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Neutronic Dimensioning of a Fast Breeder Reactor (FBR) Fuel Shipping Cask

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The purpose of this study is to establish the subcriticality of a shipping cask with the loading of 7 containers of FBR fuel pins. Calculations have been carried out with the IRSN/CEA new calculation scheme called CRISTAL, based on the APOLLO2 sophisticated spectral code and on the MORET4 3D Monte Carlo code, and adopted by the French industry. The study has been performed for a heterogeneous medium (lattice of fissile pins surrounded by water) and for a homogeneous one (homogenization of fissile matter with water). The 1.015 maximum Keff obtained in case of a heterogeneous modelling of the fissile medium implies a revision of the cask capacity in order to meet the criticality safety criteria.

KEYWORDS : criticality, dimensioning, shipping cask, fast breeder reactor fuel

1. Introduction

The purpose of the study is to establish the subcriticality of a shipping cask with the loading of 7 containers of FBR fuel pins.

The criticality safety criteria to meet are those required by the French Safety Authorities i.e. Keff + $3\sigma \leq 0.95$ for a single cask reflected by a 20 cm water thickness (accidental and normal transport conditions), Keff + $3\sigma \leq 0.98$ for an array of 5N casks in normal transport condition and an array of 2N casks in accidental transport conditions. N is the maximum number of casks to be transported.

2. Data and assumptions

2.1. Characteristics of the shipping cask and of its content

2.1.1. Shipping Cask features

The cask is composed with a 505 mm diameter and 2220 mm useful length cylindrical cavity, containing a structure equipped with 7 compartments. Containers filled with FBR fissile pins are inserted inside these compartments. The radial shielding is provided by a 37 cm carbon steel ring surrounded by a 10 cm resin compound. Lower and upper axial shieldings are made of layers with different materials such as depleted uranium and resin inserted between stainless steel layers. The most external horizontal layer is made with balsa and sequoia 45 cm thickness.

2.1.2. Inner fitting out description

2.1.2.1. Cell

Pins are bundled inside stainless steel cells, that are closed by a welded plug. Each cell is able to contain 120 pins. The main sizes of cells are a 1965-1885 mm total-useful length, and a 103-100 mm external-internal diameter.

2.1.2.2. Container

Each stainless steel container contains a cell. The main sizes of containers are a 2076-1970 mm total-useful length, and a 118-108 mm external-internal diameter, for a 10 mm bottom thickness.

2.1.3. Fuel pins characteristics

The fuel pins main characteristics are a stainless steel cladding with 6,55-5,65 mm external-internal diameter and 1793 mm length, containing a 5,47 mm diameter and 858 mm length fissile part with $(U,Pu)O_2$ and a 5,55 mm diameter and 296 mm length fertile part composed with UO_2, with a 1.5 mm boring diameter.

2.2. Fuel composition

The fissile part of the fresh fuel pin is mixed oxide with 30% plutonium, the pellet density is 11 $g.cm^{-3}$. The uranium composition is 99,29% ^{238}U and 0,71% ^{235}U. The plutonium composition of the fissile part is 74,41% ^{239}Pu, 15% ^{240}Pu, 9,71% ^{241}Pu, 0,88% ^{242}Pu.

2.3. Assumptions

2.3.1. General assumptions

Calculations have been carried out supposing that: the pin number is the same in all cells, cells and containers are centred in compartments. Radial shielding resin is not modelled, and axial shielding resin is replaced by air. The top and bottom shipping cask are not modelled. They are replaced by a total reflection condition on the upper and lower side of the cask. Only the useful length of the container is taken into account.

2.3.2. Penalising assumptions

Calculations are carried out with penalising assumptions: fresh fuel, pin whole length to be filled by fissile material, and for the most reactive configuration: accidental transport conditions (clads are supposed to be failed, the integrity of the containers is not proved, and so they are not modelled), water moderated fissile medium, cask interstices filled with air.

2.3.3. Fissile medium modelling

The fissile medium is modelled in order to keep the mass of fissile matter by pin. In order to cover the normal transport conditions as well as the accidental transport conditions, calculations are carried out for an heterogeneous medium (lattice of fissile pins surrounded by water) and for an homogeneous one (homogenization of fissile matter with water).

3. Calculation tools

Calculations are carried out with the IRSN/CEA new calculation scheme called CRISTAL, based on the APOLLO2 sophisticated spectral code and on the MORET4 3D Monte Carlo code, and adopted by the French industry. The code is used with a basic microscopic cross section library, based on JEF2.2 data with a 172 energy group structure, and called CEA 93 V4. The results are given with a 99% confidence interval (Keff + 3σ), for a 300 pcm σ.

4. Methodology and results

4.1. Criteria

The criticality safety criteria to meet are those required by the French Safety Authorities i.e. Keff + 3$\sigma \leq 0.95$ for a single cask reflected by a 20 cm water thickness (accidental and normal transport conditions), Keff + 3$\sigma \leq 0.98$ for an array of 5N casks in normal transport condition and an array of 2N casks in accidental transport conditions.

4.2. Methodology

The calculations are performed for an homogeneous modelling of the fissile medium as well as for an heterogeneous modelling, by keeping the fissile mass by pin.

4.2.1. Homogeneous modelling

The calculations are firstly carried out with the maximum loading envisaged by cell, i.e. 120 pins. Fissile matter is put in the container in a cylindrical form. All moderation ratios (H/X) that are allowed considering the container volume are investigated: calculations are carried out for moderated fissile matter height comprised between 350 mm (corresponding to the height of the non moderated fissile matter volume) and 1970 mm (corresponding to the useful height of the container). The fissile mass conservation is maintained by an adjustment of the fuel concentration in the moderated fissile matter volume.

If the optimal moderation is not obtained for the maximum volume, complementary calculations will be carried out for this volume, considering a decreasing number of pins by container.

4.2.2. Heterogeneous modelling

Calculations are carried out with the same height range as in the homogeneous modelling. The fissile mass conservation is maintained by an adjustment of the fuel radius, with a constant cell radius allowing to simulate a fixed pins number. The investigation of the optimal moderation is realised as for the homogeneous modelling.

4.3. Results

The results hereafter are concerning a single cask reflected by a 20 cm water thickness.

4.3.1. Homogeneous modelling

4.3.1.1. 120 fissile pins by container

The evolution of the intrinsic characteristics of the homogeneous modelled fissile medium are given on Table 1. Kinfinite, B^2m and H/X are given versus the height of the moderated fissile medium.

Table 1 Evolution of intrinsic characteristics for the homogeneous modelled fissile medium

Height (cm)	H/X	B^2m	Kinfinite
35.11	**0.03**	**0.0205**	**2.199**
45	0.8	0.0196	1.754
55	1.58	0.0182	1.603
65	2.35	0.0169	1.519
75	3.13	0.0158	1.465
85	3.91	0.0150	1.429
95	4.69	0.0144	1.405
105	5.46	0.0140	1.389
115	6.24	0.0137	1.377
125	7.02	0.0135	1.370
135	7.80	0.0134	1.365
145	8.57	0.0134	1.362
155	9.35	0.0134	1.361
165	10.13	0.0134	1.360
175	10.90	0.0134	1.361
185	11.68	0.0135	1.362
197	12.61	0.0136	1.364

The analysis of this table shows that the maximum reactivity of the medium is reached for the minimum moderation rate.

Table 2 gives the evolution of the effective multiplication coefficient (Keff) versus the variation of the moderated fissile medium volume (V) and the fuel concentration (C) in the moderated fissile medium.

Table 2 Evolution of Keff versus the variation of the moderated fissile medium volume (V) and the fuel concentration (C) in the moderated fissile medium

Height (cm)	V (cm^3)	C (g.l^{-1})	Keff + 3 σ (σ=300pcm)
35.11	3216	11000	0.848
45	4122	8582	0.906
55	5038	7021	0.930
65	5955	5941	0.938
75	6871	5149	0.932
85	7787	4543	0.931
95	8703	4065	0.938
105	9619	3678	0.927
115	10535	3358	0.939
125	11451	3089	0.935
135	12367	2861	0.937
145	13283	2663	0.936
155	14199	2491	0.935
165	15115	2340	0.934
175	16032	2207	0.937
185	**16948**	**2087**	**0.942**
197	18047	1960	0.938

The 0.942 maximum Keff is obtained for a 185 cm moderated fissile medium height. The difference of behaviour noticed with the intrinsic infinite medium (see Table 1) is explained by the decreasing of the interaction between cells with the H/X decreasing, due to the fissile height decrease.

4.3.1.2. Decrease of the container pins number

In order to explore higher H/X, complementary calculations have been carried out for a moderated fissile matter volume equal to the container useful volume, by changing the container pins number. Table 3 gives the evolution of intrinsic characteristics of the homogeneous modelled fissile medium, versus the container pins number.

Table 3 Evolution of intrinsic characteristics of the homogeneous modelled fissile medium, versus the container pins number (N)

N	H/X	B^{2}m	Kinfinite
120	12.62	0.0136	1.364
110	14.01	0.0138	1.368
100	15.68	0.0140	1.374
90	17.72	0.0143	1.382
80	20.27	0.0147	1.391
70	23.56	0.0151	1.404
60	27.93	0.0157	1.419
50	34.06	0.0164	1.439
40	43.25	0.0172	1.462
30	58.56	0.0180	1.489
20	**89.20**	**0.0186**	**1.512**
10	181.09	0.0172	1.486

The intrinsic reactivity of the infinite medium increases when the container pins number decreases. The maximum Kinfinite is obtained for about 20 pins. The results of Keff calculations are gathered in Table 4.

Table 4 Evolution of Keff versus the variation of the fuel mass (M) and the fuel concentration (C) in the moderated fissile medium

N	M (g)	C (g.l^{-1})	Keff + 3 σ (σ=300pcm)
120	35377	1960	0.938
110	32429	1797	0.939
100	29481	1634	0.933
90	26533	1470	0.942
80	23585	1307	0.940
70	**20637**	**1143**	**0.943**
60	17688	980	0.940
50	14740	817	0.942
40	11792	653	0.939
30	8844	490	0.924
20	5896	327	0.894
10	2948	163	0.781

The results that have been obtained are statistically equivalent for a container pins number higher than 40. the 0.943 maximum Keff is obtained for containers with 70 pins. The difference of behaviour noticed with the intrinsic infinite medium (see Table 3) is explained by an increase of the interaction between cells with neutrons that are less moderated, due to the presence of borated steel liners in cells.

4.3.2. Heterogeneous modelling

4.3.2.1. 120 fissile pins by container

The evolution of the intrinsic characteristics of the heterogeneous modelled fissile medium are given on Table 5. Kinfinite, B^{2}m and H/X are given versus the height of the moderated fissile medium.

Table 5 Evolution of intrinsic characteristics for the homogeneous modelled fissile medium

Height (cm)	B^{2}m	Kinfinite
35.11	-	-
45	**0.0195**	**1.772**
55	0.0188	1.638
65	0.0181	1.573
75	0.0178	1.540
85	0.0177	1.523
95	0.0177	1.514
105	0.0178	1.512
115	0.0180	1.512
125	0.0182	1.514
135	0.0184	1.517
145	0.0186	1.521
155	0.0188	1.525
165	0.0190	1.529
175	0.0192	1.534
185	0.0193	1.538
197	0.0196	1.543

The comportment of the infinite heterogeneous medium is qualitatively the same as the homogeneous one (see Table 1) : decrease of Keff with increase of H/X, then quasi-constant Keff with a trend to a Keff increase for the highest H/X invested. The infinite homogeneous medium reactivity is superior to the infinite heterogeneous medium one for weak H/X. This trend inverts itself from 65 cm moderated fissile height.

Table 6 gathers the Keff evolution versus the fissile matter radius variation and the height of the moderated fissile matter.

Table 6 Evolution of Keff versus the fissile matter radius variation and the height of the moderated fissile matter.

Height (cm)	R (cm)	Keff + 3 σ (σ=300pcm)
35.11	0,493	-
45	0.435	0.918
55	0.394	0.946
65	0.362	0.961
75	0.337	0.967
85	0.317	0.976
95	0.300	0.987
105	0.285	0.991
115	0.272	0.995
125	0.261	1.002
135	0.251	1.001
145	0.243	0.995
155	0.235	1.012
165	0.227	0.999
175	0.221	1.011
185	**0.215**	**1.013**
197	0.208	1.003

The results that have been obtained show a progressive Keff increasing according to the increase of the moderated fissile matter height, then a Keff stabilization from a 105 cm height. The 1.013 maximum Keff is obtained for a 185 cm moderated fissile medium height. This Keff is 7000 pcm higher than the maximum Keff obtained in the case of homogeneous medium.

4.3.2.2. Decrease of the container pins number

In order to explore higher H/X, complementary calculations have been carried out for a moderated fissile matter volume equal to the container useful volume, by changing the container pins number. Table 7 gives the evolution of intrinsic characteristics of the heterogeneous modelled fissile medium, versus the container pins number.

Table 7 Evolution of intrinsic characteristics of the heterogeneous modelled fissile medium, versus the container pins number (N)

N	B^2m	Kinfinite
120	0.0196	1.543
110	0.0199	1.555
100	0.0204	1.566
90	0.0207	1.578
80	0.0211	1.589
70	0.0213	1.599
60	**0.0214**	**1.604**
50	0.0212	1.602
40	0.0204	1.585
30	0.0186	1.538
20	0.0143	1.422
10	0.0036	1.111

The trend is an increase of the infinite medium intrinsic reactivity with the H/X increase up to 60 pins. Then the reactivity decreases for higher H/X.

Table 8 gathers the Keff evolution versus the fissile matter radius variation and the container pins number.

Table 8 Evolution of the Keff versus the fissile matter radius variation and the container pins number

N	R (cm)	Keff + 3 σ (σ=300pcm)
120	**0.493**	**1.015**
110	0.515	1.005
100	0.540	0.998
90	0.569	0.998
80	0.604	0.981
70	0.645	0.973
60	0.697	0.956
50	0.764	0.929
40	0.854	0.880
30	0.986	0.807
20	1.208	0.678
10	1.708	0.448

The 1.015 maximum Keff is obtained for a 120 cm moderated fissile medium height. The difference of behaviour noticed with the intrinsic infinite medium (see Table 7) is explained by an increase of the interaction between cells with neutrons that are less moderated, due to the presence of borated steel liners in cells.

Also in this case the heterogeneous modelling of the fissile medium leads to a very higher reactivity than the one obtained for an homogeneous modelling.

5. Conclusion

Considering the Keff obtained for an heterogeneous modelling of the fissile medium, the shipping cask subcriticality can not be proved with the calculation assumptions and the modelling used in this study.
One can ask the question of the validity to use such a modelling, that implicitly considers a variation of the pellet diameter, especially in case of fuel diameter higher than true pellet diameter. But even in accidental transport conditions, the heterogeneous modelling can not be dismissed, because configurations with damaging of only a partial number of pellets are also to be considered. For a fissile height corresponding to a fuel radius value close to the true pellet radius value (h=115 cm, r=0.272 cm), the Keff obtained remains greatly superior to the criterion required by the French transport regulation. On the other hand, it is to note that the maximum reactivity is obtained for a fuel radius inferior to the true pellet radius, that is a conceivable situation in the present case of an accidental transport conditions modelling.
The conclusion is that the shipping cask capacity has to be revised in case of conveyance of such contents. For now the modification of the cask capacity is in progress at CEA in such a way to drastically reduce the reactivity to meet the criticality safety criteria.