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Reactivity Effects due to Beryllium Poisoning of BR2

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This paper illustrates the impact of the poisoning of the beryllium reflector on reactivity variations of the Belgian MTR BR2 in SCK•CEN. Detailed calculations by MCNP-4C of reactivity effects caused by strong neutron absorbers ^{3}He and ^{6}Li during reactor operation history are presented. The importance of beryllium poisoning for the accuracy of reactivity predictions is discussed.

KEYWORDS: beryllium poisoning, BR2 reactor

1. Introduction

BR2 is a heterogeneous high thermal flux engineering test reactor, started routine operation in 1963. A specific feature is the reactor core of HEU positioned in and reflected by a beryllium matrix - a big number of prismatic hexagonal prisms which are skew and form hyperboloidical arrangement around the central 200 mm channel H1 containing mainly beryllium plugs.

At the end of 1978, the BR2 reactor was shutdown to unload the first beryllium matrix and to load a new second one. Following the safety evaluation of the first beryllium matrix surveillance program, the second replacement by the 3rd matrix was executed at 1997 [1]. The BR2 reactor has about 5 operating cycles per year, each 20÷21 days long with big shut down periods between the cycles, causing reactivity losses due to poisoning of the beryllium reflector by ^{3}He.

In this paper we discuss reactivity effects due to the poisoning of the reactor BR2 by ^{6}Li and ^{3}He following the full irradiation history of the 3rd Be-matrix and taking into account the different reactor core loads between April 1997 and December 2003.

2. MCNP whole core model

A detailed full scale 3-Dimensional heterogeneous geometry model of the whole reactor core was developed using MCNP-4C&SCALE4.4 [2]. The whole inventory of items affecting the reactivity during BR2 operation has been taken into account - exact geometry description of the various inclined channels, filled with fuel elements and experimental devices; detailed axial and radial fuel burn-up distribution, following the fuel burn-up history in different fuel elements (the number of the spatial zones with different fuel burn-up is about 2000); detailed axial and radial poisoning, following the full irradiation history of the 3rd beryllium matrix (using 3 typical core loads for the whole history); fission product poisoning - the total amount of the considered fission products in the fuel composition is about 100; the saturation of Sm-149 after reactor shutdown is taken into account.

3. Modeling of Be poisoning

The poisoning effect of beryllium appears after irradiation of Be matrix with fast neutrons due to (n,α) – reaction on ^{9}Be and following transmutations into nuclides of ^{6}Li, ^{3}T and ^{3}He according to the reactions:

$$n+{}^{9}Be\rightarrow{}^{6}He+{}^{4}He;\quad {}^{6}He\rightarrow{}^{6}Li+e^{-}+\nu_{e^{-}}\qquad (T_{1/2}^{{}^{6}He}=0.808s) \tag{1}$$

$$n+{}^{6}Li\rightarrow{}^{4}He+{}^{3}T;\quad {}^{3}T\rightarrow{}^{3}He+e^{-}+\nu_{e^{-}}\qquad (T_{1/2}^{{}^{3}T}=12.33years) \tag{2}$$

$$n+{}^{3}He\rightarrow{}^{3}T+p \tag{3}$$

The lithium-6 and helium-3 isotopes have very high absorption cross section of thermal neutrons: $\sigma_a^{{}^{6}Li}=942b$ and $\sigma_a^{{}^{3}He}=5330b$ [3], [4].

The production of ^{3}T, ^{6}Li and ^{3}He depends on the neutron spectrum in the reactor core. Accurate calculations of the axial and radial distribution of the transmutation products of the poisoning are performed in different positions of the beryllium matrix in BR2. The full irradiation history of the 3rd beryllium matrix is considered taking into account the exact duration of shutdown periods and operation cycles with 44 different reactor core loads between 1997 and December 2003.

The reaction rates (1), (2) and (3) are calculated by MCNP-4C in each position of the beryllium matrix in BR2, taking into account their axial distributions in the central channel H1, containing beryllium plugs and in the channels around H1 and filled with fuel elements. The calculated reaction rates are introduced into a system differential equations for the evolution of the concentrations of ^{6}Li, ^{3}He and ^{3}T with time [5], [6].

4. Antireactivity effects due to neutron absorption by ^{6}Li

The production of strong neutron absorbers starts with the reaction (1). The formation of lithium depends on the spectrum of fast neutrons in the beryllium matrix. However the equilibrium level of ^{6}Li is determined not only by formation but also by burn up according to the first reaction in (2). During the reactor operation history, ^{6}Li concentration reaches saturation. The duration of the irradiation time for lithium saturation in the different beryllium assemblies depends on their position in the core. It is seen from Fig.1a that in the central channel H1, containing mainly beryllium plugs, the concentration of ^{6}Li reaches saturation practically immediately after the first cycle in April 1997. For other channels, containing fuel elements, Fig.1c, the concentration of ^{6}Li increases due to its production from fast neutrons during relatively long time period and after T ≈ 500 days becomes saturated. The two large maximums on Fig. 1a illustrate the effect of location of a fuel element in the central channel H1 (cycles 03/2002A and 02/2003A). Due to the fast neutron flux the production of lithium sharply increases after BOC and consequently the antireactivity effects are large, up to ~ 0.5$ (see Fig. 1b). There were 3 operation cycles without fuel element in H1-Central between 03/2002A (first peak) and 02/2003A (second peak) and the production of lithium-6 in this period decreases due to the large thermal flux in central beryllium plugs.

The location of a fuel element in the central channel H1 influences also on the lithium-6 production in the neighboring regions. It is seen from Fig.1c that after T=1800 days the concentration of lithium in the channels from the central crown slightly increases and the

antiteactivity effects increase as well (see Fig.1d).

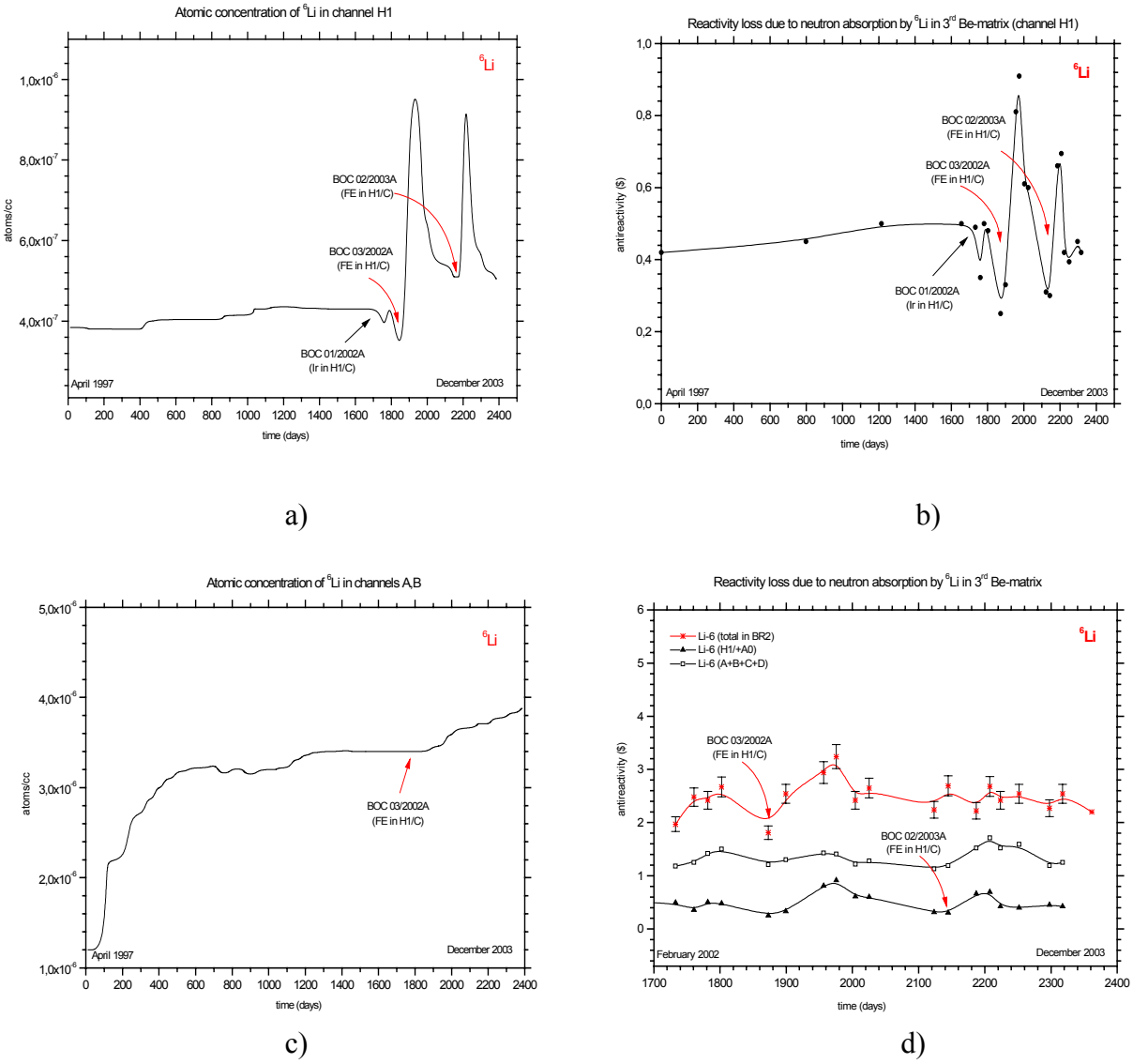


Fig.1. Antireactivity effects due to neutron absorption by ^{6}Li in 3rd Be-matrix:
a) time evolution of ^{6}Li concentration in the hot plane of the central beryllium channel H1;
b) reactivity loss due to neutron absorption by ^{6}Li in the central channel H1;
c) time evolution of ^{6}Li concentration in the hot plane of the channels A,B around the central channel H1 and filled with fuel elements;
d) reactivity loss due to neutron absorption by ^{6}Li in H1, in fuel elements located in channels A,B,C,D and total in BR2.

The calculation results of the reactivity effects due to neutron absorption by ^{6}Li in the whole beryllium matrix are summarized in Table 1. The calculations are performed for the

measured critical heights at BOC and EOC of 10 operation cycles during 2002 and 2003. The contribution from different parts of Be-matrix into the total antireactivity effect are calculated and demonstrated on Fig.1b, Fig.1d.

Table 1. Antireactivity effects due to neutron absorption by ^{6}Li during different BR2 operation cycles. Lithium-6 production rate during the cycle.

Operation BR2 cycle "i"	$\rho^{BOC_i}_{antireactivity}$ [$]	$\rho^{EOC_i}_{antireactivity}$ [$]	ΔT_{cycle} [days]	$\Delta\rho_i$ (^{6}Li) $\rho^{EOC_i - BOC_i}_{antireactivity}$ [$]	^{6}Li Build-up rate: $\Delta\rho_i(^6Li)/\Delta T_{cycle}$ [$/day]
01/2002A.2	1.97	2.48	27	0.51	0.019
02/2002A.3	2.42	2.67	20	0.25	0.012
03/2002A.4	1.81	2.54	26	0.73	0.028
04/2002A.7	2.94	3.24	18	0.30	0.017
05/2002A.2	2.42	2.65	19	0.23	0.012
01/2003A.4	2.24	2.69	20	0.45	0.022
02/2003A.6	2.22	2.68	20	0.46	0.023
03/2003A.5	2.42	2.54	26	0.12	0.005
04/2003A.3	2.27	2.54	19	0.27	0.014
05/2003A.1	2.20	2.50	20	0.30	0.015

5. Antireactivity effects due to neutron absorption by ^{3}He

5.1 Reactivity loss in shutdown and at start-up of reactor operation

During the reactor operation ^{3}He is burning out according to the reaction (3). The tritium concentration $N_{^3T} >> N_{^6Li} >> N_{^3He}$ and $N_{^3T}$ increases linearly with the energy produced [MW.days]. After reactor shutdown, the concentrations of ^{3}He increases due to the decay of ^{3}T, thereby causing reactivity losses of the reactor core. The following approximate formula for the reactivity loss due to build-up of ^{3}He in shutdown has been obtained in [2]

$$\frac{\Delta\rho(^3He)}{\Delta t} = \frac{\rho(t'') - \rho(t')}{t''-t'} \approx -\frac{1}{<\nu_f>(t''-t')F}\int_{t'}^{t''} dA^{^3He}(t)dt \qquad (4)$$

where: $A = A^{^3He}(t,r,E) = \int_E\int_r N^{^3He}(t,r) * \Phi(t,r,E)\sigma_a^{^3He}(E)dEdr$ is the neutron absorption by helium-3 in beryllium matrix per 1 source neutron at time t between t' and t'' in shutdown; $F = F(t,r,E) = \int_E\int_r N^5(t,r) * \Phi(t,r,E)\sigma_f^5(E)dEdr$ is the fission events per 1 source particle and equal to ≈ 0.41 fiss./1n for BR2 (MCNP calculations); $<\nu_f>\approx 2.43$. For BR2 one dollar (1$) is equal to a reactivity of β=0.0072, including the fraction of delayed and photoneutrons. The fraction of photoneutrons in the reactor core is $\beta_{photoneutrons}$(core)≈0.00018 and in the beryllium reflector $\beta_{photoneutrons}$(Be)≈0.00045, thus the total photoneutron source is

$\beta_{photoneutrons}(total) \approx 0.00063$ according to [9]. Then we obtain the final approximate relation between reactivity loss and neutron absorption by helium-3:

$$\frac{\Delta\rho(^3He)}{\Delta t} \approx -\frac{const}{\Delta t} \approx -\frac{139{,}4}{\Delta t}\left[A^{^3He}(t'') - A^{^3He}(t')\right]\$ / day \qquad (5)$$

MCNP-4C calculations of reaction rates (1)÷(3) include the contributions from prompt and delayed neutrons, but not from photoneutrons. It is known that deuterium and beryllium have threshold (γ,n) – reactions with energies, respectively 2.21 and 1.62 MeV [9]. The type of neutrons emitted from these reactions is monoenergetic ($E_{photoneutrons} \sim 110$ keV) and does not have the fission energy spectrum. The process involved in this artificial source is that following a shutdown of the reactor after any appreciable power operation a large gamma flux exists in and around reactor core. In a reactor with either beryllium or heavy water reflector a large photoneutron source exists for a considerable time after shutdown. The (γ,n) – reactions are not included into MCNP-4C. Therefore, an external monoenergetic neutron source with energy E=110 keV has been introduced into all beryllium pieces of the reflector for simulation calculations by MCNP. The reactivity loss due to absorbed photoneutrons has been estimated using formula (4) and included into the final results of reactivity losses.

5.2 Antireactivity effects during reactor operation

The build-up of ^{3}He in shutdown and its burning during operation cycle in fuel elements located in channels A,B is illustrated on Fig.2a. It is seen that the slope of the helium-3 build-up in shutdown becomes sharper with time, thereby being criteria for the reactivity loss during the irradiation history.

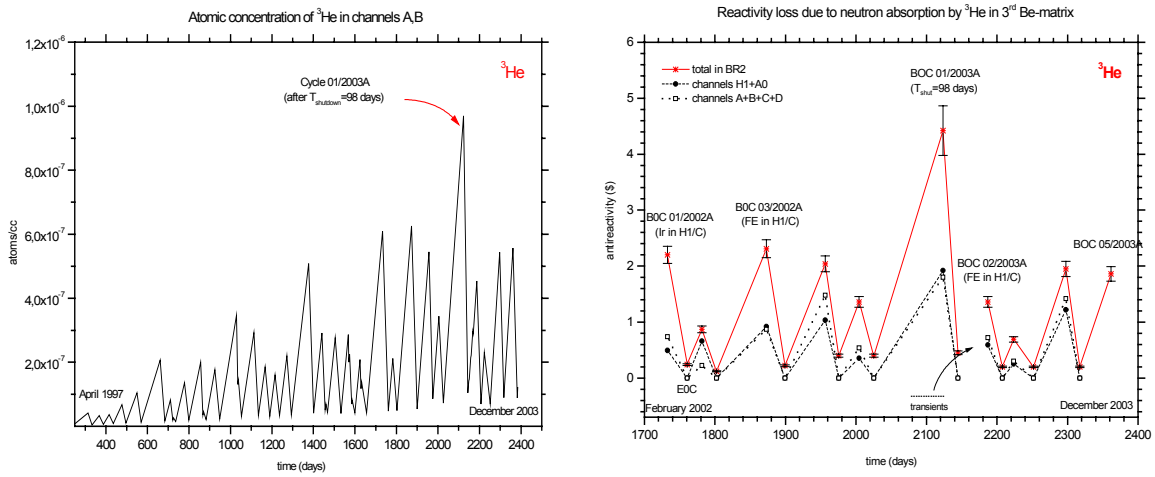
The calculation results of the reactivity effects due to neutron absorption by ^{3}He in the whole beryllium matrix are summarized in Table 2. The calculations are performed for BOC and EOC of 10 operation cycles during 2002 and 2003. The contribution from different parts of Be-matrix into the total antireactivity effect are calculated also and demonstrated on Fig.2b. The maximum ^{3}He reactivity loss (4.0±0.4)$ is obtained for BOC 01/2003A after the longest shutdown T=98 days.

In order to estimate the rate of reactivity loss due to helium-3 build-up in shutdown criticality calculations are performed using MCNP and evaluating helium-3 concentrations with time. The comparison between MCNP calculations and experiment is given on Fig.3a. The average bias of the ratio MCNP/EXP≈0.85. The black solid curve is obtained using the approximate formula (4), the black points are calculated by MCNP for the different BR2 Reference core loads [7], [8].

The total antireactivity effect in 3rd beryllium matrix due to neutron absorption both by lithium-6 and helium-3 is demonstrated on Fig. 3b. The statistical error of Monte Carlo calculations of the reactivity values in all tables and figures are within 5÷10%.

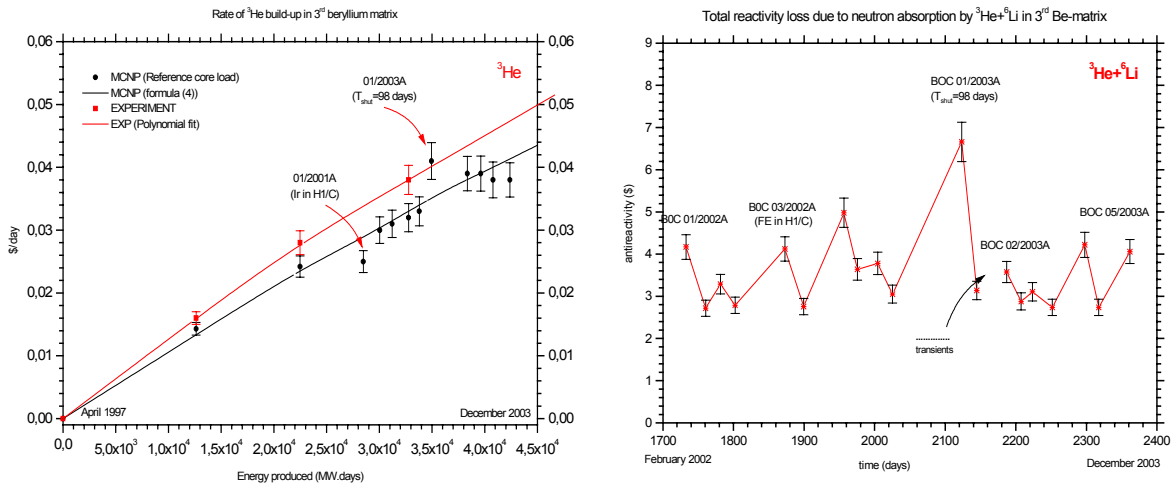
Table 2. Antireactivity effects due to neutron absorption by ^{3}He during different BR2 operation cycles. Helium-3 build-up rate during shutdown.

Operation BR2 cycle "i"	$\rho^{BOC_i}_{antireactivity}$ [$]	$\rho^{EOC_i}_{antireactivity}$ [$]	ΔT_{shut} [days]	$\Delta\rho_i$ (^{3}He) $\rho^{BOC_i - EOC_{i-1}}_{antireactivity}$ [$]	^{3}He Build-up rate: $\Delta\rho_i(^3He)/\Delta T_{shut}$ [$/day]
01/2002A.2	2.20	0.24	77	1.92	0.025
02/2002A.3	0.87	0.12	21	0.63	0.030
03/2002A.4	2.31	0.22	70.5	2.19	0.031
04/2002A.7	2.04	0.40	57	1.82	0.032
05/2002A.2	1.36	0.40	29	0.96	0.033
01/2003A.4	4.42	0.45	98	4.00	0.041
02/2003A.6	1.36	0.20	23.3	0.91	0.039
03/2003A.5	0.84	0.20	16.3	0.64	0.039
04/2003A.3	1.95	0.20	46	1.75	0.038
05/2003A.1	1.86	–	44	1.66	0.038



a) b)

Figure 2. Antireactivity effects due to neutron absorption by ^{3}He in 3rd Be-matrix: a) time evolution of the concentration of ^{3}He in the hot plane of the channels around the central beryllium channel H1 and filled with fuel elements; b) reactivity loss due to neutron absorption by ^{3}He in H1, in fuel elements located in channels A,B,C,D and total in BR2.



a) b)

Fig. 3. Antireactivity effects due to neutron absorption by ^{3}He and ^{6}Li in 3rd Be-matrix:
a) reactivity loss rate ($/day) due to helium-3 build-up in shutdown;
b) total antireactivity effect due to helium-3 and lithium-6 poisoning ($) in 2002÷2003.

6. Conclusion

The conducted study has highlighted the importance of the beryllium poisoning for reactivity predictions in BR2. The forecast for reactivity variations due to the accurate modeling of lithium-6 poisoning is about ±(0.5±0.05)$ in case of strong perturbation of the flux in the central beryllium channel (location of a fuel element or strong absorber Ir). The possible biases associated with accuracy of the modelized helium-3 poisoning after very long shutdown are within ±(0.6±0.06)$. The maximum helium-3 antireactivity effect of about (4.0±0.4)$ has been calculated after the longest shutdown T~100 days in the whole irradiation history of the 3rd beryllium matrix.

7. Future work

The study is ongoing. The detailed distribution of the poisoning in all positions of the beryllium matrix will be calculated for every operation cycle taking into account the full previous irradiation history with different reactor core loads. The reaction rates on beryllium-9, lithium-6 and helium-3 should be calculated for every reactor core load at BOC and EOC. More detailed calculations by MCNP5 of the contribution of photoneutrons into the beryllium poisoning are needed.

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