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Neutronic Design and Characterisation of HALEU Fuelled Reactor for Nuclear Thermal Propulsion

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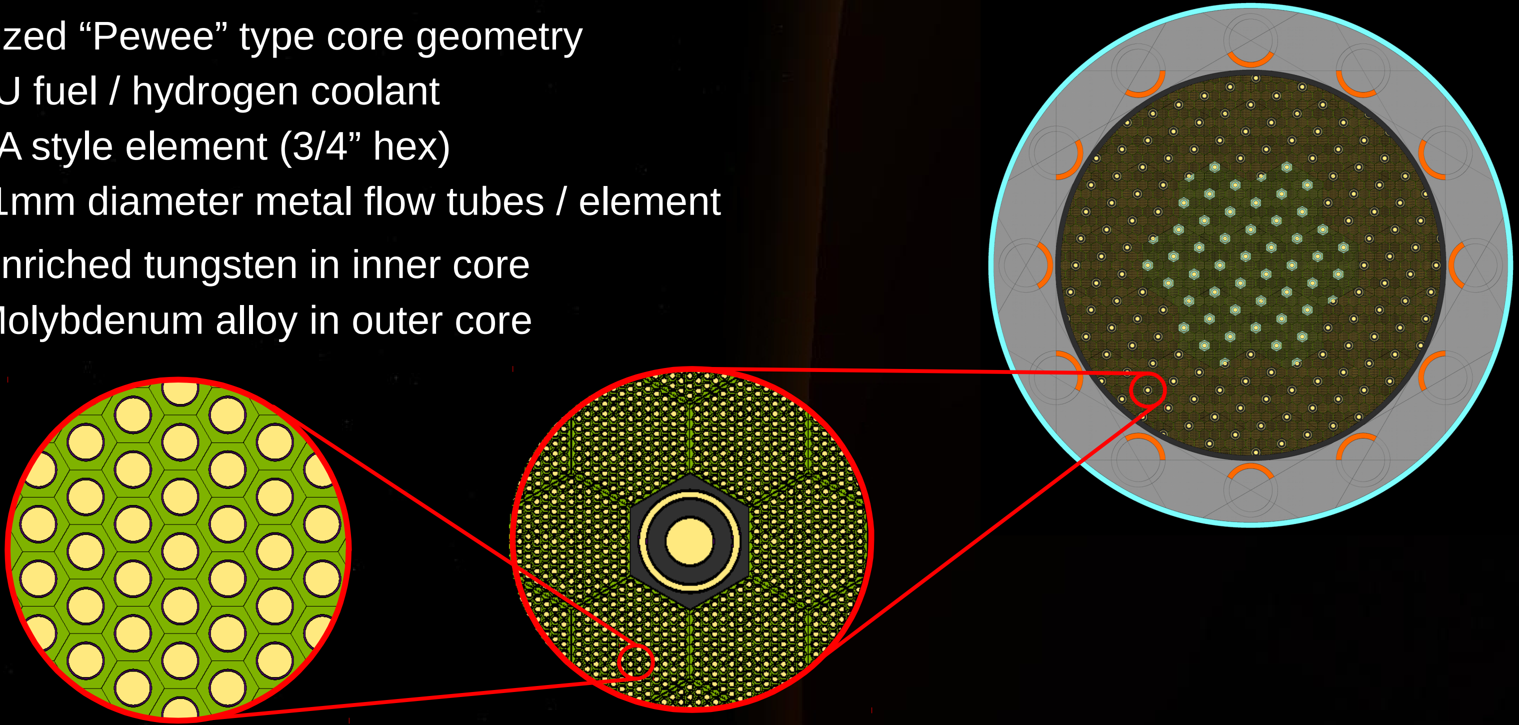
Reactor ("Emu") Overview

- Half-sized "Pewee" type core geometry
- HALEU fuel / hydrogen coolant
- NERVA style element (3/4" hex)
- 127x 1mm diameter metal flow tubes / element
  - Enriched tungsten in inner core
  - Molybdenum alloy in outer core



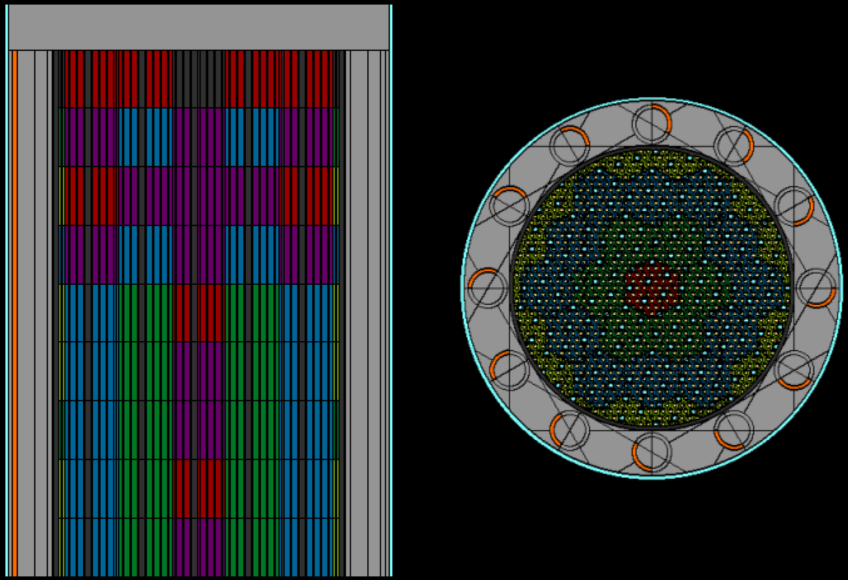
Geometry

- Reactor modelled in both MCNP and Serpent.
- Design cues from NERVA:
  - Same height as a Kiwi reactor. Required power / thrust ~½, Kiwi (500MW$_{Th}$ / 25 klbf), thus reduced in diameter by factor of √2.
  - 11.4cm (4.5”) thick radial and axial reflector
  - 5.2 cm (2”) ⌀ control drums (x12) w/ 1cm thick, 120° poison shims
  - 1cm thick outer hull.
- 127x 1mm ⌀ flow tubes per fuel element (¾” hex ⌀), 6 fuel elements surrounding 1 moderator element per assembly, core built from these.
  - Element clad: 50µm for flow tubes, 30µm peripheral.
- Original 19x 0.094” ⌀ KIWI element geometry retained as backup.

Materials

- Common fuel:
  - 127 channels: 70/30 Uranium Carbide / Zirconium Carbide
  - 19 channels: 50/50 UC/ZrC
- Non-multiplying media:
  - outer core (T~1200K): Molybdenum-0.7% Lanthanate (MoLa) metal, graphite moderator
  - Inner core (T~2500K): Tungsten metal, Zirconium Carbide moderator.
  - Beryllium reflectors
  - Boron Aluminide control shims
  - Aluminium outer hull
- Backup NERVA element Tungsten-4% Rhenium (W-4Re) alloy in inner core. Also uses 70µm flow channel clad.

Serpent Model - Material Zoning



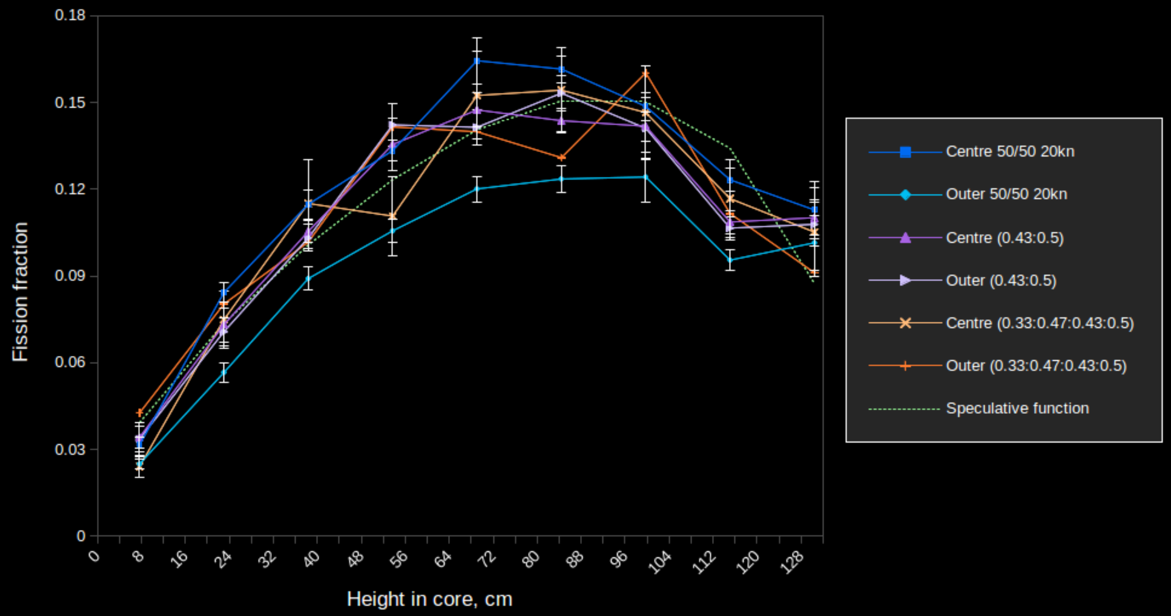
Colour	UN:2C % mix
(dark red)	37/63
(purple)	40/67
(blue)	43/57
(green)	47/53
(yellow-green)	50/50

Used mostly for power profile / detectors, but differential fuelling (shown) investigated in connection w/ neutron field harmonics caused by axial reflector.

Characterisation - Spatial (Power)

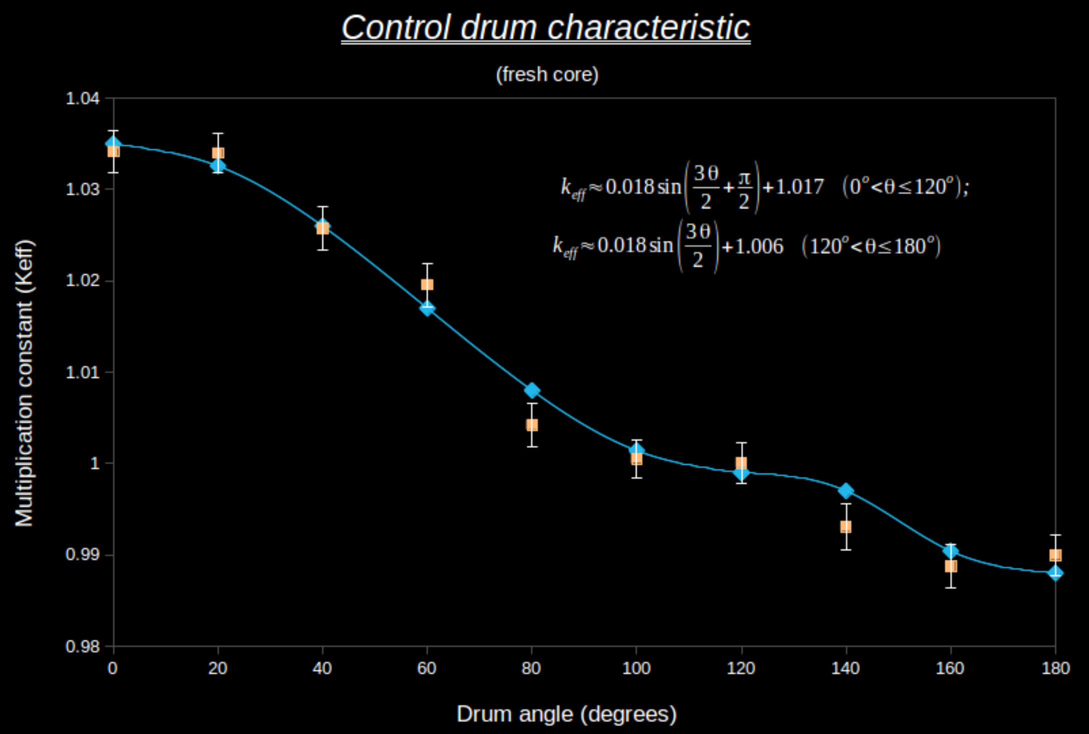
Pin Fission Fractions

$$\frac{P}{P_{max}} \approx 0.65288\sqrt{\cos\left(\pi\left(\frac{0.95\,z}{z_{max}}-\frac{1}{2}\right)\right)e^{\sqrt{2}\frac{z}{z_{max}}}}$$



Various differential fuellling profiles (radial only shown) trialled until smooth, harmonic free axial power profile found. Radial profile found to affect axial harmonics.

Characterisation - Spatial (Control)



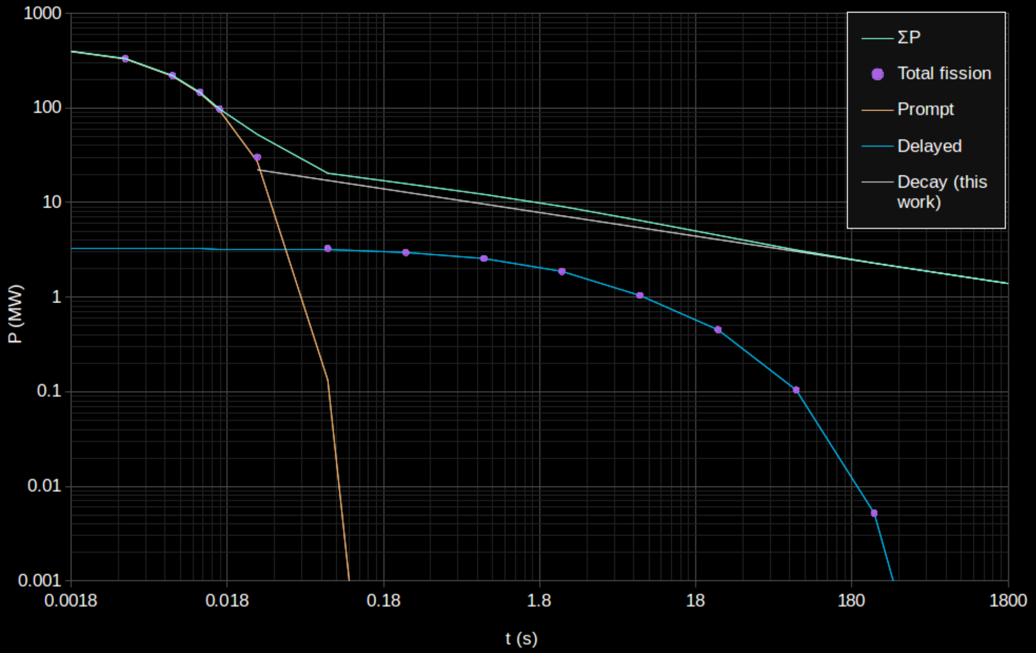
Drum profile also attempted, but with errors due to computational constraints at time of simulation. Profile run again later in MCNP, resolving errors.

Characterisation – Temporal (Spreadsheet)

Power contributions to shutdown transient:

- Prompt fission
  - 0-O(100ms)
- Delayed fission (~.7%)
  - O(100s)
- Fission / activation product decay heat
  - .1 s < t < hrs

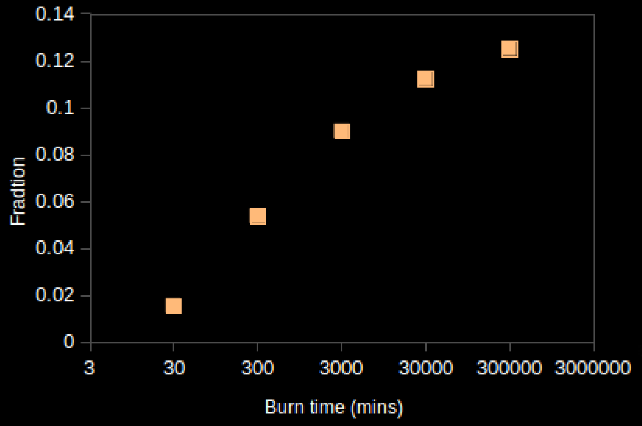
Powerdown (after drum stop)



Characterisation - Decay Heat

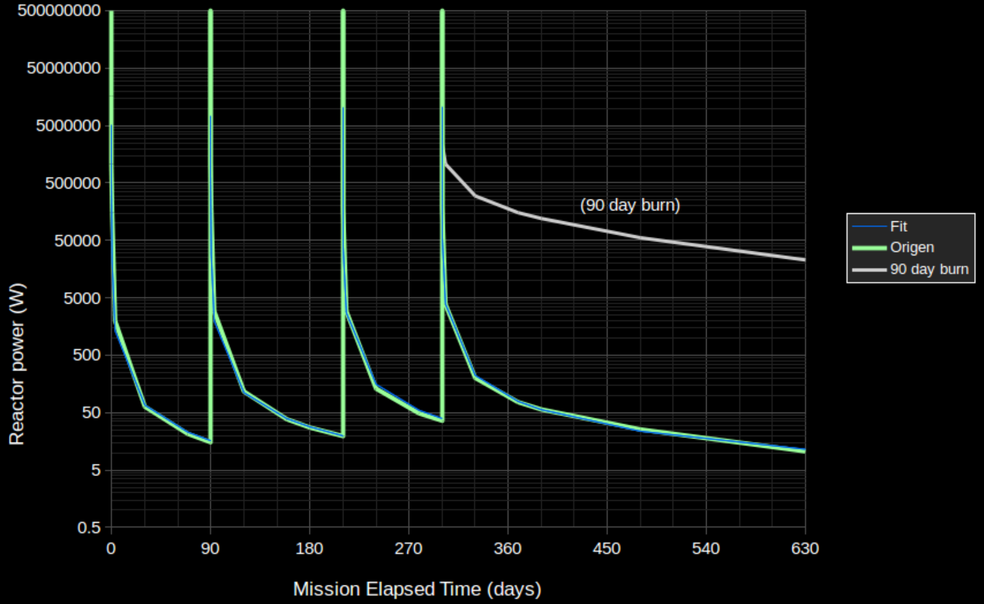
Serpent burned material files "decayed" in ORIGEN. Increased burn time decreases decay gradient. Overall fit to correlations in literature poor – needs experiment.

Fraction of shutdown decay power at ~50mins

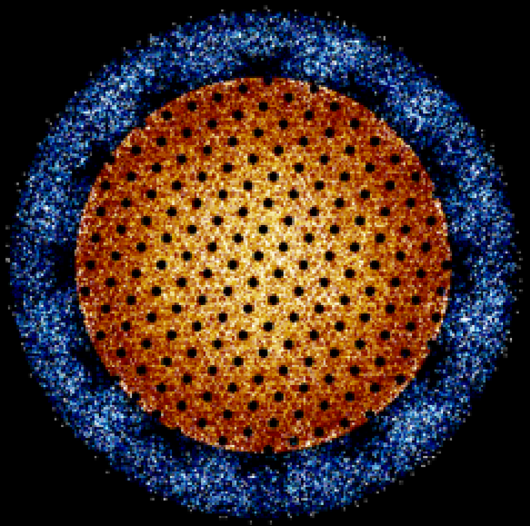


Complete Mars mission power cycle

$$\frac{P_d}{P_0} = \frac{\sum(\tau)}{55.5\tau}\left(t^{-\frac{1}{4}} - (t+\tau)^{-\frac{1}{4}}\right)$$



Serpent Φ/F Mesh



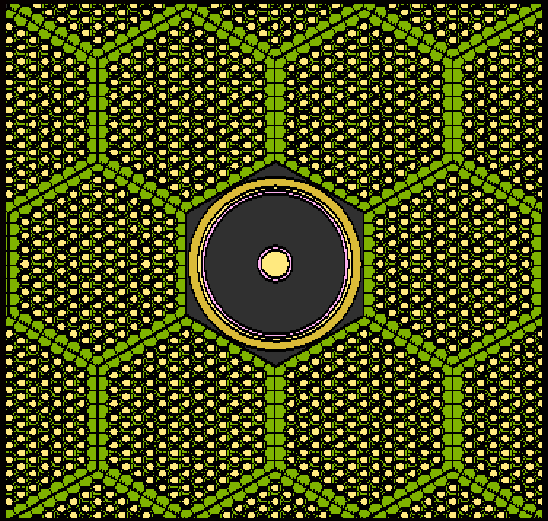
Serpent is capable of some extremely rich result visualisations from commands in the input file!

Here fission is orange/red and flux alone is blue, with brighter shades indicating higher values.

Serpent / MCNP verification

- Serpent is a comparatively new neutronics code, whilst MCNP is the industry standard- thus confirming the former's results with the latter adds credence to them.

- Results on development-stage MCNP reactor replicated in Serpent (easier than the other way around), multiplication constant (k_{eff}) agreed to <1‰ (1 part in 1,000).

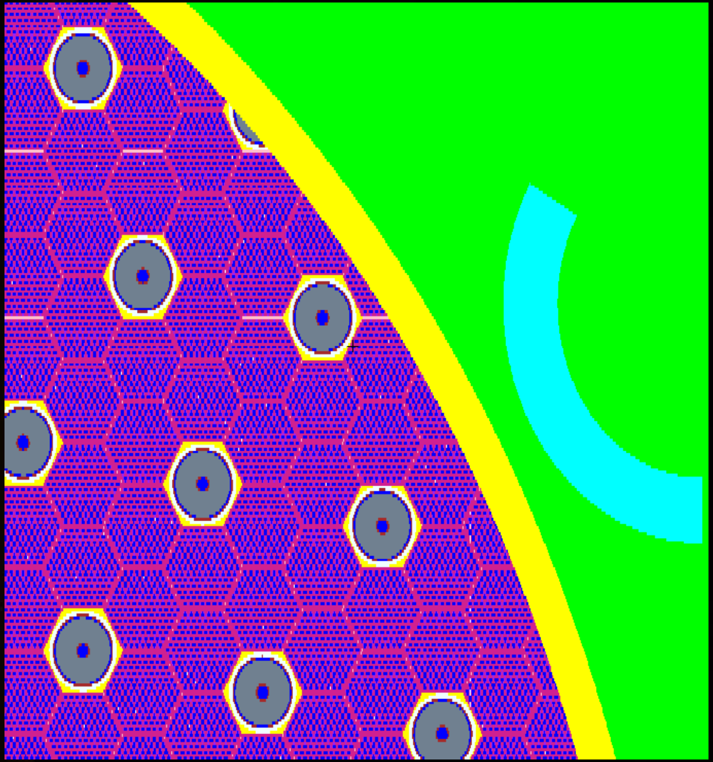


MCNP element geometry as modelled in Serpent

MCNP Realistic Geometry

- Began by matching SERPENT geometry and verifying k eigenvalue results

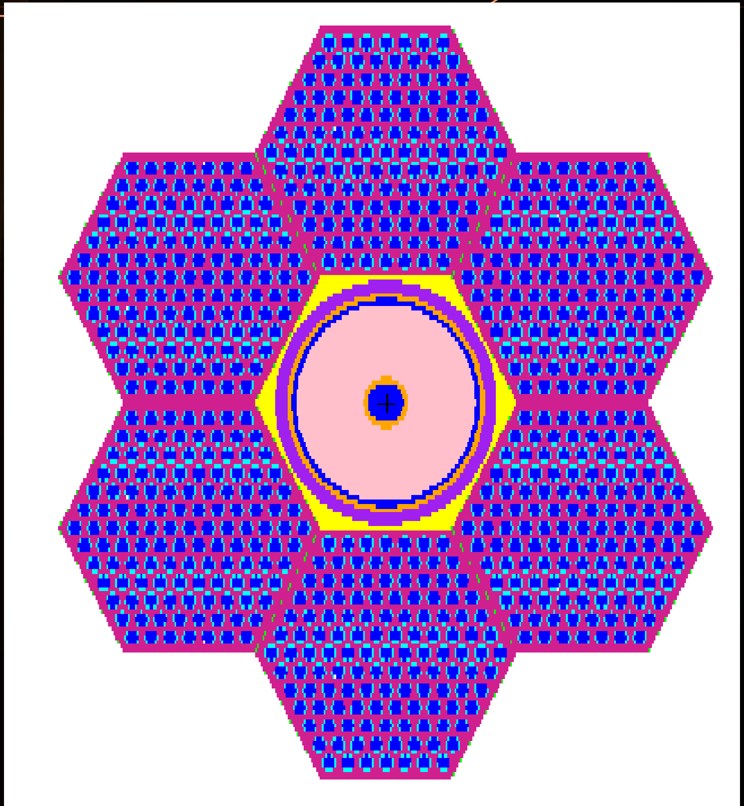
- After confirming basic SERPENT results, moved to fix geometry issues around core edge



MCNP Geometry Fuel Bundle

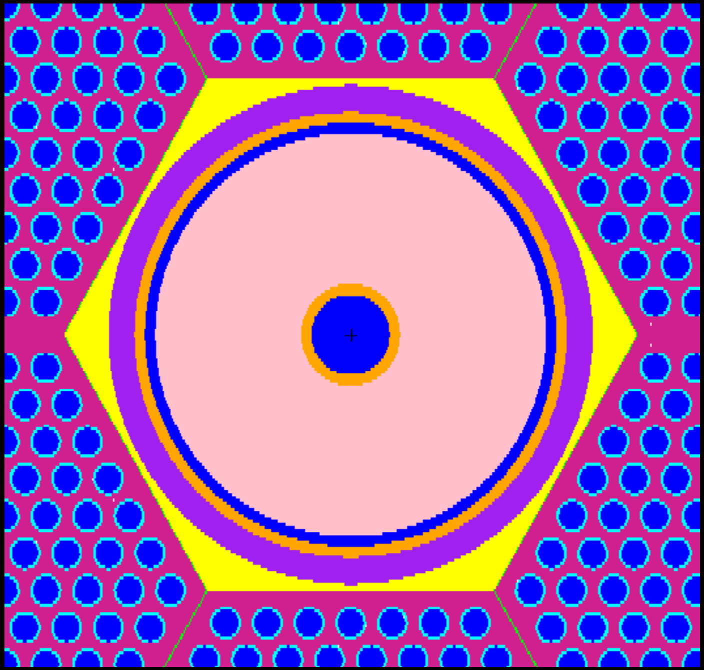
- Full fuel bundle as the building block of the reactor to avoid major cutoff areas

- Fuel matrix uses 127 1mm inner diameter flow tubes

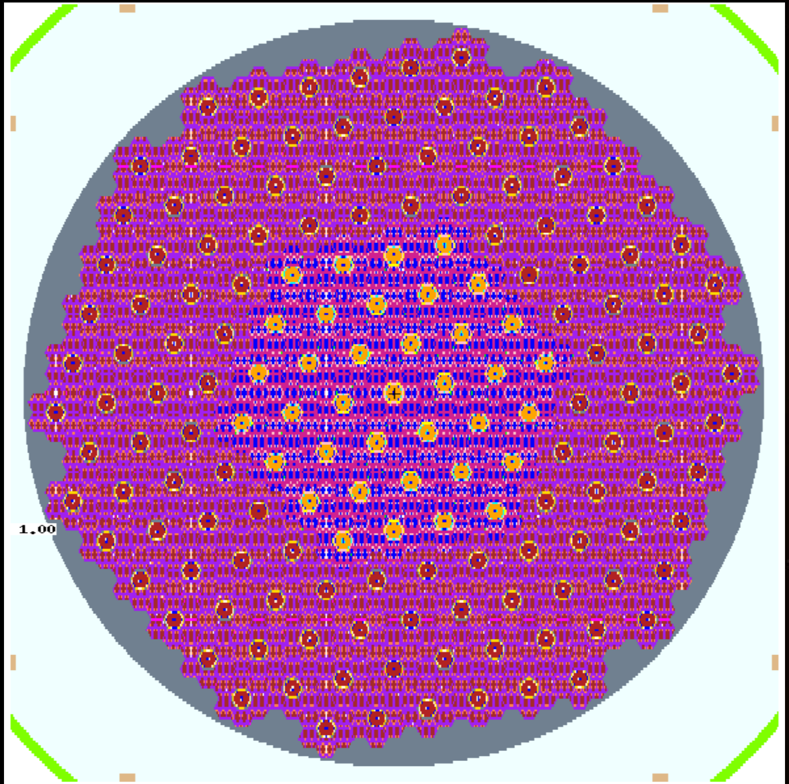


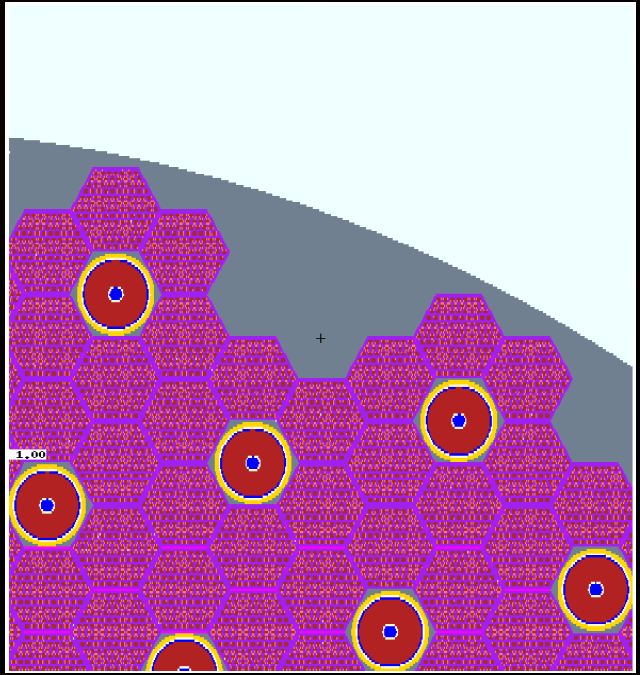
Fuel Bundle Detail

- Graphite and zirconium hydride as moderators.
- Hydrogen in flow tube expected to reach 600 K [Gates et al]



Full Bundle Only Core





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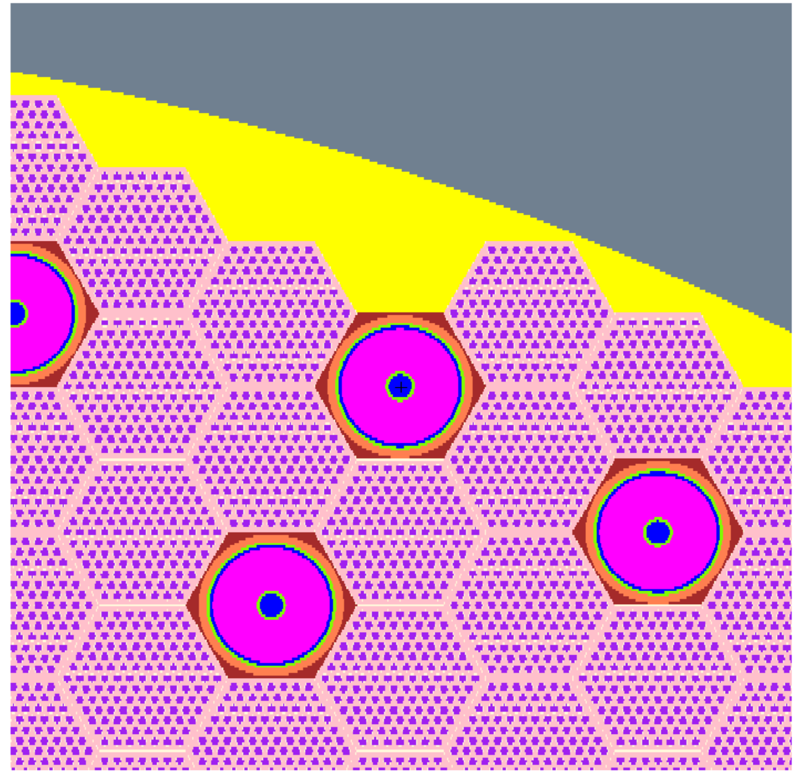
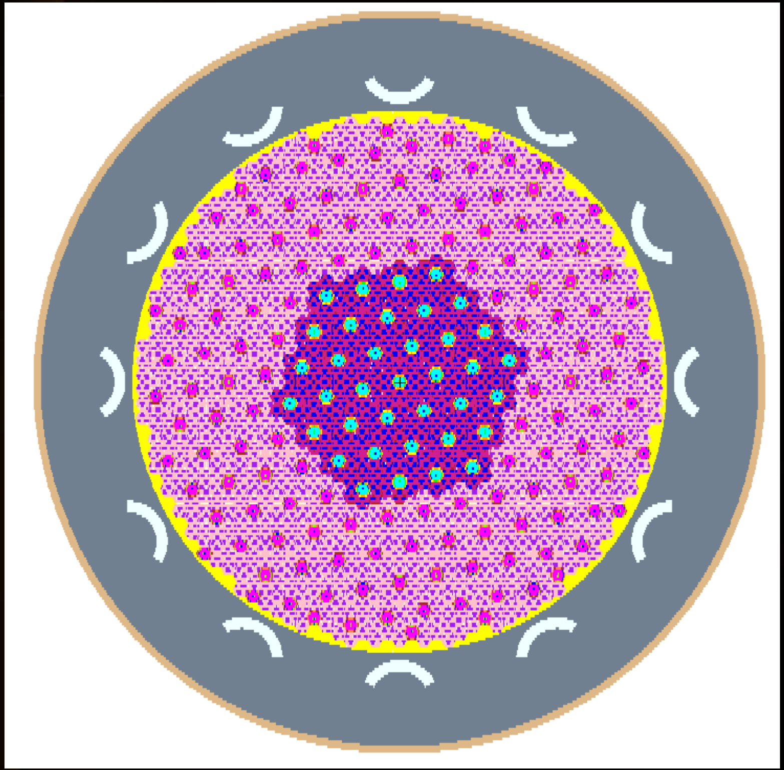
MCNP Refined Edge Detail

- Added new elements around the edges
- Added off-pitch support elements near new fuel to maintain 6:1 fuel:moderator ratio

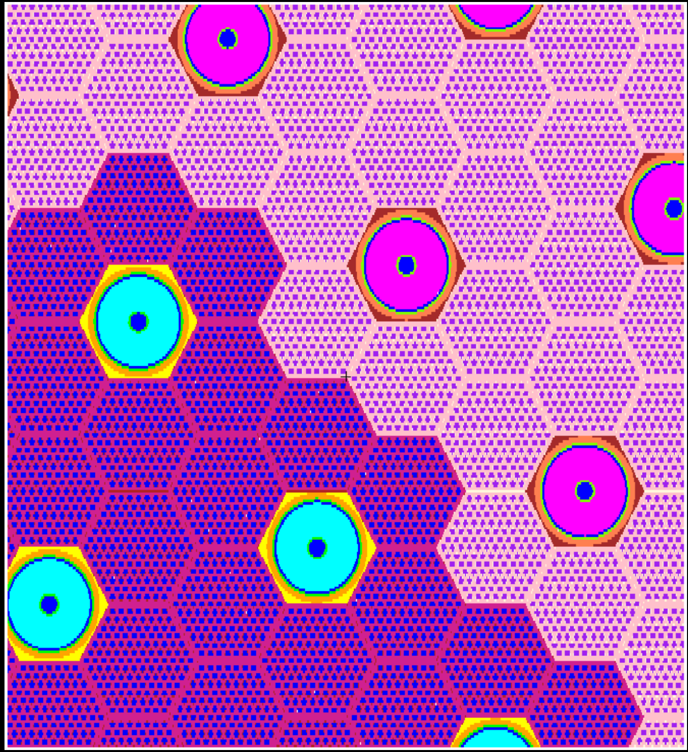


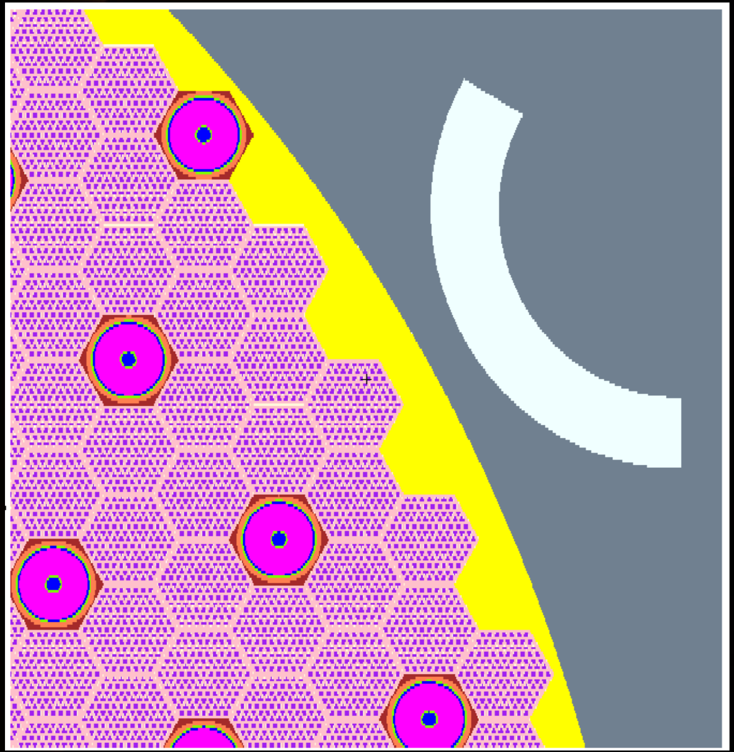
MCNP Geometry Heat Regions

- Middle (dark purple) region at 2500K
- Outer (pink) region at 1200K
- 1058 fueled elements to 179 moderator elements (5.91:1)



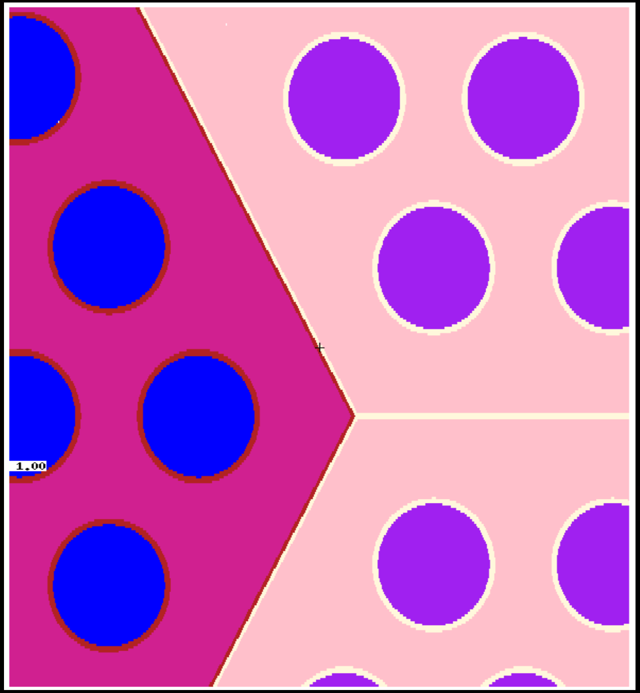
MCNP Geometry Heat / Edge Regions



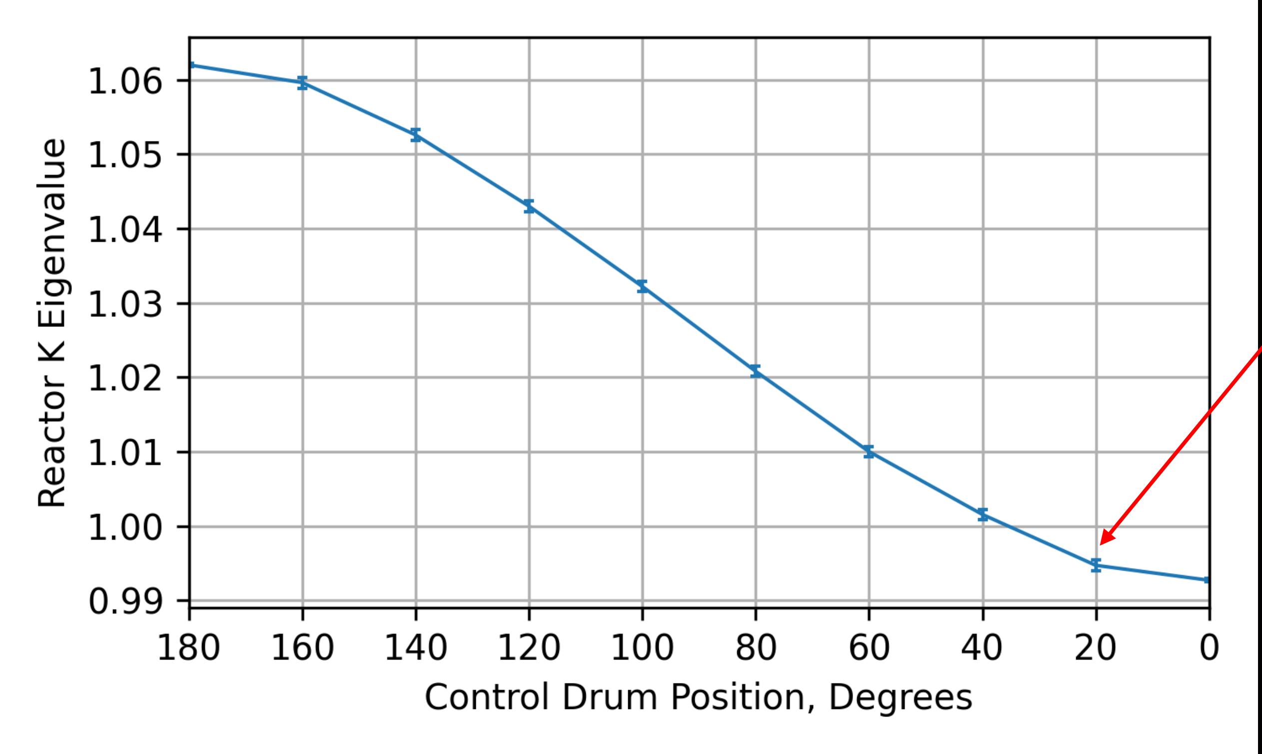


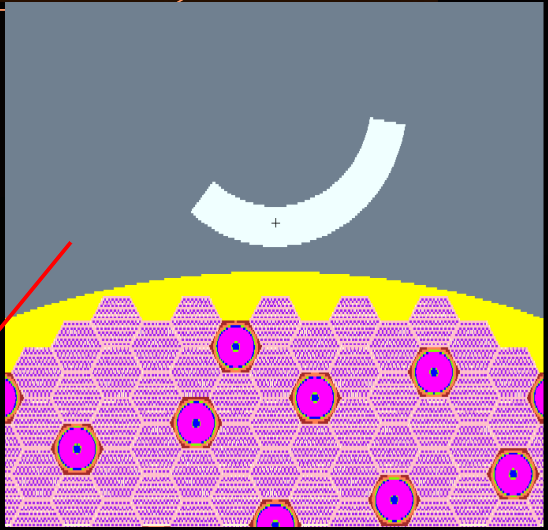
Transition Region Detail

- Close up of edge of high temp and lower temp regions
- Blue and purple circles are flow tubes
- Cladding in high temp region is 184 enriched tungsten. Low temp region is cladded with MoLa.
- Clad is 50 μm in both regions



Control Drum K Eigenvalue

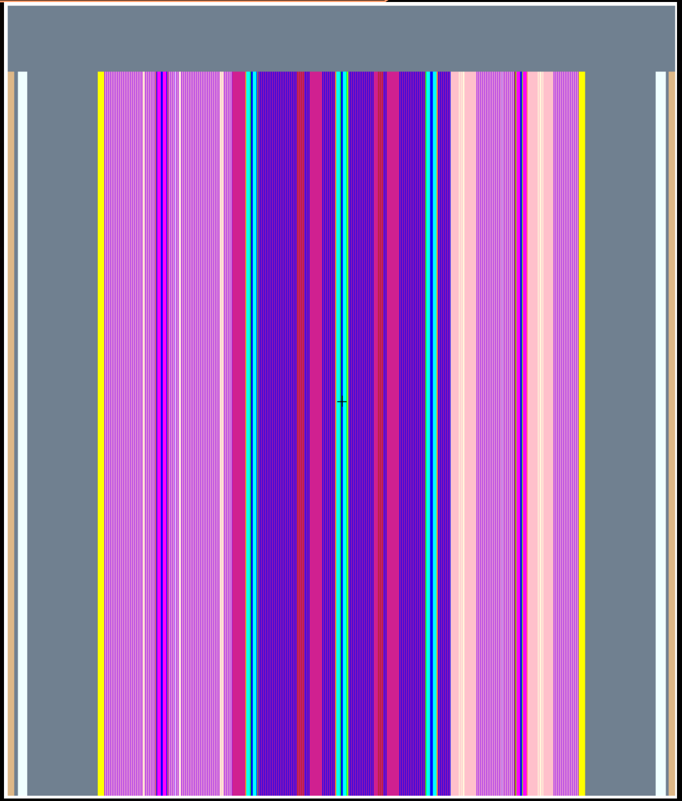




Drum Worth:
Total: $10.66
Individual: 88.85 ¢

MCNP and SERPENT Differences

- No axial fuel regions - all fuel is 70/30 HALEU/Substrate
- Minor differences in support structure geometry
- MCNP model has realistic core edge



Conclusions

- Modelling showed NERVA based reactor with “upgraded” HALEU/ZrC (rather than HEU/C) fuel is eminently possible.

- Even with enriched tungsten a large number of very small flow tubes introduces a substantial reactivity deficit.

- Division of labour between Serpent and MCNP is an effective way to approach a project. Each program has its strengths and weaknesses, but converge / agree where it is important.

Questions?

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Serpent: twiddicombe@uidaho.edu

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