MNSR Flux Performance and Core Lifetime Analysis with HEU and LEU Fuels

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ABSTRACT

This paper discusses the results of flux performance and the core lifetime analyses for conversion of an MNSR core using LEU-UO_2 fuel containing uranium with 12.5% enrichment. Detailed MCNP5 models were used to evaluate the flux performance. Diffusion theory REBUS-3 models were used to estimate fuel depletion rates under various operational schemes and to simulate the long-term fuel depletion history. Core lifetimes were estimated under realistic operational constraints. This study found a reduction of 7-10% in thermal neutron flux in the irradiation channels for the LEU-UO_2 fuel in comparison with the HEU fuel. Therefore, for an LEU fueled core, the reactor power would have to be increased by ~10% from the current level of 30 kW in order to match the nominal flux level. MNSRs have a very small window of excess reactivity for operation and are designed for a very short operational cycle to avoid excessive xenon buildup. Consequently, fuel depletion calculations need to be performed using realistic operational constraints. As fuel depletes, top Be shim plates are added periodically to restore the excess reactivity for continuing operation. The maximum allowed excess reactivity at the beginning of each operating cycle is 4 mk. This study concludes that an MNSR core with LEU UO_2-12.5% fuel and a power level of 33 kW can be operated ~25% longer than the current HEU core operated at 30 kW. Both cores will have the same thermal neutron flux in the experiment positions.

INTRODUCTION

Miniature Neutron Source Reactors (MNSR) are designed and manufactured by the China Institute of Atomic Energy (CIAE). They are used mainly for neutron activation analysis (NAA), training and teaching. Several feasibility studies for the conversion of MNSRs to LEU fuel have been performed recently [1-3]. This paper presents the results of flux performance and core lifetime analyses of MNSRs with HEU and LEU fuels using the Nigeria Research Reactor-1 (NIRR-1) as an example. A detailed description of NIRR-1 can be found in the final SAR [4].

REACTOR MODEL FOR FLUX CALCULATIONS

Detailed geometry of the HEU fueled NIRR-1 core was used to construct a three-dimensional model for MCNP5 calculations [2]. The following reactor components are modeled explicitly: 347 fuel pins and 3 Al dummies, central control rod, light water moderator, grid plates, Be reflectors, Be shim tray, irradiation channels, reactivity regulators, fission chambers, startup guide tube (also known as slant tube). The temperature measuring devices and all details of the aluminum support structure, reactor vessel as well as the reactor pool and the stainless steel liner were also modeled. A geometric representation of the reactor and various irradiations sites are shown in Figure 1.

FLUX PERFORMANCE - TWO LEU-UO_2 OPTIONS COMPARED TO HEU CORE

Based on the findings of previous MNSR conversion feasibility studies [1-3], two LEU-UO_2 fuel options were considered as the most favorable among several possible candidates. The first LEU option (enrichment 12.45%) is based on the HEU reference fuel pin dimensions, i.e., a pellet diameter of 4.3mm and a Zirc-4 clad outer diameter of 5.5mm. The second LEU option (enrichment 12.0%) is based on the Chinese design of their new Special MNSR [5, 6] (sometimes called the In-Hospital Neutron Irradiator),

i.e., a pellet diameter of 4.2mm and a Zirc-4 clad outer diameter of 5.1mm. For consistency, the enrichment in each LEU-UO_2 option was determined such that the fresh core k-effective is the same as the HEU reference core of 1.00476. The main characteristics of these two UO_2 fuel options are shown in Table 1 for comparison with the HEU fuel.

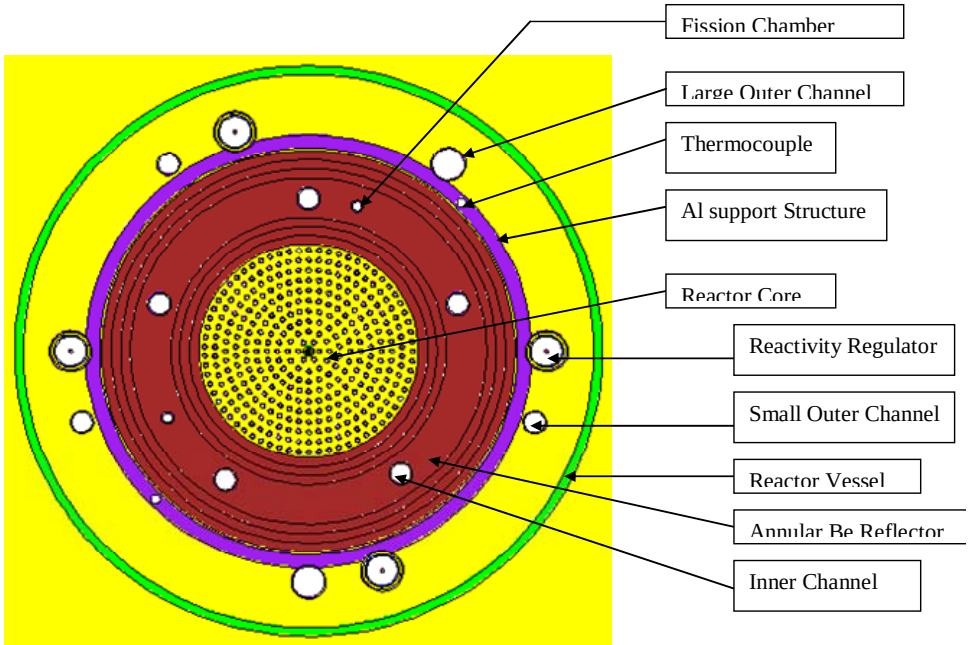

Figure 1. MNSR Core Mid-Plane and Irradiation Sites

Table 1. Characteristics of the UO_2 Fuel Options Considered for MNSR LEU Conversion Study (Based on NIRR-1 347-Pins Core)

Fuel Type	Density of Meat / U, g/cc	Meat Diameter, mm	Clad Mat. / Thick, mm	235-U loading , g	Fresh Core K-effective
HEU-U-Al_4, 90.2%	3.456 / 0.92	4.3	Al / 0.6	999	1.00476
LEU-UO_2 pellets 12.45%	10.6 / 9.35	4.3	Zirc / 0.6	1349	1.00476
LEU-UO_2 pellets 12.00%	10.6 / 9.35	4.2	Zirc / 0.45	1241	1.00473

Flux performance of the two LEU-UO_2 options are compared with HEU reference core at various irradiation sites in Table 2. The flux performance of the two LEU-UO_2 options is nearly the same. A reduction of 7-10% in thermal neutron flux was obtained in the irradiation channels for both LEU-UO_2 fuel options in comparison with the HEU core. Consequently, the power level of an LEU fueled core would need to be increased by ~10% from the current value of 30 kW in order to match the nominal flux level for the MNSRs using HEU fuel.

Table 2. Comparison of Neutron Flux Data at Inner Irradiation Channels, Outer Irradiation Channels Fission Chambers, and Slant Tube in NIRR-1

Neutron Energy	Thermal (0 – 0.625 eV) (n/cm^2-s) x 10^{11}		Epithermal (0.625 eV – 0.825 MeV) (n/cm^2-s) x 10^{11}		Fast (0.825 – 20 MeV) (n/cm^2-s) x 10^{11}	
Location	Inner	Outer	Inner	Outer	Inner	Outer
HEU-90.2%	11.6 ± 0.01	6.60 ± 0.01	12.9 ± 0.01	1.85 ± 0.01	2.69 ± 0.01	0.36 ± 0.003
UO_2-12.45%	10.4 ± 0.01	6.19 ± 0.01	12.6 ± 0.01	1.80 ± 0.01	2.59 ± 0.01	0.35 ± 0.003
UO_2-12.0%	10.5 ± 0.01	6.14 ± 0.01	12.4 ± 0.01	1.76 ± 0.01	2.55 ± 0.01	0.34 ± 0.003
Location	Fission Chamber	Slant Tube	Fission Chamber	Slant Tube	Fission Chamber	Slant Tube
HEU-90.2%	11.9 ± 0.01	0.255 ± 0.002	13.3 ± 0.01	0.036 ± 0.0005	2.60 ± 0.01	0.018 ± 0.0004
UO_2-12.45%	10.6 ± 0.01	0.241 ± 0.002	12.8 ± 0.01	0.033 ± 0.0005	2.47 ± 0.01	0.017 ± 0.0004
UO_2-12.0%	10.8 ± 0.01	0.237 ± 0.002	12.6 ± 0.01	0.033 ± 0.0005	2.43 ± 0.01	0.017 ± 0.0003

REACTIVITY RUNDOWN - WITHOUT MNSR OPERATIONAL CONSTRAINTS

An R-Z diffusion theory model using the REBUS-3 code [7] was developed to understand the basic fuel depletion characteristics of the MNSR core. Important fuel cycle parameters such as core excess reactivity, xenon worth, rate of fuel depletion, and fuel cycle length can be obtained by performing simple reactivity rundown calculations. In these calculations, a newly loaded fresh core with control rod fully-withdrawn is depleted at a fixed power level for a given length of time. Because the REBUS-3 RZ-model can run very fast, key core parameters can be calculated at many small time steps to capture the details of temporal variations during fuel depletion. These details are important to help understand the basic fuel depletion characteristics of the MNSR core under different operational schemes. Reactivity rundown results are shown in Figure 2 and Table 3 for HEU core. Similar results for LEU-UO_2-12.5% core are shown in Figure 3 and Table 4.

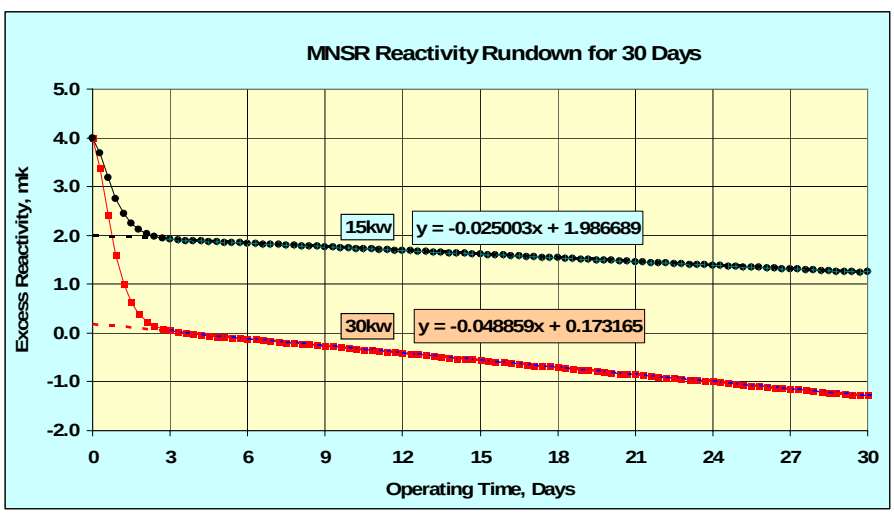

Figure 2. MNSR HEU Core Reactivity Rundown for 30 Days Operation at 15 kW and 30 kW (Reactivity is calculated every 7.2 hours)

As shown in Figure 2, xenon builds up in the HEU core as fuel depletes and reaches the equilibrium concentration in ~ 3 days of continuous reactor operation. The reactivity worth of the equilibrium xenon can be estimated from the difference between the intercepts of the trend lines back to 0 day in Figure 2 and the fresh core excess reactivity (4.0 mk). The equilibrium xenon worth is shown in Table 3 for the HEU core. The slope of the trend line in Figure 2 corresponds to the reactivity loss per day due to fuel depletion. These reactivity change rates for fuel depletion can also be converted to mk/hour as shown in Table 3 for use in cycle time estimates.

Table 3. Xenon Worth and Reactivity Change Rates for HEU Fuel Depletion at 15 kW and 30 kW

Eq. Xe Worth, mk		Fuel Depletion, mk/day		Fuel Depletion, mk/hour	
15kw	30kw	15kw	30kw	15kw	30kw
2.013	3.827	-0.025003	-0.048859	-0.001042	-0.002036
Hours to operate: before adding shim (4.0-2.3)mk				1631.8	835.1
Weeks to operate :16 hpw @15kw or 8 hpw @30kw				102.0	104.4
Years to operate : 52 weeks/year				1.96	2.01

Based on the reactivity change rates (mk/hour) due to fuel depletion, the number of hours that the reactor can be operated for a given operational scheme can be estimated. The operational cycle length is determined when the excess reactivity reaches the ~ 2.3 mk lower limit which is required by reactor operation to compensate for experimental samples and negative reactivity feedbacks. For an HEU MNSR operated at 15 kW (for 4 hours per day, 4 days per week, and 52 weeks per year), the reactor can be operated for about 1.96 years. For an HEU MNSR operated at 30 kW (for 2 hours per day, 4 days per week, and 52 weeks per year), the reactor can be operated for about 2.01 years. Thereafter, in order to continue the reactor operation, top Be shim plates must be added to restore the core excess reactivity to ~ 4.0 mk and begin the next reactor operational cycle. Thus, the HEU MNSR fuel cycle can be defined on the basis of the shim cycle length (~ 2 years) for adding the top Be shim plates.

Similarly, the equilibrium xenon worth for the LEU-UO_2 core can be obtained from the reactivity rundown calculations shown in Figure 3. Using the same methods as HEU core, the reactivity worth of the equilibrium xenon and the reactivity change rates for fuel depletion can be estimated from the trend lines in Figure 3. The results are shown in Table 4.

Table 4. Xenon Worth and Reactivity Change Rates for LEU-UO2 Fuel Depletion at 16.5 kW & 33.0 kW

Eq. Xe Worth, mk		Fuel Depletion, mk/day		Fuel Depletion, mk/hour	
16.5kw	33kw	16.5kw	33kw	16.5kw	33kw
1.617	3.099	-0.019811	-0.03886	-0.000825	-0.001619
Hours to operate: before adding shim (4.0-2.3)mk				2059.5	1049.9
Weeks to operate :16 hpw @15kw or 8 hpw @30kw				128.7	131.2
Years to operate : 52 weeks/year				2.48	2.52

Based on the reactivity change rates (mk/hour) due to fuel depletion in Table 4, the operational cycle length can be estimated. For an MNSR with LEU-UO_2 core operated at 16.5 kW (for 4 hours per day, 4 days per week, and 52 weeks per year), the reactor can be operated for about 2.48 years. For an MNSR LEU-UO_2 core operated at 33 kW (for 2 hours per day, 4 days per week, and 52 weeks per year), the reactor can be operated for about 2.52 years. Thus, the MNSR LEU-UO_2 fuel cycle can be defined on the basis of the cycle length (~ 2.5 years) for adding the top Be shim plates. In comparison, the cycle length for HEU core is 2.0 years, which is 25% shorter than the LEU-UO_2 core.

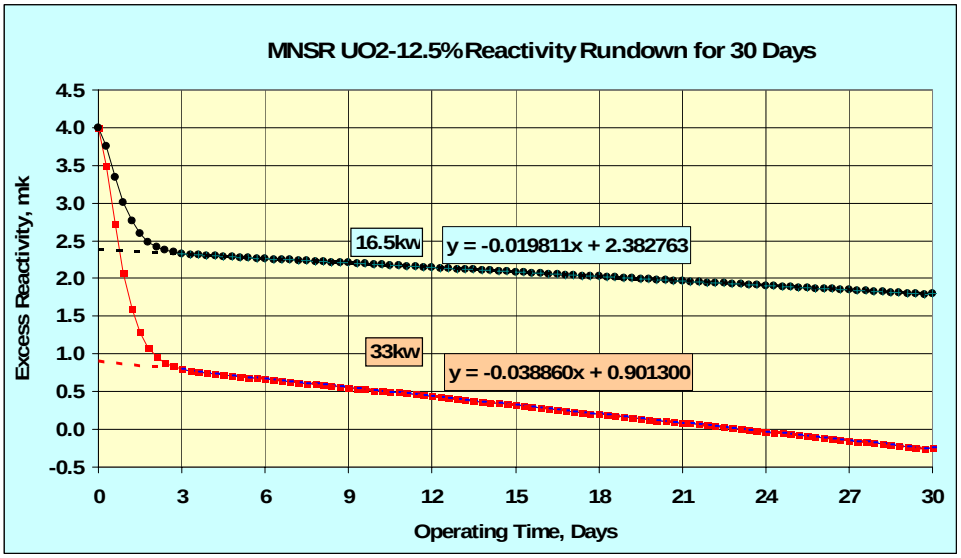

Figure 3. MNSR LEU Core Reactivity Rundown for 30 Days Operation at 16.5 kW and 33.0 kW (Reactivity is calculated every 7.2 hours).

FUEL DEPLETION - WITH MNSR OPERATIONAL CONSTRAINTS

The MNSR core has a very small window of excess reactivity (only ~ 1.7 mk) for operation (between 4.0 mk and 2.3 mk). Based on the above reactivity rundown study, it is found that the equilibrium xenon worth in the HEU core is 2.013 mk for reactor operated at 15 kW and 3.827 mk for reactor operated at 30 kW. In both cases the equilibrium xenon worth is greater than the allowed 1.7 mk excess reactivity window for typical MNSR operation. Consequently, an MNSR reactor cannot be operated continuously to let the xenon build up to its equilibrium level. In fact, the MNSRs are designed for a very short operational time, no more than ~ 4.5 hours at 15 kW or no more than ~ 2.5 hours at 30 kW to avoid excessive xenon buildup. In this section, fuel depletion calculations will be performed with more realistic operational schemes of a typical MNSR based on one week, one month, and one year operation. From the excess reactivity traces, an efficient fuel burnup calculation can be formulated to effectively simulate the long-term fuel depletion behavior and correctly estimate the core lifetime.

Operation for One Week

The excess reactivity trace shown in Figure 4 corresponds to an HEU MNSR operated for one week. The reactor is operated for 4 hours per day and shutdown, repeated for 4 days per week, and then shutdown for the rest of the week. For 15 kW operation, the excess reactivity starts at 4.0 mk at the beginning of operation, going down to 3.87 mk after 4 hours of operation. The excess reactivity continues going down to a minimum of 3.72 mk at ~ 0.5 day due to xenon buildup continuously from I-135 decays after shutdown. Beyond that minimum point, xenon decays away and the excess reactivity goes back up to 3.78 mk at the beginning of the second day operation. This pattern repeats for the next 3 days of operation. After the 4th day of operation, the reactor is shutdown for the rest of the week and the excess reactivity continues to recover and reaches the asymptotic value of ~ 3.97 mk. The difference of excess reactivity between the beginning of cycle (4.0 mk) and the end of one week cycle (3.97 mk) is the reactivity loss due to fuel depletion (0.03 mk) for the week. A similar trend with larger excess reactivity swing is observed for reactor operated at 30 kW. The reactivity loss due to fuel depletion is ~ 0.05 mk for 30 kW operation, which is roughly twice the loss for 15 kW operation, as expected.

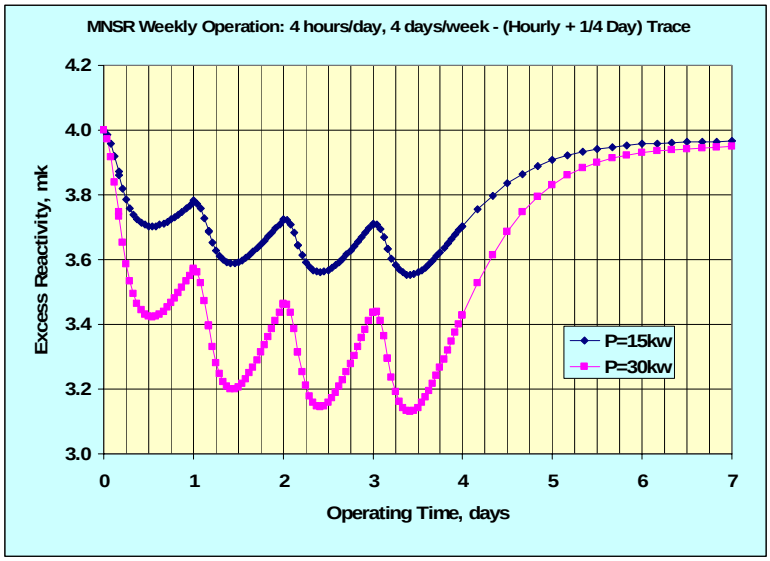

Figure 4. MNSR HEU Core Fuel Depletion for One Week Operation at 15 kW and 30 kW (Reactivity is calculated at every hour when reactor is up and at every 6 hours when reactor is down – over nights and during the weekend)

Operation for One Month

The excess reactivity trace shown in Figure 5 corresponds to an HEU MNSR operated for one month. The weekly cycle described previously is repeated 4 times per month. For 15 kW operation, the excess reactivity starts at 4.0 mk at the beginning of operation, going down to a minimum of 3.504 mk at 24.5 days after 4 weeks of operation. After the 4th week of operation, the reactor is shutdown for the rest of the

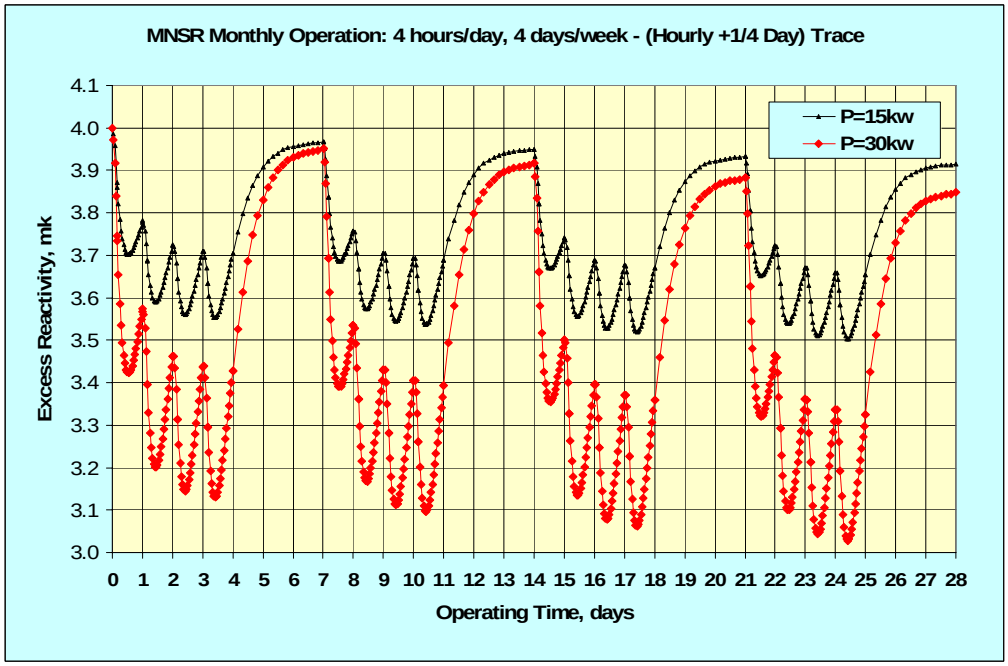

Figure 5. MNSR HEU Core Fuel Depletion for One Month Operation at 15 kW and 30 kW (Reactivity is calculated at every hour when reactor is up and at every 6 hours when reactor is down – over nights and during the weekends, repeated for 4 weekly cycles in one month)

week and the excess reactivity continues to recover and reaches an asymptotic value of ~ 3.915 mk. The difference of excess reactivity between the beginning of cycle (4.0 mk) and the end of one month cycle (3.915 mk) is the reactivity loss due to fuel depletion (0.085 mk) for the month. A similar trend with larger excess reactivity swing is observed for 30 kW operation. The reactivity loss due to fuel depletion is ~ 0.152 mk for 30 kW operation, roughly twice the loss for 15 kW operation, again as expected.

Operation for One Year

The excess reactivity trace shown in Figure 6 corresponds to an HEU MNSR operated for one year. The weekly cycle described previously is repeated 48 times for a given year, with the reactor shutdown for the last 4 weeks. For 15 kW operation, the excess reactivity starts at 4.0 mk at the beginning of operation, going down to a minimum of 2.840 mk at 332 days after 48 weeks of operation. After the 48th week of operation, the reactor stays shutdown for the last 4 weeks of the year and the excess reactivity continues to recover and reaches an asymptotic value of ~ 3.171 mk. The difference of excess reactivity between the beginning of cycle (4.0 mk) and the end of one year cycle (3.171 mk) is the reactivity loss due to fuel depletion (0.829 mk) for the year. A similar trend with larger excess reactivity swing is observed for reactor operated at 30 kW with 4 hours/day scheme. The annual reactivity loss due to fuel depletion is ~ 1.603 mk for 30 kW operation, roughly twice the loss (0.829 mk) for 15 kW operation, again as expected. The reactivity loss rate due to fuel depletion is 0.00108 mk/hour for the (15 kW-4 hours/day) operational scheme and is 0.00209 mk/hour for the (30 kW-4 hour/day) operational scheme. These results are in good agreement with the reactivity loss rate shown in Table 3 from simple reactivity rundown study (0.00104 mk/hour for 15 kW operation and 0.00204 for 30 kW operation).

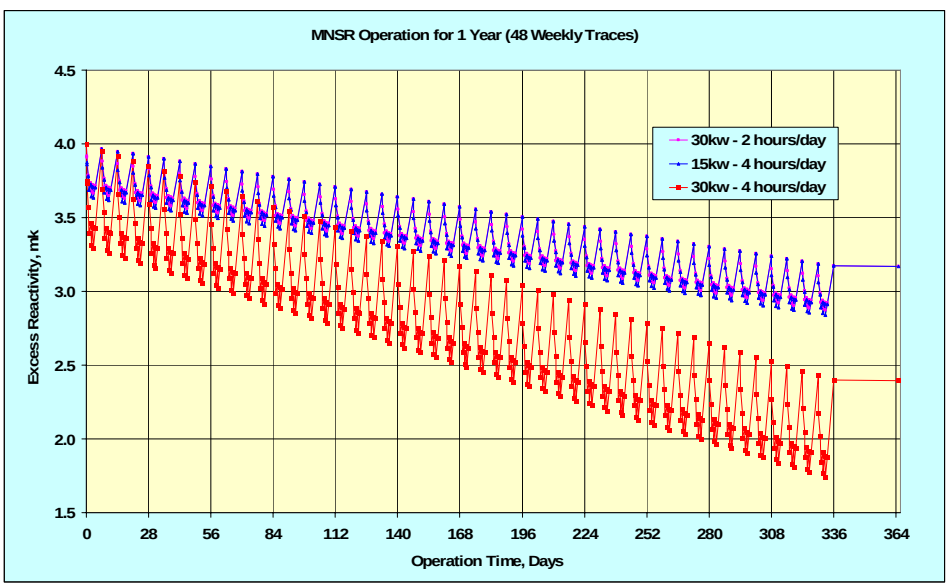

Figure 6. MNSR HEU Core Fuel Depletion for One Year Operation at 15 kW and 30 kW (Reactivity calculated at every hour when reactor is up and at every 6 hours when reactor is down – over nights and during the weekends, repeated for 48 weekly cycles in one year. Reactor is down for the last four weeks)

Also shown in Figure 6 is the excess reactivity trace for 30 kW with 2 hours/day operational scheme for one year. The excess reactivity trace between 15 kW (4 hours/day) and 30 kW (2 hours/day) are almost identical, indicating that the fuel cycle behavior is very similar for these two operational schemes since they have the same cumulative kW-hours for fuel depletion in one year.

Reduction of Computing Time with Large Time Step for Long Term Fuel Cycle Analyses

As shown in Figure 7, the excess reactivity trace corresponds to an MNSR HEU core operated for one year is given for four operational schemes. All four operational schemes have the same cumulative kW-hours of fuel depletion but having different daily, weekly, and monthly continuous hours of operation. Note that the minima of the excess reactivity of the cycles for the four operational schemes are quite different (due to the xenon buildup which depends upon the length of continuous operation). However, the maxima of the excess reactivity of the cycles for the four operational schemes are almost identical (as shown by the top black trend line in Figure 7), indicating that after the reactor recovers from xenon decay during shutdown, all cases return to the same excess reactivity levels. This is very useful for long term fuel cycle simulation study. Fuel cycle analyses can be performed using a large time step and obtain the same reactivity changes due to fuel depletion as those using many smaller time steps over a long time span in order to save computing time. However, such a large time step in continuous reactor operation will lead to xenon buildup to large saturation levels which can not be tolerated from a practical reactor operational point of view, as discussed previously.

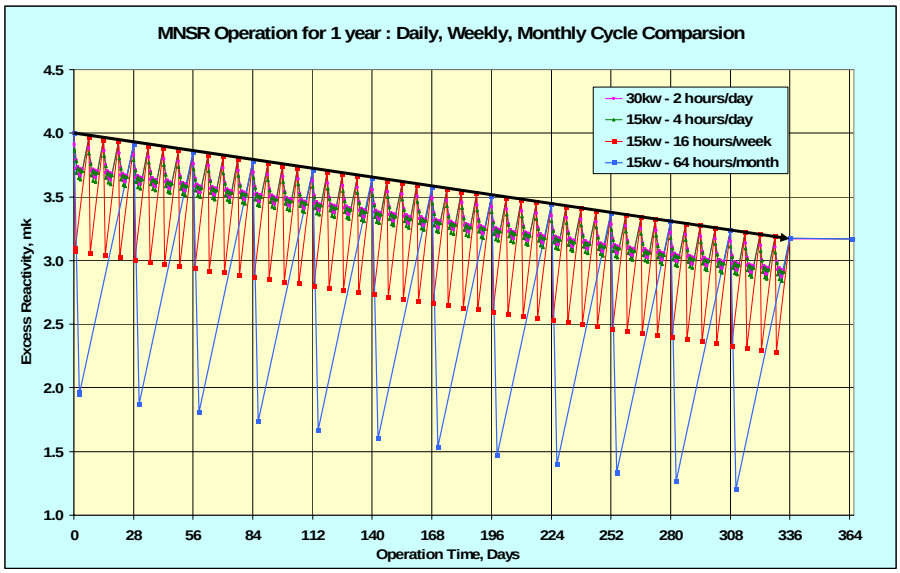

Figure 7. MNSR HEU Core Fuel Depletion for One Year Operation at 15 kW and 30 kW Using Four Different Operational Schemes. (All four schemes have the same cumulative kW-hours of fuel depletion and the same reactivity loss rate. Fuel depletion with larger time steps requires less computing time).

Fuel depletion rates of the LEU core can also be estimated from the slopes in excess reactivity calculations for one year operation under realistic weekly operational schemes (4 hours/day, 4 days/week, and 48 weeks/year) as shown in Figure 8. The results are almost the same as those shown on Table 4 (based on 30 days reactivity rundown slopes from Figure 3). In comparison, the fuel depletion rate for LEU-UO_2 core is ~ 25% smaller than that for the HEU core, indicating that the fuel cycle length for LEU-UO_2 core will be ~ 25% longer than HEU core.

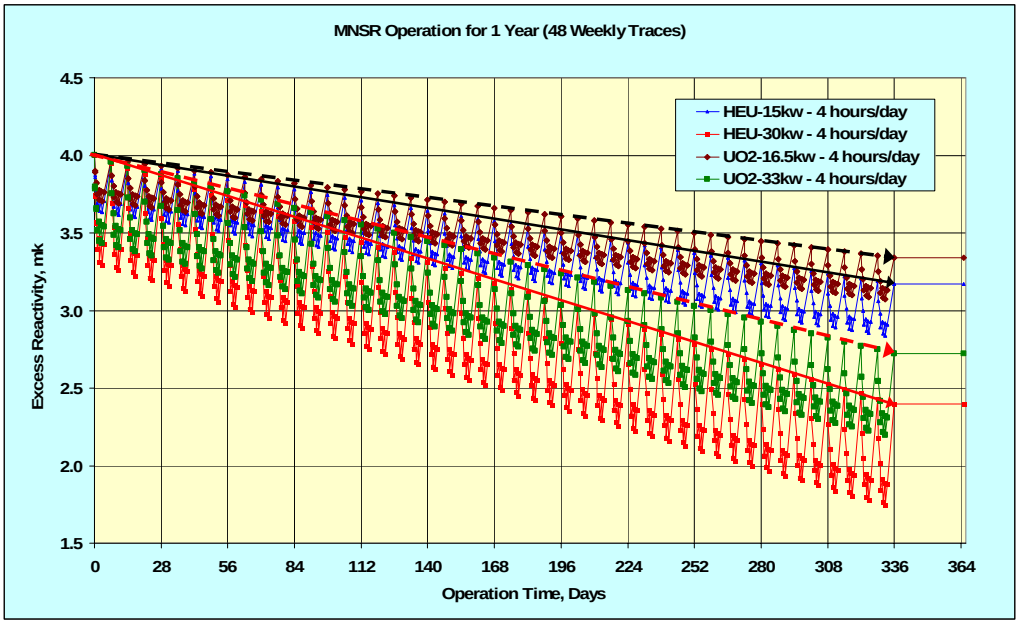

Figure 8**.** Comparison of MNSR HEU and LEU Fuel Depletion for One Year Operation. (Reactivity calculated at every hour when reactor is up and at every 6 hours when reactor is down. This is repeated for 48 weekly cycles in one year, with the reactor shutdown for the last four weeks).

CORE LIFETIME - WITH MNSR OPERATIONAL CONSTRAINTS

As shown earlier, long term fuel depletion can be simulated using large time steps. The 15 kW-64 hours/month fuel cycle scheme will be used to estimate core lifetime. For an HEU MNSR operated at 15 kW, the reactor can be operated for about 1.96 years. Thereafter, top Be shim plates must be added to restore the core excess reactivity to ~ 4.0 mk and begin the next operational cycle. Thus, the HEU MNSR fuel cycle can be defined on the basis of the shim cycle length (~ 2 years) for adding the top Be shim plates. Two steps are required to perform the fuel cycle analyses. First, the integral and differential worth of the top Be shim plates must be calculated. The results are shown in Figure 9 below for both HEU and LEU cores. Compared to HEU core, the top Be shim plates worth slightly less in the LEU-UO_2 core. The left plot shows the excess reactivity versus the Be shim thickness and the right plot shows the differential Be shim worth. After adding ~ 10-12 cm of Be shim plates, the worth diminishes for any further addition.

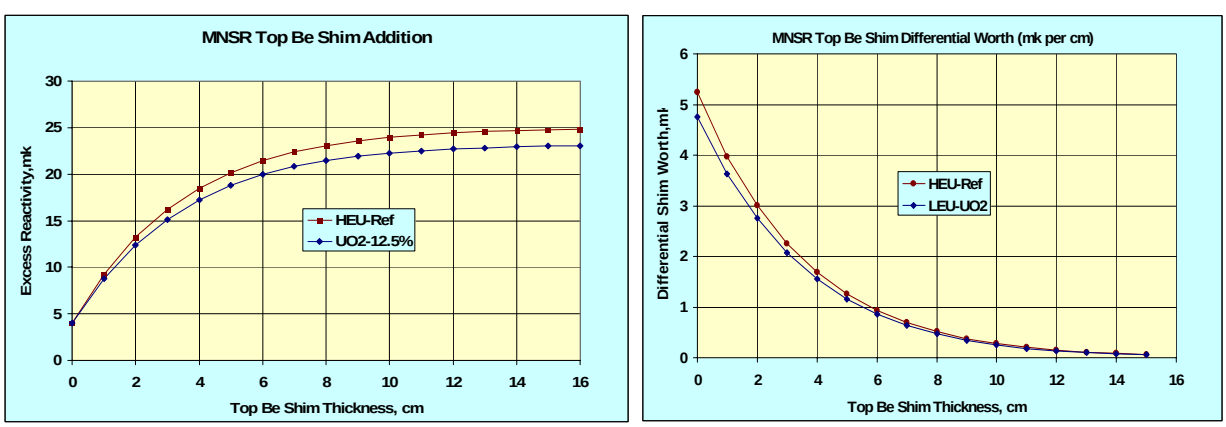

Figure 9**.** Excess Reactivity Increases Due to Top Be Shim Addition and Differential Worth of Top Be Shim Plates (mk/cm). Compare HEU Core and LEU Core with UO2-12.5% Fuel.

Subsequently, using the Be shim plate reactivity worth curves as shown in Figure 9, more realistic MNSR fuel cycle analysis can be performed based on a 2-year shim addition cycle. The goal is to add enough top Be shim plates to bring the excess reactivity at the beginning of cycle to ~ 4.0 mk as for the fresh core and let it deplete for 2 years maintaining the end of cycle excess reactivity at ~ 2.3 mk minimum to compensate for experimental samples and negative reactivity feedbacks. This can be done by trial and error for each cycle as reactor operation continues over the core lifetime. Figure 10 shows the result for the MNSR HEU core operated for 23 shim cycles in 46 years at 15 kW power level. The last 3 cycles do not meet the 4.0 mk required at the beginning of cycle. Similarly, the MNSR LEU-UO2 fuel cycle analysis can be performed based on a 2.5 year shim addition cycle. Figure 11 shows the result for the MNSR LEU-UO_2 core operated for 23 shim cycles in 57.5 years at 16.5 kW power level. All 23 cycles meet the 4.0 mk excess reactivity required at the beginning of cycle. In comparison, the MNSR HEU core can only be operated for 23 shim cycles in 46 years at 15 kW which is ~25% shorter than the LEU-UO_2 core.

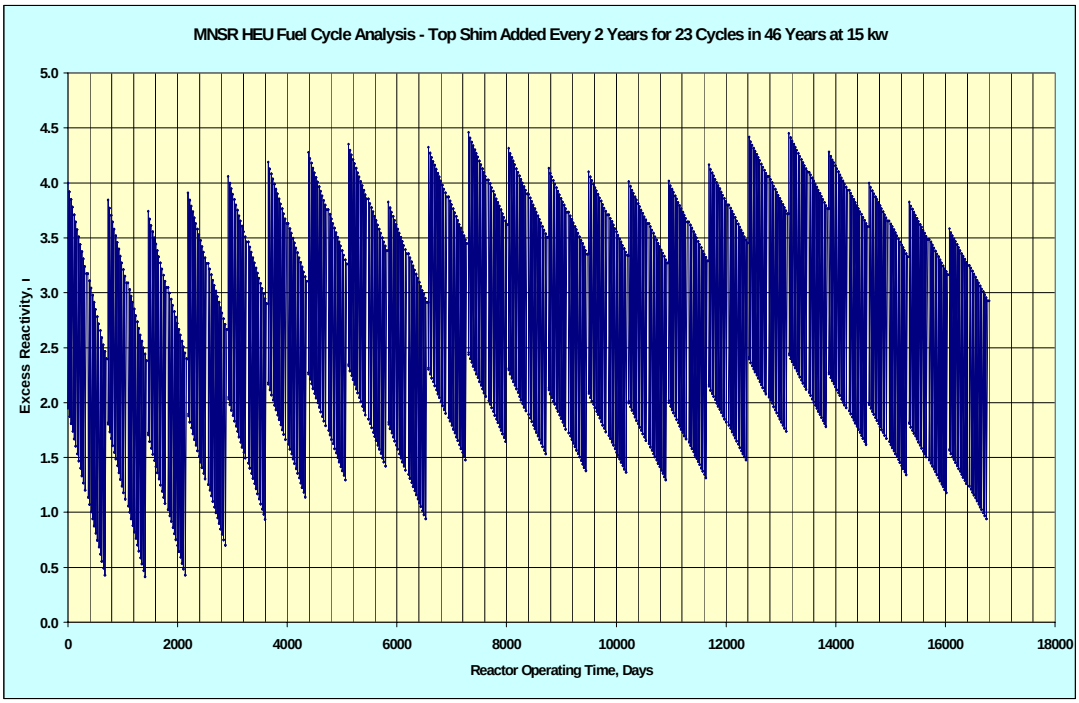

Figure 10. MNSR HEU Core Fuel Cycle With Top Be Shim Added Every 2 Years for 23 Cycles in 46 Years. (Based on 15 kW-64 hours/month fuel cycle scheme. Top shim plates are added such that ~ 4.0 mk excess reactivity is obtained at the beginning of each cycle and a minimum of ~ 2.3 mk excess reactivity is maintained at the end of each cycle).

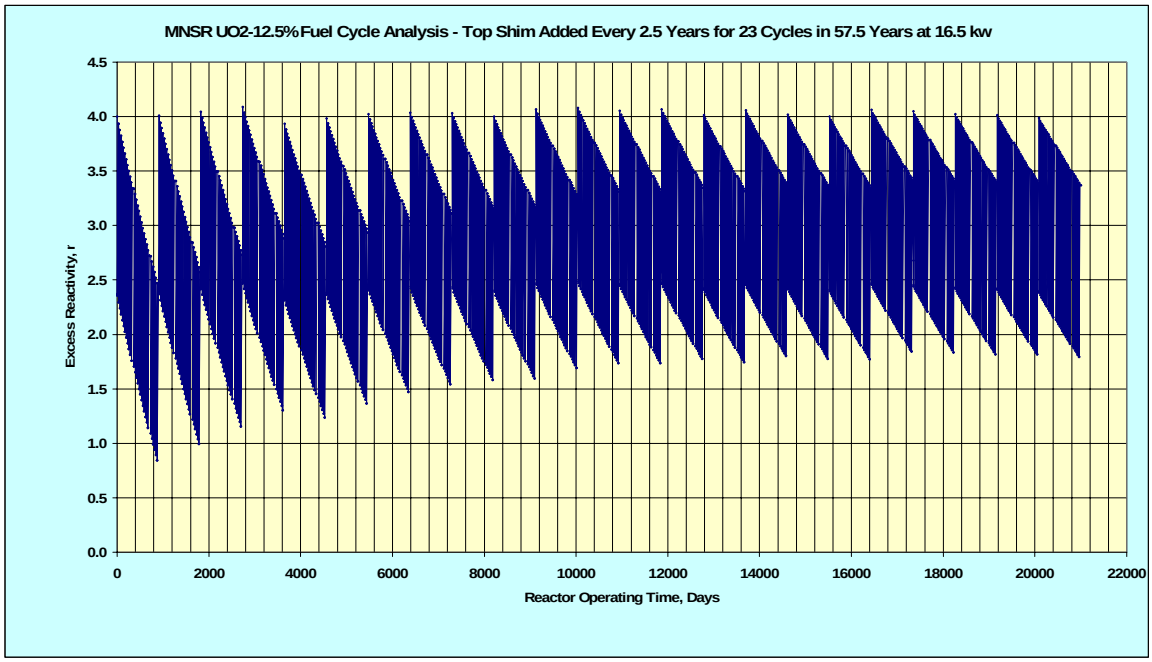

Figure 11. MNSR LEU Core Fuel Cycle With Top Be Shim Added Every 2.5 Years for 23 Cycles in 57.5 Years. (Based on 16.5 kW-64 hours/month fuel cycle scheme. Top shim plates are added such that ~ 4.0 mk excess reactivity is obtained at the beginning of each cycle and a minimum of ~ 2.3 mk excess reactivity is maintained at the end of each cycle).

The cumulative top Be shim added over the 23 cycles is shown in Figure 12 for both HEU and LEU cores. For the last three cycles, the total Be thickness is at 10, 12 and 16 cm, which is probably beyond the limit of the top Be shim tray design.

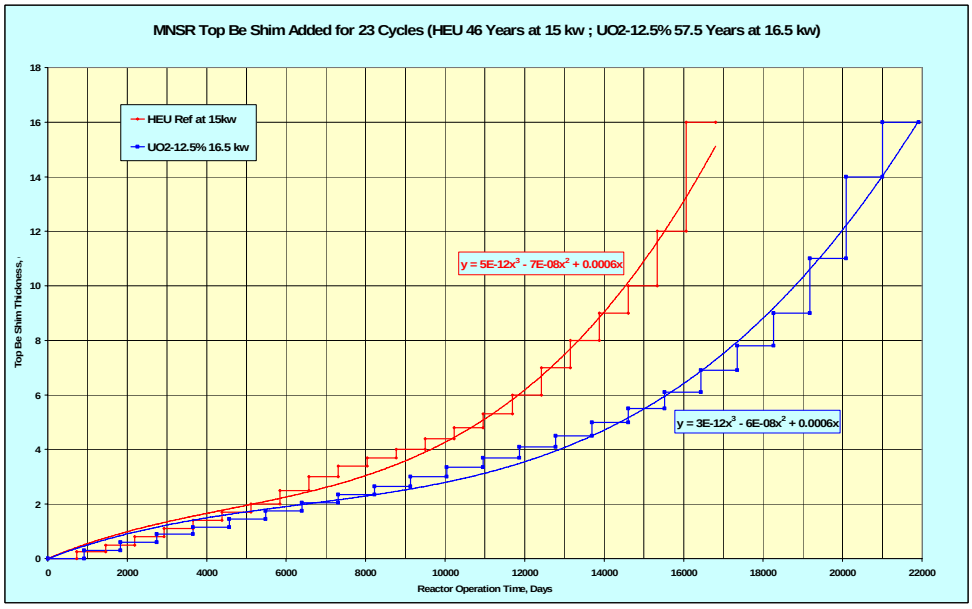

Figure 12. Cumulative Thickness (cm) of Top Be Shim Added for 23 Cycles **(**For HEU core at every 2 year interval in 46 years based on a 15 kW 64 hours/month fuel cycle scheme. For LEU core at every 2.5 year interval in 57.5 years based on a 16.5 kW 64 hours/month fuel cycle scheme).

CONCLUSION

In summary, an MNSR core using LEU-UO_2-12.5% fuel can be operated for 23 shim cycles (cycle length 2.5 years) in 57.5 years at 16.5 kW power level. All 23 LEU cycles meet the 4.0 mk excess reactivity required at the beginning of cycle. For comparison, the MNSR HEU reference core can only be operated for 23 shim cycles (cycle length 2.0 years) in 46 years at 15.0 kW power level.

It is concluded that an MNSR core with LEU UO_2-12.5% fuel and a power level of 33 kW can be operated ~25% longer than the current HEU core operated at 30 kW. Both cores will have the same thermal neutron flux in the experiment positions. We expect that these same conclusions will be obtained when this core lifetime analysis is performed using an LEU fuel pin with a UO_2 pellet diameter of 4.2 mm, a Zirc-4 clad outer diameter of 5.1 mm, and 12.0% uranium enrichment.

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