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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 light water reactors (LWRs) became a topic of serious discussion in the United States. In the Consolidated Appropriations Act, 2012, Conference Report 112-75, the U.S. Congress directed the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) to initiate a program focused on developing nuclear fuels and claddings with enhanced accident tolerance.

The United States Fuel Cycle Research and Development Advanced Fuels Campaign has been given the responsibility to conduct research and development on enhanced accident tolerant fuels with the goal of performing a lead test assembly or lead test rod irradiation in a commercial reactor by 2022. The Advanced Fuels Campaign has defined fuels with enhanced accident tolerance as 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 and operational transients, as well as design-basis and beyond design-basis events.

This paper provides an overview of the FCRD Accident Tolerant Fuel program. The ATF attributes will be presented and discussed. Attributes identified as potentially important to enhance accident tolerance include reduced hydrogen generation (resulting from cladding oxidation), enhanced fission product retention under severe accident conditions, reduced cladding reaction with high-temperature steam, and improved fuel-cladding interaction for enhanced performance under extreme conditions.

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 to that design, 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. A companion paper in these proceedings provides an update on the status of establishing these quantitative metrics for accident tolerant LWR fuel.[1]

The United States FCRD Advanced Fuels Campaign has embarked on an aggressive schedule for development of enhanced accident tolerant LWR fuels. The goal of developing such a fuel system that can be deployed in the U.S. LWR fleet in the next 10 to 20 years supports the sustainability of clean nuclear power generation in the United States.

I. INTRODUCTION

The existing U.S. nuclear reactor fleet utilizes light water reactors (LWR) with uranium dioxide (UO_2)-zirconium alloy fuel to provide 70 percent of the nation's clean energy. Decades of research combined with continued operation have produced steady advancements in technology and yielded an extensive base of data, experience and knowledge on the performance of LWR fuel during 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 unfortunate events at the Fukushima Daiichi nuclear plant, which exposed vulnerability during severe 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 and collaborating with industry on fuel reliability.

The events at the Fukushima Daiichi power 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, Conference Report 112-75, DOE-NE has initiated a program to accelerate improvements to LWR fuel performance and safety.

The goal of this program is to insert a lead test assembly (LTA) or lead test rod (LTR) into a commercial LWR within 10 years (by the end of FY 2022). Determination of the required test (LTA or LTR) will be dependent upon the complexity of the selected design and, as such, 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. 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.

II. DESCRIBING LWR 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.

II.A. 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 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 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 slower free hydrogen generation rate. Materials with lower heat of oxidation may be important in limiting the temperatures during an accident. Materials that are less susceptible to hydrogen diffusion may address the rapid embrittlement issue.

Fission Product Retention

Zirconium alloy 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 enhancement (especially for highly mobile fission products) would be a substantial improvement.

An accident tolerant fuel design goal would be to prevent melting or dispersion of the fuel by utilization of high temperature/strength materials. Additional fission product retention techniques such as 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[2].

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.

Advanced cladding materials should demonstrate 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.

It is desirable to develop fuels with reduced FCCI and FCMI, and with lower operating temperatures relative to the current zirconium alloy – UO_2 system. Higher melting point and structural integrity at high temperatures (i.e. less dispersive) are also desired improvements.

II.B. 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 enhance 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. A companion paper in these proceedings provides an update on the status of establishing these quantitative metrics for accident tolerant LWR fuel.[1]

III. 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 extremely rare events, the current UO_2-zirconium-alloy-based 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 rare events must be compliant with and 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.

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 and demonstrated in existing commercial reactors. Proposed fuel concepts should 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 levels, some of the concepts require higher fuel enrichment. While the impact of higher enrichments is fairly well understood from a technical perspective, regulatory issues would have to be addressed.

Economic Impacts

After decades of development and optimization, the UO_2-zirconium alloy fuel system is a streamlined technology that represents 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 (maximum 5%) are especially likely to cost more because enrichment is a major cost contributor and could additionally require modifications to the fuel fabrication facilities. It is important to carefully assess the economic impact of the new technology and to determine how much additional fuel cost the utilities will accept. Potential economic benefits may be realized by going to higher burnup (extended cycle with reduced amount of waste and reduced refueling cost) and operation at higher power densities (power upgrades). These actions 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-zirconium alloy 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 (RIAs) will be made. Fuel performance during anticipated transients without scram 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 Giga-Watt-days/metric ton). 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 and cladding 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 zirconium-based alloys, the enrichment required would increase by 1 to 2%. On the other hand, the very robust fuel forms with multiple layers of containment and fission-product barriers (e.g. microencapsulated fuels[2]) would require enrichment up to the low-enrichment limit of < 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 and fuel fabrication 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. 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.

IV. 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, along with the conservative approach to adopting new 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 phased 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 LTA or LTR demonstration in a commercial reactor in 2022.

PHASE I: Feasibility Assessment and Down-Selection (FY 2012 – FY 2016)

Collaboration between DOE, the nuclear industry, utilities, and others including the international community is an important first step in this process. Led by DOE, teams made up of the nuclear industry/utilities, national laboratories, universities, and international partners will be formed. Once established these teams will work in close coordination to develop and evaluate fuel concepts. This phase will continue with the selection of promising concepts for feasibility assessment.

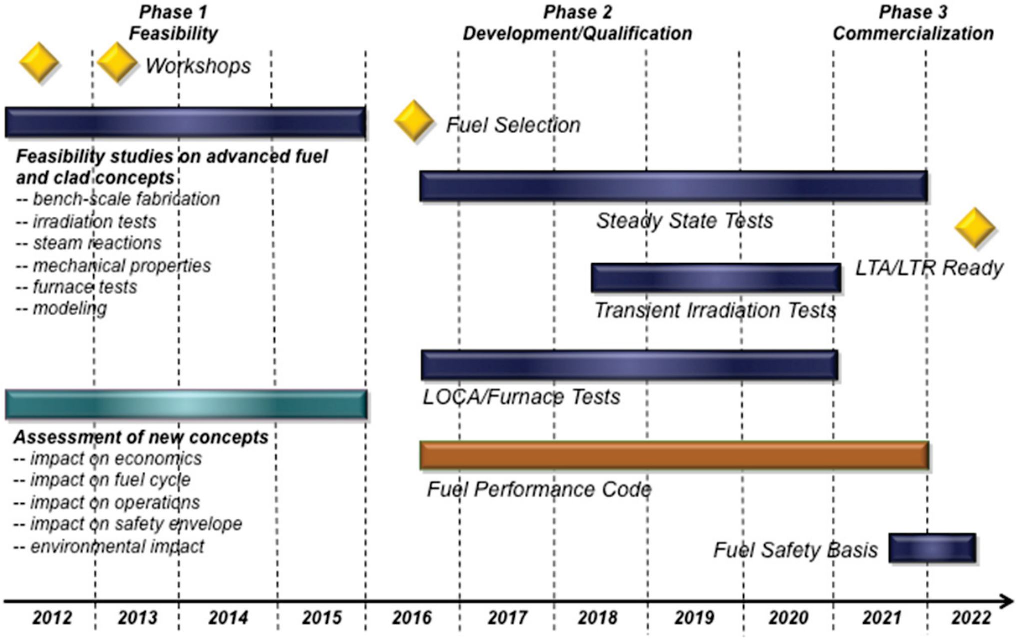

Figure 1: Accident Tolerant Fuel Development Plan

Initial small-scale and phenomenological testing will focus on obtaining the necessary data for feasibility assessment. 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).

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. Analytical assessments will be performed during this phase to evaluate promising concepts against the considerations identified in section III.

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

PHASE II: Development and Qualification (FY 2016 – FY 2022)

During this phase, the fabrication process will expand to industrial scale and fabrication of lead test assemblies (LTAs) or lead test rods (LTRs) will occur. Requirements for LTA/LTR testing will be established during the development phase. If the assembly design differs substantially from that of currently used UO_2-zirconium alloy assemblies, the qualification will likely require testing of a full assembly. If the assembly design is similar to that of the current design, a few LTRs incorporated into a fuel assembly containing UO_2- zirconium alloy 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.

Also, by 2018, a transient testing capability in a water loop will need to be established. Transient experiments on unirradiated and irradiated rodlets will begin in the FY2018 to FY2020 timeframe to establish fuel-failure modes and failure margins.

At the end of this phase (FY 2022), LTAs will be fabricated, and the safety basis for irradiation in a commercial reactor will be completed. The irradiation and subsequent PIE of the LTAs will complete the demonstration phase for LWR fuels with enhanced accident tolerance.

PHASE III: Commercialization (FY 2022 and beyond)

This phase entails the establishment of commercial fabrication capabilities and the conversion of LWR cores into the new fuel. This will primarily be a commercial activity performed by industry.

V. COLLABORATION

Technology advancements are effective only when they are widely accepted in the U.S. 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, deployment and commercialization 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 eventual cost share will be essential to success of this initiative.

A team led by DOE-NE and consisting of industry, national laboratory, and university partners will conduct the RD&D activities. The role of industry in this program must be much more prominent than with typical DOE-NE research programs because of the accelerated schedule to implement the new fuel into commercial reactors which will requirement early establishment of key utility partners for the demonstration LTR / LTA. Within the context of this program, industry must include both reactor and fuel vendors and domestic utilities.

The NRC Research Office must 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 enhance the accident tolerance of LWRs (including looking at more advanced fuel options). Bilateral and/or multilateral R&D collaboration agreements with those countries will certainly provide access to unique test facilities, data and analyses results for 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 analysis tools.

VI. 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 currently not available. In order to complete the development and qualification of a new fuel, these capability gaps will need to be addressed.

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 will also be needed to test irradiated fuel-cladding concepts at the maximum temperatures (dependent upon the accident scenario and fuel-cladding concepts). Both in-cell and out-of-cell high temperature steam testing facilities are currently being established within the DOE laboratories.

Irradiation Testing

Selected fuel concepts will need to undergo irradiation testing to determine steady state performance and failure thresholds. Steady state 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. 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, 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.

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.

While there are existing PIE capabilities, the instrumentation and facilities are 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.

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 LTRs and/or LTAs. This capability need would be best addressed by a fuel vendor and would initiate the commercialization process.

VII. 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, in the appropriation language, the U.S. Congress directed the U.S. Department of Energy, Office of Nuclear Energy to start developing nuclear fuels and cladding with enhanced accident tolerance. Although a challenging goal, the development of an enhanced accident tolerant fuel system is needed to fully investigate the possible improvements that could be made in the current reactor fleet. This activity, to be successful, requires the support and coordination of the nuclear community.

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