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 $\sim \frac{1}{2}$, Kiwi ($500\text{MW}_{\text{Th}} / 25\text{ klf}}$, thus reduced in diameter by factor of $\sqrt{2}$.
  - 11.4cm (4.5”) thick radial and axial reflector
  - 5.2 cm (2”) Ø control drums (x12) w/ 1cm thick, 120° poison shims
  - 1cm thick outer hull.
- 127x 1mm Ø flow tubes per fuel element (¾” hex Ø), 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” Ø 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.
Used mostly for power profile / detectors, but differential fuelling (shown) investigated in connection w/ neutron field harmonics caused by axial reflector.
Various differential fuel loading profiles (radial only shown) trialled until smooth, harmonic free axial power profile found. Radial profile found to affect axial harmonics.
Drum profile also attempted, but with errors due to computational constraints at time of simulation. Profile run again later in MCNP, resolving errors.
Power contributions to shutdown transient:

- Prompt fission
  - $0 - O(100\text{ms})$
- Delayed fission ($\sim .7\%$)
  - $O(100\text{s})$
- Fission / activation product decay heat
  - $.1 \text{ s} < t < \text{hrs}$
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.

\[
\frac{P_d}{P_0} = \sum_{\tau} \left( 1 - \left( \frac{t}{\tau} \right)^{\frac{1}{3}} \right) \left( \frac{t+\tau}{\tau} \right)^{\frac{1}{4}}
\]

Fraction of shutdown decay power at ~50mins

Mission Elapsed Time (days)
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 ($k_{\text{eff}}$) agreed to <1% (1 part in 1,000).
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.
• 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
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
• Middle (dark purple) region at 2500K
• Outer (pink) region at 1200K
• 1058 fueled elements to 179 moderator elements (5.91:1)
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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