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Comparing the Neutronic Behavior of LR-0 Reactor During the First 20 Shakes from Startup When Controlled by Boron vs. Silver Control Rods

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NUCLEAR reactor safety is a supreme priority in reactor design, particularly the ability to control a reactor during power excursions. Reactor safety depends primarily on its reactor period, longer reactor period, allows better control on reactor during power excursions.Buildup of neutron flux in moderator and neutron absorption in control rods of the zero power research reactor LR-0, which is a mockup of the Russian WWER-400were investigated over the first 200 nano secondsfrom reactor startup when controlled by Boronborononly,Silversilveronly, and mixed Boron boron &Silversilvercontrol rods. The aim of this work was isto investigate the effect of the energy spectrum of neutron absorption cross section of the neutron absorbing materials, on the rate of build-up of neutron flux in a reactor, to find out if this can influence the reactor period and hence reactor safety during power excursions. Calculations were carried out using MCNP5 code. Three models of LR-0 reactor were studied. One model was controlled by Boron boron control rods only, another model were controlled by Silver silver control rods only, and a third model was controlled by equal numbers ofidentical Boron boron and Silver silver control rods.In each model, the buildup of neutron flux in moderator, and the neutron absorption in control rods were tallied. Chronological variation of neutron absorption in control rods was significantly different in the three models. However, neutron flux buildup in moderator was almost unaffected by the type of control rods.AlsoMoreover, energy spectrum of the absorbed neutrons in all models was almost the same, signifying that the energy spectrum of the absorbed neutrons in control rods is not dependent on the type of control rod material.

Keywords: Boron, Silver, Control Rods, Neutron absorption, Nanosecond

Introduction

Nuclear reactors are dangerous devices and have caused some of the major catastrophes in recent history. Reactor safety is a supreme priority in reactor design, particularly the ability to control a reactor during sudden power increases (excursions). Whatever applied safety systems, reactor safety depends primarily on its neutron kinetics, especially its reactor period. Reactor periodis defined as the time required for the neutron flux to change by a factor of e [Ricker & Kerr, 1958]. Longer reactor period, allows better control on reactor during power excursions[Jevremovic, 2009].

This work hypothesized that a neutron poison that can absorb more energetic neutrons (absorption cross section is great at high neutron energies) will absorb neutrons early before being thermalized, and hence reduce the thermal neutron flux buildup and slow down the growth of fission rate. These effects should prolong the reactor period and hence improvethe reactor safety.

This work compared the chronological progression of neutronicparameters of three identical reactors controlled by different neutron poisons, viz. Boron only (mainly thermal neutron absorber),Silversilver only (mainly epithermal neutron absorber), and mixture of Boron

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boron &Silversilver; to verify our hypothesis, specifically whether earlier neutron absorption (epithermal neutron absorption) by control rods can prolong reactor period or not.

MCNP code allows tallying different neutronic parameters over chronological tally bins, which can be as short as 1 nano second or even less. This allows monitoring how different reactor neutronicparameters progress with time from the instant of start-up, or after a transient in its core;e.g. inserting or withdrawing a control rod.

LR-0 is a research reactor built simulate at a minimized scale of WWER-400 power reactors. It is originallycontrolled by Boron boron Carbide control rods.

In a reactor;neutronsare born fast, ata most probable energy of about 0.73 MeV [Lamarsh, 1966],and then theyare thermalized to thermal energy of ~ 0.0253 eV within very short time of ~5.6 microsecond [Jevremovic, 2009].

Boron is a thermal neutron absorber, whileSilver silver is mainly epithermal neutron absorber, see(figure Figure 1).

Therefore,it is postulated that Silver silver (being more epithermal neutron absorbers) should absorb neutrons earlier than Boron boron (being thermal neutron absorber). Consequently, theaverage neutron energy should be greater and the thermal neutron fluxshould buildup slower, and hence reactor period should be longerin a reactor controlled by Silver silver control rods compared with an identical reactor controlled by Boron boron control rods.

The present work investigated this postulation by investigating how the average neutron energy and neutron flux varies with time during the first 200 nanoseconds of reactor startup when controlled by boron or Silver control rods.

MCNP Models

Geometry of the LR-0 Model [Kyncl, 2005]

The LR-0 reactor model had a square vertical cylinder vessel, 250.0 cm in diameter. The core consisted of 13 hexagonal fuel assemblies, see(figures Figures 2).Height of the core was 125.0 cm.

Fuel Assembly

The LR-0 model consisted of 13 hexagonal fuel assemblies. Each fuel assembly consisted of 312 fuel pins, 1 central instrumentation tube, and 18 control cluster tubes. Fuel assembly was a vertical hexagonal prism; 125.0 cm long. The fuel assembly was divided into hexagonal lattice; with pitch = 1.275 cm.See figure (Figure 3).

Control Cluster Tube

Each fuel assembly contained 18 control cluster tubes, each had an outer radius = 0.93 cm, and an inner radius = 0.55 cm. In this paper, control rods were completely eliminated and replaced by moderator (see figure Figure 4).

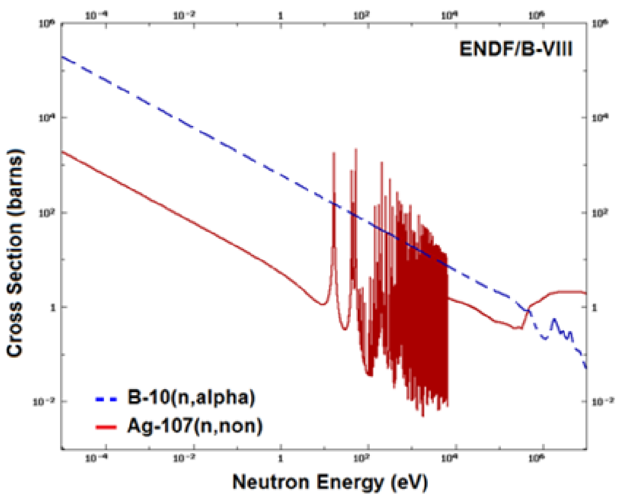

Fig.1 Neutron absorption cross sections of B-10 and Ag-107.

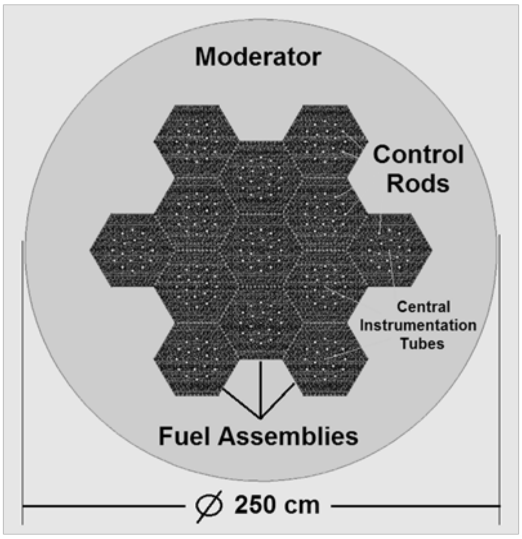

Fig. 2.Transverse section of LR-0 reactor model.

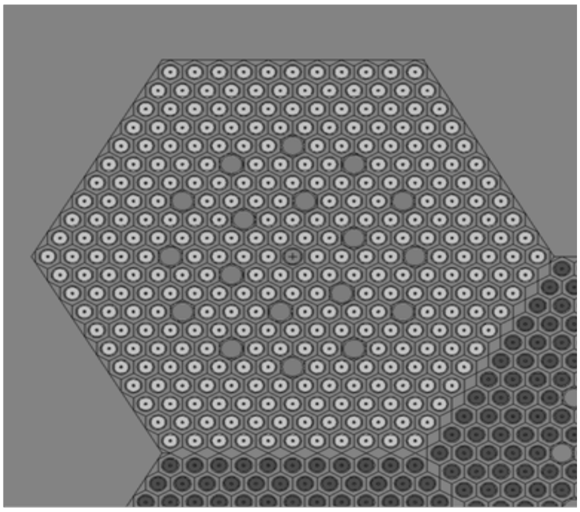

Fig 3. Fuel assembly.

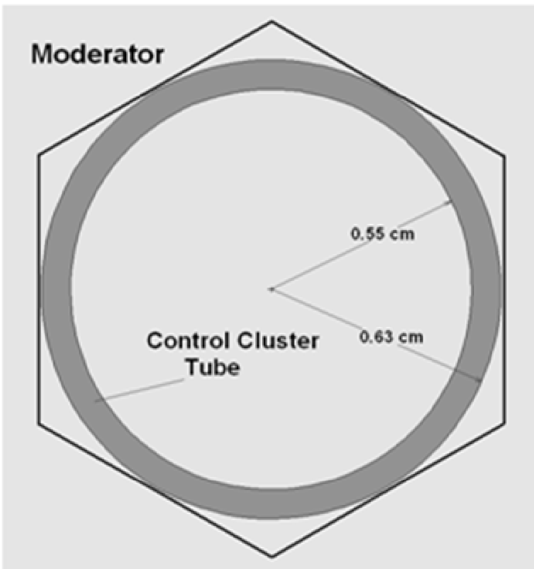

Fig. 4. Control cluster tube.

Materials of the three models

One model of LR-0 had all the control rods made of natural Boron of density = 0.744 g/cm3. Another model had all the control rods made of natural Silversilver of density = 10.5 g/cm3. A third model had mixed control rods where, each assembly had 9 control rods of natural Boron of density = 2.34 g/cm3 and other 9 control rods made of natural Silver silver of density = 10.5 g/cm3.

The fuel enrichment had to be adjusted in the three models to set exact criticality.

Materials of fuel and control rods of the three models are presented in table Table (1).

Method

All of the three LR-0 models, viz. controlled by boron control rods only, controlled by Silver silver control rods only, or controlled by mixture of Boron boron and Silver silver control rods, were setexactly critical at startup by adjusting fuel enrichment, (and also adjusting the density of control rod material in case of the Boron boron only model). Effective multiplication factors (keff) and their standard deviations for the three models are presented in table Table (2).

Each model was run using MCNP5 code and the following variables were tallied for 200 nanoseconds at 1 nanosecond steps in reactor time as measured in MCNP code:

- Neutron absorption in control rods
- Mean energy of neutrons absorbed in control rods.
- Total and 3 groups neutron flux (thermal, epithermal, and fast) in 2 moderator cells (cells 1 and 2) in core moderator (shown in figure 5)
- Mean neutron energy in each of the 4 tallied moderator cells mentioned above.

TABLE 1. Materials of fuel and control rods of the three models.

	Boron only Model	Silver only Model	Mixed Control Rods Model
Fuel Material	UO_2	UO_2	UO_2
Fuel enrichment $^w/_o$	4.4	3.6	4.4
Fuel density, g/cm^3	10.08	9.12	9.956
Control Rod Material	natural Boron	natural Silver	9 Rods perassembly ofnatural Boron 9 Rods perassembly ofnatural Silver
Control Rod Density, g/cm^3	0.744	10.5	Boron 2.34 Silver 10.5

TABLE 2. Effective multiplication factors (keff) and their standard deviations for the three models.

	Boron only Control Rods	Silver only Control Rods	Mixed Control Rods
k_{eff}	1.00004	1.00011	1.00038
standard deviation	0.00008	0.00008	0.00003

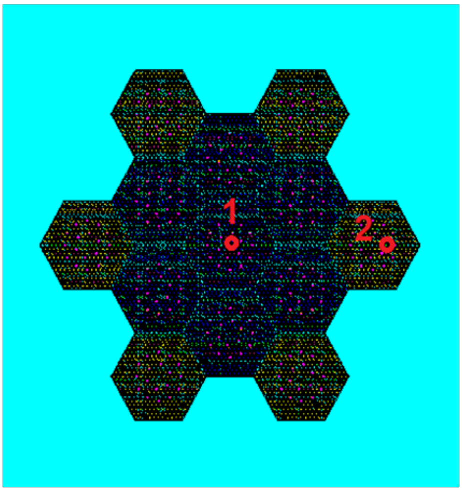

Fig. 5. Moderator cells where neutron flux was tallied.

Results & Discussion

The single species control rods models

In Silver silver only control rods model, neutron absorption rate in Silver silver sharply increased for the first 15 nanoseconds, thenmore steadily decreased, see (figure Figure 6). Compared with the Boron boron only control rods model, neutron absorption rate in Silver silver in the first 60 nanoseconds was greater than that in Boronboron;see (figure Figure 6).

During the first 130 nanoseconds of reactor life, Silver silver control rods had absorbed more total neutrons than Boron boron control rods, later on Boron boron control rods take over; see figure (Figure 7).

Figure (8) shows that the mean energy of the absorbed neutrons in either Silversilveror Boronboroncontrol rods; in both single species control rods models, were similar, being very energetic (E> 1 MeV) at first then exponentially decrease with time to about 0.2 keV at 200 nanoseconds from start of reactor life.

As seen from figures Figures (9&10) the mean neutron energy in moderator among fuel assemblies was correspondingly exponentially decreasing with time, though much faster than the average energy of neutrons absorbed in control rods. This emphasizes that energy spectrum of absorbed neutrons in control rods is mainly governed by the neutron energy spectrum in moderator rather than by the neutron absorption cross section of the control rod material.

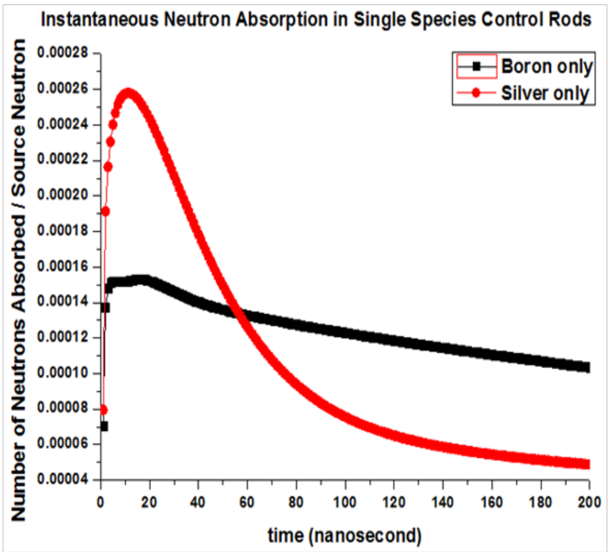

Fig. 6. Rate of neutron absorption in Silver silver and in Boron boron control rods, Silver silver only and Boron boron only control rods models.

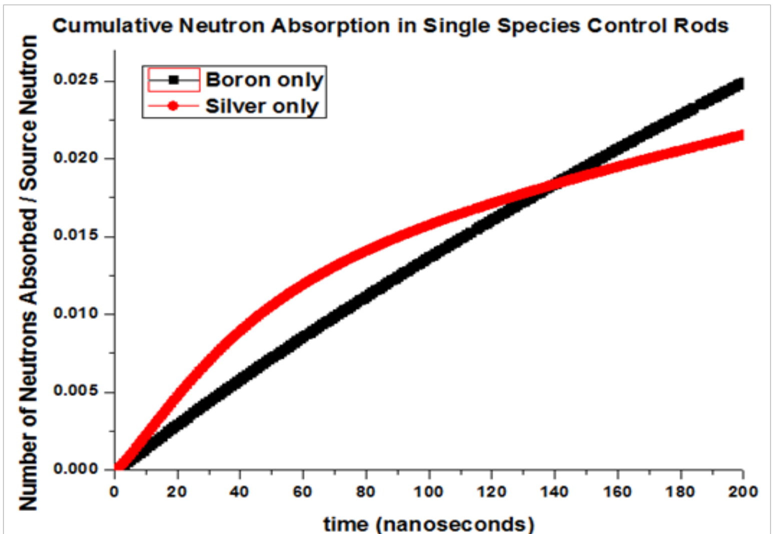

Fig.7. Cumulative neutron absorption in Silver silver and in Boron boron control rods; Silver only and Boron boron only control rods models.

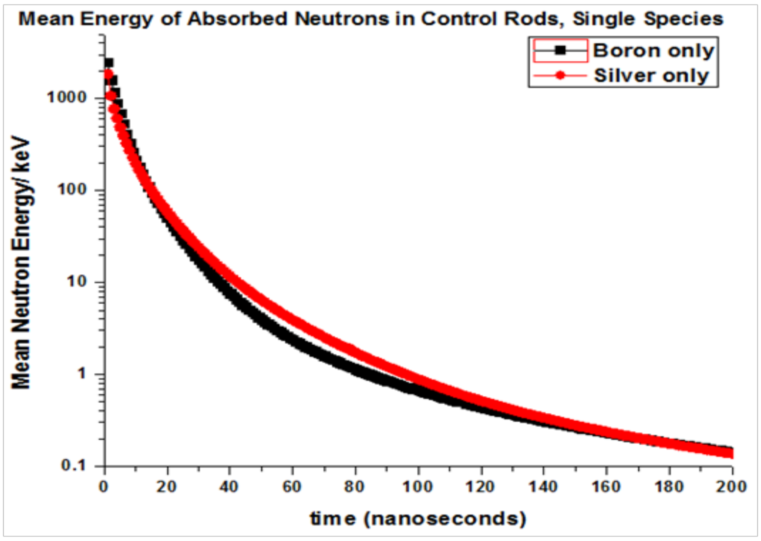

Fig. 8. Mean energy of the absorbed neutrons in either Silver or Boron control rods; inthe single species control rods models.

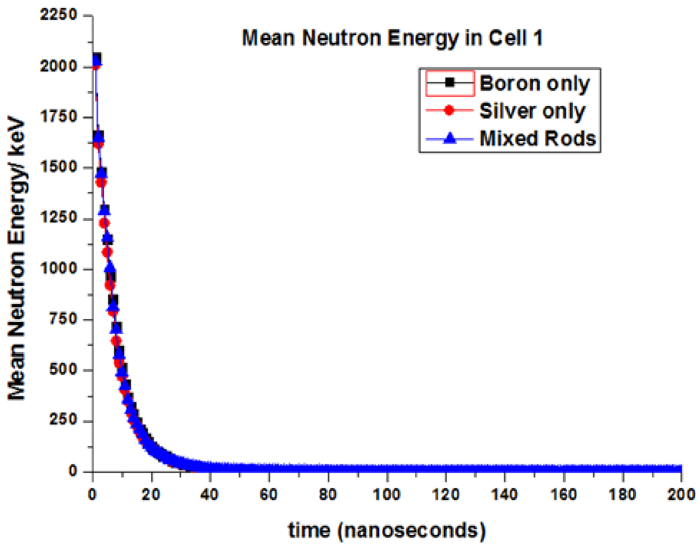

Fig. 9. Mean neutron energy in moderator, in centre of reactor core, cell 1.

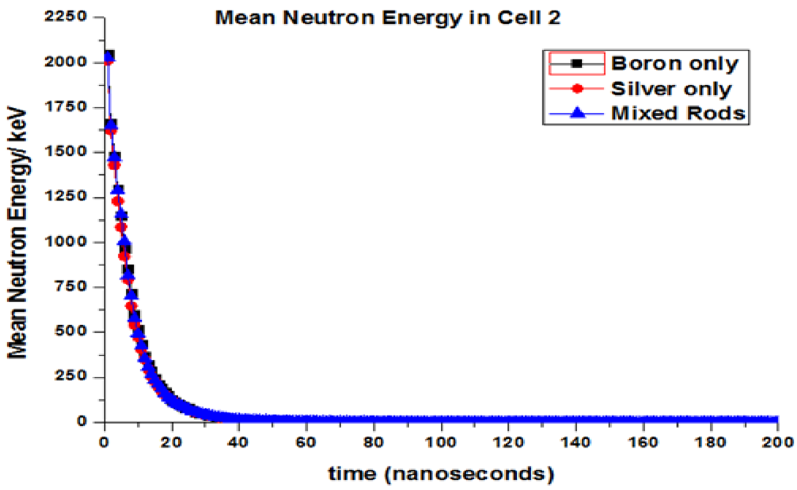

Fig.10. Mean neutron energy in moderator, in periphery of reactor core, cell 2.

The mixed Boron boron &Silver silver control rods model;

In the mixed control rods model, which contained 9 Boron boron & 9 Silver silver control rods per fuel assembly, boron and silver control rods exhibited similar profiles of neutron absorption rate with time for the first 200 nanoseconds, though the neutron absorption rate was much greater in Boron rods, which is expected since the neutron absorption cross section of Boron boron is generally greater than that of Silversilver, [ENDF, 2011]. In both boron and silver rods, neutron absorption rate increased sharply during the first nanosecond, then kept almost constant till 10 nanoseconds of reactor start up, then gently decreased. See(figure Figure 11).

Boron control rods absorbed more total neutrons than Silver silver control rods; again, because the neutron absorption cross section of Boron boron is generally greater than that of Silversilver. See(Figure 12).

Figure (13 shows,),again, that the mean energy of the absorbed neutrons in silver or boron control rods in the mixed control rods model, were similar, being very energetic (E> 1 MeV) at first then exponentially decrease with time to about 0.2 keV at 200 nanoseconds from start of reactor life.

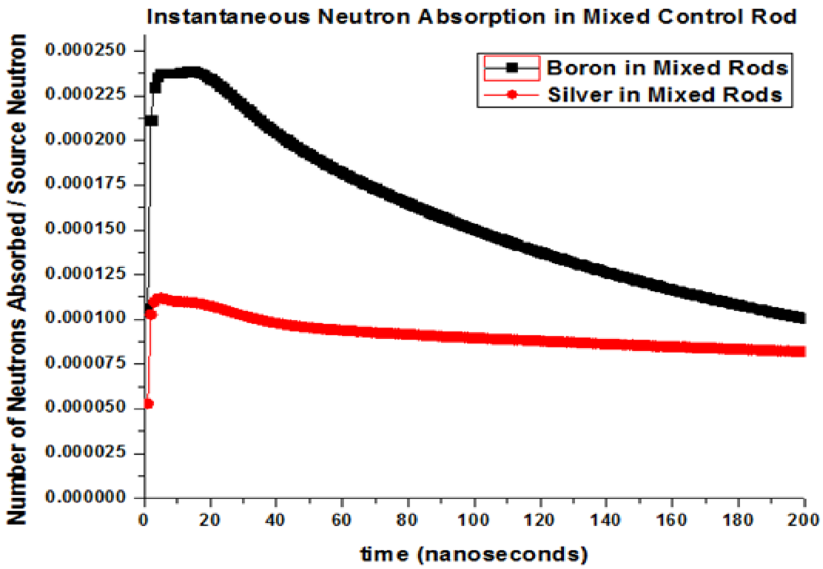

Fig. 11. Rate of neutron absorption in Silver and in Boron control rods; mixed rods model.

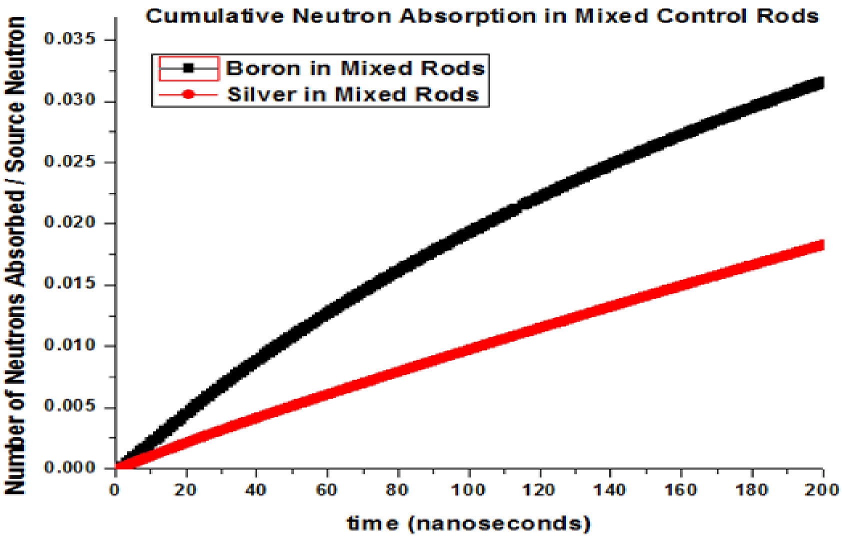

Fig. 12. Cumulative neutron absorption in silver and in boron control rods; mixed rods model.

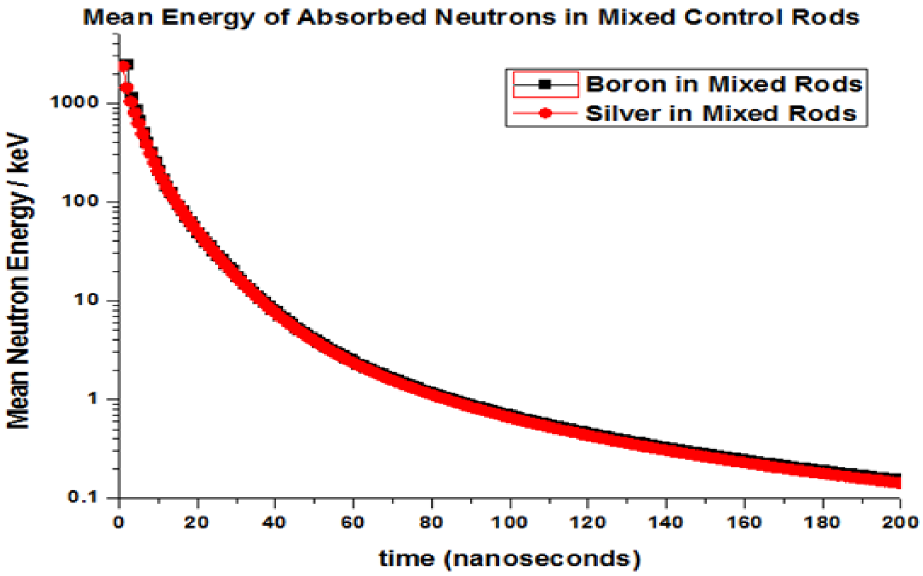

Fig. 13. Mean energy of the absorbed neutrons in Boron and in Silver control rods; mixed rods model.

Neutron flux

It is important to note that MCNP5 tallies neutron flux per neutron history, so neutron flux does not accumulate after fissions occur.

Figures 14 & 15 show that variation of the total neutron flux with time was almost identical for the first 200 nanoseconds of reactor startup in central and core boundary moderator in all of the three studied reactor models, viz. the model controlled by Boron control rods only, the model controlled by Silver silver control rods only, and the model controlled by mixture of boron and silver control rods.

Figures (16& 17) show that variation of the thermal neutron flux with time was similar for the first 200 nanoseconds of reactor startup in central and core boundary moderator in all of the three studied reactor models.

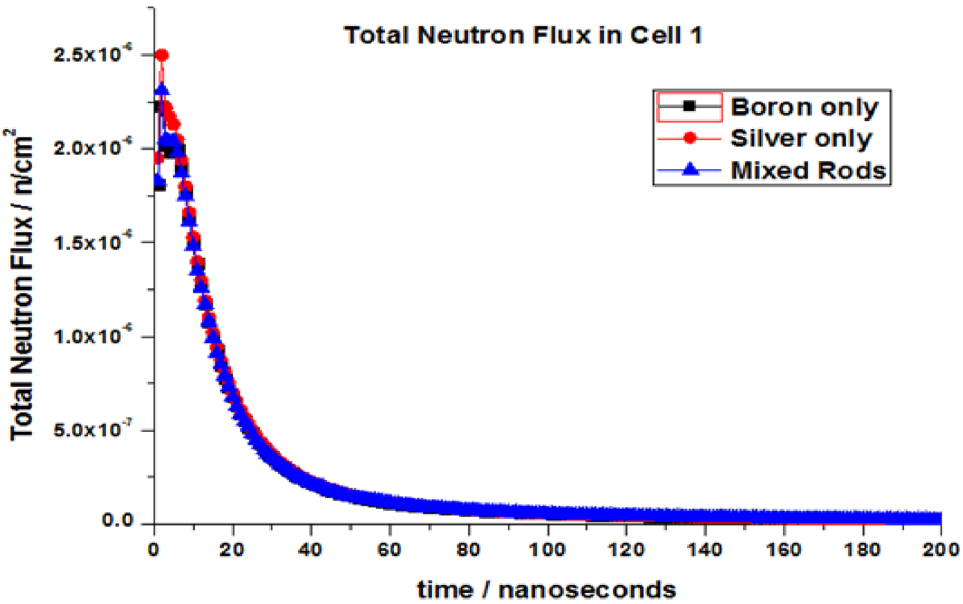

Fig. 14. Total neutron flux variation with time in central moderator cell (cell 1), for the first 200 nanoseconds from startup.

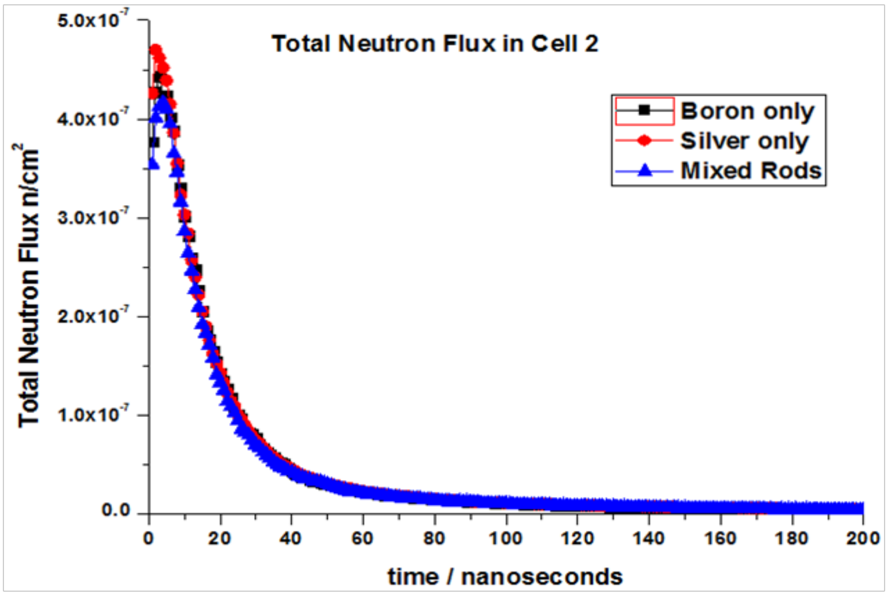

Fig. 15. Total neutron flux variation with time in a core boundary moderator cell (cell 2), for the first 200 nanoseconds from startup.

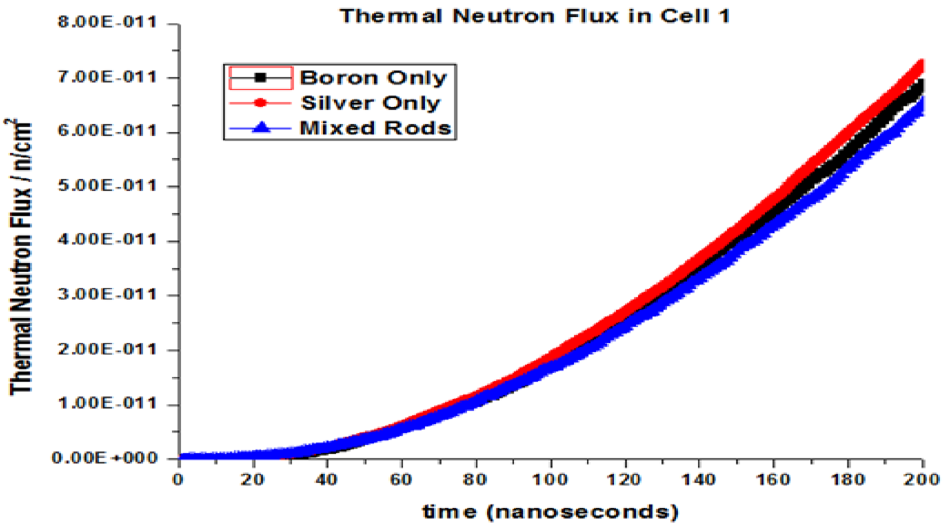

Fig. 16. Thermal neutron flux variation with time in central moderator cell (cell 1), for the first 200 nanoseconds from startup.

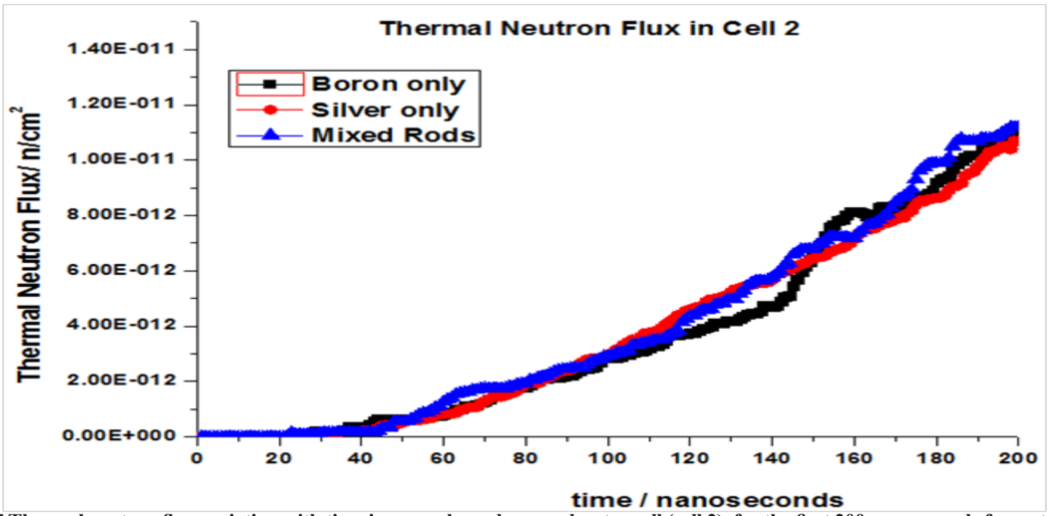

Fig. 17.Thermal neutron flux variation with time in a core boundary moderator cell (cell 2), for the first 200 nanoseconds from startup.

Variation of the neutron flux with time was almost identical for the first 200 nanoseconds of reactor startup in core moderator in all of the three studied reactor models. This signifies that reactor period does not depend on the type of the control rod material used in the reactor.

Conclusion

In Single species control rods model; neutron absorption rate in Silver silver sharply increased for the first 15 nanoseconds, then more steadily decreased. Silver silverabsorbed more neutrons per nanosecondthan Boronboronin the first 60 nanoseconds,and totally more neutrons than Boron boron till 130 nanoseconds of reactor life, later on Boron boron control rods took over.

The mean energy of the absorbed neutrons in either Silver silver or Boron boron control rods; in both single species control rods models, were similar, being very energetic at first then exponentially decrease with time to about 0.2 keV at 200 nanoseconds from start of reactor life.

In the mixed species control rods model with equal number of boron & silver control rods, neutron absorption rate was much greater in Boron boron than in silver rods, though both exhibited similar profiles of neutron absorption rate with time for the first 200 nanoseconds, where; neutron absorption rate increased sharply during the first nanosecond, then kept almost constant till 10 nanoseconds of reactor start up, then gently decreased.

This indicate indicatesthat reactor period will be the same for all the three reactor models, which signifies that reactor period does not depend on the type of the control rod material used. This is explained by the fact that was shown by the author in a previous work that only 10.5% of the neutrons in a reactor are finally absorbed in control rods [Nagy et. al; 2013].

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