The Effect of Intermittent Operation on Local Fission Rate in the McMaster Nuclear Reactor

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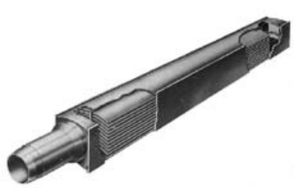
Abstract

The McMaster Nuclear Reactor operates on a 16-hr/day/5-day/week schedule causing cyclic loading of Xenon in the core and requiring compensation by the control systems to maintain operations. The constant control rod interaction affects local fission rates. This paper confirms the relationship between Xenon load and control rod movement and studies the relationship between local fission rate and control rod insertion. The results provide information related to analysis approximations used in depletion calculations. In addition, comparisons are made between the current MNR operation cycle and a proposed continuous operational approach. The results are further discussed in the context of proposed Molybdenum-99 production at MNR.

1. Background

The McMaster Nuclear Reactor (MNR) is a light water swimming pool type research reactor. The reactor currently operates at 3MWth on an intermittent schedule of weekdays from 8:30am to 11:00pm and some Saturdays from 8:30am to 4:00pm. The reactor is a robust and flexible platform used for research education and isotope production (primarily I-125).

MNR fuel is plate style, Low Enriched Uranium (19.75% enriched) held in assemblies that are approximately 8cm x 8cm with 60cm of active height, see Figure 1. Each standard fuel assembly contains 18 plates (the inner 16 contain fuel). The core is defined by a 9x6 rectangular grid plate. A representative fuel loading pattern, used for analysis purposes, is the Reference Core configuration, defined as 28 standard fuel assemblies and six control assemblies (see Figure 2).



	9	8	7	6	5	4	3	2	1
A	W	G	W	LEU 25%	LEU 25%	LEU 25%	LEU 50%	Be	W
B	W	G	LEU 25%	LEU-C 35%	LEU 50%	LEU-C 0%	LEU 25%	LEU 50%	W
C	W	G	W	LEU 25%	CIF	LEU 0%	LEU 50%	LEU-C 18%	LEU 0%
D	G	G	LEU 25%	LEU 0%	LEU 25%	LEU 0%	LEU 50%	LEU 0%	LEU 50%
E	W	G	LEU 0%	LEU-C 35%	LEU 25%	LEU-C 0%	LEU 25%	LEU-C 18%	LEU 25%
F	W	G	W	LEU 25%	LEU 50%	LEU 25%	LEU 25%	LEU 0%	W

Legend:
W = water
G = Graphite
Be = Beryllium
LEU = Standard fuel
LEU-C = Control fuel

Fuel type
Burnup

Figure 1 and 2: MNR Fuel Assembly Picture and LEU Reference Core Configuration [1]

Control is via five gang-operated Ag-In-Cd shim-safety rods and one stainless steel regulating rod. These absorber rods travel within six control-fuel-assemblies, which have a reduced number of fuel plates (9 per assembly). The shutdown system (SDS) is able to provide at least 70mk of negative reactivity into the core and the regulating rod is administratively limited to less than

6mk total worth [1]. Typically the shim-safety rod bank is positioned near the top of the core, ranging anywhere from ~65% to 100% withdrawn depending on the time from startup, day of the week and fuel depletion level. The single regulating rod moves automatically according to the core reactivity. The regulating rod will move through its range from 20% and 80% withdrawn (the range is restricted to comply with administrative limits) before requiring manual adjustment of the shim-safety rod bank. Factors influencing rod movement include fission product dynamics, fuel depletion and experimental sample movement.

1.1 Fission product poisons in MNR

The current operating schedule (referred to as "intermittent" operation, herein) results in daily/weekly fission product poison (FPP) transients that can impede startup towards the end of a fuel cycle. The main FPP of concern is Xenon-135, a direct fission product that is also produced from the decay of the fission product Iodine-135 as shown in the following decay chain [3].

$$\text{Fission} \rightarrow {}^{135}\text{Sb}^{\;1.6s} \rightarrow {}^{135}\text{Te}^{\;29s} \rightarrow {}^{135}\text{I}^{\;6.7h} \rightarrow {}^{135}\text{Xe}^{\;9.15h} \rightarrow {}^{135}\text{Cs}^{2\;My} \rightarrow {}^{135}\text{Ba (stable)}$$

It is generally simplified that Iodine is directly produced from fission as the half lives of Antimony (Sb) and Tellurium (Te) are very short compared to that of Iodine and Xenon. The reaction equations for Iodine and Xenon are presented below [2].

$$\frac{dI}{dt} = -\lambda_I I(t) + \gamma_I \overline{\Sigma}_f \phi_T \qquad (1)$$

$$\frac{dX}{dt} = -\left(\lambda_X + \overline{\sigma}_{aX}\phi\right)X(t) + \lambda_I I(t) + \gamma_X \overline{\Sigma}_f \phi_T \qquad (2)$$

Where γ_I and γ_X are the direct fission yields for Iodine and Xenon and σ_{AX} is the Xenon absorption cross-section. The Xenon-135 behavior in MNR is provided in Figure 3 for both the intermittent and continuous operation regime from an initial clean core startup. The half-lives of Xenon-135 and its parent isotope Iodine-135 are comparable to the duration of MNR operation and shutdown periods (Xe-135: 9.15Hrs, I-135: 6.7Hrs, [2]). Therefore, the concentrations are affected by the reactor's method of operation.

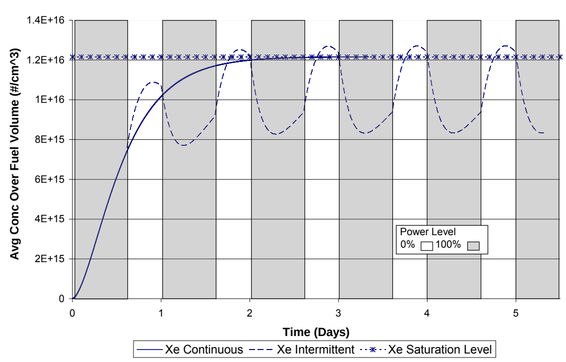


Figure 3: Xenon Concentration for Continuous and Intermittent Operation Regimes

Xe-135 has a very large neutron absorption cross section of nearly $3\text{x}10^6$ barns ($3\text{x}10^{-18}\text{cm}^2$) producing a significant effect on core reactivity and neutron absorption. The Xe-135 concentration in MNR peaks at approximately 6h 50min after shutdown as Xe-135 builds up due to the faster decay of its I-135 predecessor and then decreases as the I-135 is depleted and the Xe-135 continues to decay. When the reactor comes on power again the production from fission and burnup terms are relevant again. Initially Xe-135 concentrations will further decrease due to the increased loss from burnup until the I-135 inventory is replenished and concentrations rise back up to an eventual steady state value. In a continuous burnup case, this cycling behavior does not occur and instead, the Xe-135 levels build slowly to a steady state value.

1.2 Control movements in MNR

The change in inventory of any neutron absorbing fission products requires the reactor control rods to be moved in order to maintain the reactivity balance in the core. These control rod movements strongly affect the fission rate in their local area by influencing local flux levels. During intermittent operations, the shim-safety rods are withdrawn and inserted every day to start-up and shut-down the reactor and are adjusted throughout the operational shifts in order to compensate for the fluctuating neutron poison levels in the core.

Figure 4 displays a plot of rod positions for a one week period. The quoted error in the rod position measurements at any given time is approximately ± 0.5% withdrawn for the regulating rod and ± 0.2% withdrawn for the shim-safety rods (approx ± 0.03mk, ± 0.3mk respectively for mid range insertions, 20-80%) [4]. Early in the week there is little Xe-135 so the rods are inserted deeper to provide the necessary negative reactivity. Over the course of an operation week, Xe-135 builds up in the core and the shim-safety rods are moved out of the core.

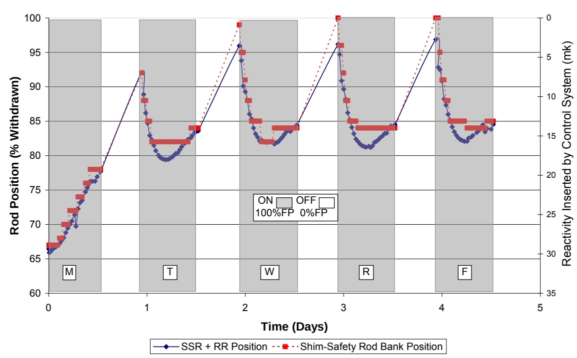


Figure 4: Relative Control Rod Positions in MNR Core for One Week [5]

The regulating rod movements are designed to compensate for small and rapid reactivity effects within the core and as previously stated stay within a range of 20-80% withdrawn with an administratively limited worth of 6mk. The regulating rod movements are common to both intermittent and continuous operations.

2. Effects of Fission Product Poisons on Control system movements MNR

The relationship between absorber rod position and Xe-135 cycling was confirmed by comparing operational rod position data (recorded every 30 minutes) to a reactivity balance calculation between the Xe-135 load and the control system rod worth [6] over an operational week.

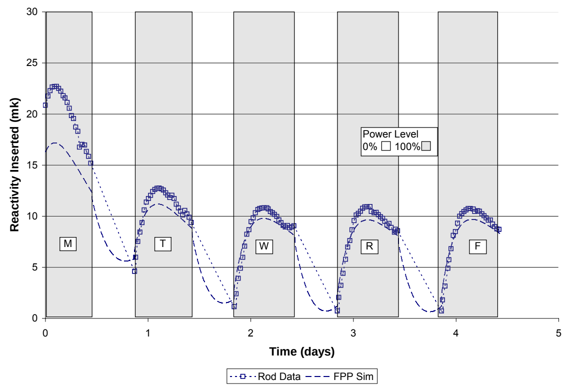


Figure 5: Comparison of Rod Position Data and FPP Simulation for One Week

The results of the comparison in Figure 5 show the high degree of correlation between the Xenon load simulation and the operational rod position data confirming that the control rod movements in MNR are primarily driven by the cycling of Xe-135. On Monday the required reactivity inserted by the control rods is considerably higher than any of the other days given the longer decay time over the weekend shutdown. Differences can be attributed to approximations used for inventory, system temperature, and initial conditions utilized in the calculations and other smaller worth perturbations such as sample and irradiation rig movement.

3. Simulation of MNR Operation Cycles

Previous work has shown that the presence of the control rods significantly reduces local fission rates not only in the rod-housing control fuel assemblies but also in the adjacent fuel assemblies [7]. The objective of this study was to quantify these effects over the typical operational cycle at MNR. Neutronic modeling was accomplished using the WIMS-ANL/REBUS-PC code combination. WIMS-ANL is a standard transport theory cell code used to provide microscopic cross sections for homogenized regions for use in full-core diffusion theory models using the fuel management code REBUS-PC [8]. Absorber material internal boundary calculations were calculated using a companion MCNP model [9]. In order to model the effects of the control systems on the fission rate, several core snapshots were made with the control rods at different positions. This study considers and compares three absorber rod movement scenarios: (i) approximating the intermittent operation movements of the absorber rods with an "average" position, (ii) a more detailed representation of the intermittent absorber rod movements, and (iii) rod movements associated with a suggested continuous operation schedule. These three scenarios are discussed in the following section.

3.1 Cases of study

A simplified approach to the incorporation of rod positions in research reactor calculations is to utilize an "average" rod bank position only. This ignores any effects related to the relatively short duration transition periods associated with rod movement following start-up and over the course of an operational period. It also does not include changes which occur over the lifetime of a core associated with fuel depletion (2 weeks of operations ~435MWh or 0.5% of full core burnup). At MNR, this approach is commonly adopted in both fuel depletion (and as such is inherently built into to inventory estimates), and longer term irradiation estimates. An average rod position is defined as effectively representing the "envelope period" shown in Figure 6. The average rod position of 83% is used for the shim safety rods and the regulating rod is held at 50% throughout the trial.

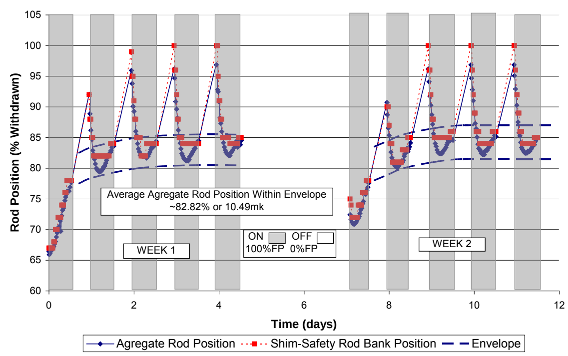


Figure 6: MNR Rod Position Data, Average Intermittent Rod Position Envelope [5]

In order to examine the effect of the average rod position approximation, a stylized rod position representation was defined based on a nominal ~14hr/5 day operation week. This representation is based on the recorded rod position data and has three phases, Monday Start-up, Daily Startup, and Daily Operating Envelope. The envelope period is the same as that used to derive the average rod approximation and during this phase the stylized curve is constant at this average value (83%). The stylized rod position approximation is shown in Figure 7.

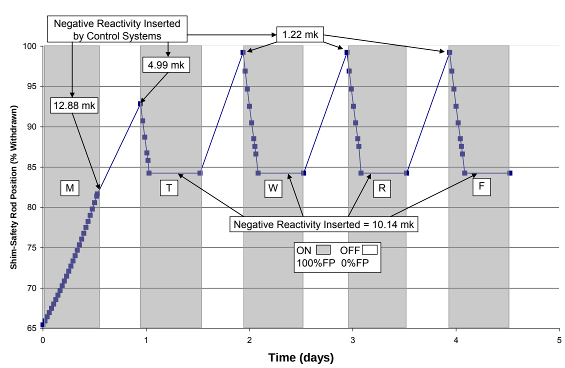


Figure 7: Stylized Shim-Safety Rod Positions (Regulating Rod at 50%), Intermittent Operations

A second comparison of interest is that of intermittent operation to continuous operations. This involves the reactor operating on a 24 hour schedule for several days followed by a few days of shutdown. A credible example would be operating from Monday morning to Friday Night and then shutting down over the weekend. This operation method significantly alters the Xenon behavior in the core. Since the reactor is continuously at power the Xe-135 will build from clean core conditions to a steady state value within about three days as seen in Figure 4. A stylized representation of the continuous operations schedule is shown in Figure 8.

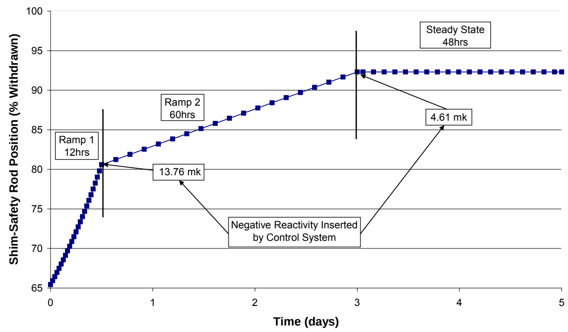


Figure 8: Stylized Shim-Safety Rod Positions (Regulating Rod at 50%), Continuous Operations

4. Effects of Rod Movements on Fission Rates

Fission rate results from the WIMS-ANL/REBUS-PC simulations are used to produce a map of relative fission rates in the core. A base comparison was made between two shim-safety rod positions (regulating rod held at 50% withdrawn), the Average rod approximation position (83% withdrawn) and the steady state rod position from the continuous case (92% withdrawn). The percentage differences in fission rates between these two cases were determined. The differences in average assembly fission rates were relatively insignificant (±1-2%). Figure 9 shows the differences in fission rate over the axial height of the fuel (between Daily Envelope and Steady State rod positions, [DE-SS]/DE) for selected fuel assemblies, 6B (control assembly), 2E (regulating rod assembly), 4C (highest power, central standard fuel), and 5D (high power central assembly). The differences are as high as 30% in the top axial nodes of the control sites.

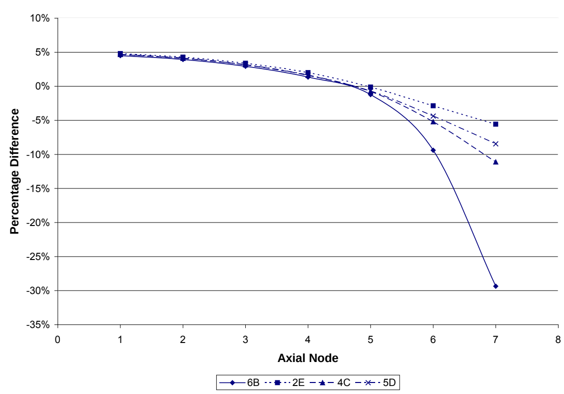


Figure 9: Axial Profile of Percentage Difference in Fission Rate Between Daily Envelope and Steady State Rod Positions [DE-SS/DE], Assemblies 6B, 2E, 4C, 5D

Average fission rates change by at most on the order of 10% for the entire range of typical shim safety rod movement (*i.e.* 65-100% withdrawn). However, there are more notable effects seen within the fuel assemblies. Figures 10 and 11 track the effects of rod position on the axial fission rates in assembly 6B and 4C respectively.

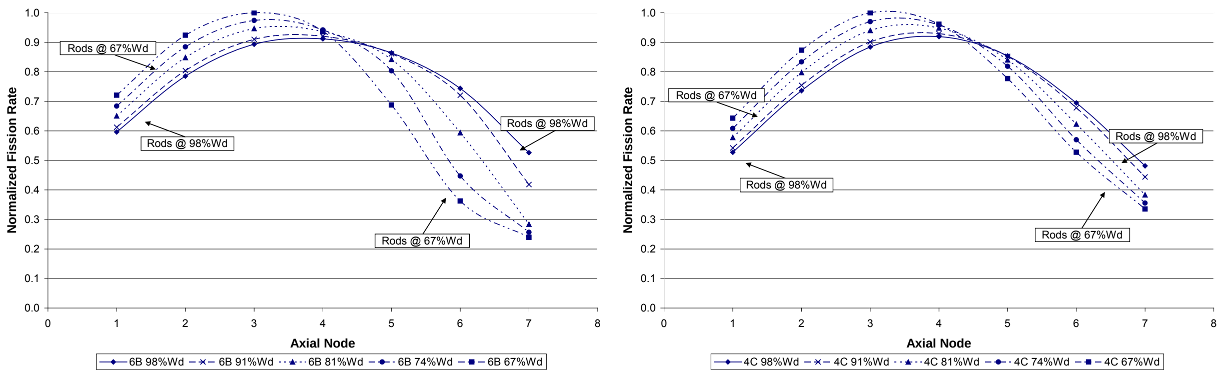


Figure 10 and 11: Effects of Shim-Safety Position on Axial Fission Rate for Assembly 6B and 4C, Regulating Rod at 50% for all Trials, [Normalized to max fission rate (node 3 rods 67%Wd)]

The fission rate in the upper axial nodes (5-7) increases as the rods are withdrawn from the core due to the reduction in local neutron absorption. The lower axial nodes experience the opposite effect since the flux pushing effects of the rods is reduced as they are removed from the core. The changes in the fission rate and the skewing of the parabolic shape are more prominent in the control assembly, 6B, as it is directly interacting with the shim-safety rod.

5.0 Fission Rates during the Operation Cycle

Using the information from the previous sections, the integrated fission rate for the three approaches can be determined. This can be expressed as the number of fissions per MWh of operations and can be found for the full core, a single assembly or an axial node in an assembly.

5.1 Comparison of Average to Detailed Rod Position Representation

The intermittent operations cycle employed by MNR is currently modeled using an average rod position approach where rods are set at a constant fixed position throughout the operational period and the transitions are considered to be negligible. The intermittent cycle is a more realistic model that follows rod movement closer and includes transition periods.

This comparison is based on a "standard week" of operations defined as 120hrs from Monday to Friday with on periods of 14.5h and overnight shutdowns of 9.5h. Therefore, the reactor is operating on power at 3MW for 72.5 hours each week and is off for the remainder of the time, resulting in 217.5MWh of burnup per week. Figure 12 shows the rod insertion levels for both approaches over the course of the standard week.

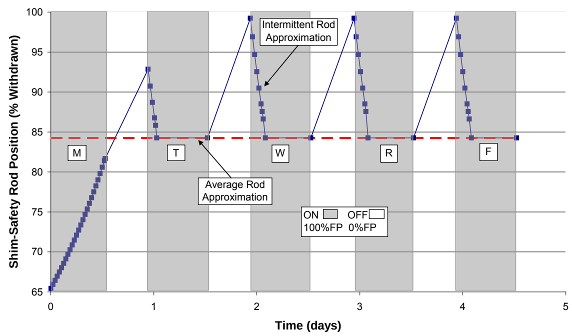


Figure 12: Safety-Shim Rod Positions (Regulating Rod at 50%), Average Rod Approach and Intermittent Operations Approach

The two approaches to approximating rod position will result in different local and global fission rate results during a week of operations. The fission rates for both approaches are integrated over the full 217.5MWh of operations during the week. The integrated fission rate is simply fissions/sec * time in sec producing fissions per week. The value of Fissions/MWh is (fissions/week)/(MWh/week).

The differences in average assembly fission rates calculated by the two approaches are insignificant (<1%). When the investigation is extended to individual assemblies exploring the axial variation in fissions/MWh more significant results are found. Figure 13 displays the percentage differences in the axial nodes for assemblies 6B, 2E, 4C and 5D.

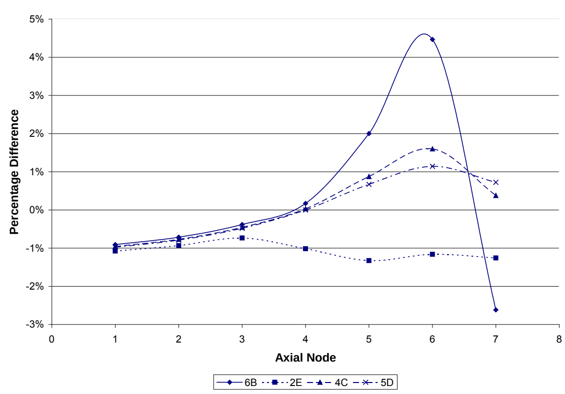


Figure 13: Percentage Difference in Fissions/MWh in Axial Nodes between Average Rod Position Approach and Intermittent Rod Position Approach [(Avg-Int)/Avg]*100%

As seen in Figure 13, the effects of the modeling approach on axial Fissions/MWh are more pronounced that those averaged over the assembly. The control assemblies (*e.g.* 6B) are the most affected and exhibit larger differences in the top 3 axial nodes. For 6B, the largest difference is in axial node 6 of 4.5%, this is due to the Monday start-up period included in the intermittent case where the rods are deeper in the core causing a direct effect on the local fission rates in node 6. At node 7 the intermediate case shows more Fissions/MWh due to the fact that in the early portions of the Wednesday to Friday start-up periods the control rods are almost completely out of the core to start and gradually move in, hence absorbing fewer neutrons than in the average rod position approach. The regulating rod assembly, 2E, remains relatively consistent about an average of -1.1% for all the nodes since the regulating rod is maintained at 50% withdrawn for both approaches. The fluctuations about the average are caused by effects from the shim-safety rods. The high-power central assemblies, 4C and 5D, tend to follow the control assembly with slightly smaller results since they are further away from the control rod interaction. In axial node 7 however, the high-power assemblies experience slightly more Fissions/MWh in the average case since the consistent insertions of the control rods alter the core flux shape increasing the neutron concentration about the top of these assemblies.

The difference over the full core between the two approaches is quite small but the local differences in the specific assemblies and the upper axial nodes are notable. The control sites experience the most change for the given assemblies and axially, node 6 is the most affected. In a typical control assembly, axial node 6 can differ as much as 4.5% due to the Monday start-up. Power density in the regulating rod assembly is reduced almost evenly along the assembly length when an intermittent approach is considered due to the changes in the flux distortions caused by more accurate representations of the rods.

5.2 Comparison of Intermittent & Continuous Operation Cycles

The current intermittent operations strategy is compared to a proposed continuous operations schedule with constant 24hr operations for 5 days followed by a shutdown period. In this continuous case the rods withdraw from the core up to a steady state level. The rod movements over the week for both operation schemes are shown in Figure 14.

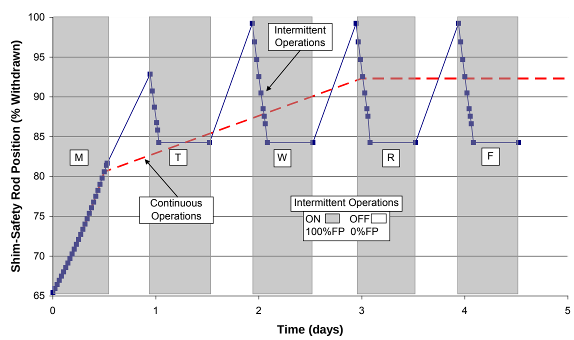


Figure 14: Shim-Safety Rod Positions (Regulating Rod at 50%), Continuous and Intermittent Operations

The continuous operations cycle is defined as 120 hours at the full power level of 3MW resulting in 360MWh. The intermittent cycle spans five days of 14.5 hours of operation each at the full power level of 3MW resulting in 217.5MWh. In MNR 1% of the full core burnup takes about 34MWd or 818MWh given end of life targets of 50% burnup for standard fuel and 35% burnup for control fuel assemblies [10]. The percentage difference in Fissions/MWh between the continuous and intermittent cases [(Cont-Int/Cont)*100%] averaged over each assembly produce insignificant differences (±1-2%) between the two operation regimes.

Notable differences in Fissions/MWh are found along the axial length of the core for the two operating regimes. The percentage difference in Fissions/MWh along the axial length of assemblies 6B (Shim-Safety Rod Assembly), 2E (Regulating Rod Assembly), 4C (Highest Power Assembly) and 5D (Central High Power Assembly) is provided in Figure 15.

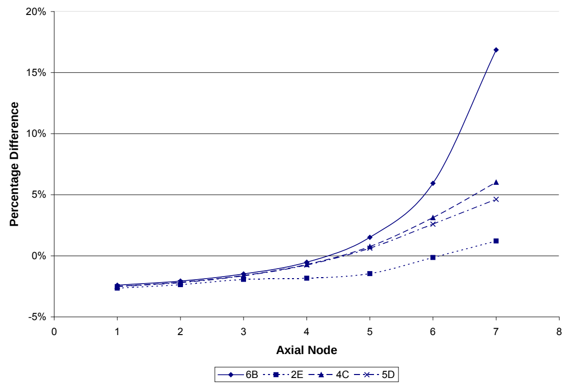


Figure 15: Percentage Difference in Fissions/MWh in Axial Nodes between Continuous and Intermittent Operations [(Cont-Int)/Cont]*100%

The control assemblies such as 6B are significantly affected by the operating regime especially in the upper axial nodes. The fissions/MWh is increased by as much as 16.9% in the top of the assembly during continuous operations, due to the reduced shim-safety rod interactions. The regulating rod position, 2E, experiences a reduction in fission rates for most of the axial length of -2.64% to -0.14% except in the top node with an increase of 1.22%. This is due to the reduced flux pushing found in the continuous regime. The central high power assemblies, 4C and 5D, follow a similar curvature to that of 6B but only reach differences of 6.0% and 4.6% respectively. This is the result of less neutron absorption from the control rods and a more stable Xe-135 cycle.

6. Application to the Production of Molybdenum-99

Recently MNR has considered revisiting Mo-99 production prompted by the current problems at the NRU reactor. The fission based process has been used before at MNR in the 1970s during an NRU extended outage. Fuel targets used in MNR can be either high or low enriched uranium targets (HEU or LEU). The targets, used previously, are similar to standard MNR fuel except with removable and segmented fuel plates. Since Mo-99 is a fission product, the production of Mo-99 in the irradiation targets is directly proportional to the fission rate in the specific target (the fission yield of Mo-99 is approximately 6% for U-235 fission [11]). Subsequently, the relations between fission rate and rod position are directly applicable to that of Mo-99 yield.

For the purposes on Mo-99 production the control assemblies are not available as irradiation sites but the central high power core positions such as 5D, 4C, 4D, 3C and 3D are suitable for use. Less central assemblies such as 3B and 3E are also useful, allowing spreading out of the fresh fuel and reducing the reactivity concerns of excessive fresh fuel packed into high power areas.

The estimated yield of Mo-99 is directly related to the rod position model used during burnup calculations. As evidenced in Section 5.1, there is a difference between the local fission rates when using an average rod position model and a more realistic stylized intermittent rod position model especially in the top portions of the fuel assemblies. The choice of rod position model will therefore affect the predicted fission rates and hence Mo-99 yields. The percentage difference in fission yields for the Mo-99 irradiation sites between the average and stylized intermittent rod position models is provided in Figure 16. As per this data the Mo-99 yield will be slightly over predicted in the upper nodes up to 1.6%, and under predicted in the lower nodes, by as much as 1%, when using the average rod position model. Over the full axial length the full difference is not significant (maximum 0.13%).

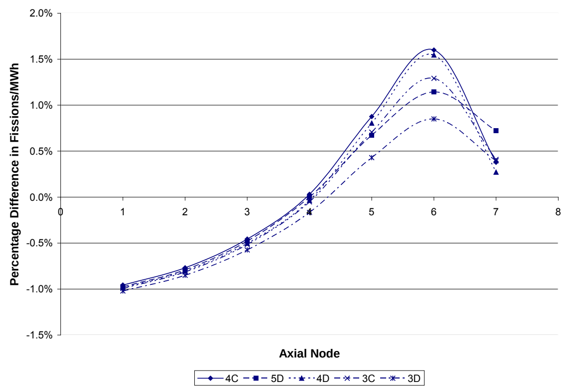


Figure 16: Percentage Difference in Fissions/MWh in Axial Nodes between Average Rod Position Approach and Intermittent Rod Position Approach [(Avg-Int)/Avg]*100%

Since Mo-99 production is directly tied to fission rate a more constant cycle will allow for more consistent production and a quicker turnaround time. Also, Mo-99 production is more efficient at higher power levels. In MNR power levels >3MWth require a continuous operations strategy as the use of intermittent operations produces Xe cycling that exceeds the compensation capabilities of the control system. Therefore we can compare the effects of utilizing a continuous operations strategy as described in Section 5.2.

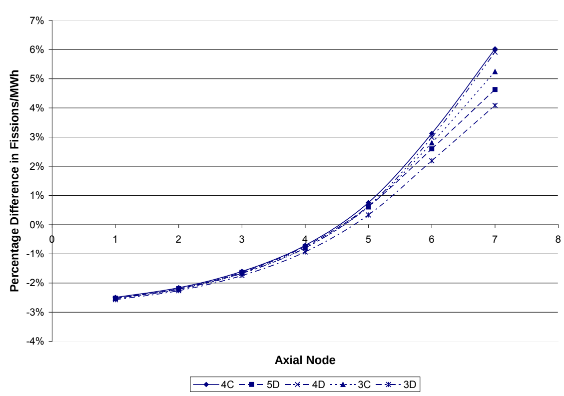


Figure 17: Percentage Difference in Fissions/MWh in Axial Nodes between Continuous and Intermittent Operations [(Cont-Int)/Cont]*100%

As seen in Figure 17, the difference in fissions/MWh is quite significant in the possible Mo-99 production sites especially near the top of the fuel assembly. The yield/MWh is 4-6% higher for a continuous operating strategy in the top node due to less interaction of the control rods in the smoother continuous operation strategy. The continuous operation strategy also operates for 360MWh per week compared to 217.5MWh in the intermittent case providing more irradiation time (~39.6%) and producing the required yields of Mo-99 in less time (clock time).

These investigations show that a more realistic rod position representation increases the accuracy in estimating fission rates and isotope yields on the order of 1-2% axially. The average rod position approximation does not appear to introduce any significant inaccuracies in terms of average assembly yield. In addition, the use of a continuous operation strategy provides for a smoother and more efficient method (as related to high power operation) for isotope production. These results generated can be used in further Mo-99 production optimization studies at MNR.

7. Conclusions

The control rod positions have a noticeable affect on the local fission rates in MNR. The fission rate is most affected in the top of the assemblies (the shim-safety rod bank is inserted from the top of the core). The current weekday operation cycle of intermittent day time only produces a cycling of the fission product poison Xe-135, which requires the control system to interact with the core to compensate and maintain the reactivity balance. The effects of control rod position on fission rate are shown to be linear and most significant in the control assemblies.

The choice of modelling approximation for the shim-safety rods during burnup studies will affect the accuracy of calculations. In the current method of using an average rod position, the average assembly fission rates are not significantly affected by the approximation but the axial values experience more pronounced effects near the top of the core (over predictions as high as 4.5%)

The current operating strategy in MNR generates the Xe-135 cycling that forces the compensating control rod movements. A continuous operation strategy will smooth this cycling and lead to a more stable rod movement cycle. The effects on average assembly fission rates were insignificant but axial effects on the order of a 17% increase in Fissions/MWh for control assemblies and 4-6% increase for standard assemblies are noted.

The effects of the average rod approximation and the move to continuous operations are directly applicable to potential fission Mo-99 production in MNR. The average rod approximation has minimal effects on predicted Mo-99 production rates (axial variations of ~1.5%). The continuous operations strategy showed axial variations of 4 to 6% in the upper nodes and provided a more stable cycle (in terms of Xe-135 oscillation) and potentially a more efficient cycle (considering a move to higher power) for Mo-99 production.

8. References

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