Business from technology

# Universal Fuel Performance Code Interface in Serpent 2

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# Structure of this talk

1. Multi-Physics
2. Fuel behavior interface in Serpent 2
   - Implementation
   - Usage
3. Demo calculation with Serpent 2 - ENIGMA
4. Future directions
5. Summary

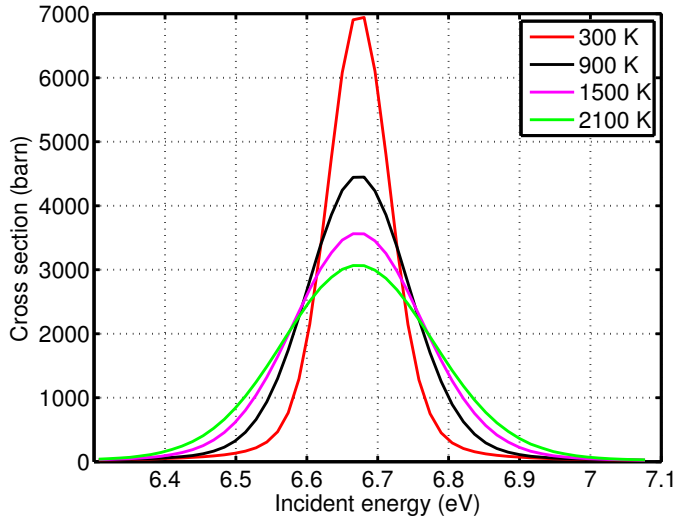
# What is Multi-physics?

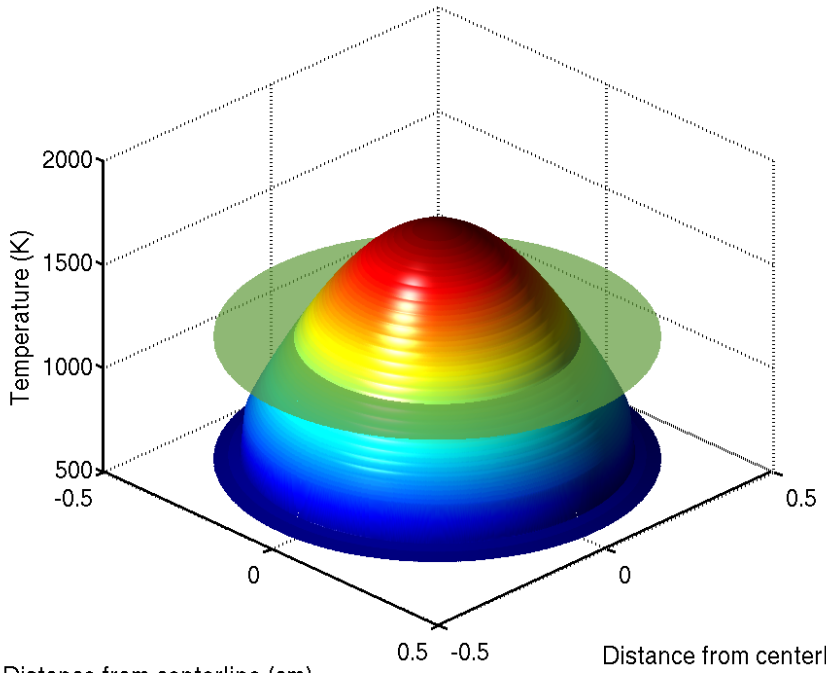
- Modeling more than one traditional aspect of nuclear reactors at the same time
  - Neutronics, fuel behavior, thermal hydraulics etc.
- Passing state variables between codes dedicated to modeling different things.
- Coupling the different solutions with each other.
- A more physical representation of the system.

# Doing multi-physics with neutronics

# Doing multi-physics with neutronics - temperature

- Higher fuel temperature → broader resonance peaks in cross-sections
- Main physical effect through differences in resonance capture of neutrons by U238.
- Higher fuel temperature = Lower reactivity.
- Increased transmutation of U238 to Pu239 especially near the surface of the fuel pellet.



# Effect of temperature discretization on depletion[1]

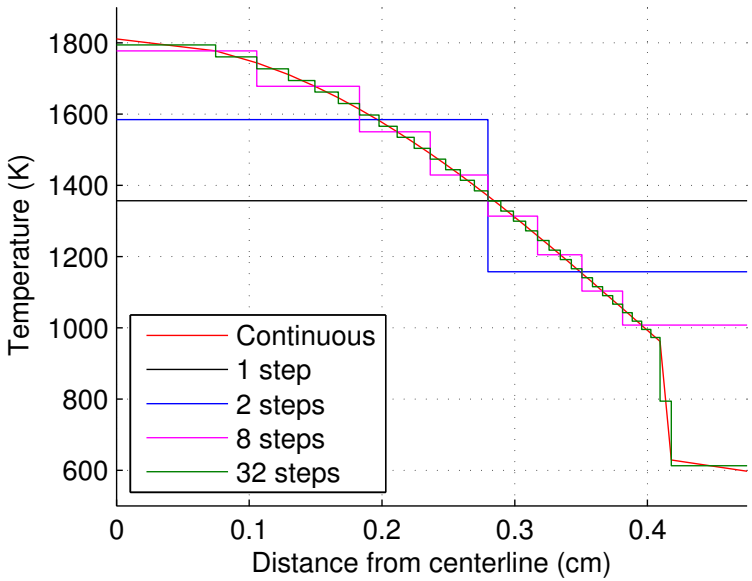



Figure: Approximating the continuous temperature distribution with a step distribution.

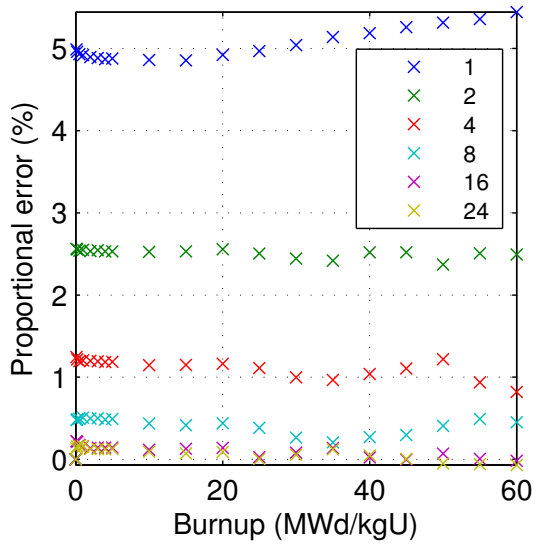
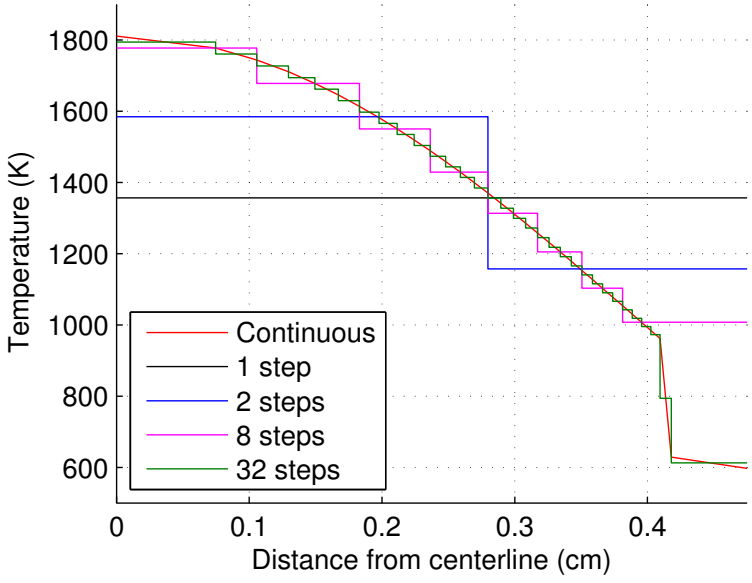



Figure: Relative difference in Pu239 production with N temperature steps (ref. 32 steps)

[1] A. Rintala, "Effect of temperature discretization on the results of neutronics calculations," Bachelor's thesis, Aalto University School of Science (2012)

# Effect of temperature discretization on depletion (Contd.)

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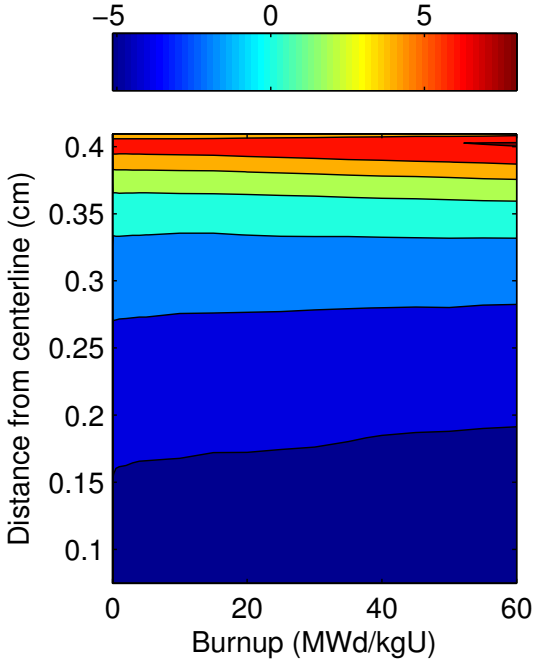
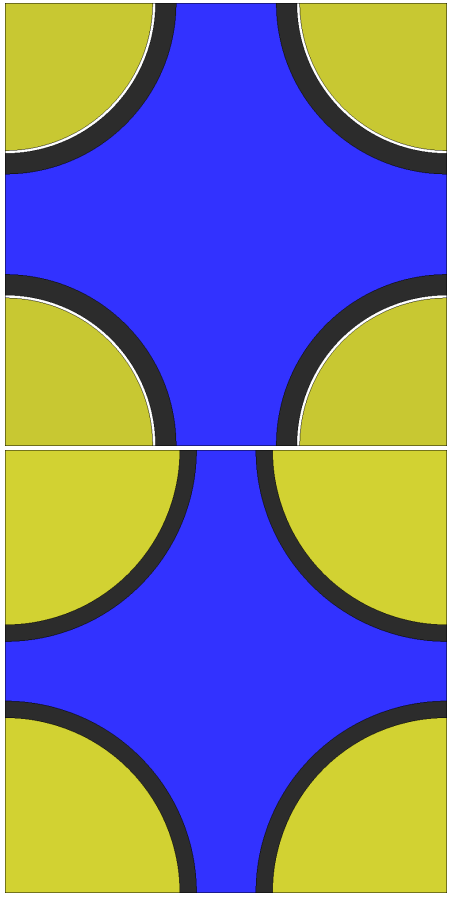



Figure: Relative difference in radial Pu239 production with 1 temperature steps (ref. 32 steps)

# Doing multi-physics with neutronics - geometry

- Thermal expansion of core. $\rightarrow$ Higher leakage of neutrons. Lower reactivity.
- Changes in flow channel cross-section area $\rightarrow$ Changes in moderation and amount of soluble absorber.



# Background

- Studies on fuel behavior feedback since the implementation of the doppler preprocessor.

[2] T. Viitanen and J. Leppänen, "Explicit treatment of thermal motion in continuous-energy Monte Carlo tracking routines," *Nucl. Sci. Eng.*, 171, pp. 165 (2012)

[3] J. Leppänen, "Modeling of Non-uniform Density Distributions in the Serpent 2 Monte Carlo Code," *Nucl. Sci. Eng.*, 174, pp. 318-325 (2013)

[4] J. Leppänen *et al.*, "Multi-physics Coupling Scheme in the Serpent 2 Monte Carlo Code," *Trans. Am. Nucl. Soc.*, 107, pp 1165-1168 (2012)

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- New capabilities to model continuous temperature[2] and density[3] distributions.

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# Background

- Studies on fuel behavior feedback since the implementation of the doppler preprocessor.
- New capabilities to model continuous temperature[2] and density[3] distributions.
- Multi-physics a chosen focus area in Serpent 2 development[4].

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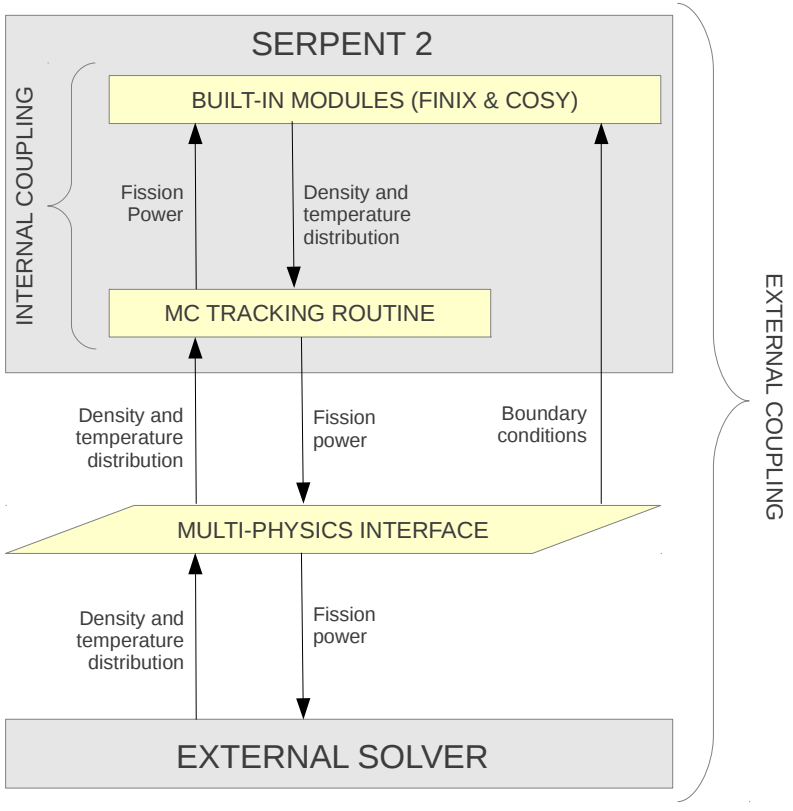
# Multi-physics approach in Serpent 2



# Why a standardized interface

- Writing new input each time is cumbersome.
- Setting the temperature via `mat`-card gives 1 material zone per temperature (not feasible).
- Making the users' life easier.

# Fuel behavior interface in Serpent 2

Works with the pin-geometry type.

```
pin 1
fuel    0.5245
gas     0.5335
clad    0.6135
cool

lat 313 2 0.0 0.0 15 15 1.23
99 99 99 99 99 99 99 99 99 99 99 99 99 99 99
 99 99 99 99 99 99 99 1  2  3  4  3  2  1  99
  99 99 99 99 99 99 2  5  6  7  7  6  5  2  99
   99 99 99 99 99 3  6  8  9  10 9  8  6  3  99
    99 99 99 99 4  7  9 11 12 12 11  9  7  4  99
     99 99 99 3  7 10 12 13 14 13 12 10  7  3  99
      99 99 2  6  9 12 14 15 15 14 12  9  6  2  99
       99 1  5  8 11 13 15 16 15 13 11  8  5  1  99
        99 2  6  9 12 14 15 15 14 12  9  6  2  99 99
         99 3  7 10 12 13 14 13 12 10  7  3  99 99 99
          99 4  7  9 11 12 12 1  9  7  4  99 99 99 99
           99 3  6  8  9 10  9  8  6  3  99 99 99 99 99
            99 2  5  6  7  7  6  5  2  99 99 99 99 99 99
             99 1  2  3  4  3  2  1  99 99 99 99 99 99 99
              99 99 99 99 99 99 99 99 99 99 99 99 99 99 99
```

# Fuel behavior interface in Serpent 2

Serpent 2 takes in: Temperatures and strains @ radial nodes.

Serpent 2 prints out: Fission power distribution, Fast flux distribution.

Input and output meshes independent from each other as well as from material zones.

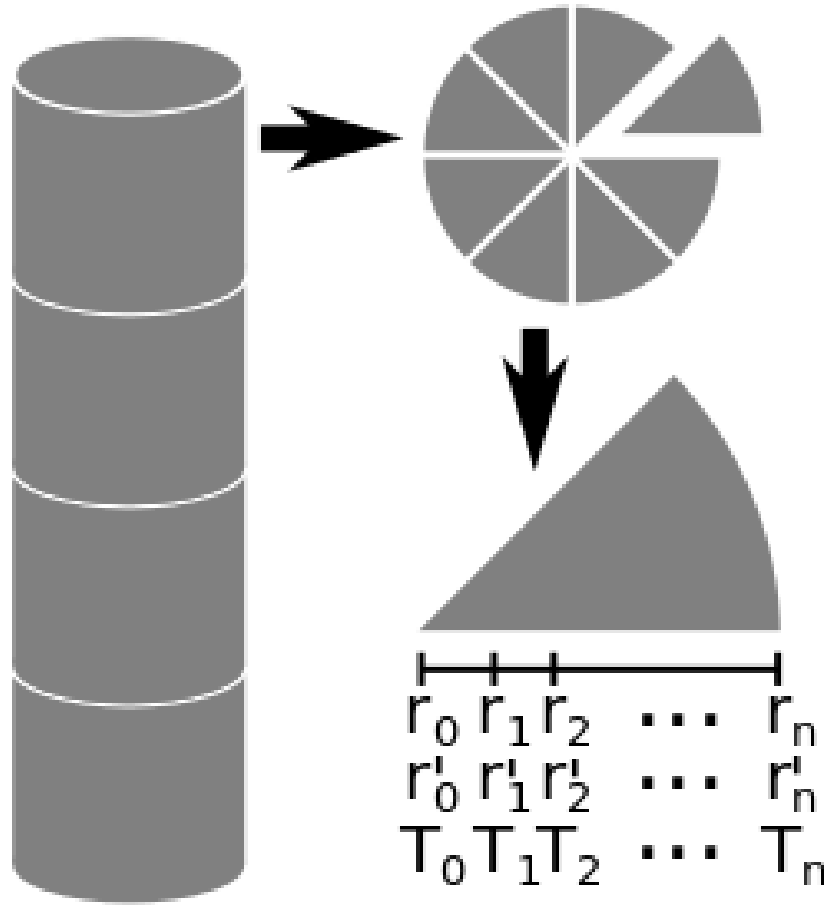



Figure: The input through the interface consists of lists of three values.

# Input-format

```
6 ./Interface.out 1     %Interface type | output file | number of pin definitions

0808                    %First pin universe

5 -12.880000 12.880000 1 0 360 1 0.000000 0.469500         %Power tally mesh
5 -12.880000 12.880000 1 0 360 1 0.000000 0.469500 1 15    %Fast flux tally mesh

1                       %Number of axial zones
-12.880000 12.88 1      %Limits of 1st axial zone    | Number of angular zones
0 360 7                 %Limits of 1st angular zone | Number of radial points

0.000000 0.000000 923.345141  %Cold radius | Hot radius | Temperature
0.103290 0.103918 912.418033  %Cold radius | Hot radius | Temperature
0.206580 0.207814 880.402984  %Cold radius | Hot radius | Temperature
0.300480 0.302229 834.054809  %Cold radius | Hot radius | Temperature
0.403770 0.406027 765.816605  %Cold radius | Hot radius | Temperature
0.479100 0.479320 585.505190  %Cold radius | Hot radius | Temperature
0.546400 0.546811 571.484171  %Cold radius | Hot radius | Temperature
```

# Radially expanded geometry

Temperature consideration by TMS on-the-fly Doppler-treatment.

$$T(x, y, z) = ?$$

Coordinate transformation between nodes by linear interpolation:

$$r_{\text{hot}} = R^i_{\text{hot}} + (R^{i+1}_{\text{hot}} - R^i_{\text{hot}}) \frac{r_{\text{cold}} - R^i_{\text{cold}}}{R^{i+1}_{\text{cold}} - R^i_{\text{cold}}}$$

Updated densities calculated relative to initial density:

$$DF^{i,i+1} = \frac{\rho_{\text{hot}}}{\rho_{\text{cold}}} = \frac{m/V_{\text{hot}}}{m/V_{\text{cold}}} = \frac{(R^{i+1}_{\text{cold}})^2 - (R^i_{\text{cold}})^2}{(R^{i+1}_{\text{hot}})^2 - (R^i_{\text{hot}})^2}$$

# Output-format

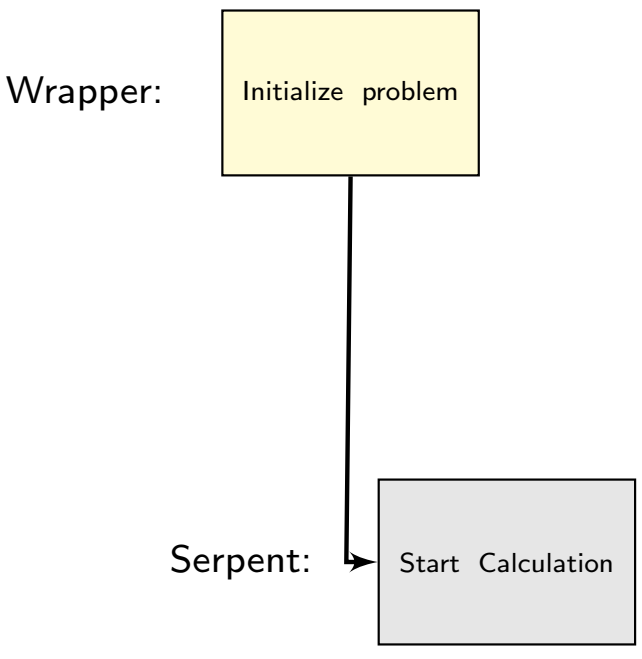
# Capabilities & Limitations

- Continuous density and temperature distributions without memory limitations.
- Axially segmented rods are OK.
- Equally spaced or user defined output tallies.
- Axial geometry changes not modeled.
- Density factor maximum at 1.0

Calculation time decided by required statistics for power tallying.

# Coupled calculation, signaling

Basic POSIX-signalling capabilities for multi-step (depletion) coupled calculation.



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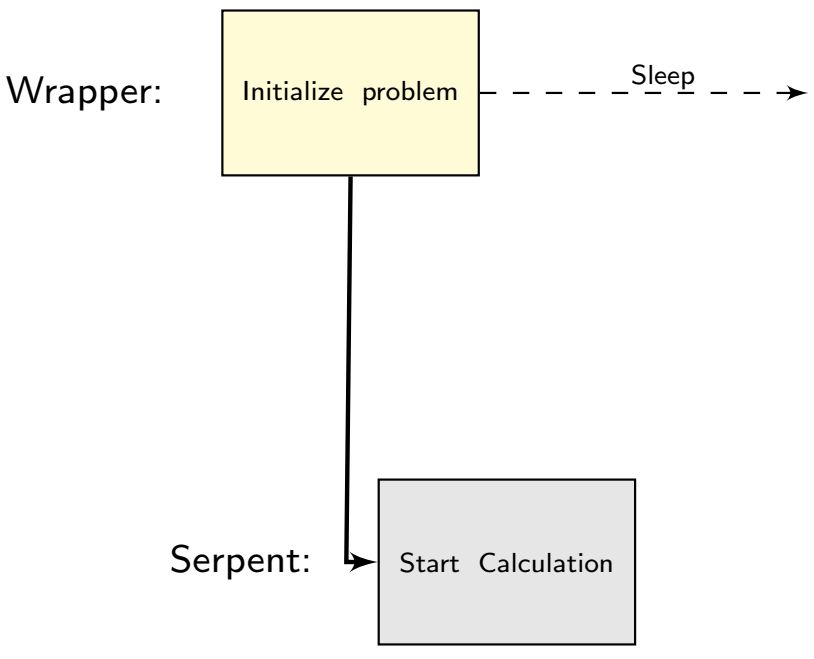

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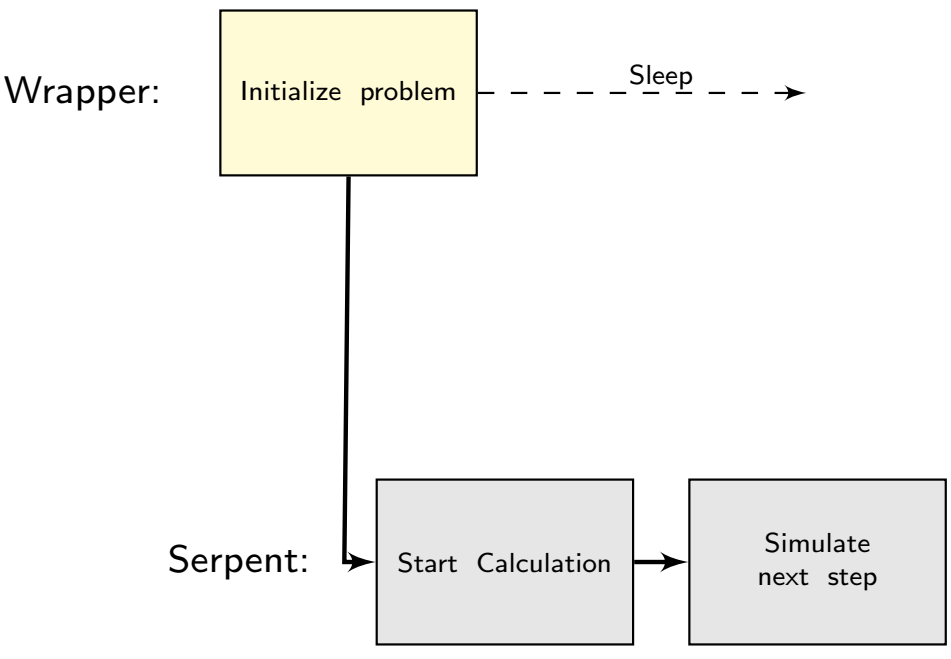

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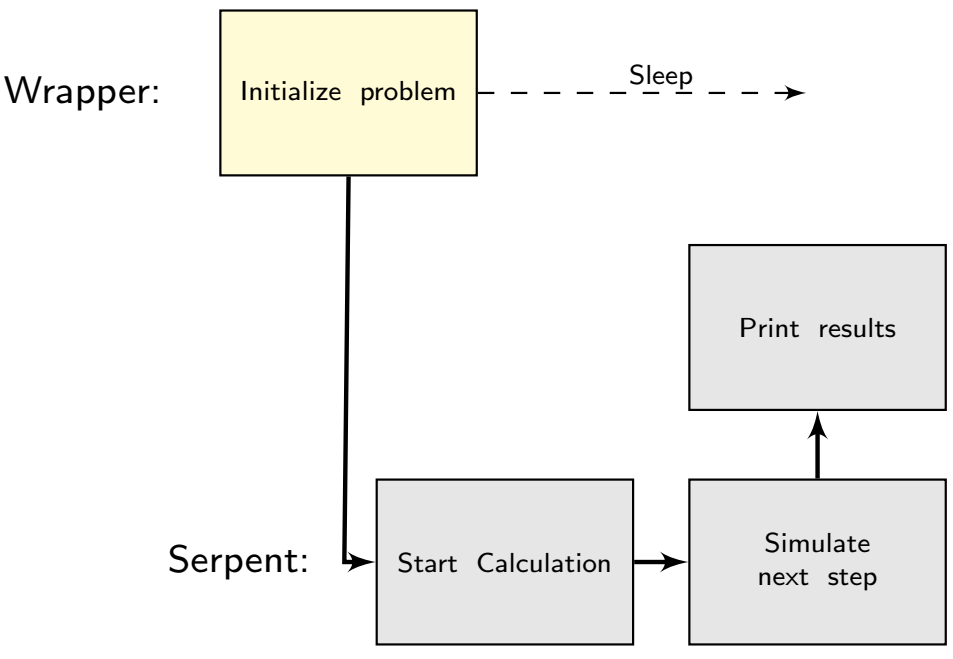

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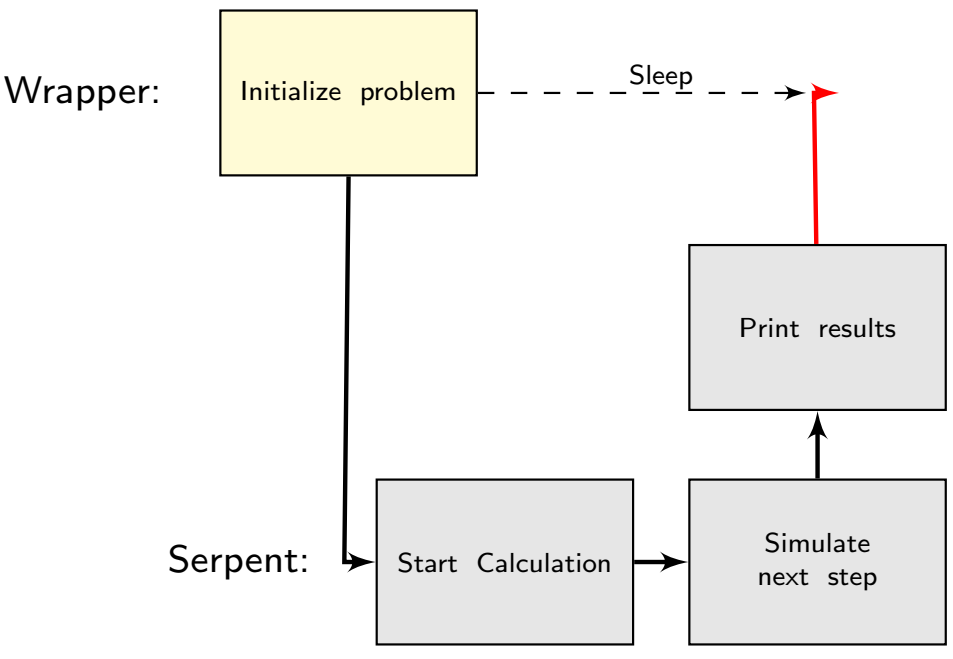

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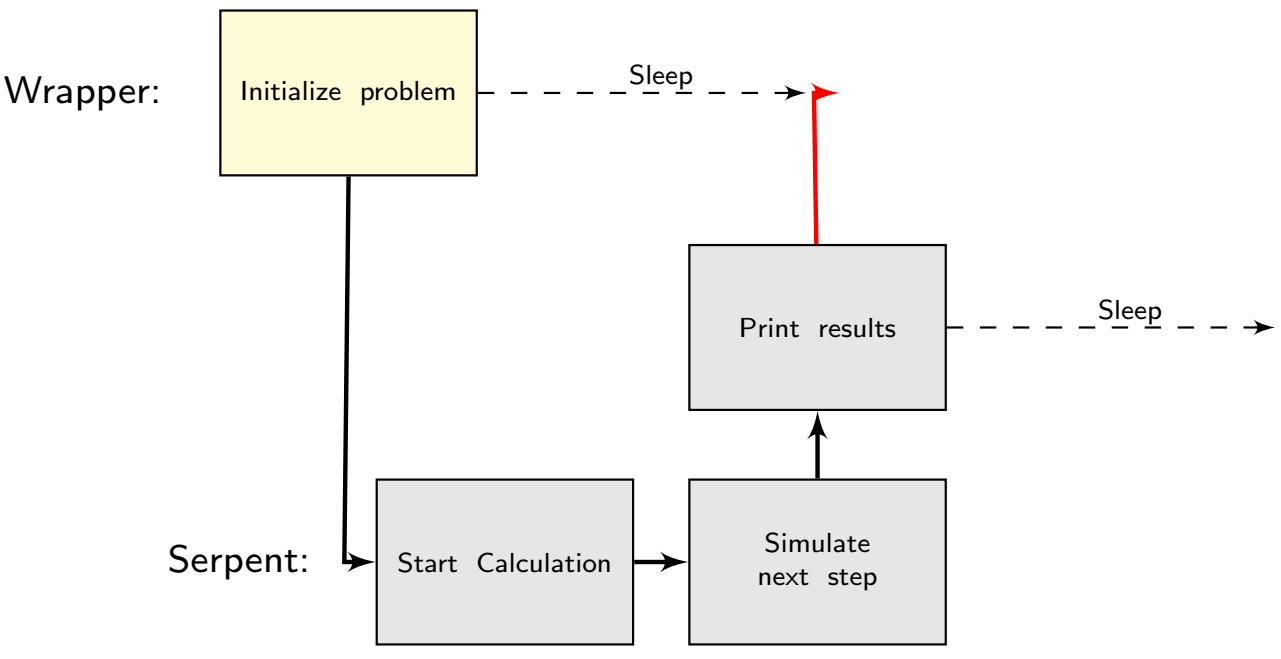

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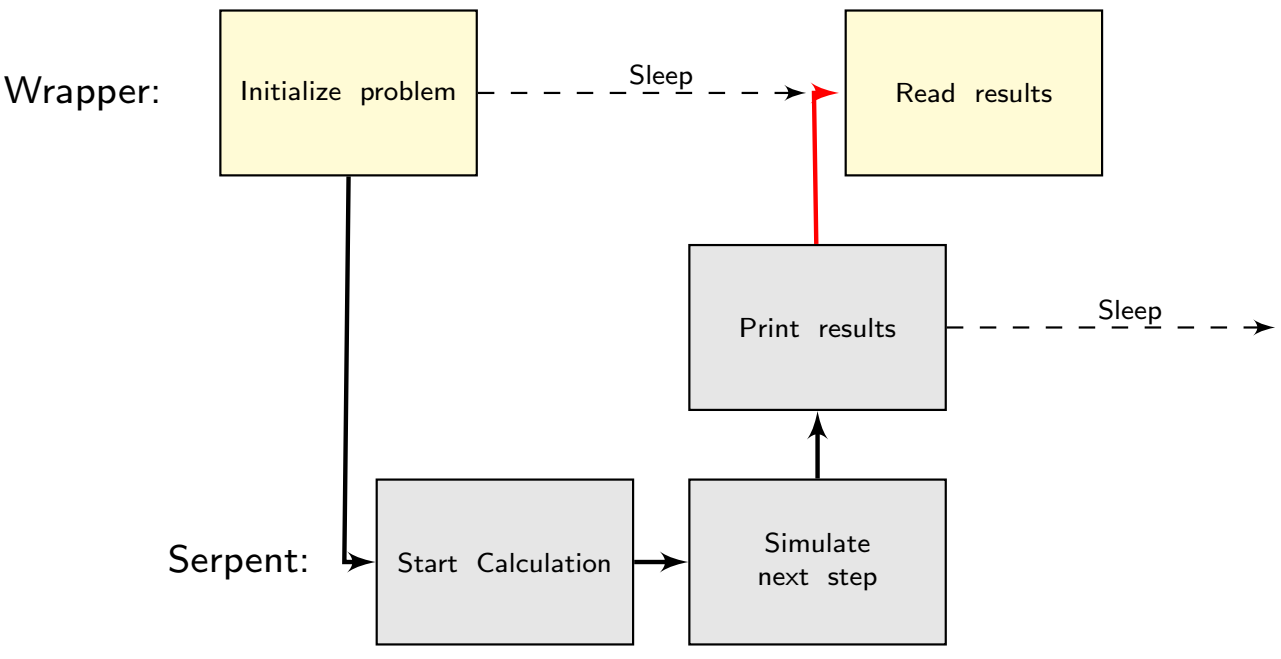

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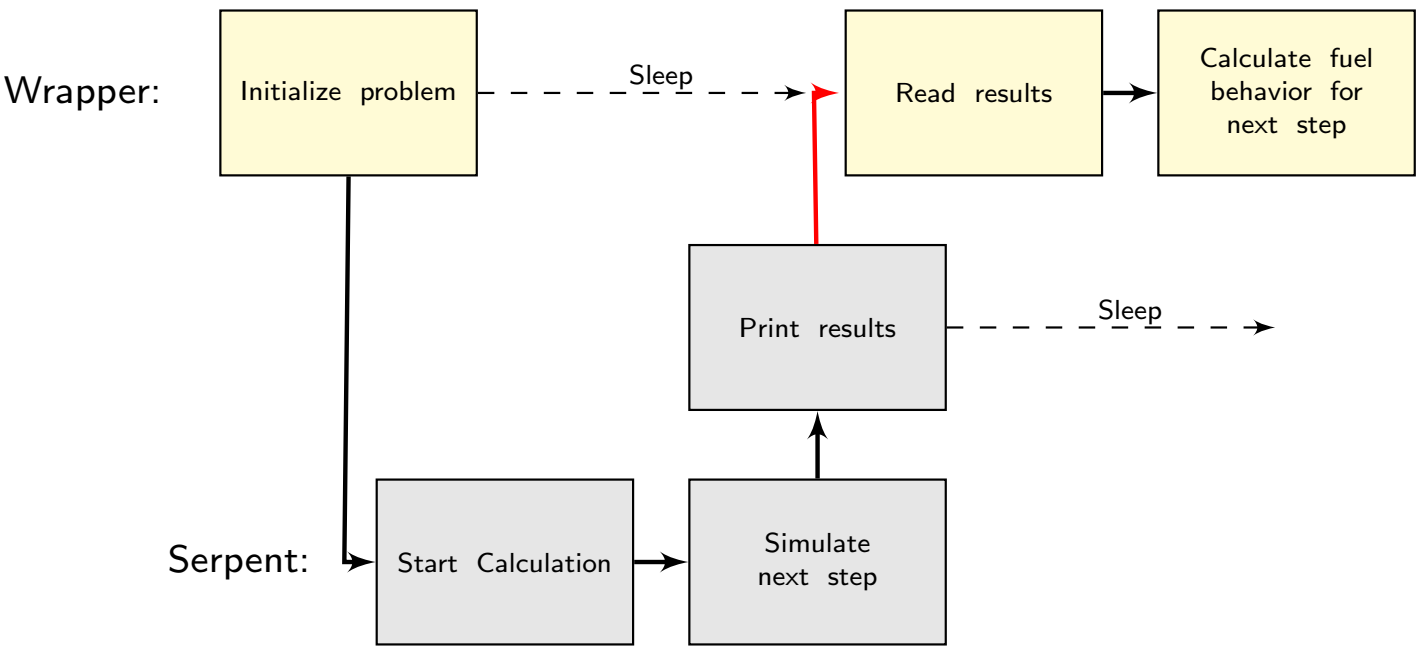

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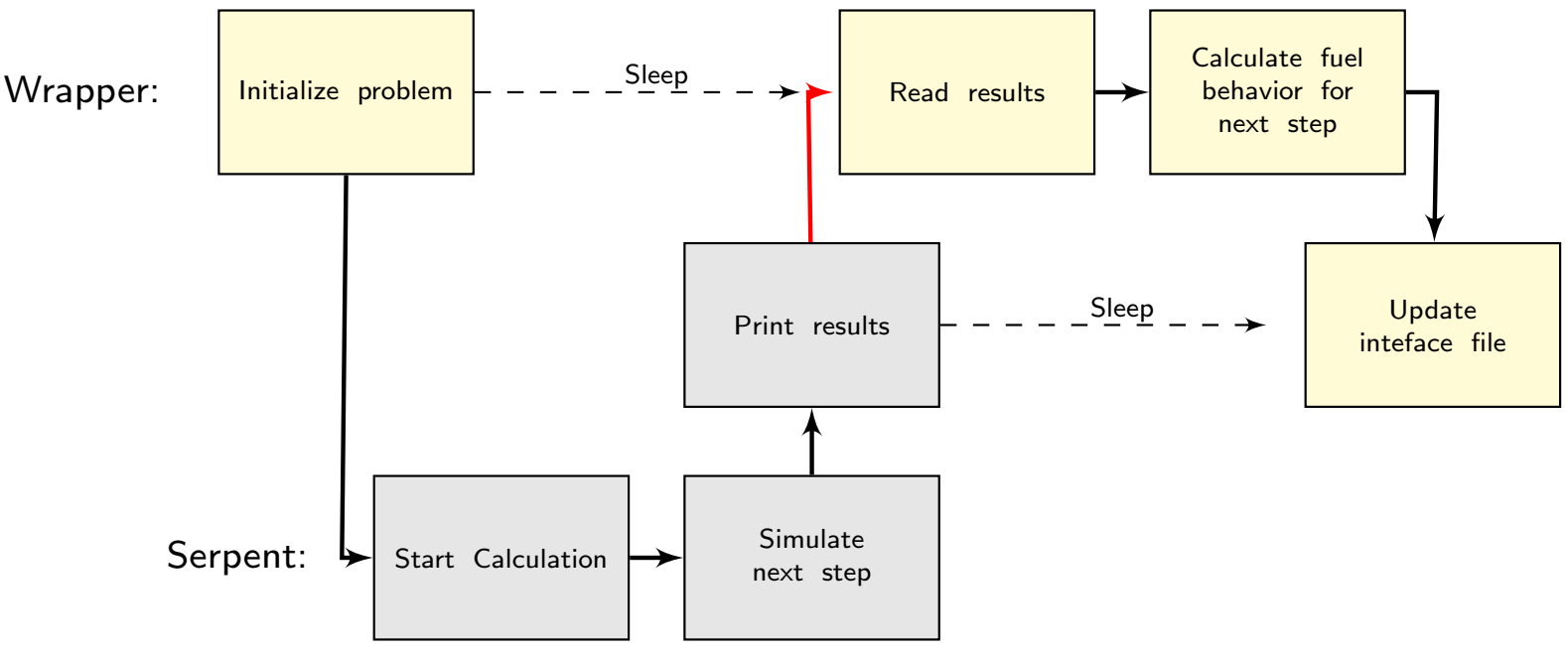

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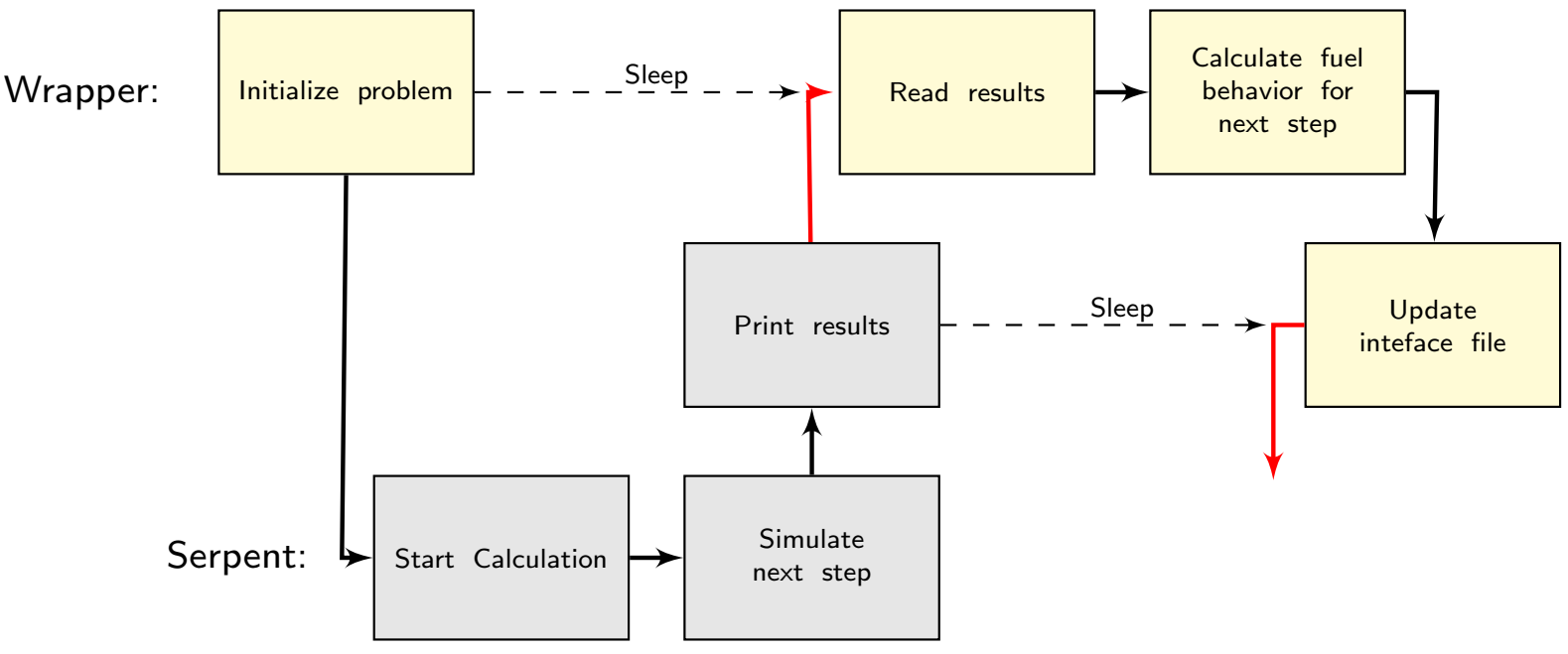

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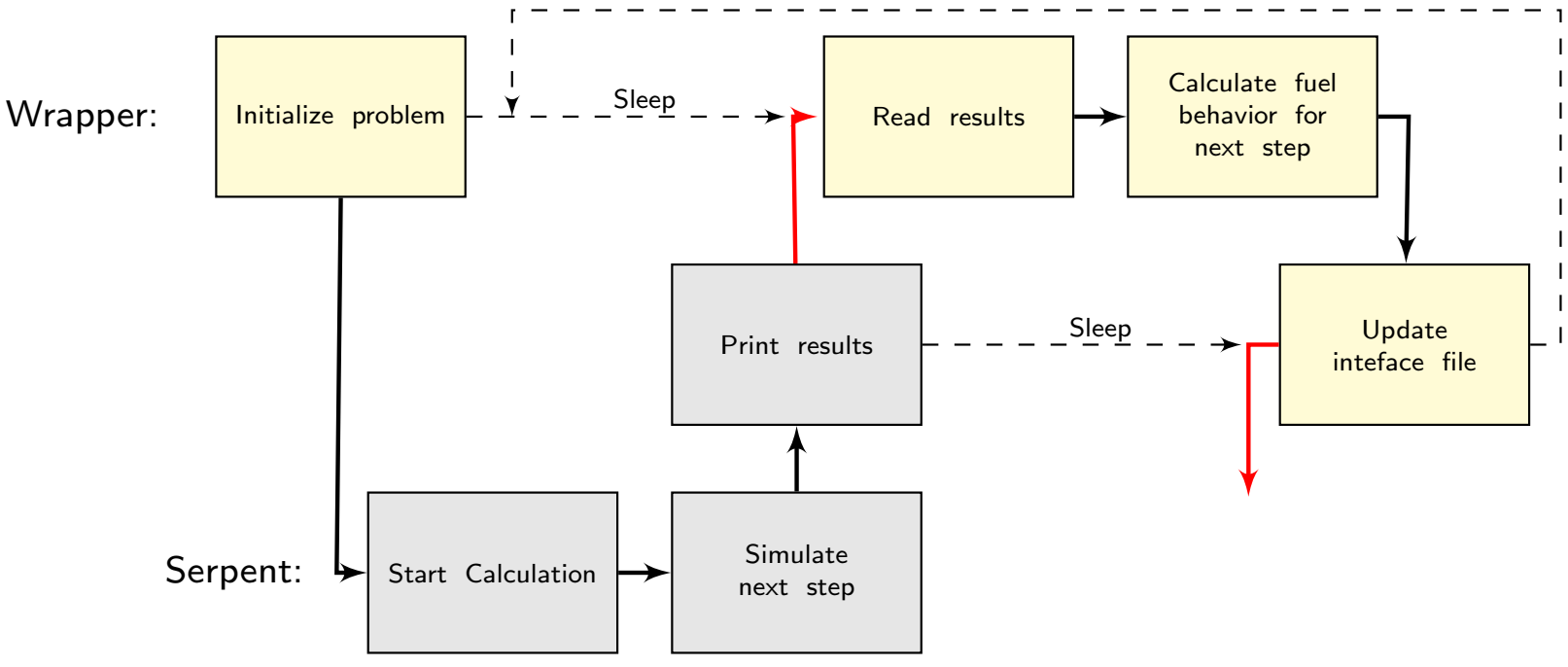

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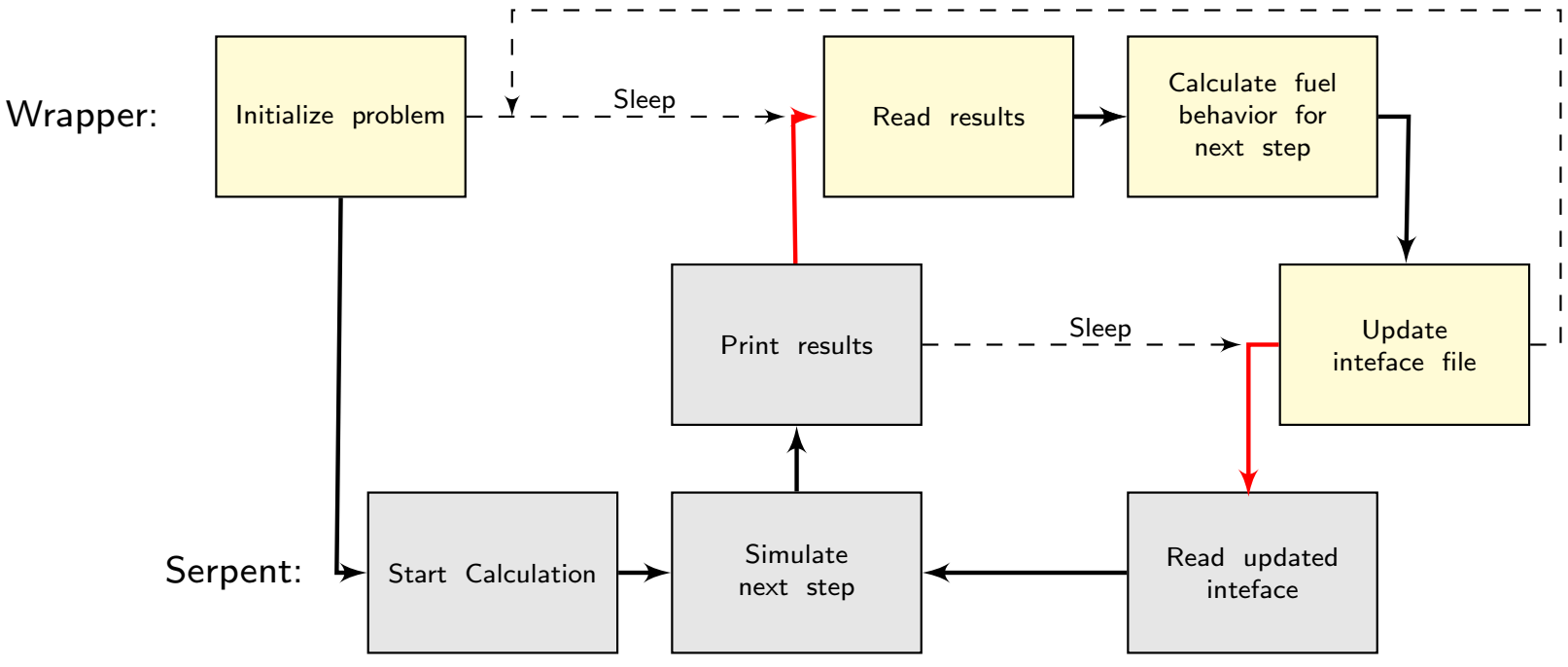


# Doing multi-physics - a demo

# Test case

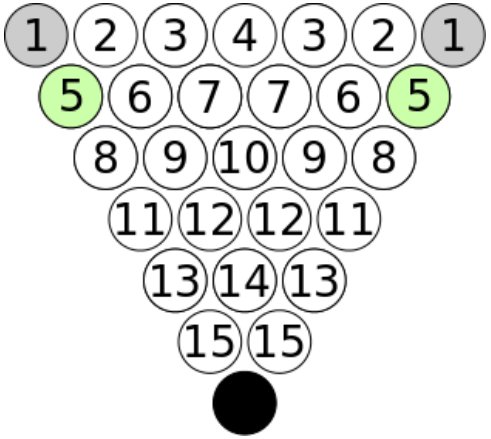
60 cm high VVER-440 assembly in infinite lattice. 10 cm water reflectors on top and bottom.

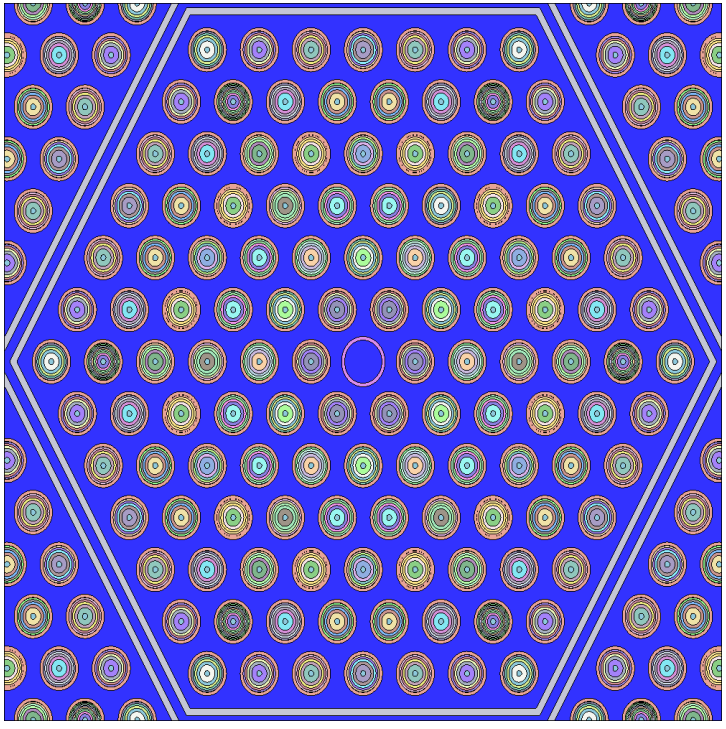
15 Unique lattice positions.

Coupling with a modified ENIGMA v. 5.9b

Depletion calculation to 43.1 Gwd/tU. At a total power of 1.198 MW ($\approx$ 16 kW/m).

Depletion zones: 5 (or 10) radial zones.
Fission power tallies: 10 radial zones.
Fast flux tallies: 1 radial zones.
T & strain meshing: 83 radial nodes.
15 axial zones for everything.

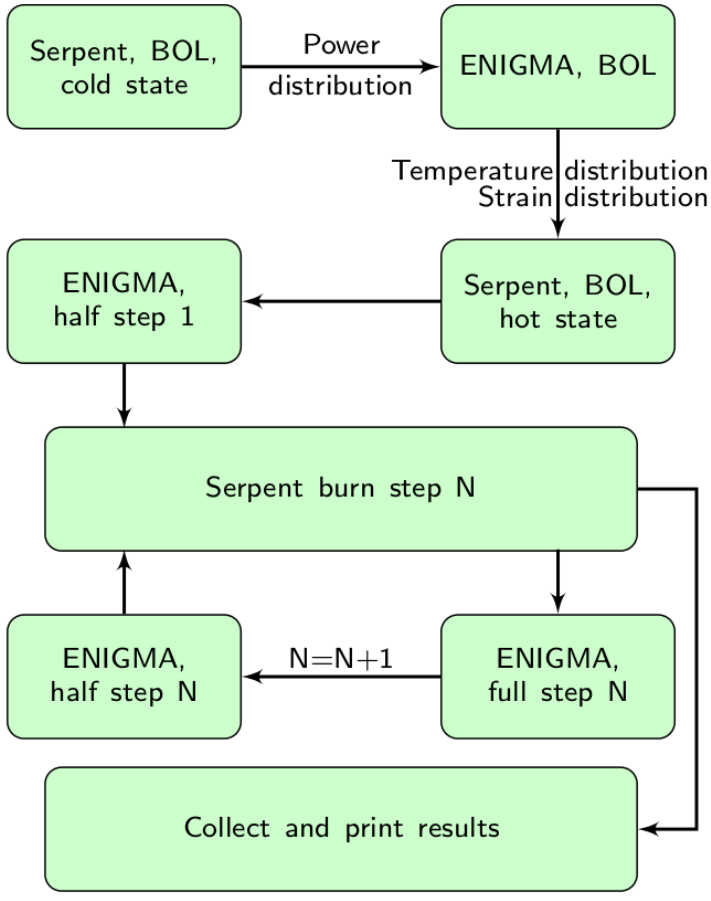


# Iteration scheme in depletion calculation

Wrapper C-program for I/O parsing between programs and running Serpent and ENIGMA.

POSIX-signalling between Serpent and wrapper



# Results

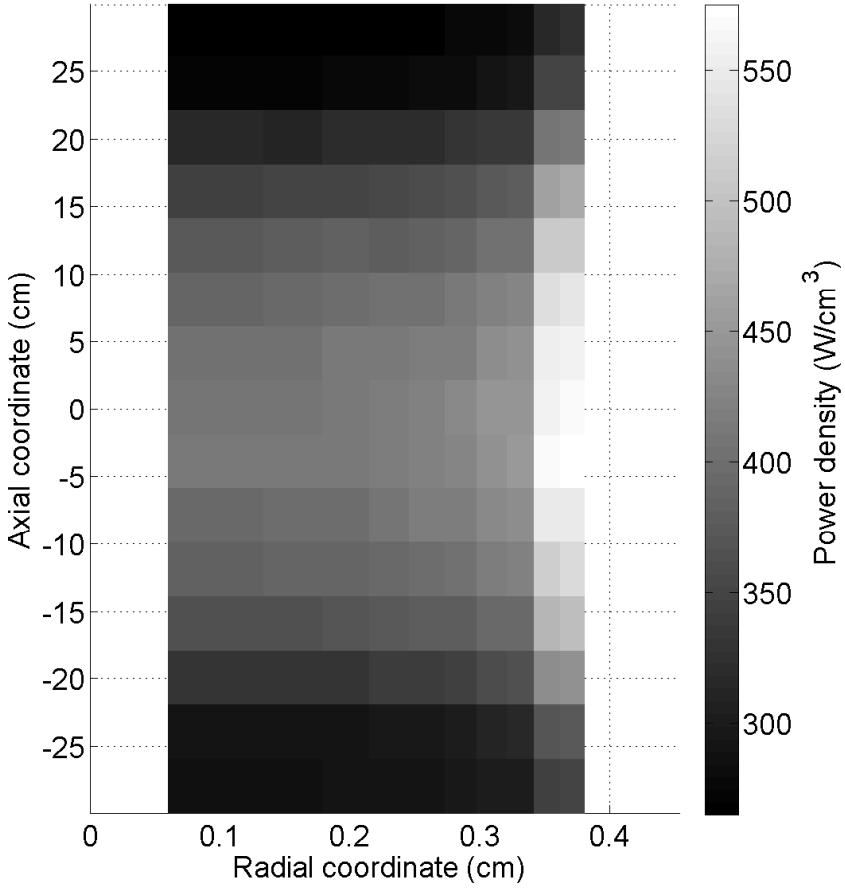



Figure: The power distribution in the corner rod at 21.4 GWd/tU.

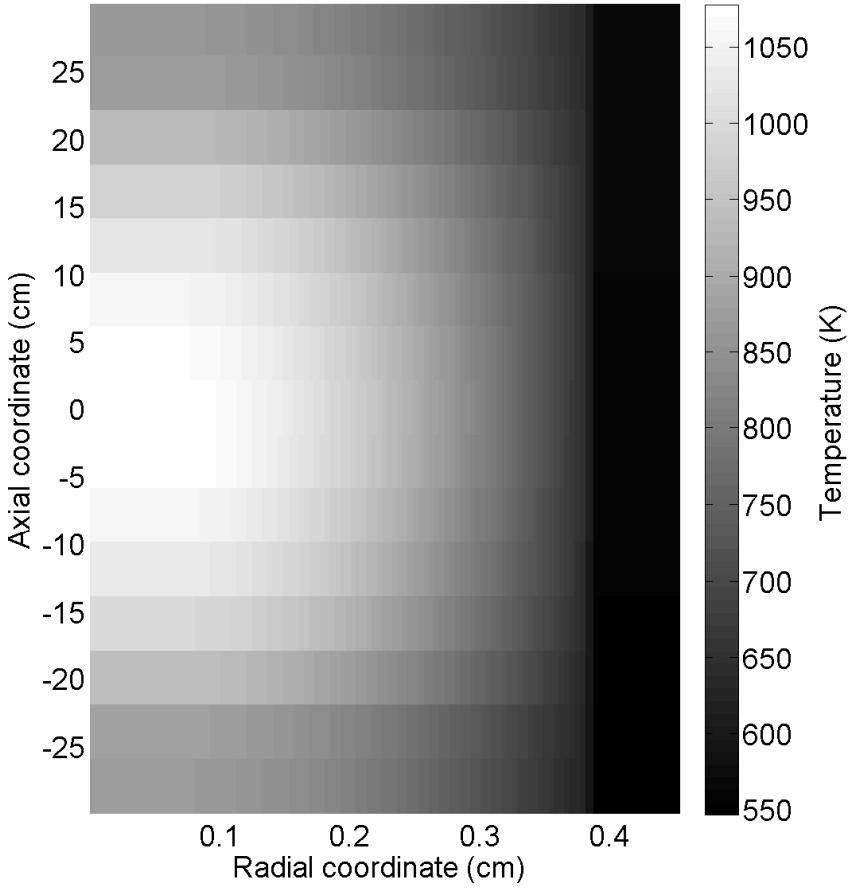



Figure: The temperature distribution calculated by ENIGMA from the power distribution.

# Results

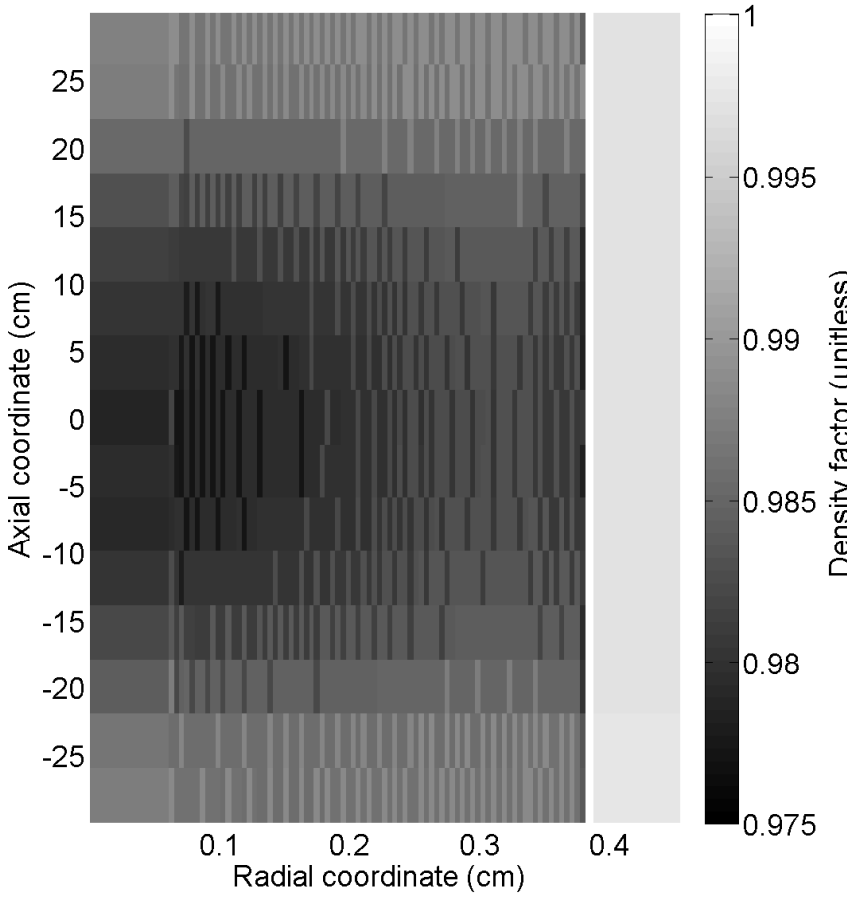



Figure: Material densities in the corner rod at 21.4 GWd/tU. (relative to cold state)

# Comparison calculation

To demonstrate the effect of feedback on neutronics calculation.

- No feedback during depletion.
- $T_{\mathrm{fuel}} = 800$ K.
- BOL hot geometry.

Analysis of differences in

- Reactivity.
- Power distribution.
- Nuclide distributions.

# Radial power distributions

$$\Delta X_{\mathrm{rel}} = \frac{X_{\mathrm{Ref.}} - X_{\mathrm{Feedback}}}{X_{\mathrm{Feedback}}}$$

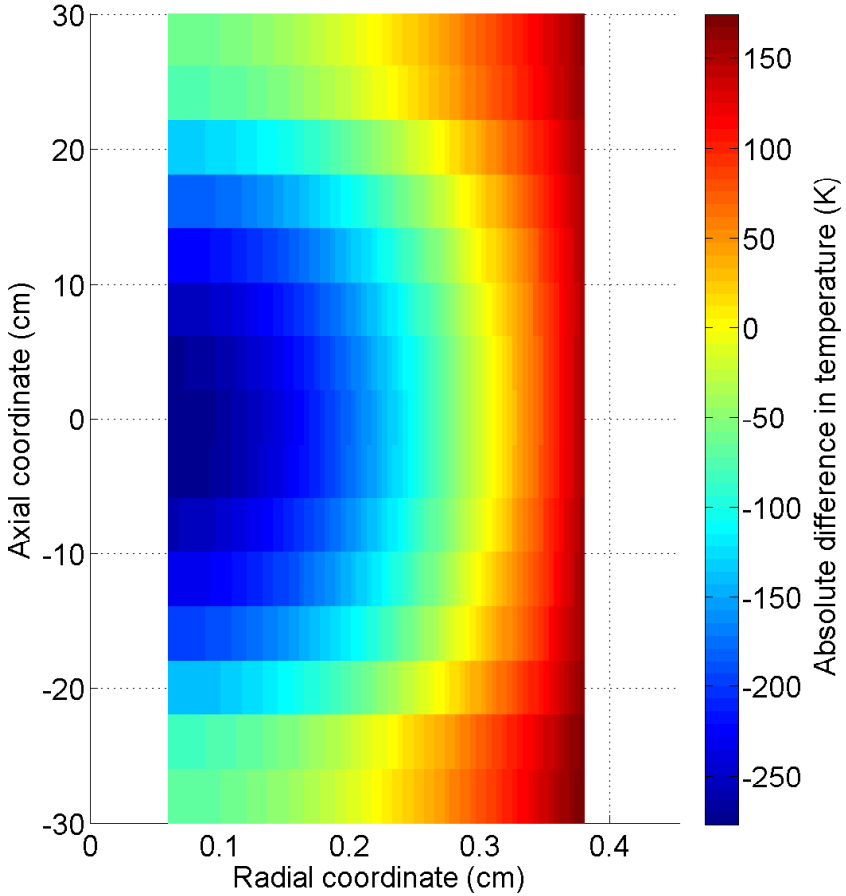



Figure: Temperature differences at LP 1 at 21.4 GWd/tU.

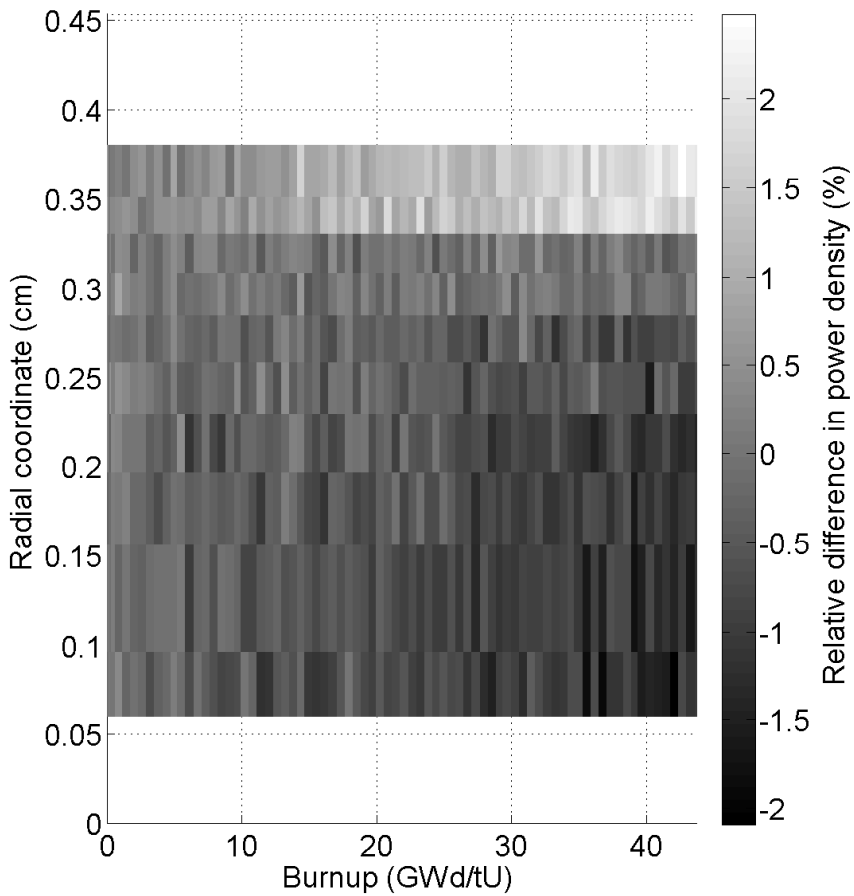



Figure: Relative differences in radial power distribution at different burnups (LP 1).

# Nuclide distributions

$$\Delta X_{\mathrm{rel}} = \frac{X_{\mathrm{Ref.}} - X_{\mathrm{Feedback}}}{X_{\mathrm{Feedback}}}$$

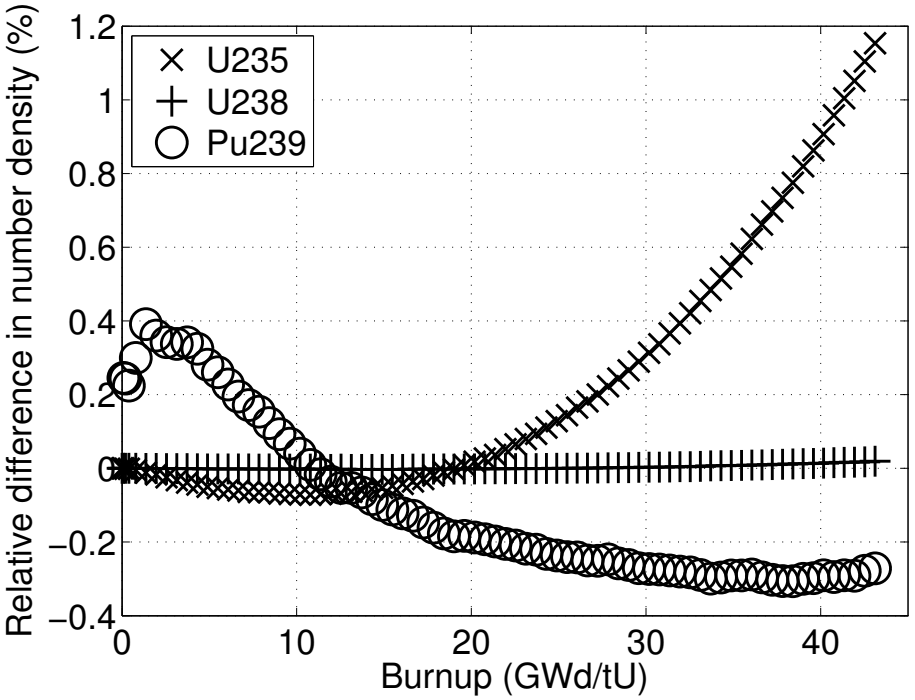



Figure: Relative differences in atomic densities of U235, U238 and Pu239.

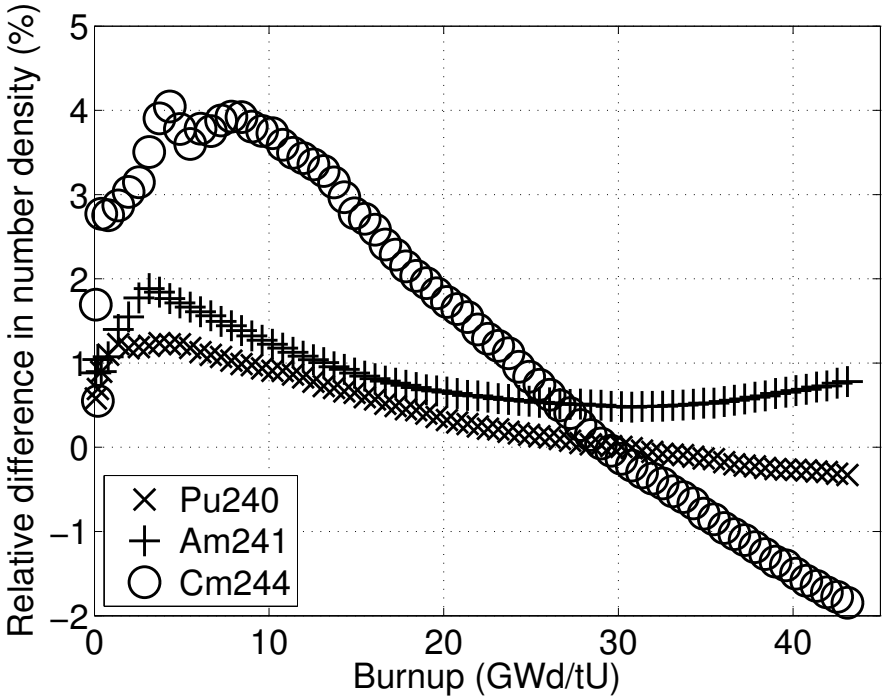



Figure: Relative differences in atomic densities of Pu240, Am241 and Cm244.

# Future directions

- Changes in axial dimensions.
- Depletion iteration scheme.
- Alternative mesh types.
- Couplings with different codes (users).
- Time dependent input.
- FP - neutronics - TH -coupling

# Summary

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- In: Temperatures & Strains at radial nodes in axial and azimuthal segments.
- Out: Fission power & Flux at radial, axial and azimuthal segments.

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- Fuel Performance Code interface implemented in Serpent 2.
- In: Temperatures & Strains at radial nodes in axial and azimuthal segments.
- Out: Fission power & Flux at radial, axial and azimuthal segments.
- A beginning of a long journey.

# Thank you!

Ideas, suggestions and questions are appreciated.

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