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Revision 4

A Microreactor Program Plan for The Department of Energy

May 2025

An Integrated, Strategic Program Plan for Research and Development supporting Demonstration and Deployment of Nuclear Microreactors

Idaho National Laboratory

MRP Microreactor Program

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An Integrated, Strategic Program Plan for the Research and Development Supporting Demonstration and Deployment of Nuclear Microreactors

March 2025

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FIGURES

ACRONYMS

ARPA-E	Advanced Research Projects Agency - Energy
ART	Advanced Reactor Technology
EPP	Elastic Perfect Plastic
GAIN	Gateway for Accelerated Innovation in Nuclear
HALEU	High assay low enriched uranium
MAGNET	Microreactor AGile Non-nuclear Experimental Testbed
MARVEL	Microreactor Applications, Research, Validation, and Evaluation
M&S	Modeling and Simulation
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEET	Nuclear Energy Enabling Technologies
NEUP	Nuclear Energy University Program
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
NTD	National technical director
R&D	Research and development
TALs	Technical Area Leads
WPM	Work Package Manage

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A Microreactor Program Plan for The Department of Energy

1. INTRODUCTION

The DOE Microreactor Program was established in FY 2019 to support research and development (R&D) of technologies related to the development, demonstration, and deployment of low-power, transportable reactors to provide power and heat for decentralized generation in civilian, industrial, and defense energy sectors. The program conducts both fundamental and applied R&D to de-risk technology performance and manufacturability readiness of microreactors. R&D projects and work packages are selected to support concept-neutral technology maturation. The intent is to ensure those concepts can be licensed and deployed by commercial entities to meet specific use case requirements. At the same time, the program will also support R&D specific to certain reactor technology groups (e.g., heat pipe reactors and gas-cooled reactors) to ensure relevancy and address the technology needs of commercial developers.

The program will ensure coordination of work and activities across participating laboratories and universities, establish, and manage stakeholder interactions, and support program meetings. These stakeholders include, but are not limited to, industry developers, the U.S. Nuclear Regulatory Commission, the Department of Energy, policymakers, and end users.

This document provides an overview of the overall Microreactor Program, including its vision, key technical objectives, and scope of the current and proposed R&D portfolio. It covers a 5-year rolling period currently from Fiscal year 2025 through Fiscal year 2030. This document will be revised biennially to reflect changing priorities.

1.1 What are Microreactors?

Microreactors are a class of very small modular reactors (0.1-50MW_e[a]) targeted for non-conventional nuclear markets. These include remote communities, mining sites, and remote defense bases, as well as applications such as humanitarian assistance, and disaster relief missions. Such applications currently face economic and energy security challenges that can be uniquely addressed by this new class of innovative nuclear reactors.

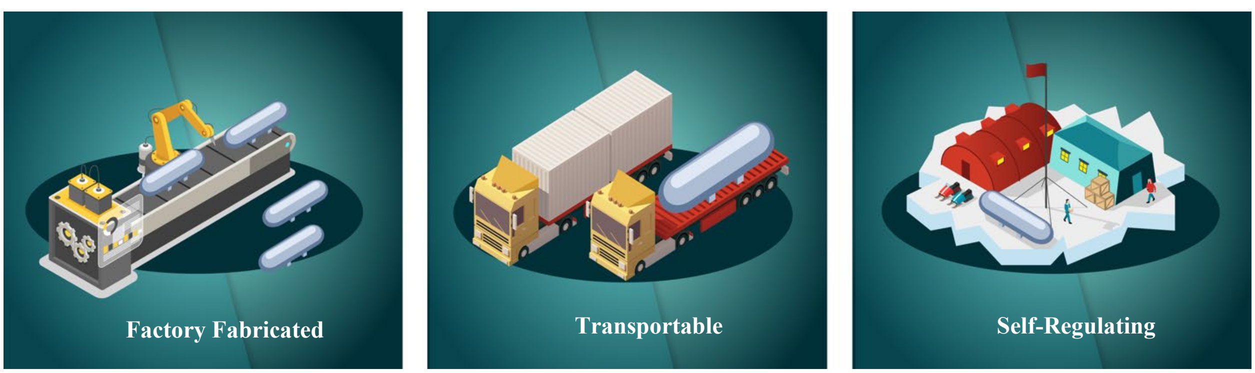

Figure 1 Key features of Microreactors.

[a] Infrastructure and Jobs Act of 2021

1.2 Microreactor Features

Microreactors have key features enabled by their small size that distinguish them from the existing large reactors and near-term small modular reactors. Primarily they share three main features (Figure 1):

Factory Fabricated

The majority of components of a microreactor are anticipated to be fully assembled in a central factory and shipped out to the locations of operation. This allows shifting from large-scale unique construction to repeatable factory construction, thus reducing marginal cost of production, and helping to install the reactor on-site and achieve operation quickly.

Transportable

Smaller unit designs can enable multi-modal transportation in their fully assembled configuration. Transportation by truck, rail, ship, or perhaps air are envisioned.

Self-regulating

Simple and responsive design concepts can enable remote and semi-autonomous microreactor operations that may significantly reduce the number of specialized operators required onsite. In addition, microreactors plan to utilize inherent passive safety systems that prevent overheating or reactor meltdown.

Microreactor designs vary based on coolant medium extracting the heat from the core for power conversion or process heat production. Depending on the end user and purpose for a microreactor, various social, economic, environmental, or operational factors will influence deployment of the reactor and, subsequently, the type of reactor.

Microreactors can be used to generate clean, reliable electricity for commercial use or for non-electric applications such as district heating, water desalination, hydrogen and synthetic fuel production.

Other benefits may include:

- Load following capability and seamless integration with renewables within microgrids.
- Rapid deploy-ability and availability during emergency response to help restore power to areas hit by natural disasters.
- Low downtime using a longer core life, operating for up to 10 years or more without refueling.
- Potential for quick removal from sites and exchange for replacements.

Due to their compactness, most designs will require high assay low enriched uranium (HALEU) fuel with a higher enrichment of U-235 than currently used in today’s commercial reactors. Some concepts may benefit from use of high-temperature moderating materials to improve fuel utilization while maintaining small system footprint. Reactors being designed to operate at high temperatures will need high temperature structural materials, and a means of passive heat removal. Furthermore, transportation of the microreactors may require additional technology such as vibration/shock absorbing shipping containers and advanced shielding materials or configurations to meet the safety requirements and standards for transportation.

The US Department of Energy supports a variety of advanced reactor designs, including gas-, liquid-metal-, molten-salt-, and heat-pipe-cooled concepts. In the U.S., microreactor developers are currently focused on designs that could be deployed as early as the late-2020s.

1.3 Microreactor Reactor Types

Similar to larger reactors, microreactors can be designed using any reactor coolant technology, as long as their aforementioned unique features, simplicity and robustness are realized. Based on the microreactor concept types being pursued by domestic industry, the Microreactor Program is primarily focused on developing technologies for the following types of reactors:

Heat-pipe-cooled reactors – Benefits of this reactor include the use of heat pipes that enable passive primary coolant, minimal moving parts, and low-pressure operation. Integrating individual components into the reactor system poses some technical risks.

Gas-cooled reactors – These are low-power density reactors with relatively low technical risks given the extensive previous experience using gas coolants. These reactors operate at higher temperatures and higher pressures with moving parts that may require more frequent inspection and maintenance.

Liquid-metal-cooled reactor and molten-salt-cooled reactor concepts are also being pursued by microreactor developers with related technologies being supported by other DOE programs that are focused on these reactor types. However, there are development opportunities within the program to enable adoption of these technologies for microreactors. Scope for these areas will be included as needed through the program's annual planning process and informed by engagements with stakeholders.

2. PROGRAM CHARTER

2.1 Program Benefits

This program was established to perform unique microreactor-related research and development activities that can directly reduce the technology risks and uncertainties for demonstration and deployment of near-term designs or next-generation microreactor applications as they near deployment. An over-arching objective of the program is to improve economics and license-ability of microreactor technology, thus enabling broad market penetration. This program specifically supports the DOE-NE goals to enable the deployment of advanced nuclear reactors and to maintain U.S. leadership in nuclear energy technology.

Microreactors are programmatically unique because there is a sense of urgency among industry, policymakers, regulators, and end users to achieve domestic energy security and be a leader in global markets. The Department of Energy's Microreactor Program remains closely engaged with these stakeholders to ensure maximum cross-cutting benefits of its civilian-focused R&D. Congressional legislation and budgets seek deployment of advanced reactors within the next 5 to 7 years, providing ample opportunity for microreactor demonstrations. Further, DOE maintains close interaction with the Department of Defense, specifically programs that have a similar mission to demonstrate microreactor technologies.

Because microreactors are novel and will possess unique technology features (e.g., full factory fabrication, automated operation, inherent safety, and full transportability), there is a significant need for research and development support. The DOE national lab complex is uniquely positioned to fulfill those needs to support industry and other stakeholders. Hence, the DOE Microreactor Program was established. This program performs research and development in areas that pertain specifically to civilian commercial microreactors that are not being pursued in other government and industry development programs.

2.2 Program Vision

Through cross-cutting research and development and technology demonstration support, the Microreactor Program will enable broad deployment of microreactor technology by:

- Achieving technological breakthroughs for key features of microreactors.
- Identifying and addressing technology solutions to improve the economic viability and licensing readiness of microreactors.
- Enabling successful demonstrations of multiple domestic commercial microreactors.

2.3 Program Objectives

The key objectives of this program are:

1. Address critical cross-cutting R&D needs of existing developers that require national laboratory or university expertise or capabilities.
2. Develop R&D infrastructure to support design, development, demonstration, regulatory issue resolution, and modeling and simulation (M&S) code validation Develop advanced technology and technology concepts that enable improved performance, economics, license-ability, or integration of microreactors.

2.4 Program Success Criteria

The main objective of the program is the near-term development, demonstration, and deployment of microreactors with its success measured based on its delivery of research results, the benefits and value proposition to industry, and its successful management. The following criteria will be considered:

1. Management of the program through development of the program’s annual scope by completing work planning by October 1 of each year and achieving timely scope updates to reflect program funding.
2. Successful completion of at least 90% of the program’s annual Level 2 milestones, on time and within budget.
3. Engagements with key program stakeholders to seek out feedback on program deliverable impact and inputs for program priorities that support the program’s vision and key objectives. The primary engagement is through an annual program review and as needed workshops on specific topics, either conducted alone, or conducted in coordination with other entities such as the GAIN Initiative, NRC, NEI, and EPRI. Feedback from this and other engagements (one-on-one discussions, conference attendance, etc.) are documented to satisfy this criterion.

All three criteria are a measure of the successful execution of the program, with the second and third also indicating the impact of the program.

2.5 Program Risks and Mitigation Strategy

The following risks could affect the performance of the program and limit the resources, schedule, scope, or quality of the program:

Funding:

Annual program funding and associated scope of work is dependent on Congressional fiscal year budget cycles. Due to changing Administration, Congressional, and/or Departmental direction, planned fiscal year budget allocations and associated program work scope may be impacted. This could impact the overall program mission and timelines.

Availability of national laboratory resources:

Availability of national laboratory resources and facilities supporting multiple programs and projects can be a major constraint, especially due to the aggressive nature of R&D timelines for this program.

Changing stakeholder needs:

Industry stakeholders are likely to make technology decisions that will impact relevancy of research and development conducted in this program. These decisions have significant impact on internal pivots.

Coordination with other DOE programs:
The Microreactor Program is dependent upon other DOE programs to perform required R&D for the development of microreactors. Changing direction in supporting programs could impact key R&D in the Microreactor Program.

These program risks are mitigated through an active management approach. The program's national technical director (NTD) is engaged with the DOE Federal Manager, national laboratory leadership, and stakeholders to develop priorities for program activities that are aligned with funding and resources. The NTD will also use the flexibility offered by engagement with other DOE programs to leverage work scope that is relevant to more than one program.

3. PROGRAM ORGANIZATION, DEPENDENCIES, AND STAKEHOLDERS

The Microreactor Program is organized to execute the program scope through its governance and technical R&D areas. It is executed under the oversight of a Federal Manager within the DOE-NE Office of Advanced Reactors (NE-52). This section discusses the overall program organization, program dependencies, and program stakeholders.

3.1 Program Structure and Key Roles

The organizational structure of the DOE Microreactor Program is shown in the organization chart in Figure 2.

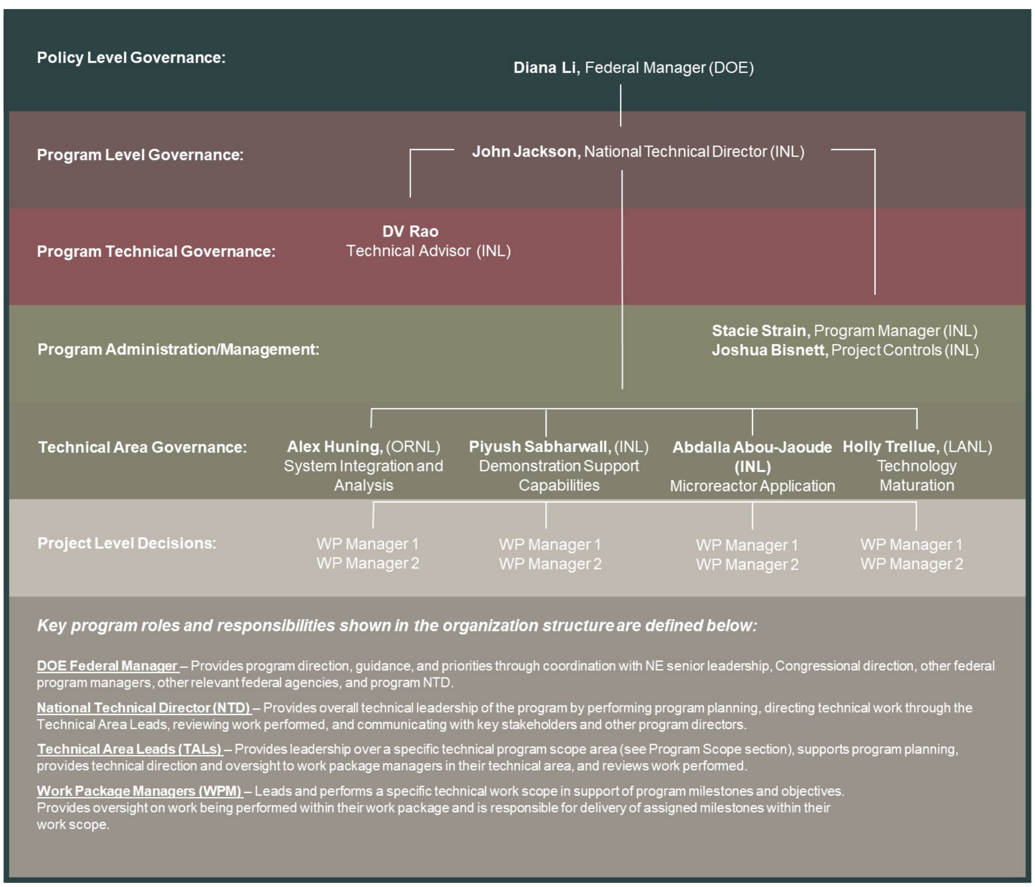

Figure 2. Organizational Structure.

Key program roles and responsibilities shown in the organization structure are defined below:

DOE Federal Manager – Provides program direction, guidance, and priorities through coordination with NE senior leadership, Congressional direction, other federal program managers, other relevant federal agencies, and program NTD.

National Technical Director (NTD) – Provides overall technical leadership of the program by performing program planning, directing technical work through the Technical Area Leads, reviewing work performed, and communicating with key stakeholders and other program directors.

Technical Area Leads (TALs) – Provide leadership over a specific technical program scope area (see Program Scope section), supports program planning, provides technical direction and oversight to work package managers in their technical area, and reviews work performed.

Work Package Managers (WPMs) – Lead and perform specific technical work scopes in support of program milestones and objectives. Provides oversight on work being performed within their work package and is responsible for delivery of assigned milestones within their work scope.

3.2 Interfaces with Other NE Programs

The DOE Microreactor Program collaborates and interfaces with other DOE programs and activities to advance its mission to support development and deployment of microreactor concepts. DOE has several programs covering a range of technologies relevant to microreactor development. The program will engage with these programs through the DOE NE planning process, coordination meetings, and review and planning meetings to ensure that scope is aligned and not duplicative. Leveraging commonalities and successfully cross-collaborating between different DOE programs enables programs to achieve their respective goals and empowers advanced nuclear technologies to achieve successful commercialization.

The following are key NE programs that directly interface with the Microreactor Program:

Advanced Reactor Technology (ART) Campaigns – The ART Program performs research and development to advance the technology readiness and to reduce technical risk for specific classes of reactor concepts. ART includes the Fast Reactor Campaign, the Gas-Cooled Reactor Campaign, and the Molten Salt Reactor Campaign. These reactor technologies are all relevant to microreactor development. The Microreactor Program remains engaged with the ART campaigns in the areas of materials development and properties, component development and testing, and reactor-technology-specific areas.

Spent Fuel and High-Level Waste Disposition – The Department of Energy's (DOE) Office of Nuclear Energy (NE) is responsible for ongoing research and development (R&D) related to long-term disposition of spent nuclear fuel (SNF) and high-level radioactive waste (HLW), which are managed by the Office of Spent Fuel and High-Level Waste Disposition, whose purpose is to develop and implement a plan for the safe and secure long-term management of the Nation's spent nuclear fuel (SNF) and high-level radioactive waste (HLW). SFWD has three sub-program offices that cover different aspects of this oversight: the Office of Disposal R&D, the Office of Storage & Transportation, and the Office Integrated Collaboration-Based Siting. Although the Office of Spent Fuel and High-Level Waste Disposition is not currently engaged explicitly in microreactor related R&D, it is anticipated this will become an important interface for the Microreactor Program following initial commercial deployments.

National Reactor Innovation Center (NRIC) – NRIC provides resources for testing, demonstration, and performance assessment to accelerate demonstration and deployment of new advanced nuclear technology concepts. This specifically includes those capabilities needed to demonstrate microreactor concepts to validate their performance. The Microreactor Program will collaborate with NRIC to perform research and development that supports demonstrations by maturing the relevant technologies and through developing novel, advanced microreactor concepts. Additionally, the NRIC Demonstration of Microreactor Experiments (DOME) facility is expected to be a highly utilized facility for microreactor developers to perform initial pre-commercialization demonstration and testing. NRIC has previously funded microreactor transportation projects, most recently on microreactor maritime transport.

Gateway for Accelerated Innovation in Nuclear (GAIN) – GAIN provides the nuclear community with access to the technical, regulatory, and financial support necessary to move innovative nuclear energy technologies toward commercialization while ensuring the continued safe, reliable, and economic operation of the existing nuclear fleet. The Microreactor Program will work with GAIN to engage industry microreactor developers and to provide technical resources that support the GAIN mission.

Nuclear Energy Enabling Technologies (NEET) programs – NEET supports cross-cutting technologies that are broadly applicable to nuclear systems. Key subprograms within NEET for microreactors include: Advanced Materials and Manufacturing Technologies (AMMT), Integrated Energy Systems (IES), Advanced Reactor Safeguards and Security (ARSS), and Advanced Sensors and Instrumentation (ASI). The Microreactor Program will engage with these programs to communicate needs for microreactors as well as to adopt and adapt technologies developed in these programs for microreactor applications. Some notable collaborations include addressing materials research and development needs relevant to microreactors with AMMT, and development of the Microreactor Automated Control System with ASI.

Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program – The NEAMS program develops predictive modeling and simulation tools that provide the ability to perform multi-physics simulation of reactor concepts, including microreactor concepts. The Microreactor Program will utilize these tools in performing systems analysis and integration activities; the experimental programs will be specifically designed and operated to produce data to validate the NEAMS tools for unique or novel microreactor applications. This will enable stakeholder confidence and adoption of these tools.

Nuclear Energy University Program (NEUP) – The U.S. Department of Energy's Office of Nuclear Energy created NEUP in 2009 to consolidate its university support into one program. NEUP funds nuclear energy research and equipment upgrades at U.S. colleges and universities and provides educational support to students. The Microreactor Program will work with NEUP to provide relevant topics for NEUP calls and participate in proposal selection. It will also provide guidance for university support to the program.

3.3 Program Stakeholders

The program is performing research and development activities that support efforts to develop, demonstrate and deploy microreactors. Key stakeholders important to the program's success include:

Department of Energy, Office of Nuclear Energy – The Microreactor Program performs its research and development under the funding and policy guidance of the DOE Office of Nuclear Energy. The Microreactor Program will work under the direction of the DOE-NE Federal Manager on all scope and program execution to ensure it is effective and efficient in its support of DOE NE's mission.

Advanced Research Projects Agency – Energy (ARPA-E) – ARPA-E is a United States government agency tasked with promoting and funding research and development of advanced energy technologies. ARPA-E recently expanded its R&D portfolio to include nuclear energy research, including activities related to microreactors, most notably through the MEITNER program. The agency is also considering future programs. The Microreactor Program will engage with ARPA-E to coordinate on scope to ensure that activities are coordinated rather than duplicative to support demonstration and deployment**.**

Industry microreactor developers – There are numerous microreactor developers that are currently designing microreactors and progressing towards demonstrations and commercialization. A primary objective of the Microreactor Program is to support these developers to accelerate the demonstration and deployment of microreactors by de-risking technology, improving economics of microreactor deployment, and improving the license-ability of microreactor technology. The Microreactor Program will:

- Participate in and hold topical workshops, webinars, and meetings to communicate with the developer community to receive input on their priorities and needs and to communicate program outcomes.
- Ensure that the program's research products (e.g., reports and data) and access to program-developed capabilities (e.g., experimental test beds) are readily and easily available to the developers.
- Seek feedback from the developers on the execution and impact of the program and potential improvements.

Nuclear Regulatory Commission (NRC) – The NRC is responsible for the licensing and regulation of reactors for commercial use. The Microreactor Program, in collaboration with industry vendors, will engage with the NRC to understand its needs to support microreactor licensing. It will consider program scope and activities that can help meet these needs. The Microreactor Program will participate in NRC meetings as needed to communicate program activities and outcomes. Similarly, NRC staff will be invited to participate in Microreactor Program activities as a means of information sharing and learning in an informal community of practice. NRC is also engaged in microreactor transportation issues and recently endorsed the Department of Defense Strategic Capabilities Office-developed risk assessment approach for NRC transportation package approval of the Project Pele transportable nuclear power plant for domestic highway shipment.

Department of Defense – The Microreactor Program's cross-cutting research and development directly supports the maturation of commercial microreactor technologies. Realizing the potential synergies between the civilian and defense applications of these commercial technologies, the Microreactor Program will remain engaged with relevant Department of Defense organizations to offer technical expertise and share publicly available cross-cutting programmatic R&D results. Specific organizations include the Department of Defense Strategic Capabilities Office, the Army Reactor Office, and the Nuclear Power Branch, Office of the Chief of Engineers, U.S. Department of the Army. Specific projects have included the development of a risk assessment approach for NRC transportation package approval of the Project Pele transportable nuclear power plant for domestic highway shipment and extending this approach to microreactor maritime transport. In addition, the Department of Defense liaises with the International Atomic Energy Agency (IAEA) on international microreactor transport.

End users – There are numerous applications for microreactors with a variety of end users, such as geographically remote communities, islands, mining companies, and others that need resilient, reliable, dedicated energy usage for civilians and governments. The Microreactor Program will seek out these end users to understand their needs and applications, as well as to provide information and outreach about microreactors. Market analysis, representing different regions and applications, will be performed to understand and inform developers on the most promising areas for deployment of microreactors.

University researchers – Development of additional technology and research opportunities for students benefit from the research and development that take place in the Microreactor Program.

4. PROGRAM SCOPE

The scope of the DOE Microreactor Program is to perform necessary R&D to support the development, demonstration, and licensing case of microreactors being developed by the private sector in the United States. The scope is focused to the extent possible on those items unique to microreactors and the program will seek to collaborate and inform other DOE programs performing supporting related R&D. It is recognized that certain work scope will be of common interest to multiple programs and collaborations will be a natural consequence of this. The current technical areas in the program are as follows:

System Integration & Analyses – This technical area will identify the needs, applications, and functional requirements for microreactors through market analysis which will be used to drive future focus of the Microreactor Program toward improving economics and/or viability of microreactors. It will seek understanding of the microreactor design space by investigating innovative microreactor technology supporting concepts and will perform regulatory research to help develop the regulatory basis for microreactor deployments. The technical area will also support investigations of the efficient fabrication, assembly, and transportation of microreactors with an eye toward identification of technical risks that the other technical areas can work to offset.

Technology Maturation – This technical area will mature key technologies used for the design and development of microreactors. This includes research into advanced microreactor technology enabling components such as high-temperature moderators and automated control systems; investigation of heat removal technologies such as heat pipes and heat exchangers; and the coupling of these components. Research into improved utilization of advanced instrumentation and sensors to support structural health monitoring and other operating conditions in a microreactor core will also be considered.

Demonstration Capabilities – This technical area will develop cross-cutting capabilities that can be used to support a variety of microreactor technology demonstrations, primarily focusing on non-nuclear testing capabilities supporting thermo-mechanical testing, systems integration, and controls testing, and applications. The technical area may also explore demonstration of disruptive future microreactor supporting concepts and technologies. The success of these concepts should represent significant improvements in performance, safety, mobility, manufacturability, operations, deployment, and economics. Finally, the technical area will be responsible for identification and development of other infrastructure needed to support microreactor technology demonstrations and support verification and validation needs.

Microreactor Application – This technical area will focus on applied research and development supporting the evolution of technology fundamental to enhancing the efficacy of microreactor operation. Examples include partially autonomous control systems as integrated with a reactor, shielding systems, and technology associated with transportation of mobile concepts. The Microreactor Program will design, construct, and operate a fully functional microreactor called the Microreactor Applications Research Validation and Evaluation (MARVEL) reactor. The purpose of this project is to provide a non-commercial demonstration of the potential for microreactor technology and to enable commercial microreactor deployments. It is intended to accelerate the development and demonstration and deployment of commercial concepts through technology sharing, process development, and end user/stakeholder question resolution.

Future technical areas may be developed to match the changing needs of the program, specifically noting that an advanced technologies and concepts focus for the program is anticipated to emerge as research and development to support near-term demonstrations. However, it is important to note that the scope of the DOE Microreactor Program does not include specific commercial demonstrations of microreactors. This is intentional and is necessary to avoid duplication of efforts with the NRIC program's DOME mission.

As indicated in the discussion of the overall program structure, the Microreactor Program is organized around its key technical scope, represented by technical areas. The following section provides additional details of each of these technical areas of the program. A 5-year scope roadmap for the program has been developed to inform program planning over multiple budget cycles and is discussed in the following section by technical area (see Figure 3). This program scope will be evaluated annually and will be adjusted to meet emerging opportunities and priorities.

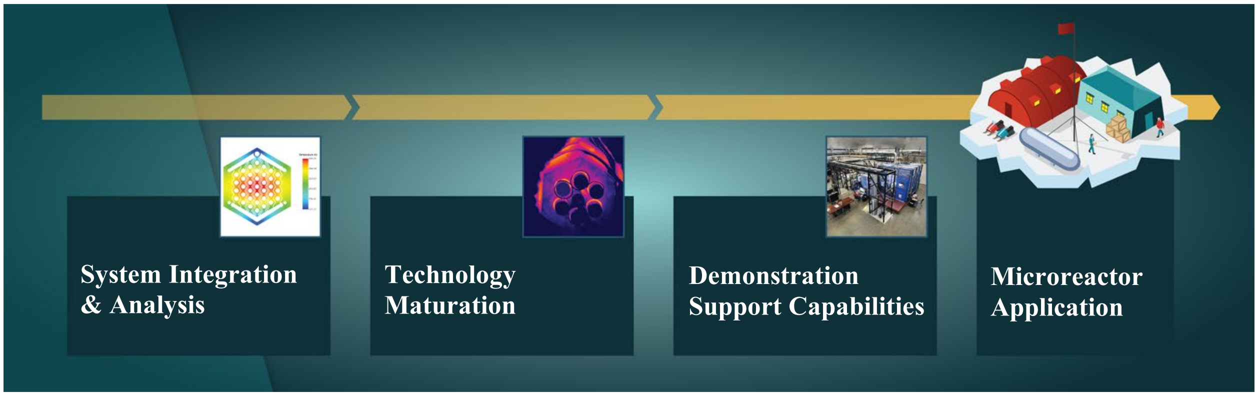

Figure 3. Program technical areas supporting nuclear microreactor demonstrations.

4.1 Technical Areas

4.1.1 System Integration and Analyses

The Systems Integration and Analyses Technical Area covers licensing and regulatory analysis, application of modeling and simulation tools, and performance of economic and market analysis. The following are the sub-areas targeted under this technical area.

1. Techno-economic Analyses – Microreactors will not achieve economic viability unless they can successfully compete in the various markets in which they could be used. To that end, microreactors need to be analyzed in the context of their potential applications. This includes domestic power production in industrial settings, international power production for remote settings, and military or disaster relief power production for emergency settings. Each of these applications has a different cost and profit driver with different competitors. The purpose of the economic and market analysis work is to guide the development of the reactor designs to meet those economic targets for competitiveness. A key activity includes development and maintenance of a framework that will help quantify the effect of different technology considerations (e.g., advanced hydride moderator, novel shield material, autonomous I&C) that are being supported by the MRP R&D efforts. The intent is to develop a wholistic framework that can help guide the MRP and stakeholders to technological solutions that can drive microreactor competitiveness. The scope will account for broad system-wide considerations including siting, transportation, and factory fabrication.

2. Licensing and Regulatory – The goal of licensing and regulatory research is to understand the licensing pathways for microreactor deployment and work with industry, academia, and other key stakeholders to inform NRC on issues related to those pathways. For areas in which there are no existing regulations, such as autonomous control, the program will work with industry and others to develop the safety, reliability, and operational bases to generate those regulations. Additionally, this area will focus on research to enable factory fabrication and servicing. Thus, the goal is to develop technical information, data, and knowledge that can support both industry and the regulators for an initial license application.

3. Transportation – The goal of microreactor transportation research is to provide vendors and their transportation contractors a basis for NRC transportation package approval, transportation planning

and enabling the commercial deployment and, in some cases, re-deployment of microreactors by identifying those issues unique to microreactor transport. The Transportation sub-area works closely with the Department of Defense, the NRC, the Department of Transportation, industry, and States and Tribes to develop the framework by which microreactors can be safely and efficiently transported by highway, rail, ship/barge, and ultimately by air.

4.1.2 Technology Maturation

The purpose of the work in this technical area is to advance the technology and manufacturing readiness of many technologies that enable microreactor designs. The current work scope includes three subcategories: high-temperature moderators, enhanced heat transfer mechanisms, and instrumentation and sensors. Future topics may include, but are not limited to, gas coolants and shielding/reflector/vessel/containment systems, advanced cladding and containment of all materials, power conversion techniques, and more for microreactors as needed by various microreactor developers. Note that although fuel and structural material is important in a microreactor core, structural material work is examined as part of the Advanced Materials and Manufacturing Technologies (AMMT) program, and fuel research occurs as part of the Advanced Fuel Cycle (AFC) and other programs that collaborate with the Microreactor program.

1. High-Temperature Moderator Materials – Moderating material is an important component in a microreactor because its presence can significantly decrease the overall mass of fuel required. This reduction is possible because moderators will thermalize neutrons and increase the probability of fission. Under this area, the program will investigate technology for retention of moderating capability at high temperatures, moderating materials performance, fabrication, and irradiation testing as well as encapsulation of moderators. The near-term focus is on yttrium-and zirconium hydride, but other moderator materials and containment needs for these materials may be considered in the future.
2. Heat Transfer– Advanced technologies to transport heat from the microreactor core must overcome unique challenges due to the compact footprint, radiation field, transportability, and high temperatures presented by the inherent features of these nuclear systems. Operation at high temperature is preferred since this translates to higher power production efficiency. Novel concepts will be explored to not only transport the heat, but to dampen transients that could affect the structural integrity and performance of the core structures and associated components. Research and testing of nonnuclear components required for a microreactor is also important for advancing technology and increasing our understanding of system performance. Although gas coolant is a relevant heat transfer mechanism, it is assumed that this technology is already being pursued through the gas reactor and other programs; thus, the microreactor program focuses on advancing the technology readiness level of heat pipes as well as the integration of a heat exchanger to heat pipes or other systems. Techniques for fabricating test articles with these features are developed and demonstrated.
3. Instrumentation and Sensors – Instrumentation and sensors research falls into three main categories: microreactor automated control systems (MACS), embedded sensors for determining operating parameters, and techniques for determining structural health. Goals are to adapt and apply technologies for monitoring and controlling microreactors to ultimately enhance automation and reduce operation and maintenance costs. Note that the sensor development activities leverage work being performed under the NEET Advanced Sensors and Instrumentation (ASI) program. First, a key collaboration between the Microreactor Program and ASI to develop, demonstrate, and utilize a Microreactor Automatic Control System (MACS) as a platform for development of automated control and monitoring systems is led by the Microreactor Program. Second, leveraging sensor development activities with the NEET Advanced Sensors and Instrumentation (ASI) program, developing fiber optic and other technologies to place in the core during fabrication to measure operating parameters during the lifetime of the core is important. Finally, the ability to determine defects in materials (particular solid structure) in the core is important to structural health integrity of the system once it is sealed and inaccessible. Techniques, including machine learning assessments, for evaluating the

robustness of the system over time from instrumentation outside the core is important and being developed through this program.

4.1.3 Demonstration Support Capabilities

This technical area encompasses non-nuclear testing and support activities crucial for microreactor deployment. It mainly includes the testing and demonstration of scaled heat transfer systems and further support validation activities working closely with other DOE programs. The technical area is subdivided into four sub-areas as follows:

1. Microreactor Agile Non-nuclear Experimental Testbed (MAGNET) – Development of a thermal-hydraulic and integrated systems testing capability, called the MAGNET, to simulate core thermal behavior, heat pipe and primary heat exchanger performance, and passive decay heat removal will support verification and validation of detailed microreactor thermal hydraulic models. This is applicable under startup, shutdown, steady-state, and off-normal transient behavior in steady-state operation, transient operation, and load-following conditions. This testing is to be done in advance of nuclear system demonstration. The test bed will ultimately be integrated into the broader INL Systems Integration Laboratory, encompassing thermal and electrical energy applications such as steam electrolysis, real-time digital simulators for power systems emulation, the thermal energy distribution system (TEDS), a microgrid test bed, the Brayton power cycle, and various other renewable energy generation sources
2. Single Primary Heat Extraction and Removal Emulator (SPHERE) – Development of a platform to support non-nuclear thermal and integrated systems testing capabilities. This capability shall provide a better understanding of operational regimes and thermal performance of the heat pipe under a wide range of heating values and operating temperatures, further enhancing the understanding of heat pipes during startup, shutdown and transient operation. The data obtained also supports with validation of modeling tools and workflows that industry can utilize for their reactor designs and development.
3. Evolving Demonstration Support – Demonstration and testing infrastructure needs are expected to evolve as technology readiness of microreactors advance. Development of capability necessary to support this evolution is covered under this sub-area.
4. Verification and Validation Support –This subarea concentrates on specialized testing to support the verification and validation processes, addressing the requirements of industrial stakeholders and licensing organizations (such as the NRC). The goal is to enhance understanding of a phenomenon of interest and reduce associated uncertainties.

4.1.4 Microreactor Application

This technical focus area involves the research and development of applied microreactor technologies. The intent of this technical area is to integrate, demonstrate and collect operational data to directly support enhanced efficiency and operational robustness of microreactor concepts with other end users.

1. Microreactor Applications Research, Validation, and Evaluation (MARVEL) – (MARVEL) is a key component of the national strategy to demonstrate and deploy microreactors to meet and improve energy security and reliability goals. The program is divided into three phases: 1) design, construction, and start-up of a microreactor; 2) operation and demonstration of the microreactor (includes physics testing) and associated hybrid energy systems, and 3) decommissioning and disposition of the microreactor and used nuclear fuel. The first phase of the program is an operationally funded demonstration project to design, construct, and start the reactor. MARVEL will be a 100 KWth microreactor with sodium-potassium eutectic (NaK) coolant and power generation and process heat extraction from a secondary coolant.

4.2 Program Key Milestones

The program's progress is defined through key planned milestones, which are categorized as Level 2 milestones. Additional Level 3 and Level 4 milestones will be defined to support the Level 2 milestones and to execute other R&D scope as needed. The table below provides key, defined Level 2 milestones for FY 2025 and notional key milestones through FY 2028. Milestones for FY 2029 and beyond will be developed as part of the annual program planning and will be included in future revisions of this plan.

Milestone ID	Milestone Title
FY 2025	
M25.1	MARVEL- Compile lessons learned report for MARVEL Guard Vessel Fabrication & Stirling Engine Testing to facilitate continued reactor island component fabrication.
M25.2	MARVEL- Complete Upper Support Shield (USS) drawings and finalize interface with T-REXC final design.
M25.3	MARVEL- Award limited funded contract of PCS Fabrication
M25.4	MARVEL- Release fully funded PCS fabrication contract enabling fabrication to maintain on schedule.
M25.5	MARVEL- Complete initial configuration of the MARVEL reactivity control system, including fabrication of the CIA rods and assembly of components onto the stand.
M25.6	MARVEL- Complete qualification testing per project plan MFC-EQP-0453 for RCS System Completed & prep system for transfer to TREAT.
M25.7	MARVEL- Finish F&ORs for MARVEL alternative heat extraction and power conversion
M25.8	MARVEL- Complete Primary Coolant Apparatus Test (PCAT) Thermohydraulic Testing
M25.9	Systems Analysis & Integration- Complete a bottom-up microreactor cost estimation tool to support developers and investors
M25.10	Systems Analysis & Integration- Finalize Microreactor Transportation Safety Program Planning Framework
M25.11	Demonstration Capability- Complete PCU Shakedown Testing
M25.12	Demonstration Capability- Integrate Power Conversion Unit with MAGNET
M25.13	Technology Maturation- Deliver graphite test article to INL to provide an industry relevant analog to a core and heat extraction system
M25.14	Technology Maturation- Identify, implement, and demonstrate a MARVEL startup sequence, including reactor calibration, utilizing MACS and ViBRANT to document basis for startup planning in microreactors.
M25.15	Technology Maturation- Complete full Post Irradiation Examination of HFIR irradiated YHx specimens to fill irradiation performance knowledge gaps
FY 2026	
M26.1	MARVEL- Complete Reactor Structure Frame (RSF) fabrication to enable the MARVEL project to maintain schedule

Milestone ID	Milestone Title
M26.2	MARVEL construction assembly initiates
M26.3	MARVEL- Complete Primary Coolant System (PCS) fabrication to enable the MARVEL project to maintain schedule
M26.4	MARVEL fuel fabrication complete, and fuel is shipped for storage to INL
M26.5	Integrate MACS and structural health monitoring capability to demonstrate remote operation (Resonant Ultrasound Spectroscopy, etc.) Complete Test of First Test Article in Nonnuclear Microreactor Testbed
M26.6	Demonstrate power conversion from MAGNET to supply a microgrid and power an application
M26.7	Develop framework for risk-informed transportation package approval for rail transport of microreactors
M26.8	Award initial end user feasibility study participants for MARVEL connected demonstrations
M26.9	Develop streamlined process for high performance (increased temperature and efficiency) heat pipe fabrication
M26.10	Demonstrate MACS functionality on VIBRANT system for additional transients beyond startup
FY 2027	
M27.1	MARVEL construction and installation completed
M27.2	Complete installation of MARVEL Power Conversion
M27.3	Develop moderator system based on irradiated results for ideal hydride moderating material
M27.4	Design and fabricate advanced heat exchangers and/or shielding for microreactors
FY 2028	
M28.1	Receive Startup Approval Authority confirmation for MARVEL reactor start-up from Secretary of Energy
M28.2	Complete MARVEL Training and Procedures for startup and turnover to operations
M28.3	MARVEL full power: zero power physics testing completed and release to unrestricted operations
M28.4	Determine optimal instrumentation and sensors to be placed in factory-fabricated microreactor core to monitor structural health and other conditions during operation
FY 2029	
M29.1	MARVEL- Complete initial demonstration of electric power delivered to a microgrid

4.3 Program Planned Accomplishments

In addition to the milestones, which are a typical indication of progress, there are key accomplishments that the program targets to maximize the impact and program value that are planned to be achieved over the next 5-year period. For each technical area, they are as follows:

4.3.1 System Integration and Analyses

1. Establish the technical bases for licensing and operation of unique microreactor features; the main areas for consideration are transportation of fresh and spent cores, control systems and strategies for automated and semi-autonomous reactor control.
2. Complete techno-economic and market analysis for commercial feasibility of mature microreactor designs, as well as early phase concepts. This will inform designers on cost drivers and the performance trades associated with them, which in turn will increase understanding of the sensitivity and robustness of microreactors to shifts in the market. This accomplishment may be supplemented by completing (i) targeted market studies performed by stakeholders and other experts to estimate demand and (ii) a detailed cost model of a reactor to estimate the cost and supply of microreactors.
3. Enable near term commercial microreactor deployment by engaging with industry stakeholders, including the Nuclear Regulatory Commission (NRC) to understand, address, and assist in resolving microreactor-specific regulatory issues.

4.3.2 Technology Maturation

1. Achieve high Technology and Manufacturing Readiness Levels for high-temperature neutron moderators and moderator systems, to aid qualification for use in microreactors. Maintain Advanced Moderator Handbook as a resource for commercial designers.
2. Develop capability to fabricate high fidelity individual heat pipes and heat pipe test articles with multiple heat pipes for non-nuclear testing and demonstration (see next section).
3. Achieve high Technology and Manufacturing Readiness Levels for the most compact heat removal and heat exchanger designs compatible with both heat-pipe and gas-cooled microreactors, regardless of power conversion fluid.
4. Mature the Microreactor Automatic Control System (MACS) and Visual Benign Reactor as Analog for Nuclear Testing (ViBRANT) platforms to enable a robust, adaptable, interchangeable, hardware in the loop control platform that enables graded automation for microreactor control systems.
5. Improve readiness levels for radiation resistant instrumentation and control that automatically, and non-invasively senses operating and structural integrity parameters within microreactor cores.

4.3.3 Demonstration Support Capabilities

1. Deliver non-nuclear test beds for both separate and integral effects to validate modeling and simulation codes for selected microreactor designs and serve both industry developers and regulators.
2. Complete non-nuclear integrated system testing for core, heat exchanger, and power conversion systems to inform microreactor concept development, design, and operation.
3. Develop a testing roadmap for targeted demonstration support by strategically addressing knowledge gaps for high importance phenomena.
4. Demonstrate heat to power conversion from a microreactor surrogate (MAGNET) and connected Brayton Cycle power conversion system by connecting to and powering a small microgrid.
5. Accomplish a verified and validated, tightly integrated group of multi-physics modeling and simulation codes for microreactors targeting initially heat-pipe and gas-cooled microreactors.

6. Develop testing capability to support high temperature and high-pressure testing of helium cooled reactor components.
7. Reducing experimental risks through scaled demonstrations and supporting the verification and validation needs of the industry.

4.3.4 Microreactor Application

1. Deliver an operational nuclear microreactor applications testbed (MARVEL) to validate technology, integration, and performance of microreactors to provide for research and demonstrations to support microreactor end users.
2. Identify opportunities to de-risk technology associated with deployment and operation of microreactors.

4.4 Program Activities by Year

Consistent with programmatic objectives outlined earlier in the report, the current and nearest term activities are focused on understanding how microreactors can meet market needs, to mature technologies and to provide experimental and testing capabilities that can support and accelerate demonstrations. As progress is made in these areas, the program will then include activities that are related to microreactor deployments as well as initiate efforts that can enable advanced technologies in order to fill the innovation pipeline for development of higher performance microreactors technologies, improved economics, and expanded deployment and applications capabilities.

Based on this strategy, the level of effort of each of these technical areas will differ from year to year to better serve the industry's needs. This yearly program focus could also guide funding allocations for each of these technical areas for the duration of the program. Based on this strategy, the following figure provides a snapshot of the planned level of effort based on today's understanding of value generated from this program. This strategy is subject to change as the program matures, through DOE guidance, and stakeholder engagement and subject to the annual appropriations and budgeting process.

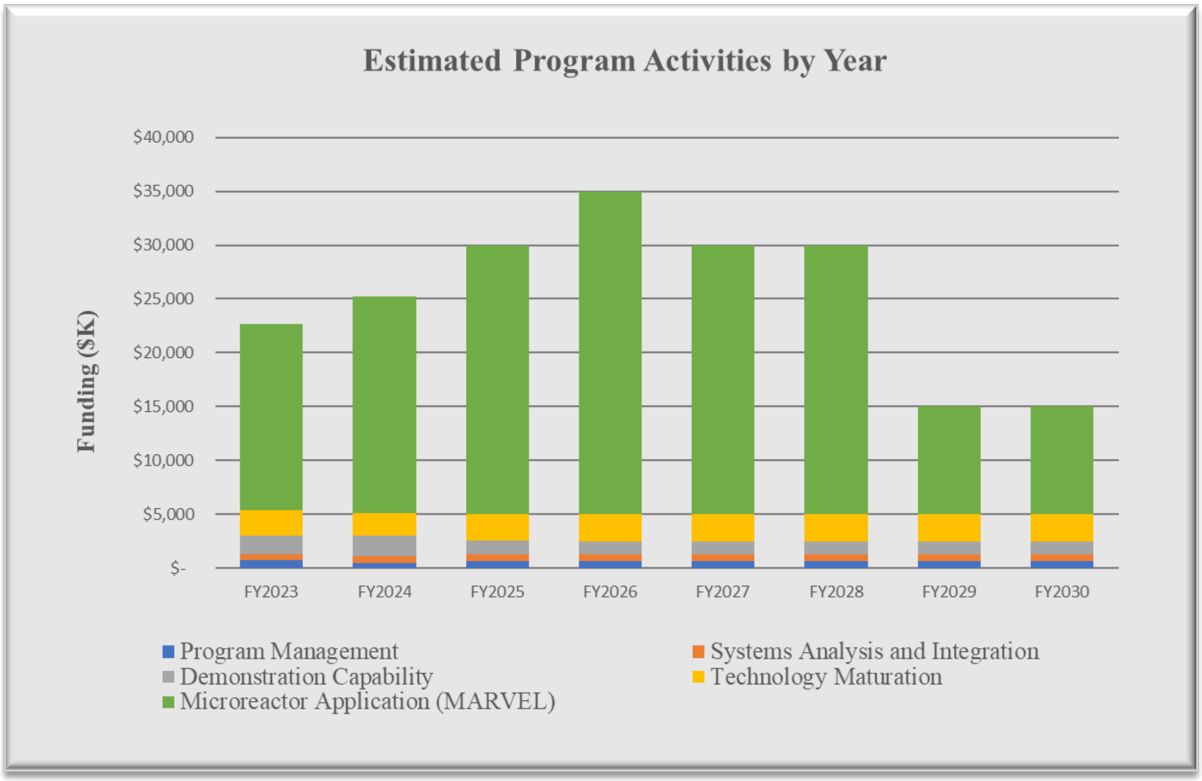

Figure 4. Actuals (FY23-FY24 and anticipated (FY-25-FY30 funding levels for the Microreactor Program.)

5. REVISION HISTORY

Revision #	Details of Change	Date Change Reviewed/Approved
0	New release	June 30, 2020
1	Org. Structure, page 4, FY21 Milestones added, page 2, and Personnel changes, page 17	Sept. 30, 2020
2	Sections 2.3, 2.4, 3.1, 4.1, 4.2, 4.3, Figure #4, and Appendix A to reflect current program status.	Mar. 3, 2021
3	Sections 1.1, 1.2, and 2.4 to update language, Figure 2 to update personnel, Section 4 to add new Microreactor Application Technical Focus Area, Figure 3 to add new TFA, Section 4.1 to update scope in TFAs, Section 4.2 to update key milestones, Section 4.3 to update planned accomplishments, and Figure 4 to update funding profiles.	March 23, 2022
4	Update entire document for release in FY25	June 03, 2025

Appendix A

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