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Phased Development of Accident Tolerant Fuel

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Abstract. The United States Department of Energy (U.S. DOE) Advanced Fuels Campaign (AFC) has adopted a three-phase approach for the development and eventual commercialization of enhanced, accident tolerant fuel (ATF) for light water reactors (LWRs). Extending from 2012 to 2016, AFC is currently coming to the end of Phase 1 research that has entailed *Feasibility Assessment and Prioritization* for a large number of proposed fuel systems (fuel and cladding) that could provide improved performance under accident conditions. Phase 1 activities will culminate with a prioritization of concepts for both near-term and long-term development based on the available experimental data and modeling predictions. This process will provide guidance to DOE on what concepts should be prioritized for investment in Phase 2 *Development/Qualification* activities based on technical performance improvements and probability of meeting the aggressive schedule to insert a lead fuel rod (LFR) in a commercial power reactor by 2022. While Phase 1 activities include small-scale fabrication work, materials characterization, and limited irradiation of samples, Phase 2 will require development teams to expand to industrial fabrication methods, conduct irradiation tests under more prototypic reactor conditions (i.e. in contact with reactor primary coolant at LWR conditions and in-pile transient testing), conduct additional characterization and post-irradiation examination, and develop a fuel performance code for the candidate ATF. Phase 2 will culminate in the insertion of an LFR (or lead fuel assembly) in a commercial power reactor. The Phase 3 *Commercialization* work will extend past 2022. Following post-irradiation examination of LFRs, partial-core reloads will be demonstrated. The commercialization phase will further entail the establishment of commercial fabrication capabilities and the transition of LWR cores to the new fuel. The three development phases described roughly correspond to the technology readiness levels (TRL) defined for nuclear fuel development. TRL 1–3 corresponds to the "proof-of-concept" stage (Phase 1), TRL 4–6 to "proof-of-principle" (Phase 2), and TRL 7–9 to "proof-of-performance" (Phase 3). This paper will provide an overview of the anticipated activities within each phase of development and will provide an update on the current ATF development status.

Keywords: accident tolerant fuel, enhanced LWR fuel

INTRODUCTION

In the Senate Appropriations Committee Report (Senate Report 112-75), included in the Fiscal Year 2012 Energy and Water Development Appropriations Bill, the Committee recommended appropriations for the United States (US) Department of Energy, Office of Nuclear Energy (DOE-NE) "to give priority to developing enhanced fuels and cladding for light water reactors to improve safety in the event of accidents in the reactor or spent fuel pools," and urged "that special technical emphasis and funding priority be given to activities aimed at the development and near-term qualification of meltdown-resistant, accident-tolerant nuclear fuels that would enhance the safety of present and future generations of Light Water Reactors."

Development and qualification of nuclear fuel is a well-established process. However, due to the scientific and engineering challenges associated with nuclear technology, along with the conservative approach to adopting new technology, fuel qualification is a long, complicated process. The ATF development effort adopts a three-phase approach to commercialization, as illustrated in Figure 1. Each development phase roughly corresponds to the Technology Readiness Levels (TRL) defined for nuclear fuel development, where TRL 1-3 corresponds to the "proof-of-concept" stage, TRL 4-6 to "proof-of-principle," and TRL 7-9 to "proof-of-performance" [1]. Each step in the fuel development effort will necessarily consider the requirements set out by the Nuclear Regulatory Commission (NRC) to support the fuel licensing effort in planning, executing and documenting all phases of fuel development, including fabrication, experiments, model development and validation, etc.

The complex multiphysics behavior of LWR nuclear fuel makes defining specific material or design improvements challenging. However, establishing desirable performance attributes is critical in guiding the selection and development of fuels and cladding with enhanced accident tolerance. Desired attributes of fuel designs with enhanced accident tolerance include reduced steam reaction kinetics, lower hydrogen generation rate (or generation of other combustible gases), and reduction of the initial stored energy in the core, while maintaining acceptable cladding and fuel thermo-mechanical properties, fuel-clad interactions, and fission-product behavior. Targeting improvements in these attributes provides guidance in establishing the critical parameters that must be considered in the development of fuels and cladding with enhanced accident tolerance.

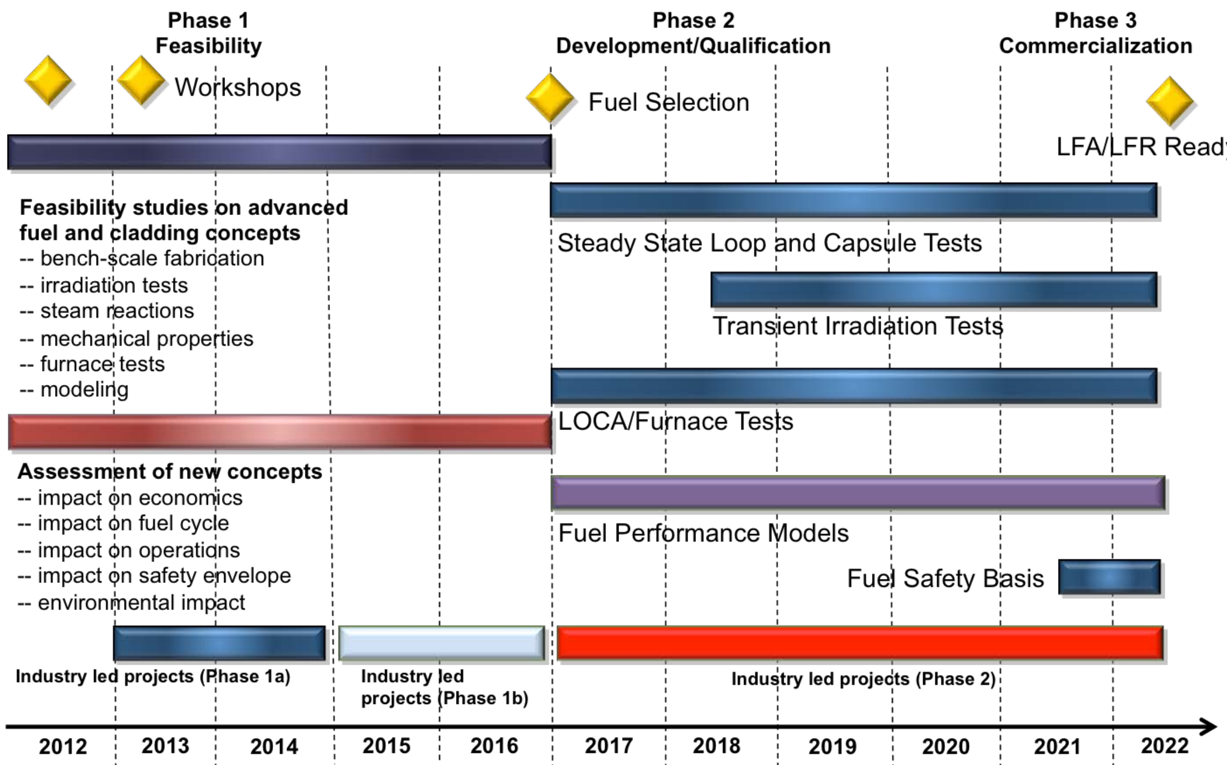

FIGURE 1. Research, development, and demonstration strategy for enhanced accident tolerant fuel development; an estimated timeline for each phase is included.

Technical Performance Evaluation of ATF Concepts

A technical evaluation methodology is proposed within the U.S. to aid in the optimization and prioritization of candidate ATF designs. A complete description of the proposed metrics and associated sensitivity studies is provided in Bragg-Sitton et al. [2]. This methodology is also being used as a starting point for a similar international document that will be produced by the Nuclear Energy Agency (NEA) Expert Group on Accident Tolerant Fuel for LWRs (established in 2014 under the NEA Nuclear Science Committee). As used herein, "metrics" describes a set of technical bases used to objectively evaluate multiple concepts relative to a common baseline and one another.

The metrics are designed for application at any stage in the concept development to assess the ability of each concept to meet performance and safety goals relative to the current UO_2 – zirconium alloy system, although application of such a review process becomes more direct and the results increase in fidelity as more performance data and material properties become known through testing and characterization. Evaluation of anticipated benefits will be based on existing characterization and test data as well as reasonable extrapolations of that data based on modeling and simulation. Potential vulnerabilities will also be assessed based on known or anticipated operational vulnerabilities; the evaluation also considers development risk to be vulnerability early in the development process when important performance parameters are not yet measured or fabrication processes at-scale are not yet developed. Application of the metrics to multiple concepts supports development of a prioritized set of candidate accident tolerant fuel systems, such that the most promising option(s) can continue to be developed.

ATF Characterization and Testing Overview

To fully characterize a material for its potential performance under LWR operating and accident conditions, a number of properties must be measured and characterized for their evolution under the temperature, chemistry, and irradiation environment characteristic of the intended application environment (e.g. a pressurized or boiling water water [PWR or BWR] in the current program). For some of the materials of interest significant data may already be available, whereas for more revolutionary concepts a significant number of characterization activities may be required before moving to more complex and expensive tests.

Performance under the full range of performance regimes that the fuel system will experience must be well understood. These regimes include fabrication (and handling), normal operating conditions, design basis accident (DBA) conditions, severe accident or beyond DBA conditions, and end-of-life storage, transportation, and disposition. Determination of fabrication potential for a given concept includes assessment of compatibility with large-scale fabrication needs, including material availability and potential for quality control, and evaluation of the welding or sealing behavior for cladding materials. Known (or predicted, if necessary) properties of materials will be used to assess the anticipated neutronic performance of the fuel system design using a number of analysis tools, as described in the Phase 1 development activities below.

A series of out-of-pile tests is performed for each fuel and cladding concept to develop a database of pre-irradiation properties. Such characterization includes measurement of thermo-mechanical properties over the range of anticipated operating temperatures (thermal conductivity, ductility, strength, hermeticity, thermal expansion); corrosion behavior under nominal LWR environments and upon exposure to high temperature steam (including the potential for hydrogen production and subsequent embrittlement); and chemical compatibility (with fuel, coolant, and other fuel assembly components). Specific out-of-pile tests for corrosion typically include short-term and long-term autoclave exposure under selected water and steam conditions. A series of mechanical tests is also conducted (e.g. tensile, creep, burst, thermal cycling), with conditions selected to characterize performance under both normal operating conditions and accident conditions.

A detailed overview of the irradiation testing program for ATF is provided in reference [3]. This test program is being conducted in four phases for test reactor irradiation: 1) ATF-1 drop-in capsule testing in the Idaho National Laboratory (INL) Advanced Test Reactor (ATR), 2) ATF-2 loop testing in ATR and ATF-H-x loop testing in the Halden Reactor, 3) ATF-3 transient testing of fuel rodlets (from the ATF-2 series) in the Transient Reactor Test (TREAT) facility, and 4) ATF-4 transient testing of fuel rods from the commercial power plant irradiated LFR/LFA program in TREAT. The irradiation test series for the commercial power plant irradiations (CM-ATF-x) is included as a separate "phase" that will be conducted by a utility partner and requires approval from the Nuclear Regulatory Commission (NRC). Each phase is a series of irradiation experiments conducted to meet specific objectives. More detail on each of the four phases of the irradiation testing program can be found in references [3-5]. The ATF-1 test series is considered a part of the Phase 1 Feasibility Assessment; ATF-2, ATF-H-x, and ATF-3 are a part of Phase 2 Development and Qualification; CM-ATF-x and ATF-4 (and beyond) are initiated as the final step in Phase 2 and continue into the Phase 3 Commercialization activities. It should be noted that the TREAT facility is

PHASE 1: FEASIBILITY ASSESSMENT AND PRIORITIZATION

Feasibility assessment focuses on obtaining data from initial small-scale and phenomenological testing in order to conduct an informed concept prioritization. This work includes activities such as: laboratory scale experiments, e.g., fabrication, preliminary irradiation, and material properties measurements; fuel performance code updates for specific concepts, applying measured property and behavior data; and analytical assessment of economic, operational, safety, fuel cycle, and environmental impacts. Fuel performance codes are used during this phase to the degree the relevant fuel and cladding property measurements and/or models are available for the various concepts. Analytical assessments are performed to evaluate promising concepts against the defined attributes for ATF. A primary goal of Phase 1 is the elimination of infeasible or impractical concepts and ultimate selection of a subset of the most attractive candidates to carry forward.

Within the DOE ATF development efforts, collaboration between DOE, the nuclear industry, utilities, and others, including the international community, has been an important first step. Phase 1, led by DOE, includes formation of teams made up of the nuclear industry/utilities, national laboratories, universities, and international partners. These teams have worked in close coordination since the program was initiated to develop and evaluate a large number of fuel concepts.

Phase 1 Analysis

Analysis of proposed fuel and cladding concepts must be conducted using a number of different tools to evaluate potential performance under normal operating conditions, anticipated operational occurrences (AOOs), and DBAs, and prediction of possible behavior under BDBAs. It is also necessary to assess the possible magnitude of enhanced accident tolerance offered by a proposed concept. Analysis tools rely on availability of experimental data to properly model the performance of the candidate materials under each of the modeled scenarios. In many cases, only limited data is available for proposed fuels and cladding materials, or on the interaction between fuel and cladding or cladding and coolant. Hence, some analyses must apply approximations and assumptions early in the development stage before data becomes available. These approximations result in increased uncertainty in the predicted performance until improved data become available.

A major focus of the Phase 1 feasibility/scoping analysis activities is to evaluate the impact of a proposed fuel and cladding concept on reactor performance and safety characteristics. Assessments include assembly and core analyses to determine impacts on burnup/cycle length, reactivity coefficients and control worths, and transient analyses for selected accident scenarios. The analysis approach and summary of results for specific concepts are provided in various reports [6-11]. The best available material properties are used in the screening analyses, but it is noted that material properties of candidate fuel and cladding materials depend on radiation damage, fraction of cold working, temperature, and other conditions. These dependencies may be unknown or have significant uncertainty for proposed novel candidate fuel or cladding materials, resulting in significant uncertainty in the predicted performance early in the concept development.

Phase 1 Irradiation, ATF-1: Drop-in Capsule Irradiation

The ATF-1 test series focuses on investigating the performance of a wide variety of proposed ATF concepts under normal LWR operating conditions. Data generated in this test series will be used to assess the feasibility of certain aspects of proposed ATF concepts, as well as provide information to support screening among concepts. Initiated in February 2015, the ATF-1 test series is performed as a series of drop-in capsule tests irradiated in the INL ATR.

Fuel rodlets are isolated from the ATR primary coolant in the ATF-1 design by a secondary capsule filled with an inert gas, such that the cladding of the test rodlets is not in contact with water coolant during irradiation. Thus, the ATF-1 test series investigates the irradiation behavior of new fuels (i.e., pellets/compacts) and their interaction with the cladding; however, ATF-1 is not designed to assess the interaction of the cladding with water coolant. The ATF-1 test series is employed to obtain fuel behavior and fuel-cladding interaction data to further characterize candidate materials and to inform the prioritization of fuel system concepts to carry into the next (much more expensive) phase of the irradiation testing program (i.e., ATF-2). ATF-1 is intended as an early screening evaluation experiment series.

A summary of the test article design and rodlet materials included in the ATF-1 test series are provided in references [5] and [12]. The initial set of 19 ATF-1 rodlets were provided by AREVA, Westinghouse, GE, and ORNL. An additional 31 rodlets are being prepared for ATF-1, Phase 1B, to be inserted during ATR cycle outages in 2016; these rodlets will be provided by ORNL, LANL, Westinghouse, AREVA, and AREVA/EPRI. Three ATF-1 rodlets have been removed for post irradiation examination to date.

PHASE 2: DEVELOPMENT AND QUALIFICATION

During this phase, the fabrication process will expand beyond bench-scale, and fabrication of lead fuel rods or assemblies (LFRs or LFAs) will occur. Requirements for LFA/LFR testing will be established during the development phase. If the assembly design differs substantially from that of currently used UO_2 – zirconium alloy assemblies, the qualification will likely require testing of a full assembly. If the assembly design is similar to that of the current design, a few LFRs incorporated into a fuel assembly containing UO_2 – zirconium alloy rods may be sufficient for qualification.

Test reactor irradiation using long rodlets (about 36-inch-long [91-cm] fuel column) will provide data on fabrication variations, temperature variations, and linear heat-rate limits. Characterization, post-irradiation examination (PIE), and the development of a fuel performance code will be part of the qualification process. Sufficient testing must be completed to establish the statistical database of performance data. By 2018 a transient irradiation testing capability in a water loop will also need to be established. Transient experiments on unirradiated and pre-irradiated rodlets will begin in the 2018 timeframe to establish fuel-failure modes and failure margins.

At the end of this phase, LFRs or LFAs will be fabricated and the safety basis for irradiation in a commercial reactor will be established. The irradiation and subsequent PIE of the LFRs/LFAs will complete the demonstration phase for LWR fuels with enhanced accident tolerance. Due to the time required for irradiation and PIE, the characterization of the LFRs/LFAs will not be conducted until after the timeframe shown in Figure 1.

Phase 2 Analysis

During Phase 2, the characterization and performance data collected via out-of-pile and in-pile testing will be applied to develop and validate concept-specific behavioural models that will be necessary to perform detailed fuel performance and core-level analyses for normal and off-normal conditions at higher fidelity (reduced uncertainty) than the scoping analyses that were performed using existing tools and models in Phase 1. The enhanced behavioral models will be applied in a more detailed system analysis intended to evaluate specific concepts under normal and postulated accident conditions with a reduced uncertainty relative to what was possible earlier in the development. Calculations at this stage should enable quantitative estimation of the “coping time” under a reference severe accident scenario, where coping time is defined as the time, after onset of accident conditions, to significant loss of geometry of the fuel assemblies such that the reactor core can no longer be cooled or the fuel cannot be removed from the reactor using standard tools and procedures. Results of this analysis will provide input on the degree of accident tolerance of a particular concept and will support the decision to proceed (or not proceed) to LFR irradiation.

Phase 2 analysis activities will also include a more detailed constraints analysis. This analysis will assess the anticipated economics associated with the proposed fuel system (covering the complete fuel life cycle); challenges to fuel fabrication, with particular interest given to the required fuel enrichment determined by neutronics analysis; and potential fabrication challenges that could arise when ramping up production to the scale (e.g. cladding length) and quantities necessary for full-scale deployment in the operating LWR fleet. Constraints associated with handling, storage, transportation and disposal of used fuel will also be addressed. Preliminary engagement of regulators will occur in parallel with Phase 2 to aid future licensing activities.

Phase 2 Irradiation Testing, ATF-2 and ATF-H-x: Loop Testing

Following the Phase 1 feasibility assessments and drop-in capsule test (ATF-1) irradiation, the ATF-2 test series will take the most promising concept(s) into loop testing in the ATR. In the ATR loop, experimental ATF rods will be in direct contact with high-pressure water coolant with active chemistry control to mimic the conditions of PWR primary coolant [13]. In addition to continuing the investigation of fuel behavior and fuel-cladding interaction initiated in ATF-1, the ATF-2 experiment series will include cladding-coolant interaction. ATF-2 will be the most prototypic irradiation test possible in the ATR to assess the performance of ATF concepts under normal LWR operating conditions. ATF-2 testing in the ATR under PWR conditions is currently planned to begin in mid-2017. Testing in the Halden Reactor loop, which is currently in discussion, will allow testing of fuel and cladding concepts under BWR coolant conditions. This test series will be designated ATF-H-x. The Halden reactor loop test series and requirements are currently being defined by AFC and Industry project leadership.

It is desirable to have real-time data collection for some of the fuel rodlets during the ATF-2 irradiation. The primary parameters of interest for on-line measurement are centreline temperature, fuel and cladding elongation, and fission gas pressure. Additional pressure and fuel elongation measurements can be made during ATR outages. A sensor qualification test (SQT) will be performed prior to the fuelled test to validate sensor functionality under ATR loop operating conditions. Details of the instruments to be included in the SQT are provided in Barrett et al. [14]. To ensure that the selected instrumentation will operate properly in the ATR environment, a flowing-loop out-of-pile autoclave test will be conducted in late 2016 or early 2017, which will run for approximately 2 weeks. This test will also allow for evaluation of cable routing and potential effects of vibration and/or fretting during the test. The autoclave test will be followed by an in-pile SQT of the most promising candidate sensors.

The ATF-2 test series will produce a significant number of irradiated fuel rods. Many of the irradiated fuel rods will be subjected to comprehensive non-destructive and destructive post-irradiation examination (PIE). However, a substantial portion of these irradiated fuel rods will only be examined non-destructively, such that they can be carried over to be prototypic test articles in the next phase of the irradiation testing program (ATF-3). Irradiated fuel rods from this test series could also be used for out-of-pile experiments to simulate LOCAs.

Phase 2 Irradiation Testing, ATF-3: Transient Testing

The ATF-3 test series will take the most promising concept(s) from ATF-2 into testing in the Transient Reactor Test (TREAT) facility at INL. After operating for 35 years, the TREAT facility was placed in operational standby in 1994 due to reductions in the domestic Sodium Fast Reactor programs. The facility is currently being refurbished for restart following a February 2014 decision. For more information on the TREAT facility, see Woolstenhume et al. [15] for more details on the preparation of TREAT to support Phase 2 irradiation testing.

In TREAT, experimental ATF rods will be subjected to reactivity-initiated accident (RIA) scenarios to investigate their integral performance under this class of accident conditions. It is anticipated that this phase of testing will begin with fresh (unirradiated) fuel rodlets/rods to assess performance under a beginning-of-life (BOL) scenario and progress to the irradiated fuel rodlets/rods of multiple burnup levels obtained from the ATF-1 and ATF-2 test series. The ATF-3 experiment series is currently in the design phase, which will continue over the next few years.

PHASE 3: COMMERCIALIZATION

The synergistic relationship between fuel vendors and the U.S. DOE national laboratories allows vendors to play the essential role in bridging a fuel technology through the regulatory and technical requirements for insertion in a domestic power reactor necessary for Phase 3 commercialization. The vendors, however, require both the technical expertise and advanced equipment within the national laboratory complex to provide the earlier (Phase 1 and 2) development and performance data required to mature a concept to the point that it can be presented to a regulator. The commercialization phase entails the establishment of commercial fabrication capabilities and the conversion of LWR cores to the new fuel. This phase will primarily be a commercial activity performed by industry. However, it is noted that DOE expects to continue to interact with the industry teams to support LFR characterization following irradiation and to conduct transient testing of fuel rods that have been pre-irradiated in a commercial reactor.

Irradiation Testing: CM-ATF-x and ATF-4: Transient Testing of LFRs

The CM-ATF-x test series will be conducted at a commercial power reactor facility. This test series requires leadership from an industry (vendor) team working in close coordination with a utility partner to define the LFR/LFA configuration and to gain NRC approval for the irradiation. Preparation for this test series will require ample time for the involved parties, with initial planning and discussions beginning two to three cycles (up to 4.5 years) in advance of the planned insertion date.

The ATF-4 test series assumes that the irradiation of ATF concept(s) in a commercial LWR as part of an LFR/LFA program begins in 2022 (via the test series designated CM-ATF-x). The logical final phase of the irradiation test program is to subject a subset of LFRs to transient testing in TREAT. Since LFRs will be much longer than can be accommodated in TREAT, either shorter, segmented rods will need to be included in the LFR/LFA program or a sectioning/remanufacturing capability will be needed in the PIE facility in order to prepare appropriate test rods for TREAT. As in the ATF-3 test series, it is anticipated that this phase of testing will begin with fresh (unirradiated) fuel rods, fabricated by the same vendor and process as used for the LFRs, to assess performance under a BOL scenario and progress to irradiated LFR segments of multiple burnup levels.

OVERVIEW OF RECENT ATF DEVELOPMENT ACTIVITIES

The U.S. DOE program is currently nearing the end of Phase 1 feasibility assessment activities. During this phase, the investigation of a number of technologies that may improve fuel system response and behavior under accident conditions has been conducted. The U.S. DOE AFC continues to sponsor multiple teams within national laboratories, universities, and the nuclear industry who are developing and testing fuel and/or cladding concepts. The technologies investigated during Phase 1, and the teams conducting that R&D, are summarized in Table 1. ATF concepts are also being investigated internationally, with growing programs in Europe, Japan, South Korea, and China. In many cases, the materials selected for ATF development are similar across each of these programs. Some of the technologies undergoing collaborative international development include enhanced UO_2 fuels, fully ceramic microencapsulated (FCM) fuel, FeCrAl steel cladding, and SiC cladding concepts. The OECD/NEA Expert Group on ATF for LWRs is currently working to produce state-of-the-art reports on ATF fuel and ATF cladding materials that are under development by the NEA member countries to summarize their state of development, testing and/or development needs, and associated development risks. These reports are expected to be complete in mid to late 2017.

TABLE 1. Summary of ATF fuel and cladding materials investigated in Phase 1 activities.

Lead Organization	**Category – Major Technology Area**	**Additional Collaborators**
Industry-Led Teams		
AREVA	**Fuel:** High conductivity fuel (UO_2+Cr_2O_3) **Cladding:** Coated Zr-alloys (protective materials, MAX phase), Advanced molybdenum alloys (multi-layer design)	U. Wisconsin, U. Florida, SRNL, TVA, Duke, EPRI, LANL
Westinghouse	**Fuel:** U_3Si_2 fuel **Cladding:** Coated Zr-alloy; SiC concepts	General Atomics, EWI, INL, LANL, MIT, TAMU, National Nuclear Laboratory (UK), Paul Scherrer Institute, Ceramic Tubular Products, Southern Nuclear Operating Company
GE Global Research	**Cladding:** Advanced Steel (Ferritic / Martensitic, including FeCrAl)	Global Nuclear Fuels, LANL, ORNL, U. Michigan
Laboratory-Led Teams		
Oak Ridge National Laboratory	**Fuel:** Fully Ceramic Microencapsulated (FCM)-UO_2; FCM-UN **Cladding:** FeCrAl alloy; silicon carbide (SiC)	LANL, INL support FeCrAl weld development work
Los Alamos National Laboratory	**Fuel:** Enhanced UO_2, Composite Fuels	
University-Led Teams		
University of Illinois *(project complete)*	**Cladding:** Modified Zr-based cladding (coating or modification of bulk cladding composition)	U. Michigan, U. Florida, INL, U. Manchester, ATI Wah Chang **UK contributions
University of Tennessee *(project complete)*	**Cladding:** Ceramic Coatings for Cladding (MAX phase; multilayer ceramic coatings)	Penn State, U. Michigan, UC Boulder, LANL, Westinghouse, Oxford, U. Manchester, U. Sheffield, U. Huddersfield, ANSTO **UK and Australian contributions

Industry Team: AREVA Federal Services, LLC

The AREVA-led team, comprised of the U.S. utilities Tennessee Valley Authority and Duke Energy, the University of Wisconsin, the University of Florida, and Savannah River National Laboratory, has been working on the first phase of this project since 2012. The team has evaluated promising technologies that would provide nuclear power plant operators more time to manage an accident situation, including coatings on Zirconium cladding and additives to uranium pellets, as well as modifications to coolant loops. The team is building on previous fuel development work within AREVA while also investigating concepts that offer incremental performance improvements. Pellets with several additives were manufactured at the University of Florida, shipped to INL, and inserted in the INL ATR to begin ATF-1 irradiation in February 2015.

Industry Team: General Electric Global Research

With a team including Global Nuclear Fuels, the University of Michigan, Los Alamos National Laboratory, and Oak Ridge National Laboratory, GE Global Research is conducting R&D activities to demonstrate that ferritic/martensitic alloys can provide enhanced accident tolerance as fuel cladding materials for current LWRs. In addition, the use of these materials is expected to maintain or increase the periods between refuelling and to improve the behavior of the fuel bundle under severe accident scenarios, such as a loss-of-coolant accident (LOCA). It is expected that the iron-based and chromium containing candidate materials will have much slower reaction kinetics with steam than the current zirconium-based alloys used in nuclear fuel cladding at temperatures associated with LWR accident conditions.

Industry Team: Westinghouse Electric Company, LLC

The Westinghouse team is comprised of General Atomics, Edison Welding Institute, Southern Nuclear Operating Company, Massachusetts Institute of Technology, Texas A&M University, Los Alamos National Laboratory, and Idaho National Laboratory. This team is conducting a series of tasks to identify, produce, and test the technical and economic feasibility of a variety of near-term and longer-term ATF concepts. Concepts under consideration include both advanced cladding and advanced fuel. Cladding research includes both evolutionary concepts, such as coated Zirconium alloys, and revolutionary concepts, such as those based on silicon carbide (SiC) and SiC ceramic matrix composites. Fuel research focuses on high density/high thermal conductivity fuel pellets, such as uranium silicides and uranium nitride/uranium silicides.

Independent Technical Review

An independent Technical Review Committee (TRC) was established in 2015 to provide review and evaluation of proposed fuel systems investigated during Phase 1. The committee is comprised of technology experts selected based on their knowledge of the technologies under review, reactor operations, and fuel fabrication plant operations. The cross-section of experts includes experience in the areas of materials (metals and ceramics), neutronics, thermal-hydraulics, and severe accidents to enable assessment of the technology feasibility for near-term development of the ATF design concepts. The TRC has reviewed industry and national laboratory concepts based on existing performance data; potential benefits and vulnerabilities, including development risk; and their potential to meet near-term goals for LFR/LFA insertion in a commercial reactor. Concepts requiring a longer time for development were not omitted from consideration, but were instead evaluated in parallel to the near-term concepts. As such, the TRC discussed potential prioritization of concepts within two categories – near-term, capable of meeting the LFR/LFA goal of 2022, and long-term, having the potential for significant performance benefits but not capable of meeting the LFR/LFA goal. TRC input was provided to the U.S. DOE Program Managers to inform the selection of Phase 2 concepts for development by the Industry teams. Information on Phase 2 R&D that will be conducted by Industry teams will be available in Fall 2016.

CONCLUSION

The U.S. DOE ATF development teams are nearing the end of Phase 1 and are now preparing to enter the more rigorous irradiation testing and associated modeling activities defined for Phase 2. In doing so, the number of concepts being investigated will necessarily be reduced to ensure sufficient funding to support the fabrication, testing, and modeling activities that will be required through Phase 2. The U.S. DOE program will continue to support the development of near-term ATF concepts by Industry, in coordination and collaboration with the national laboratories, and the development of selected longer-term ATF concepts as funding allows.

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