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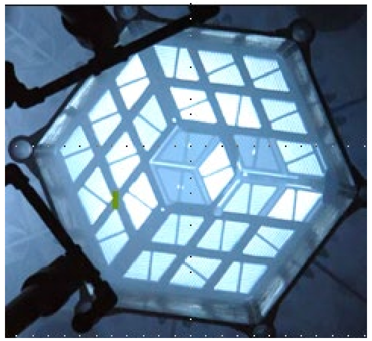
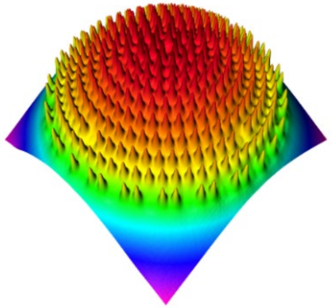
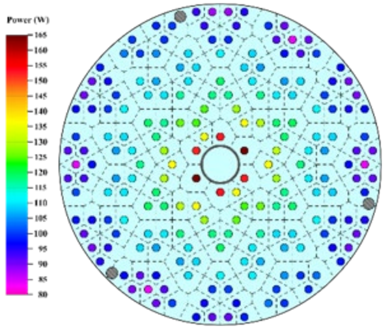
The Advanced Dimensional Depletion for Engineering of Reactors (ADDER) software: Software Overview and Future Developments



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Argonne National Laboratory

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Outline

- INTRODUCTION
- ADDER CAPABILITIES
- ADDER APPLICATIONS
- NEXT RELEASE: ADDER v1.1.0
- CONCLUSIONS

INTRODUCTION

- The **Advanced Dimensional Depletion for Engineering of Reactors (ADDER)** is an open-source software which was developed at Argonne to provide a **flexible fuel cycle analysis tool in support of research reactor conversion.**

- ADDER has been developed **under an NQA-1 compliant Software Quality Assurance Program** in support of the U.S. High Performance Research Reactor (USHPRR) conversion projects, which will convert 5 USHPRR and 1 critical assembly from high-enriched uranium (HEU) to low-enriched uranium (LEU).

- ADDER **version history**
  - v1.0.0 released in April 2021
  - v1.0.1 released in May 2022 with open-source license (MIT License)
  - v1.1.0 planned to be released by the end of 2024

WHY ADDER?

- ADDER is open-source, written in Python 3 using an **object oriented programming approach** and **includes parallelization capabilities**

- ADDER has a modular structure that **couples an external neutronics software and a depletion solver**, implemented as plugins:
  - Current neutronics solvers: MCNP5 v1.60 and MCNP6.2
  - Current depletion solvers: ORIGEN2.2 and an internal Chebyshev Rational Approximation Method (CRAM) solver

- **ADDER simplifies engineering work** for reactor design and neutronics analysis by:
  - Reducing the need to produce locally-generated scripts to perform common tasks
  - Providing a user-friendly interface for complex fuel management operations

ADDER INPUT & OUTPUT

ADDER input

- The ADDER input is **divided into sections** (similar to INI configuration files) to define metadata, material, geometry data, and operations for the depletion calculation

ADDER output

- ADDER returns results in an **HDF5 output file** and **log file**
- Among other parameters the result files include
  - At a reactor system level: k_{eff}, Q recoverable, power, flux
  - At a material level: flux, atom fractions
  - Control group positions
- The MCNP input and output files are retained

```
            ....
[universes]
    [[metadata]]
        [[[list]]]
            neutronics_ids = 1, 2, 3, 4, 5
            names = P1, P2, P3, P4, PS

[control_groups]
    [[control_rod]]
        set = 41, 42
        type = surface
        axis = z

[operations]
    [[state 1]]
        label = "First day"
        [[[transform_0]]]
            group_name = control_rod
            value = 100
        [[[deplete]]]
            powers = 1
            durations = 1
            execute_endpoint = False
    [[state 2]]
        label = "Second day"
        [[[deplete]]]
            powers = 1
            durations = 1
            execute_endpoint = False
             ....
```

ADDER CAPABILITIES

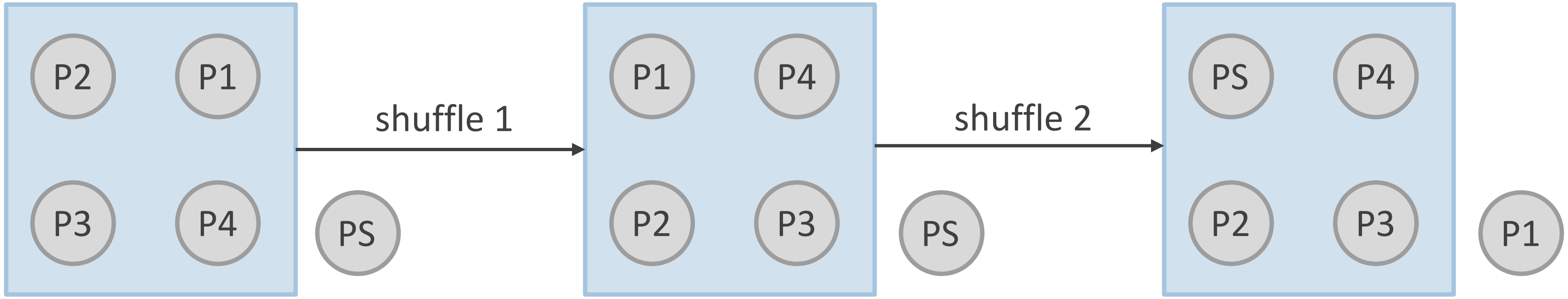
- ADDER provides several **key capabilities in support of neutronics analysis**. These capabilities, including operations that can be performed during the depletion analysis, are reported as follows:
  - **Automated geometry transformation**: Rotate and translate surfaces, universes, and cells in the MCNP model to represent the motion of fuel elements and control mechanisms.
  - **Criticality search operation:** Automate criticality search so that each depletion step may be run at the critical position of the control mechanism (control rods, blades, etc.).
  - **Fuel management operations:** Shuffle and rotate fuel elements within the core, and move fuel elements in and out of storage.
  - **On-the-fly XS recalculation:** Recalculate depletion cross sections at each depletion step.
  - **Flowing fuel:** Model fuel depletion across customized flow loops for Molten Salt Reactor (MSR) analyses

EXAMPLE FUEL MANAGEMENT OPERATION: SHUFFLE

- The *shuffle* operation allows **components** (materials/cells) **to be moved** into, out of, and within the reactor
- **Components shuffled out of the reactor will continue to be decayed** during the depletion time steps
- Shuffling can be performed on groups of components. In large and highly discretized core models, this allows **many components to be moved at once** through an easy setup of the ADDER input

```
[[[shuffle 1]]]
   type = universe
   moves = P1, P2, P3, P4
[[[shuffle 2]]]
   type = universe
   moves = PS, P1
```

Adder input section example

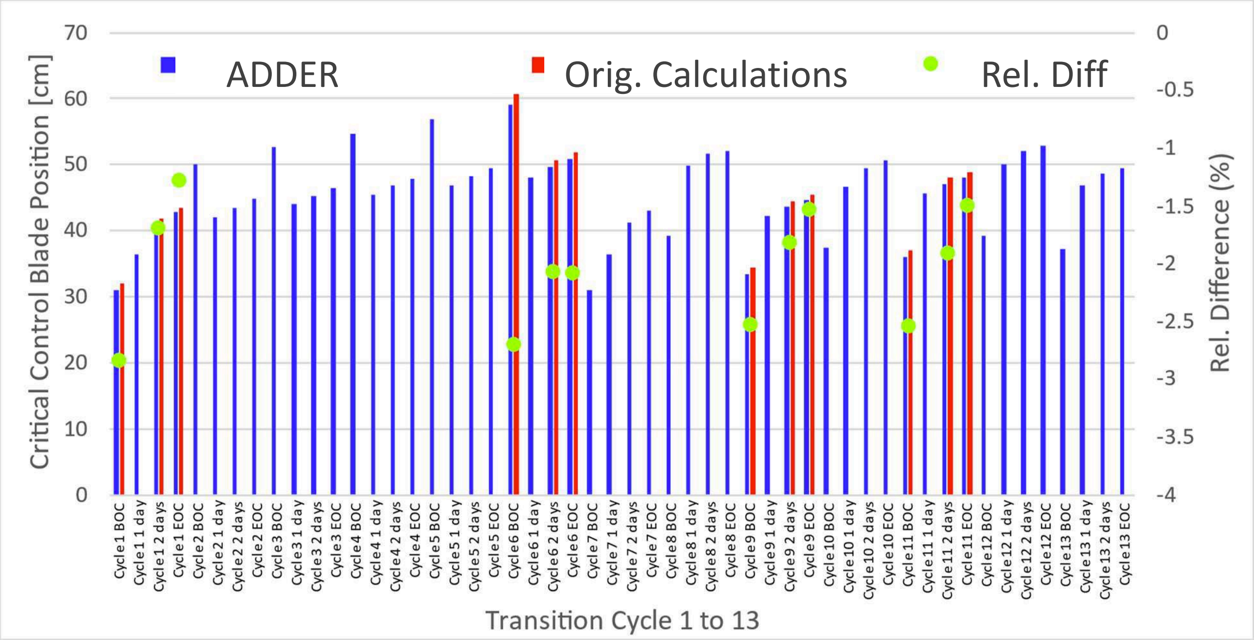


ADDER APPLICATIONS

Reactor/Experiments Analyzed	• **MITR** (Massachusetts Institute of Technology Reactor) • **MURR** (University of Missouri Research Reactor) • **NBSR** (National Bureau of Standards Reactor) • **AFIP-7** (ATR Full-size plate In center flux trap Position) • **PRO-X** (Application of Proliferation Resistance Optimization) • **MSRE** (Molten Salt Reactor Experiment)
Analyses Performed	• Neutronics design verification (MURR, NBSR, MITR) • Radiological design verification (MURR, NBSR) • Mixed HEU/LEU Transition core analysis (MITR) • Fuel fabrication specification impact analysis (MURR, MITR) • Benchmark with experimental data (AFIP-7) • Feasibility study to replace analysis software at MIT • Radionuclide inventory calculation (MSR application) • Neutronics analysis to optimize research reactors (PRO-X)
Scale of models	• From pin cell models (1 depleting material) to three-dimensional full core reactor models (100,000 depleting materials)

ADDER APPLICATION: MURR PRELIMINARY DESIGN VERIFICATION

- MURR is planned for **conversion from a dispersion HEU** (Highly Enriched Uranium) **to a high-assay U-10Mo LEU** (Low-Enriched Uranium) fuel system.
- ADDER and MCNP5 have been used for:
  - **verification of key neutronics characteristics** of transition cycles, starting at fresh LEU fuel after conversion, and LEU equilibrium cycle.
  - verification of **depletion simulations across several transition cycles** and calculate **critical control blade positions** at each depletion step (figure below)
  - **fuel management operations** handled by ADDER include shuffling fuel within the core, loading/unloading fuel and control blade movements.



The critical control blade position calculated by ADDER and a previous analysis (DIF3D/REBUS-PC) are in agreement with a maximum relative difference of 3.67 %

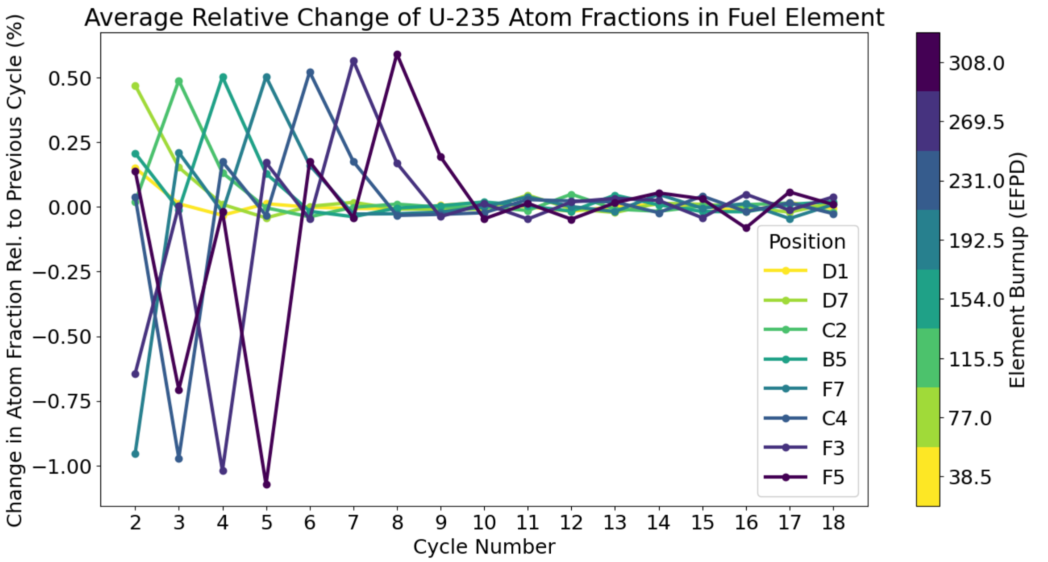
ADDER APPLICATION: NBSR PRELIMINARY DESIGN VERIFICATION

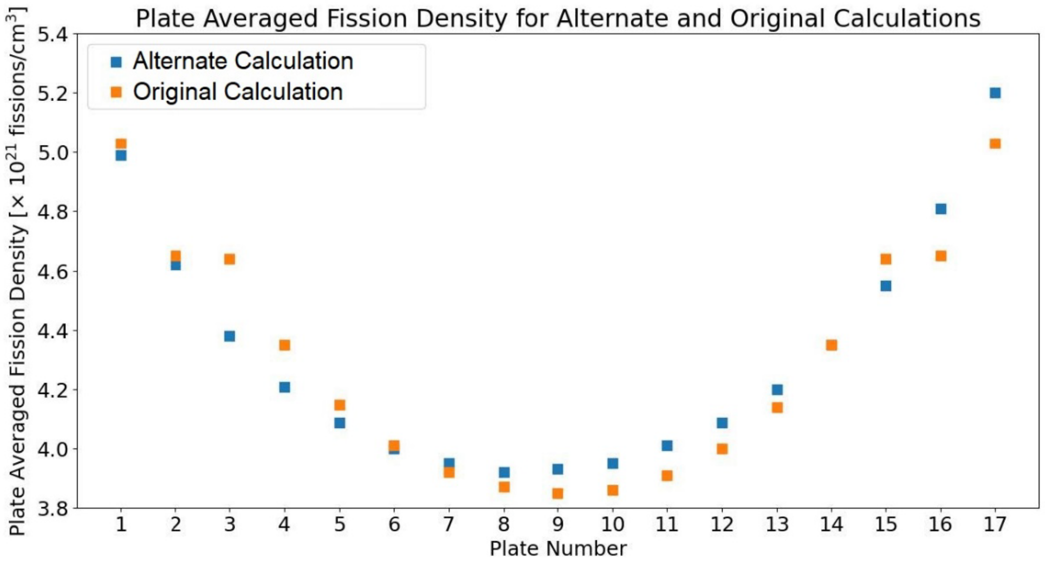
Background and Methods

- NBSR is planning for **conversion from a dispersion HEU to a high-assay U-10Mo LEU fuel system.**
- ADDER was used to **verify key neutronics parameters** of the preliminary design by carrying out depletion calculations including fuel shuffling and control element movement.
- **Equilibrium HEU and LEU cores**, **and mixed HEU-LEU transition cores** were modeled over many cycles.

Results

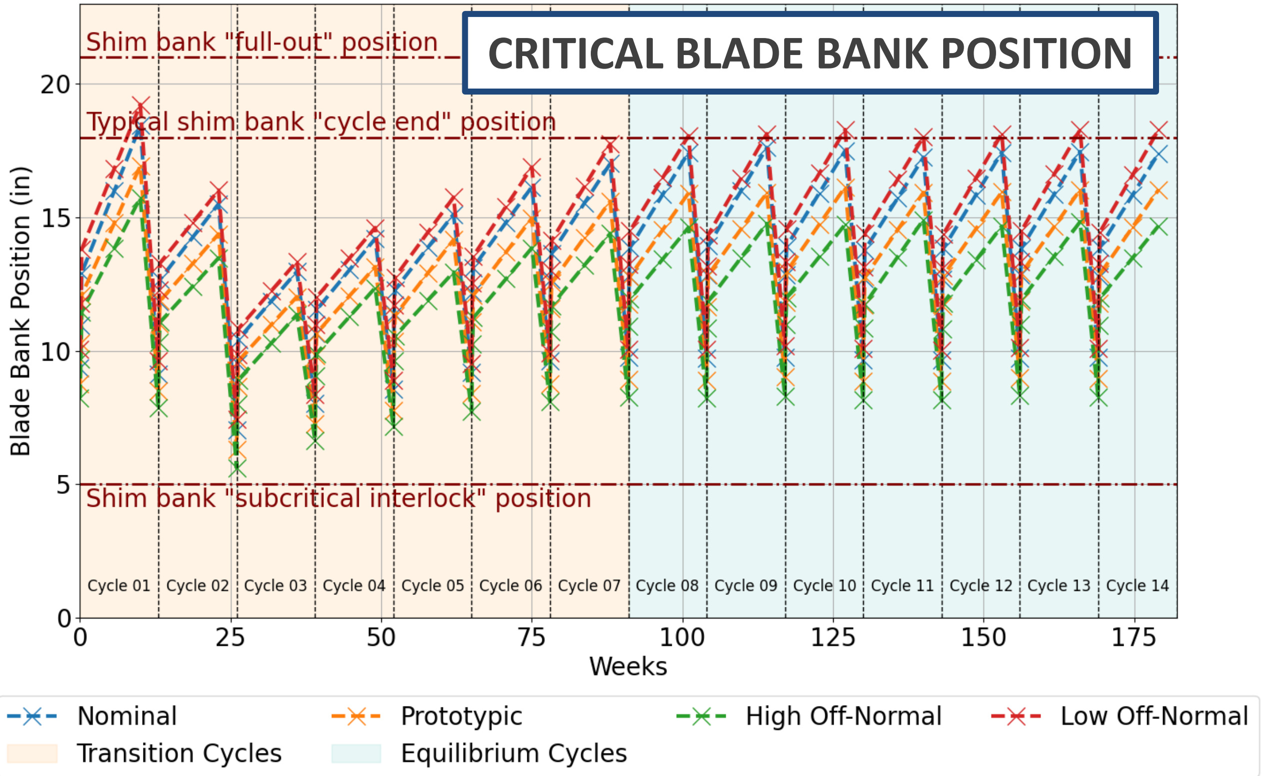
- The results obtained with ADDER (fission densities, shutdown margin, powers, etc.) were in **good agreement with previous calculations.**

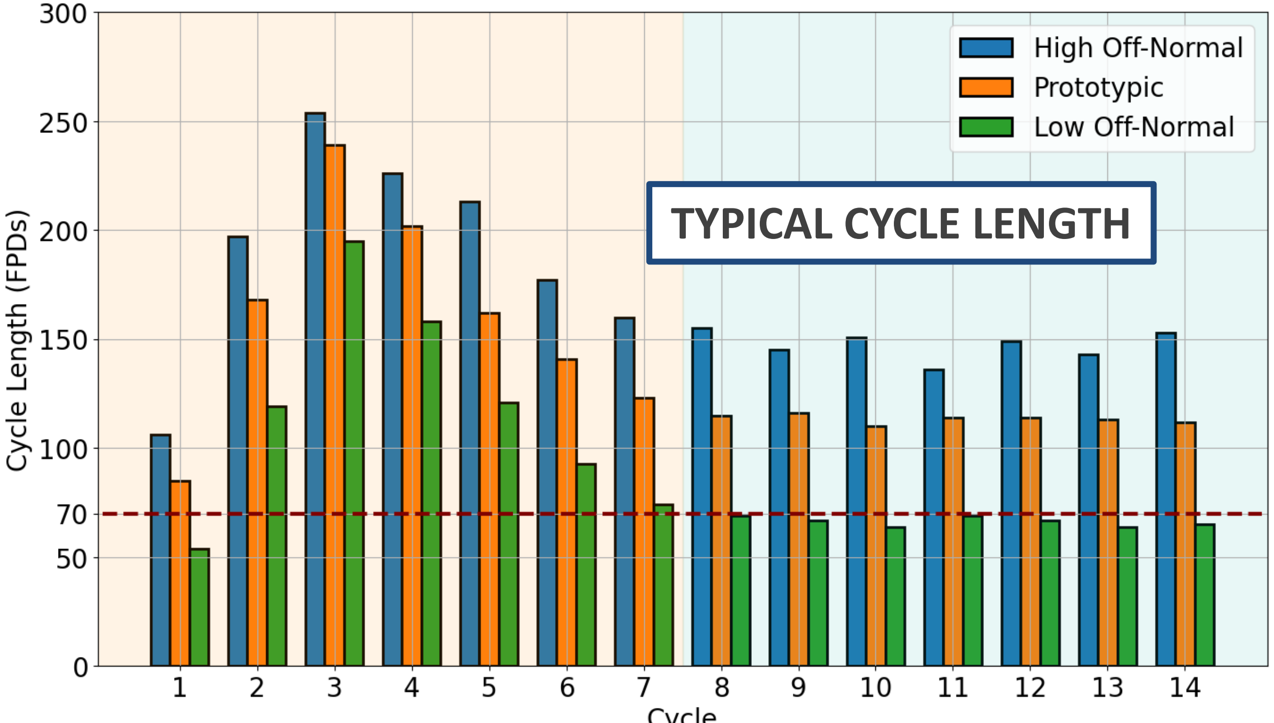




ADDER APPLICATION: MITR LEU FUEL SPECIFICATION IMPACT

- The **impact of the U-10Mo LEU fuel specification** on select **neutronics characteristics** was assessed using ADDER for the calculation of:
  - fuel isotopics during all-LEU transition cycles
  - fuel isotopics for equilibrium cycle
  - typical cycle (transition and equilibrium) length
  - critical blade positions (transition and equilibrium cycles)

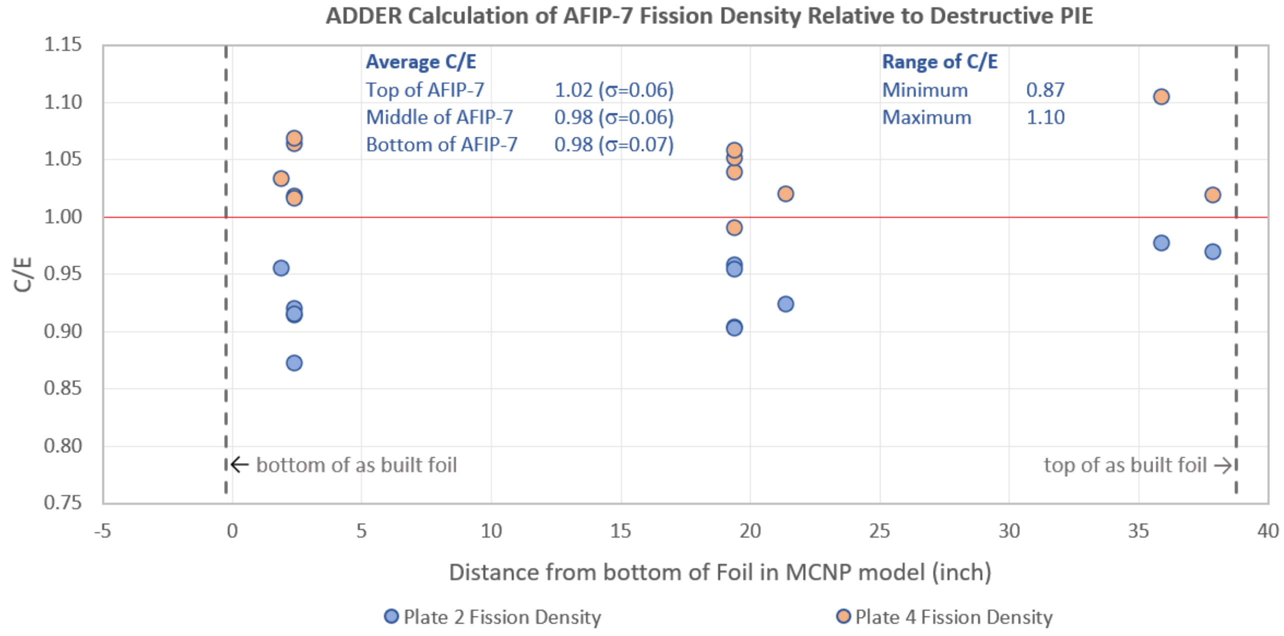


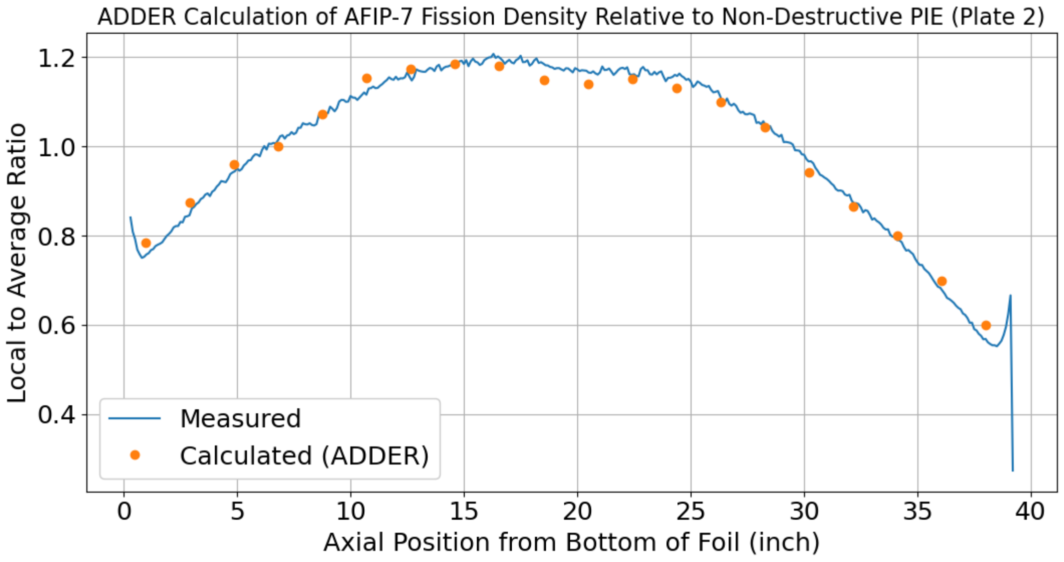


- The neutronics characteristics were studied as a **function of various specification parameters (SP):**
  - The results for 3 combinations of the SP are shown in the figures based on their effect on core reactivity (Prototypic, High Off-Normal, Low Off-Normal)
- MITR fuel management involves several operations such as **fuel elements rotations and flips** that are **easily handled by ADDER**
- Fuel depletion always performed at critical blade position

ADDER APPLICATION: AFIP-7 BENCHMARK

- AFIP-7 was an experiment in the center flux trap of ATR to evaluate **U-10Mo LEU** fuel performance in a **geometry and irradiation conditions prototypic of USHPRR fuel** plates.
- A benchmark model of the experiment has been created using ADDER. The model includes a **detailed power history and control element movement** over two cycles of ATR.
- The benchmark shows that **ADDER can properly predict fission densities in U-10Mo LEU fuel** (detailed below).
- Additional metrics of interest **(U-235 burnup, reactor lobe powers, k_{eff})** were calculated with ADDER to help inform fission density results.





NEXT RELEASE: ADDER v1.1.0

The next release will provide the following main enhancements:

- **Improved parallelization efficiency** through enhanced memory management
- Automatic calculation of **power/fission density and burnup in each depleting material**
- **Tally management to link user-defined tallies to specific components**

NEW FEATURE: TALLY MANAGEMENT DURING DEPLETION

- In MCNP, tallying is the process of scoring the quantities of interest, i.e., flux, energy deposition, reaction rates, etc.
- The tally **feature allows us to tally components (in-core, supply, storage elements) during fuel management operations** by modifying the MCNP inputs accordingly.
- In this way, **physical quantities of interest** (e.g., heat flux) **can be automatically tracked** during the entire depletion history
- It **facilitates I/O management for tallies** by avoiding the need to run additional MCNP simulations after depletion.
- This unique feature will be beneficial in support of design and safety analysis

CONCLUSIONS

- ADDER is **open-source** and available in GitHub: ***https://github.com/anl-rtr/adder***
- **ADDER has unique capabilities to perform fuel management operations**, including shuffling and geometric transformations, allow us to speed-up and facilitate engineer work for design and neutronics analysis
- ADDER has been a powerful tool in **support of the analysis for the activities of the reactor conversion program** (MITR, MURR, NSBR, AFIP-7) and others (PRO-X, MSR application)
- **The next version (v1.1.0) is planned to be released with new capabilities** including enhanced parallelization, automatized tally management and additional calculations in materials.

ACKNOWLEDGMENT

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MATERIAL MANAGEMENT AND MINIMIZATION

THANKS FOR YOUR ATTENTION!