CRITICALITY SAFETY OF STORAGE BARRELS FOR ENRICHED URANIUM FRESH FUEL AT THE RB RESEARCH REACTOR

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Abstract

Study on criticality safety of fresh low and high enriched uranium (LEU and HEU) fuel elements in the storage/transport barrels at the RB research reactor is carried out by using the well-known MCNP™ computer code. It is shown that studied arrays of tightly closed fuel barrels, each entirely loaded with 100 fresh (HEU or LEU) fuel slugs, are far away from criticality, even in cases of an unexpected flooding by light water.

1. INTRODUCTION

Nuclear reactor RB at the Institute of nuclear sciences 'Vinča' operates since 1958 using heavy water and natural or low-enriched (2% U-235) metal uranium, or high-enriched (80% U-235) uranium dioxide [1,2] fuel elements. The reactor is entirely designed by Yugoslav scientists as zero-power critical assembly without shielding. Uranium fuel and heavy water are bought in former USSR.

The high-enriched uranium fuel elements (HEU) are manufactured in form of cylindrical slugs (112.5 mm height and 37 mm diameter). Fuel meat (10.6 g UO_2) is dispersed in an aluminum cylindrical annular layer (99.2 mm height, ID/OD 31/35 mm), covered with 1 mm thick aluminum cladding at both sides. The 2% enriched U-235 metal uranium (LEU) fuel elements have the same geometry shape as the HEU fuel slugs. Mass of the uranium cylindrical annular layer inside the slug is roughly 385 g. Fuel irradiation is negligible because the RB reactor operates at very low power (0.01 - 50 W) and all fuel elements are considered and handled (manually) as the fresh ones.

2. FUEL STORAGE/TRANSPORT BARRELS

A cylindrical steel barrel (766 mm height, 300 mm OD, 10 mm wall width) is provided by manufacturer for transport and storage of the fresh HEU fuel elements (slugs), but, at the RB reactor, it is used also for the LEU fuel slugs. There are 100 fuel slugs in five 'layers' inside the barrel. The layers are placed one above the other in the barrel. Each layer is designed as an expanded polystyrene cylindrical (138 mm height, 280 mm diameter) supporter (carrier) containing 20 fuel slugs arranged in three radial rows (1 slug in the centre of the layer, 6 in the inner radial row and 13 in the outer radial row). Vertical cross-section of the enriched uranium fuel slug, used at the RB and RA reactors in the 'Vinča' Institute, is given in Figure 1. The horizontal and vertical cross-sections of the polystyrene layer are shown in Figure 2. Vertical cross-section of the steel barrel filled with 5 fuel layers is given in Figure 3.

Now, there are total 11 fuel barrels at the RB reactor. Usually, the fuel elements are partially placed in the reactor core and in the fuel storage. Depending of the RB reactor core composition, maximum 10 barrels of fresh HEU fuel (985 fuel slugs) or maximum 7 barrels of fresh LEU fuel (708 fuel slugs) can be loaded and arranged in the storage. Other fresh fuel elements of the RB reactor, including natural uranium, are placed nearby in two separate wooden storage cases.

3. CALCULATION

The USSR fuel manufacturer did not provide any information on criticality safety data regarding fuel barrels in normal or in an accident (e.g., flooded by water) situation during storage or transport. It is supposed that complex geometry of the fuel slug itself, fuel slug layers and their unusual material (expanded polystyrene, $-[-CH(C_6H_5)-CH_2-]_n-$) were the main obstacles to obtain, by calculation, any reliable data for criticality of these barrels in the conditions mentioned above.

These problems are partially overcome by using the well-known MCNP™ computer code [3] for calculations of criticality of the fresh fuel barrels in normal and in the accidental (fully flooded and reflected by light water) cases. It is assumed that the steel barrels, completely loaded by fuel slugs, are placed as tight as possible in an array to form a square lattice or a nonequilateral triangular lattice (Figure 4). A minimum distance of 11.5 cm between edges of the barrels is predetermined by their construction details (handles) and so the minimum lattice pitch of any barrels' array is 41.5 cm. In the accident, a thickness of 20 cm water reflector is assumed around all lateral sides and above the top of the barrels' array, that adequately models an infinite neutron reflector. At the bottom, 20 cm thick concrete is considered as more realistic approximation.

Geometry and material composition of the fuel slugs, layers and barrels are reproduced in the input data for the MCNP™ code as close as was possibly to the real ones. Only minor approximations (e.g., aluminum 'star' of the slug is homogenised with belonging fraction of air or water, some smaller construction details of the steel barrel, e.g., handles, are neglected) are approved. Density of the expanded polystyrene (0.0745 ± 0.0025 g/cm^3, p=68%) is found out as an average value of 10 randomly selected polystyrene layers. Their mass is measured in (surprisingly) broad range from 264.0 g to 369.2 g, and the average mass of one layer is determined as 304.2 ± 29.7 g, p=68%.

The main cross-section problem is unknown scattering law $S(\alpha, \beta)$ in thermal neutron energy range for hydrogen (H) connected in the expanded polystyrene. For H_2O (in the accident case) appropriate $S(\alpha, \beta)$ is used. But, the $S(\alpha, \beta)$ for polystyrene is not given in the MCNP™ code's thermal neutron cross-section library nor in any other well-known available library of nuclear data (ENDF/B-IV, -VI, JEF-2.2, JENDL-3.1). It is not replaced in the calculations, as it is recommended [4], with scattering law for H connected in some similar material (e.g., polyethylene or benzene). It is because a structure of connection of H in molecules of the polystyrene and these materials is different. Instead, after carefully examinations of the influence of replacing the $S(\alpha, \beta)$ with the simple free gas model for the polystyrene, the last one, as the conservative approach, is used. These analyses were carried out for all cases of the calculations. It was shown that difference in the calculated multiplication factor k_{eff} introduced by assumption of the free gas model for the polystyrene instead the unknown $S(\alpha, \beta)$ law is always less than 7%, even in the case where the whole expanded polystyrene is replaced by light water, while when it is replaced with polyethylene - the difference is less than 5%. These differences are considered negligible because the calculated values of the k_{eff} are far away from criticality (i.e., $\ll 1$).

4. RESULTS

Calculations of criticality safety of the RB reactor transport/storage fuel barrels are carried out by the MCNP™ computer code with assumption that maximum possible number of the barrels is filled with fresh HEU or LEU fuel slugs. Square lattice or nonequilateral triangular lattice of the barrels are assumed. The majority of the calculations is carried out in 150 active cycles (after initial 15 ones) with 1000 neutron histories per cycle. It was sufficient to meet a required criteria that the relative uncertainty of the k_{eff} calculation ($\sigma_{k_{eff}}/k_{eff}$) should be less than 1%. The initial point neutron source was selected in every fuel layer of each slug in all barrels. Continuous-energy neutron cross-sections data for materials are primary generated from the Lawrence Livermore National Laboratory's ENDL file [5], distributed as a part of the MCNP™ libraries. Results of the k_{eff} calculations are given in Table I. Further criticality studies will include influence of different neutron data libraries and other types of fresh fuel storage at both research reactors in the 'Vinča' Institute.

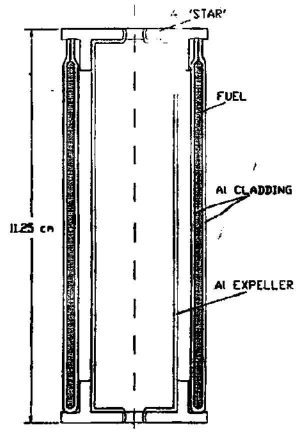

Figure 1 Vertical cross-section of the HEU/LEU fuel slug

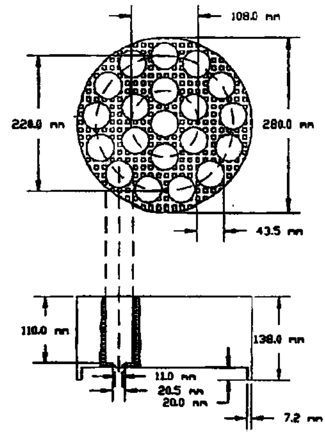

Figure 2 Cross section of the polystyrene layer for HEU or LEU fuel slugs

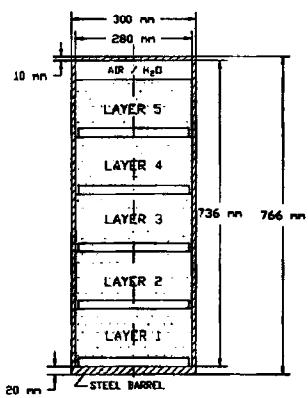

Figure 3 Vertical cross-section of the storage/transport barrel with 5 layers of HEU/LEU fuel slugs

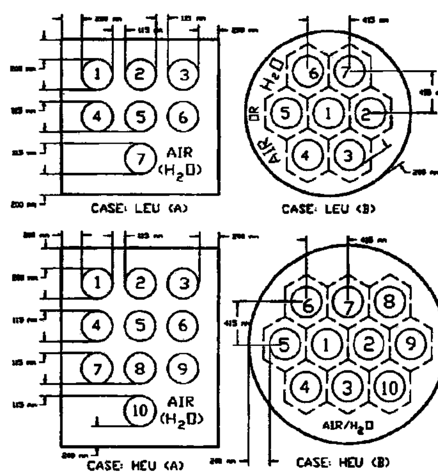

Figure 4 Arrays of fuel barrels in the RB reactor storage (horizontal cross-sections)

5. CONCLUSION

Study on criticality safety of the storage/transport barrels for the fresh enriched uranium fuel at the RB reactor is carried out by using the MCNP™ computer code. The calculations, done in the conservative way, have shown that observed arrays of tightly closed fuel barrels, each entirely loaded with 100 slugs of the fresh enriched uranium fuel elements, are far away from criticality, even in the cases when they are unexpectedly and entirely flooded by light water.

Table I. Calculated values for k_{eff} [10^{-5}] for fresh fuel storage/transport barrels used at the RB reactor

Case	HEU	LEU
Fuel slug alone in air	170 ± 1[a]	1999 ± 10
Layer with 20 fuel slugs, air	308 ± 1	3379 ± 15
Layer with 20 fuel slugs, flooded by H_2O	1317 ± 21	4156 ± 37
Fuel barrel (100 fuel slugs, air)	501 ± 4	4487 ± 16
Fuel barrel (100 fuel slugs, flooded by H_2O)	17698 ± 115	18454 ± 106
Fuel barrel (100 fuel slugs, air) surrounded by 20 cm H_2O	14796 ± 95	16441 ± 74
Fuel barrel (100 fuel slugs, flooded and surrounded by H_2O)	34825 ± 127	32625 ± 122
Array of 7 fuel barrels in air (square lattice)	nc[b]	6270 ± 27
Array of 7 fuel barrels in air (triangular lattice)	nc	6312 ± 26
Array of 10 fuel barrels in air (square lattice)	2223 ± 26	ipc[c]
Array of 10 fuel barrels in air (triangular lattice)	2295 ± 26	ipc
Array of 7 fuel barrels flooded by H_2O (square lattice)	nc	34146 ± 145
Array of 7 fuel barrels flooded by H_2O (triangular lattice)	nc	33766 ± 126
Array of 10 fuel barrels flooded by H_2O (square lattice)	36945 ± 141	ipc
Array of 10 fuel barrels flooded by H_2O (triangular lattice)	36563 ± 145	ipc

Notes: a. Statistical uncertainty given at the 68% confidence level, i.e., at the standard deviation (1σ);
b. nc = not calculated;
c. ipc = impossible case for the transport/storage fuel barrels at the RB reactor.

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