Fluoride-Salt-Cooled High-Temperature Reactor Generative Design Optimization with Evolutionary Algorithms
Ph.D. Final Defense

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Outline

Overview

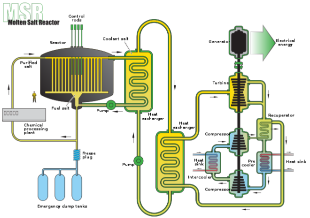
Additive manufacturing will radically transform reactor design.

For this dissertation, I successfully

1. Furthered our understanding of the Advanced High-Temperature Reactor (AHTR) design's complexities through neutronics and thermal-hydraulics modeling
2. Created an open-source tool that enables nuclear reactor design evolutionary algorithm optimization for non-conventional reactor geometries and fuel distributions
3. Applied the optimization tool to the AHTR design

Why Generation IV Reactors?

- Energy use and production contribute $\frac{2}{3}$ of Greenhouse Gas emissions [1]
- Large scale emissions-free nuclear power deployment could significantly reduce GHG production but faces both cost and perceived safety challenges
- The Generation IV International Forum identified six systems that promise significant advances in safety, sustainability, efficiency, and cost over existing designs: GFR, LFR, MSR, SFR, SCWR, and VHTR.



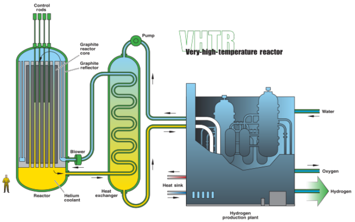


Figure 1: Left: Molten Salt Reactor System, Right: Very High-Temperature Reactor System [2].

MSRs and VHTRs

Molten Salt Reactor (MSR) System Advantages

- Molten Fluoride Salts: chemical stability, low vapor pressure at high temperatures, good heat transfer, resistance against radiation damage
- Inherent System Safety: passive cooling, fail-safe drainage

Very High Temperature Reactor (VHTR) System Advantages

- TRISO Fuel: withstands high burnup and temperature
- High Outlet Temperature: increases power conversion efficiency, reduces waste heat generation, enables high-temperature heat applications

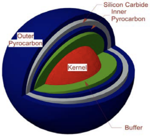


Figure 2: TRISO particle. Diameter: $\sim 8mm$

Fluoride-Salt-Cooled High-Temperature Reactor

FHR concept combines the best aspects of MSR and VHTR: low-pressure liquid fluoride-salt coolant and TRISO fuel

Fluoride-Salt-Cooled High-Temperature Reactor (FHR) Advantages

- Molten salt coolant vs. VHTR helium coolant: superior cooling, moderating properties, low operating pressure, large thermal margin
- TRISO fuel vs. MSR circulating liquid fuel: solid fuel cladding adds an extra barrier to fission product release

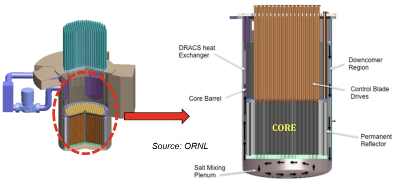


Figure 3: Advanced High-Temperature Reactor (AHTR) schematic (left) and vessel (right) reproduced from [3].

Advanced High Temperature Reactor Design

- Design developed by Oak Ridge National Laboratory
- Prismatic FHR design with 252 hexagonal fuel assemblies consisting of 18 fuel planks arranged in 3 diamond-shaped sectors.

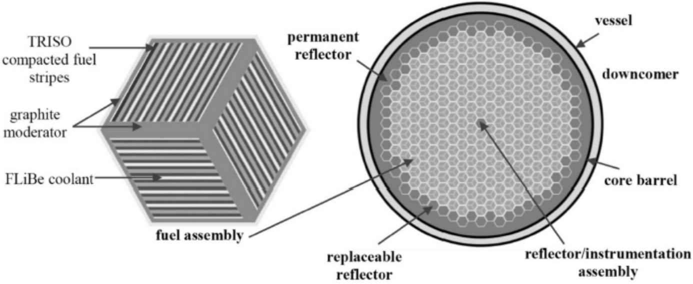


Figure 4: Advanced High-Temperature Reactor fuel assembly (left) and core configuration (right) reproduced from [4].

Advanced High Temperature Reactor Geometry

The AHTR fuel has a *triple heterogeneity*: hexagonal fuel elements with fuel planks, and TRISO particles embedded in stripes within each plank.

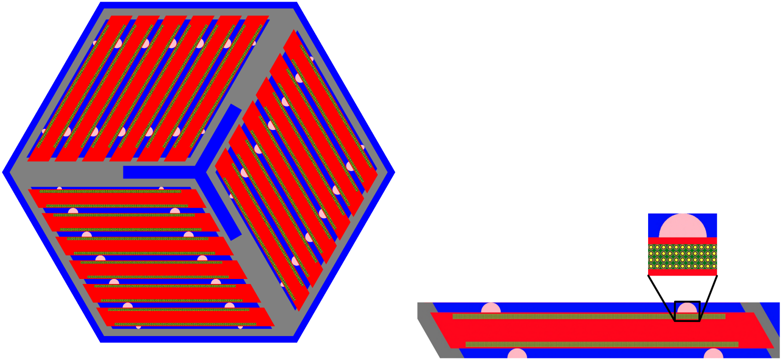


Figure 5: AHTR fuel assembly with 18 fuel plates arranged in three diamond-shaped sectors, with a central Y-shaped and external channel graphite structure.

FHR Benchmark

- The AHTR's fuel geometry's triple heterogeneity results in complex reactor physics and significant modeling challenges
- In 2019 the OECD-NEA initiated a FHR benchmark exercise. Its objective is to identify the applicability, accuracy, and practicality of the latest methods and codes to assess the current state of the art for FHR simulation and modeling

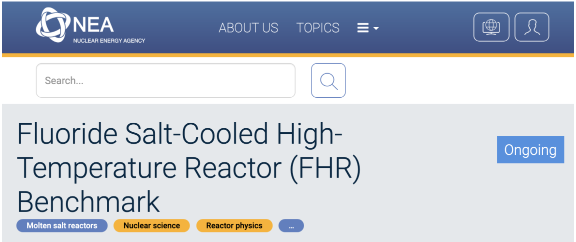


Figure 6: OECD NEA's FHR Benchmark [5].

Outline

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References I

[1] *Climate Change and Nuclear Power 2018*.
Non-serial Publications, Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2018.

[2] GIF, "A Technology Roadmap Updtate for Generation IV Nuclear Energy Systems," Tech. Rep. GIF-002-00, US DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002.

[3] "Fluoride Salt-Cooled High-Temperature Reactor (FHR) Benchmark."

[4] K. M. Ramey and B. Petrovic, "Monte Carlo modeling and simulations of AHTR fuel assembly to support V&V of FHR core physics methods," *Annals of Nuclear Energy*, vol. 118, pp. 272–282, Aug. 2018.

[5] B. Petrovic, K. Ramey, and I. Hill, "Benchmark Specifications for the Fluoride-salt High-temperature Reactor (FHR) Reactor Physics Calculations," tech. rep., Nuclear Energy Agency, Mar. 2021.