STATUS OF U.S. FAST REACTOR FUEL RESEARCH DEVELOPMENT AND DEPLOYMENT

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INTRODUCTION: Metallic fast reactor fuels are planned for near-term U.S. deployment by multiple advanced reactor designers. The United States Department of Energy Office of Nuclear Energy (DOE NE) has supported research and development of metallic fast reactor fuel for several decades as a primary national interest, with more limited continued research into oxide and nitride fast reactor fuels due to limited potential national stakeholders. More than five years ago, significant R&D effort was placed in innovative designs to support an actinide transmutation mission in future reactors. Some design innovations were studied to increase burnup potential, primarily aimed at mitigating Fuel-Cladding-Chemical Interaction [1][2]. Recently, the U.S. national program has shifted significantly towards R&D that focuses on near-term deployment of the reference fuel design of U-10Zr fuel in HT9 cladding with internal sodium fill, based on a large existing knowledgebase. This focus prioritizes investigating data and knowledge gaps to bolster the performance design basis including significant characterization, testing, and data qualification of the legacy materials. A few experimental activities on legacy fast reactor oxide fuels have also been performed in the past decade [3]. Liquid fuel technologies are not addressed in this paper.

1. OVERVIEW

Metallic fuels are the most important fast reactor fuels in the U.S. since the 1980's, primarily for their characteristics including proven excellent performance and reliability with high fissile density and high thermal conductivity, good fabricability with low fabrication sensitivities, as well as good compatibility with proliferation-resistant recycling technology and especially passively safe reactor design strategies [4]. Today, several U.S. reactor designers plan to deploy metallic fueled sodium fast reactors (SFR). All SFR designers plan near-term deployments with fuel systems largely based on the historically developed DOE design using U-10Zr fuel in HT9 cladding with in-pin sodium to thermally accommodate sufficient fuel-cladding gap to allow for adequate fuel swelling. The fuel design and corresponding performance provide a unique, invaluable technical basis for successful near-term deployment of these reactor designs.

Recently, the U.S. initiated an effort to establish a reference fuel design basis, which provides potential benefits to all stakeholders supporting deployment of metallic fuels in SFRs [5]. This effort includes consolidation of existing physical fuel design detail with defined performance limits based on supporting evidence and uncertainty. Historical experimental data from the EBR-II and FFTF metallic fuel irradiation programs is now being collected and undergoing qualification for a metallic fuel database. New characterization and transient testing are being performed on legacy materials to improve the existing database where opportunities have been identified. These opportunities are described briefly in the following sections. There is residual interest in oxide fuels due to the long, successful historical experience. However, relatively few industrial or technical drivers currently exist for fast reactor application, except in international collaborations. Limited R&D is currently underway for nitride fuels, again due to limited clear fast reactor applications in U.S. strategies. However, some important legacy materials exist for these other fuels systems as well.

2. U.S. FAST REACTOR FUEL R&D ACTIVITIES

The DOE Advanced Fuels Campaign program is home to the nationally sponsored R&D effort in fast reactor fuel R&D. The AFC program has defined a 5-year program with specific goals to establish a reference fuel design basis for metallic fast reactor fuel, provide national stewardship of the fast reactor fuel testbed, innovate the next-generation metallic fuel design, and develop and implement accelerated fuel development and qualification methods. Major R&D activities in the program center on these goals [5].

The reference fuel design basis is focused on the fuel design with significant knowledgebase from experimental programs. The recent Nuclear Regulatory Commission publication provides a framework for advanced fuel qualification that is being followed for the fuel design qualification basis development by the AFC program [6]. Additionally, the primary activities being pursued in the U.S. to support these efforts currently include:

- Resolution of data gaps in legacy injection casting technique and characterization of corresponding fuel product microstructural-properties relationships to support accelerated development of next-generation technology.
- The state of the art and research in fuel-cladding chemical interaction by lanthanide attack and decarburization supported by artificial intelligence tools to improve measurement and interpretation. Figure 1 shows an example of new analysis with development of AI.
- Advanced characterization and modeling to understand and predict in-pile cladding creep leveraging multiscale understanding of creep physics to bridge limited data to irradiation conditions. Additionally, the dose-temperature range of HT9 is being extended based on new availability of FFTF material, which had irradiation extended in the BOR-60 reactor.
- Transient testing and model development to reinforce metallic fuel safety performance based on representative accident conditions for key performance phenomena including high temperature fuel-cladding eutectic interaction and transient stress rupture. TREAT experiments for irradiated MOX pins are also being executed in collaboration with Japan. **Error! Reference source not found.** shows an irradiated EBR-II pin being loaded into a TREAT capsule in the hot cell.
- Completion of a qualified EBR-II/FFTF legacy metallic fuels database in collaboration with the DOE Fast Reactor Program. First steps have been taken to develop an intelligent metallic fuel database with AI tool integration.
- Realization of a modern fuel performance assessment capability to support key design basis evaluations and bridge towards innovative design screening.
- Advancement of irradiation testing approaches via experimental validation of scaled diameter/fission rate testing to accelerate burnup accumulation rate for high burnup effects testing and instrumented fuels experiments.

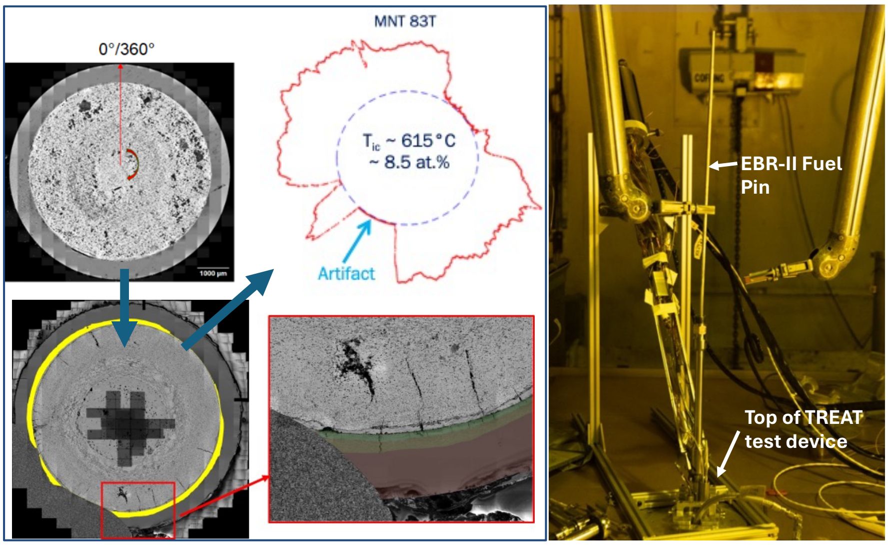

Figure 1. (Left) Example of modern detailed FCCI characterization utilizing AI tools. AI tracks FCCI layers to provide quantified circumferential thickness. Adapted from [7]. (Right) Example of high burnup EBR-II pin being loaded into TREAT test device.

3. FAST REACTOR FUELS TESTBED

The primary infrastructure comprising the U.S. fast reactor testbed is housed at the Idaho National Laboratory with a backbone including the metallic fuel fabrication facilities, the thermal-spectrum Advanced Test Reactor (ATR), the Transient Reactor Test Facility (TREAT), and the large hot-cell, Hot Fuels Examination Facility (HFEF). In addition, the thermal-spectrum High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory complements materials testing needs. Other facilities across the DOE national laboratory complex are also used primarily for testing unirradiated and irradiated cladding/structural materials. Ceramic fuel fabrication developmental capabilities also exist at Los Alamos National Laboratory and Idaho National Laboratory.

The restart of the TREAT facility in 2017 launched the development of sodium test devices for TREAT with the ability to load previously irradiated fuels for testing in TREAT via HFEF. Investments in transient testing infrastructure continue to ensure the range of conditions corresponding with design basis transients can be tested adequately supporting an expanded database and novel design performance. These capabilities are currently being used to test advanced metallic and MOX fuels at high burnup [8]. A fast-neutron testing capability for fuels and materials remains a critical gap in the testbed, though ATR is used routinely for meaningful fuel development testing using thermal-neutron-filtered test positions to integrally evaluate fuel burnup evolution [9]. A recent development effort with ongoing post-irradiation examination (PIE) activities has focused on scaling fuel diameter along with fission density (and temperature gradient) to boost burnup rates while maintaining prototypic temperature difference in the fuel [10]. Without a fast-spectrum test reactor, meaningful development of advanced cladding materials to high exposures remains limited (filtered testing is provides very low dose rates), though testing in the ATR and HFIR is invaluable towards screening and initial evaluations of irradiation effects. HFEF is a unique large inert-atmosphere hot cell capable of handling large scale fuels and experiments, which also enable complex experiments in ATR and TREAT. HFEF is also supported by multiple neighboring shielded microscopy laboratories. A primary capability gap for SFR fuels testing remains a transient furnace capability to better match testing conditions corresponding to many reactor transient events of interest.

4. CONCLUSIONS

Metallic fast reactor fuel technology is at a critical juncture in the U.S. with multiple planned reactor deployments to use it for the driver fuel. Fuel qualification is sought by reactor designers while the DOE national laboratories are supporting those efforts via bilateral R&D and DOE AFC program directed R&D. A primary goal of the DOE effort is to provide a technical rationale for a reference fuel design basis. Several additional supporting activities were summarized that support this goal, ongoing R&D activities are focused on reduction of uncertainties which impact fuel design limits. Many of these activities are supported by accelerated fuel development and qualification activities.

With successful deployment of metallic fueled SFR's, optimization of fuel performance and design innovations are expected to follow the focus on the reference fuel design qualification basis focus. Several promising design innovations have been explored via irradiation testing with some particular interest in designs to achieve higher core outlet temperatures and fuel burnups such as low smear density fuel forms, FCCI mitigating designs such as fuel-cladding interaction barriers and fuel doped with lanthanide getters, as well as claddings with higher temperature creep strength. Meanwhile a long-term goal for fast reactor fuel development remains development of recycle fuel designs, fabrication, and performance basis for improved fuel cycle management.

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