Enhanced Shuffling and Fuel Management capability in PHISICS code

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INTRODUCTION

PHISICS (**P**arallel and **H**ighly **I**nnovative **S**imulation for the **I**NL **C**ode **S**ystem) code [1] [2] is a reactor physics package, under development at the Idaho National Laboratory since few years ago. This package is aimed to provide a modern analysis and design tool for reactor physics investigation. It has been designed with the idea to maximize accuracy for a given availability of computational resources and to give state of the art tools and advanced solutions to the nuclear engineer. This is obtained through the implementation of several different solution algorithms and meshing approaches among which the user will be able to choose, in order to balance his computational resources and accuracy needs.
PHISICS has been coded following an object-oriented mindset, evolving in a complete modular design; this determines remarkable simplifications in the development of modules by different teams and future maintenance.
The different modules currently available in the PHISICS package are a nodal and semi-structured transport core solver (INSTANT), a depletion and burn-up module (MRTAU), a time-dependent solver (TimeIntegrator), a cross section interpolation and manipulation framework (MIXER), a criticality search module (CRITICALITY) and a fuel management and shuffling component (SHUFFLE), which is the subject of this paper, having been recently redesigned and improved.
PHISICS is fully parallelized to take advantage of multi-core workstations and High Performance Computing systems (4 to 500 cores). In addition, the package is coupled with the system safety analysis code RELAP5-3D [3]. Using the coupling between PHISICS and RELAP5-3D is possible to drive a accurate dynamic analysis switching between a steady state and time-dependent calculations.

SHUFFLE MODULE

As already mentioned, this paper is aimed to report the improvements of the shufflling and fuel management module within the PHISICS code. As reported in [4], the PHISICS team already delivered such module: SHUFFLE. The SHUFFLE module had been designed to allow PHISICS users to define fuel-shuffling information for fuel cycle analysis. The module provided the tools to simulate the procedures that are involved in fuel loading activities and fuel management studies. This additional PHISICS component allowed performing calculations related to the so-called optimal fuel reloading problem, which consists in optimizing the rearrangement of all the assemblies. This included burned and fresh assemblies, while still maximizing the reactivity of the reactor core in order to maximize fuel burn-up and minimize fuel cycle costs. As easily inferable, the module provided most of the needed capabilities, but was characterized by some limitations that have been addressed, redesigning most of the software infrastructure. These lacks in the design were due to the constrained time that had been allocated for such development (1 month of a Master's student).
The main limitations are listed below:

- ***Dimension***: the user was able to easily input the shuffling information for 2-Dimensional problems only. Indeed, the module was not able to leverage the geometry information for grouping (axially) the computational nodes that, for example, represented a fuel assembly. In case of 3-Dimensional simulations, the user was forced to input shuffling information for each axial layer, making very difficult the creation of the input;
- ***Geometry***: The SHUFFLE module was able to handle Cartesian geometry only;
- ***Parallel***: No parallel implementation was available for the SHUFFLE module; it could be used for serial calculations only;
- ***Grouped rotation***: Grouped nodes' rotation (e.g. assembly rotation) was available for Cartesian 2x2 and 3x3 geometry only.

In order to overcome these limitations, a redesign has been performed:

- simplifying the input structure;
- developing MPI support for arbitrary number of processors;
- implementing arbitrary rotation configuration (rotation matrix approach);

- eliminating geometry limitations (i.e. all the geometry types available in PHISICS are compatible with the SHUFFLE module: Cartesian, Hexagonal, etc.).

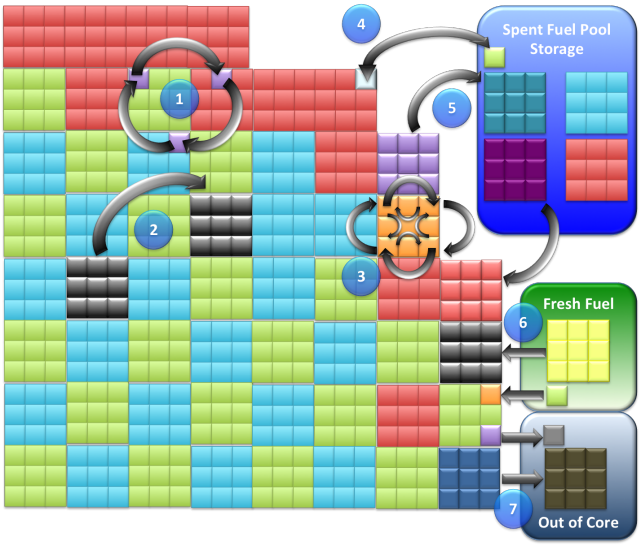

Fig. 1. SHUFFLE module available radial movements

Figure 1 shows the capabilities currently available in the redesigned tool:

1. Arbitrary in-core movements;
2. Grouped in-core movements (for assemblies);
3. Group rotation;
4. Individual core to/from pool movements;
5. Grouped core to/from pool movements;
6. Fresh fuel to core movements (Individual and Grouped);
7. Grouped/individual movements out of the core

As briefly mentioned, the bullet 3 in the list above refers to the capability to rotate groups of nodes through the"Rotator" operator. The "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 it had been rotated. It handles counter-clockwise rotation without (now) any limitation in the "grouped" computational nodes. The rotation can be applied on all the possible movements performed by SHUFFLE.
Figure 2 shows how the redesigned SHUFFLE module can handle the axial connections, when applied on 3-Dimensional simulations:

1. all the axial nodes (at a certain radial location) con be easily linked in order to be commonly moved;
2. an "exclusion" operator can be applied to link all the axial nodes, excluding some of them (e.g. all the nodes representing a fuel assembly, excluding the top and bottom axial reflector);
3. individual nodes can be moved, avoiding the link with the nodes above and/or below.

The SHUFFLE module now can be considered completed. It allows simulating shuffling of fuel elements, fuel loading and unloading, and storage of spent fuel in a cooling pool, both in 2-D and 3-D simulations. The materials (e.g. assemblies) stored in the "spent fuel pool storage" are decayed during the whole multi-cycle simulation, in order to take into account the transmutation of the nuclides during the cooling.
It is important to mention that this development has been performed in order to address the problem of the revision of the requirements in 10 CFR 50.46C rules, focused on the ECCS rule in LOCA scenarios [5], for which a 10 Cycles 3-D simulation was needed, as testified in ref. [6].

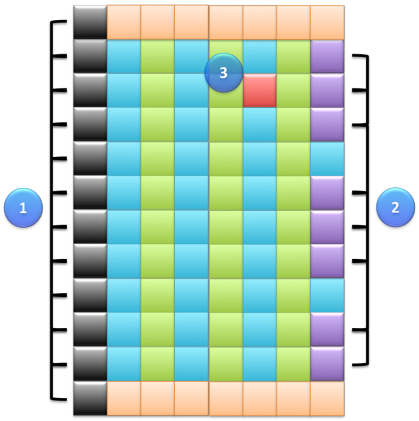

Fig. 2. SHUFFLE module available axial connections

CONCLUSIONS

The main purpose of this paper is to present the redesigned module SHUFFLE, within the PHISICS toolkit.
All the functionality limitations of the old design have been faced and resolved. The functionality of the module has been fully tested and represented a key development in order to face a challenging problems, such as the revision of the requirements in 10 CFR 50.46C rules, focused on the ECCS rule in LOCA scenarios.
The renovated SHUFLLE module is now completed and represents a key feature of the PHISICS 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.

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