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Reactivity cost for different top reflector materials in miniature neutron source reactors

M. Albarhoum*

Department of Nuclear Engineering, Atomic Energy Commission, P. O. Box, 6091, Damascus, Syria

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ABSTRACT

The cost of reactivity of the top reflector in MNSRs was investigated based on the market prices. A 3-D model for the reactor components was used. Three reflectors were compared, namely: graphite, beryllium and heavy water. The average cost of reactivity revealed to be minimum for graphite (maximum value of 3.92 US$/mk), while the second cheapest reflector resulted to be beryllium up to the price of 650 US$/kg. Heavy water can compete with beryllium only for higher prices of beryllium. The best reflector for MNSRs results to be graphite from the economy and safety points of view.

1. Introduction

Miniature Neutron Source Reactors (MNSRs) are research reactors still utilizing beryllium as reflector for all lateral, bottom and top sides (See Fig. 1). These reactors are reflected at their 1st start-up only from the lateral and bottom sides. From the top side there is only a so-called Shim Tray (ST), an empty tray for hosting the top reflector pieces when required (Guo et al., 1993).

After 1–2 years of operation from their 1st start-up MNSRs require the top side reflector to be added partially; i.e. piece by piece. As long as the reactor runs, and consequently the reactivity decreases, the other pieces of top reflector are added. The reactivity in MNSRs decreases with time for various reasons the first of which is the fuel burn-up.

Since the required Initial Excess Reactivity (IER) in these reactors is about 4 mk (Guo et al., 1993), there exist two mechanisms for reactivity decrease: the fuel consumption which every day makes the IER available at start-up smaller than the IER which was available at start-up the day before, and the daily decrease of the available reactivity during reactor operation which is due to the coolant heat-up and fission products poisoning.

A generic MNSR has a rate of reactivity decrease of about 0.1 mk/°C in average which is due to coolant heat-up, while the fission products poisoning depends on the rated power of the reactor, and generally is co-shared by xenon and samarium effects in addition to the other minor fission products effects.

Although from the neutronic point-of-view beryllium is the best reflector (See Table 1) it is required to be highly pure to be used in nuclear reactors which increases a lot its cost.

The cost of beryllium affects the operation cost of the reactor. Even if the cost of beryllium may compare with the double of that of heavy water, the versatility of heavy water may induce to prefer the latter as reflector on beryllium.

Unlike heavy water graphite (nuclear grade) usability is not versatile as well. It is a solid material like beryllium, but it is much cheaper than beryllium. The upper reflector is a very important component of the reactor (Albarhoum, 2009). The reactor would not be able to work without the addition of the top reflector, which begins, as afore-mentioned, after about 1–2 years from the 1st start-up of the reactor, and ends up only at the end of the fuel cycle life which is expected to be about 10 years at rated power. The top reflector is therefore responsible for more than 8 years of the fuel life which constitute more than 80% of its life. The cost of the reactivity deriving from the addition of the top reflector in MNSRs will be investigated in this paper and possibly optimized so that the operation cost of the reactor can be reduced to the minimum.

2. Evaluation of the reactivity equivalent of the various reflectors

The worth (or equivalent reactivity) of the various reflectors is evaluated using the BMAC package (Albarhoum, 2008). This system

* Tel.: +963 11 2132580; fax: +963 11 6112289.
E-mail address: pscientific@aec.org.sy.

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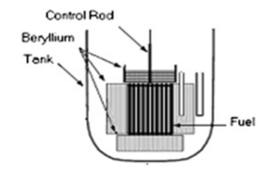

Fig. 1. A schematic view of the core fuel rods.

uses a cell code namely: WIMSD4 (Askew et al., 1966), and a core calculation code, namely: CITATION (Fowler et al., 1971). The concatenation of these two codes together with other interface programs, which BMAC incorporates, allows to calculate the IER resulting from whatever configuration of the reactor including the addition of the top beryllium reflector in the ST.

The capability of the system to treat the various reflector materials depend on the availability of such materials cross sections in the library of WIMSD4, which is built for 69 neutron groups.

Although 69 neutron groups are available in WIMSD4 library, the 3-D calculations with CITATION are made with only 4 neutron groups. This is because it is too much costly to perform calculations with this huge number of neutron groups compared with the derived advantages on the accuracy of the calculated IER, which are modest in value.

The 4 neutron groups upper energy limits are:10 MeV, 0.821 MeV, 5530 eV, and 0.625 eV, respectively. Table 2 reports the principal group constants of the top beryllium (when graphite is used) for a typical MNSR, where the meaning of the symbols are:

XS = Macroscopic Cross Section

Coeff. = Coefficient

Scattering XS Gn = The macroscopic cross section of scattering from of the neutronic group *n* to the other groups (1,2, 3, and 4).

3. Results and discussion

The upper reflector is filled in the ST using different approaches; the ST can be filled either with blocks of reflector having the same height of the ST with different external and internal radii (Radial Approach), or with circular plates having the same internal and external radii of the ST, but with different thicknesses (Axial Approach).

Both approaches can be further detailed as follows:

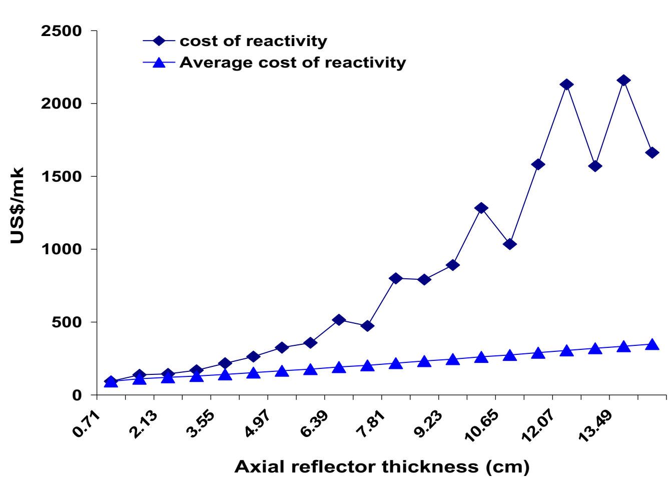

Fig. 2. A comparison between the cost of reactivity/sector and the average cost of reactivity.

Table 1
Slow-down properties of some universal reflectors (Albarhoum, 2007).

Reflector	Diff. coeff.(cm) Diff. Length(cm)	$\xi\sum_s/\sum_a$	[a]	$\xi\sum_s$
Beryllium	0.477	21	159	0.176
Heavy Water	0.8	171	12000	0.370
Graphite	1.043	53	170	0.064
Light Water	0.16	2.85	72	1.53

[a] ξ is the average logarithmic energy decrement, $\sum_s$ is the macroscopic scattering cross section(cm^{-1}), and $\sum_a$ is the macroscopic absorption cross section (cm^{-1}).

3.1. The radial dimension

The radial dimension can be subdivided following various modes such as:

3.1.1. The so-called in-out radial approach

In this approach the reflector is added in the form of cylindrical sectors having the same height of the ST (14.2 cm), but with increasing different internal and external radii beginning from the center of the ST to the periphery (from 0.915 cm to 12.15 cm). This is performed in two ways: the so-called In-Out Radial Cumulative (IORC) mode, in which sectors are added cumulatively, and the In-Out Radial Singular mode (IORS), in which each sector is added alone, and the resulting reactivity worth is calculated.

3.1.2. The so-called out-in radial approach

In this approach the reflector is added in the form of cylindrical sectors of equal height (still equal to 14.2 cm), but with decreasing different internal and external radii beginning from the periphery of the ST towards its center. This mode is performed in two ways as well: the so-called Out-In Radial Cumulative (OIRC) mode, in which sectors are added cumulatively, and the Out-In Radial Singular (OIRS) mode, in which each sector is added alone. The OIRS and the IORS modes give out substantially the same results, while the OIRC mode give different results as shown in the following tables. The sectors external and internal radii are shown in Table 3 in the 2nd and 3^{d} columns.

3.2. The axial dimension

The axial dimension can be subdivided following various modes as well:

3.2.1. The axial singular mode (ASM)

In which sectors are added axially but singularly.

3.2.2. The axial cumulative mode (ACM)

In which sectors are added axially but cumulatively. The singular unique thickness for the axial sectors, and the cumulative thickness for the cumulatively added sectors both are shown in Table 3 in the 3d and 4th columns. The various reflectors were treated in detail from the physical point of view, but not from the economical nor safety points of view (Albarhoum, 2010; Albarhoum, 2011).

The prices of the various reflectors can be seen in Table 4. Prices are only indicative of this period (2011) because of their continuous variation. For beryllium prices various reports were considered (Cunningham, 2004), the same was done for heavy water (Carey Sublette, 1999), and for graphite (Michael Berger Nanowerk LLC, 2008).

Based on these prices the cost of the unit reactivity (mk) per sector of beryllium is reported in Table 5 (Columns 2 and 5), and the average cost of unit reactivity for the whole reflector is reported in columns 3 and 6.