Flowing-pebble depletion modeling in ORIGAMI

Steve Skutnik

Oak Ridge National Laboratory
SCALE Users’ Group Workshop
April 27-29, 2022
Overview

• Modeling strategy
  – What assumptions do we make in modeling flowing-pebble fuel?
  – What physical characteristics need to be captured?

• Implementation in ORIGAMI
  – Axial zone definition
  – “Transit”-based depletion
  – Applications to LWRs (“static” axial zones)
Modeling strategy for pebble-based reactors
HTGR analysis with SCALE: Overview

• **Main goals**
  – Evaluate neutronic characteristics
  – Generate individual pebble inventory within a core zone/batch (e.g., difference between fresh vs. once-through pebble in a single core zone)
  – Generate discharge pebble inventory/decay heat with sensitivity/uncertainty analysis

How do we do this for moving / reloading pebbles?
“Equilibrium” assumption for flowing fuel

For moving fuel, effectively add an advection term to the Bateman Equations:

\[
\frac{\partial N_k}{\partial t} + \frac{\partial N_k}{\partial z} v_z = \phi \sum_{i=l}^{m} N_i \sigma_f^{i} y_{i\rightarrow k} + \phi \sum_{s=r}^{q} N_s \sigma_s^{a} y_{s\rightarrow k} + \phi \sum_{j=n}^{p} N_j \lambda_j \alpha_{j\rightarrow k} - \lambda_k N_k N_k - \phi N_k \sigma_a^k
\]

At equilibrium, compositions are invariant with respect to axial position:

\[
\frac{\partial N_k}{\partial z} v_z \rightarrow 0
\]
Fast: thermal flux ratio (spectral index) sensitive to radial zone; relatively invariant axially

**Axial**
Spectral index: Equilibrium core (1200 K)

- **Central regions**
- **Reflector-adjacent (outer)**

**Radial**
Spectral index: Equilibrium core

Elevation (cm)
- -1050
- -900
- -750
- -600
- -450
- -300
- -160

Major spectral shifts primarily occur across radial zones; i.e., primarily need radial zone ORIGEN libraries
Radial, temperature effects drive differences in ORIGEN library 1-group cross-sections
ORIGEN “Archive” format for multi-dimensional libraries
ORIGEN “Archive” format & ORIGAMI

• New ORIGAMI (SCALE 7.0) will rely exclusively on HDF5-formatted “Archives” with descriptive interpolation data written on the file

• Users can convert existing LWR libraries in arpdata.txt for use with ORIGAMI

  obiwan convert -format=hdf5 -alias=[lib_alias] [path_to_arpdata.txt]

• Flexible Archive data format allows for run-time specification & checking of interpolation parameters
  - Handled via a new “state” block
ORIGEN reactor data library interpolation relies on an ASCII database with hard-coded interpolation dimensions.
New HDF5-based “Archive” format designed to accommodate arbitrary interpolation dimensions

HDF5 “Archive”

DecayData

TransitionStructure

Lib #1

Lib #2

Lib #3

Loss XS

Fission XS

Neutron yields

Energy per fission

Energy per capture

Transition matrix

Tags

Tags

Tags

particle

neutron

Loss XS

Fission XS

Neutron yields

Energy per fission

Energy per capture

Transition matrix

Initial enrichment

Relative proximity to reflector

Reflector temperature
New ORIGEN “Archive” format will pair with HDF5 to facilitate consolidated storage & interpolation

• Motivation:
  - How can we collect “similar” libraries together into a collection for interpolation?
  - How can we “archive” a set of similar libraries to disk as a consolidated archive?
State block interpolation example

State block user input
(used for problem-specific interpolation)

```plaintext
state{
    radial_pos = INNER
    reflector_temp = 750.0
}
```

- Library tags referenced directly as **keys**
- Use only libraries from categorical (ID) tag **radial_pos**
- Interpolate to 750 K for continuous tag **reflector_temp**
Flowing pebble depletion implementation in ORIGAMI
New ORIGAMI input based on using flexible “axial zone” definitions

• Two types of “zone” definitions
  – **Transit Zone**: Axial region where flowing pebbles will “transit” through as they flow through the core
  – **Static Zone**: Fixed spatial region of an (unmoving) assembly

**Transit zone**

Radial definitions of:
  • Population distribution (PDF)
  • Power shape
  • Library interpolation parameters (e.g., position, temperature)

**Static zone**

x-y definitions of:
  • Material composition (defined in fuel mixtures)
  • Power shape
  • Library interpolation parameters
Transit-based depletion histories

- Depletion modeled in the core as a series of sequential transit “zones” corresponding to axial regions of the core
- Assumes fixed axial “streamlines” for now
  - i.e., constant radial probability distribution
- Independent radial characteristics for each axial “transit zone”
Combining core transits into a depletion history

• At the end of a core transit, radial region masses are summed, decayed, and redistributed according to the next radial probability distribution

• Process is repeated (“chained transits”) throughout the entire pebble depletion history
Example: Defining a transit history

```python
=origami
axial_configs=

transit_zone(top){
    rpower=[ 1.1 0.92 0.85 ]
    state{
        position=[ INNER CENTER OUTER ]
        temperature=[ 1100.0 1000.0 950.0 ]
    }
    pz=1.0
}

transit_zone(mid){
    ...
}
```

Transit zone identifier (key)
Radial power shape
Library interpolation tags (1 per radial zone)
Example: Defining a transit history

```python
=origami
axial_configs={
    transit_zone(top) {
        ...
    }
}

hist=[
    transit(first) {
        power=100.0 burn=60.0 down=5.0
        rdist=[ 0.25 0.5 0.25 ]
        transit_path=[
            top={ frac=0.3 }
            mid={ frac=0.5 }
            bottom={ frac=0.2 }]
    }
    ...
]
```

- Cross-reference transit zone by unique key
- Radial probability (mass) distribution defined for each transit
- Transit path through core defined as a sequence of transit zone objects
- Chain together multiple “transits” to define the irradiation history
Summary of new features for flowing pebble depletion

• The new ORIGAMI (targeted for SCALE 7.0-beta1) will afford modeling of flowing pebble depletion via chained “transit zone” blocks & multiple transit passes through the core

• New features also include a new HDF5-based “Archive” format for libraries with descriptive metadata and generic interpolation capabilities
  – Necessary to represent unique neutron spectrum characteristics seen in non-LWR systems