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Revision 2

A Microreactor Program Plan for The Department of Energy

March 2021

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

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

March 2021

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CONTENTS

FIGURES

No table of figures entries found.

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 currently from Fiscal year 2021 through Fiscal year 2026. This document will be revised annually to reflect changing priorities.

1.1 What are Microreactors?

Microreactors are a class of very small modular reactors targeted for non-conventional nuclear markets. These include remote communities, mining sites, and remote defense bases, as well as applications such as back-up generation for power plants, 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.

1.2 Microreactor Features

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

Factory Fabricated

The majority of components of a microreactor are anticipated 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 help install the reactor on-site and go operational quickly.

Transportable

Smaller unit designs can enable multi-model 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 use utilize passive safety systems that can prevent overheating or reactor meltdown.

Microreactor designs vary, but to achieve these features most would produce less than 20 megawatts of thermal energy that could be converted to electric power, used directly as heat or both. They can be used to generate clean, reliable electricity for commercial use or for non-electric applications such as district heating, water desalination, and hydrogen 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. Designs operating at high temperature also need high temperature structural materials and transportation will require vibration/shock absorbing shipping containers.

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 mid-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 and 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. 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. 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 by 2024.

Because microreactors are novel and will possess unique technology features (e.g., autonomous 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 will perform 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, by 2025 the Microreactor Program will:

- Achieve technological breakthroughs for key features of microreactors.
- Enable successful maturations of multiple domestic commercial microreactor technologies.
- Empower initial demonstrations of the next advanced reactor in the U.S.

2.3 Program Objectives

The key objectives of this program are:

1. Meet 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, demonstration, regulatory, and safety-related tests and to collect data to validate modeling and simulation (M&S) tools.
3. Develop advanced technology and technology concepts that enable improved performance, economics, or integration of microreactors.

2.4 Program Success Criteria

The ultimate goal 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 achieved, 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 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 an annual workshop conducted in coordination with the GAIN Initiative, 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 for performing R&D needed 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 Reactor Fleet and Advanced Reactor Deployment (NE-5). 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.

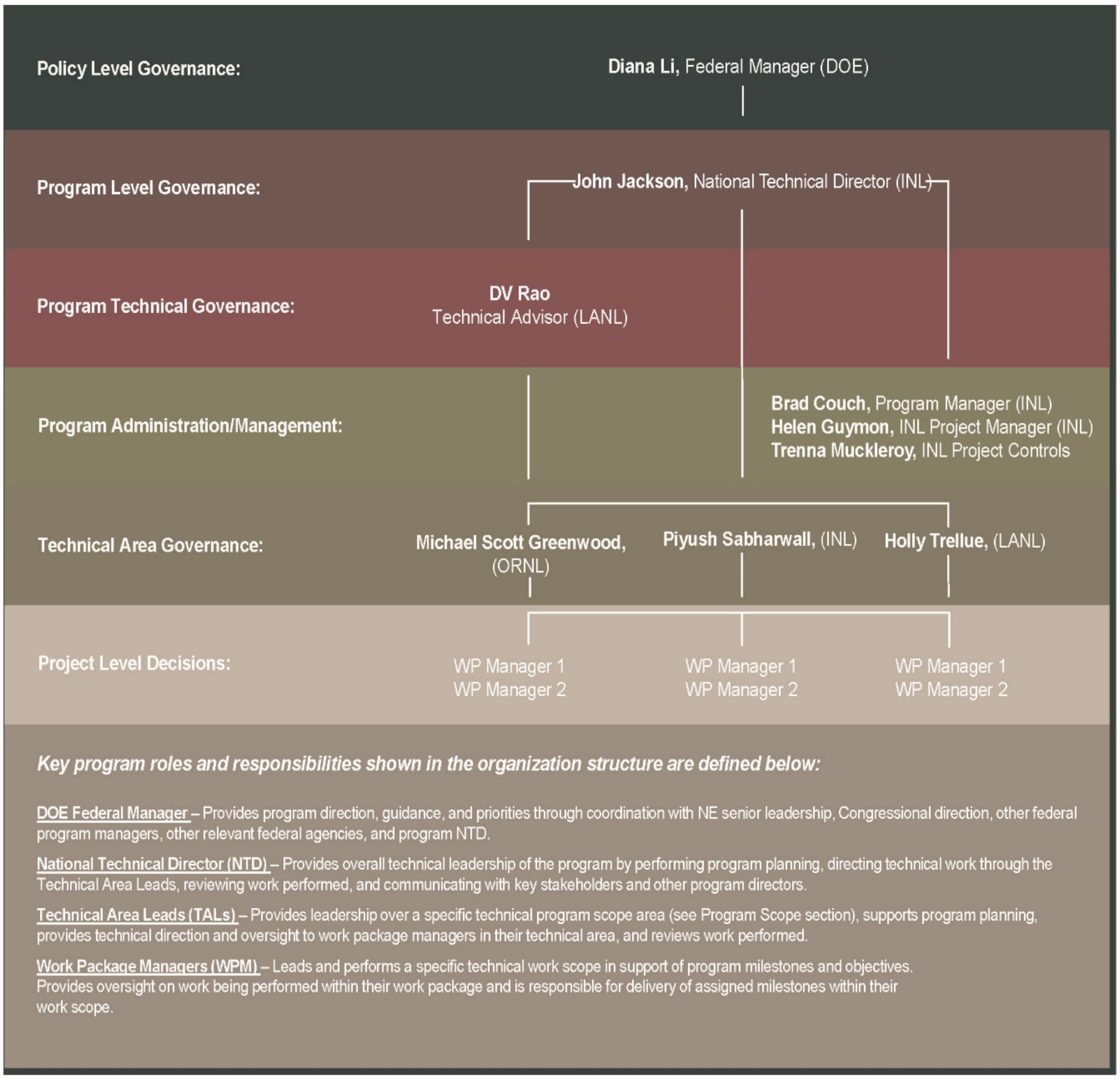

Figure 2. Organizational Structure.

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.

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 Waste Disposition (SFWD) – 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 Waste Disposition (SFWD). SFWD has two offices that cover different aspects of this oversight: The Office of Spent Fuel & Waste Science and Technology (SFWST) and the Office Integrated of Waste Management (IWM). The SFWST office has developed and is executing an R&D program that will address critical scientific and technical issues associated with the long-term management of spent nuclear fuel. The IWM office supports evaluations, planning, and preparations for transport and disposal of SNF and HLW and the possibility of interim storage for SNF. Although SFWD and IWM are not currently engaged explicitly in microreactor related R&D, it is anticipated this will become an important interface for the Microreactor Program in the near future.

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.

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 Manufacturing Methods and Advanced Sensors and Instrumentation. 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.

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 program's experimental programs will be specifically designed and operated to produce data to validate the NEAMS tools. 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.

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, through the MEITNER and LISA programs. 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.

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.

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. The Microreactor Program will:

- Participate and hold 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.

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.

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.

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. The scope is focused on those items unique to microreactors and will seek to collaborate and inform other DOE programs performing supporting R&D. The current technical areas in the program are as follows:

System Integration & Analyses – This scope 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.

Technology Maturation – The Microreactor Program will mature key technologies used for the design and development of microreactors. This includes research into advanced materials such as high-temperature moderators and structural materials; investigation of heat removal technologies such as heat pipes, gas cooling, heat exchangers, and power conversion; and the coupling of these components. Research into improved instrumentation and sensors as well as intelligent or autonomous control will also be considered.

Demonstration Capabilities – The program will also develop cross-cutting capabilities that can be used to support a variety of microreactor technology demonstrations, primarily focusing on both nuclear and non-nuclear testing capabilities supporting thermo-mechanical testing, systems integration, and controls testing, and applications. The program may also explore 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 program will also support investigations of the efficient fabrication and assembly of microreactors and identification of other infrastructure needed to support demonstrations.

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 is completed. However, it is important to note that the scope of the DOE Microreactor Program does not include specific commercial demonstrations. This is intentional and is necessary to avoid duplication of efforts.

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 adjusted to meet emerging opportunities and priorities.

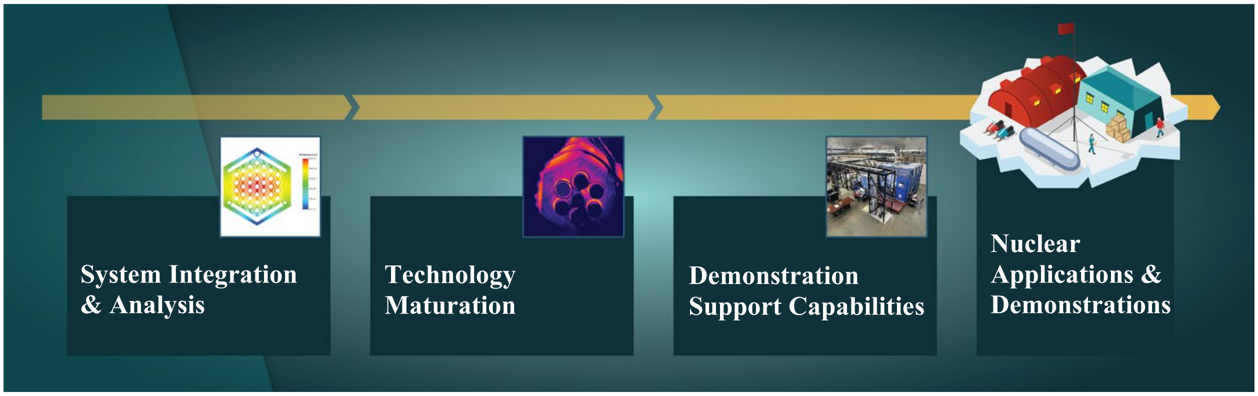

Figure 3. Program technical areas supporting nuclear microreactor demonstrations.

4.1 Technical Areas

4.1.1 System Integration and Analyses

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

1. Integrated Modeling and Simulation of Microreactors – The goal of the modeling and simulation effort is to establish the areas of applicability and gaps in experimental data needed to improve the performance prediction capabilities of existing modeling and simulation tools developed by other DOE programs, specifically NEAMS. It is important to note that this program will not prioritize funding of code development, rather apply existing tools to simulate and predict microreactor behavior and performance. The program will use modeling and simulation tools to analyze and understand the performance and behavior of microreactors to inform scope within the program and to support stakeholders.

2. 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 contexts 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.

3. 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. Thus, the goal is to develop technical information, data, and knowledge that can support both industry and the regulators for an initial license application.

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 five subcategories: high-temperature moderators, heat transfer and power conversion, advanced structural material manufacturing and testing, instrumentation and sensors, and legacy metallic fuel data. Future topics may include, but are not limited to, gas coolants and reflector/vessel/containment systems for microreactors as needed by various microreactor developers.

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 materials performance, fabrication, and testing of moderators. The near-term focus is on the development of yttrium-hydride, but other moderator materials may be considered in the future.

2. Heat Transfer and Power Conversion– 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 efficiencies. 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. Feasible heat exchanger and power conversion units for microreactors will be developed and analyzed as well as integration of these components including integrated testing. Techniques for fabricating test articles with these features will also be developed and demonstrated.

3. Advanced Structural Material Manufacturing and Testing – Microreactor core and reactor structures, such as cladding, vessels, and core monolithic structures typically require understanding of performance under extreme conditions and detailed manufacturing processes. Types of stainless steel have been used in reactors for years and provide the highest technical readiness levels for core structures. However, operating temperatures needed to provide the highest efficiency of thermal output cannot be achieved with stainless steel; thus, additional materials need to be researched such as grade 91 stainless steel, graphite and/or molybdenum. For a new material to become useable in a microreactor, researchers first need to gain a full understanding of the behavior of materials such as stainless steel at lower temperatures with a progression to explore materials capable of operation at higher temperatures.

4. Instrumentation and Sensors – Instrumentation and sensors research falls into three main categories: primary instrumentation for nonnuclear testing, sensors for structural health, and autonomous sensing and control. As part of nonnuclear test bed demonstrations, the program will research techniques for measuring parameters from heat pipes and/or other materials tested. Instrumentation technologies to monitor the structural integrity of microreactor structures operating at high temperatures (e.g., > 600°C) will also be developed. Note that the sensor development activities leverage work being performed under the NEET Advanced Sensors and Instrumentation program.

5. Legacy Fuel Data – DOE-NE has supported efforts to recover and preserve metallic fuel data generated throughout the U.S. Sodium-Cooled Fast Reactor program. Those efforts have been focused on establishing databases of the experimental data that were mainly generated during the Integral Fast Reactor program. This includes data generated at the EBR-II, FFTF, and TREAT reactors, as well as out-of-pile data. The data are essential for future licensing activities of metallic-fuel-based advanced fast reactors, as well as analysis and modeling and simulation activities. A Quality Assurance Program Plan for the data qualification has been developed and communicated to the NRC.

4.1.3 Demonstration Capabilities

This technical area involves both nuclear and non-nuclear testing and support of activities needed to deploy microreactors. The technical area is subdivided into three 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, which includes thermal and electrical energy users such as steam electrolysis, real-time digital simulators for power systems emulation, a microgrid test bed, and renewable energy generation.
2. Microreactor Applications Research, Validation, and Evaluation (MARVEL) – MARVEL is focused on the development of a platform that can be used to support development and demonstration of the integration of end use technologies with a small-scale nuclear microreactor. The purpose of this project is to develop a microreactor applications test bed at INL site to perform research and development on various operational features of microreactors to ultimately improve integration and of microreactors to end-user applications. End users will be engaged to provide application systems to be used for integrated testing. Such applications as computer systems for remote use, heating, ventilation and air conditioning systems, energy storage, water purification, chemical products, and microgrid applications.
3. 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 thermal performance of the heat pipe under a wide range of heating values and operating temperatures, further enhancing the understanding of heat pipe startup and transient operation.

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 Level 2 milestones for FY 2019 through FY 2021. Milestones for FY 2022 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 2019	
M20.1	Complete EBR-II HALEU Decontamination Study
M20.2	Complete and Issue Final Draft Report to Congress on Microreactors to DOE-NE
M20.3	Complete the Drafting of Code Rules to Extend Elastic Perfect-Plastic (Epp) Design Methods to Grade 91 For Incorporation into ASME Section III Division 5, Enabling the Efficient Engineering Design of Structural Components Constructed of Grade 91 By U.S. Reactor Vendors
M20.4	Issue Report on High-Temperature Moderator Fabrication and Materials Performance
M20.5	Report On 2019 Siting and Fuel Fabrication to Support Microreactor Demonstration
M20.6	Complete Engineering Design of Nonnuclear Microreactor Test Bed

Milestone ID	Milestone Title
FY 2020	
M20.1	Announcement of EBR-II HALEU Notice of Opportunity Recipients
M20.2	Completion of Evaluations of INL Sites for Microreactor Demonstrations
M20.2	Complete Test of First Test Article in Nonnuclear Microreactor Testbed
M20.3	Complete the Initial Development of a Primary Load Design Method Based on Elastic-Perfectly Plastic Analysis and Issue a Report
M20.4	Perform Creep Testing on Additively Manufactured Gr91
M20.5	Prepare Initial Version Of "Advanced Moderator Material Handbook"
M20.6	Complete Fabrication and Assembly of the 37-Heat Pipe Microreactor Test Article to Be Ready for Sodium Filling
FY 2021	
M21.1	Complete Market Study on the Case for Microreactors as on-site Generators at Government Installations
M21.2	Finalize decision on approach for fabrication and obtaining MARVEL reactor fuel
M21.3	Complete detailed engineering design for MARVEL fabrication and construction
M21.4	Complete Test Matrix for First Test Article in MAGNET
M21.5	Complete Preparation of Yttrium Hydride Irradiation Experiment for Insertion into ATR
M21.6	Complete Integral Critical Experiment on Yttrium Hydride Moderator Material
M21.7	Complete Fabrication of 37 Heat Pipe Test Article Components
M21.8	Complete Assembly of 37 Heat Pipe Microreactor Test Article Components and have Article in a Ready-to-Insert Configuration for MAGNET Testing
M21.9	Complete Planned Creep Testing on Additively Manufactured Grade 91 Material

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 this program plan 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 autonomous and semi-autonomous reactor control.
2. Accomplish a validated and verified, tightly integrated group of multi-physics modeling and simulation codes for microreactors targeting initially heat-pipe and gas-cooled microreactors.
3. 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 will 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.

4. Support licensing and regulatory needs to safely construct and operate commercial or government-owned microreactors on the INL Site and beyond.

4.3.2 Technology Maturation

1. Achieve high Technology and Manufacturing Readiness Levels for high-temperature neutron moderators, to aid qualification for use in microreactors.
2. 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.
3. Improve readiness levels for future qualification of high-temperature, low-creep structural materials for microreactors, including core materials (e.g., Grade-91 steel, graphite, and refractory metals).
4. Develop advanced technologies that progress toward enabling autonomous control for both safety and operability using high-temperature, radiation resistant instrumentation and control that automatically 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. Deliver a nuclear microreactor applications test bed to validate technology, integration, and performance of microreactors to provide for research and demonstrations to support microreactor end users.

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, many of which are planned in the mid 2020-time frame. 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.

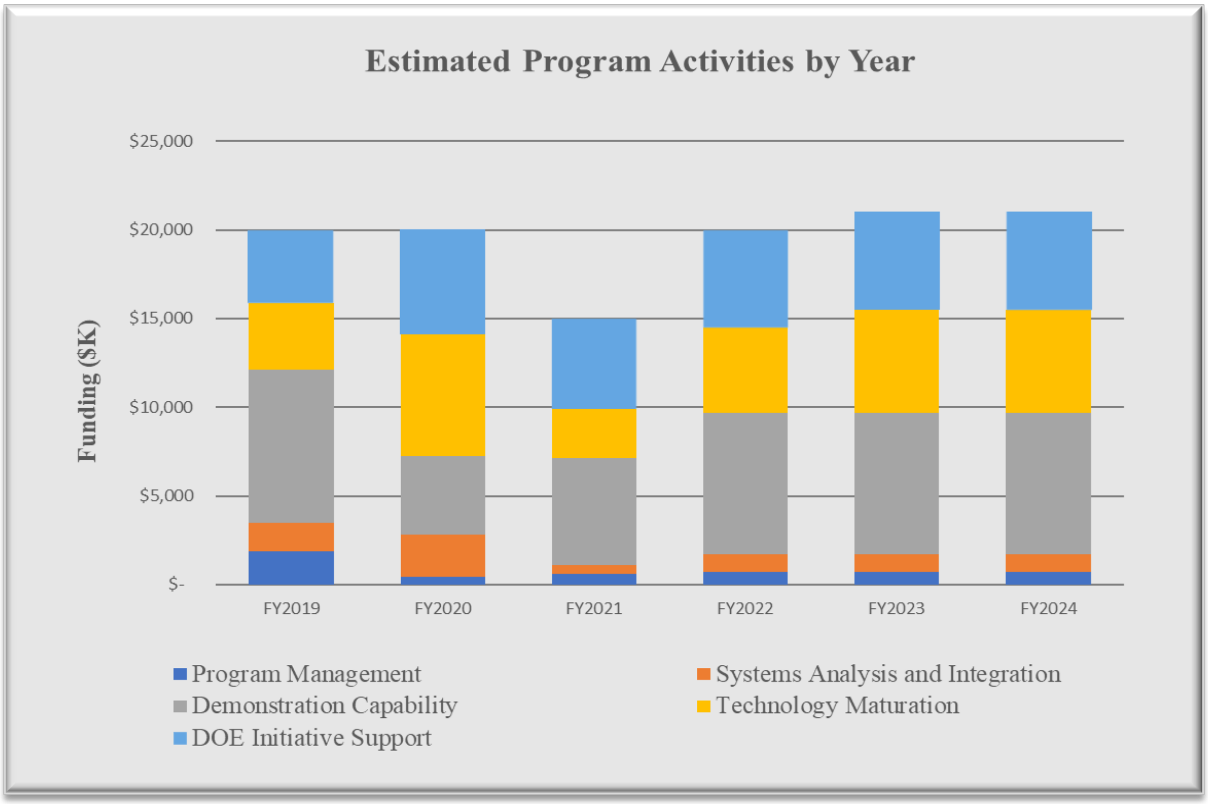

Figure 4. Estimated program activities.

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

Appendix A

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