Reactor Power Detector Shadowing Effects and the Possibility of Violating Licensed Reactor Power Limits

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Abstract

The measurement of core-wide reactor thermal power relies on neutron-sensitive power detectors that are calibrated to a neutron flux in a discrete location. It is proposed that this value can change significantly if a reactor is operated in a manner where the neutron flux distribution or profile throughout the core is not representative of the profile that existed when the power detectors were calibrated. This phenomenon raises the possibility that the power detectors could measure a reactor power level that is not representative of core-wide power. To study this possibility, the Oregon State TRIGA® Reactor (OSTR) MCNP model is used to predict detector responses both in a banked-rod configuration at 1.06 $\mathrm{MW_{th}}$ and in various titled configurations, such as one rod completely withdrawn, at 1.1 $\mathrm{MW_{th}}$. It is proposed that if the detector responses are similar in both cases it is possible to unknowingly violate licensed reactor power limits due to extreme neutron flux distribution asymmetries.

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1. Introduction

Previous work at the Oregon State TRIGA® Reactor (OSTR) [1] sought to determine the cause of disagreement between measured and calculated reactivity worth of the shim and transient control rods at beginning of core life in 2008 despite the OSTR MCNP® model having a low reactivity bias of \$0.07±0.04 at beginning of core life. It was believed that control rod shadowing effects were influencing the response of the fission chamber power detector by causing an under response or shadowing of the detector, resulting in skewed time of power rise measurements using the rod pull calibration method. This work found that neutronic shadowing of the fission chamber detector is negligible compared to actual control rod shadowing effects where control rods neutronically interact with one another, and their reactivity worth at any one withdrawn position is a function of the positions of the other three due to changes in the neutron flux distribution in the core.

This effect raised the question of whether the OSTR could be operated in a manner where total core power exceeds the licensed steady-state power limit of 1.1 $\mathrm{MW_{th}}$, despite the reactor power measuring channels reading nominal 1.0 $\mathrm{MW_{th}}$ due to localized flux/power peaking in regions of the core furthest from the power detectors. It was proposed that such a situation could be the result of operating the reactor in an extremely ”tilted” or non-banked configuration where one control rod is completely withdrawn and the other three more inserted than they would be in a banked configuration, causing a flux distribution across the core that is different than that which the detectors were calibrated to in a banked configuration at 1.0 $\mathrm{MW_{th}}$.

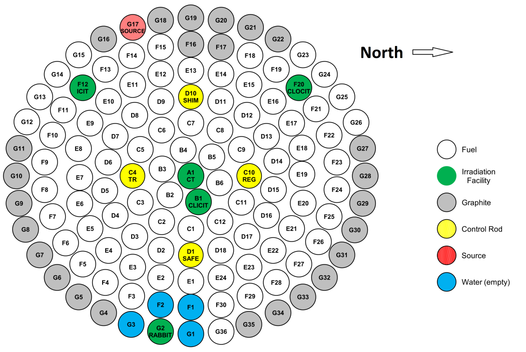

Figure 1: OSTR CLICIT core configuration.

This raises the possibility that the reactor power detectors could see a flux corresponding to 1.0 $\mathrm{MW_{th}}$ despite total core power being higher. However, it is believed that it would be difficult to operate the current cadmium-lined in-core irradiation tube (CLICIT) core configuration in such a way that total core power unknowingly exceeds the license limit because of diverse detector placement radially and axially around the core. A diagram of the OSTR CLICIT core configuration is shown above in Figure 1, and Figure 2 below is a rendering of the OSTR MCNP model with control rods and reactor power detectors labeled.

Any flux distribution or profile tilt that results in a reduced response of one detector should cause an increased response of another. One possibility is to operate with the shim rod in grid position D10 fully withdrawn. This moves the location of peak power and neutron flux from the SW region region of the core to the NW region, which is furthest from the three power detectors. The OSTR MCNP® model was used to investigate this effect using volume-averaged flux tallies in fuel elements and running a k-eigenvalue problem with both the control rods banked at 67% withdrawn and non-banked with the shim fully withdrawn and the other three at 42.5%. The change in distribution for the CLICIT core is shown in figures 3 and 4. It may be possible to increase the localized power in this region and achieve a total core power of 1.1 MW_{th} while maintaining the same flux incident on the detectors as that at a total core power of 1.0 MW_{th}.

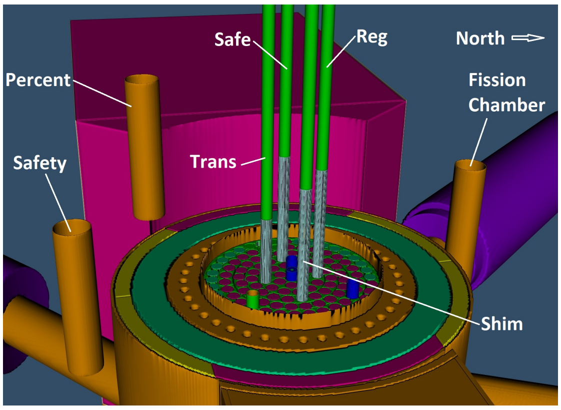

Figure 2: GXSView rendering of the OSTR MCNP® model.

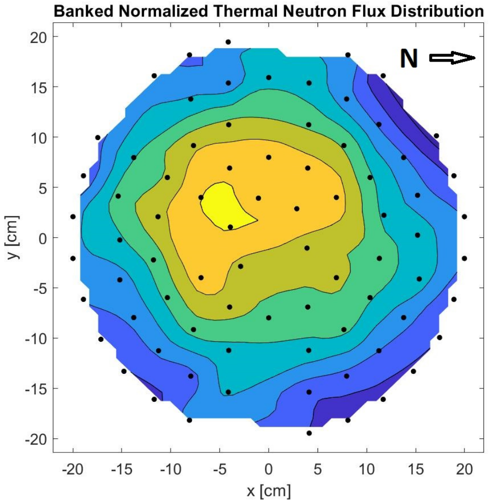

Figure 3: Banked thermal neutron flux distribution in the OSTR core.

2. Methods

To investigate this possibility, the three detector volumes were added to the OSTR model and volume-average flux tallies taken in each fuel element and the detector volumes. Two flux multiplier cards are used where one normalizes the flux tallies for a reactor power of of 1.06 MW_{th} and the other for 1.1 MW_{th}. 1.06 MW_{th} is chosen versus 1.0 MW_{th} because this is the SCRAM set-point for the percent power and safety power measuring channels. The idea is to compare the volume-averaged thermal flux incident on each detector in both a banked configuration at 1.06 MW_{th} and a non-banked configuration at 1.1 MW_{th}. If the amount of thermal flux incident on a particular detector is similar in both situations then it would suggest that the detector cannot distinguish between a total core power of 1.06 MW_{th} and 1.1 MW_{th} for the given core flux distribution.

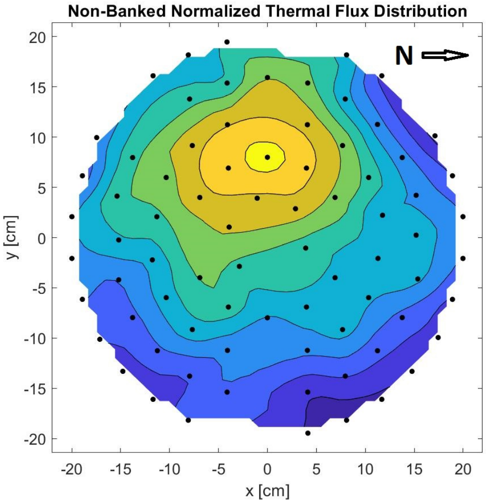

Figure 4: Non-banked thermal neutron flux distribution in the OSTR core.

Additionally, an alternative core configuration was proposed in hopes of maximizing the peaking effect in the NW region of the core by moving the cadmium-lined irradiation tube from F20 to F24 and replacing graphite elements in the western region with fuel from the North and South. This hypothetical core configuration is shown in Figure 5.

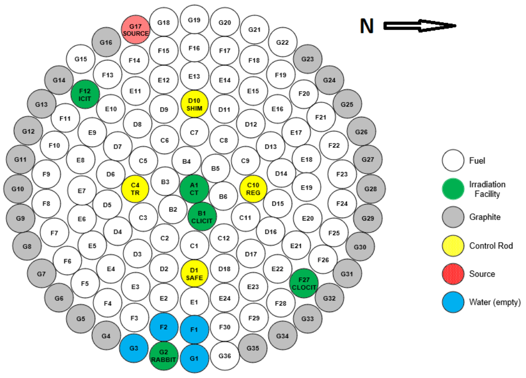

Figure 5: OSTR alternate core configuration.

A non-banked situation is created for both the real CLICIT core and hypothetical core configurations by setting the shim rod to fully withdrawn and incrementally withdrawing the other three until a k_{eff} of approximately 1.0 is achieved.

A k-eigenvalue problem is run for all four models with two million neutrons per cycle for 100 cycles with 50 active cycles. A significant problem encountered was a lack of neutrons being tallied at the percent power detector volume which is located 1.16 meters above core axial center. Very few fission neutrons survive beyond 1 meter in light water [2] and the neutron

Table 1: CLICIT Core Percent Chamber

Energy Group	Banked 1.06 MW_{th} [n/cm^{2}s]	2σ error [%]	Non-Banked 1.1 MW_{th} [n/cm^{2}s]	2σ error [%]
Thermal	3.693E+09	±4.40%	4.141E+09	±4.58%
Epithermal	1.338E+09	±9.74%	1.375E+09	±9.92%
Fast	2.878E+09	±7.22%	3.055E+09	±7.32%

Table 2: CLICIT Core Safety Chamber

Energy Group	Banked 1.06 MW_{th} [n/cm^{2}s]	2σ error [%]	Non-Banked 1.1 MW_{th} [n/cm^{2}s]	2σ error [%]
Thermal	3.145E+10	±1.58%	3.620E+10	±1.54%
Epithermal	1.153E+10	±3.16%	1.341E+10	±3.02%
Fast	1.444E+10	±3.10%	1.662E+10	±3.00%

Table 3: CLICIT Core Fission Chamber

Energy Group	Banked 1.06 MW_{th} [n/cm^{2}s]	2σ error [%]	Non-Banked 1.1 MW_{th} [n/cm^{2}s]	2σ error [%]
Thermal	1.086E+11	±1.44%	1.193E+11	±1.44%
Epithermal	4.938E+10	±2.92%	5.635E+10	±2.94%
Fast	1.492E+11	±1.22%	1.663E+11	±1.22%

Table 4: Alternate Core Percent Chamber

Energy Group	Banked 1.06 MW_{th} [n/cm^{2}s]	2σ error [%]	Non-Banked 1.1 MW_{th} [n/cm^{2}s]	2σ error [%]
Thermal	3.472E+09	±6.46%	3.800E+09	±7.10%
Epithermal	1.114E+09	±14.84%	1.252E+09	±16.04%
Fast	2.390E+09	±11.18%	2.425E+09	±12.66%

Table 5: Alternate Core Safety Chamber

Energy Group	Banked 1.06 MW_{th} [n/cm^{2}s]	2σ error [%]	Non-Banked 1.1 MW_{th} [n/cm^{2}s]	2σ error [%]
Thermal	2.779E+10	±2.34%	3.022E+10	±2.56%
Epithermal	9.843E+09	±4.78%	1.034E+10	±5.30%
Fast	1.273E+10	±4.66%	1.333E+10	±5.06%

Table 6: Alternate Core Fission Chamber

Energy Group	Banked 1.06 MW_{th} [n/cm^{2}s]	2σ error [%]	Non-Banked 1.1 MW_{th} [n/cm^{2}s]	2σ error [%]
Thermal	9.473E+10	±2.22%	9.607E+10	±2.44%
Epithermal	4.267E+10	±4.50%	4.363E+10	±5.18%
Fast	1.277E+11	±1.90%	1.326E+11	±2.06%

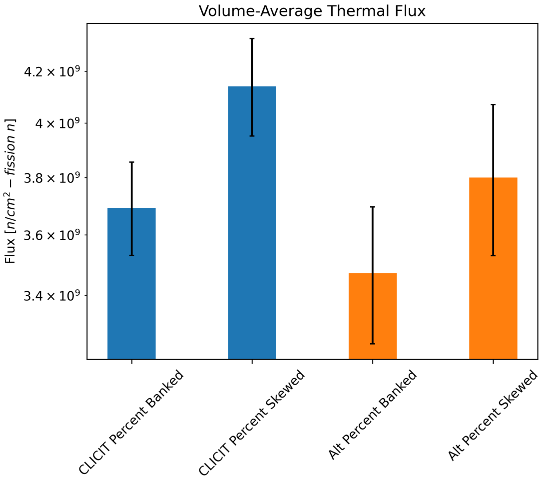

Figure 6: Percent power detector tally results.

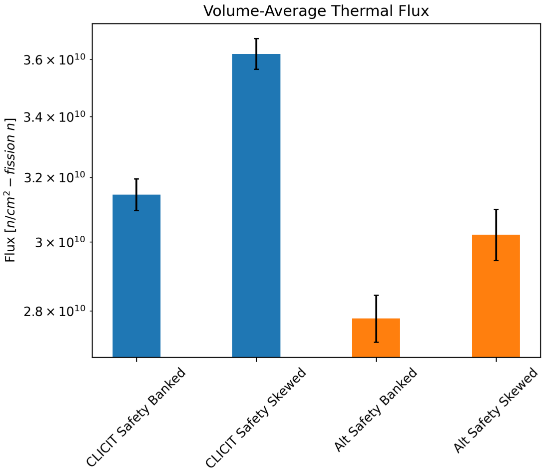

Figure 7: Safety power detector tally results.

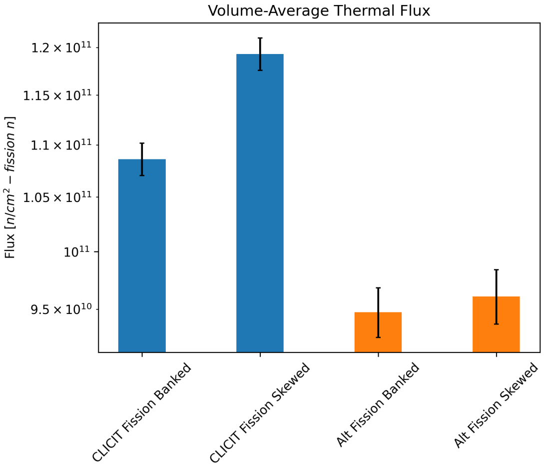

Figure 8: Fission chamber power detector tally results.

population in the actual system is many orders of magnitude beyond what can be modeled in terms of current computational capabilities. To overcome this, the percent chamber height was reduced to 40 cm above core axial center to arrive at a tally relative error similar to the other two detector tallies. An energy binning card is used to tally thermal neutrons below 0.5 eV, epithermal neutrons from 0.5 eV to 100 keV, and fast from 100 keV to 2 MeV. While all three energy groups are considered, the most importaint for detector response is the thermal flux as the percent and safety power detectors are uncompensated ion chambers that rely on the ^{10}B(n,α) reaction and the fission chamber relies on fission of ^{235}U for ionization and response.

3. Results/Discussion

The volume-average flux tallies for the CLICIT core and alternate core detector volumes are shown in Figures 6 - 9 and values are listed in Tables 1 - 6. If both the banked 1.06 MW_{th} and non-banked 1.1 MW_{th} thermal flux values fall within one another's 2σ relative errors for a particular detector, it suggests that it is possible the detector may not be able to distinguish between the two total core powers because the flux tilt in the non-banked situation is resulting in a similar flux incident on the detector, despite the higher total core power.

For the CLICIT core configuration all flux values incident on the detectors in the two situations are unique and fall outside of each other's relative errors with the exception of the percent power detector epithermal and fast flux. However, the relative errors on the percent power detector tallies are high relative to the other detectors, likely due to distance from the core, and the thermal flux incident on the detector has a greater influence on detector response. These results suggest that operating the current OSTR CLICIT core in this particular non-banked manner is unlikely to result in unknowingly violating a license limit.

For the alternate core configuration all flux values incident on the detectors in both situations fall within each other's relative errors with the exception of the safety power detector thermal flux values. These results for the alternate core configuration would suggest that it may be possible to operate this core configuration in a way such that the detectors cannot distinguish between a banked 1.06 MW_{th} and non-banked 1.1 MW_{th}. It should be noted again that the relative errors on the percent power detector tallies are higher than other detectors and it may not be possible to make definitive conclusions from the percent power detector data.

The alternate core results suggest it may be possible to unknowingly violate a license limit by operating the OSTR in an extremely tilted manner, close to the SCRAM set-points, in certain core configurations. However, a power detector calibration would take place with any core configuration change. While these results are interesting, they are perhaps irrelevant in practical terms due to the fact that calibrations are performed following configuration changes. However, they do demonstrate why it is importaint to perform calibrations with any core configuration change. Additionally the results show the importance of the fact that, in the calorimetric method for calibrating power detectors, the calibration process is calibrating power detectors to a neutron flux distribution that existed during that process, and illustrates why operating in banked control configurations consistently is good operating practice.

Perhaps the most important takeaway is the results suggest that the current OSTR CLICIT core is resilient to violating its steady-state license limit of 1.0 MW_{th} due to operating in this manner, and this may be due to both operating a core configuration that minimizes power peak shifting effects and, perhaps more importantly, diverse detector placement around the core. Of interest for future study is the effect these tilted oper-ating configurations have on assemblies where all of the reactor power detectors are located on one side of the core.

4. Conclusions

The OSTR MCNP® was used to investigate whether it may be possible to unknowingly violate the steady-state license limit of 1.1 MW_{th} by operating the reactor with the shim rod completely withdrawn and at a power level close to the SCRAM set-point of 1.06 MW_{th}. It was proposed following an investigation of the effects of control rod shadowing on control rod calibrations that operating the reactor in such a way might result in a total core power exceeding 1.1 MW_{th} despite reactor power detectors indicating a value corresponding to 1.06 MW_{th}.

Power detector volumes were added to the OSTR model and volume-average flux tallies taken with multiplier cards corresponding to a total reactor power of 1.06 MW_{th} and 1.1 MW_{th}. The thermal flux incident on a particular detector was compared in both the control rods banked at 1.06 MW_{th} and the shim fully withdrawn at 1.1 MW_{th}. The results for the current CLICIT core configuration suggest that is is unlikely the steady-state power license limit can be violated by operating the OSTR in this manner.

A hypothetical alternative core configuration was investigated in the hopes of maximizing the power peaking effect in the NW region of the core and results for this configuration suggest that it may be possible to violate the license limit in particular core configurations or if power detector calibrations are not performed following configuration changes. The results also demonstrate the importance of diverse power detector placement around the assembly.

5. References

[1] Spoerer T., "Control Rod Shadowing Effects in Control Rod Calibrations of The Oregon State TRIGA® Reactor," M.S. Thesis, Oregon State University, Corvallis, 2022.

[2] Aronson R., Certaine J., Goldstein H., Preiser S, "Penetration of neutrons from a point isotropic fission source in water," United States Atomic Energy Commission, NYO-6267, 1954.