U.S. DEPARTMENT OF ENERGY

Development of Light Water Reactor Fuels with Enhanced Accident Tolerance

Report to Congress
April 2015

United States Department of Energy
Washington, DC 20585

Message from the Assistant Secretary for Nuclear Energy

In the Senate Appropriations Committee Report (Senate Report 112-75), accompanying the Fiscal Year 2012 Energy and Water Development Appropriations Bill, the Committee recommended appropriations for the Department of Energy, Office of Nuclear Energy "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."

In the Conference Report accompanying the Consolidated Appropriations Act, 2012, H.R. Conference Report 112-331, 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."

The attached report provides the Department of Energy's plan, and initial steps already taken, to develop advanced light water reactor (LWR) fuels with enhanced accident tolerance in response to the Congressional request.

The timeline shown in the attached summary report extends to 2022. The Department developed this date in consultation with nuclear industry and national laboratory experts and believes this is a realistic and achievable demonstration date for this newly expanded area of work. Every effort will be made to accelerate this schedule, with the funding made available from Congress and expected cooperation from industry, to address this important area in a manner that best satisfies national requirements.

If you have any questions or need additional information, please contact me or Mr. Brad Crowell, Assistant Secretary for Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Peter B. Lyons
Assistant Secretary
for Nuclear Energy

This report is being provided to the following Members of Congress:

- **The Honorable Thad Cochran**
  Chairman, Senate Committee on Appropriations

- **The Honorable Barbara A. Mikulski**
  Ranking Member, Senate Committee on Appropriations

- **The Honorable Lamar Alexander**
  Chairman, Senate Subcommittee on Energy and Water Development Committee on Appropriations

- **The Honorable Dianne Feinstein**
  Ranking Member, Senate Subcommittee on Energy and Water Committee on Appropriations

- **The Honorable Lisa Murkowski**
  Chairman, Senate Committee on Energy and Natural Resources

- **The Honorable Maria Cantwell**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Harold Rogers**
  Chairman, House Committee on Appropriations

- **The Honorable Nita M. Lowey**
  Ranking Member, House Committee on Appropriations

- **The Honorable Mike Simpson**
  Chairman, House Subcommittee on Energy and Water Development Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Ranking Member, House Subcommittee on Energy and Water Development Committee on Appropriations

- **The Honorable Fred Upton**
  Chairman, House Committee on Energy and Commerce

- **The Honorable Frank Pallone, Jr.**
  Ranking Member, House Committee on Energy and Commerce

- **The Honorable Lamar Smith**
  Chairman, House Committee on Science, Space and Technology

- **The Honorable Eddie Bernice Johnson**
  Ranking Member, House Committee on Science, Space and Technology

- **The Honorable Mac Thornberry**
  Chairman, House Committee on Armed Services

- **The Honorable Adam Smith**
  Ranking Member, House Committee on Armed Services

- **The Honorable John McCain**
  Chairman, Senate Committee on Armed Services

- **The Honorable Jack Reed**
  Ranking Member, Senate Committee on Armed Services

Executive Summary

Development of Light Water Reactor Fuels with Enhanced Accident Tolerance – Report to Congress

After the March 2011 events at the Fukushima Daiichi Nuclear Power Plant in Japan, enhancing the accident tolerance of light water reactors (LWRs) has become a topic of serious discussion. In the Senate Report 112-75, the Senate Appropriations Committee requested a report from the Department of Energy (DOE) regarding the Department's plan for development of fuels with enhanced accident tolerance. In the Conference Report to accompany the Consolidated Appropriations Act, 2012, H.R. Conference Report 112-331, the U.S. Congress provided funding to the DOE Office of Nuclear Energy (DOE-NE) to start developing nuclear fuels and claddings with enhanced accident tolerance. This report provides DOE's plan to develop light water reactor (LWR) fuels with enhanced accident tolerance in response to the Congressional direction and funding authorization.

The result of the accident tolerant fuel development activities, if successful, will be a commercial product that is utilized in existing and future nuclear power plants. While the end user of the new technology will be the nuclear industry, the government has a major role in performing the initial RD&D to support the effort, because the effort is primarily focused on continued use of clean energy technology with enhanced safety that is in the public's interest. This is consistent with the historical government-industry partnerships in the development of the existing nuclear fuel systems.

In the first year of funding (FY 2012) the DOE issued two competitive funding opportunities, one specifically for industry led projects where the work was to be performed on a cost share basis (industry provides an increasing portion of the funds to supplement the government funds as the technology nears commercialization). Three awards were made to multi-institutional teams led by Westinghouse, General Electric, and AREVA. These awards demonstrated industry commitment to and leadership of the technology development of accident tolerant nuclear fuels. The second funding opportunity was made specifically for U.S. university led projects for research and development of accident tolerant fuel technology. These two efforts, fully integrated with DOE laboratory efforts under the Fuel Cycle Research and Development Advanced Fuels Campaign, also demonstrated the complementary role of U.S. industry and universities in technology development. DOE infrastructure and resources will be used primarily for supporting activities related to the testing and qualification of accident tolerant fuel systems and the nuclear industry will retain the primary responsibility commercializing specific accident tolerant fuel technology.

The current UO_2-Zircaloy fuel system used today in commercial nuclear reactors around the world has been in use, in its basic form, since the first deployment of commercial nuclear power reactors. Incremental improvements in the basic design have been made over the years for the purpose of increasing life and performance, and improving manufacturing efficiency. It has an excellent performance history but it is proposed that improvements in the fuel system's normal and off-normal performance could be made with coordinated cooperation between the DOE and the nuclear industry with the purpose of developing a high performance fuel system with enhanced accident tolerance. The UO_2-Zircaloy fuel system we have today is a result of at least half a century of research, development, and operational experience gained through fabrication process optimization, extensive out-of-pile testing, in-pile steady-state, and transient test reactor experiments, and finally operation of commercial nuclear power plants around the world. The infrastructure used to perform this extensive research, development, qualification, and licensing partially exists today in the DOE Complex, but many capabilities have been shut down, decommissioned, or otherwise removed from service. Hence, development and qualification of a new more accident tolerant fuel system will require the combined effort of DOE, industry, and university resources, including strategic investment in DOE laboratories.

Fuels with enhanced accident tolerance are those that, in comparison with the standard UO_2-Zircaloy system currently used by the nuclear industry, can tolerate loss of active cooling in the reactor 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, operational transients, as well as design-basis and beyond design-basis events.

The vision is a light water reactor fleet using fuels with enhanced accident tolerance to provide a substantial fraction of the world's clean energy.

The current fleet of commercial nuclear power reactors (GEN II) as well as the next generation of commercial nuclear power reactors will benefit from a more robust and accident tolerant fuel system. Next generation reactor designs (GEN III and GEN III+) incorporate many features that improve the performance, safety, coolability, and survivability of the nuclear power plant system under accident conditions. Fuel system design objectives already identified as potentially important to improve accident tolerance include: reduced hydrogen generation, improved fission product retention, improved cladding reaction to high-temperature steam, and improved fuel cladding interaction for improved performance under extreme conditions. Additional performance benefits may also be possible depending on the accident tolerant fuel technology. Performance improvement may improve the overall economics of the nuclear fuel cycle.

RD&D strategy for enhanced accident tolerant fuels

The overall strategy for development, demonstration and deployment is comprised of three phases:

1. Feasibility Assessment and Down-Selection

2. Development and Qualification
3. Commercialization

The report focuses on the activities that will take place prior to Phase 3, Commercialization. Based on the technologies demonstrated in the previous phase, commercialization would be the primary responsibility of the nuclear industry. The activities performed during the initial feasibility assessment (Phase 1) include laboratory scale experiments; fuel performance code updates; and analytical assessment of economic, operational, safety, fuel cycle, and environmental impacts of the new concepts, leading to down-selection. Development and qualification (Phase 2) consists of larger-scale testing and the establishment of the safety basis for the new fuel.

Recommendations

To sustain a strong program through the aggressive 10-year development and demonstration period, the following early recommendations were made:

- Program implementation must involve a collaborative industry/national laboratory/university team working together with DOE-NE every step of the way. The U.S. Nuclear Regulatory Commission (NRC) must be engaged early and integrated through every phase of development. The program has been initiated by establishing competitive funding opportunities for the nuclear industry and universities. Three competitively selected projects have been awarded to industry that includes industry matching funds and two competitively selected projects have been awarded to universities.
- The technical requirements and the detailed implementation strategy should be developed through a series of national workshops that focus on the execution strategy for the program and the technical requirements (metrics) for enhanced accident tolerance.
- To review the international perspective on attributes and metrics for enhanced accident tolerance, an international workshop will be conducted as early as possible into the program implementation.
- Once the candidate concepts are selected, the establishment of a national working group would enable the continuous review of the findings and progress and readjustment of the activities as needed. With specific task assignments, the NRC Office of Research would coordinate with the working group.

Fuel system design objectives important to improve accident tolerance, include:

- *Reduced hydrogen generation,*
- *Improved fission product retention,*
- *Improved cladding reaction to high-temperature steam, and,*
- *Improved fuel cladding interaction for improved performance under extreme conditions.*

- To continuously review and benchmark the international progress, an international working party/expert group will be established under the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) and coordinated with the International Atomic Energy Agency (IAEA).

Development of Light Water Reactor Fuels with Enhanced Accident Tolerance

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I. LEGISLATIVE LANGUAGE

This report responds to a request in the Senate Appropriations Committee Report accompanying the Fiscal Year 2012 Energy and Water Development Appropriations bill, Senate Report 112-75 on page 83, wherein it is stated:

"The Committee further recommends $59,000,000 for the Advanced Fuels program. With the increased funding the Department is directed 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. While the Committee acknowledges the value of engineering upgrades and regulatory enhancements to ensure the safety of the Nation's current fleet of nuclear reactors following the disaster at Japan's Fukushima Daiichi nuclear power plant, it is becoming increasingly clear that failure of the nuclear fuel upon loss of coolant was the ultimate cause of the destruction of the Japanese reactors and the extensive environmental damage. The Committee continues to support the Department's advanced fuels activities, in particular the ongoing coated particle fuel (deep burn) effort, and urges 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. Last, the Department is directed to 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."

In the Conference Report accompanying the Consolidated Appropriations Act, 2012, H.R. Conference Report 112-331, 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."

This report is provided to establish a roadmap defining the government/industry relationship and near term activities to be pursued in development of an accident tolerant LWR fuel technology in the 10 years envisioned for this program.

II. INTRODUCTION

The existing U.S. nuclear reactor fleet that provides 70 percent of the nation's clean energy utilizes light water reactors (LWR) that are fueled with uranium dioxide (UO_2) pellets and clad with zirconium alloy tubing. Decades of research combined with continued operation have produced steady advancements in technology and yielded an extensive operational database, experience, and knowledge about the performance of LWR fuel during normal, off-normal, and accident conditions. The nuclear industry has deployed technologies to optimize economic operation and continually enhance the safety and reliability of LWR fuel.

However, existing LWR fuel technology is near its inherent limit of performance. The Department of Energy, Office of Nuclear Energy (DOE-NE), in collaboration with the nuclear industry, has been conducting research and development (R&D) activities on advanced LWR fuels for the last few years. Prior to the March 2011 events at the Fukushima Daiichi nuclear plant, which exposed plant vulnerabilities during severe beyond-design-basis accidents; the emphasis for DOE-NE's R&D activities was on improving LWR fuel performance. Emphasis was placed on developing higher burnup fuels for waste minimization, increasing power density for power upgrades ("uprates"), plant life extensions, and collaboration with industry on fuel reliability.

The events at the Fukushima Daiichi nuclear plant, along with progress in the development of advanced materials, have provided the impetus to improve nuclear fuel performance and safety, thereby mitigating the effects of a severe accident. As a result, the emphasis of DOE-NE and industrial activities has shifted. With the support and funding provided in the Consolidated Appropriations Act, 2012, DOE-NE has initiated a program to accelerate improvements to LWR fuel performance and safety. This report outlines the plan to develop the next generation of LWR fuels with enhanced accident tolerance.

Vision

The vision is a national and international LWR fleet providing a substantial fraction of the world's clean energy while using fuels with enhanced accident tolerance that provide an increased retention of fission products within the fuel during extreme accident conditions.

Mission

The mission is to develop the next generation of LWR fuels with improved performance, reliability, and safety characteristics during normal operations and accident conditions while minimizing waste generation.

Scope

Enhancing the accident tolerance of LWR fuel is the focal point of the initiative. The initial RD&D efforts will focus on applications in operating reactors or reactors with design certifications. However, the knowledge and technologies developed will be incorporated, as appropriate, into the design of future reactor systems.

While outside the scope of this initiative, it should be noted that there are factors, in addition to advanced fuel designs, that will enhance the overall safety of the reactor system. Improvements that can be made to the system without intruding into plant operations or certified designs must also be considered. Examples include advanced instrumentation, advanced reactor components, plant equipment, auxiliary emergency power supplies, etc.

Goal

Consistent with the guidance provided by Congress accompanying the Consolidated Appropriations Act, 2012, the goal of this DOE effort is to insert a lead fuel assembly (LFA) or lead fuel rods (LFR) into a commercial LWR within 10 years (by the end of FY 2022).

Determination of the required test (LFA or LFR) will be dependent upon the complexity of the selected design and as such will be specified during the first 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. If the design changes at the assembly level are minimal, a standard assembly with only a few advanced fuel rods may be sufficient for commercial power plant irradiation. After this Government supported activity (Phases 1 and 2) the primary effort will be the responsibility of the nuclear industry.

III. DESCRIBING LWR FUELS WITH ENHANCED ACCIDENT TOLERANCE

Definition of Fuels with Enhanced Accident Tolerance

Fuels with enhanced accident tolerance are those that, in comparison with the standard UO_2-Zircaloy system currently used by the nuclear industry, can tolerate loss of active cooling in the reactor 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, operational transients, as well as design-basis and beyond design-basis events.

Attributes for Fuels with Enhanced Accident Tolerance

To mitigate or reduce the consequences of fuel failure due to steam exposure at elevated temperatures, the attributes identified in the following subsections will be considered.

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.

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.

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 which could result 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.

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.

Metrics for Fuels with Enhanced Accident Tolerance

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. Thus, an initial step in program implementation will be the development of quantitative metrics.

In addition, a primary early task associated with the DOE awarded, industry led technology development efforts is to evaluate all aspects of the development, qualification, and deployment of an accident tolerant fuel. This evaluation is to consider the above attributes and metrics as well as cost and economics best understood by the nuclear industry equipment vendors and utilities. It is expected that this type of evaluation led by the industry will provide a full measure of the approach and success of accident tolerant fuel deployment.

IV. CONSIDERATIONS FOR DEVELOPMENT

As stated in the introduction, the current nuclear power industry is based on mature technology and has a stellar safety and operational record. Except for a few extreme events, the current UO_2-Zircaloy fuel system meets all performance and safety requirements while keeping nuclear energy an economically competitive clean-energy alternative for the United States. Any new fuel concept proposed for enhanced accident tolerance under extreme events must be compliant with and evaluated against current design, operational, economic, and safety requirements. Fuel life cycle considerations must also be considered, especially for concepts that represent a significant departure from the current technology. Storage and handling requirements are examples of life cycle considerations beyond in-pile performance that must be evaluated prior to conducting significant development activities on any particular technology.

Current LWR Designs

In order to meet the desired development timeline, advanced fuel and/or cladding concepts developed under this initiative must be suitable for use in existing LWRs or reactor concepts with design certifications (GEN-III+). Longer term concepts may be considered in conjunction with the near-term focus as resources permit. Regardless of whether the actual deployment target is a current or future reactor, the fuel must be qualified in an existing commercial reactor. To contain development costs, the proposed fuel concepts should also not require significant plant modifications to implement.

Operational Considerations

Before introducing a new fuel into an existing or planned reactor system, plant operations must be considered. The new fuel system must maintain or extend plant operating cycles, reactor power output, and reactor control. Reducing the availability or power output would be disruptive to utilities; who would not readily accept this unless the benefits outweighed the lost productivity. To maintain current operation, some of the concepts may require higher enrichment. While the impact of higher enrichments is fairly well understood from a technical perspective, regulatory issues would have to be addressed. Because increased enrichment implies increased cost, a goal of the research and development program will be to develop technologies that either offset this increased cost or reduce the need for increased enrichment over current licensed levels.

Economic Impacts

After decades of development and optimization, the UO_2-Zircaloy fuel system is a streamlined technology that is a relatively small percentage of the overall nuclear electricity production cost. Any proposed fuel system is unlikely to be able to compete economically with the current system; at least not initially. Fuels that require enrichment higher than that of current fuel (about 4 to 4.5%) are especially likely to cost more because enrichment is a major cost contributor. Therefore, it is important to assess carefully the economic impact of the new technology and determine how much additional fuel cost the utilities will accept. As a potential solution, going to higher burnup (extended cycle with reduced waste and reduced refueling cost) and to higher power densities (power upgrades, or “uprates”) could mitigate some of the impact. While focusing on enhanced safety, it may be desirable, therefore, to maintain enhanced performance goals as an economic consideration.

Safety Envelope

The performance of the new fuel system will be compared to the performance of the UO_2-Zircaloy system to assess its accident tolerance. However, operational transients and design-basis accidents must be considered in evaluating the new fuel system. Specific emphasis on long-term station blackout, loss-of-coolant accidents (LOCAs), and reactivity insertion accidents will be made. Fuel performance during normal power transients (not resulting in forced reactor shutdown) must also be evaluated and must be shown to be similar or better than the current system.

For design-basis LOCAs, the U.S. Nuclear Regulatory Commission (NRC) is currently in the process of evaluating the safety envelope for high-burnup fuels, about 50 GWd/MTU (gigawatt-days per metric ton uranium). Because some of the issues are similar to those that need to be addressed by the new fuel system, this is an opportunity to closely work with NRC on assessment methodologies.

Fuel Cycle Impacts

The impact of new fuels on the front end of the nuclear fuel cycle must be carefully assessed within the framework of current and future regulations and policies. Some of the fuel systems that will be considered require higher enrichment. For instance, if an advanced stainless steel cladding replaces Zircaloy, the enrichment required could increase by 1 to 2%. On the other hand, the very robust fuel forms with multiple layers of containment and fission-product barrier (e.g. microencapsulated fuels) would require enrichment up to the low-enrichment limit of less than 20%. 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) must not be degraded; otherwise, engineering solutions must be augmented during storage and disposal.

V. DEVELOPMENT STRATEGY

Development and qualification of nuclear fuel is a well-established process. However, due to the scientific and engineering challenges associated with nuclear technology, fuel qualification can be a long and complicated process. This section details the strategy for development and qualification of advanced LWR fuels with enhanced accident tolerance. Figure 1 illustrates the three-phase approach leading to commercialization and the following subsections elaborate on the activities to be conducted during each phase. Table 1, found at the end of this section, summarizes the major milestones to realize demonstration in a commercial reactor by 2022.

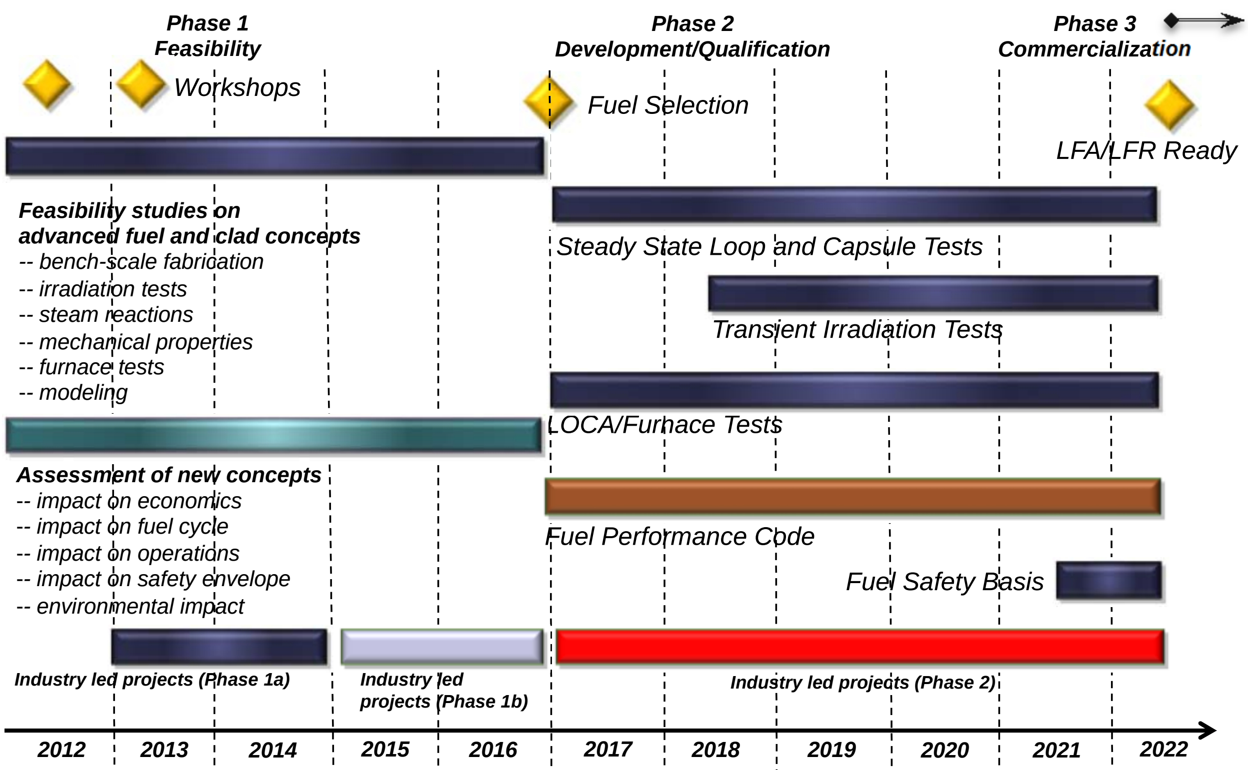

Figure 1: Development Plan

Phase 1: Feasibility Assessment and Down-Selection (FY 2012 – FY 2016) – Collaborative partnerships between DOE, industry, and universities

Collaboration between DOE, nuclear vendors, utilities, and others, including the international community, is an important step in this process. Led by DOE, teams made up of the nuclear vendors/utilities, national laboratories, universities, and international partners have been formed. These teams work in close coordination to develop and evaluate fuel concepts under development and qualification.

Initial small-scale and phenomenological testing will focus on obtaining the necessary data for feasibility testing. This will include activities such as: characterization of fabricated samples; high-temperature steam testing of cladding materials and fuel-cladding concepts with unirradiated and irradiated samples; mechanical and chemical property testing of cladding and fuel material before and after steam testing; irradiation testing of small samples; and associated post-irradiation examination (PIE).

Analytical assessments will be performed during this phase to evaluate promising concepts against the attributes and metrics identified in the previous section. Fuel performance codes will be used during this phase to the degree the relevant fuel and cladding property measurements and/or models are available for the various concepts.

The feasibility assessment phase will end in FY 2016 with a down-selection of one (or possibly two) concept(s) for further development.

Phase 2: Development and Qualification (FY 2016 – FY 2022) - Industry led efforts supported by DOE national infrastructure and universities

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

Qualification testing in a test reactor using long rodlets (about 36-inch fuel column) will cover fabrication variations, temperature, and linear heat-rate limits. Characterization, PIE, and the development of a fuel performance code will be part of the qualification process. Sufficient testing will be completed to establish the statistical database.

A transient testing capability with a water loop will need to be established. Experiments on unirradiated and irradiated fuel pins will be needed to establish fuel-failure modes and failure margins.

Table 1. Major milestones leading to commercialization

Fiscal Year	Milestones/Deliverables
Phase 1: Feasibility Assessment and Down-Selection	
2012	· Establish industrial, national laboratory and university collaborations through competitively selected, jointly funded projects.
2013	· Confirm attributes and develop quantitative evaluation metrics · Identification of promising candidate concepts for feasibility studies · High-temperature steam testing capability established
2014	· Start irradiation testing of candidate fuel samples · High-temperature steam testing with candidate material samples continue · Short-duration irradiation testing of initial candidate materials completed · PIE initiated · Selection of Transient Testing Alternative
2015	· High-temperature steam testing with high-dose irradiated samples initiated · High-dose irradiation testing and PIE on candidate materials initiated
2016	· Feasibility assessments completed · Down-selection of concepts for further development
Phase 2: Development and Qualification (dates indicated are subject to revision based on industry proposed actions)	
2017	· Arrangement established with vendor/utilities to jointly qualify fuel concepts · Test reactor irradiations of integral 36" fuel rod candidates initiated
2018	- Fuel experiments capability established for transient testing in water loop
2019	· Commercial-scale fabrication process established for candidate fuel(s) · Reactor-based impact assessment provided by vendor/utilities

2020	· Commercial reactor identified for LFA/LFR testing · Requirements for commercial reactor LFA/LFR established
2021	· DOE and its partners adequately meet NRC requirements and achieve acceptance to make the 2022 LFA/LFR goal occur.
2022	· Lead commercial power reactor LFA/LFR ready for insertion · Transfer to industry for commercialization

At the end of Phase 2 (FY 2022), LFA/LFRs will be fabricated, and the safety basis for irradiation in a commercial reactor will be completed. The irradiation and subsequent PIE of the LFA/LFRs will complete the development/qualification phase for LWR fuels with enhanced accident tolerance.

Phase 3: Commercialization (FY 2022 and beyond) - Industry commercial activity deploying ATF into existing and future reactor systems

This phase entails activities undertaken by the nuclear industry such as the establishment of commercial fabrication capabilities and the conversion of LWR cores into the new fuel. The commercialization phase primarily consists of up-scaling the technologies developed jointly by the government and the industry in the previous phases.

VI. COLLABORATION

Technology advancements are effective only when they are widely accepted in the United States and by the global nuclear community. New technologies must meet the needs of industry and have regulatory approval. DOE-NE is working with the nuclear industry, national laboratories, universities, the NRC, and the international community to define and implement specific goals for technology deployment.

The path forward for this collaborative development and deployment effort will demand industry engagement to identify prioritized industry-valued requirements for advanced LWR fuels and establish a business case based on the advantages of new fuels in life cycle economics, safety performance, and waste reduction. Industry teaming and cost share will be essential to success of this initiative.

Teams consisting of industry, national laboratory, and university partners will conduct the RD&D activities in the first two phases of this effort. The role of industry in this program is necessarily more prominent than with typical DOE-NE research programs to implement the new fuel into commercial reactors. Within the context of this program, industry includes both reactor and fuel vendors, as well as domestic utilities. Current costs of ATF technology development are born by both the industry leads and DOE-NE through cost-shared competitively awarded agreements. Once an LFA or LFR has been irradiated in a commercial nuclear power plant the cost burden will necessarily shift to the industry for full deployment.

The NRC Research Office is to be engaged from the beginning and participate in the RD&D team throughout development and commercialization, possibly through a joint working-group arrangement.

International collaborations can be very beneficial and must be leveraged whenever possible. After the March 2011 events at the Fukushima Daiichi nuclear plants, other countries with strong nuclear energy infrastructure also are investigating options to improve the accident tolerance of LWRs (including looking at more advanced fuel and core component options). Bilateral and/or multilateral R&D collaboration arrangements with those countries will provide additional data and analyses for input to the U.S. program. In addition, during the feasibility assessment phase, a working party/expert group type of arrangement will enable development of fuel attributes and evaluation metrics, as well as comparison and benchmark of R&D data and analyses tools.

VII. CAPABILITY NEEDS

Infrastructure for laboratory-scale fuel fabrication, characterization, irradiation, PIE, and fuel performance modeling and design is required for the development of advanced fuel concepts. Capabilities exist across the DOE national laboratory complex, the nuclear industry, universities, and internationally. Existing infrastructure will be used to the extent possible to support the program, although minor upgrades or adjustments may be necessary. A portion of the required testing and development program will require capabilities that are no longer available. In order to complete the development and qualification of a new fuel, some of the capabilities used to originally qualify the UO_2-Zircaloy system will need to be reestablished for use developing a new accident tolerant fuel. Currently, the DOE is in the process of restarting the needed test capabilities to support the evaluation and development of accident tolerant fuel.

High-Temperature Steam Testing

A high-temperature steam testing capability is required to evaluate cladding performance. Initial material tests will be performed on proposed cladding (without the fuel) and will serve as the first step in the down selection process. An in-cell high-temperature furnace testing capability is also needed to test irradiated fuel-cladding concepts at the maximum temperatures (dependent upon the accident scenario and fuel-clad concepts). This capability previously existed at the Argonne National Laboratory and it was extensively used in the development and understanding of current LWR fuel systems.

Irradiation Testing

Selected fuel concepts will need to undergo irradiation testing to determine steady state performance and failure thresholds. Test reactors are currently available to support this need.

Transient Testing

The ability to generate fuel performance data during a reactor transient is required for safety analyses and licensing purposes. In the regulatory licensing system, the data from transient testing provides an understanding of the margins to failure, failure thresholds, failure modes, and fuel behavior under a destructive sequence of events. Additionally, such data will be utilized to improve advanced computer models that predict fuel and reactor core performance in existing nuclear power plants and to guide the design of future generation nuclear plants.

Currently, very limited capabilities exist throughout the world to conduct transient fuel testing and the only domestic capability was suspended in 1994 and put in standby mode. Without re-establishment of such a capability, licensing and deployment of new fuels is unlikely. Therefore, some of the capabilities used to originally qualify the UO_2-Zircaloy system will be reestablished for use in qualifying a new accident tolerant fuel. The DOE is in the process of restarting needed transient test capabilities and oxidation environmental testing capabilities.

Post-Irradiation Examination

Significant out-of-reactor testing will be required to fully characterize the mechanical, physical and chemical properties of proposed materials and fuel concepts. Testing of cladding after irradiation and extended exposure to steam will be required to understand interactions with the fuel. Irradiated fuel and cladding will need to undergo detailed characterization to understand irradiation performance and failure mechanisms.

As a result of extensive efforts by DOE-NE, the U.S. PIE capabilities have been modernized in the last five years to a great extent. Previously, the instrumentation and facilities used were several decades old and based on first-generation technology. Modern, state-of-the-art instrumentation requirements are difficult to meet in existing facilities and with existing equipment. The United States is once again working toward world-class PIE capabilities through recent investments and the investments planned for the next few years.

Fuel Fabrication

Finally, towards the end of the development phase an engineering scale fuel fabrication capability will be needed for scale-up demonstration of the fabrication process and fabrication of the LFRs and/or LFAs. This capability need would be completed by a fuel vendor and would initiate the commercialization process.

Regulatory Framework

When development, qualification, and licensing of the UO_2-Zircaloy fuel system used today was first undertaken, the NRC and the DOE nuclear research organizations were combined under the U.S. Atomic Energy Commission. This relationship no longer exists in its original form for very specific reasons. It will be imperative that an excellent communication and data exchange be established as a key part of this effort to ensure that an independent NRC is well-informed in its public safety role in this R&D effort.

VIII. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

After the events at the Fukushima power plants in Japan in March 2011, enhancing the accident tolerance of LWRs became a topic of serious discussion. In December 2011, the U.S. Congress provided funding for the DOE Office of Nuclear Energy to start developing nuclear fuels and cladding with enhanced accident tolerance. This report is written in response to a request in the Senate Committee Report that accompanied the FY 2012 Energy and Water Development Appropriations bill.

This report outlines the path forward for development of advanced LWR fuels with enhanced accident tolerance. The proposed fuel concepts will be evaluated against current design, operational, economic, and safety requirements. Fuel cycle considerations must also be considered, especially for concepts that represent a significant departure from the current technology.

The outcome of this activity will be commercial demonstration of an advanced LWR fuel with enhanced accident tolerance by 2022. It is envisioned that once initial irradiation of accident tolerant technology is achieved then deployment of this technology across the entire United States commercial nuclear fleet would be pursued by the industry.

Recommendations

To sustain a strong program through the aggressive 10-year development and demonstration period, the following were recommended:

- Program implementation must involve industry/national laboratory/university teams working together with DOE-NE every step of the way. NRC must be engaged early and integrated through every phase of development. (This was initiated in 2012 with 3 industry and 2 university led efforts. Engagement with NRC has been initiated).

- The technical requirements and the detailed implementation strategy will be developed through a series of national workshops that focus on the execution strategy for the program and the technical requirements (metrics) for enhanced accident tolerance. (This was completed in 2012 and 2013).

- To review the international perspective on attributes and metrics for enhanced accident tolerance, an international workshop will be conducted as early as possible into the program implementation. (This was completed in 2012 with follow-on meetings planned).

- Once the candidate concepts are selected, the establishment of a national working group will enable the continuous review of the findings and progress and appropriate adjustments of the activities as needed. With specific task assignments, communications with NRC must be a key requirement of the working group. (This is an ongoing activity).

- To continuously review and benchmark the international progress, an international working party/expert group should be established (possibly under the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) and the International Atomic Energy Agency (IAEA) umbrellas). This was completed in 2012.