Development of Fuel Shuffling Module for PHISICS

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INTRODUCTION

PHISICS (**P**arallel and **H**ighly **I**nnovative **S**imulation for the **I**NL **C**ode **S**ystem) [4] code toolkit is being developed at the Idaho National Laboratory. This package is intended to provide a modern analysis tool for reactor physics investigation. It is designed with the mindset to maximize accuracy for a given availability of computational resources and to give state of the art tools to the nuclear engineer. This is obtained by implementing several different algorithms and meshing approaches among which the user will be able to choose, in order to optimize his computational resources and accuracy needs. The software is completely modular in order to simplify the independent development of modules by different teams and future maintenance. PHISICS can be run in parallel to takes advantage of multiple computer cores (10 to 100 cores). In addition, the package is coupled with the system safety analysis code RELAP5-3D [3].
In the following the structure of the different PHISICS modules is briefly recalled, focusing on the new shuffling module (SHUFFLE), which is the object of this paper.

INSTANT

INSTANT [3] is the neutron transport solver. It is based on the spherical harmonics approximation of the angular dependence of the neutron flux. Currently the Cartesian, hexagonal, and extruded triangle nodal spatial meshes are available.

MRTAU

MRTAU [2] is a generic depletion/decay/burn-up code. The code tracks the time evolution of the isotopic concentration of a given material accounting for nuclear reaction happening in presence of neutron flux and also due to natural decay (Bateman equation). Moreover the code can provide ad additional output information regarding integral quantities associated to different nuclear reactions.

MIXER

The MIXER is tasked to perform the interpolation of the microscopic or macroscopic cross sections and generate the macroscopic cross sections used by INSTANT.
PHISICS has an enormous flexibility in the treatment of cross sections since both microscopic and macroscopic cross sections can be combined together in the same simulation. Cross sections can be tabulated for an unbounded number of parameters and having an unbounded number of tabulation points for each parameter.

CRITICALITY SEARCH MODULE

The Criticality Search module (CSM) adjusts isotope densities (user defined) for a specified location in the geometry until a prescribed value of k_{eff} is reached or the densities get out from user specified boundaries.
A classical usage of this module is to search for critical boron concentration, fissile enrichment or control rod positioning.

SHUFFLE

The SHUFFLE module has been designed to allow PHISICS users to define fuel-shuffling information for fuel cycle analysis.
The module provides all the tools to simulate the procedures that are involved in fuel loading activities and fuel management studies. This module allows performing calculations related to the so-called optimal fuel reloading problem, which consists in optimizing the rearrangement of all the assemblies. This includes burned and fresh assemblies, while still maximizing the reactivity of the reactor core so as to maximize fuel burn-up and minimize fuel-cycle costs.
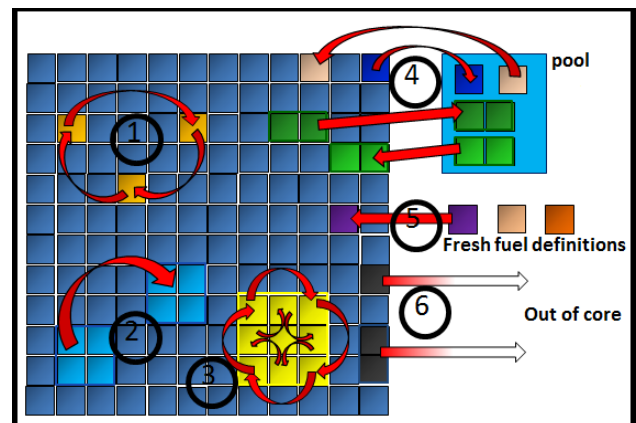

Fig. 1. SHUFFLE module available movements.

Figure 1 shows the capabilities currently available in the new tool:
1) Arbitrary in-core movements
2) Grouped in-core movements (for assemblies)

3) Group rotation
4) Grouped/individual core to pool movements
5) Fresh fuel to core movements
6) Grouped/individual movements out of the core

The balloon 3 in the list above refers to the capability to rotate groups of nodes through the "operator" "Rotator". Rotator was designed to allow the user to group nodes into "assemblies" and then effectively rotate the assembly in the simulation. The rotation is merely a rearranging of the nodes to the position it would occupy if had been rotated. It handles counter-clockwise rotation.
This "operator" can be applied on all the possible movements performed by SHUFFLE.

The SHUFFLE module now allows simulating shuffling of fuel elements, fuel loading and unloading, and storage of spent fuel in a cooling pool. The assemblies stored in the pool are decayed through the whole multi-cycle simulation, in order to take into account the transmutation of the nuclides during the cooling.
SHUFFLE is not made to operate in stand-alone mode, but is integrated into the PHISICS driver[2].

MULTI-CYCLE CALCULATION FLOW
Figure 2 shows the calculation flow in case of multi-cycle calculation.
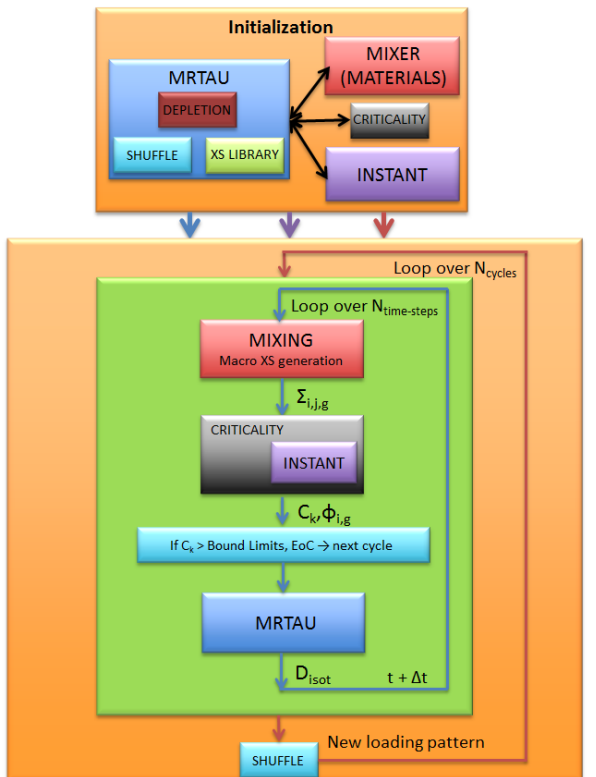

Fig. 2. Multi-Cycle calculation flow scheme.

After the initialization, in which all the information needed to run the simulation is stored in the corresponding modules, the simulation starts. One single iteration (time step evaluation) consists in the following steps:
1. Mixing: creation of the macroscopic cross sections based on microscopic/macroscopic cross sections library and material compositions
2. Criticality search (if, as in this case, needed to adjust the Boron Concentration): a) k_{eff} and fluxes evaluation is performed by INSTANT; b) a new guess for the value of (C_k) is computed; c) cross sections are changed according to the variation of C_k; d) a new evaluation of k_{eff} and fluxes is performed by INSTANT. If the k_{eff} value is satisfactory the fluxes are passed to the next step otherwise a new iteration is performed. If k_{eff} is not satisfactory, and the C_k are outside of the predefined boundaries, the current cycle is ended (EoC) and PHISCS jumps to the beginning of the next cycle
3. MRTAU calculation: the new densities D_{isot} $(t + \Delta t)$ are computed solving the depletion/burn-up set of equations for each isotope
4. If the time $\geq$ 'end of current cycle time', PHISICS moves to the next cycle
5. At the end of the cycle, SHUFFLE provides the new loading pattern.

2D PWR MODEL, TWO-LOAD CYCLE MODEL
This benchmark, proposed by K. Koebke, R. Wagner et al. in 1985 [1], has been designed to provide a test for the capabilities of coarse mesh methods for PWR fuel management calculations. It is set up to allow the use of computer codes, which model either a quarter of a core or a reactor octant. The 2D geometry consists of 5 assembly types, characterized by different cross sections and compositions (presence or absence of burnable poison - BP). The benchmark is a two groups and two depletion cycles problem. The reactor is maintained critical at all times by adjusting the amount (ppm) of soluble boron (SB). The xenon in the benchmark is treated as in equilibrium while the transient equation (Bateman) is solved. The scattering matrix is given as a macro cross section attributed to the structural material STRM. The cycle length is defined by requiring the critical boron concentration to become equal to zero. The model that has been chosen consists of 504 depletion zones (9 nodes for assembly) in a quarter of the core. The square assemblies have a side 23.0 cm long and the global dimension of the core is approximately 195.5 x 195.5 cm.
In the first loading pattern, all of the materials specified throughout the core are fresh materials. In the second loading pattern, one third of the fuel without burnable poisons is fresh material.
Control rods were also specified as part of the benchmark, but were not modeled to test the Shuffle

implementation. Since this is the case, the only results that are considered for these reports are cycle length and boron concentrations.

RESULTS

Table I indicates the end of cycle days.

Table I. End of Cycle Days			
Cycle Number	Simulation	Benchmark	Delta
1	392.10	381.49	10.60
2	260.50	262.042	1.54

There are slight differences between the length of the cycles computed by PHISICS and the ones provided by the benchmark. The first cycle is within 11 days of the benchmark data (~ 383 pcm) while the second cycle is only 1.54 day off (~ 56 pcm). Given the quite large differences in the numerical algorithms used by PHISICS and the code used to compute the benchmark results these differences seems more than reasonable. Figures 3 and 4 show the boron concentration evolutions for the first and second cycle.
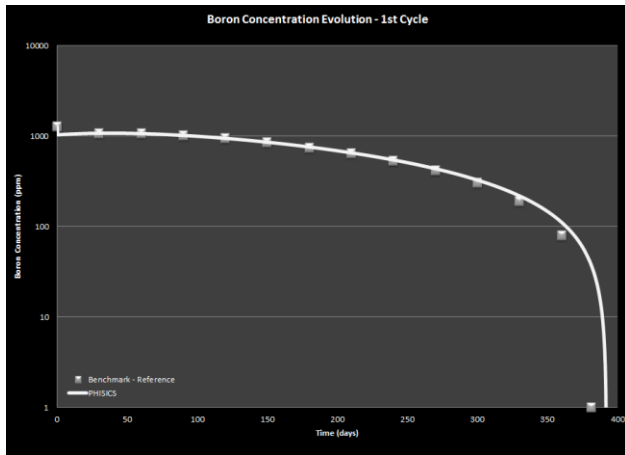

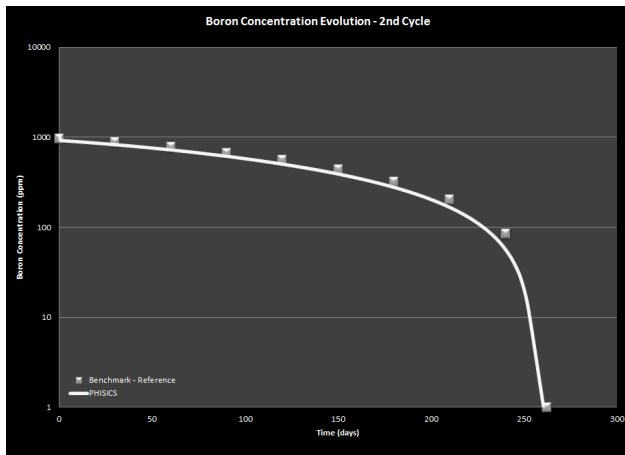Fig. 3. Critical Boron Concentration for the first Cycle.

Fig. 4. Critical Boron Concentration for the second Cycle.

As can be seen above, the boron concentration evolution is slightly different but the shape is indeed preserved.

Figure 5 is generated by VISIT® using the VTK format files generated by PHISICS for the power distribution. The smoothing effect of the xenon is worth noticing: the xenon build up (from right to left in the picture) decreases the peack power (maximum value on the scale).
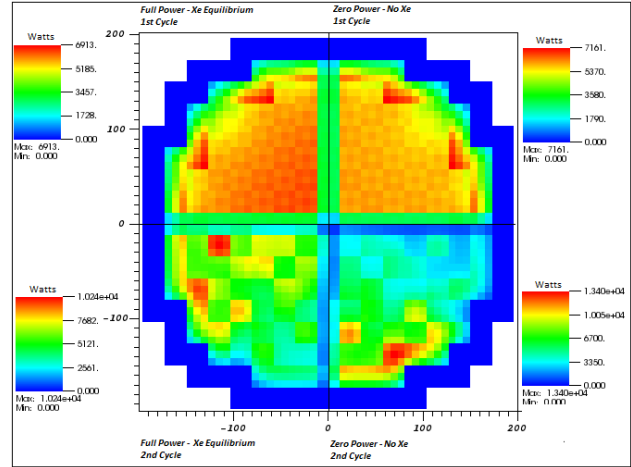

Fig. 5. Power distribution first and second cycle, No Xe and Xe at the equilibrium.

CONCLUSION

The main purpose of this paper is to present the new module in the PHISICS toolkit, SHUFFLE.

The functionality of the module has been tested simulating the previously explained benchmark. Since the goal of this paper focuses on the new tool only, the convergence of the code has not been pushed to exactly match the benchmark results. A previous publication [2] has already demonstrated the convergence trend for this particular benchmark.

The reported case shows that all the modules in PHISICS work with a multi-cycle simulation.

SHUFLLE was designed to give PHISICS the ability to simulate fuel management and perform multi-cycle simulations. Since this capability had been unavailable before [2], it is an important development step for PHISICS to become a valuable tool also for fuel cycle studies and optimization. Currently it is possible to perform multi cycle full core analysis including accounting for the thermal-hydraulic feedback by the coupling with RELAP-5. PHISICS and RELAP5-3D are moving toward becoming a full nuclear reactor design and analysis tool.

REFERENCES

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