U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Fuel Cycle Research and Development

Advanced Fuels FC-2 Overview

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DOE-NEUP FY2016 Webinar
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The FCRD Advanced Fuel Campaign is tasked with development of near term Accident Tolerant LWR fuel technology and performing research and development of long term resource enhancement options.

Advanced LWR fuels with enhanced performance, safety, and reduced waste generation

Transmutation fuels with enhanced proliferation resistance and resource utilization

Capabilities Development for Science-Based Approach to Fuel Development

- Advanced characterization and PIE techniques
- Advanced in-pile instrumentation
- Separate effects testing
- Transient testing infrastructure

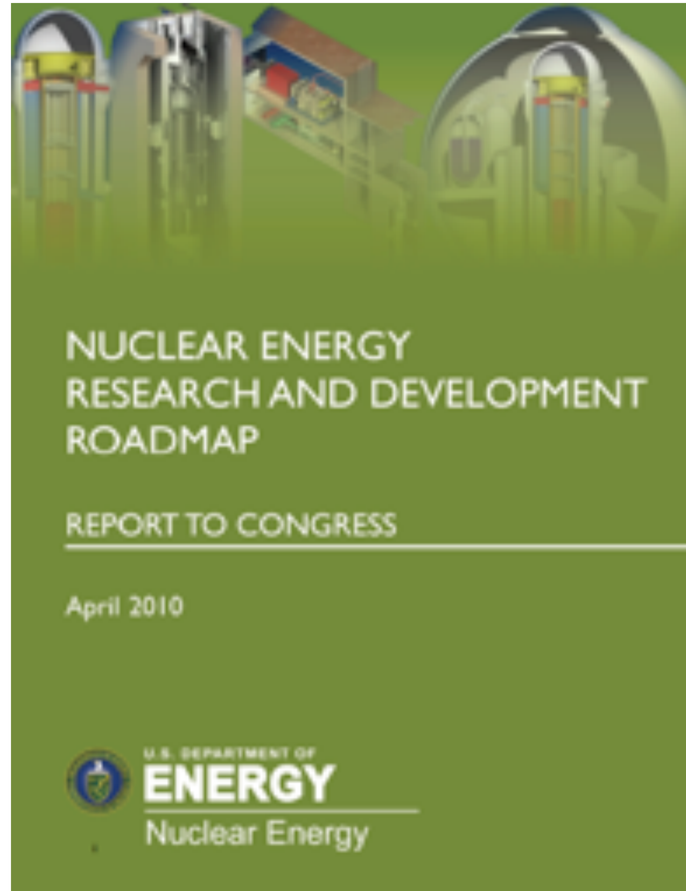
Multi-scale, multi-physics Fuel Performance M&S

ADVANCED FUELS CAMPAIGN

NEAMS

AFC High Level Technical Objectives (5-year)

- Identify and select advanced LWR fuel concepts for development towards lead test rod testing within the subsequent 5 to 7 years
- Complete the conceptual design for the baseline transmutation fuel technologies with emphasis on the fundamental understanding of the fuel fabrication and performance characteristics
- Identify and demonstrate feasibility of innovative concepts that provide considerable advantage compared to baseline technologies (Grand Challenge)
- Achieve state-of-the art R&D infrastructure that can be used to transition to “science-based” approach that can be used to accelerate further development of selected concepts
- Support the development of the predictive, multi-scale, multi-physics fuel performance code.



http://energy.gov/sites/prod/files/NuclearEnergy_Roadmap_Final.pdf

Accident Tolerant Fuel (ATF) Goal: Enhanced "Grace Time"

*Fuels with **enhanced accident tolerance** are those that, in comparison with the standard UO_2 – Zr system, can **tolerate loss of active cooling** in the core for a **considerably longer time period** (depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations.*

Improved Reaction Kinetics with Steam
- Decreased heat of oxidation
- Lower oxidation rate
- Reduced hydrogen production (or other combustible gases)
- Reduced hydrogen embrittlement of cladding

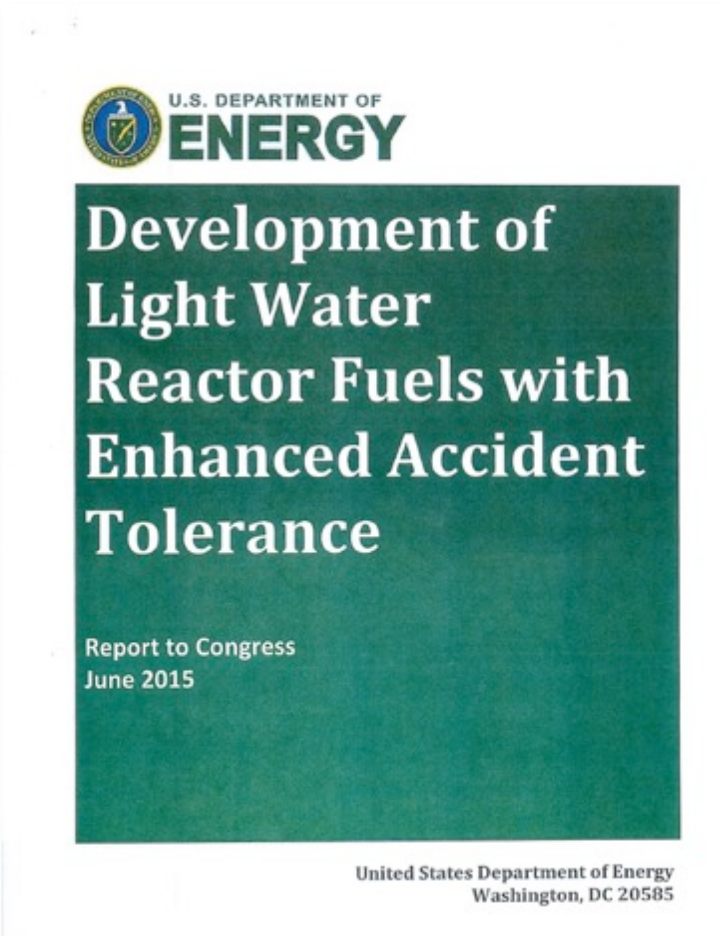
Improved Fuel Properties
- Lower fuel operating temperatures
- Minimized cladding internal oxidation
- Minimized fuel relocation/dispersion
- Higher fuel melt temperature

Enhanced Tolerance to Loss of Active Core Cooling

Improved Cladding Properties
- Resilience to clad fracture
- Robust geometric stability
- Thermal shock resistance
- Higher cladding melt temperature
- Minimized fuel - cladding interactions

Enhanced Retention of Fission Products
- Gaseous fission products
- Solid/liquid fission products

DOE ATF Report to Congress – June 2015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Development of Light Water Reactor Fuels with Enhanced Accident Tolerance

Report to Congress
June 2015

United States Department of Energy
Washington, DC 20585

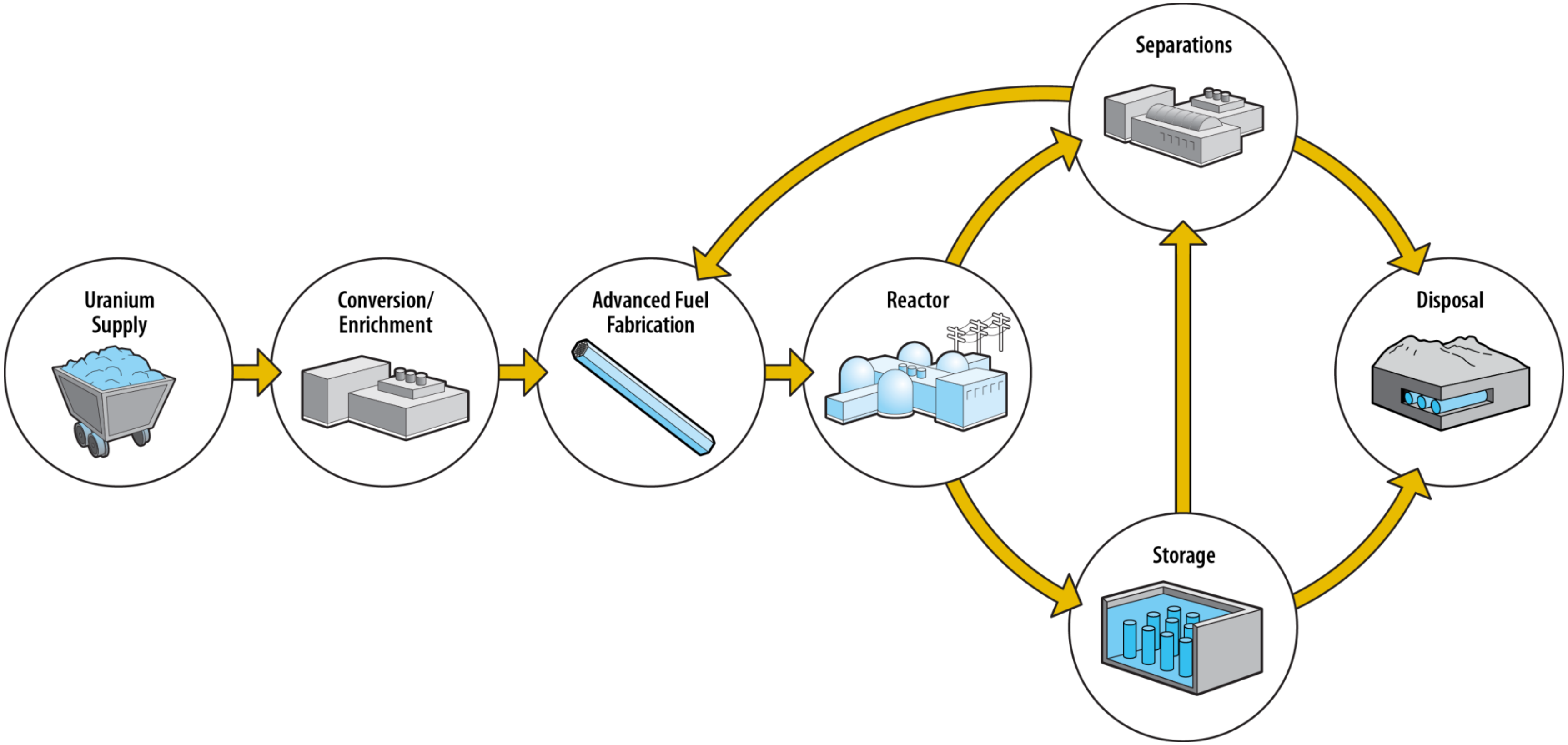
- ***Defines the general attributes of ATF***
- ***Lays out an aggressive 10-year schedule starting in 2012.***
- ***Establishes 2022 insertion of a LFA or LFR in an operating commercial LWR as the goal.***

https://nuclearfuel.inl.gov

Near Term Goals for Advanced and Accident Tolerant Fuels for LWRs

- **Utilize infrastructure at laboratories to support fabrication, irradiation, and testing of accident tolerant concepts.**
- **Initiate irradiation in ATR of initial ATF concepts, additional concepts will follow.**
- **Initiate test planning and preliminary design of loop testing for ATF in the ATR, needed for cladding/coolant interaction.**
- **Begin preliminary design of TREAT transient loop for ATF.**
- **Begin Phase II of industry led ATF projects.**

Fuel Cycle as a System with Recycle drives work on Advanced metallic fuels



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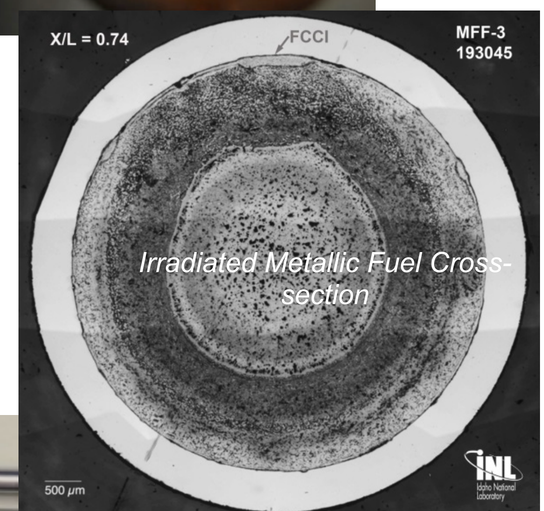
Advanced Fuel Technology Development for Actinide Management

Focus Priority on Metallic Fuels

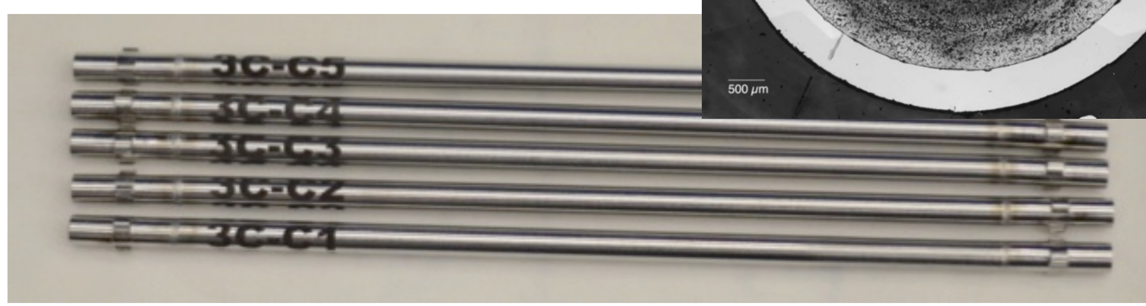
- ***Advanced fabrication techniques***
- ***Characterization of material properties of minor actinide bearing fuels***
- ***Irradiation behavior of actinide bearing fuel compositions***
- ***Development of advanced claddings having high burnup capability***


Advanced Metallic Fuel Fabrication



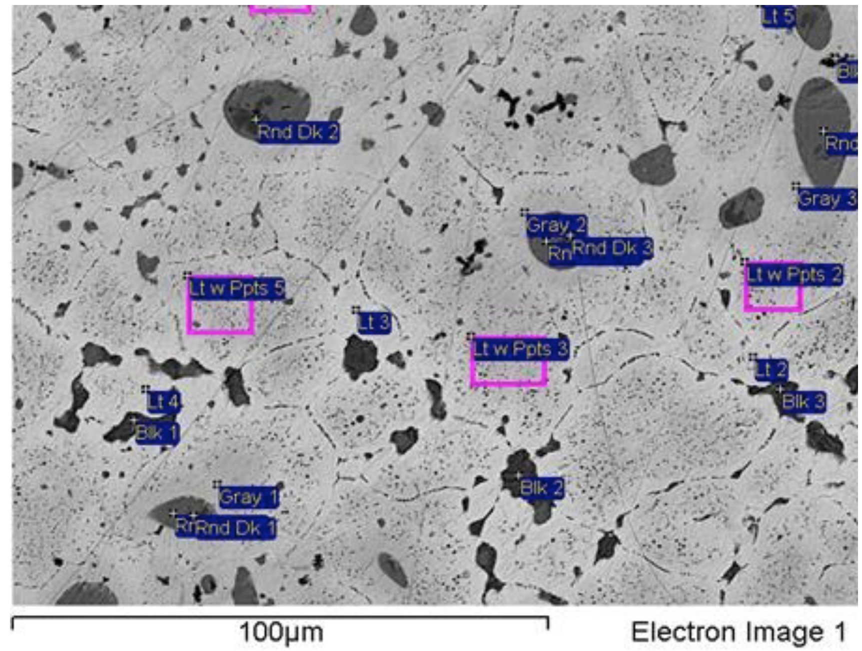
Irradiated Metallic Fuel Cross-section

ODS Steel Alloys



Immobilizing Lanthanide Fission Products

- **Lanthanide fission products migrate to fuel surface and interact with cladding, the primary source of FCCI**
- **Use minor alloy additions to chemically bind the lanthanides and immobilize in fuel matrix**
- **<u>Double Benefit:</u>**
  1. Homogenize/stabalize Lanthanides carried over from recycle
  2. Mitigate FCCI during irradiation



Back scattered electron image of **U-15Zr-3.86Pd-4.3Ln** (Ln = 53Nd-25Ce-16Pr-6La, in wt%)

Palladium (Pd) combines with the lanthanides, as expected from analysis of thermodynamic and PIE data.

R.D. Mariani, D.L. Porter, T.P. O'Holleran, S.L. Hayes, J.R. Kennedy, *Journal of Nuclear Materials*, **419** (2011) 263.

Advanced Metallic Fuel Concept

Fuel	Fuel Alloy	Geometry & Bond	Smear Density	Alloy Additions	Burnup (HM)	Cladding
U	Zr	Solid w/Na	55%	none Pd In Ga other combos	8-10%	HT-9
U+Pu	Ta-Zr		65%		15-20%	liner
U+Pu+MA	Mo-Ti-Zr	Annular w/He	75%		30-40%	coating

- Short-term irradiations: early PIE to show feasibility
- Long-term irradiations: demonstrate ultra-high burnup
- Early materials testing of lined/coated cladding for incorporation in subsequent short-term irradiations
- Investigate alloy additions to immobilize lanthanide fission products

Cross Cutting Technology Development Activities

- **Initiate prototypic testing of advanced in-situ and advanced in-pile measurement techniques.**
- **Continue development of advanced characterization techniques including hot cell mockup of multi-sensor apparatus, IMCL population, and advanced PIE methods.**
- **Continue developing experiment modeling and simulation with capability Bison code. Expand use to Accident Tolerant Fuel concepts.**
- **Obtain Am and Np feedstock for use in the domestic programs as well as fulfilling US commitments to international agreements.**

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2013 NEUP, IRP, and Mission Supporting Awards related to FCRD AFC

Award Title	University	Lead PI
(Project 13-5443) Optical Fiber Based System for Multiple Thermophysical Properties for Glove Box, Hot Cell and In-Pile Applications	Utah State University	Heng Ban
(Project 13-5161) Developing ultra-small scale mechanical testing methods and microstructural investigation procedures for irradiated materials.	University of California-Berkeley	Peter Hosemann
(Project 13-4823) In-pile Thermal Conductivity Characterization with Single-laser Heating/Time Resolved Raman	Iowa State University	Xinwei Wang
(Project 13-5346) U3Si2 Fabrication and Testing for Implementation into the BISON Fuel Performance Code	University of South Carolina	Travis Knight
(Project 13-5505) Mechanical Behavior of UO2 at Sub-grain Length Scales: Quantification of Elastic, Plastic and Creep Properties via Microscale Testing	Arizona State University	Pedro Peralta
(Project 13-5292) Correlating Thermal, Mechanical, And Electrical Coupling Based Multiphysics Behavior Of Nuclear Materials Through In-Situ Measurements	Purdue University	Vikas Tomar
(Project 13-4818) Multiphase Nanocrystalline Ceramic Concept for Nuclear Fuel	University of California, Irvine	Martha Mecartney

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2014 NEUP, IRP, and Mission Supporting Awards related to FCRD AFC

Award Title	University	Lead PI
(Project 14-6472) Computational and Experimental Studies of Microstructure-Scale Porosity in Metallic Fuels for Improved Gas Swelling Behavior.	University of Arkansas	Paul Millett
(Project 14-6893) Enhanced Accident-Tolerant Fuel Performance and Reliability for Aggressive iPWR/SMR Operation	University of Tennessee-Knoxville	G. Ivan Maldonado
(Project 14-6482) Studies of Lanthanide Transport in Metallic Nuclear Fuels	Ohio State University	Jinsuo Zhang
(Project 14-6767) Thermal Conductivity in Metallic Fuels	Virginia Polytechnic Institue and State University	Celine Hin
(Project 14-6317) Assessment of Corrosion Resistance of Promising Accident Tolerant Fuel Cladding under Reactor Conditions	University of Notre Dame	David Bartels
(Project 14-6604) Development of high performance ODS alloys	Texas A&M University	Lin Shao
(Project 14-6356) Development of Self-Healing Zirconium-Silicide Coatings for Improved Performance of Zirconium-Alloy Fuel Cladding	University of Wisconsin-Madison	Kumar Sridharan
(Project 14-6311) SiC-ODS Alloy Gradient Nanocomposites as Novel Cladding Materials	Virginia Polytechnic Institue and State University	Kathy Lu

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2015 NEUP, IRP, and Mission Supporting Awards related to FCRD AFC

Call	Award Title	University	Lead PI
FC-2.1: Advanced Nuclear Fuel, Cladding, and Core Components	Electrically-Assisted Tubing Processes for Enhancing Manufacturability of Oxide Dispersion Strengthened Structural Materials for Nuclear Reactor Applications	Northwestern University	Jian Cao
FC-2.1: Advanced Nuclear Fuel, Cladding, and Core Components	Multilayer Composite Fuel Cladding for LWR Performance Enhancement and Severe Accident Tolerance	Massachusetts Institute of Technology	Michael Short
FC-2.2: Advanced Characterization Techniques	Radiation-induced swelling and microcracking in SiC cladding for LWRs	University of Wisconsin, Madison	Izabela Szlufarska
FC-2.2: Advanced Characterization Techniques	Developing a macro-scale SiC-cladding behavior model based on localized mechanical and thermal property evaluation on pre- and post-irradiation SiC-SiC composites.	University of California, Berkeley	Peter Hosemann
IRP-FC-1: Evaluation of Fuels and Systems with Enhanced Accident Tolerance	Development of Accident Tolerant Fuel Options For Near Term Applications	Massachusetts Institute of Technology	Mujid Kazimi
MS-FC-1: Fuel Cycle R&D	Radiation Effects on High Thermal Conductivity Fuels	University of Tennessee at Knoxville	Steven Zinkle

FY2016 NEUP Call – FC 2.1

A number of advanced fuel concepts are currently being investigated by the FCRD AFC for application as accident tolerant fuels for the LWR fleet and advanced recycle fuels for future reactors. Proposals for separate effect experiments linking integral experimental data with microstructural-level material properties of candidate fuel system components are desired. These experimental activities should produce data to be used in the validation of material property and fuel performance models. The model(s) supported and developed should be consistent and compatible with the NEAMS MBM fuel performance tools. Proposals focused on advancing LWR accident tolerant fuel and advanced recycle fuel concepts currently under study by the FCRD AFC will be given higher priority.

Models and Phenomena of interest include:

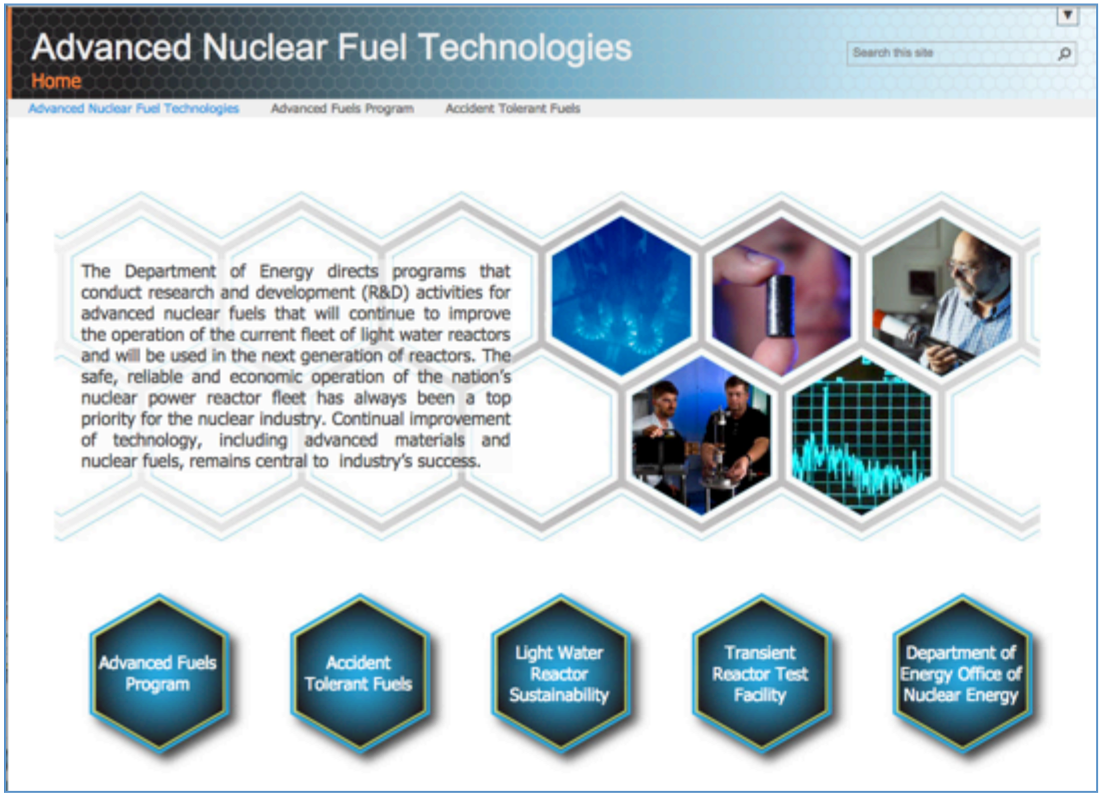
1) **Metallic fuel swelling, fission gas behavior, and fuel-cladding chemical interaction (vs. FMS cladding materials)**
2) **Creep and swelling of FMS cladding materials**
3) **Nitride-silicide composite ATF fuel swelling, fission gas behavior**
4) **Creep and corrosion resistance of FeCrAl cladding materials**

FY2016 NEUP Call – FC 2.2

The FCRD program is investigating transmutation fuels for use in fast reactors, which have the potential to significantly increase resource utilization, maximize energy generation, minimize waste generation and decrease the burden on future repositories. A current focus of the development effort is metallic fuel alloys. Proposals for optimized metallic fuel alloys which could improve the performance of traditional fast reactor fuels are requested. Improved performance is especially desired in the area of identification of minor alloy additions capable of immobilizing the lanthanide fission products, prevent their transport to the fuel-cladding gap, and thus minimize or eliminate the traditional fuel-cladding chemical interaction issue between metallic fuels and stainless steel cladding. Proposals should identify optimized alloys and/or alloy additions to be studied and develop an experimental plan to demonstrate improvements. Of particular importance is that the data generated be integrated with the development of a metallic fuel performance modeling capability using the NEAMS tools, BISON and MARMOT.

New Advanced Fuels Website

https://nuclearfuel.inl.gov



Accident Tolerant LWR Fuel Information Sheet

ENERGY | Nuclear Energy

Advanced Nuclear Fuels

Enhanced Accident Tolerant Fuels for Light Water Reactors

The safe, reliable, and economic operation of the nation's nuclear power reactor fleet has always been a top priority for the United States' nuclear industry. Continual improvement of technology, including advanced materials and nuclear fuels, remains central to the industry's success. Decades of research combined with continual operation have produced steady advancements in technology and have yielded an extensive base of data, experience, and knowledge on light water reactor (LWR) fuel performance under both normal and accident conditions. Thanks to efforts by both the U.S. government and private companies, nuclear technologies have advanced over time to optimize economic operations in nuclear utilities while ensuring safety.

Development Goal: Demonstrate performance by inserting a lead test rod or lead test assembly into a commercial power reactor by 2022 with deployment in the U.S. light water reactor fleet to follow within 20 years.

One of the missions of the U.S. Department of Energy's (DOE) Office of Nuclear Energy (NE) is to develop nuclear fuels and claddings with enhanced accident tolerance for use in the current fleet of commercial LWRs or in reactor concepts with design certifications (GEN-III+). In 2011, following the Great East Japan Earthquake, resulting tsunami, and subsequent damage to the Fukushima Daiichi nuclear power plant complex, enhancing the accident tolerance of LWRs became a topic of serious discussion. As a result of direction from Congress, DOE-NE initiated the Enhanced Accident Tolerant Fuel (ATF) Development program.

Current LWR Fuel

Today's U.S. commercial LWR fleet uses uranium dioxide (UO_2)-zirconium alloy fuel system to provide 70 percent of the nation's clean energy. Decades of industry research and operational experience have produced an extensive database supporting the performance of LWR fuel during normal power operations and during postulated accident conditions. 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.

ATF Program Goals

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-emitting electrical power in the United States.

Enhanced accident tolerant fuels would endure loss of active cooling in the reactor core for a considerably longer period of time than the current fuel system –

(Continued)

Improved Reaction Kinetics with Steam
- Decreased heat of oxidation
- Lower oxidation rate
- Reduced hydrogen production (or other combustible gases)
- Reduced hydrogen embrittlement of cladding

Improved Fuel Properties
- Lower fuel operating temperatures
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- Minimized fuel - cladding interactions

Enhanced Retention of Fission Products
- Gaseous fission products
- Solid/liquid fission products

Key considerations in establishing accident-tolerant fuel attributes

U.S. Department of Energy – Nuclear Energy

Recent Advanced Fuels Campaign Documents – Now Available

OSTI Document Links of Interest:

Overview of Accident Tolerant Fuel Program
http://www.osti.gov/scitech/servlets/purl/1130553

Accident Tolerant Fuel Performance Metrics
http://www.osti.gov/scitech/servlets/purl/1129113

2013 Accomplishments Report
http://www.osti.gov/scitech/servlets/purl/1120800

2014 Accomplishments Report
http://www.osti.gov/scitech/biblio/1169217

Contact Information

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  - Ken Kellar (Advanced Fuels Experimental Capabilities lead) kenneth.kellar@nuclear.energy.gov
- **AFC National Technical Director: Jon Carmack**
  - jon.carmack@inl.gov
- **Please review previous fuel related awards on www.neup.gov.**