DESIGN AND DEMONSTRATION OF THE KALEIDOS PORTABLE NUCLEAR MICROREACTOR

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The Kaleidos reactor is a 3.5 MWt high temperature gas-cooled microreactor (micro-HTGR) cooled with helium that incorporates a fuel form with demonstrated fission product retention characteristics and high temperature margins (TRISO in cylindrical compacts) and a highly volumetrically efficient zirconium hydride moderator. As the first microreactor of this type, several development activities are focused on testing materials and components at a range of pressure and temperature conditions to generate performance data and reduce uncertainties before more focused nuclear testing within the Idaho National Laboratory Experimental Breeder Reactor–II dome facility in the form of the Kaleidos Demonstration Project (KDP). A host of reactivity and nuclear heating tests are planned, culminating with full-power operation and a subsequent decay heat removal test. Experimental data and experience gained from demonstration activities will be used in future Radiant design, validation, and demonstration activities. The safe deployment and operation of the KDP would have broader implications for the nuclear engineering community, demonstrating a new commercial-driven design for the first time in the United States in decades.

1. Introduction

Increased industry development of nuclear microreactors over the last several years is largely due to their portability and operational flexibility, making them a feasible carbon-free technology for a variety of electrical grid sizes and remote locations. Reliability and operational flexibility, with several years of operation without refueling, are some of the unique characteristics of microreactors [1]. These are designed characteristics of Radiant Nuclear's Kaleidos, a 3.5 MWt portable nuclear microreactor intended to replace diesel generators and provide power in remote or emergency deployment applications [2]. Radiant is pursuing a fueled demonstration of this microreactor at the National Reactor Innovation Center Experimental Breeder Reactor (EBR)-II Test Bed [3] at Idaho National Laboratory.

Small nuclear microreactors designed for flexible deployment scenarios face different design challenges with respect to larger commercial reactors. Portability constraints drive the need for smaller and lighter core, reactor, and system components. Small cores enable external control mechanisms while driving higher leakage. Additional leakage reduces neutron economy while increasing shielding requirements and overall system mass. Remote operations require more intentional design of safety systems that allow for passive cooling in off-normal events without inducing additional radionuclide release. These constraints have framed the Kaleidos design process and have produced a safe and robust conceptual reactor design focused on a near-term demonstration and deployment.

This paper summarizes characteristics of the conceptual design for the Kaleidos nuclear microreactor, focusing on the core and core-adjacent components, and the modeling and simulation tools used in characterizing the system.

2. Design

Kaleidos is a 3.5 MWt gas-cooled thermal-spectrum nuclear microreactor incorporating the TRISO particle-in-compact fuel form drawn from AGR irradiation experiments [4]. The core consists of graphite fuel blocks, fuel compacts, and encapsulated metal hydride moderator (see Figure 1). Reactivity is controlled external to the core region via rotating drums with boron absorber material distributed across a selected arclength. Pressurized helium is forced through coolant channels formed by the fuel blocks and encapsulated moderator materials. In this way, moderators are directly provided cooling, limiting peak temperatures in the moderator elements, reducing thermal gradients, and limiting hydrogen migration. Heat is transferred from the helium loop through a heat exchanger to a supercritical carbon dioxide Brayton cycle. Insulation is incorporated in the configuration to reduce temperatures in ex-core regions to meet temperature limits for shielding materials. Shielding consists of a multilayered set of materials for gamma attenuation and neutron slowing down and absorption.

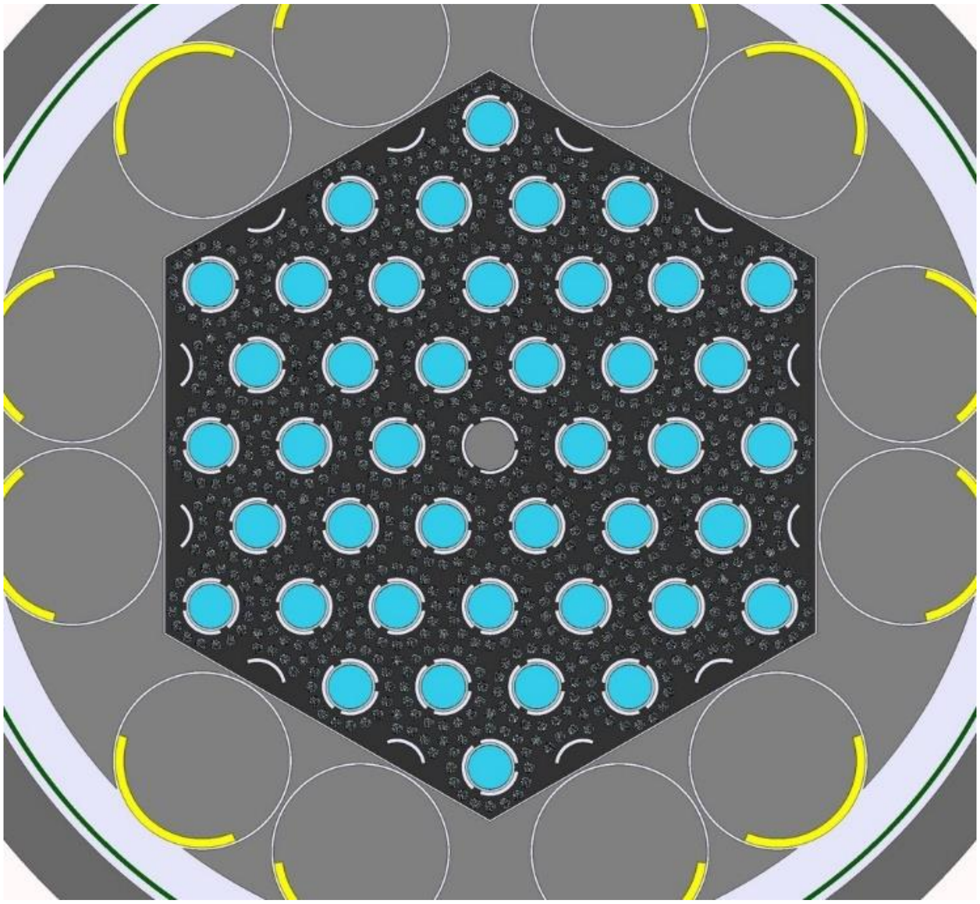

Figure 1: Section of the active core at the axial midplane.

In between the reactor pressure vessel and the shielding configuration is a circumferential annular channel that provides for the passive flow of ambient air to remove decay heat at the reactor pressure vessel interface. Thus, the shielding configuration must be designed with care to balance natural flow resistance with the retention of neutrons and gamma rays to mitigate activation, dose, and radiological hazard. The shielded reactor is integrated into a transportable container designed to meet transportation dose constraints as it is moved to and from an operational site.

3. Simulation

For this microreactor, Monte Carlo-based reactor physics tools are ideal for characterizing configuration reactivity, power distribution, and nuclide transmutation without concern for multigroup structure optimization or leakage correction methods. Thus, the bulk of the reactor physics characteristics are estimated with OpenMC [5] with fully resolved TRISO particle geometries (see Figure 2). Additional reactivity-adjusted TRISO homogenization methods are used for improved calculation efficiencies when appropriate. Other reactor physics tools are used for verifying OpenMC results and identifying any potential issues with Monte Carlo–based metrics.

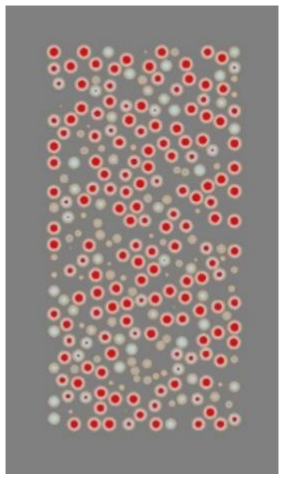

Figure 2: Explicit TRISO particles modeled within the fuel compact in OpenMC.

Radiant has internally developed a software simulation and hardware control package for building digital twins called SimEngine. SimEngine provides for real-time simulation of the reactor under startup, shutdown, and off-normal scenarios using a digital twin of Kaleidos [6]. Core axial temperatures are calculated for each unit cell using heat transfer correlations built in the digital twin and information from reactor physics simulations. Coupled spatial kinetics simulations requiring more efficient reactor physics solutions are planned to leverage Griffin reactor physics and NEAMS thermofluidic capabilities [7]. Higher fidelity thermofluidic models inform lower order models, and form the basis for performance predictions for some of the more challenging fluidic components in the reactor [8]. All of these fluidic structures and components will be manufactured, assembled, and tested under prototypic conditions to form a basis for validation of the higher fidelity simulations and the measurement of key safety features. Additional physics tools may be leveraged when needed for analysis verification (see Figure 3).

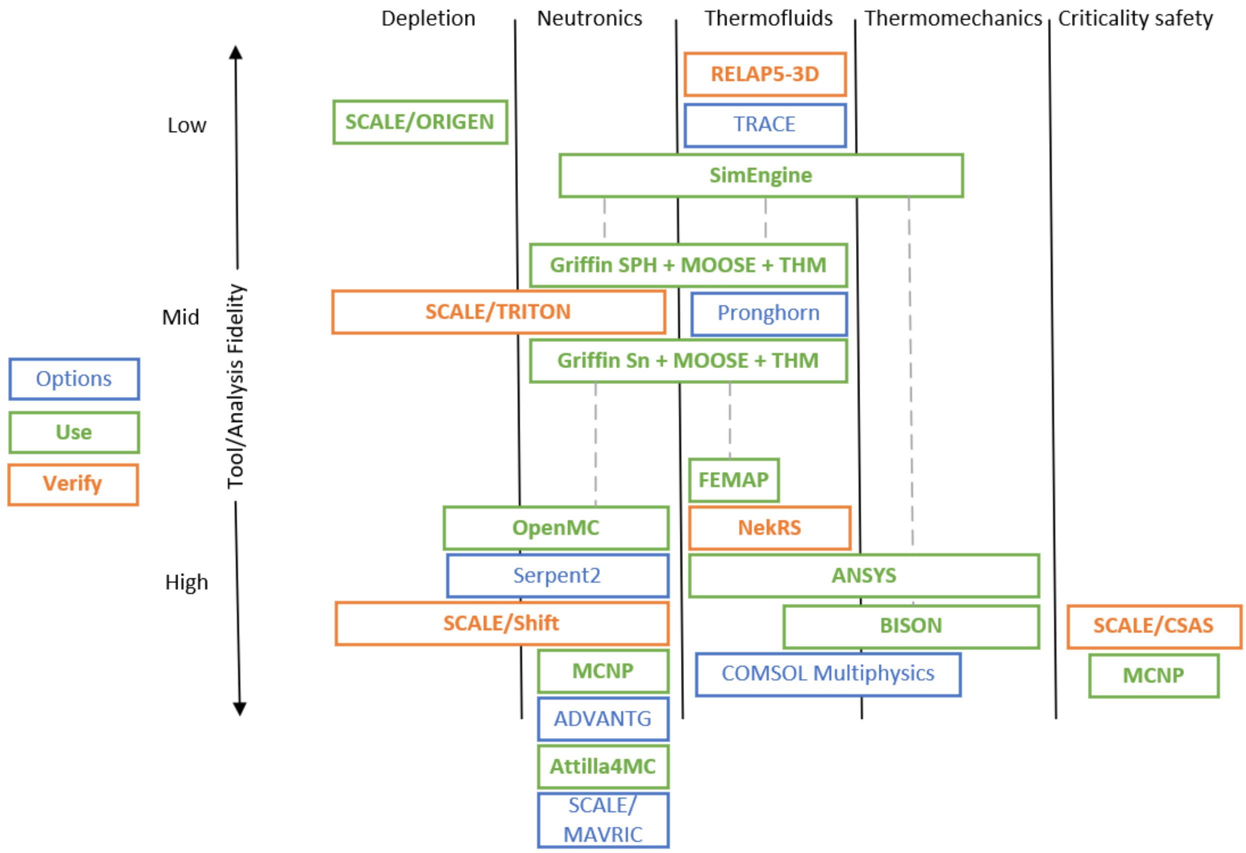

Figure 3: Modeling and simulation toolsets for core performance and safety analysis, with tools highlighted for use in reactor design and analysis (green) and additional analysis verification (orange).

Off-normal events for Kaleidos include familiar gas-cooled reactor events, including a loss of flow, loss of coolant, loss of heat sink, and loss of power (see Figure 4). Significant reactivity insertion events are mitigated through limiting drum rotation speeds. In these events, forced cooling is lost, and the reactor must sufficiently reject decay heat from a shutdown reactor without exceeding fuel or other material temperatures. In an unplanned shutdown event, the remaining core decay heat is conducted from the core, through the reflector materials, through the pressure vessel, and into the air jacket channel [6], in which natural air circulation is established. Due to the core size, air jacket design, and low power density, fuel material temperature limits are not challenged during these events. Insulation materials are used to manage temperature distributions and peak temperatures in the core–pressure vessel unit, as the pressure vessel has a limited time for operation at full pressure with elevated temperatures.

Software installation and management will meet rigorous quality standards commensurate with their use in the reactor's safety basis and design workflows (see Table I). Use in the safety basis of Kaleidos will elevate software quality assurance requirements and will require rigorous checking and review work. Testing is critical in validating thermofluidic predictions and for the quantities highlighted above cannot be replaced by analysis alone.

Figure 4: A simplified event analysis tree for the Kaleidos microreactor.

Table I: Example of some Kaleidos quantities of interest

Quantity of Interest	Method(s)	Purpose
Configuration criticality	MCNP	Initial critical configurations, reactivity worth
Excess reactivity & shutdown margin	OpenMC & MCNP	Condition reactivity worth measurements
Time-dependent decay heat	OpenMC & SCALE	Heat source for postulated scenarios
Time-dependent source term	OpenMC & SCALE	Radiological source for mechanistic source term evaluation
Power distribution	OpenMC	Power peaking factors
Control drum worth	OpenMC & MCNP	Safety margins, reactivity insertion rates, conditions for postulated scenarios
Temperature and other reactivity coefficients	OpenMC	For transient simulations
Steady-state coolant temperatures	SimEngine	Initial conditions for postulated scenarios
Time-dependent core temperature during loss of coolant/flow	SimEngine & ANSYS	Margin to fuel, moderator, and steel limits
Fuel thermomechanical performance	BISON	Failure probability/margin

4. Demonstration

The National Reactor Innovation Center is currently preparing the EBR-II dome facility for hosting reactor demonstration projects (see Figure 5). This facility provides the necessary passive heat rejection capability to remove the decay heat from a Kaleidos unit under a shutdown decay heat removal condition. A full prototypic demonstration of the primary loop and decay heat removal mechanism will be performed at Radiant's facility in California, while testing within the EBR-II dome will focus on measuring nuclear reactivity and heat removal characteristics. This includes a demonstration of the removal of decay heat through the air jacket component. Temperature, reactivity, and radiological data will be recorded to support future reactor design, licensing, and validation efforts.

Operations within the EBR-II dome facility require integration of safety into the design process and regular design reviews. The design for coolability of Kaleidos without external power is centric to the development of the product, as should be required for any design of a flexibly deployable microreactor.

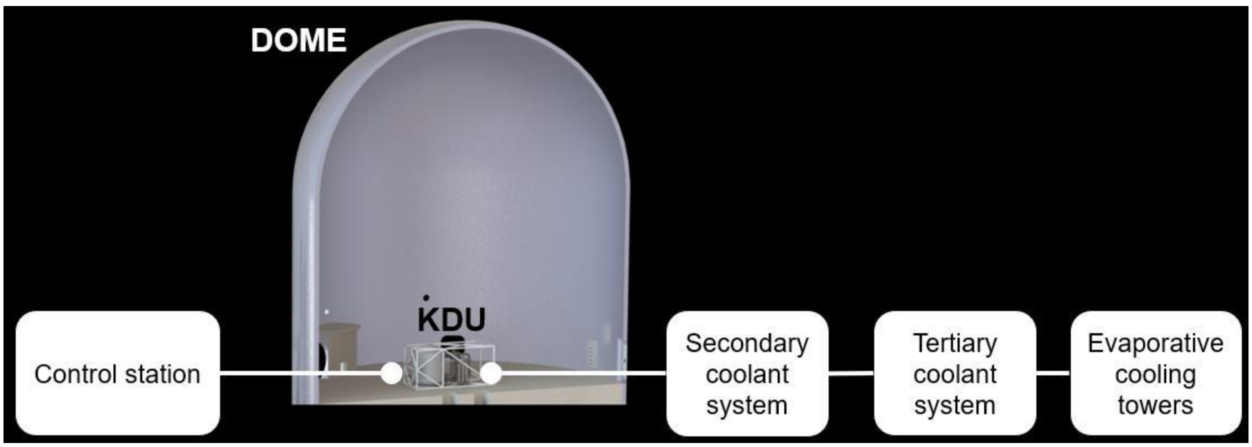

Figure 5: Kaleidos configuration within the EBR-II dome facility.

5. Conclusions

The design of Kaleidos is heavily influenced by nuclear microreactor constraints that provide for enhanced portability, remote operation, and near-term deployment. The AGR-based TRISO fuel form is familiar and has significant temperature margin to fuel failure, such that the material will not reach these temperatures even during extended loss of power events. Incorporation of metal hydride into the core and supercritical carbon dioxide in the secondary loop both enhance reactor portability by minimizing size. In addition, the small reactor core provides for more simple external control mechanisms and enhanced conduction to the air jacket to meet temperature constraints during off-normal scenarios.

Hardware demonstrations are planned for all control, instrumentation, and thermofluidic components of Kaleidos. Data gathered during these tests will be used to make design decisions and validate models before demonstrating core operation at the EBR-II dome. The designs of the components discussed herein will continue to change during this design and testing process.

References

[1] What is a Nuclear Microreactor? US Department of Energy, Office of Nuclear Energy. Published February 26, 2021. Accessed February 3, 2023. https://www.energy.gov/ne/articles/what-nuclear-microreactor

[2] Kaleidos: A Portable Nuclear Reactor that Replaces Diesel Generators. Radiant Nuclear. Published October 2022. Accessed January 2023. https://www.radiantnuclear.com/

[3] A. L. BALSMEIER and T. P. BURNETT, "NRIC EBR-II Test Bed Pre-Conceptual Design Report," INL/EXT-20-59733-Rev000, Idaho National Laboratory, Idaho Falls, Idaho, USA. https://doi.org/10.2172/1690269

[4] Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance: Topical Report EPRI-AR-1(NP). EPRI, Palo Alto, California, USA (2019).

[5] P. K. ROMANO, N. E. HORELIK, B. R. HERMAN, A. G. NELSON, B. FORGET, and K. SMITH, "OpenMC: A State-of-the-Art Monte Carlo Code for Research and Development," *Ann. Nucl. Energy*, 82, 90–97 (2015).

[6] Introducing Kaleidos, a Portable Nuclear Microreactor from Radiant. Radiant Nuclear, El Segundo, California, USA (2021). https://youtu.be/9cc1j-MbVVA

[7] T. M. PANDYA, F. BOSTELMANN, M. JESSEE, J. ORTENSI, "Two-step neutronics calculations with Shift and Griffin for advanced reactor systems," *Ann. Nucl. Energy*, 173, 109131 (2022). doi: 10.1016/j.anucene.2022.109131.

[8] J. SAGOFF, "Argonne to Work with Nuclear Companies in 3 Projects Funded by the Department of Energy," Published February 2, 2023. Accessed February 3, 2023. https://www.anl.gov/article/argonne-to-work-with-nuclear-companies-in-3-projects-funded-by-the-department-of-energy