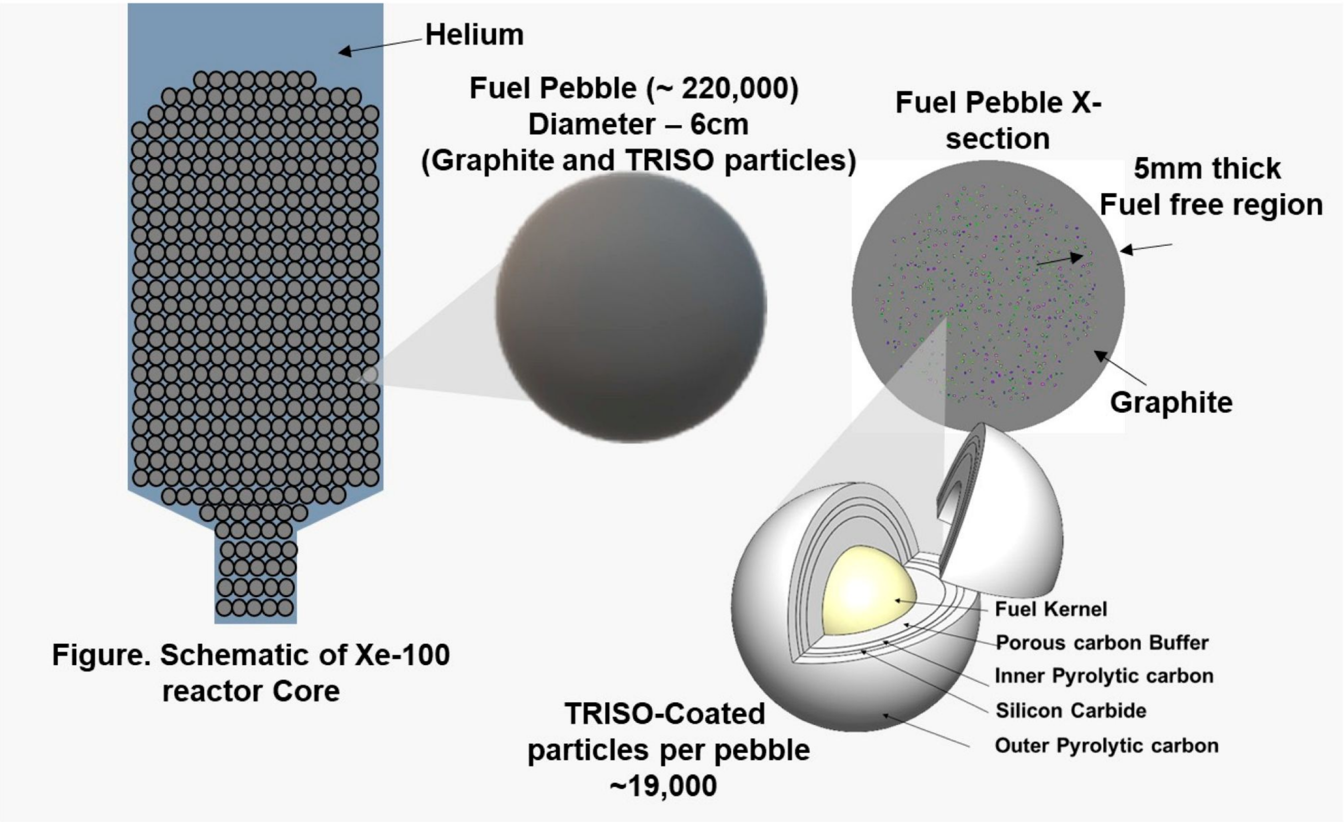
AMERICAN NUCLEAR SOCIETY
ALBUQUERQUE
2025 Old & Nu
NEW MEXICO
STUDENT CONFERENCE

Innovative Fuel Designs for Pebble Bed Reactors

Michael Divittorio, Matt Manuel, Cece Warren

Introduction

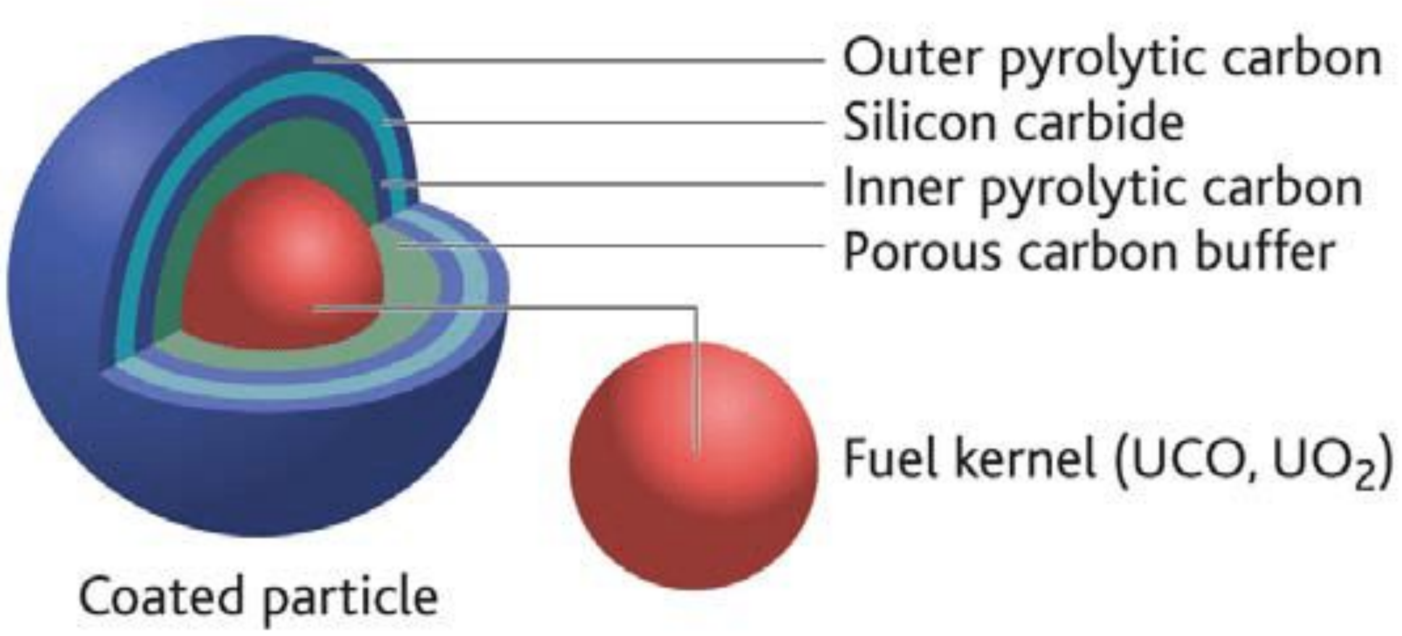
- Pebble bed reactors are high-temperature gas reactors (HTGRs) that use graphite spheres embedded with uranium particles, known as tri-structural isotropic (TRISO) fuel, to moderate and sustain nuclear fission. The fission reaction creates heat, which is transferred to a turbine to generate electricity.



Pebble bed reactor core and fuel diagram [1]

Introduction

- This project aims to investigate alternative pebble fuel configurations to improve nuclear efficiency and safety. Possibilities include evaluating new fuel sources, such as plutonium, fast reactor fuel, and inert matrix fuels for better burnup rates and reduced waste management times.



TRISO particle diagram [2]

Objectives

- The design will use a primary fuel other than uranium.
- The design will be examined for non-proliferation benefits.
- The design will be able to operate safely under reactor conditions.
- The design will result in a reactor burnup that produces less long-lived isotopes compared to UCO (current fuel) resulting in a shorter waste storage period for spent fuel.
- The design will have similar or improved heat transfer characteristics compared to UCO (current fuel).

Xe-100 fuel pebble [3]

Methods

- Various fuel types are simulated using the Monte Carlo N-Particle (MCNP 6.3) software developed by Los Alamos National Laboratory to model real world reactor conditions. MCNP enables researchers to determine neutronic characteristics such as activity, flux, and burnup under set parameters without the need to perform calculations for each individual neutron in a reactor.
- Thermal performance was assessed by analyzing heat transfer properties of the different designs, ensuring that the thermal characteristics compare or improve upon the current uranium-based design. The heat transfer performance is analyzed in 3D models using SolidWorks.

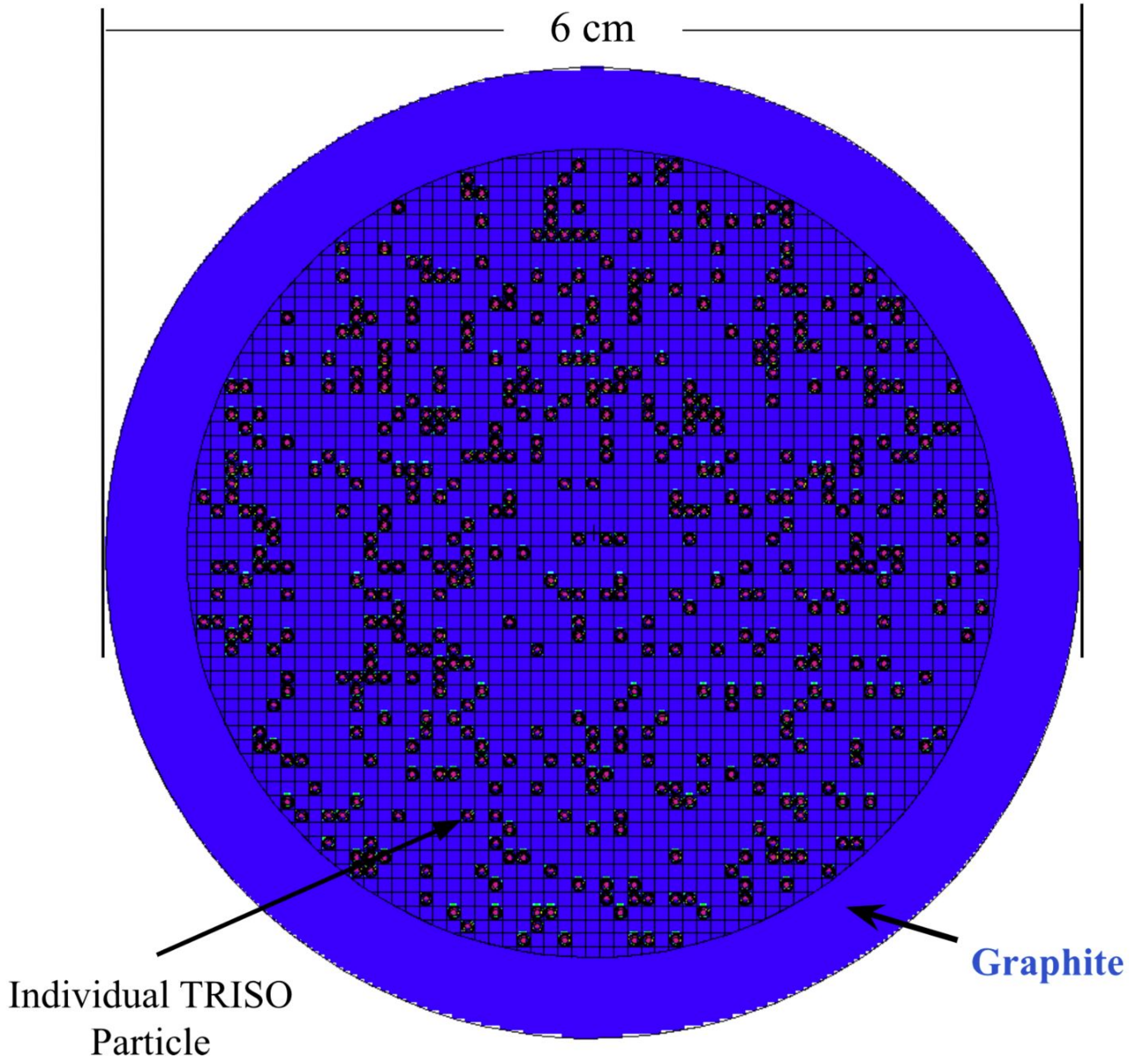


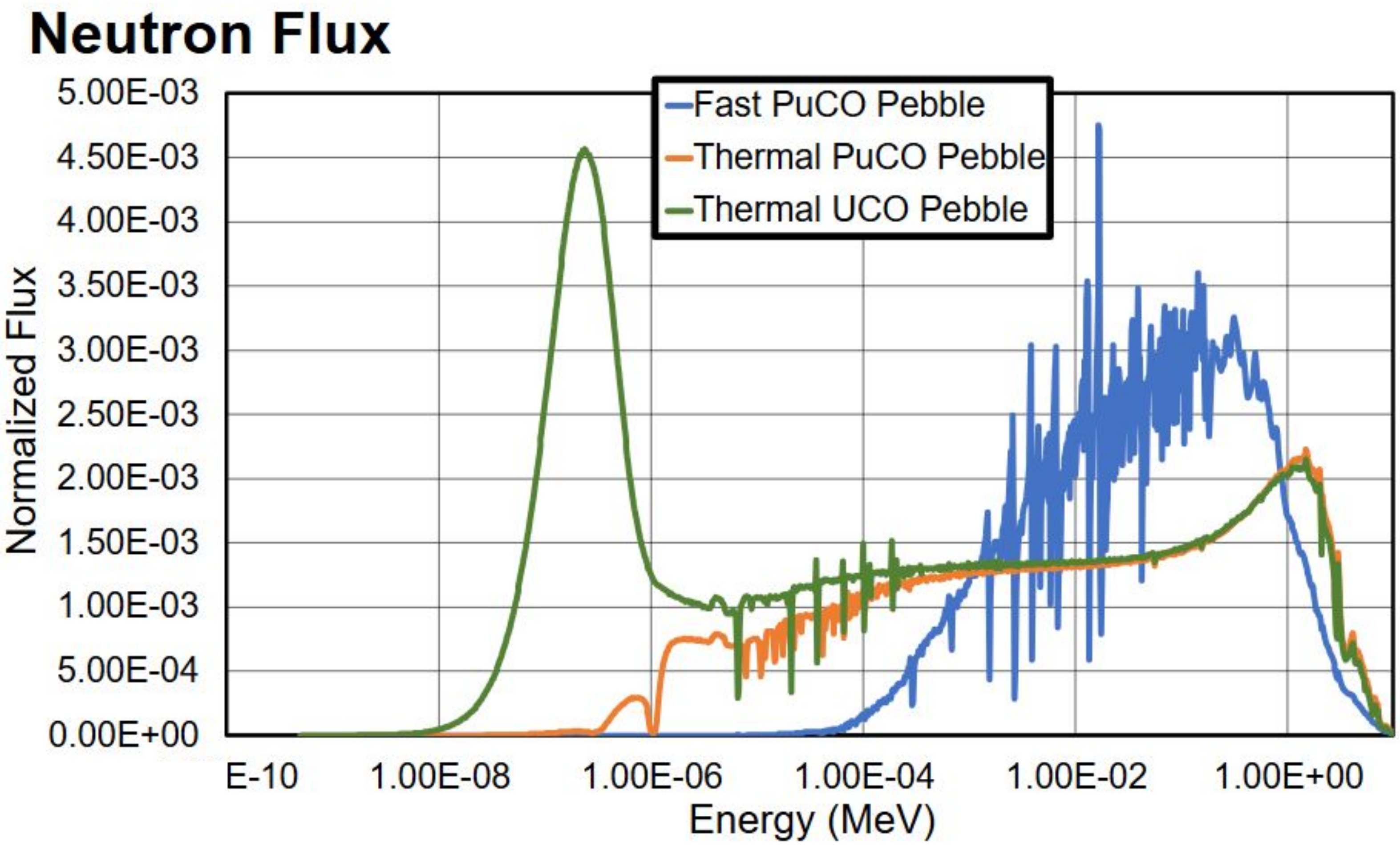
Image taken from MCNP 6.3 plotting tool based on work from Ben Impson

VCU College of Engineering

ANS

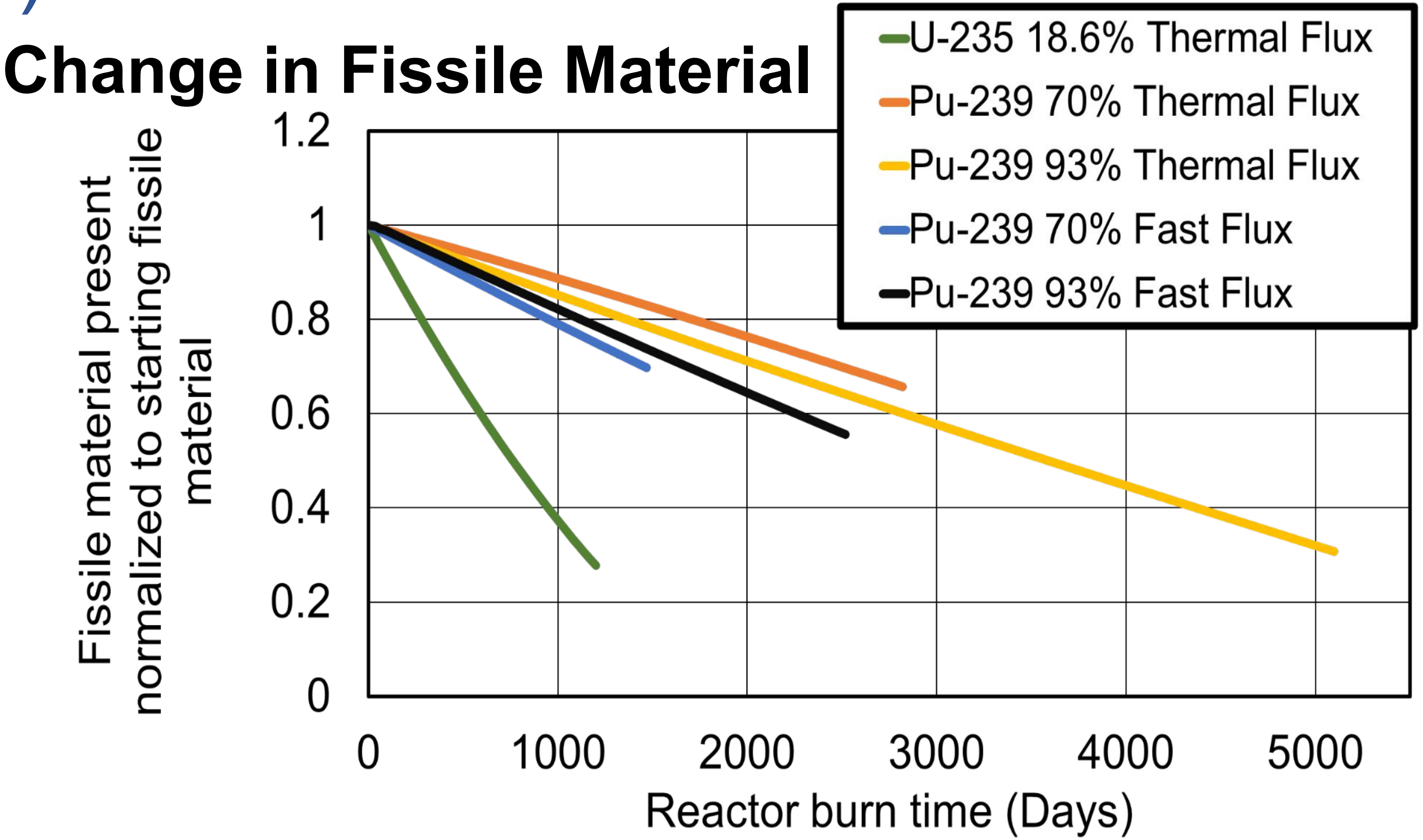
Results (MCNP)

- Three pebble types have been tested. A thermal graphite pebble in both PuCO and UCO fuel forms, as well as a fast zirconium pebble fueled with PuCO.
- Neutron flux analyses had a notable lack of thermal region for plutonium-based fuels, this lead to the proposal of a fast reactor utilizing plutonium pebble fuel.



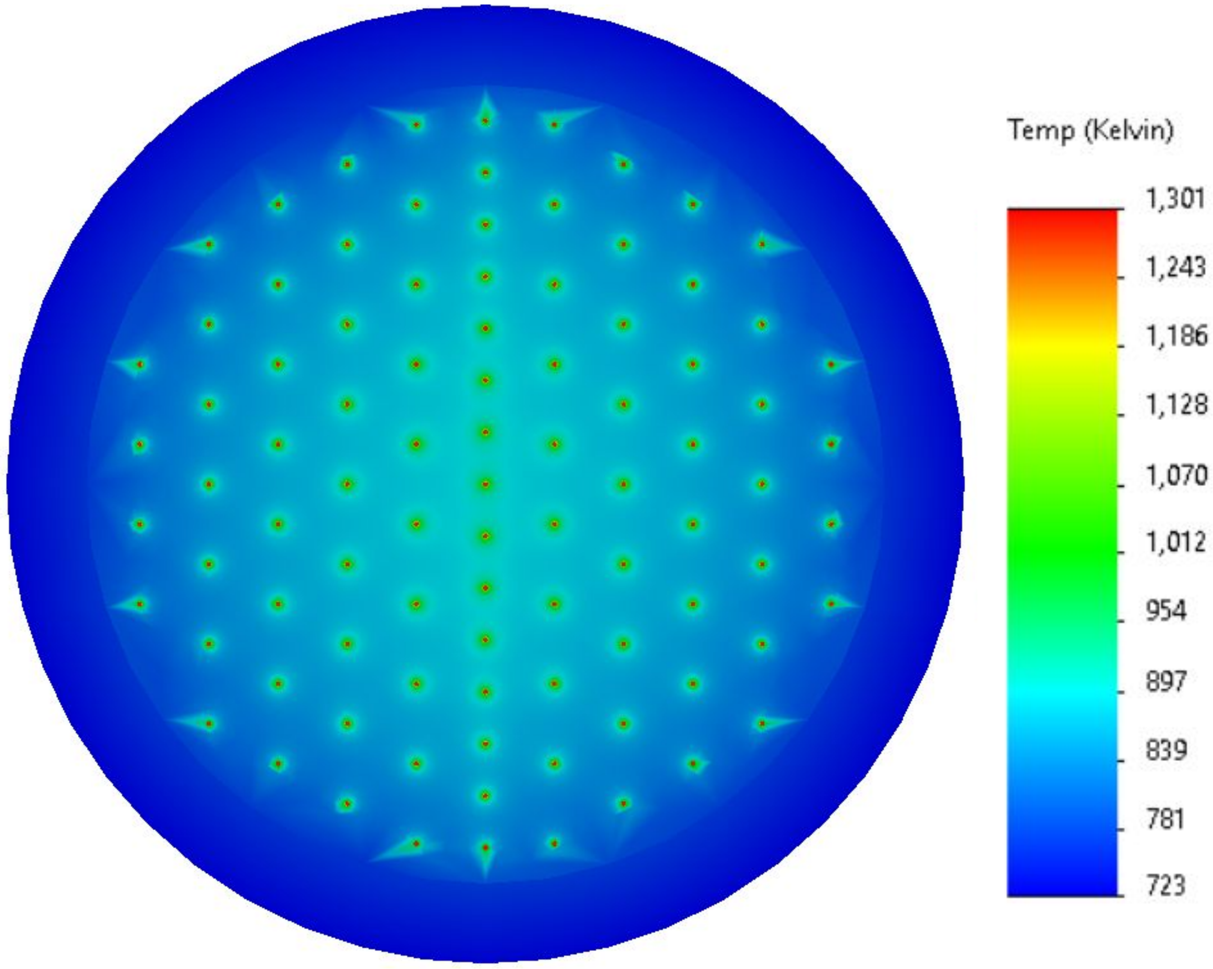
Results (MCNP cont.)

- Five fuel compositions and pebble designs were tested.
- The results indicated that plutonium fueled pebbles have a much **longer potential burn time**.



Results (Thermal Analysis)

- Utilizing SolidWorks, a 3D-modeled uranium fuel pebble was created, consisting of a scaled-down array of TRISO particles.
- The TRISO particles were also 3D-modeled with attention to material properties for each layer
- The model correctly shows a higher temperature in the center that dissipates within the graphite region.
- The maximum fuel temperature is 1301 K at the center of each TRISO particle
- The graphite region of the pebble is 723 K
- Other fuel pebble models such as plutonium-based and fast-reactor pebbles are currently under thermal analysis



VCU College of Engineering

ANS

Results (Nonproliferation)

- The United States has 87.6 tons of unirradiated plutonium [5].
- The plutonium-based fuel can utilize weapons-grade materials that need to be reduced globally in the interests of nonproliferation.
- 70%-enriched (reactor-grade) PuCO performs similarly to 93%-enriched PuCO (weapons-grade plutonium) with less proliferation risk.
- Since the fast-reactor plutonium pebble achieves comparable burnup results with the benefits of **burning away fission products, like Am-241**, that thermal fuel cannot, it results in potentially shorter waste storage time.

West Valley Demonstration Project (WVDP) waste management site [5]

VCU College of Engineering

ANS

Key Takeaways

- The thermal neutron flux for UCO is much higher than that of the PuCO due to the high absorption from Pu-240.
- The plutonium-based pebbles retain more fissile material over time, leading to longer fuel burn time and **higher energy generation potential**.
- Plutonium-based fuels were found to have slightly lower infinite multiplication factors than uranium-based fuels, making them safe for current pebble designs

Conclusion

- The impact of this research involves:
  - Potential for increased reactor and fuel efficiency
  - Reduced fuel waste and improved spent fuel management
  - Enhanced fuel safety
  - Utilization of plutonium stockpile to generate energy
- By proposing improved fuels for modern nuclear reactors, more companies may be willing to support nuclear energy research and infrastructure.

References

[1] Mehta, K. S., Goddard, B., & Wu, Z. (2024). Neutronics Analysis on High-Temperature Gas-Cooled Pebble Bed Reactors by Coupling Monte Carlo Method and Discrete Element Method. Energies, 17(20), 5188. https://doi.org/10.3390/en17205188

[2] Bruna, Giovanni & Baudrand, Olivier & Blanc, Daniel & Ivanov, Evgeny & Bonneville, Herve & Bourgois, Thierry & Repussard, Jacques & Hache, Georges & Nicais, Grégory & Monhardt, Daniel & Meignen, Renaud & Kissane, Martin & Bernard, Clément & Bonneville, Hervé. (2012). Overview of Generation IV (Gen IV) Reactor Designs - Safety and Radiological Protection Considerations.

[3] *X-energy is developing a pebble bed reactor that they say can't Melt Down*. Energy.gov. (2021, January 5). https://www.energy.gov/ne/articles/x-energy-developing-pebble-bed-reactor-they-say-cant-melt-down

[4] *United States*. International Panel on Fissile Materials. (2024, April 13). https://fissilematerials.org/countries/united_states.html

[5] *West Valley Demonstration Project (WVDP)*. Energy.gov. (n.d.). https://www.energy.gov/em/west-valley-demonstration-project-wvdp

VCU College of Engineering

ANS