Progress in Nuclear Energy 81 (2015) 1–5

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Investigation of BeO as a reflector for the low power research reactor

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ARTICLE INFO

Article history:
Received 28 August 2014
Received in revised form
17 November 2014
Accepted 1 December 2014
Available online

Keywords:
Beryllium
Beryllium oxide
GETERA and MCNP4C codes
MNSR reactor
Burnup

ABSTRACT

Calculations of the fuel burnup, core excess reactivity, and the reactivity worths of the top beryllium shim plates for two reflector types (beryllium and beryllium oxide (BeO)) in the Miniature Neutron Source Reactor (MNSR) have been presented in this paper using the GETERA and MCNP4C codes. The results showed that the reactor infinity multiplication factors were 1.7030 and 1.6824, the core unadjusted excess reactivities were 31.9 and 5.0 mk, and the reactivity worths of the top beryllium shim plates were 22 and 19 mk for the BeO and Be reflectors respectively. Finally, using the beryllium oxide instead of the existing Be reflector in the MNSR reactor increased the core excess reactivity and reactor operation time.

1. Introduction

The MNSR was manufactured by the Chinese Institute of Atomic Energy (CIAE, 1993). It is a low power tank-in pool type research reactor. The reactor employs highly enriched uranium as fuel, light water as moderator and coolant, and metal beryllium as reflector. Heat generated in the core is removed through natural convection. There are 10 irradiation sites in the reactor. Five of them are inside the annulus beryllium reflector and the other five surround the annulus reflector externally. The maximum thermal neuton fluxes in the inner and the outer sites are 1.0×10^{12} and 5.0×10^{11} n/cm^2 s, respectively. The nominal thermal power of the reactor at this neutron flux level is 30 kW. The cold excess reactivity was adjusted to less than 4 mk using the reactivity regulators.

The excess reactivity of the MNSR decreases with the reactor operating time due to the fuel burnup and accumulation of fission products in the reactor core. During the processes of irradiation and fuel burnup, fissile nuclides are consumed by fission and several hundred fission products are formed, some directly and other by radioactive decay (Lamarsh, 1983). There are 46 beryllium shim plates giving a total thickness of 10.95 cm in the MNSR. These beryllium shim are used as a top beryllium reflector to compensate the reactivity losses caused by fuel burnup and poisoning build up of xenon and samarium during the reactor operation time. Since the reactor safety operation limits do not allow the excess reactivity available in the core to be more than 4mk, calculation of the shim reactivity worth is an important matter in the MNSR reactor. Beryllium is a good moderator material from the neutronic point of view. Beryllium oxide as well can be used as a reflector in the low power research reactor. Its density is higher than the density of the Be reflector (Ding and Kloosterman, 2013). Table 1 shows the physical characteristics of different types of reflectors usually used in the low power research reactors (U.S. Atomic Energy Commission, 1960).

Among the three common reflectors (water, beryllium and graphite), beryllium is consider the best reflector since it increases the thermal and epithermal fluxes in the peripheral assemblies. Beryllium can be used in the form of beryllium oxide. The BeO has a melting temperature of about 2800 K. One advantage of using the BeO rather than the pure Be is the increase in melting temperature of the reflector material. The melting temperature of Be is much less than the melting temperature of BeO at 1560 K. Using the BeO will give a higher temperature margin. However, Be is a more effective neutron moderator than BeO, since the oxygen is not an efficient neutron moderator. The beryllium density is a good indicator of the relative effectiveness of the two moderator materials. The density of beryllium in BeO is about 3.08 g/cm^3 while the density of the pure Be is 1.85 g/cm^3 (Nader, 2011).

Beryllium oxide possesses attractive nuclear and high-temperature properties which justify its consideration and use in a number of reactor systems (Manly, 1964). Its early consideration for the moderator and fuel matrix material in the proposed Daniels

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http://dx.doi.org/10.1016/j.pnucene.2014.12.001
0149-1970/

Table 1
Physical characteristics of different types of reflectors at 20 °C.

Parameters	H_2O	D_2O	Graphite	BeO	Be
Density (ρ), g cm^{-3}	1.00	1.10	1.60	3.025	1.85
Scattering cross section (Σ_s), cm^{-1}	1.47	0.35	0.38	0.72	0.76
Thermal absorption cross section (Σ_a), cm^{-1}	0.0220	0.000036	0.00036	0.00066	0.0011
Diffusion coefficient (D), cm	0.16	0.85	0.86	0.59	0.54

Reactor in 1945 is of historical significance. Through the intervening years, information has been developed on the basic and applied properties of BeO leading to its use in reactor systems. Currently, BeO is being used, or planned for use, in the General Atomic Experimental Beryllium Oxide Reactor (EBOR), the Aerojet General Gas-Cooled Reactor (GCRE), the Atomic International SNAP reactors, and the Lawrence Radiation Laboratory Pluto ramjet reactor. Beryllium oxide is also under consideration for nuclear power plants for satellites and other space vehicles. Intrinsically, BeO is an excellent moderator and reflector material. Its physical and mechanical properties are in most cases sufficient to meet the basic material and engineering requirements for core components. Some of its more outstanding attributes are: high thermal conductivity, good shock resistance, high refractoriness, compatibility with fuels, and inertness with gas coolants of interest up to 1600 °C.

2. Methodology

The fuel group constants and infinite multiplication factor of the reactor were calculated using the GETERA code for the tow reflector types (beryllium and beryllium oxide). The core excess reactivity and the reactivity worths of top shim plates were calculated using the MCNP4C code.

The MNSR nominal power, as mentioned earlier, is 30 kW and the total amount of uranium originally located in the reactor core is 1120.4 g (CIAE, 1993). The power density required in the burnup card calculation using the GETERA code is 3.14 MW/m^3 (Khattab and Dawahra, 2011). The MNSR is operated for approximately 2 h a day for five days a week. The reactor core expected life as mentioned earlier, is 10 years. This time is equivalent to 200 operating days. Therefore, to conduct the burnup calculations in the MNSR, the GETERA input file was prepared and run for 200 days with 20 days time step. The fuel group constants and the MNSR infinite multiplication factor were calculated versus the burnup time. The group constants for the reactor components were generated with four energy groups (usually four energy groups are enough for research reactor calculation). The boundaries of the energy groups were as follows: from 10 to 0.821 MeV for the first group, from 0.821 MeV to 5.53 keV for the second group, from 5.53 keV to 0.625 eV for the third group, and finally from 0.625 eV to 0 eV for the fourth group. Group 1 represents the fast group, group 2 represents the 1/E or the slowing down group, group 3 represents the resonance absorption group, and finally group 4 represents the thermal group. These group constants are required as input for the 3-D reactor calculation using one of the diffusion codes such as CITATION code. Fig. 1 shows the MNSR unit cell which consisted from 6 zones. The last zone represented the Be or BeO reflectors. The radius of each zone was presented in Table 2.

The shim reactivity worth for each of the tow reflector types was calculated by subtracting the reactor reactivity with a shim from the reactor reactivity without a shim. The thickness of these plates was varied from 0.14 to 10.95 cm to cover the thickness of all the shim plates. To calculate the worth of the top beryllium shim plate, the multiplication factor and the reactivity of the reactor were calculated first for the base case (before the addition of the top beryllium plate to the reactor tray). Then, a top beryllium shim plate with a known thickness was added to the reactor shim tray and calculation of the reactor multiplication factor and the reactivity were conducted. The reactivity worth of this thickness was calculated by subtracting the reactivity of the second case from the reactivity of the base case. Changing the thickness of the beryllium shims from 0.14 to 10.95 cm and calculating the reactivity of the reactor for each thickness, we were able to calculate the reactivity worth of the top beryllium shim plate ranging from the minimum to the maximum thickness.

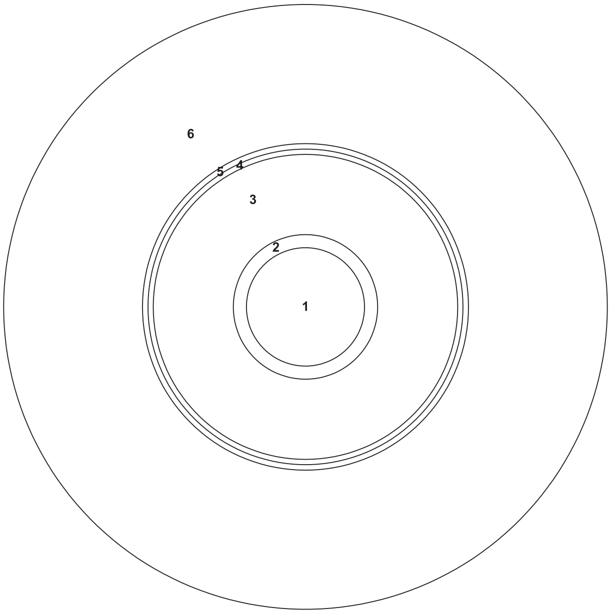

Fig. 1. The MNSR unit cell modeled by the GETERA code, where: 1 – fuel, 2 – clad, 3 – water,4 – tie rods, 5 – dummy rods, 6 – reflector.

The MCNP4C Monte Carlo code is a powerful and versatile tool for particle transport calculations. It can be used for transport calculations of neutrons, photons and electrons. Transport calculations of neutrons in the reactor are required for reactor physicists to design the reactor core. The MCNP4C code can be used to calculate the effective multiplication factor, reaction rate, and flux and power distributions. It can be used to design any complex core geometry without any approximation. The MCNP4C code is provided with seven standard tallies (Briesmeister, 2000). All tallies are normalized to one starting particle. The effective multiplication factor is one of the most important properties of the reactor. The KCODE card in the MCNP4C code is usually used for criticality calculation in the reactor. Since the MCNP4C results are normalized to one source neutron, the result has to be properly scaled in order to get the absolute flux, reaction rate, fission density, etc.

A Monte Carlo simulation of the MNSR reactor was carried out previously using the MCNP4C code and continuous energy cross

Table 2
The unit cell dimension.

Zone	Diameter, cm
1	0.2150
2	0.2750
3	0.6182
4	0.6187
5	0.6197
6	1.1500