

IDAHO NATIONAL LABORATORY

Accelerating safe deployment of small nuclear reactors for grid use

Using simulation, real-time grid emulation, and incremental laboratory testing with components and controllers to reduce demonstration and deployment risk.

OBJECTIVE: Small nuclear reactors, including microreactors and small modular reactors, can power microgrids for years without refueling. They can supply reliable electricity to remote areas, data centers and mission-critical facilities. The Idaho National Laboratory is accelerating the safe and affordable deployment of microgrids powered by small nuclear reactors.

Using an approach like black starts of run-of-the river hydroelectric systems, INL is using its real-time simulation capabilities to help nuclear reactor vendors and microgrid developers mitigate technical and financial risks. INL researchers develop representative models for small nuclear reactors and other energy assets such as battery storage, diesel generators and flexible load with advanced control systems in a real-time simulation environment.

Researchers conduct hardware-in-the-loop tests with models, gradually replacing simulated components with physical hardware, avoiding the risks and costs associated with direct experimentation on one-of-a-kind equipment.

Small reactors are particularly suited for microgrids

Microgrids are small-scale power grids that can supply electricity, independently of an electric utility, to remote areas, data centers, military sites and areas affected by natural disasters.

Small reactors serve as a dependable power supply without reliance on continuous fuel delivery or variable resources. **These reactors have small footprints**, will be factory produced and can be easily transported and used in applications with tight space constraints.

Although advanced small nuclear reactors should be more flexible than traditional nuclear power plants, they are not designed to manage all aspects of grid fluctuation on their own. Pairing nuclear energy with battery storage can result in **robust and flexible solutions** for many mission-critical and energy-intensive applications.

The characteristics of small nuclear reactors make them a compelling option to power the next generation of microgrids.

Nuclear-powered microgrids can run for up to 10 years without refueling, operate at a capacity factor of 95% or more, require approximately 1 acre to serve a load of 20 megawatts, and lower electricity bills by more than 50% in rural areas and military or industrial applications that use diesel generators.

Based on Nichol and Desai's (2019), "Cost Competitiveness of Micro-Reactors for Remote Markets," Nuclear Energy Institute. <https://www.nei.org/resources/reports-briefs/cost-competitiveness-micro-reactors-remote-markets>

Model creation and use

INL researchers are developing models of the Microreactor Agile Non-Nuclear Experimental Test bed (MAGNET), the Microreactor Application Research Validation and Evaluation (MARVEL) microreactor and the Microgrid in a Box (MIB) within the Real-Time Digital Simulator (RTDS) to study their behavior in microgrids.

MAGNET and MIB models can integrate with other energy assets, like diesel and natural gas generators or variable resources when their location offers a strategic

MAGNET is an electrically heated thermal emulator of microreactors for non-nuclear microreactor integration testing.



MIB is a portable energy storage and microgrid management system with advanced inverter controls.



MARVEL is a sodium-potassium-cooled microreactor expected to be operational at INL's Transient Reactor Test Facility in 2028.



advantage, to support real-time analysis of operating conditions such as startup sequences and frequency regulation, providing insights into microgrid design.

After validation, these models support a step-by-step transition from simulation to physical implementation. The step-by-step process of including real-world equipment begins with connecting controllers, followed by integration of battery storage (like MIB), a non-nuclear representation of a nuclear reactor (as in MAGNET), and electricity loads (such as a "data center in a box"), in preparation for the full demonstration of a nuclear-powered microgrid using a nuclear reactors (MARVEL).

RTDS modeling facilitates the testing of physical components and control systems together with simulated components, particularly when certain elements are under development or too risky to test directly without prior operational experience.

Real-time simulation models reduce demonstration and deployment risk

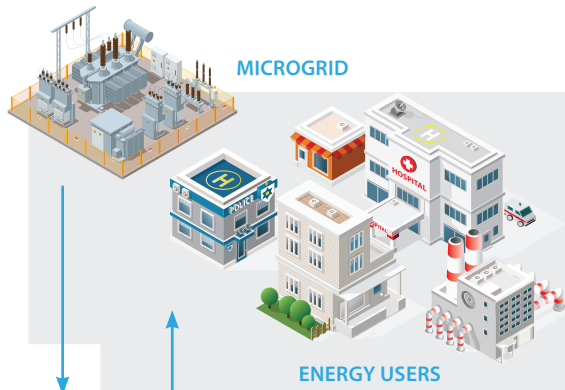
Using models early in the development process allows microgrid developers to reduce deployment risks. Testing components with simulated models and physical hardware allows developers to evaluate system behavior, validate control strategies and identify integration challenges well before a physical reactor is built and tested.

Studying the reactor's performance in real time, alongside simulated and physical microgrid equipment, allows researchers to assess whether the system architecture, asset mix and control logic are appropriately configured for first-of-a-kind deployment.

Real-time grid emulation

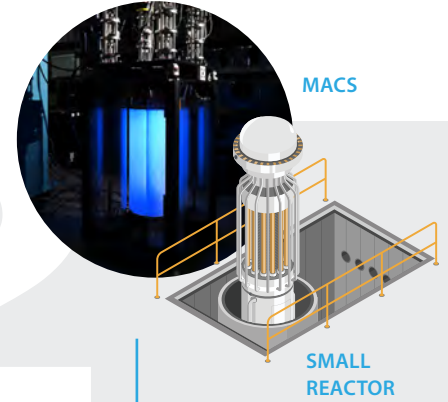


WITH RTDS



Simulation

Smaller nuclear reactor, energy storage, control and energy users modeled and simulated in RTDS



Control

Introduce real control hardware like the Microreactor Automatic Control System (MACS)



WITH RTDS



RAPID MIB



MAGNET

Introduce real hardware

Starting with a battery energy storage system like Microgrid-in-a-box, and later, non-nuclear representation of a small reactor using MAGNET (Microreactor Agile Non-Nuclear Experimental Test bed)

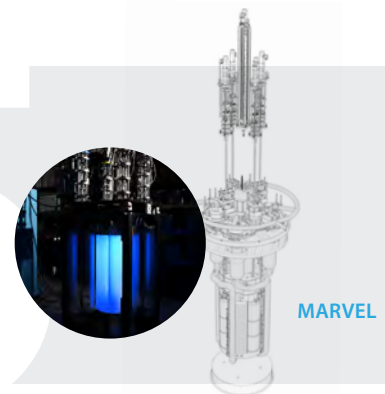


WITHOUT RTDS



Physical applications

Introduce the real world devices the microgrid is designed to power, like INL's Data Center-in-a-Box



MARVEL

Nuclear microgrid demonstration

Integration with MARVEL, controlled by MACS

The MARVEL (Microreactor Applications Research Validation and Evaluation) project, led by INL under the Department of Energy Microreactor Program, is a nuclear microreactor demonstration test bed.

RTDS and grid emulation enables:

Modeling complex or in-development components

such as small reactors described by neutronics, gas-Brayton heat transfer mechanisms and power conversion systems. This allows testing with high-fidelity representation of the system components without putting one-of-a-kind equipment at risk.

- **Control systems integration** including controller system hardware such as MACS, the MIB controller and the overarching microgrid management system or distribution energy management system. The functionalities provided by these controllers include temperature control and load-following capabilities.
- **Testing of real-world equipment** through integrating physical hardware into the RTDS test bed, as it becomes available, to gain operational experience. In this case, MAGNET/MARVEL will be paired with MIB via RTDS for real-time physical demonstration of grid scenarios, to be as prepared as possible for full demonstration using MARVEL.

A customizable system for any nuclear-microgrid system

The nuclear microgrid modeling framework is adaptable to support modeling a wide range of nuclear technologies and microgrid architectures. With minimal parametric changes, the RTDS-based model can simulate various small nuclear reactor designs, heat transfer systems and power conversion units. For example, point kinetics equations are used to model reactor dynamics, allowing quick adaptation to different core behaviors. Likewise, the gas-Brayton thermal system can be tuned or swapped to reflect alternatives such as Rankine or Stirling cycles.

Because any part of the system can be simulated in real time, it can easily be reconfigured to incorporate both simulated and physical distributed energy assets, and adapt to different microgrid topologies. This flexibility allows developers to test a wide range of configurations and control strategies before physical deployment, reducing risk and accelerating design iteration.

Future applications of the model

INL's real-time simulation platform will continue to evolve as a critical tool for validating nuclear-microgrid systems.

Ongoing real-time simulation and hardware-in-the-loop testing with assets such as MAGNET, MARVEL and MIB, along with advanced controllers like MACS, **will support the safe, efficient and scalable deployment of microreactor-based energy systems under realistic grid conditions.**

Looking ahead, this capability will support a broader range of emerging nuclear technologies, including those being demonstrated at INL and deployed by industry partners across the United States.

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