# Overview of U.S. Fast Reactor Technology Program

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**Abstract**

This paper provides an overview of fast reactor research and development efforts in the United States. The diverse R&D activities are funded by several Programs in the DOE nuclear energy portfolio. Growing national interest in advanced (non-LWR) reactors includes industry led Projects pursuing demonstration reactors for several fast reactor options, and a fast test reactor Project for fuels and materials testing. The complementary R&D Program is focused on innovative technology that may yield significant cost reduction benefits. Technology development efforts for component testing, fuels performance, and new structural materials are ongoing. Another priority effort is the identification and resolution of key licensing challenges. Working in conjunction with the NRC, non-LWR system design criteria and accident categorization techniques have been developed. The benchmarking and validation of fast reactor safety analysis tools uses transient testing data from U.S. and international experience. To provide an indication of current status, recent references and major accomplishments for each area are summarized in this paper.

## **INTRODUCTION**

A growing interest in the development and deployment of advanced nuclear reactors has been observed in the United States. New non-LWR technologies have the potential to reduce costs and extend nuclear energy beyond conventional electricity applications; these features are vital to support the widespread deployment of future nuclear power, supporting clean energy carbon reduction goals. The Department of Energy (DOE) Advanced Reactor Demonstration Program (ARDP) was launched in 2020 to speed the demonstration of advanced reactors through cost-shared partnerships with U.S. industry; the three award categories for this Program are described at Ref. 1. The ten selected advanced reactor demonstration projects are shown in Figure 1.



Fig. 1. United States Advanced Reactor Demonstration Program (ARDP) Projects

A variety of fast reactor concepts with different technology options (e.g., coolant) and diverse missions (e.g., once-through high burnup, small modular, etc.) are being proposed by U.S. industry. An industry Fast Reactor Work Group (FRWG) has been established that includes sixteen vendor, utility, and industry institutes. The scope and priorities of the DOE R&D Program are informed by annual recommendations provided by the industry FRWG. Furthermore, the recent ARDP awards include several fast reactor designs:

* The Terrapower Natrium reactor is a Sodium-cooled Fast Reactor (SFR) coupled with molten salt energy storage to provide flexible electricity output. The concept utilizes enriched uranium metal alloy fuel and will complete a near-term commercial demonstration. [2]
* The Southern Company Molten Chloride Reactor Experiment (MCRE) will be a first small scale demonstration of molten chloride fast reactor technology. [3]
* The Advanced Reactor Concepts ARC-100 is a small, modular SFR leveraging U.S. experience with inherent safety and metal alloy fuel. [4]
* The General Atomics Fast Modular Reactor is a small, modular 50 MWe Gas-cooled Fast Reactor (GFR) with direct helium Brayton cycle. [5]

The United States DOE also initiated a Project to design and construct the Versatile Test Reactor (VTR) with the approval of mission need Critical Decision-0 in February 2019.[6] Following conceptual design and establishment of a cost and schedule baseline, alternative selection Critical Decision-1 was approved by DOE in September 2020.[7] The VTR is a 300 MWt SFR that will provide important testing capabilities for nuclear fuels, materials, instrumentation, and sensors for a variety of reactors in a high fast neutron flux and representative cooling environments. VTR utilizes conventional SFR technology, including ternary (U-Pu-Zr) metal alloy fuel, as demonstrated in prior United States test and demonstration reactors. The mission statement, design decisions, and current status of the VTR Project are provided in Ref. 8. *The VTR contributions to the FR22 Conference are identified in that paper and are not included in this R&D overview paper.*

Fast reactor research and development (R&D) is motivated by fundamental physics characteristics (e.g., significant excess neutrons, high fission ratio, high neutron leakage) that provide favorable performance for diverse energy production and fuel cycle applications. A sustained U.S. fast reactor infrastructure (both testing/demonstration facilities and associated expertise) is fundamentally important. This infrastructure is needed in the near-term to support ARDP projects and the VTR Project, in the mid-term for development of technology innovations, and in the long-term for deployment of advanced fuel cycle.

Most of the United States fast reactor R&D activities are being conducted as part of the Department of Energy’s Office of Nuclear Energy (DOE-NE) Advanced Reactor Technologies (ART) Program; the mission of ART is to enable near-term commercial deployment of advanced reactors. Several important fast reactor technology issues are being pursued in other DOE-NE Programs: the ARDP regulatory development R&D, the Microreactor R&D Program, the DOE Advanced Fuels Campaign, and fast reactor simulation in the Nuclear Energy Advanced Modeling and Simulation Program. In this paper, the current status of the complete suite of United Status fast reactor R&D work is summarized.

For commercial deployment of fast reactor technology, the R&D Program priorities are focused on two recurring challenges:

* Because capital investment in reactors is the dominant cost of any nuclear fuel cycle, R&D efforts to improve system cost and performance are the primary focus of technology development activities. Current work on component testing, fast reactor fuels, and structural materials are described in Section 2.
* Another key challenge is the need to establish and exercise a pathway for licensing of non-LWR technologies. Recent work to define a regulatory framework, and R&D efforts to validate fast reactor analysis tools and safety approach are described in Section 3.

## **R&D on Technology INNOVATIONS**

### Component Testing

A broad range of component technologies have been conceived for fast reactors including compact fuel handling, electromagnetic pumps, compact heat exchangers, and advanced energy conversion. These innovations support cost reduction by size compaction, reduced commodities, and/or improved reactor performance. To provide capabilities for component testing and technology maturation, the Mechanisms Engineering Test Loop (METL) facility was designed, built, and now operating at DOE’s Argonne National Laboratory.[9] METL is a multipurpose intermediate-scale sodium test facility for testing of liquid metal systems and components in prototypic reactor-grade sodium conditions. The METL facility has an initial configuration of four test vessels, which are connected to the main flowing sodium in parallel allowing flexible, simultaneous operations of multiple test articles. METL also provides development opportunities for young scientists, engineers, and designers who will ultimately lead the advancement of liquid metal technologies in the U.S. Sodium was transferred into the facility in April 2018, and operations began in September 2018; the facility has sustained operational state since that time with the exception of a six month shutdown for repair of the building scrubber system.

The first test article deployed in METL is the Gear Test Assembly (GTA) designed to test the performance and durability of gears and bearings, intended for use in advanced liquid-metal fuel handling systems.[10] Testing of the GTA began in February 2019 and is ongoing. The test article has been inserted and operated for four experimental campaigns, with more than 17,000+ simulated fuel assembly maneuvers; testing has been paused four times to replace failed mechanical bearings. Operational techniques for the insertion, operation, removal, cleaning, and reinsertion of METL test articles have been demonstrated and refined. Extensive post-test evaluation procedures have been developed to assess the state of the gear and bearing components. To date, the gears have operated with minimal observable degradation, and testing will continue until the gears fail.

The second test article for METL, the Thermal Hydraulic Test Article (THETA), provides an adjustable, scaled pool configuration, as utilized in most SFR power reactors. The primary system is submerged in the sodium pool and consists of a pump, electrically heated core, intermediate heat exchanger, and connected piping. The THETA test article was designed with extensive instrumentation to monitor the temperatures and flow conditions.[11] The THETA loop has been constructed and water tested and was inserted into METL in 2021. THETA will perform an exhaustive testing campaign for steady state and transient validation testing of important liquid metal thermal hydraulic phenomena, such as thermal stratification and natural circulation.

In addition to the initial METL test articles for component testing (GTA) and validation testing (THETA), research and development has also continued on fast reactor sensors and instrumentation. Tailored sensor applications are demonstrated and utilized in METL to support facility operations. In addition, a diffusion type meter to detect hydrogen in sodium has been developed and tested;[12] this sensor can be utilized for early detection of potential steam generator leaks.

### Fast Reactor Metal Alloy Fuels

The objective of fast reactor fuels R&D is to develop transmutation fuels for use in fast reactors with associated closed fuel cycle. To improve the economic performance of fast reactor recycle, research is also conducted to extend fuel burnup. Recent irradiation experiments have explored new alloys and geometric forms. Metallic fuel samples were irradiated in a cadmium-shrouded position in the Advanced Test Reactor at Idaho National Laboratory, and compared to previous irradiations in EBR-II and the French Phenix reactor FUTURIX-FTA experiment. Initial results indicate that fuel performance is not adversely impacted by the presence of minor actinides.[13]

### Advanced Structural Materials

Enhanced structural materials can improve performance by enabling compact configurations, higher operating temperatures, higher reliability, and longer lifetimes. Advanced steel alloys with improved strength have been developed in recent decades, but new structural materials have not yet been qualified for fast reactor utilization. In previous work, the austenitic stainless steel Alloy 709 was identified as a leading candidate to replace SS316 because of improved high temperature strength. Initial scoping tests confirmed material behavior at liquid metal reactor operating conditions and general compatibility with sodium coolant. Thus, materials testing is being executed to create a high temperature ASME code qualification case for Alloy 709. Two commercial heats of the alloy have been procured and a full suite of short and long-term materials testing is being conducted.

Another materials qualification effort is the extension of the Grade 91 qualification to the 60 year lifetime targeted by modern fast reactor designs. Long-term testing data has been compiled for Grade 91 and the package for extension of Grade 91 ASME code qualification has been submitted. In related work, statistical design methods for high temperature components have been developed. This technique can better quantify the design margin and is applied to Grade 91 load design in Ref. 14.

Research also continues on behavior of advanced structural materials in a sodium environment. Results show that for the carbon level of the sodium test loops, Grade 91 would be in the equilibrium decarburization regime at 650°C and carburization regime at 600°C. These results will provide a basis for predicting the long-term decarburization-carburization effects on the integrity of reactor components in sodium environments. Similar testing is being conducted to evaluate the behavior of Alloy 709.

## **R&D on Safety and Licensing**

### Regulatory Framework

The commercial deployment of fast reactor technology requires the establishment of a licensing pathway for advanced (non-LWR) technology. A first step was to identify modifications to general safety design criteria to eliminate LWR specific items and reflect unique aspects of advanced technology. In 2013, a DOE and NRC collaboration started with a first phase DOE proposal for SFR, High Temperature Gas Reactor (HTGR), and general Advanced Reactor System Design Criteria.[15] In Phase 2, this work was reviewed and revised by the NRC with draft design criteria published in April 2016 and, after public comment, a final Regulatory Guide in April 2018.[16]

The industry-led Licensing Modernization Project (LMP) is a subsequent effort to clarify and refine advanced reactor licensing. The LMP focused on the risk-informed process to identify licensing basis events; categorize and establish performance criteria for structures, systems, and components; and evaluate defense in depth for advanced reactor designs.[17] This work was reviewed by the NRC, including exercise applications to several fast reactor designs, and resulted in another June 2020 NRC Regulatory Guide on risk-informed, performance-based process to inform licensing.[18]

### Safety Approach and Validation of Analysis Tools

The safety design philosophy of modern fast reactor designs relies on inherent safety features including favorable reactivity feedbacks, low pressure cooling, and redundant/diverse decay heat removal systems. The safety analysis of commercial concepts (e.g., Ref. [19] for the ARC-100 design) and the VTR test reactor [20] show the effectiveness of this approach for pool-type SFRs using metal alloy fuel. The safety analysis results will be utilized as part of NRC licensing for commercial demonstrations or DOE licensing of the fast test reactor; thus, quality assurance of both the analysis tools and the verification data is important in the near-term.

This inherent and passive safety approach was demonstrated by reactor transient testing in both EBR-II and FFTF under severe plant conditions. The EBR-II inherent safety tests for a complete loss-of-flow without control rod insertion were investigated in detail by a recent IAEA Coordinated Research Project (CRP); this international benchmark culminated in a 2017 IAEA technical report.[21]

Efforts on fast reactor knowledge recovery and information preservation continue to capture fast reactor historical operating information and key testing data. Over 20,000 documents have been converted from hard copy at the DOE’s Office of Scientific and Technical Information. Reactor safety testing, fuel irradiation testing, and component reliability data from EBR-II, FFTF, TREAT, and previous R&D Programs are being captured in modern databases. Specific procedures to qualify the metal fuel alloy testing data have been reviewed and approved by NRC.[22]

Experimental data from the FFTF “loss of flow without scram” testing is being shared as part of an ongoing IAEA CRP. The international results from this CRP are summarized in Ref. 23; the United States contribution for the FFTF neutronics benchmark is summarized in Ref. 24. Related studies of the FFTF individual reactivity feedbacks are described in Ref. 25. The United States is also a participant in the IAEA CRP on China Experimental Fast Reactor (CEFR) startup testing; the neutronics results from this benchmark are provided in Refs. 26-27.

Other R&D work includes the assessment of fast reactor licensing source term modeling. The relevant requirements and gaps in current analysis techniques have been identified.[28]

### Transient Fuel Testing

 The recent restart of the Transient Reactor Test (TREAT) facility in 2017 provides a renewed opportunity for transient testing of fast reactor fuels. A joint United States and Japan Project is designing a TREAT experiment and instrumentation for testing of high burnup metal alloy and MOX fuels. The experiments will utilize fuels previously irradiated in the EBR-II and FFTF. A series of fresh fuel commissioning tests is planned in TREAT for 2021. [29]

## Summary

The growing interest in advanced reactors is reflected in the industry-led Advanced Reactor Demonstration Program; four of the ten demonstration awards are for fast reactors with several technology options. The primary objective of the U.S. fast reactor R&D program is to enable and support commercial deployment. To this end, technology development R&D for innovative cost reduction technologies is being performed:

* *Component Testing*. Operating METL facility allows for component testing (e.g., GTA), sensors and instrumentation, and validation testing (e.g., THETA) in a reactor grade sodium environment.
* *Fast Reactor Metal Alloy Fuels*. Irradiation testing of high burnup and recycle fuels (i.e., minor actinide loading) continues.
* *Advanced materials*. Code qualification of austenitic alloy A709 is underway; design methods and sodium testing are being conducted to confirm/extend structure lifetimes.

Safety and Licensing R&D is also being performed to resolve non-LWR regulations:

* *Licensing Pathway*. NRC Regulatory Guides on principal design criteria and risk-informed performance-based licensing design basis event selection are complete.
* *Validation of Safety Analysis Tools*. Fast Reactor testing data has been recovered and is being qualified for validation. United States is participating in international benchmark efforts, including the IAEA CRPs.
* *Transient Fuel Testing*. Fuel failure experiments have restarted in the TREAT facility.

In conclusion, a sustained R&D infrastructure is fundamentally important. This capability is needed in the near-term to support ARDP reactor demonstrations and VTR Project. Furthermore, the DOE R&D infrastructure provides the facilities and expertise to stimulate technology innovations and support future deployment.

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