DEVELOPMENT OF THE MNR OSCAR-5 CORE FOLLOW AND RELOAD CALCULATIONAL MODEL FOR OPERATIONAL SUPPORT

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The McMaster Nuclear Reactor (MNR) is a medium-power open-pool MTR-type research reactor, located on the campus of McMaster University in Hamilton, Ontario, Canada. To better support operations, research, and production activities, a multi-code reactor calculational model has been developed, using the OSCAR-5 reactor analysis platform. This paper describes the model development, workflow construction, and verification and validation of the model, and highlights important features of the system. Operational support performance is shown in terms of multi-cycle core follow and reload analysis, and areas of future development and application are outlined. Focus is placed on demonstrating the capability of the system to utilize a single, code-independent reactor model which is synergistically deployed to both Monte Carlo and deterministic solvers.

1. Introduction

The McMaster Nuclear Reactor (MNR) is a medium-power open-pool MTR-type research reactor, located on the campus of McMaster University in Hamilton, Ontario, Canada. First critical in April 1959, MNR, licensed to 5MW$_{th}$, is Canada's only major neutron source and currently operates on a 5-day-per-week, 16-hour-per-day schedule, supporting a wide range of research and isotope production activities.

In the context of a growing user base, and future expansions of the application scope of MNR, work has been ongoing to enhance the level of calculational analysis support to the utilization and safety of the reactor. The overall vision for this work has been to create an integrated, expandable, and flexible analysis toolset, ultimately available to support operations, licensing, and research and development activities.

The overall improvement of the role and fidelity of computational analysis support to research reactor operation and safety is indeed an international trend, and is strongly supported by recent IAEA guidelines and projects on this topic [1][2]. This leads to the need for more accurate, multi-code, multi-physics approaches in performing research reactor analysis, and includes aspects such as depletion analysis, core design evaluation, model verification and validation, as well as established model management and documentation systems. More recent advances in research reactor modelling, which should also be taken into account at the outset of devising an analysis platform, include coupled neutronic and thermal-hydraulic analysis schemes, combined with the capability for propagating uncertainties through these solutions.

The effort in establishing such a computational platform for research reactors is an extensive multi-year endeavour; McMaster University embarked on this project five years ago. This paper describes the current technical outcomes of this work, the tools utilized, and the derived benefits obtained. Focus is placed on the developed schemes and workflows for model creation, core follow analysis, core reload design, and verification and validation. These developments are now at the necessary maturity to support planned enhancements at MNR with regard to expanded operational regimes and further utilization development.

2. The OSCAR-5 System

In order to establish the objectives as set out above, the OSCAR reactor calculational system, as developed by Necsa in South Africa, was selected [3]. The system is primarily used to support the operation of the SAFARI-1 research reactor at Necsa [3], South Africa, but is also applied at other international research reactors, i.e. HOR (TU-Delft, the Netherlands) [4], and HFR (NRG, the Netherlands) [5], as a reactor core follow and core reload design tool.

The OSCAR-5 system (the latest generation) aims to allow for multi-fidelity, multi-code, multi-physics support for research reactor analysis, with the primary aim to allow the use of fit-for-purpose tools in support of reactor operations. This release of the code system introduces a pre- and post-processing framework called RAPYDS (Reactor Analysis Python Driver System), which adds many system features and facilitates interaction with the various plugins (or connected physics packages). A schematic representation of the system is provided in Figure 1, illustrating the design scheme of generating geometry, material, and application input in a code-independent space and translating this information to use with actual target codes.

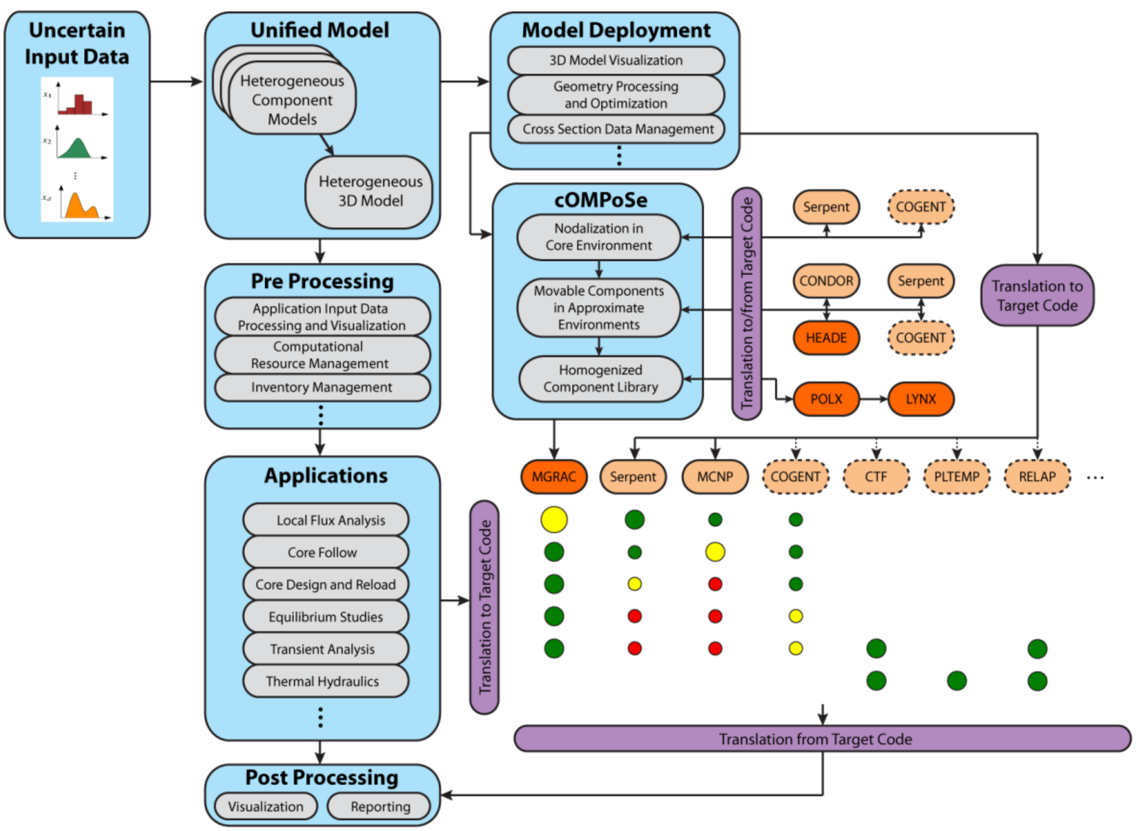

Figure 1: OSCAR-5 system schematic

The figure highlights some of the codes coupled to the system (dark orange indicates codes that are owned by Necsa and internal to the system, lighter orange indicates external codes for which coupling is in place, dashed outlines indicate coupling that is under development), and illustrates the relationship between a code and an application choice. In this mapping, the dot under each code illustrates the suitability of that code to the intended application. A green dot means that the code is perfectly suitable, a yellow dot means that it can be used but that it is not necessarily the best choice, and a red dot indicates that, although possible, the code is not well suited due to feature or resource limitations. The size of the dot indicates the error or level of uncertainty, typically associated with each code for that application. Although the illustration is of course conceptual, it provides some guidance on how to combine multiple codes for a synergistic application.

The main entry point into the system is the creation of a unified, code-independent reactor model, using the Constructive Solid Geometry (CSG) module of the system. This code-independent model is a central construct of the system. When actual calculations are to be performed, translators are used to write the geometry and material description of the model to the input for target physics codes. These translators are defined once in the system, and therefore do not depend on the model, and are generally developed to apply best-practice approaches to code input specification. This mechanism ensures that the model remains consistent when it is exported to multiple codes.

OSCAR-5 supports code input generation not only to heterogeneous code packages (such as MNCP and Serpent), but also to codes using homogeneous model representations (such as nodal-diffusion codes), via the sub-system called cOMPoSe (OSCAR Model Preparation System). The cOMPoSe sub-system is used to systematically move from the heterogeneous unified description with point-wise cross-section data, to a set of homogenized mixtures with energy condensed to a few-group representation which can make use of any lattice codes connected to the system.

In the cOMPoSE sub-system, this typically involves the following steps:

1. Define a coarse radial mesh, which defines the node sizes for homogenization. Next, a number of axial slices are chosen along the height of the model. This effectively divides the model into a number of two-dimensional layers.
2. Homogenized cross-sections are then calculated on the nodal mesh for each axial layer, by performing a two-dimensional transport calculation over the entire slice. Generalized equivalence theory is used to ensure that reaction rates and leakages are preserved for each node.
3. Loadable components often need additional treatment. This is because, for a fast operational support tool, we do not want to re-homogenize the entire core every time the configuration changes, due to reload. Thus, loadable assemblies are treated in a more traditional fashion, by performing assembly level lattice calculations in approximate environments (so-called coloursets). These calculations also account for burnup and state changes. Such loadable representations are then introduced into the model at all loadable positions.
4. Finally, all two-dimensional layers are stacked together to form a three-dimensional model.

At each of these steps, the system has a set of accuracy metrics defined to assist in monitoring and managing the offset associated with the homogenized model particular to that specific stage.

Once a suitable model is prepared, it can be deployed to various analysis applications. The system also treats the input and execution of applications in a code-independent manner. Moreover, the deployment to various hardware architectures, ranging from single-node workstations to multi-core, multi-node computing clusters, is automated and handled internally. A generic inventory management system, which stores the material states of burnable assemblies, makes it possible to use analysis codes that are lacking this feature for long term core management, and to deploy the appropriate depletion state of the core to all connected codes.

In particular, in this work, the following codes connected to the OSCAR-5 system were applied:

1. MGRAC [6], is a steady-state, three-dimensional, multi-group nodal-diffusion solver, employing the Analytic Nodal Method. MGRAC utilizes a microscopic depletion model. This deterministic code provides fast calculation for core tracking and core design purposes.
2. HEADE [6], is a low-order response-matrix based collision probability transport solver, for two-dimensional Cartesian geometry. This code provides traditional cell-level calculations as part of the deterministic calculation line.
3. Serpent [7], a Monte Carlo criticality and burnup code developed at the VTT Technical Research Centre of Finland, is capable of cell-level and full-core calculations for determining group constants as well as for a standalone simulation suite. The main advantage of the Serpent code is the use of a fast tracking-algorithm, significantly increasing performance in complicated geometries, and the use of a unified energy mesh to accelerate cross-section queries.
4. MCNP, v.6.2 [8][9], is a well-known general purpose Monte Carlo code for the transport of neutral (and selected charged) particles. The code has advanced tally features, making it the preferred tool for difficult, localized flux estimation.

Specific uses of these codes in the MNR model are explained in subsequent sections.

3. MNR OSCAR-5 Model Development

The MNR core is defined by a 9 × 6 grid (shown in Figure 2). The core typically contains 31 standard fuel assemblies and six control fuel assemblies, a row of graphite reflectors, a single beryllium assembly, and multiple in-core irradiation positions. Control is via a bank of five In-Ag-Cd shim-safety rods and a single low-worth stainless steel regulating rod. Not shown are the set of six radial beam tubes on the North and East faces of the core. Refuelling is on a burnup basis with no fixed fuelling pattern.

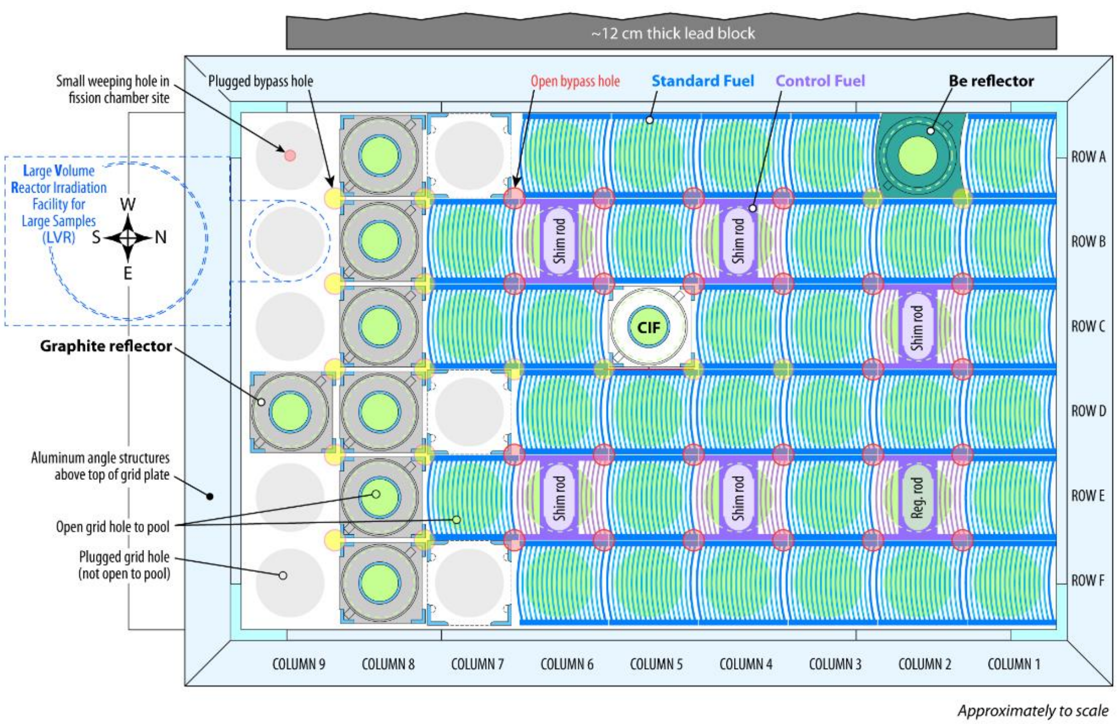

Figure 2: The typical MNR core configuration

Prior to the work reported in this paper, the fuel management process at MNR has used a simplified model combining measurements and calculational factors. More detailed analysis has mainly involved enveloping approaches for operating limits and licensing applications. While this has proven sufficient for typical operation, the approach lacks the flexibility for considering more extensive changes to the core loading configuration or operational regime. At the same time detailed simulation of cycle specific points has not been readily available and has only been done for validation purposes and on a special project basis.

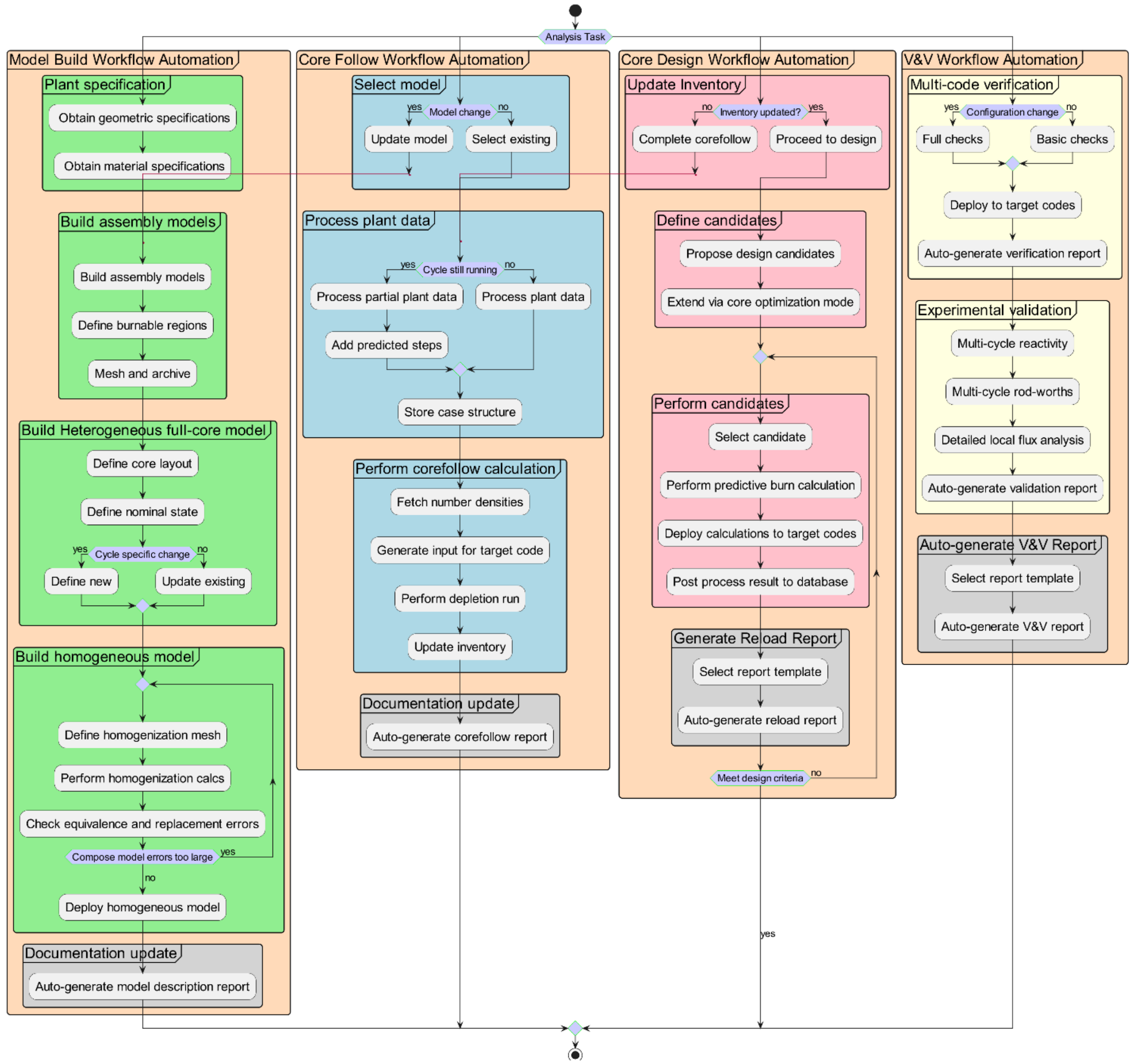

Figure 3: MNR OSCAR-5 code-independent workflow structure

As a first practical step towards the objectives of enhanced and expanded analysis capabilities a feasibility analysis for applying the OSCAR system to MNR was initiated in 2016, after which the following phases of work were undertaken:

1. Development of the MNR reactor core model,
2. Development of appropriate workflows for core follow and reload design analysis,
3. Historical modelling of operating cycles as from 2007 to present,

4. Verification and validation of the multi-cycle model, and
5. Application to new operating cycles as from 2023.

The OSCAR-5 system supports the development of high-level workflows for enhanced automation. This can be accomplished at the Python interface level, but OSCAR-5 further supports the usage of more general workflow managers (such as Prefect) to simplify interaction with the system for mature processes. A schematic diagram of the developed workflows for MNR is presented in Figure 3.

In the depicted workflows, each partition (boxed area) represents an OSCAR-5 application. Each of these applications are supported by system tools which allow either full system automation of routine tasks or customization of tasks/sequences to suit the specific reactor being modelled. This customization captures the particular operating regime, safety limits, input data formats and output documentation requirements related to the reactor. For the MNR model, customization work was performed in many of these areas including: (1) plant data processing, (2) design calculations, (3) verification and validation calculations, and (4) report template development. These applications are then grouped into larger automated workflows with simplified sets of input data addressing the typical use cases in the MNR environment.

The remainder of this section describes the activities in each of these major workflow areas, and the primary results obtained.

3.1. Model Build

In accordance with the OSCAR-5 philosophy, the code-independent OSCAR-5 model was developed and is illustrated in Figure 4. The figure depicts both the code-independent (heterogeneous) model, and the overlaid nodal (homogeneous) meshing structure.

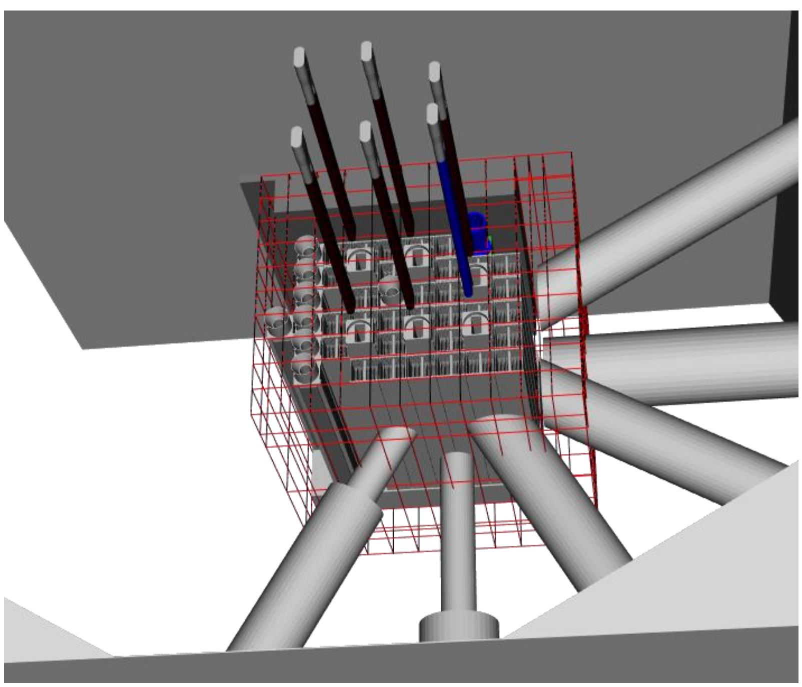

Figure 4: OSCAR-5 model of MNR (including homogeneous meshing structure)

The geometry definition of the model uses the Constructive Solid Geometry (CSG) module of the system, where components of the model are built and then combined to define the reactor geometry. This method and approach are conceptually much the same as used in the geometry definition for common Monte Carlo codes such as MCNP. The system also contains an import capability from MCNP, to allow the code-independent model components to be imported from an existing MCNP deck. Reciprocally, once constructed, the heterogeneous model is directly deployable to both Serpent and MCNP.

The homogeneous model was developed as a six-group, nodal-diffusion representation, with homogenization zones discretized on the order of a fuel assembly. At the outer edge of the nodal model, albedo boundary conditions are applied to capture the effect of returning neutrons from the rest of the system. For fuelled components, the nodal model makes use of a microscopic depletion model tracking 37 isotopes, consisting of actinides and the most neutronically important fission products. The OSCAR-5 system automatically manages the interaction between the code-independent inventory (tracking hundreds of isotopes) and the nodal depletion result, by interpolating the concentration of the remainder of the isotopes from a generated database of isotopic content as a function of exposure (generated in an infinite-lattice environment of the given fuel design).

For the MNR nodal model, the HEADE code is used for cross-section generation for standard fuel assemblies, following a traditional infinite-lattice approach. Control fuel assemblies are modelled with Serpent, using a 3 × 3 assembly colourset (mini-core). These loadable components are then combined with non-loadable cross-sections derived from 2D full-core slice calculations, again using Serpent. This use of 2D full-core transport solutions for cross-section generation allows significant reduction of environmental errors associated with more traditional and approximate modelling approaches [10]. For the MNR nodal model, a total of six axial slices are used; two to capture the active region of the core, two for the upper fittings and structure, and two for the lower fittings and structure. The pair of active slices was chosen to address the two elevations of the beam ports as well as the extent of the internal guide in the MNR control fuel assemblies.

A key aspect of the OSCAR-5 system is the automated error monitoring capability at each step during the nodal model build. Heterogeneous and homogeneous model performance is evaluated during the model building process, starting with convergence checking of the baseline 2D Monte Carlo solutions and error checking of the generated equivalent nodal parameters. In addition to these checks, the system yields a set of metrics from the cOMPoSe step-wise process [3], as given in Table I.

Table I: The OSCAR5 error checking metrics for the MNR nodal model build - core configuration 5

Model Description	**k-eff/ Δk-eff (Error)**	**Maximum Assembly Power Error (%)**
2D Slice (Top Cut)		
Serpent ARO	1.22110	-
MGRAC ARO – Equivalence	8 pcm	0.48 (1F)
MGRAC ARO – SFA Replacement	605 pcm	1.94 (7C)
MGRAC ARO – CFA Replacement	-82 pcm	0.90 (2E)
MGRAC ARO – All FA Replacements	516 pcm	1.94 (7C)
2D Slice (Bottom Cut)		
Serpent ARO	1.21908	-
MGRAC ARO – Equivalence	44 pcm	0.76 (1C)
MGRAC ARO – SFA Replacement	658 pcm	1.86 (7E)
MGRAC ARO – CFA Replacement	-54 pcm	1.04 (2E)
MGRAC ARO – All FA Replacements	560 pcm	2.03 (2E)
3D Tests		

Serpent ARO	1.13369	-
MGRAC ARO	-374 pcm	2.86 (2E)
Serpent ARI	1.03066	-
MGRAC ARI	-258 pcm	2.38 (2C)
Serpent 3D – Rods at Mid-Core	1.08090	-
MGRAC 3D – Rods at Mid-Core	-245 pcm	2.28 (2C)

Note: ARO = All Rods Out, ARI = All Rods In, SFA = Standard Fuel Assembly, CFA = Control Fuel Assembly, FA = Fuel Assembly (i.e. both standard and control), power error locations are indicated by core grid ID.

This table provides important insight into the predicted offset of the homogeneous model. If this offset is too large, various mechanisms exist in the OSCAR-5 system to improve the accuracy of the representation; these can be applied until the homogeneous model performs suitably. For the MNR model, these error monitoring features led to refinements for control fuel modelling, moving from an infinite-lattice approach using HEADE to a mini-core approach using Serpent. In addition, meshing was found to need adjustment around the large beam tubes to address equivalence theory limits and minimize in-core nodal model errors.

Future analysis with the homogeneous model can then be expected to be within the predicted range of the difference to the reference Monte Carlo solution. In this case we find the expected offset in reactivity for the MNR nodal core model is in the range of -250 to -375 pcm and could result in a maximum nodal power error of 2 – 3%.

In reality, in order to span the 16 years of operation considered in this work (2007 to present), five different core configurations and associated homogeneous representations have been developed. Results presented in Table I reflect typical offsets associated with the nodal model for MNR.

Following the model building stage, the homogeneous model can be further compared to the heterogeneous model for burnt core inventories, i.e. extending and expanding the 3D tests to burnt core cases. For the MNR model these burnt core tests include total rod worth, rod worth from specific set points, and axial power and flux comparisons. The reactivity offsets found for the 3D burnt core generally match well to the offsets predicted from the 3D fresh core tests (shown in Table I). These tests are valuable to ongoing verification of the model and are performed periodically including on any change in base configuration (see V&V Workflow Automation in Figure 3).

3.2. Core follow and Reload Applications

Initial application development was done for operational support of fuel management, i.e. tracking the fuel used in the core (core follow) and performing calculations associated with fuelling operations (reload). The generic calculational workflow for cycle-to-cycle fuel management is shown in Figure 3. The strengths of the OSCAR-5 system, when applied to this workflow, are the automation of this process, the available reporting features, and the user-side customization ability. The development process involved the creation of MNR specific tools, including one to manage operational data for core follow (referred to as *plant data* in OSCAR), the specification and build of calculations associated with the core design/reload activities, and the creation of custom reporting for these two applications.

In OSCAR-5, plant data processing generally contains a few steps (see Core follow Workflow Automation in Figure 3). Firstly, the plant data is read, and can be automatically translated into a proposed *case structure*, which in essence represents a set of consecutive calculational flux and depletion steps representing the cycle. After generating the initial structure, the analyst is expected to engage (interactively and visually) with the case structure, using their experience to identify appropriate depletion steps (periods of relative stability) and points appropriate for critical estimates (snap-shot points in time where the reactor can be expected to be at steady-state).

Plant data management is a facility specific activity. For MNR the plant data input takes the form of daily start-up time, associated critical rod positions, and duration of operation. Despite the complex nature of the on/off MNR operating cycle, the model successfully tracks the core operation based on only this simple input, following the xenon dynamic and rod movements throughout the cycle. This emphasizes the value of the low-overhead deterministic nodal-diffusion solver MGRAC in the OSCAR-5 system, which allows calculation of a complete core cycle in a matter of minutes (a standard operational week of core follow requires 40 calculation cases with rod searching which takes two to three minutes of CPU time on a well-equipped laptop). Such a calculation set is not feasible with a stochastic code such as Serpent.

The custom developed MNR core-follow report (built to provide continuity with previous reporting content) contains a brief cycle summary, critical estimates throughout the cycle (plotted, with average and standard deviation noted), Beginning-of-Cycle (BOC) and End-of-Cycle (EOC) core loading maps, and an inventory table. This report is auto generated as a PDF as part of the core follow workflow.

In conjunction with the core-follow application, a design reload application was developed. Reload calculations for MNR include a set of safety and performance parameters for the given change and upcoming core cycle. These include checks on start-up bank position, core reactivity via a limiting rod configuration for shutdown (called a shim-test at MNR), evolution of the daily start-up bank position for the projected cycle (indicating expected cycle length), power distribution, and rod worth estimates. Other performance indicators include irradiation position flux estimates and zonal burnup averages. The calculations are expandable and captured in the auto-generated reload report. The reload calculations are common to both the design stage for an upcoming fuel change and on the final fuel loading.

In terms of the design use of reload, this planning tool enables the analyst to run predictive core change calculations for a set of candidate core loadings. Execution of a set of design calculations for multiple loadings can be completed in a short time (on the order of an hour for a few candidates) using the nodal model. An example of a simple design reload comparison for MNR is shown in Table II.

Table II: Example of design reload comparisons for candidate core loadings

Parameter	**Candidate 1**	**Candidate 2**	**Candidate 3**
BOC Core U-235 Mass	5729.65 gram	5794.95 gram	5912.15 gram
Reload Worth	-25 pcm	187 pcm	938 pcm
Startup Shim Bank (Extracted)	77.9%	76.4%	69.1%
Xenon Worth	724 pcm	822 pcm	953 pcm
Excess Reactivity	1573 pcm	1772 pcm	2480 pcm
Excess Reactivity (Xenon Free)	2297 pcm	2595 pcm	3433 pcm
3 Shim Test	-1889 pcm	-1720 pcm	-996 pcm
3 Shim Test (Xenon Free)	-1165 pcm	-897 pcm	-0.43 pcm
Shim Bank Worth	10055 pcm	10076 pcm	9997 pcm
Regulating Rod Worth	302 pcm	313 pcm	306 pcm
Maximum Plate Power (Standard)	12.85 kW	13.95 kW	13.73 kW
Maximum Plate Power (Control)	7.30 kW	7.33 kW	7.34 kW

Note: 100 pcm = 1 mk

4. Model Performance

Model performance is gauged by comparison to measured data. This involves critical estimates which are generated as part of the core follow and reload applications.

Part of the MNR model development was the tracking of historical core cycles, starting from 2007 (the beginning of full LEU loading) and performed for each subsequent cycle. As the fuel residence time in MNR is quite long, the initial model burn-in period for the materials was on the order of 6 – 7 years of core follow for full-core turnover. The model of the current cycle represents a core in which all the fuel has been replaced twice and is thus well removed from initial conditions. In terms of core-follow performance, the multi-cycle critical estimates are examined as the model tracks operations. Figure 5 shows the multi-cycle critical estimate, based on daily start-up measurements.

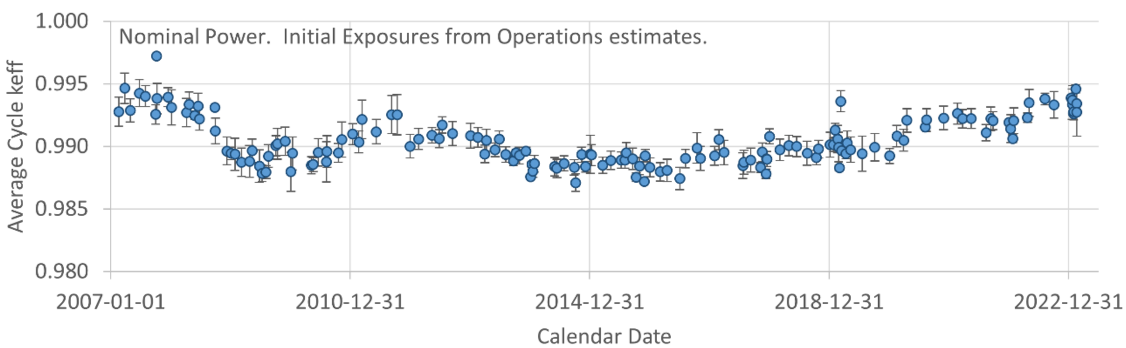

Figure 5: MNR OSCAR5 model cycle average critical estimates 2007 – 2023

This comparison of MGRAC critical estimates over the 16 years of modelled operation shows a k-eff estimate with an average value of 0.99047 and a standard deviation of 0.00197. These results are not atypical for research reactors of medium to high power. While the degree of the critical estimate offset suggests that we may still be able to identify some improvements in the model (e.g., to bring the average k-eff value closer to 0.995), the achieved standard deviation (197 pcm) is already at a desired target of less than 250 pcm. It should be noted that a relatively stable k-eff (low standard deviation) such as this is indeed important for operational support, as it can effectively be used as a reactivity target for obtaining critical rod positions for design calculations.

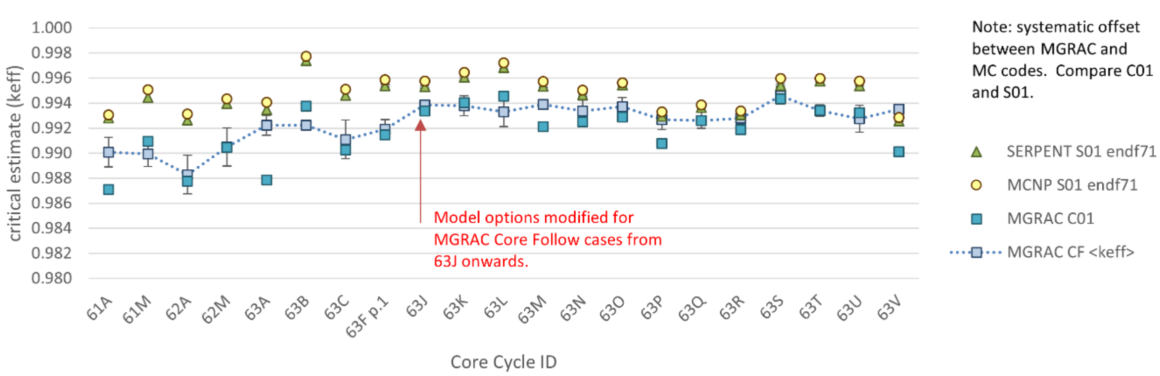

Figure 6: Monitoring of critical estimate for multi-cycle tracking, comparison of all deployment codes

To further assist in clarifying the source of discrepancy, we can use the capabilities in OSCAR-5 to deploy the critical cases to both Serpent and MCNP, and as such determine whether the offset from k-eff = 1 is related to the nodal model or is present in all the codes that are based on the OSCAR-5 model. Figure 6 shows this comparison. In Figure 6, S01 and C01 refer to the snap-shot critical cases at BOC, and CF <keff> refers to the cycle average critical estimate.

Here we note that MGRAC typically under-predicts the Monte Carlo critical estimates by a few hundred pcm (as was also expected after the model building step), which partly explains the under-predicted reactivity of the homogeneous model as in Figure 5. However, this deviation does not fully explain the full offset from critical, and as such we can conclude that other components of the code-independent model, and/or applied cross-section library, are responsible for the remainder of the offset (a further 400 – 500 pcm). Although such observations do not conclusively resolve the source of the discrepancy, the capability of OSCAR-5 to deploy the same model to multiple codes significantly assists in guiding the analyst to the source of the issue.

Reload was also performed for these historical cycles, building a large database of fuel management information from which trends can be extracted and insight gained on the management of the core loading. Another related metric to the critical estimate is the predicted start-up bank positions after reloading the core. Figure 7 shows recent model predictions vs measured values indicating good agreement over the range of typical start-up bank positions. This result builds confidence in the design calculation capability for candidate core loading. Note that in this case an average-keff from the multi-cycle analysis is used as criticality search target for the rod position prediction.

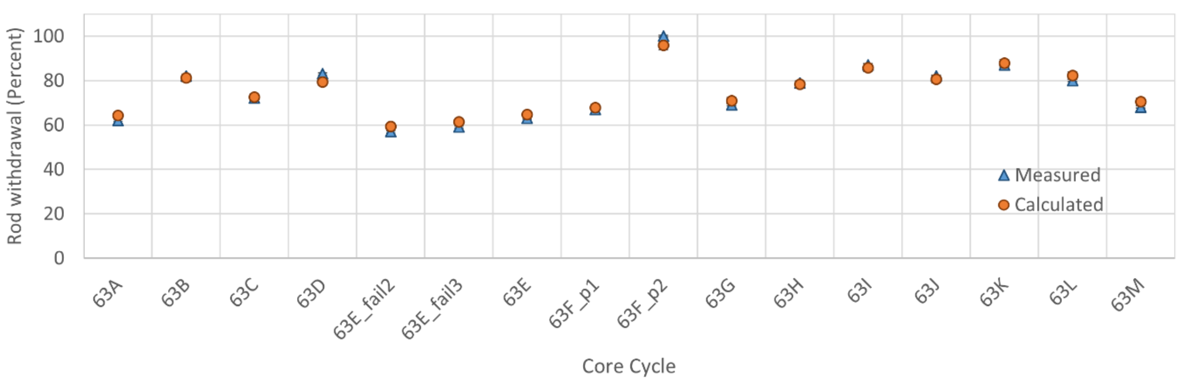

Figure 7: Measured vs calculated start-up bank position for recent reloads

These comparisons indicate the value in obtaining a relatively stable k-eff offset, which allows the prediction of accurate rod and bank positions during the predictive reload analysis. As of 2023 the system has now been used to support upcoming fuel changes at MNR.

Other validation points for the model (as per Figure 3) are comparisons against local flux measurements and multi-cycle rod worth measurements. With respect to the former, comparisons have been made between model estimates and a 2019 flux wire irradiation campaign using NiCr wire, covering multiple core cycles and multiple irradiation positions. Model estimates are found to be in very good agreement for the Cr50(n,γ) thermal reaction. An example is shown in Figure 8.

Similar comparisons for the Ni58(n,p) fast reaction suggest a 15 – 20% discrepancy between the simulation and measured results. This work is to be continued to further investigate differences and validate the model against additional wire materials/reactions and is planned as regular and ongoing validation checks of the model.

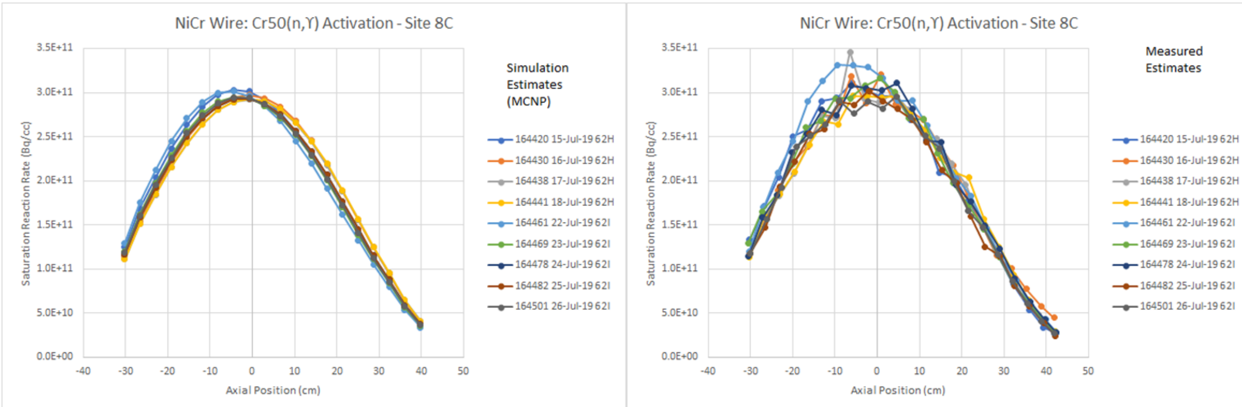

Figure 8: Side-by-side comparison of simulation (left) and experimental (right) axial wire activation estimates

With respect to the rod worth comparisons, the multi-code synergistic aspect of the system is again being used; with kinetic parameter calculation via deployment to the heterogeneous Monte Carlo codes coupled with deployment of the set of critical cases to the homogeneous nodal code. This produces model-consistent kinetic parameter input for doubling time reactivity estimates alongside critical-case difference calculations for rod worth estimates. These comparisons are still in progress at the time of writing.

5. Future Development and Application

With the model build, and core follow and reload application development successfully completed to functional maturity, a number of further improvements and areas of expansion are being considered for the model. These include:

1. Further investigation into the consistent under-estimation of reactivity from the model (visible in deterministic and stochastic models);
2. Improvement of the nodal-diffusion model via correction schemes in OSCAR-5 for improved homogeneous cross-section generation. These options include multi-colourset fuel models or on-the-fly, embedded homogenization schemes in MGRAC, in particular in positions where the assembly environment is not well represented by an infinite-lattice approximation;
3. Application of the model to support the various expansions of the MNR operational regime, which potentially includes core design changes, a power level increase and extensions to a 24-hour operating schedule;
4. Application of multi-physics analysis in both core-follow and reload design calculations. Initially this will be done via the existing neutronic/thermal-hydraulic coupling options in the MGRAC code (using an internal plate-type thermal-hydraulic solver module), and will further be expanded to use the PLTEMP [11][12] code once it is connected to the OSCAR-5 platform;
5. Usage of the OSCAR-5 sampler mode to propagate input uncertainties through to safety and utilization parameters of interest. This approach intends to improve the definition safety margins applied to calculated quantities [13];
6. Application of the OSCAR-5 core optimization mode to support the design of future cycles. This option uses various heuristic multi-objective optimization schemes in OSCAR to propose improved core loadings [14]; and
7. Modelling of safety cases for MNR, via the OSCAR-5 link (under development) to the RELAP code [15]. In future steps it is intended to use the spatial kinetics option in MGRAC, coupled to RELAP to investigate the impact of such higher fidelity transient modelling on safety limits (as compared to the traditional point-kinetic approach to research reactor safety analysis).

These identified areas are in various stages of development, and require enhancements to the MNR model, but further also to the OSCAR-5 code system itself. Items above related to uncertainty propagation and multi-physics coupling for research reactors are further related to the topic of an ongoing IAEA CRP [16], to which the MNR model is submitted as one of the benchmark cases.

6. Concluding Remarks

In the context of a growing user base, and future expansions of the application scope of MNR, the OSCAR-5 calculation system was selected as the basis for development of an enhanced level of calculational analysis support. Key aspects of the system, as applied to the MNR model and applications, include:

1. Construction of a unified, code-independent reactor model;
2. Deployment of the model to a variety of codes, including industry standard neutronic Monte Carlo codes both for direct solution and for the generation of nodal equivalence parameters;
3. Error monitoring during and following the development of the homogenized nodal model; and
4. An integrated model management and documentation system.

The MNR OSCAR-5 model has been developed to a functional maturity and can thus be used to support MNR operation from the perspective of applications such as core-follow, reload design and local flux analysis. The verification and validation performed thus far provides a good quantification of the performance of the model over multiple cycles and supports the future definition of calculational margins on most of the safety and utilization parameters generated by the model.

This successful model development provides the foundation for further analysis enhancements and expansion of calculational analysis support at McMaster University. Areas of interest include core optimization calculations, the addition of steady-state and transient thermal-hydraulic target codes to both the OSCAR-5 system and the MNR model, and safety margin evaluation via the propagation of uncertainties. Work in these areas will support planned operational changes and further utilization development at MNR.

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