OPTIMIZED DESCRIPTION OF RADIOACTIVE CONTENTS OF PACKAGES FOR IRRADIATED FUEL ASSEMBLIES

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SUMMARY

For package approval the IAEA regulations require a detailed description of the proposed radioactive contents with reference to their physical and chemical states and the nature of the radiation emitted.

Former approvals of casks for irradiated fuel assemblies in Germany were based on fixed combinations of max. enrichment, max. burnup and min. cooling time with respect to dose rate and temperature limitations.

Recently, due to higher enrichment, higher burnup, and a great variety of burnup histories, these parameters in the approval led to strong and unnecessary restrictions for the use of the casks.

In the present paper the physical parameters for performing the safety analysis with respect to maximum dose rate and temperatures are investigated to derive an optimal description of radioactive contents in package approvals. Presently, this set of parameters is already realised in some German package approvals for CASTOR casks.

INTRODUCTION

To obtain a type B(U)F approval, it is necessary to perform a safety analysis and to show that the requirements with respect to dose rate, temperature, containment and criticality are fulfilled. This requires "a detailed description of the proposed radioactive contents with particular reference to their physical and chemical states and the nature of the radiation emitted" (IAEA, 1990, para. 705).

To describe the radioactive contents former approvals of casks for irradiated fuel assemblies in Germany were based on fixed combinations of max. enrichment, max. burnup and min. cooling time with respect to dose rate and temperature limitations as well as detailed geometrical parameters of fuel assemblies with respect to criticality safety. Due to the change of irradiation histories during the last decade which was possible by higher enrichment and higher burnup, the above mentioned parameters were no longer uniquely connected to the gamma and neutron source strengths and decay heat.

This situation resulted in excessively conservative cooling times and/or frequent approval revisions.

To overcome these problems, approvals for CASTOR casks were recently applied for with a general set of physical parameters which is independent of the burnup history of fuel assemblies.

In the present paper, the problems connected with the definition of fixed combinations of max. enrichment, max. burnup and min. cooling time are analysed in detail. After that the new form of inventory description based directly on gamma and neutron source strengths and decay heat, which is up to now realised in the package approvals for the CASTOR V/19 and V/52 casks, is presented.

DESCRIPTION OF RADIOACTIVE CONTENTS BY MAX. ENRICHMENT, MAX. BURNUP AND MIN. COOLING TIME

The German approval for the CASTOR Ic cask for 16 BWR fuel assemblies is an example for the former kind of inventory description (by max. enrichment, max. burnup and min. cooling time). The corresponding parameters are listed in Table 1.

Kind of fuel	max. number of fuel assemblies	max. U-235 [%]	max. Pu-239, 241 [%]	max. burnup [GWd/tHM]	min. cooling time [month]
Uranium	16	4	-	35 45 50	12 21 26
MOX	4	1.04	2.19	45 50	30 34
Total heat output: max. 28.5 kW					

Table 1: Selected parameters of fuel assemblies in the CASTOR Ic approval

This inventory description leads in many cases to much higher cooling times than physically necessary. This concerns the definition as well as the use of the parameter sets.

In using the parameters in Table 1, a fuel assembly with a burnup slightly above e.g. 35 GWd/tHM must have a min. cooling time of 21 months, even though from the physical point of view, some days above 12 months would be sufficient.

In defining the parameters it has to be taken into account that other data also influence the physical parameters gamma and neutron source strengths and heat output.

These are in particular

- the specific power in the last cycle,
- the lowest enrichment which can lead to the max. burnup, and

- the contents of higher Pu-isotopes.

To include all possible variations, the most unfavourable combinations must be chosen, thus, again leading to excessive cooling time for the bulk of fuel assemblies.

Because of the higher average enrichment today, the fuel assemblies are used in a larger number of cycles. Thus, some of them can have low specific power in the last cycles or others can reach higher burnup with lower initial enrichment.

The influence of the specific power in the last cycle is shown in Fig. 1. It can be seen that there are factors of 1.16 for the γ-source strength and 1.19 in the heat output in a practical relevant thermal power range between 20 and 40 MW/tHM.

This results in cooling time differences of 5.1 and 4.8 months, respectively.

Fig. 2 shows the influence of the initial enrichment on γ- and n-source strengths and decay heat. In the physically plausible range between 2.9 % and 4 % enrichment there is a strong influence on neutron-source strength. The factor 1.3 corresponds to an increase in cooling time of 82 months.

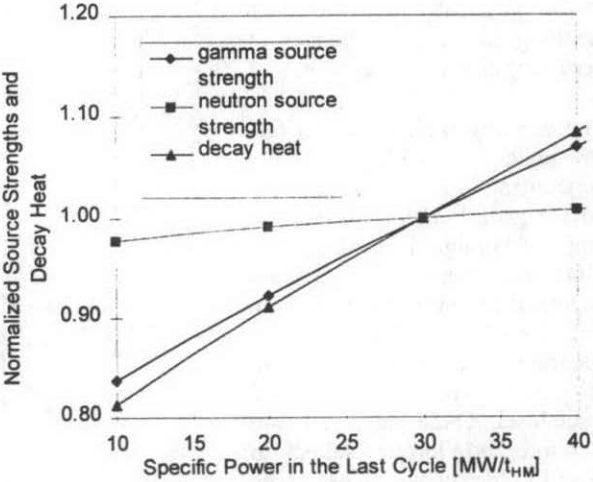

Fig. 1 *γ- and neutron-source strengths and decay heat for BWR fuel assemblies with 3.7 % enrichment, 50 GWd/tHM burnup and 26 months cooling time as function of the specific power in the last cycle.*

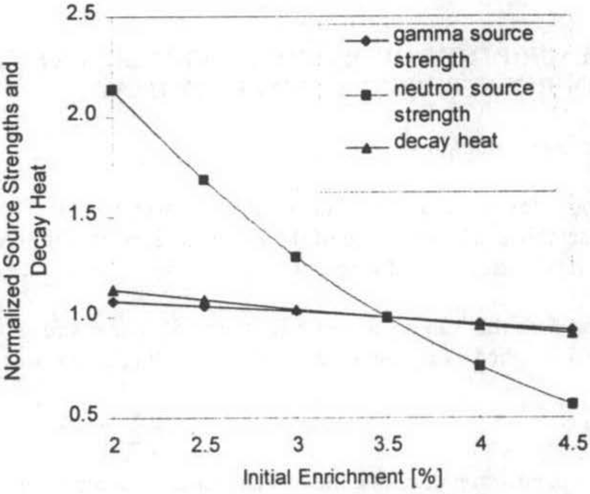

Fig. 2 *γ- and neutron-source strengths and decay heat for BWR fuel assemblies with 50 GWd/tHM burnup and 26 months cooling time as function of initial enrichment*

In the case of MOX-assemblies, the Pu-isotope distribution depends strongly on the burnup of the reprocessed spent fuel assemblies. Especially, small variations in the contents of Pu-242 (and Pu-241) result in large differences in the neutron source strength of spent MOX-assemblies.

Fig. 3 gives examples showing differences of up to a factor of 1.5 in the physically relevant range resulting in large differences of necessary cooling times.

These examples show that for fuel assemblies with higher enrichment, which is connected with higher burnup and a wide range of burnup histories, and for MOX-fuel, there are more parameters than enrichment, burnup and cooling time, which determine the physical relevant properties of spent fuel assemblies. These parameters are therefore no longer suited to describe the contents of type B(U)F packages.

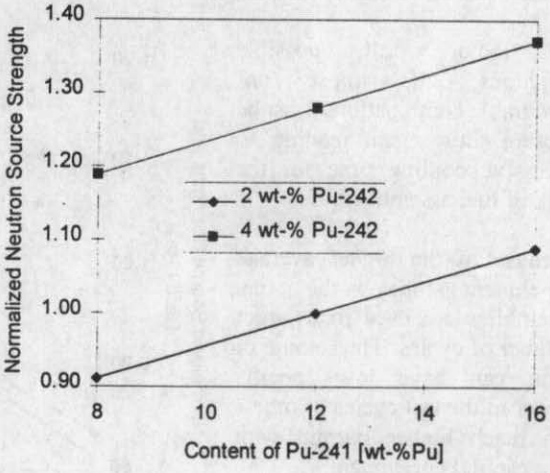

Fig. 3 *Neutron source strength for BWR fuel assemblies with 0.71 % U-235, 2.19 % Pu-fiss, 45 GWd/tHM burnup, and 30 months cooling time as function of the contents of Pu-241 and Pu-242*

DESCRIPTION OF RADIOACTIVE CONTENTS BY GAMMA AND NEUTRON SOURCE STRENGTHS AND DECAY HEAT

Dose rate limitations

There are several dose rate limitations which must be observed by casks for spent fuel assemblies. The dose rate of 0.1 mSv/h at 2 m from the external surface of the conveyance is in all practical cases the most restrictive one.

The dose rate can be considered as sum of source strength in different gamma energy groups G_i multiplied by an energy dependent shielding factor φ_i of the cask:

$$D\gamma = \sum_i \varphi_i \cdot G_i$$

For the neutron dose rate the two contributing spectral types must be considered:

$$D_n = \varphi'_1 \cdot N_1 + \varphi'_2 \cdot N_2,$$

where N_1 and N_2 are the neutron source strengths due to (α, n)-reactions on the fuel oxygen and spontaneous fission, respectively, and φ'_1 and φ'_2 the corresponding shielding factors.

As shown above, the G_i and N_j are dependent on several parameters. Furthermore, their time dependence is very different. Therefore, in the type B(U)F-approval special reference source strengths G_{io} and N_{jo} can be fixed, which are determined by

$$D_{max} = \varphi_i \cdot G_{io}$$

and

$$D_{max} = \varphi'_j \cdot N_{jo}$$

By this method the approval contains only the shielding quality of the cask expressed by the quotients of maximum dose rate divided by the shielding factors in the single groups. This shielding quality is the requirement for the spent fuel assemblies. Then, for a spent fuel assembly must be shown by a burnup calculation that

$$S = \sum_i G_i / G_{io} + \sum_j N_j / N_{jo} \leq 1.$$

In this way the shortest possible cooling time can be determined by taking into account all the special dependencies only into the calculation before loading and not into the safety analysis.

Gamma and neutron source strengths for the CASTOR V/52

The V/52 is a cask of the second CASTOR-generation for 52 BWR fuel assemblies, 16 of them may be MOX-assemblies. The cask is designed for transport and storage of spent fuel. Because of the different attenuation of gamma and neutron dose rates between the cask and the fence of a storage facility, there are separate limits for gamma and neutron dose rates in German storage facility licenses. As these limits are more restrictive for the source strengths than the dose rate limits from the transport regulations, the storage values are applied for in transport approval procedure, too. The approved values of the gamma and neutron reference source strengths are shown in column 3 of Table 2 and 3, respectively.

i	**Energy group [MeV]**	**Reference source strength G_{io} [1/(s·tHM)]**	**Real source strength G_i [1/(s·tHM)] cooling time [month]**		
			45	**48**	**51**
1	0.57	2.01E18	1.06E16	1.00E16	9.56E15
2	0.85	3.80E16	3.46E15	3.19E15	2.95E15
3	1.25	1.42E15	6.82E14	6.44E14	6.11E14
4	1.75	1.37E14	2.02E13	1.82E13	1.64E13
5	2.25	3.50E13	1.28E13	1.03E13	8.37E12
6	2.75	1.38E13	4.16E11	3.50E11	2.94E11
7	3.50	5.73E12	5.33E10	4.49E10	3.78E10
$\sum_{i=1}^{7} G_i/G_{io}$			**1.13**	**1.00**	**0.90**

Table 2: **Approved gamma source strength G_{io} and calculated source strength for a BWR fuel assembly of 3.7 % enrichment and 50 GWd/tHM burnup for different cooling times.**

j	Spectral type	Reference source strength N_{io} [1/(s·tHM)]	Real source strength N_i [1/(s·tHM)] cooling time [month]		
			45	48	51
1	(α, n)-reactions	1.69E9	2.53E7	2.51E7	2.49E7
2	spont. fission	2.29E9	1.79E9	1.77E9	1.75E9
$\sum_{i=1}^{2} N_j/N_{jo}$			**0.80**	**0.79**	**0.78**

Table 3: **Approved neutron source strength N_{jo} and calculated source strength for a BWR fuel assembly of 3.7 % enrichment and 50 GWd/tHM burnup for different cooling times.**

Furthermore, in Tables 2 and 3 it is shown how the shortest possible cooling time can be determined. In this example, a loading after a cooling time of about 48 months is permitted.

To take into account spent fuel assemblies of widely different neutron source strengths and decay heat (see below), in particular, MOX-assemblies and Uranium-assemblies of very high burnup (up to 65 GWd/tHM), a second set of reference source strength is approved (see Table 4). This heterogeneous arrangement allows 16 fuel assemblies with higher neutron source strength at the expense of lower values at 36 positions.

j	Spectral type	Reference source strength N_{jo} [1/(s·tHM)]		
		36 positions	16 positions	
			MOX	Uranium
1	(α, n)-reactions	1.29E9	2.82E9	2.58E9
2	spont. fission	1.73E9	3.75E9	3.44E9

Table 4: **Approved neutron source strength N_{jo} for a heterogeneous loading of the CASTOR V/52**

Decay heat

Due to the much higher number of fuel assemblies in the CASTOR-casks of the second generation, the limitation of the total heat output is no longer sufficient to perform the necessary safety analysis. Especially, the structural analysis of the basket under accident conditions requires a limitation of the decay heat of single fuel assemblies. This is realised in the new approvals; the corresponding values of the CASTOR V/52 are shown in Table 5. As mentioned above, there is a heterogeneous arrangement in addition to the homogeneous one to allow for the loading of fuel assemblies with higher decay heat.

Decay heat [kW]	Homogeneous loading	Heterogeneous loading	
		36 positions	16 positions
per fuel assembly	0.769	0.654	0.877
per cask	40	37.6	

Table 5: **Decay heat of single fuel assemblies and of the total loading of CASTOR V/52**

Minimum cooling time

The purpose of the new parameter specification is to obtain the shortest possible cooling time for the loading of a fuel assembly into a cask. This time is determined by the limitations on the gamma and neutron source strengths as well as the decay heat. These three physical parameters have different time dependencies, and which of these is decisive for the minimum cooling time depends mainly on the burnup state. As can be seen in Fig. 4, the gamma source strength determines the cooling time for a burnup up to about 50 GWd/tHM. Above this, the neutrons determine the cooling time. Only in some cases around 50 GWd/tHM the limit for the decay heat may be decisive.

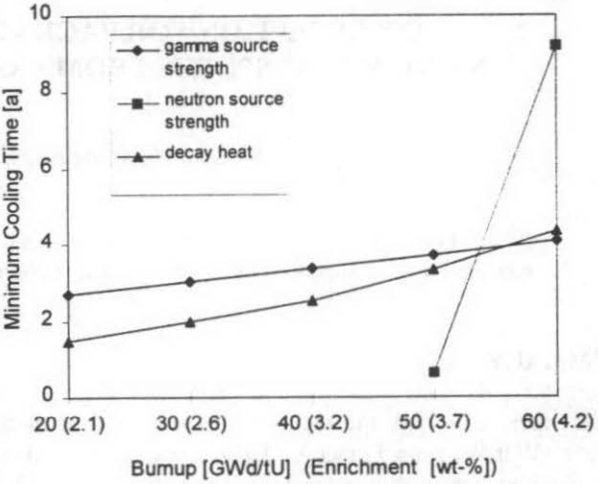

Fig. 4 *Required cooling time to fulfill the limitations of gamma and neutron source strengths as well as decay heat as function of burnup*

CONCLUSIONS

It is shown that max. enrichment, max. burnup and min. cooling time are no longer suitable parameters to describe the radioactive inventory of casks for spent fuel assemblies.

Instead of these, the real gamma and neutron source strengths and decay heat can describe the inventory in such a way that the minimum cooling time can be achieved.

REFERENCES

Regulations for the Safe Transport of Radioactive Material. 1985 Edition (As Amended 1990). Safety Series No. 6, Vienna, 1990. IAEA