INL/CON-22-69938-Revision-0

Equilibrium Core Pebble Bed Depletion Algorithm Development at INL

November 2022

Changing the World's Energy Future

Sebastian Schunert

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PBR Depletion at INL

Equilibrium Core Pebble Bed Depletion Algorithm Development at INL

INL is developing several approaches for pebble depletion

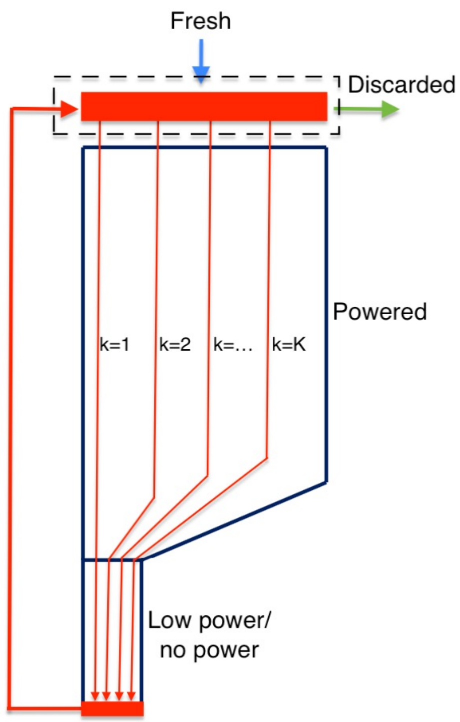
Approach	Neutron transport solver & cross sections	Depletion algorithm	TH feedback
Deterministic, homogenized method in Griffin (*Griffin*)	• Homogenized pebbles • Deterministic neutronics solve (Diff, PN, SN) • Currently two-step cross sections from DRAGON	• Homogenized* • Eulerian discretization on streamlines • Discharge by accumulated burnup** • Direct equilibrium core	• Pronghorn porous media • Natural coupling to all MOOSE apps (e.g., BISON)
Monte Carlo, heterogeneous method using Serpent (*kugelpy*)	• Explicit pebble and TRISO geometry • Serpent neutronics solve • Continuous energy cross sections	• Homogenized batches • Batches of pebbles on n-th path moving in lockstep • Discharge by #passes • Running-in to steady-state	• FY22: constant temperature or linear temperature profile • FY23: coupled with Pronghorn porous media

*The pebbles are treated as ensembles and not as separate pebbles during depletion.
** This idea goes back to Massimo's Kugel code.

Note, there is another pebble-by-pebble method based on pebble tracking transport (PTT) in Griffin developed in collaboration with TAMU!

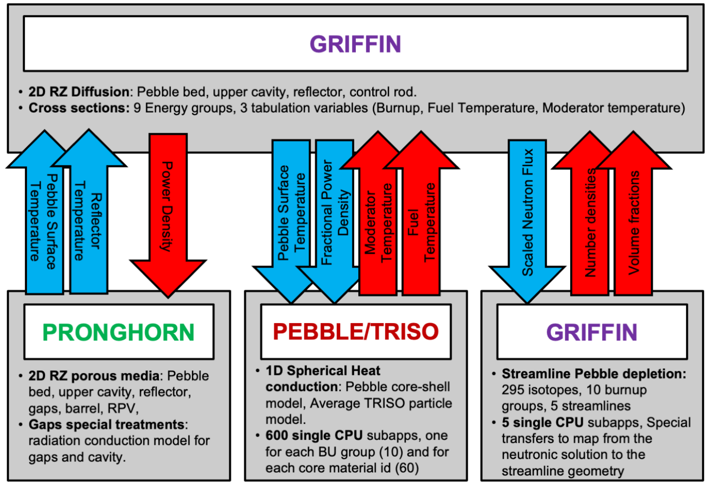
Approach 1: Griffin (NEAMS, NRC)

- Purpose: fast method for computing equilibrium core depletion using a homogenized model (intermediate fidelity)
- Solve pebble & nuclide *detailed* balance equations on streamlines (balance over space & burnup, Eulerian frame)
- We distinguish pebbles by burnup by solving for:
  - Pebble volume fraction: $n(\text{space}, \text{burnup})$
  - Isotope density *i:* $N_i(\text{space}, \text{burnup})$
- ”Flow rates” of pebbles are reloaded/discharged based on their burnup and <u>not</u> the number of passes
- Neutronics: multigroup (diffusion, S_N) solver
- Cross sections: currently 2-step cross sections from DRAGON (online cross sections are being implemented)
- Converge coupled steady-state multiphysics using fixed point iterations



Assumptions & simplifications

- Pebble move along streamlines
- Homogenized neutronics & depletion
- Discretization error on approximating spatial and burnup derivatives
- Currently limited to 2-step cross sections



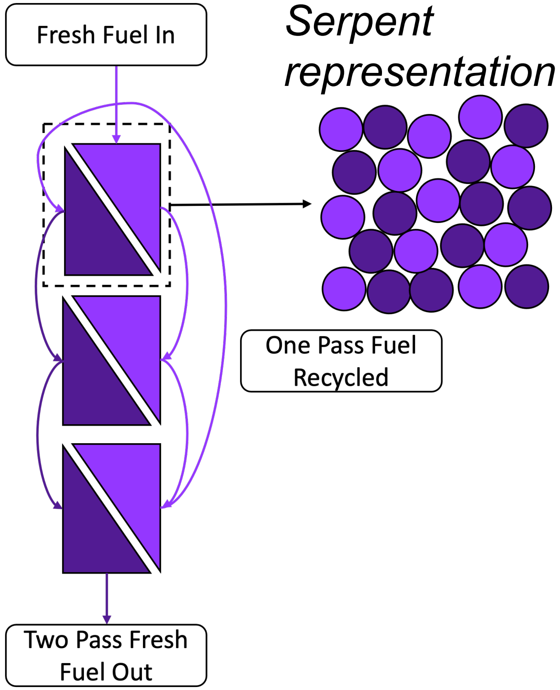
Approach 2: Using Serpent in kugelpy (ART)

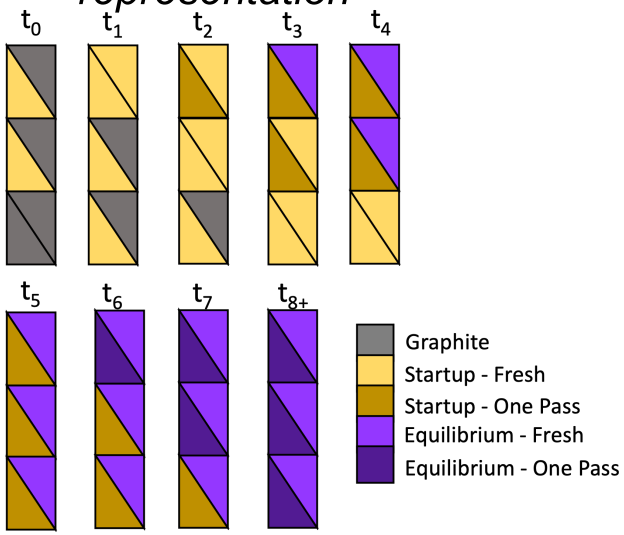
- Python module wrapped around Serpent to simulate pebble movement through the core
  - Divide the core into channels and axial volumes

Algorithm Outline

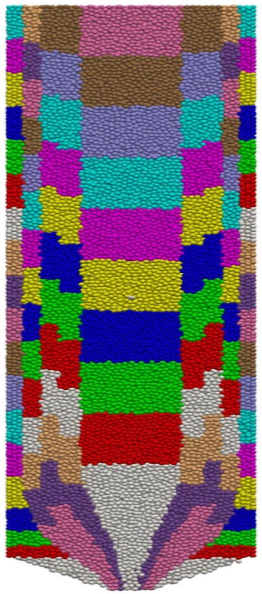
- Generate critical core configuration

1. Perform burn-up step
2. Shift pebbles down
3. Recycle/discharge pebbles
4. Update power (Serpent solve), temperature, pebble type, etc.





DEM input



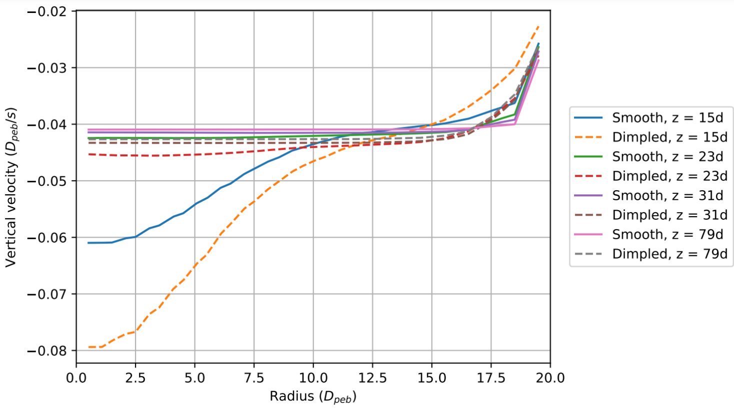
Colors indicate burnup mesh & channels

Assumptions & simplifications

- Solves running-in problem and not direct equilibrium core
- Pebbles are grouped in the depletion solve and distinguished only by #passes
- Utilize DEM to generate pebble distribution and assume random distribution of pebbles of different groups to construct Serpent distribution

Thoughts on common approximations for PBRs

- Should we take a fresh look at top/bottom cones?
  - Top cone region: maximum power density ~2 meters below cone, power peaking affects loss of flow incidents
  - Bottom cone region: some decay heat & hot pebbles (in steady-state)
  - FHRs potentially different & fewer study and experience
- Radial speed distribution (GCRs)
  - Uniform flow in the upper regions of the core (see [1])
  - Radial flow distribution has significant shape to it ~2 meters above bottom cone (see [1])
  - We have significant radial speed differences in >20% of the core height. Modern tools should capture this!
- Tools should have the flexibility to do 3D simulations to check RZ assumption (e.g., gray curtain in PBRs, asymmetry designs)
- Lower fidelity codes should be benchmarked with higher fidelity codes; **need higher fidelity depletion & multiphysics** (e.g. [2] and [3])



Vertical velocity of pebbles as a function of radius for different elevations adopted from [1]

[1] "Discrete Element Method Investigation of Reflector Dimples for a General Pebble Bed Reactor Design" by D. Reger et al. in Reactor Analysis Methods 1

[2] Y. Robert et al., "Proof of Concept for Hyper-Fidelity Depletion of Full-Scale Pebble Bed Reactors".

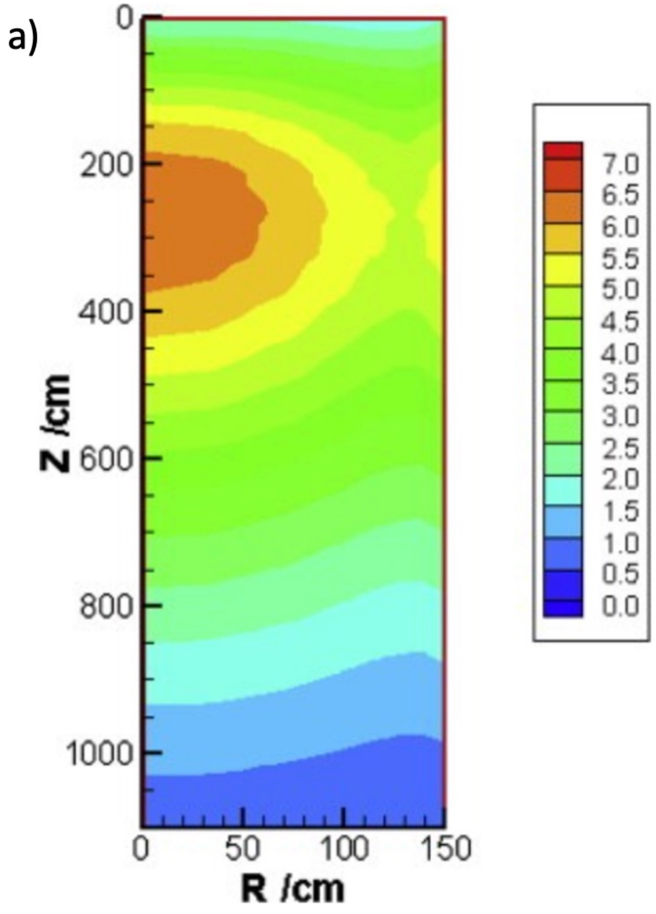
*[3] J. Ragusa, "*High-fidelity, data science-informed pebble-bed reactor simulation*", NEUP project funded 2021.*

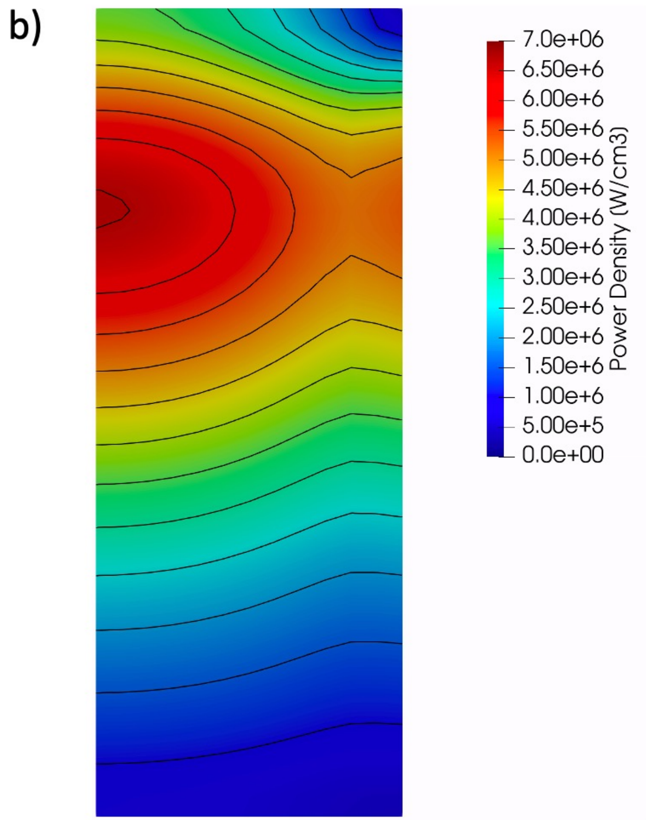
Results Griffin: Comparison of HTR-PM with VSOP (Zheng et al. Annals 36)

Quantity	Value
Power	250MW
Bed size	D=3m, H=11m
Fuel	UO2, 8.7% enriched 7g/pebble
Discharge burnup	90MWd/kg
Av. # passes	15
Pebble diameter	6cm

Quantity	Zheng et al. (VSOP)	Griffin
k_{eff}	Presumed 1	1.001525
Power peaking	2.04	2.035
Max. power	6.57 MW.cm^3	6.54 MW/cm^3

a) VSOP power distribution, b) Griffin power distribution

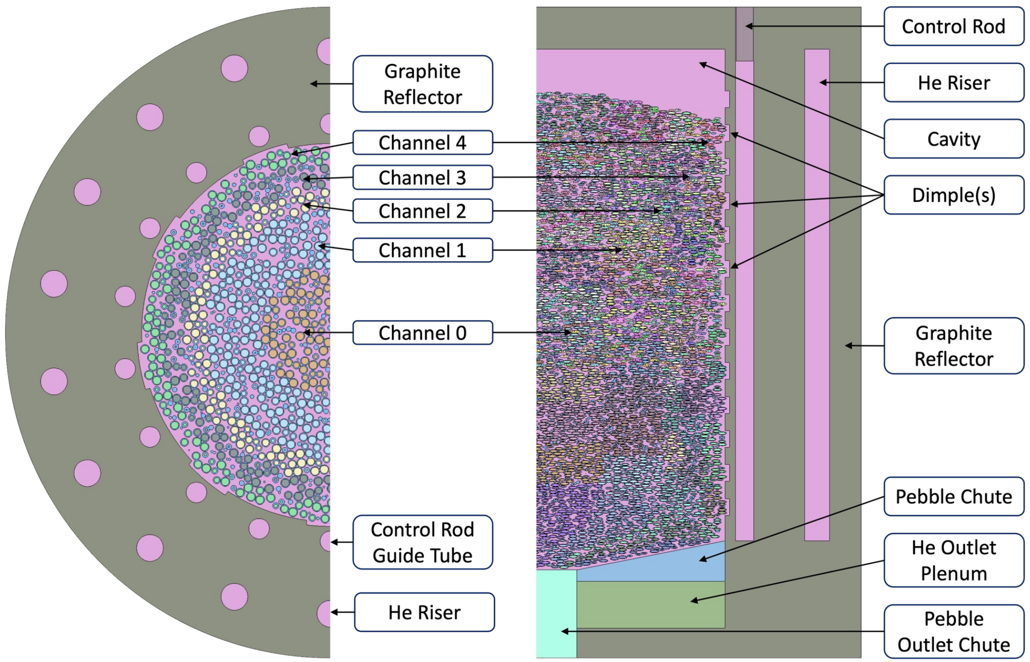




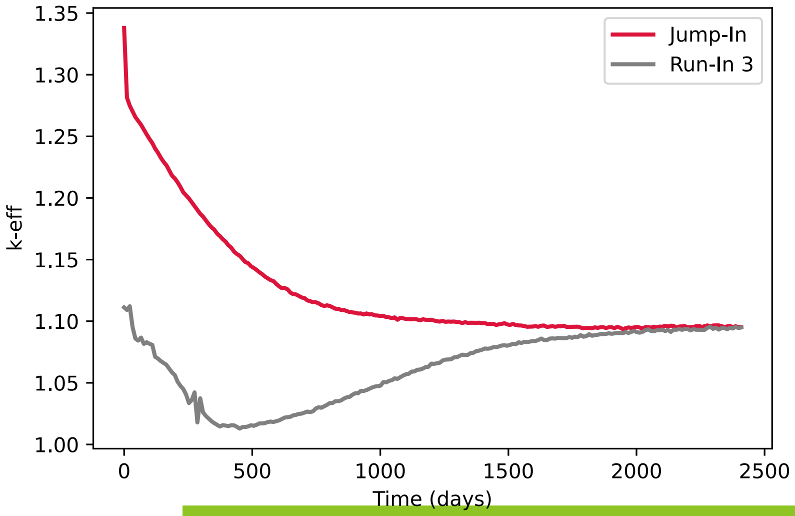
Results kugelpy:

- Examine the ability to obtain an equilibrium core
  - Jump-in equilibrium
  - Run-in scenario
- Run-in scenario follows power ramp in table
  - Startup fuel: 5.0 wt% U-235
  - Equilibrium fuel: ~15.5 wt% U-235
    - Inserted at 180 days
- Jump-in scenario
  - Equilibrium fuel
  - Fuel was split equally as 1st, 2nd,…,6th pass
  - Cycled until k_{eff} converged

gPBR Geometry



Days	Power (MW)	Fuel Temp (K)	Mod Temp (K)	Graphite Fraction Added
0	1	300	300	0.5
11	10	300	300	0.4
…	…	…	…	…
55	50	400	400	0.0
…	…	…	…	…
110	100	600	500	0.0
…	…	…	…	…
273	200	800	650	0.0



Conclusions

- Presented 2 approaches for PBR depletion developed at INL in the NEAMS and ART programs
- Approach 1: Intermediate fidelity, Griffin
  - Implemented in Griffin
  - Deterministic homogeneous neutronics and homogeneous depletion
  - Eulerian approach to pebble depletion
  - Pebbles are grouped by burnup, not passes
- Approach 2: Higher fidelity, kugelpy & Serpent
  - Implemented as python wrapper around Serpent
  - Continuous energy Monte Carlo with explicit representation of pebbles and stochastic treatment of TRISOs
  - Homogeneous depletion model using a Lagrangian approach & classifying pebbles by #passes (“batches”)

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.