DRAFT: Accident Tolerant Fuels Implementation Plan

Fuel Cycle Research & Development

Prepared for U.S. Department of Energy

Advanced Fuels Campaign

September 2015

FCRD-FUEL-2015-000020

INL/EXT-15-36609

Submitted by:

AFC Systems Engineer

Lori Braase	Date

Concurred by:

AFC National Technical Director

Jon Carmack	Date

Approved by:

FCRD Federal Project Manager

Bill McCaughey	Date

EXECUTIVE SUMMARY

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." The Committee further requested that the Department "report to the Committee, within 90 days of enactment of this act, on its plan for development of meltdown resistant fuels leading to reactor testing and utilization by 2020." [1]

In Conference Report 112-331 of the Consolidated Appropriations Act, 2012, H.R., Congress provided $59 million to the Office of Nuclear Energy for "efforts to develop and qualify meltdown-resistant, accident-tolerant nuclear fuels that would enhance the safety of light water reactors."

Since the inception of the focus on Accident Tolerant Fuel (ATF) for Light Water Reactors (LWR), a number of potential ATF technologies have been under fundamental investigation for possible inclusion in a Lead Fuel Rod (LFR) or Lead Fuel Assembly (LFA) irradiation in a U.S. commercial nuclear power plant. It is difficult to generate the necessary irradiation performance data and pedigree for any new nuclear technology to the point that it can be licensed for use in a commercial nuclear power plant, due to the strict safety requirements in place for public safety. Hence, the process for performing the necessary research, development, and data qualification is a rigorous process that has typically taken longer than 10 years to accomplish for even relatively minor changes to technologies.

In the abstract, the research, development, and implementation of a technology for a single-purpose reactor application (i.e. the insertion of a LFR or LFA into a commercial light water reactor) is a relatively straightforward undertaking. Given the significant commercial and nuclear R&D assets native to US national laboratory and industrial sectors, a focused effort on such a technical implementation should be relatively routine. However, the ATF program does not represent the development of a single technology, but the development of a spectrum of technologies of different functions and differing levels of maturity. In some cases the technologies are being developed from a point near application maturity, and in some cases researchers are engaged in discovery science. Moreover, the technologies under development are not only being brought forward by the DOE AFC program, but by an array of national and international universities, corporations and governmental laboratories.

ATF technologies include those that are currently under investigation by the nuclear industry, universities, and national laboratories that are funded in whole or part by DOE. These include the following general class technologies: iron-based cladding, ceramic cladding, coated Zircaloy cladding, molybdenum-based cladding, high density fuel, fully ceramic matrix fuel, and metallic alloy-based nuclear fuel.

Specific technology implementation plans (TIP) or systematic technology evaluation plans (STEP) have been developed for each of the above technologies for execution by the nuclear research and development complex. These plans are summarized and referenced in this document to show the activities that will be conducted primarily by research and development (R&D) institutions in support of the development of specific ATF technologies by industry led projects. Most of the technologies under consideration and described in this document are at technology readiness level (TRL) 1 through 4. According to the TRL definitions described in "Technology Readiness Levels for Advanced Nuclear Fuels and Materials

Development," [1] at the end of this phase of R&D, the technologies would be ready for rod and assembly scale demonstration in a commercial nuclear power reactor.

The ATF Implementation Plan integrates DOE's objectives and goals with the national laboratory's expertise and infrastructure in support of the technology development by three industry partners. DOE's plan is to develop advanced LWR fuels with enhanced accident tolerance in response to the Congressional request and to install a lead fuel assembly containing accident tolerant fuel technology in a U.S. commercial nuclear power plant by 2022. DOE has three contracts in place with each of the principle US commercial nuclear fuel vendors in support of ATF research and development, AREVA Services LLC, General Electric, and Westinghouse LLC.

The purpose of the ATF Implementation Plan is to describe the technology development and progress required to insert one (or possibly two) concepts as a LFR or LFA in a commercial LWR by 2022. In particular, this document shows the integration between the functional documents guiding ATF development and provides a rough order of magnitude estimate of the required budget from FY2016 through FY2022. It is expected that after FY2022, the needed budget request would significantly decrease as works transitions from Phase 2 to Phase 3, corresponding to a decrease in DOE project responsibility and an increase in industry responsibility and associated funding support.

CONTENTS

FIGURES

ACRONYMS

AFC	Advanced Fuels Campaign
AGR	Advanced Gas Reactor
AOO	Anticipated Operational Occurrence
ATF	Accident Tolerant Fuels
ATR	Advanced Test Reactor
BOL	Beginning of Life
DBA	Design Basis Accidents
BDBA	Beyond Design Basis Accidents
DOE	Department of Energy
EPRI	Electric Power Research Institute
FCCI	Fuel Cladding Chemical Interaction
FCM	Fully Ceramic Microencapsulated
FCMI	Fuel Clad Mechanical Interactions
FCRD	Fuel Cycle Research and Development
FCT	Fuel Cycle Technologies
FFRDC	Federally Funded Research and Development Center
FOA	DOE Funding Opportunity Announcement
FR	Fast Reactor
FY	Fiscal Year
HFIR	High-Flux Isotope Reactor
INL	Idaho National Lab
LANL	Los Alamos National Lab
LAR	License Amendment Request
LFA	Lead Fuel Assembly
LFA	Lead Fuel Rod
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
NE	Nuclear Energy
NRC	Nuclear Regulatory Commission
PIE	Post Irradiation Testing
R&D	Research and Development
RD&D	Research, Development, and Deployment
SBIR	Small Business Innovative Research Grants
SiC	Silicon Carbide
TRC	Technical Review Committee
TRISO	Tristructural-isotropic
TRL	Technology Readiness Level
TRU	Transuranic
US	United States

ACCIDENT TOLERANT FUELS IMPLEMENTATION PLAN

1. INTRODUCTION

DOE-NE, in collaboration with the nuclear industry, has been conducting R&D activities on advanced LWR fuels for the last few years. The emphasis for DOE-NE R&D activities was on improving the fuel performance in terms of increased burnup for waste minimization and increased power density for power upgrades, as well as collaborating with industry on fuel reliability.

In 2011, following the Great East Japan Earthquake, resulting tsunami, and subsequent damage to the Fukushima Daiichi nuclear power plant complex, the emphasis shifted to accident performance of fuels under extended loss of active cooling and steam exposure. Subsequently, in Fiscal Year (FY) 2012, Congress included specific language for DOE-NE to initiate the Enhanced Accident Tolerant Fuel (ATF) program for aggressive research development and deployment (RD&D) for LWR fuels with enhanced accident tolerance. The nuclear power industry is focused on continuous improvement and reliable operation, deploying design enhancements to the fuel system (typically small, incremental improvements) as they become available.

The overall goal of ATF development is to identify alternative fuel system technologies to enhance the safety, competitiveness, and economics of commercial nuclear power. The development of an enhanced fuel system supports the sustainability of nuclear power, allowing it to continue to generate clean, low-CO_2-emmiting electrical power in the US. The initial RD&D effort will focus on applications in operating reactors or reactors with design certifications. Advancements made during this process may be applicable to new LWR designs.

Per congressional direction, the development goal is to demonstrate performance by inserting a lead fuel rod (LFR) or lead fuel assembly (LFA) into a commercial power reactor by 2022 with deployment in the US LWR fleet to follow within 20 years. The definition of the LFA will be specified during the development phase. If there are substantial design changes at the assembly level, it is likely that a full assembly populated with the advanced fuel rods may be required. However, the 10-year goal for such a major design change may not be achievable. If the design changes at the assembly level are minimal, a standard assembly with only a few advanced fuel rods may be sufficient for demonstration.

In the abstract, the research, development, and implementation of a technology for a single-purpose reactor application (i.e. the insertion of a LFR or LFA into a commercial light water reactor) is a relatively straightforward undertaking. Given the significant commercial and nuclear R&D assets native to U.S. national laboratory and industrial sectors, a focused effort on such a technical implementation should be relatively routine. However, the ATF program does not represent the development of a single technology, but the development of a spectrum of technologies of different functions and differing levels of maturity. In some cases the technologies are being developed from a point near application maturity, and in some cases researchers are engaged in discovery science. Moreover, the technologies under development are not only being brought forward by the DOE AFC program, but by an array of national and international universities, corporations and governmental laboratories.

The purpose of the ATF Implementation Plan is to describe the technology development and progress required to insert a LFR or LFA in a commercial LWR by 2022. In particular, this document shows the integration between the functional documents guiding ATF development and provides a rough order of magnitude estimate of the budget required to fund the needed activities in the DOE laboratories, industry, and university projects.

1.1 Advanced Fuels Campaign

The *Advanced Fuels Campaign (AFC) Execution Plan* [4] outlines the strategy, mission, scope, long-term and near-term goals, structure, and management associated with nuclear fuels and materials RD&D activities within the Fuel Cycle Research and Development (FCRD) program. AFC has been given responsibility to develop advanced fuel technologies for DOE using a science-based approach focused on developing a fundamental understanding of nuclear fuels and materials. The science-based approach combines theory, experiments, and multi-scale modeling and simulation to achieve predictive understanding of the fuel fabrication processes and fuel and clad performance under irradiation (in contrast to more empirical observation-based approaches traditionally used in fuel qualification).

The traditional scope of AFC includes evaluation and development of multiple fuel forms to support two fuel cycle options: Once-Through Cycle and Full Recycle. The word "fuel" is used generically to include fuels, targets, and their associated cladding materials. The once-through fuel cycle addresses advanced light water reactor (LWR) fuels with enhanced performance and reduced waste generation. In FY-2012, AFC's scope was expanded to include RD&D for LWR fuels with enhanced accident tolerance. AFC is responsible for evaluating new concepts for accident tolerant LWR fuel and cladding technologies. Any new fuel concept proposed for enhanced accident tolerance under rare events must comply with current operational, and safety constraints, as well as fuel cycle impacts and current LWR design constraints.

There are currently a number of ATF concepts and potential technologies that are being investigated by industry, academia, DOE national laboratories and the international community. Each concept must be systematically evaluated to gauge its ability to meet performance and safety goals relative to the current UO_2 – zirconium alloy system. Assessments of a number of performance attributes within each performance regime will be used to rank the expected performance and potential vulnerabilities of each of these concepts relative to the baseline UO_2 – Zirconium alloy system. Performance regimes considered include fabrication, normal operation and anticipated operational occurrences (AOOs), design basis accidents (DBAs), severe accidents (beyond DBAs, BDBAs) and used fuel storage, transportation and disposition.

1.2 Accident Tolerant Fuel

Fuels with enhanced accident tolerance are those that, in comparison with the standard UO_2-zirconium alloy fuel system currently used by the LWR industry, can tolerate loss of active cooling in the reactor core during design-basis and beyond design-basis events for a considerably longer time period (depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations and operational transients. To mitigate or reduce the consequences of fuel failure at elevated temperatures with steam exposures, the following issues must be considered along with the attributes in Figure 1.

- **Improved Reaction Kinetics with Steam** – When exposed to high temperature steam, the current zirconium alloy cladding experiences rapid oxidation and an associated exothermic reaction, which increases the clad temperature even further during the oxidation phase.
- **Improved Cladding Properties** – When exposed to steam at high temperatures, there are multiple issues that need to be considered, including clad failure (fracture) and/or melting, thermal-shock

resistance during emergency coolant injection (reflood), and ballooning (loss of coolable geometry).

- **Improved Fuel Properties –** Under accident conditions, the potential for fuel melting and relocation, as well as fuel dispersion into the coolant, must be addressed. Attributes associated with the accident tolerance of a given fuel are fuel clad chemical interactions (FCCIs) and fuel clad mechanical interactions (FCMIs), as well as the stored (sensible) heat during normal operations before the initiation of the accident.

- **Enhanced Retention of Fission Products –** In the case of cladding failure, the primary concern is retention of both gaseous and solid fission products within the vessel to minimize releases to the environment. While total retention may not be possible, even partial retention (especially for highly mobile fission products) would be a substantial improvement.

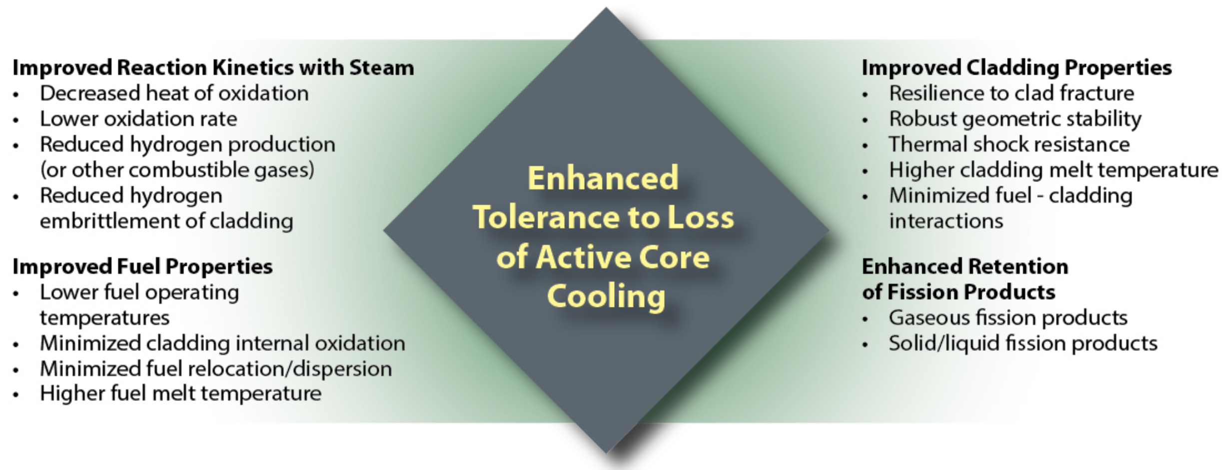

Figure 1. Key considerations in establishing accident tolerant fuel attributes.

These fuel and cladding attributes provide qualitative guidance for parameters that must be considered for fuels with enhanced accident tolerance. It is not likely, and possibly not necessary, to improve in all the attributes. It is more likely that some attributes provide marginal benefits, while others may provide meaningful gains in accident tolerance. In addition, it is more likely that a combination of certain attributes would be necessary to achieve the desired gains. Thus, the next step in the program implementation is the development of quantitative metrics.

1.3 ATF Evaluation Metrics

The ATF program is in the early phases of research and development, supporting the investigation of a number of technologies that may improve fuel system response and behavior in accident conditions. DOE is sponsoring multiple teams to develop ATF concepts within national laboratories, universities, and the nuclear industry. These concepts offer both evolutionary and revolutionary changes to the current nuclear fuel system. Mature concepts will be tested in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL). The research team is simultaneously developing a set of technical evaluation metrics to support prioritization of ATF concepts in FY 2016.

A common set of technical evaluation metrics is required to aid in the optimization and prioritization of candidate designs on a more quantitative basis. Due to the complex multiphysics behavior of nuclear fuel and the large set of performance requirements that must be met, evaluation metrics proposed in *FCRD*

AFC Light Water Reactor Accident Tolerant Fuel Performance Metrics Report, 2014 [3] describe a technical methodology for concept evaluation rather than establish specific quantitative targets for each property or behavior.

An independent technical review committee (TRC) will be established to review the ATF concepts under development. This team will be composed of technology experts selected based on their knowledge of the technologies under review, including materials (metals and ceramics), neutronics, thermal-hydraulics, and severe accidents. Candidate designs will be evaluated for their relative benefits or vulnerabilities (development or performance risks) across relevant performance regimes, including:

1. Fabrication/manufacturability (to include the ability to license)
2. Normal operation and anticipated operational occurrences
3. Postulated accidents or design basis accidents (DBAs)
4. Severe accidents or beyond design basis accidents (BDBAs)
5. Used fuel storage/transport/disposition (to include potential for future reprocessing).

The proposed technical evaluation methodology will result in a ranked, prioritized list of candidate ATF designs based on estimated benefits and remaining gaps or vulnerabilities that must be addressed via performance characterization or design modifications. The review panel may choose to develop two ranked lists: one for near-term technologies, fitting within the defined 10-year development window (to meet the 2022 deadline for LFR insertion in a commercial reactor), and a second for longer-term technologies that appear to offer a significant benefit at this early development stage but are unlikely to meet the desired development timeframe. Prioritization using a ranked evaluation will enable the continued development of the most promising ATF design options given budget and time constraints.

Figure 2. ATF will be evaluated over all potential "performance regimes."

1.4 Constraints

The impact of new fuels on the front- and back-end of the fuel cycle must be carefully assessed within the framework of current and future regulations and policies. Some of the fuel-cladding systems considered require higher enrichment than current fuels. For instance, if an advanced stainless steel cladding replaces Zirconium, the enrichment penalty would be 1 to 2% if no other changes are made to the fuel-cladding system. On the other hand, the very robust fuel forms with multiple layers of containment and fission-product barrier (e.g., microencapsulated fuels) could require enrichment up to the low-enrichment limit (low-enriched uranium < 20%) if they are not coupled with cladding modification. In addition to the economic penalty, higher enrichments would result in lower uranium utilization and would have a major impact on the current enrichment plants.

A new fuel system could also have an impact on the back-end of the fuel cycle. The storage (wet and dry) and repository performance of the fuel (assuming a once-through fuel cycle policy continues) must not be degraded; otherwise, engineering solutions must be augmented during storage and disposal. Over the long term, U.S. policy changes to transition to a closed fuel cycle with reprocessing and recycling would require evaluation of the impact of the new fuel form on reprocessing.

1.5 Goals

As described in the AFC ATF Metrics document [3], a three-phase approach has been adopted to commercialize new accident tolerant fuels (Figure 3). Within Phase 1 a concept undergoes preliminary evaluation including modeling, initial fabrication and property evaluation. 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. These assessments include: laboratory scale experiments, e.g., fabrication, preliminary irradiation, material properties measurements; fuel performance code updates; and analytical assessment of economic, operational, safety, fuel cycle, and environmental impacts. In Phase 2, a specific fuel pedigree is chosen and its fabrication processes are expanded to industrial scale for LFRs and LFAs. Within this phase, a complete performance database is established, including both non-irradiated and irradiated properties, to support modeling activities and the eventual fuel licensing efforts. Finally, Phase 3 establishes the ultimate goal of commercial fabrication capabilities embracing complete technology transfer between the national laboratory complex and the commercial fuel vendor and vigorous interaction with the appropriate regulatory authorities. Within this phase the final fuel form produced to commercial specifications is irradiated at prototypic conditions. Each development phase roughly corresponds to the TRLs 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." [2]

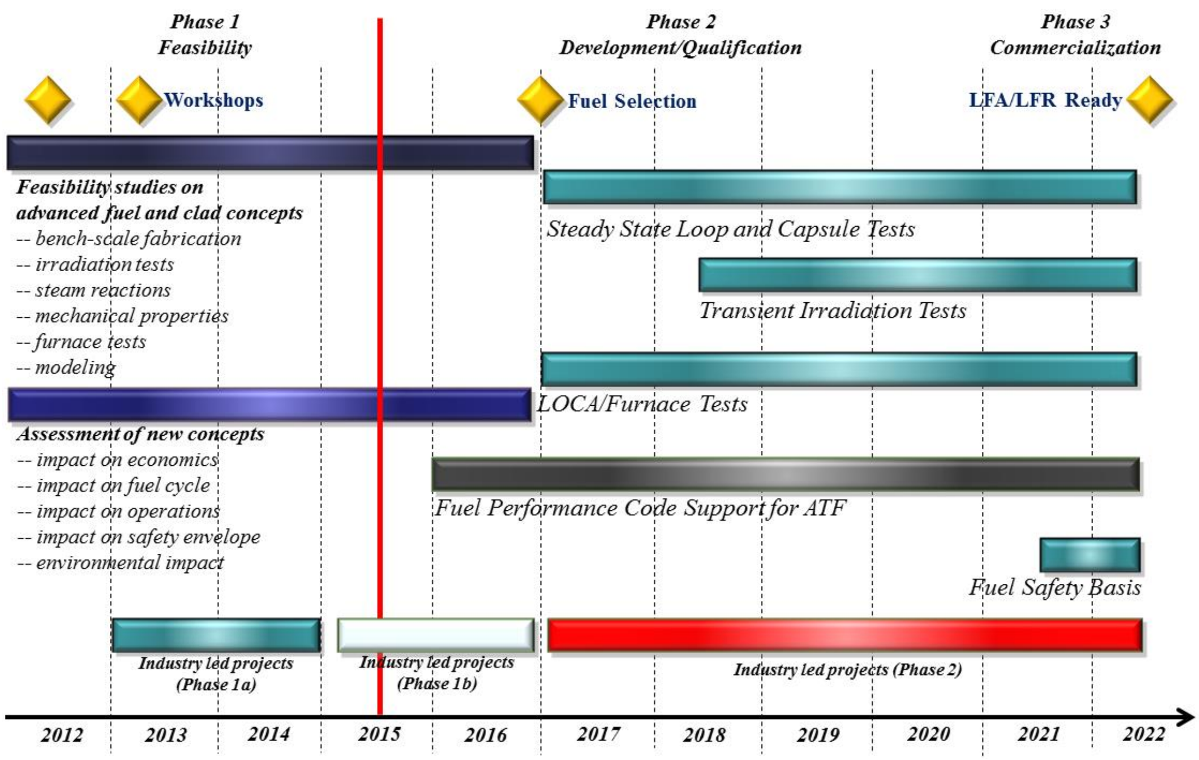

Figure 3. RD&D Strategy for Enhanced Accident Tolerant LWR Fuels.

The metrics utilized to evaluate a particular ATF concept and the TRL criteria by which the maturity of the concept is expanded are described in subsequent sections of this document; the concept-specific technology roadmaps are also included. The ultimate goal of the DOE-NE led ATF program is to first identify likely advanced fuel and cladding concepts and then mature those technologies, through a dedicated R&D program in collaboration with industry, to the point at which a specific technology can be transferred to the private sector. This document provides the structure and approach AFC takes to achieve that goal.

1.6 Nuclear Energy ATF Roadmap

The Senate Appropriation Committee Report (Senate Report 112-75) that accompanied the Fiscal Year 2012 Energy and Water Development Appropriations Bill, recommended that the Department of Energy, Office of Nuclear Energy "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." This report went on to stress 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." To better understand the planned activities in this area the Committee requested that the Department "report to the Committee, within 90 days of enactment of this act, on its plan for the development of meltdown resistant fuels leading to reactor testing and utilization by 2020."

In compliance with this request a document was submitted on the "Development of Light Water Reactor Fuels with Enhanced Accident Tolerance" as a *Report to Congress* Dated April 2015 [1]. That report describes the Phased-flow of Figure 1 and describes the key attributes of an ATF fuel system, specifically:

1. **Hydrogen Generation Rate.** Hydrogen buildup in the reactor vessel during a beyond design-basis event can lead to energetic explosions as seen in the Fukushima events. Under a high-temperature steam environment, it is not possible to totally avoid hydrogen generation. Rapid oxidation of cladding results in free hydrogen generation. This exothermic reaction further increases the cladding temperature, which further accelerates free hydrogen generation. A related issue is the diffusion of free hydrogen into the unoxidized portion of the cladding, resulting in enhanced embrittlement and potential cladding failure. A desired alternative would be a cladding material that resists oxidation or reduces the rate of oxidation, therefore resulting in a reduced hydrogen gas generation rate. Materials with lower heat of oxidation may also be important in reducing the amount of cooling required during accident conditions.

2. **Fission Product Retention.** Zircaloy cladding provides the initial barrier to release of fission products in nuclear fuel. Upon cladding failure, retention of the fission products within the vessel is required to minimize releases to the environment. This includes both gaseous and solid fission products. Due to the potential severity of fission product release to the environment, retention within the fuel is of the utmost importance. While total retention may not be possible, even partial retention (especially for highly mobile fission products) would be a substantial improvement. The desired improvement would be to prevent melting or dispersion of the fuel by utilization of high temperature/strength materials. Additionally, fission product retention techniques or chemically linking the fission products in a fuel matrix may be options, as long as the concepts can tolerate high temperatures. Building additional barriers around the fuel to contain fission products (as a backup to containment provided by the cladding) also may be envisioned. An example for this concept is microencapsulated fuels.

3. **Cladding Reaction with Steam.** When exposed to steam at high temperature, there are multiple issues that need to be considered. As previously stated, the high temperature steam interaction with fuel cladding causes an exothermic oxidation reaction and resulting hydrogen generation. In addition, this reaction deteriorates the structural integrity of the cladding possibly resulting in fission product release into the reactor vessel. The design option would be to develop cladding

materials with enhanced tolerance to radiation and oxidation under high-temperature exposure while specifically considering mechanical strength and structural integrity at the end of life and when exposed to high-temperature steam for an extended duration.

4. **Fuel Cladding Interactions**. In the event of cladding failure, fuel behavior is important. The issues are fuel melting and relocation, as well as fuel dispersion into the coolant. Fuel Cladding chemical interactions (FCCIs), fuel cladding mechanical interactions (FCMIs) and fuel heating are important properties that must be understood during normal operation and accident conditions. The design option would be to develop fuels with reduced FCCI and FCMI and with lower operating temperatures. Higher melting point and structural integrity at high temperatures (i.e. less dispersive) are also desired improvements.

The Nuclear Energy ATF Roadmap goes on to discuss the need to gauge the viability of ATF concepts against each other and to determine whether a concept has the potential to meaningfully impact reactor coping time in the event of an accident. The ATF Roadmap discusses the application of metrics in the following manner:

> *To demonstrate the enhanced accident tolerance of candidate fuel designs, metrics must be developed and evaluated using a combination of design features for a given LWR design, potential improvements, and the design of an advanced fuel/cladding system. The aforementioned attributes provide qualitative guidance for parameters that will be considered for fuels with enhanced accident tolerance. It may be unnecessary to improve in all attributes and it is likely that some attributes or combination of attributes provide meaningful gains in accident tolerance while others may provide only marginal benefits. [1]*

As the adoption of Accident Tolerant Fuels is an initiative to rapidly introduce new technologies to the nuclear industry the absolute need for close collaboration between the interested R&D organizations, the nuclear industry, and nuclear regulators, is clearly identified in the Nuclear Energy ATF Roadmap. Moreover, the roadmap acknowledges and identifies a number of critical infrastructure improvements considered necessary to support the ATF program. These improvements include: High Temperature Steam Testing, Continued Support for and Improvement of Irradiation Testing, Reintroduction of Domestic Fuel Transient Testing, Enhanced Post Irradiation Examination Capabilities, Upgraded Fuel Fabrication Facilities, and an Enhanced Regulatory Framework. In summary, the Nuclear Energy ATF Roadmap provides a higher-level overview of this ATF Implementation Plan.

1.7 Metrics and TRLs as Related to the STEP and TIP Roadmap Documents

As the ATF technologies span technical maturity from basic concept definition and basic research to prototypic in-reactor testing, the program has adapted by adopting a fuel-specific TRL approach to development [2]. How technological advancement is judged along those TRLs is in-turn judged by a set of program ATF Metrics [3]. Combined, these TRLs and ATF Metrics are used as guiding documents to determine and execute specific ATF technology roadmaps.

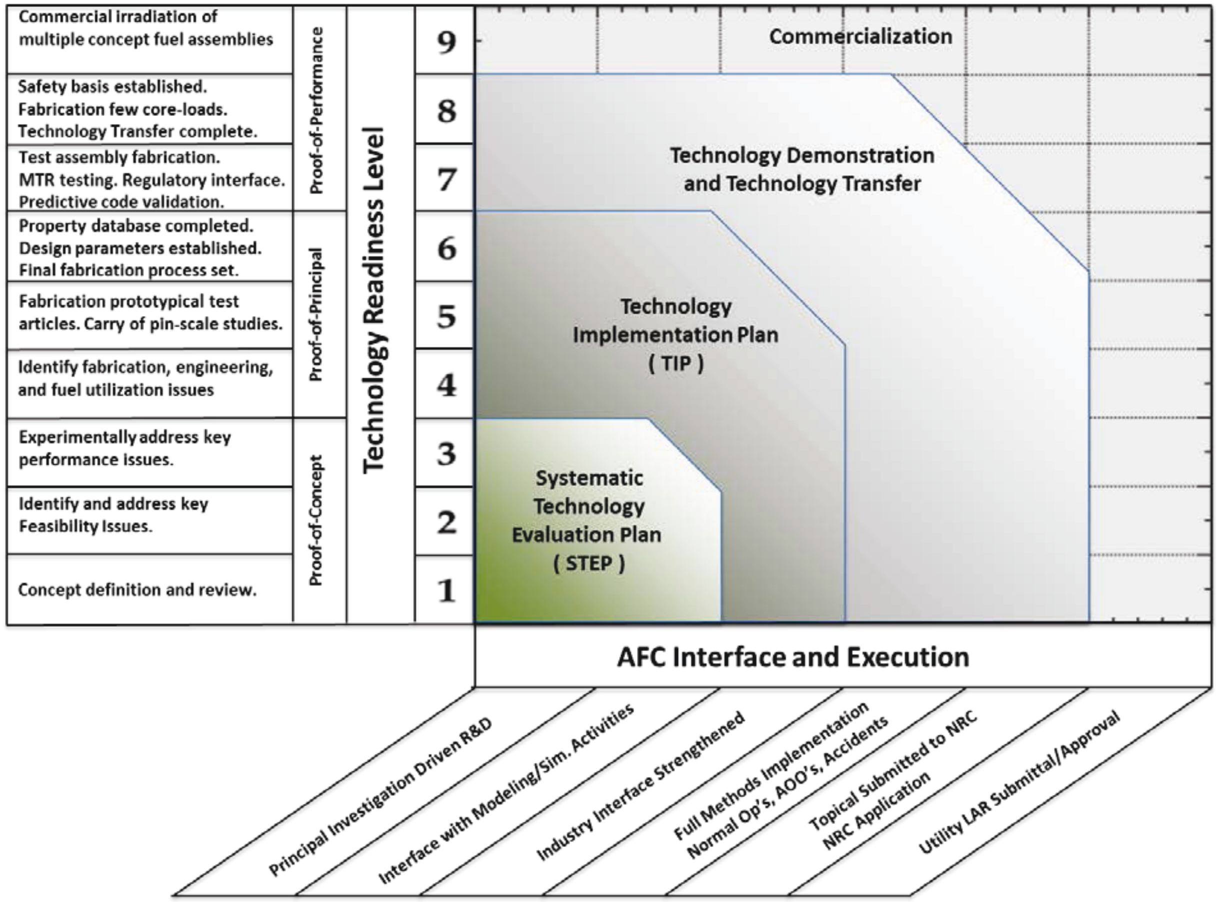

Figure 4. Relation of Fuel Technology Readiness Levels and methods of FCRD technical execution: STEP, TIP and Technology Demonstration and Transfer (L. Snead).

Specifically, there are three generic evolutionary levels for a concept (Figure 4):

- **Proof-of-Concept (TRL 1-3):** The cladding, fissile fuel, or combined cladding/fuel concept undergoes modeling and experimental studies to evaluate fundamental proof-of-concept issues. These studies encompass a wide array of factors from fundamental material properties related to fabrication, normal operation, off-normal (accident) conditions, fuel utilization, and touch on practical application issues, economics, etc. In some cases an emerging fuel technology, or one that is at the "conceptual" level, is supported through an ad-hoc approach combining modeling and experimental studies to determine whether more comprehensive study is warranted. For ATF technologies deemed sufficiently mature for a Concept Evaluation a Systematic Technology Evaluation Plan (STEP) document is formalized and executed. The STEP document is a technical roadmap document covering relevant technological questions to mature an ATF technology from the Concept Evaluation (TRL 1-3) level to the Concept Maturation (TRL 3-6) level. It can be considered as the document that addresses the fundamental "go / no-go" issues surrounding the concept that must be addressed prior to a concept moving into the Concept Maturation phase, which will consume more time and resources.

- **Proof-of-Principle (TRL 3-6):** The cladding, fissile fuel, or combined cladding/fuel concept undergoes core level modeling and prototypic (pin-level) fabrication, irradiation data-basing and qualification-level irradiation of pins. An ATF technology that is deemed sufficiently mature and of high potential to warrant a Concept Maturation study will follow a Technology Implementation Plan (TIP) document. The TIP document is a roadmap document to address all the relevant application technologies required for eventual fuel qualification. At the successful completion of the TIP process the technology should have a sufficient database to allow the concept to be taken to the Concept Implementation phase (TRL 7-9 or LFR/LFA phase.)

- **Proof-of-Performance (TRL 7-9):** In this phase research and development on the ATF concept is completed and the concentration of effort is on proving engineering viability through irradiation in a materials test reactor, predictive code validation, and regulatory interface and approval. At this point the technology should be essentially entirely translated to the commercial sector.

While AFC has adopted the STEP and TIP formalisms for maturing potential ATF technologies, these documents themselves do not provide a mechanism for determining the benefit in terms of added reactor coping time for any specific ATF technology nor do they provide a comparison of the relative merits of the various ATF concepts. To accomplish this, AFC uses a system of "metrics" described as a set of technical bases by which multiple concepts can be fairly evaluated against a common baseline and against one another. In some cases this may equate to a specific quantitative target value for selected properties or behaviors. Metrics can also describe a clear technical methodology for evaluation that can be used to rank two or more concepts. Because of the complex multiphysics behavior of nuclear fuel and the large set of performance requirements that must be met, the latter definition is adopted for the current evaluation of candidate accident tolerant fuel options. A series of national and international meetings were held in FY2013 to begin establishing a consensus on how to approach ATF design, optimization and evaluation for down-selection [5,6]. Each of these meetings provided expert direction on an appropriate set of enhanced accident tolerant fuel attributes, metrics, and associated screening evaluations for different classes of fuel and cladding material leading to the AFC ATF Metrics document [3].

Technical evaluation and comparison of ATF candidates are performed using appropriate modeling tools. Moreover, this process is carried out in close relationship with development activities, governed by the STEP and TIP activities, and evaluated by the TRC, whose function is to determine concept viability. The interrelation of these three functions is shown schematically in Figure 5.

As can be seen from the schematic, those concepts that are in the "Proof-of-Concept" Phase, otherwise associated with TRL levels of 1-3, are either undergoing pre-conceptual or early-phase (pre-STEP) development or development as guided by a formal STEP document. In this concept evaluation phase the overarching goal is to provide adequate performance data and information on key go/no-go issues for the fuel system such that 1) a preliminary ranking of fuel technologies can be ascertained, and 2) balanced information on these technologies can be passed to the TRC to determine if the concept can pass to the next level of development.

As can be seen from Figure 5 the metrics activities (highlighted in tan) and the fuels R&D activities guided by STEP and TIP documents (highlighted in blue) are carried out in tandem. As a technology is elevated from the "Proof-of-Concept" (TRL 1-3) to the "Proof-of-Principle" Phase (TRL 4-6), the milestone is generally associated with an implied significant increase in budget requirement. For this reason the TRC will likely opt to reduce the number of concepts that move forward in the development process based on the prioritized list of technologies.

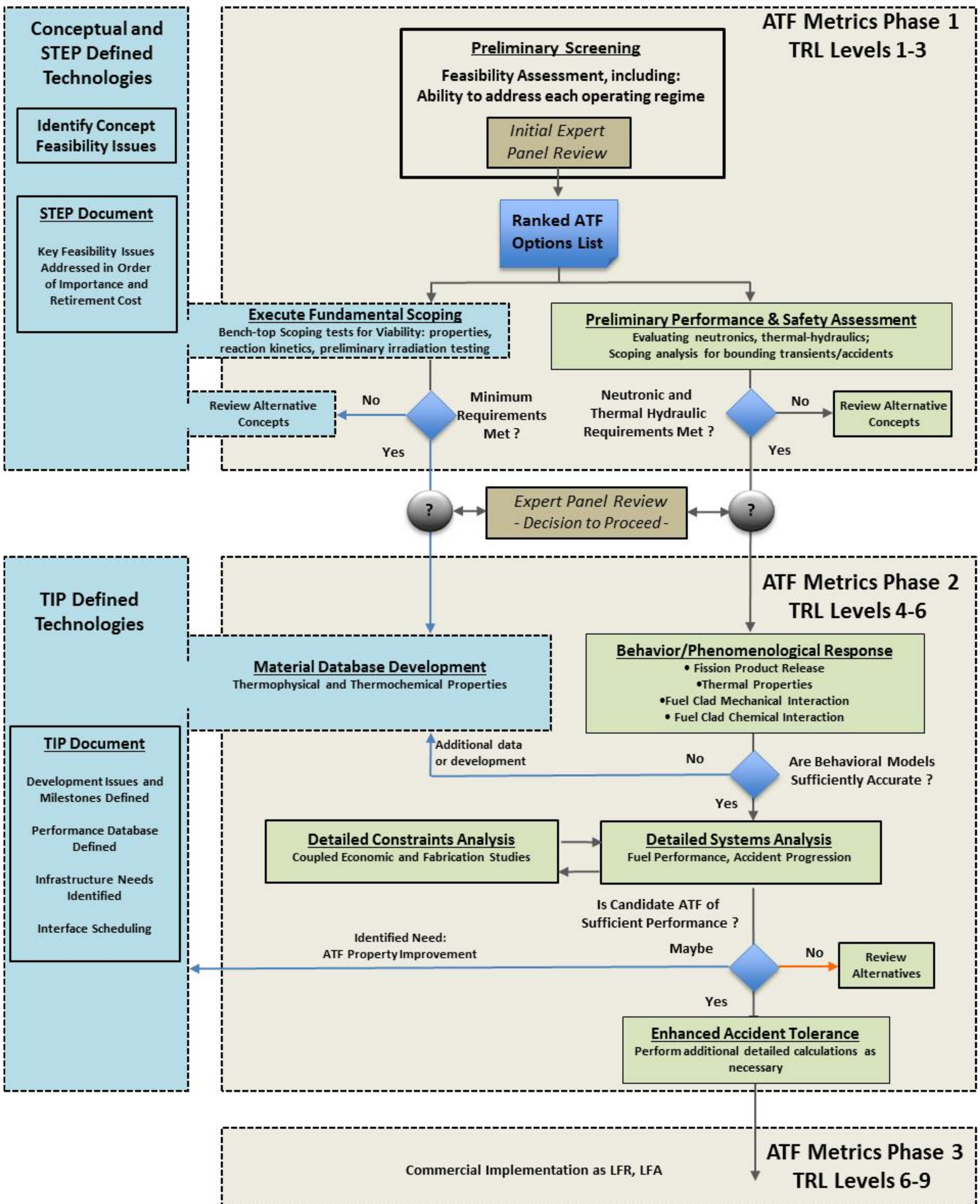

Figure 5. Application of FCRD metrics analysis and relation to program execution documents: STEP and TIP. Based on the AFC "Enhanced LWR Accident Tolerant Fuel Performance Metrics" plan [3] L. Snead.

Phase 2 provides the scheme for development of those technologies that pass such a process, enter into technology development, and are generally governed by a TIP. Detailed fuel system phenomenological response and reactor systems analysis is carried out in tandem with fuel development and real time provision of fuel properties. Moreover, as the practical issues of fabrication and other practical fuel handling issues are sorted out for a particular ATF concept, this information is passed forward to support an economic analysis. Given this information the ultimate benefit of a generic ATF concept can be evaluated and the decision made to pass it to the "Proof-of-Performance" Phase (TRL 7-9), to suggest specific property improvement that may provide it with competitive advantage, or to abandon the concept.

2. CURRENT ACCIDENT TOLERANT FUEL CONCEPTS

The ATF program is currently in the early R&D phases, supporting the investigation of a number of technologies that may improve fuel system response and behavior in accident conditions. The program is sponsoring multiple teams to develop ATF concepts within national laboratories, universities, and the nuclear industry.

2.1 DOE-Supported ATF Concepts

Since the inception of the Accident Tolerant Fuels initiative this area of research has broadened from the work conducted by the DOE AFC to become an international initiative with growing programs in Europe, Japan, Korea, and China. The totality of international ATF technologies is beyond the scope of this document, although some technologies such as the fully ceramic microencapsulated (FCM) and enhanced UO_2 fuels and FeCrAl steel and SiC cladding concepts are undergoing collaborative international development.

This document focuses on those technologies which are actively under development, at the various TRL levels, via Department of Energy support, either directly through national laboratory research or DOE sponsored initiatives. A list of those ATF technologies being funded by DOE is provided in Table 1, specifically including those technologies led by the national laboratories, those being developed by domestic fuel vendors under DOE grant, and those led by Universities under DOE-funded Integrated Research Projects (IRPs). In each case the specific technology is categorized as a fuel, a fuel cladding, or a fuel coating development with the relative TRL defined. Technologies that are being led by the national laboratories and are emergent "pre-STEP" concepts (TRL1/2) graduate to development under formal program STEP or TIP documents. In the case of industry-led ATF development, company-internal documents control the technology development. However, in some cases as exemplified by the FeCrAl advanced steel development, the TIP is common to both the FCRD and industry development activities.

Table 1. ATF Technologies and Associated Experiments.

ATF Technology Lead Organization	Fuel	Cladding	Coating	Technology Readiness			
				Concept Stage TRL 1/2	STEP TRL 2/3	TIP TRL 4/6	Planned Irradiation
ORNL	FCM	-	-	-	-	-	TBD
	-	FeCrAl-Steel	-	-	-	-	ATF-1
	-	SiC Composite	-	-	-	-	TBD
PNNL	U-Mo	-	-	X	-	-	TBD
LANL	-	Mo	-	-	-	-	TBD
	Enhanced UO_2	-	-	X	-	-	ATF-1B
Westinghouse	UN /U_3Si_2	SiC Composite	Ti_2Al, Nanosteel	Internal Westinghouse Coordination			ATF-1
	U_3Si_2	Standard Zircaloy	Ti_2Al, Nanosteel				ATF-1
AREVA Federal Services	UO_2 + SiC	Standard Zircaloy	MAX Phase Ceramic	Internal AREVA F. S. Coordination			ATF-1
General Electric GRC	-	Advanced Steels including FeCrAl	-	-	-	GE FOA	ATF-1

2.2 Industry Support and Interface

Given the congressional mandate to insert an ATF LFR or LFA into a commercial reactor by 2022, a close collaboration between Federally Funded Research and Development Center (FFRDC) contractors involved in nuclear research and U. S. domestic nuclear industry has been initiated and maintained. This synergistic relationship allows the fuel vendors to play the essential role to bridge a fuel technology through the regulatory and technical requirements for insertion into domestic power reactors. Conversely, fuel vendors require both the technical expertise and advanced equipment residing in the national laboratory complex to provide the development and performance data required to mature a concept to the point it can be presented to a regulator.

For this reason the Department of Energy initiated a Funding Opportunity Announcement DE-FOA-0000712 “Accident Tolerant Fuel Program” as a cooperative agreement in May 2012 with an initial funding level of $10M. From this initial Phase 1a, the three industry-led teams listed in Table 1 were selected: Westinghouse Electric Company LLC, AREVA Federal Services LLC, and General Electric Global Research Corp In each case the teams include a broad range of university and FFRDC partners. Also shown in Table 1 are individual concepts that are currently being pursued by the industry teams. This activity has recently been renewed as Phase 1B for continued funding and activities in the FY15/16 timeframe. Assumed within these cost-shared proposals is budget for any special facilities or testing to be carried out at an FFRDC with the exception of neutron irradiation services, which are provided for within the base program. Table 1 notes the initial irradiation experiments planned for the ATF technologies, and

Figure 6 provides a brief overview of the focus of each industry-led effort and accomplishments since 2012.

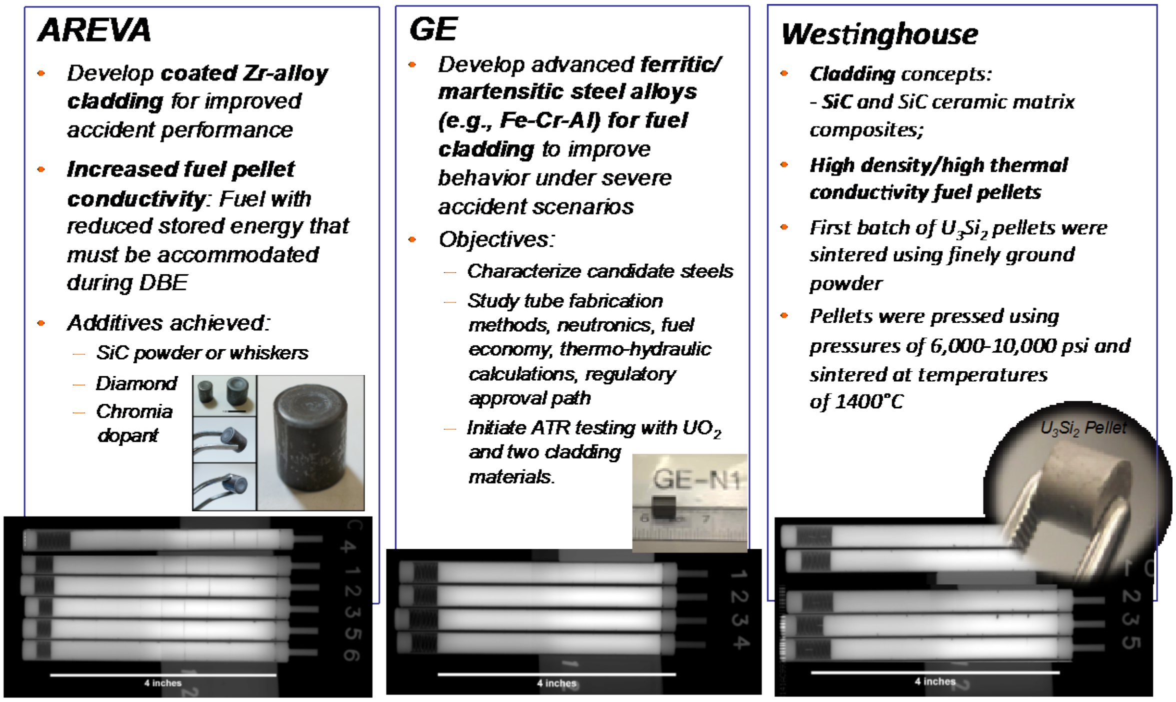

Figure 6. Summary of Industry-Led Accident Tolerant Fuel Development Projects.

2.3 Industry – 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 evaluated promising technologies that would provide nuclear power plant operators more time to manage an accident situation. These technologies included, for instance, coatings on Zirconium cladding, additives to uranium pellets as well as modifications to coolant loops. Pellets with several additives were manufactured at the University of Florida and shipped to Idaho National Laboratory in the summer of 2014 for insertion into the Advanced Test Reactor.

The objective of the Phase 1B contract is to complete the initial research and development phase, select the most promising solutions and move forward with the Enhanced ATF (EATF) design to deploy LFRs or LFAs into a commercial power reactor in 2022. The Electric Power Research Institute (EPRI) and U.S. nuclear operator Dominion Generation join the AREVA-led team for Phase 1B. Dominion Generation's role, like those of the other participating electric utility team members, is an advisor to the project.

The objective of the AREVA team EATF project is to build on existing work that AREVA is conducting in fuel development while examining technology improvements that offer incremental benefits to the current fuel design. Therefore, the team is investigating a coating on the nuclear fuel cladding material and improvements to the fuel pellets to increase the coping time of the nuclear fuel in currently postulated accident conditions. Multiple technical concepts will be evaluated, analyzed, and tested to assess their viability, suitability, and manufacturability. The concepts will be evaluated with a "gate" review process to determine the best approach to pursue at each phase of development process.

Implementing Documents prepared by AREVA Federal Services, LLC:

- Regulatory Plan for Enhanced Accident tolerant Fuel, RPT-3008873-000, May 8, 2013
- Appendix B, Preliminary Business Plan for the Draft Final Report for Enhanced Accident Tolerant Fuels, RPT-3011235-000, September 30, 2013
- Appendix K, Enhanced Accident tolerant Fuel Test Plan for the Final Draft Report for EATF, RPT-3011235-000, September 23, 2014

2.4 General Electric Global Research

With a team including industry, universities, and national laboratories, GE Global Research proposes to demonstrate that ferritic/martensitic alloys can provide enhanced accident tolerance as fuel cladding materials for current light water reactors; in addition, the use of these materials is expected to maintain or increase the periods between refueling and to improve the behavior of the fuel bundle under severe accident scenarios such as a loss-of-coolant accident (LOCA). The major partners are University of Michigan, Los Alamos National Laboratory, and Global Nuclear Fuels.

The GE proposal, "Ferritic Alloys as Accident Tolerant Fuel Cladding Material for Light Water Reactors," is based on the idea that the current zirconium based cladding can be replaced using an advanced steel concept; that is, this concept will replace one alloy with another (i.e., not relying on coatings for protection against steam). At temperatures associated with LWR accident conditions, metals inside the reactor core will react with steam to produce an oxide and release gaseous hydrogen. It is known that zirconium alloys react very rapidly with steam in an autocatalytic reaction. It is expected that the newer iron-based and chromium containing candidate materials will have much slower reaction kinetics with steam. Table 2 shows the materials that were selected for testing under the current contract.

Table 2. Candidate Alloys for Accident Tolerant Cladding

Alloy	ID Letter	Nominal Composition
Materials in the Proposal		
Zircaloy-2	A	Zr + 1.2-1.7 Sn + 0.07-0.2 Fe + 0.05-0.15 Cr + 0.03-0.08 Ni
Ferritic steel T91	B	Fe + 9 Cr + 1 Mo + 0.2 V
Ferritic steel HT9	C	Fe + 12 Cr + 1 Mo + 0.5 Ni + 0.5 W + 0.3 V
Nanostructured ferritic alloys - 14YWT	D	Fe + 14 Cr + 0.4 Ti + 3 W + 0.25 Y_2O_3
Other Candidates Added		
MA956	E	Fe + 18.5-21.5 Cr + 3.75-5.75 Al + 0.2-0.6 Ti + 0.3-0.7 Y_2O_3
APMT	G	Fe + 22 Cr + 5 Al + 3 Mo
E-BRITE – S44627,	H	Fe + 25-27.5 Cr + 1 Mo + 0.17 (Ni + Cu)
To be developed NFA	I	To be determined
Alloy 33 – R20033	J	33 Cr + 32 Fe + 31 Ni + 1.6 Mo + 0.6Cu + 0.4 N

All the ferrous materials listed in the Table are expected to have lower reaction kinetics with steam than Zirconium alloys, such as Zircaloy-2. At 1200°C, the degradation of APMT is practically nil (no mass change) after 8 h exposure, while at 1000°C the degradation of Zircaloy-2 is complete for the same period of time [Pint et al. 2012]. APMT offers extraordinary resistance to reaction with steam at temperatures higher than 1000°C because it first allows for the formation of a protective Cr_2O_3 scale, which subsequently allows for the formation of a continuous protective Al_2O_3 scale between the metal and the Cr_2O_3 scale. It is this Al_2O_3 scale what protects the alloy against further oxidation in steam [Opila 2004, Pint et al 2012].

Reference documents include:

- GE, Initial Technical Analysis Report, January 30, 2013.

2.5 Westinghouse Electric Company, LLC

With a team including industry, universities, and national laboratories, Westinghouse proposes a series of tasks to identify, produce, and test for technical and economic feasibility of accident tolerant light water reactor fuel. Concepts under consideration include cladding concepts, such as silicon carbide (SiC), SiC ceramic matrix composites, and coated Zirconium alloys, and high density/ high thermal conductivity fuel pellets, such as Uranium nitride-uranium silicides. Organizations participating as contractors to Westinghouse on this project include: General Atomics, Massachusetts Institute of Technology, Idaho National Laboratory, Texas A&M University, Edison Welding Institute, Los Alamos National Laboratory and Southern Nuclear Operating Company.

An accident tolerant fuel LFA/LFR project plan will be issued to explain how the next period of qualification and development will be implemented with a larger role of industry participation. Also, a report on the ATF feasibility will be delivered to outline the merits of the proposal as measured and evaluated against a set of metrics developed by experts in the field.

There are two main differences between the current fuel designs described in Section 2.1 and ATF, both of which stem from material differences. These differences exist in the form of modifications to materials used in cladding and fuel pellet composition. With the exception of the material used in these two components, all of the features of ATF remain consistent with those of fuel currently in use. If in the future a higher burnup or higher enrichment limit is requested, additional licensing work will be required.

Currently two different cladding types are being investigated by the Westinghouse team for use in ATF designs: SiC_f/SiC_m Ceramic Matrix Composite (CMC) and coated Zr alloy cladding. SiC_f/SiC_m CMC cladding consists of SiC fiber reinforced SiC composites: a two or three-layer tube of high purity beta or alpha phase stoichiometric silicon carbide covered by a central composite layer of continuous beta phase stoichiometric silicon carbide fibers infiltrated with beta phase SiC and, in the case of three layers, an outer protective layer of fine grained beta phase silicon carbide. Zr alloy coated cladding investigations currently consist of evaluating the performance of two separate coatings: Ti_2AlC known as MAX Phase, and an amorphous stainless steel known as NanoSteel™. The coatings consist of fine particles of the coating materials that are sprayed onto the outside surface of the zirconium alloy rod at high velocity to form a 10 to 20 micron thick layer.

Similar to the cladding, there are two different pellet types currently under investigation for use in ATF:

1. UN pellets which have been waterproofed by the addition of U_3Si_2 or UO_2 using N enriched to >90% ^{15}N.

2. U_3Si_2 pellets.

Implementing documents by Westinghouse Electric Company LLC:

- Development of LWR Fuels with Enhanced Accident tolerance. Task 3: Licensing Plan for Accident Tolerant Fuel, RT-TR-13-19, September 30, 2013
- Development of LWR Fuels with Enhanced Accident tolerance. Task 4: Preliminary Business Plan, RT-TR-13-20, October 2, 2013.

3. CURRENT STEP AND TIP DOCUMENTS

Brief summaries of the current STEP and TIP documents are provided below. The STEP document is a technical roadmap document covering relevant technological questions to mature an ATF technology from the Concept Evaluation (TRL 1-3) level to the Concept Maturation (TRL 3-6) level. The TIP document is a roadmap document to address all the relevant application technologies required for eventual fuel qualification. At the successful completion of the TIP process the technology should have a sufficient database to allow the concept to be taken to the Concept Implementation phase (TRL 7-9 or LFR/LFA phase.)

3.1 Systematic Technology Evaluation Program (STEP) for SiC/SiC Composite-based Accident Tolerant LWR Fuel Cladding and Core Structures, June 2014 [7]

Fuels and core structures in current LWRs are vulnerable to catastrophic failure in severe accidents as unfortunately evidenced by the March 2011Fukushima Daiichi Nuclear Power Plant Accident. This vulnerability is attributed primarily to the rapid oxidation kinetics of zirconium alloys in a water vapor environment at very high temperatures. Zr alloys are the primary material in LWR cores except for the fuel itself. Therefore, alternative materials with reduced oxidation kinetics as compared to zirconium alloys are sought to enable enhanced accident tolerant fuels and cores.

Among the candidate alternative materials for accident tolerant LWRs, silicon carbide (SiC) – based materials, in particular continuous SiC fiber-reinforced SiC matrix ceramic composites (SiC/SiC composites), are considered a leading option to provide outstanding passive safety features in beyond design basis severe accident scenarios. In addition, they possess other potential benefits including exceptional radiation resistance as catalogued in extensive neutron irradiation experiments and data.

However, it is noted that SiC composites as a family of materials are still immature, only now finding limited structural application and lacking many of the application technologies required for them to become truly attractive engineering materials. To date there are no examples of SiC composite in nuclear structures and nuclear fuel cladding designs are still in an evolutionary stage yet to define a robust architecture. In order to translate the promise of this family of materials into a reliable fuel cladding a coordinated program of component level design and materials development must be carried out with many key feasibility issues addressed *a priori* to inform the process.

The primary objective for the Systematic Technology Evaluation for SiC/SiC Composite Accident-Tolerant LWR Fuel Cladding and Core Structures, is to develop a draft blueprint of a technical program that addresses the critical feasibility issues; assesses design and performance issues related with manufacturing, operating, and off-normal events; and advances the technological readiness levels in essential technology elements.

The plan consists of three main elements: a technology review, a critical technology gap analysis, and a draft technical program plan. The technology review and the gap analysis are largely derived from discussions during the Workshop on Accident Tolerant Fuels SiC Technology that was held in February 2014 for the U.S. Department of Energy's Fuel Cycle Research and Development Program. Many of the technical gaps identified are related to the three key feasibility issues: coolant compatibility (hydrothermal corrosion), cracking-induced failure, and fuel compatibility. Additional very important gap issues, mainly the critical performance issues including accident-tolerant features and fission product retention during the normal operation, have also been identified.

The program plan was designed to systematically address the key gap issues and is formulated in a work breakdown structure. Simultaneously, the plan would establish a technical program for advancing the technology readiness levels of essential technologies in three top-level categories of Design and Failure, Environmental Effects, and Off-normal Behavior. Table 3 depicts key technical elements of the plan and their relevance with the critical feasibility and performance issues. The current document provides precise descriptions of individual issues to be addressed, the technical approaches proposed, and how individual task elements are anticipated to interact.

Table 3. Proposed high level task items and their relevance to critical gap issues forSiC/SiC composite-based accident tolerant fuel technologies for light water reactors.

⦿ Primary relevance
○ Secondary relevance

	Critical feasibility issues			Critical performance issues	
Task	**Coolant compatibility**	**Cracking-induced failure**	**Fuel compatibility**	**Accident-tolerance**	**Fission product retention**
Design & Failure					
Comprehensive analysis tool		⦿	⦿		⦿
Statistical failure assessment		⦿			⦿
Fission product transport			○		⦿
Design and manufacture	⦿	⦿	○	○	⦿
Environmental Effects					
Hydrothermal corrosion	⦿			○	○
FCCI and FCMI			⦿	○	⦿
Irradiation effects	⦿	⦿	⦿	○	⦿
Off-normal Behavior					
Steam oxidation		○		⦿	○
Thermal shock		○	○	⦿	○
Accident analysis		○	○	⦿	○

Finally, the intent of this STEP document is that it evolves based on community input and through execution and review of the technical program plan progress.

3.2 ATF Technology Implementation Plan (TIP) for ATF FeCrAl Cladding for LWR Application, May 2015 [8]

This intent of the FeCrAl TIP document is to provide a plan for the development of a nuclear-grade FeCrAl alloy for fuel cladding in LWRs. The purpose of the TIP is not design and licensing work to support LFR insertion into a commercial LWR in the US, but rather to provide confidence in the ATF FeCrAl clad concept before significant investments of time and money are made toward licensing efforts. The results of testing and analyses should be documented and shared with the licensee to support their licensing analyses, but LFR analysis would need to be performed separately by the reactor licensee in conjunction with the vendor using approved methodologies and codes and submitted to the Nuclear Regulatory Commission (NRC) by the licensee of the reactor in question.

Front-end and back-end issues such as fuel storage in spent fuel pools or dry storage, repository impacts, uranium mining, fuel fabrication, fuel transportation, fuel handling, impacts on reprocessing if desired, etc. are not addressed in the TIP. These fuel cycle impacts will need to be analyzed and addressed at some point.

The development of nuclear-grade ATF FeCrAl alloys targets a new, metal-based structural material for nuclear fuel cladding, substituting for zirconium alloys, that exhibits greatly improved accident tolerance, including good mechanical properties in a wide temperature range as well as oxidation and irradiation resistance under normal and transient operating conditions. ATF FeCrAl alloys will be selected based on their excellent oxidation resistance in high temperature steam environments up to 1475°C (provided by the sufficient amounts of Cr and Al additions), compared to the industry standard zirconium alloys which would not have such good temperature oxidation resistance in steam. This is the key for enhancing safety margins under severe accident conditions by limiting the heat and hydrogen production, which occurs when the fuel cladding reacts with steam during a severe accident.

With superior high temperature strength compared to zirconium alloys, utilization of this class of alloys is expected to enhance burst margins during design basis accident scenarios and potentially for conditions extending beyond those limits. The current alloy design strategy is focused on developing a nuclear-grade material that exhibits comparable or superior behavior under normal operating conditions (at 320°C in pressurized water environments) when compared with today's commercial Zr-based alloys. Once this step is accomplished on the laboratory scale, a commercial-based processing route for thin-wall tube production will be developed to enable deployment of this class of alloys as nuclear fuel cladding. This document only focuses on the development of FeCrAl clad in combination with UO_2 fuel.

3.3 Technology Implementation Plan: Molybdenum and MoLa Alloy Cladding for Light Water Reactor Application [9]

The TIP for Mo and MoLa fuel cladding materials involves elements required for the design, testing, characterization, and demonstration of this technology. These elements are currently integrated in the cladding development plan. The TIP describes the development plan leading to cladding materials and technologies providing significant performance and safety advantages over current LWR fuel cladding. Other key objectives are meeting the fabrication, economic and licensibility requirements needed to deploy ATF in operating commercial LWRs. The bulk of recent update work has been funded and performed by EPRI with some collaboration with Los Alamos National Laboratory (LANL). Future activities may involve collaboration with AREVA under funding by DOE's Funding Opportunity Announcement (FOA).

There are advantages of using Mo and MoLa fuel claddings as compared to Zircaloy during postulated severe accidents, i.e. LOCA and beyond LOCA conditions, including postulated station blackout (SBO) sequences. The sequence for cladding temperature response and overall accident progression will be evaluated for representative PWR (Zion---like) and BWR (Peach Bottom---like) plants. Mo and MoLa claddings have the advantage of low or no hydrogen generation and no heat release during these abnormal event scenarios. Previous studies utilizing the MAAP4.0.7 code have shown the benefits of several different hypothetical new cladding types as compared to Zircaloy cladding in both PWR and BWR plants. In particular, sensitivity studies forBWR plants varying the injection flow rates are needed to determine the impacts on clad oxidation and hottest core node temperatures with Mo versus Zr cladding, and the effect of other materials (spacers, channel boxes) in the core region.

3.4 Technology Implementation Plan: Fully Ceramic Microencapsulated Fuel for Commercial Light Water Reactor Application [10]

The fully ceramic microencapsulated (FCM) fuel consists of tristructural isotropic (TRISO) particles embedded inside a fully dense SiC matrix and is intended for utilization in commercial light water reactor application. This fuel design differs widely from the previous dispersion type fuel approaches, since the damage due to 100 MeV fission fragments and noble gas release is fully contained within the TRISO particle and the inert SiC matrix is solely exposed to neutron irradiation. In addition to offering exceptional stability under neutron irradiation conditions, the thermal conductivity of the SiC matrix, even in the irradiated condition, is at least two times higher than that of uranium dioxide. This implies that while operating at the same linear heat rating as a commercial UO_2 fuel, the temperature gradient across the FCM fuel is significantly reduced. Even accounting for the temperature drop across the fuel cladding gap, fuel centerline temperatures on the order of a few hundred degrees above that of the coolant are expected.

The fuel development and qualification process for FCM fuel has benefited from and will continue to benefit from decades of gas reactor TRISO fuel development and optimization activities, including the recent progress made as part of the DOE-NE Advanced Gas Reactor (AGR) experiments. However, in contrast to the gas cooled reactor application, the significantly lower application temperature and replacement of graphite matrix by SiC for LWR application raises a host of issues not previously addressed. Moreover, a range of practical issues involving fuel utilization, the performance of this new potential fuel under normal and off-normal operating conditions, and its fabrication and development path into a viable commercial product require deliberate study.

3.5 Technology Implementation Plan for LWR Ceramic Composite Fuels: Assessment of UN/U-Si and UO_2/U-B Systems [11]

Several ceramic composite nuclear fuels are under consideration by AFC as candidate accident tolerant nuclear fuels. In this TIP, three properties are targeted for specific focus: thermal conductivity, fracture toughness, and oxidation resistance. A general development plan for ceramic composite fuels is proposed that provides a framework to guide research prioritization for these systems within four key areas: validation of hypothesized material properties relevant to the anticipated fuel benefits, assessment of potential vulnerabilities relevant to light water reactor service, composite system performance in each of the above categories, and finally evolution of the above under representative irradiation conditions. Execution of ceramic composite research according to the proposed strategy will ensure that major weaknesses are not overlooked during initial stages of development, and property datasets necessary for fuel performance modeling and design of test irradiations are produced as early as possible during the experimental program. This architecture ensures that the data obtained during exploration of a candidate ceramic composite system prioritizes the criteria specified by the Metrics report [3].

The proposed methodology is relevant to any ceramic composite nuclear fuel. This TIP assesses the current knowledge base for two families of fissile ceramic composite fuels currently under consideration, UN/U-Si and UO_2/U-B. The state of knowledge with respect to both systems is then translated to immediate, near-term, and mid-term research direction up through the point of post irradiation examination of the initial test irradiations. Key property or performance aspects that remain uncertain are emphasized for prioritized evaluation.

3.6 FY-15 Technology Implementation Plan for the U-Mo Fuel Concept [12]

As an advanced fuel form for LWR applications, the U-Mo metal alloy fuel material provides some important potential benefits over the traditional UO_2 ceramic pellets. These benefits include: 1) higher fissile atom density to achieve extended burnup operations within the existing ^{235}U enrichment limits; 2) limited fuel-cladding mechanical interaction, which reduces the potential for stress-corrosion cracking and allows for more operational flexibility to meet load following power demands; and 3) higher fuel material thermal conductivity. This leads to lower fuel temperatures and more efficient energy transfer, reducing the fuel's stored heat energy during accident conditions.

U-Mo fuel has the potential to provide superior performance based on these benefits, but significant development is still required. With sufficient development, it may be able to provide the LWR industry with an accident tolerant fuel having improved safety response. The current activities at PNNL are focused on multi-component fuel rod extrusion development, tubing development and ex-reactor corrosion testing to characterize the performance of the U-Mo metal fuel in both these areas.

4. MAJOR INFRASTRUCTURE AND IRRADIATION PROJECTS

Table 4 shows an overview of the irradiation testing program in 4 phases: 1) ATF-1 drop-in capsule testing in 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 TREAT, and 4) ATF-4 transient testing of fuel rods from the commercial power plant irradiated LTR/LTA program in TREAT. Each phase is a series of irradiation experiments conducted with specific objectives. More detail on each of the four phases of the irradiation testing program and their objectives is given in subsequent sections.

4.1 ATF-1 Test Series: Drop-in Capsule Testing in ATR

The ATF-1 test series will investigate 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. The ATF-1 test series will be performed as a series of drop-in capsule tests irradiated in the ATR.

The ATF-1 test series was initiated in February 2015 and will irradiate fuel rodlets that are isolated from the ATR primary coolant by a secondary capsule filled with an inert gas; the cladding of the test rodlets will not be in contact with water coolant during irradiation. Thus, the ATF-1 test series will investigate the irradiation behavior of new fuels (i.e., pellets/compacts) and their interaction with the cladding; however, ATF-1 is not a test series designed to assess the interaction of the cladding with water coolant. The ATF-1 test series will obtain fuel behavior and fuel-cladding interaction data needed to down-select to one or more promising concepts to carry into the next (much more expensive) phase of the irradiation testing program (i.e., ATF-2). It is intended as an early screening evaluation experiment series. This initial complement of test fuels were provided by the Industry led accident tolerant fuel development teams at AREVA, GE, and Westinghouse.

4.2 ATF-2 Test Series: Loop Testing in ATR and Halden

The ATF-2 test series will take the most promising concept(s) from the drop-in capsule test (ATF-1) 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. In addition to continuing the investigation of fuel behavior and fuel-cladding interaction 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. Testing in the Halden Reactor loop 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 the AFC and Industry project leadership.

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 as well as destructive PIE. However, a substantial portion of these irradiated fuel rods will be only examined non-destructively so 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.

Table 4. Irradiation Testing Program for Accident Tolerant Fuels.

Test Series	ATF-1	ATF-2	ATF-H-x	ATF-3	CM-ATF-x	ATF-y
Test Reactor	ATR	ATR	Halden	TREAT	Commercial Power Plant	TREAT
Test Type	Drop-in	Loop	Loop	Loop	LTR/LTA	Loop
Test Strategy	Scoping – Many Compositions	Scoping – Focused Compositions	Focused	Focused Compositions	Focused Composition	Focused Compositions
	Nominal conditions	Nominal conditions	Nominal	Accident conditions	Nominal conditions	Accident conditions
Fuel	UO_2, U_3Si_2, UN	Down-selected concepts	Selected	Fuel rodlets from ATF-1 and test rods from ATF-2 irradiations	Concepts selected in 2016	Test rods from LTR/LTA irradiations
Cladding	Zr w/coatings, stainless steels, advanced alloys, SiC					
Key Features	Fuel-cladding interactions	PWR Conditions	BWR Conditions	Integral testing	Steady State Irradiation	Integral testing
Timeframe	FY14 – FY18+	FY16 – FY22	FY15-FY22	FY18 – FY25	FY22 – ?	FY – ?

4.3 ATF-3 Test Series: Transient Testing of ATF-2 Rods in TREAT

The ATF-3 test series will take the most promising concept(s) from the ATR loop testing phase (ATF-2) into transient testing in the Transient Reactor Test (TREAT) facility. 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 would 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 will continue through the design phase over the next few years.

4.4 CM-ATF-x: Lead Fuel Rod or Lead Fuel Assemblies irradiated in commercial nuclear power plant

The near term goal of the DOE Accident Tolerant Fuel development program is to insert a lead fuel rod or lead fuel assembly into a commercial nuclear power plant by 2022. This lead fuel irradiation will then progress for 1 to 3 years in the commercial nuclear power plant and then will be removed, examined, and subjected to further testing and qualification.

4.5 ATF-4 Test Series: Transient Testing of LTR/LTA Rods in TREAT

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 FY22. The logical final phase of the irradiation test program is to subject a subset of these 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 would 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. [13, 14]

5. FUNDING NEEDS

AFC is tasked with not only the development of new ATF technologies for LWRs, but also the development of advanced fuels for future recycling and the development of techniques that improve the research and development of advanced nuclear fuels and materials. The budget required to fund AFC activities is extensive. Appropriated by Congress, approximately 20 to 25% of the authorized budget is allocated to competitively selected multi-year basic and applied research projects led by the University community. Approximately 3% of the budget is allocated to competitively selected Small Business Innovative Research (SBIR) Grants. Table 5 provides a summary of the direct budget needed to fund the AFC program and the competitively selected industry ATF, university, and SBIR projects. These budget totals assume that only two competitively selected industry projects are continued in Phase 2 (at 20% industry contribution). Selection of additional industry projects at less than 20% industry cost share will clearly require additional funding. Selection of industry projects at more than 20% industry cost share will clearly reduce the amount of DOE funding needed for industry led projects.

Table 5. Advanced Fuel Campaign Appropriated Budget Targets FY17-FY22 (Total, includes Laboratory, Industry, and University funding.

Fiscal Year	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022
Total ($M)	**60.1**	**78**	**85**	**89**	**89**	**89**	**89**
ATF Lab	23	23	23	28	28	28	28
Industry ATF	7.5	16	20	28	28	28	28
AR and CX Lab	15	15	15	18	18	18	18
University and SBIR	13	16	16	15	15	15	15

Laboratory activities support development and operation of infrastructure needed to support industry-led ATF project activities as well as pursuing longer term ATF and advanced reactor fuel concepts that may be beyond the near term 2022 commercial reactor irradiation goal. Laboratory activities are conducted on fabrication, characterization, irradiation testing, post-irradiation examination, transient testing, and analysis of ATF concepts and in general are expected to rise in Phase 2 to support industry activities and then level off across the Phase 2 time period. It has become clear in the conduct of Phase 1 that industry projects critically depend upon the infrastructure available in the DOE national laboratory system. Variation is expected as irradiation testing and evaluation of ATF concepts is conducted and completed. Also shown in Table 5 is the AR and CX (Advanced Reactor Fuels and Cross-Cutting technology development) programs that are conducted under the Advanced Fuels Campaign. These activities are not strictly a part of the ATF program but programmatic responsibilities of the AFC and included for completeness in the identification of budget.

Transition from Phase 1B to Phase 2 of the Industry-led projects will require significant increase in the request for funding. Currently, the projects are operated with 80% DOE provided funding and 20% industry provided funding. Phase 2 funding required will depend on the number of projects selected and the DOE/industry funding split. As a estimate in Table 5, each industry led project could cost between $150 to $180M over 6 years, hence possibly requiring between $12M and 40M per year (DOE contribution) depending on how many teams are selected and funded and the agreed DOE/industry contribution. Table 5 provides a summary of the estimated funding needed on behalf of DOE assuming 1 or 2 projects are selected and then an average between 12 and 40M is used as a rough order of magnitude estimate. Continuing multiple industry projects through phase 2 and insertion of multiple LFR/LFAs in 2022 at the current 20% industry – 80% DOE funding agreement could require significantly more than 89M budget request per year during Phase 2, possibly as high as 100M per year.

6. SUMMARY AND CONCLUSIONS

The purpose of the ATF Implementation Plan is to describe the technology development and progress required to insert one (or possibly two) concepts as a LFR or LFA in a commercial LWR by 2022. In particular, this document shows the integration between the functional documents guiding ATF development and provides a rough order of magnitude estimate of the required budget from FY2016 through FY2022. It is expected that after FY2022, the needed budget request would significantly decrease as works transitions from Phase 2 to Phase 3, corresponding to a decrease in DOE project responsibility and an increase in industry responsibility and associated funding support.

This implementation plan will be updated as the ATF program progresses from Phase 1 into Phase 2 in the 2016 to 2017 timeframe. The budget requirements will depend greatly on the scope and number of industry led projects that continue into Phase 2.

7. REFERENCES

1. Energy., U.S.D.o. (2015). Development of Light Water Reactor Feuls with Enhanced Accident Tolerance. Report to Congress. April 2015.

2. Carmack, J. (January 2014). Technology Readiness Levels for Advanced Nuclear Fuels and Materials Development. INL/EXT-14-31243 FCRD-FUEL-2014-000577.

3. Sitton, S.B., Merrill, B., Teague, M., Ott, L., Robb, K., Farmer, M., Billone, M., Montgomery, R., Stanek, C., Todosow, M., et al. (February 2014). AFC: Enhanced LWR Accident Tolerant Fuel Performance Metrics. INL/EXT-13-29957 FCRD-FUYEL-2013-0002664.

4. Carmack, J., "Advanced Fuels Campaign Execution Plan," Revision 5, May 27, 2015, FCRD-FUEL-2011-000105

5. Braase, L.A., Bragg-Sitton, S.M. (2013). Advanced Fuels Campaign Cladding & Coating Meeting Summary. INLEXT-13-28628. Idaho National Laboratory.

6. Braase, L.A. (2013). Enhanced Accident Tolerant LW Fuels National Metrics Workshop Report. INL/EXT-13-28090, Idaho National Laboratory.

7. Katoh, Y., Terrani, K.A., and Snead, L.L. (June, 2014). Systematic Technology Evaluation Program for SiC/SiC Composite-based Accident-tolerant LWR Fuel Cladding and Core Structures. ORNL/TM-2014/210 Revision 1. In. (Oak Ridge National Laboratory).

8. Snead, M., Snead, L., Terrani, K., Worrall, A., Robb, K., Yamamoto, Y., Powers, J., Drypondt, S., Pint, B., and Hu, X. (May 2015). Technology Implementation Plan: ATF FeCrAl Cladding for LWR Application. ORNL/TM-2014/353. In. (Oak Ridge National Laboratory.

9. Caro, M., Cheng, B., and Rahn, F. (January 2015). Technology Implementation Plan: Accident Tolerant Fuel Mo and MoLa Alloy Cladding for Light Water Reactor Application: LANL-FT-15LA020218. In. (Los Alamos National Laboratory.

10. Snead, L.L., Terrani, K.A., Powers, J.J., Worrall, A., Robb, K.R., and Snead, M.A. (April, 2015). Technology Implementation Plan: Fully Ceramic Microencapsulated Fuel for Commercial Light Water Reactor Application. ORNL/TM-2015/220. In. (Oak Ridge National Laboratory.

11. Nelson, A.T., and McClellan, K.J. (2015). Technology Implementation Plan for LWR Ceramic Composite Fuels: Assessment of UN/U-Si and UO2/U-B Systems. LA-UR 15-22574. In. (Los Alamos National Laboratory.

12. Bennett, W.D., Doherty, A.L., Geelhood, K.J., C H Henager, J., Lavender, C.A., Love, D.L., Omberg, R.P., and Smith, M.T. (February 20, 2015). FY-15 Technology Implementation Plan for the U-Mo Fuel Concept. PNNL-24078.

13. Hayes, S. L., Barrett, K. E. Barrett, "Irradiation Testing of Accident Tolerant Fuels in the ATR (The ATF 1 Test Series)," Idaho National Laboratory, INL/PLN-4444, April 2013.

14. Carmack, J., Barrett, K., Chichester, H., "Light Water Reactor Accident Tolerant Fuels Irradiation Testing," TopFuel 2015