWER-1200 reactors.

| nuclide   | $T_{1/2}$, y | $Q_{\beta,\gamma}$, keV | $A_{0}$, Bq/t (WWER-1000) | $A_{0}$, Bq/t (WWER-1200) |
|-----------|---------------|-------------------------|----------------------------|----------------------------|
| $^{95}$Kr | 10.73         | 252                     | $3.11 \cdot 10^{15}$      | $5.31 \cdot 10^{15}$      |
| $^{90}$Sr | 28.9          | 1127                    | $3.23 \cdot 10^{15}$      | $5.23 \cdot 10^{15}$      |
| $^{95}$Zr | 0.18          | 849                     | $6.44 \cdot 10^{16}$      | $7.43 \cdot 10^{16}$      |
| $^{95}$Nb | 0.096         | 808                     | $6.44 \cdot 10^{16}$      | $7.51 \cdot 10^{16}$      |
| $^{106}$Ru | 1.02          | 1626                    | $2.02 \cdot 10^{16}$      | $3.77 \cdot 10^{16}$      |
| $^{137}$Cs | 30.08        | 702                     | $4.42 \cdot 10^{15}$      | $7.93 \cdot 10^{15}$      |
| $^{134}$Cs | 0.78          | 1338                    | $4.85 \cdot 10^{16}$      | $6.01 \cdot 10^{16}$      |
| $^{147}$Pm | 2.62          | 62                      | $1.47 \cdot 10^{16}$      | $1.96 \cdot 10^{16}$      |

The activities of all nuclides listed in Table 1 with the exception of $^{95}$Nb change with time according to the law of radioactive decay (1).

$$A = A_{0} \cdot e^{-\lambda t}. \quad (1)$$

To calculate the activity of $^{95}$Nb, it is necessary to take into account its formation during the decay of $^{95}$Zr. A simple calculation of the radioactive chain of two elements gives

$$A(95\text{Nb},t) = \alpha \cdot A_{0}(95\text{Zr}) \cdot e^{-\lambda(95\text{Zr})t} + \left[ A_{0}(95\text{Nb}) - \alpha \cdot A_{0}(95\text{Zr}) \right] \cdot e^{-\lambda(95\text{Nb})t} \quad (2)$$

$$\alpha = \frac{\lambda(95\text{Nb})}{\lambda(95\text{Nb}) - \lambda(95\text{Zr})}.$$

To obtain heat generation per unit time associated with the decay of a particular nuclide its activity must be multiplied by the corresponding value $Q_{\beta,\gamma}$.

3. Actinide and $^{134}$Cs activities

Among nuclides having a high contribution to the residual heat generation, $^{134}$Cs plays a significant role. This nuclide is not a fission product or a piece of the FP decomposition chain. It is acquired as a result of the reaction $^{133}$Cs (n, $\gamma$) $^{134}$Cs. For this reason $^{133}$Cs cannot be calculated according to the procedure described in [1]. The estimation of $^{134}$Cs activity in the WWER-1200 reactor was based on the assumption that its yield during operating time in the WWER-1000 and WWER-1200 reactors is approximately the same. The following assumptions will be made for the assessment: the formation rate of $^{134}$Cs from $^{133}$Cs is proportional to the number of $^{133}$Cs, the proportionality coefficient between the rate of operating time and the number is the same for both reactors. Based on these assumptions, the activity value by the end fuel campaign of the WWER-1200 reactor was obtained and equals to $1.53 \cdot 10^{16}$ Bq/t. The activity of $^{134}$Cs at the end of the campaign of the WWER-1000 reactor equals to $7.50 \cdot 10^{15}$ Bq/t [8].

The relative contribution of actinides to the total heat release in the early years is small and increases as the FP decay. The main part of the residual heat release of actinides is formed by $^{241}$Am, $^{244}$Cm, $^{239}$Pu, $^{240}$Pu and $^{239}$Pu heat release. The data on the initial activities by the end of WWER-1000 fuel campaign was taken from [8], for the WWER-1200 reactor – from [2]. All actinides are $\alpha$-decay with energies of 5-6 MeV. The initial activities and the necessary characteristics of the actinides of interest are presented.
in Table 2. The activities of these nuclides, with the exception of $^{241}$Am, vary according to the law of radioactive decay (1). Spent fuel contains a significant amount of $^{241}$Pu — about 1.5–2 kg/t. $^{241}$Pu is a β-disintegrator, with a half-life of 14.29 years and an insignificant average energy of β-particles — only 5 keV, which can be ignored in the calculations. But as a result, $^{241}$Am is gaining, which leads to a gradual increase in its activity and corresponding heat release. The dependence of its activity on time will be similar to (2), since in this case we are dealing with a similar radioactive chain of 2 nuclides.

Activity and the necessary parameters of actinides $^{[2]}$ and $^{134}$Cs are presented in Table 2.

Table 2. Initial values of activities and important characteristics of actinides and $^{134}$Cs in spent fuel of stationary campaigns of WWER-1000 and WWER-1200 reactors.

| nuclide   | $T_{1/2}$, y | $Q_{β,γ}$, keV | $A_0$, Bq/t (WWER-1000) | $A_0$, Bq/t (WWER-1200) |
|-----------|--------------|----------------|--------------------------|--------------------------|
| $^{134}$Cs | 2.06         | 1711           | 7.50×10^{15}             | 1.53×10^{16}             |
| $^{238}$Pu | 88.7         | 5592           | 7.97×10^{13}             | 1.75×10^{14}             |
| $^{239}$Pu | 24110        | 5246           | 1.27×10^{13}             | 1.51×10^{13}             |
| $^{240}$Pu | 6561         | 5256           | 2.03×10^{13}             | 2.80×10^{13}             |
| $^{241}$Am | 433          | 5624           | 9.07×10^{12}             | 2.86×10^{13}             |
| $^{244}$Cm | 18.1         | 5903           | 1.36×10^{14}             | 6.76×10^{14}             |

Attention should be paid to a strong increase in the contribution of $^{244}$Cm to the residual heat release of the WWER-1200 reactor. This isotope is produced from $^{238}$U by capturing six neutrons. This leads to a strong dependence of its quantity on the fuel burnup. With a relative increase in burnout value of less than two, the amount of $^{244}$Cm increases about 5 times. This issue deserves separate consideration.

4. Compassion of residual heat of WWER-1000 and WWER-1200 reactors

The total residual heat of FP and actinides of the WWER-1000 and WWER-1200 reactors are presented in figures 1a and 1b.

![Figure 1. Total residual heat of FP and actinides of WWER-1000 (a) and WWER-1200 reactors (b)](image)

It is worth noting a significant increase in the relative contribution of long-lived actinides to the residual heat of the reactor WWER-1200.

Figures 2a and 2b show the absolute and relative comparison of the residual heat of spent fuel from both reactor types. Also on graph 2a for comparison, the triangles show the data on the residual heat $^{[8]}$. 
**Figure 2.** Absolute and relative comparison of the residual heat of spent fuel from WWER-1000 (a) and WWER-1200 (b) reactors.

Figures 3 and 4 show the relative contributions of the main nuclides to the WWER-1000 and WWER-1200 reactors’ residual heat release.

**Figure 3.** Relative contribution of nuclides to the total heat release of WWER-1000
The role of $^{244}$Cm and $^{241}$Am actinides increases noticeably in WWER-1200. $^{244}$Cm deserves special attention when studying the MOX fuel where the chain of plutonium isotopes is presented initially. This can lead to a significant increase in curium production, compared with reactors with fuel based on $^{235}$U [9,10].

5. Conclusion
It has been established that the main nuclides having a significant effect on the residual heat of spent fuel in WWER-1000 and WWER-1200 reactors are: $^{90}$Sr, $^{137}$Cs, $^{134}$Cs, $^{106}$Ru, $^{144}$Ce, $^{85}$Kr, $^{147}$Pm, $^{241}$Am, $^{244}$Cm, $^{238}$Pu, $^{249}$Pu, $^{239}$Pu.

The residual heat of spent fuel from stationary fuel campaigns of WWER-1200 and WWER-1000 reactors is significantly different and amounts to 62-96% depending on the storage time.

The difference is due to an increase in the number of fission products and actinides due to a deeper burning out of the fuel in the WWER-1200 reactor.

Special attention should be paid to the $^{244}$Cm isotope, the amount of which has a strongly pronounced dependence on a burnout.
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