Accident Tolerant Fuel Technical Update

Valuation 1.0, Gap Analysis, and Valuation 2.0

3002012250

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Technical Update, May 2018

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ABSTRACT

Following the accident at the Fukushima Daiichi nuclear power plant, international research programs have led to the development of accident tolerant fuels (ATFs). ATF is defined as an improved fuel form that exhibits enhanced material response, when compared to traditional uranium dioxide fuel clad by zirconium-based alloys, while maintaining or exceeding fuel performance during normal operations, operational transients, and design-basis accidents. The goals of ATF are to reduce cladding oxidation reaction kinetics, minimize hydrogen generation rate, improve cladding thermomechanical properties, reduce pellet–cladding interaction, and increase fission product retention, among others. A number of ATF designs have been proposed: SiC cladding, FeCrAl (iron-chromium-aluminum alloy) cladding, coated zirconium-based alloy cladding, additive/doped UO_2 fuel pellets, and uranium silicide (U_3Si_2) fuel pellets. These ATF concepts have been categorized as either near-term or subsequent, based on the anticipated implementation time to full core deployment. Near-term concepts include those that maintain the existing UO_2-Zr fuel design with relatively minor changes designed to enhance safety. Longer-term or subsequent concepts significantly change the fuel system by replacing the fuel and/or cladding with materials that have not previously been reviewed and approved for use in commercial nuclear reactors; these concepts will likely require significantly more modeling and testing to support their licensing and deployment.

Keywords

Accident tolerant fuel
Benefits analysis
Gap analysis

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EXECUTIVE SUMMARY

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PRIMARY AUDIENCE: Engineers from U.S. and international nuclear power utilities who are interested in accident tolerant fuel (ATF) concepts.

SECONDARY AUDIENCE: U.S. and international managers, contractors, regulators, and others involved in development or review of ATF concepts.

KEY RESEARCH QUESTION

- Does the use of ATF provide enhanced safety with regard to severe accidents; if so, how can these enhanced safety benefits be used to improve plant efficiencies?
- Are there any material testing and/or unidentified new phenomena that would potentially pose a challenge to regulatory licensing and deployment of near-term ATF concepts, specifically for coated cladding and doped UO_2?

RESEARCH OVERVIEW

This report presents an update of the results from the safety and risk benefits analysis as well as gap analysis of the near-term ATF designs. The specific areas of interest include material data and modeling requirements, current U.S. technical licensing/regulatory criteria, and fuel and overall system performance during normal operation, transient conditions, design-basis events, and beyond-design-basis accidents. Future reports will provide more detailed information in these areas.

KEY FINDINGS

- For accidents in which all core cooling is lost for an extended period of time, the ATF Valuation 1.0 analyses identified that the current ATF concepts provide approximately 1 to 2 hours of additional time from the loss of cooling until the onset of core damage beyond that from conventional Zr-UO2 fuels.
- ATF provides delay in core damage, but restoration of core cooling is needed to prevent core damage during accidents in which all core cooling is lost for an extended period of time.
- In Valuation 1.0, Three Mile Island-2 (TMI-2) accident results indicated that the use of certain ATF concepts could have limited the core damage.
- The gap analysis of the technical regulatory requirements for the near-term ATF coating concepts indicate no new technical phenomena that would challenge the U.S. technical regulatory criteria.

WHY THIS MATTERS

This update will provide the nuclear industry with the required information to make informed business and technical decisions as related to the development, licensing, and deployment of ATF concepts. Furthermore, these reports could be used to inform ATF stakeholders as to what data are required to demonstrate enhanced safety to support the development of an economic business case.

HOW TO APPLY RESULTS

This report provides an update to the safety benefit and gap analysis of near-term ATF concepts that are expected to be deployed as full reloads by 2025. The safety benefits analyses include a broad spectrum of events including assessment of anticipated operational occurrence, design-basis accidents, other regulated events, and beyond-design-basis accident scenarios, and the near-term gap analysis assesses the technical licensing/regulatory criteria and full core deployment. The results of this research are intended for key stakeholders to use as input to ATF business case valuations, guide further development and licensing of ATF technologies, and lead to their eventual deployment.

Although the analyses in this update are mainly U.S.-centric, these results can be used for information and decision making for international utilities, vendors, and regulators.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- During the conduct of the research described in this report, EPRI has worked with the full spectrum of ATF stakeholders to develop a collaboration to provide technical input to the analyses. This collaboration currently consists of representatives from the U.S. Department of Energy, U.S. National Laboratories, fuel vendors and suppliers supporting the development of ATF, and U.S. operating utilities. As ATF technology development matures, it is anticipated that this collaboration will expand in scope in the United States and international entities.

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INTRODUCTION

1.1 Status of Accident Tolerant Fuel Development in the United States

Following the Fukushima Daiichi accident in 2011, the global nuclear community has engaged in research to develop advanced nuclear fuel designs commonly referred to as Accident Tolerant Fuel (ATF). The goal of ATF concepts is to increase the time to mitigate potential beyond design basis accident scenarios while meeting or exceeding current fuel safety/performance metrics for design basis accidents (DBAs), anticipated operational occurrences (AOOs), and normal operations. For this report, ATF has been defined as fuels with enhanced accident tolerance that can tolerate a severe loss of active cooling in the reactor core for a longer period of time as compared to current Zr/UO_2 fuel system. With this improved accident performance, ATF concepts are also expected to maintain or improve the fuel performance during normal operations, AOOs, and DBAs [1]. Therefore, ATF is a subset of advanced fuels that can provide improved fuel characteristics and material response during accidents while maintaining or exceeding normal reactor operational expectations. Key ATF targeted parameters under consideration and development include:

- Improved Performance under Severe Accident Conditions
  - Improve the current Zr-steam reaction kinetics
  - Reduced hydrogen production (or other combustible gases)
  - Reduce the generation or eliminate the heat produced from the exothermic Zr-steam reaction
  - Higher cladding melting temperature maintains fuel in a coolable geometry longer
- Improved Fuel Performance under Normal Operating and DBA Conditions
  - Higher fission gas retention that reduces rod internal pressure and thus reduce concerns with burnup extension and overpressure under transient conditions
  - Higher clad melting temperatures coupled with improved high temperature thermal-mechanical properties may provide increased tolerance to a short duration of DNB
  - Reduce/eliminate cladding embrittlement
  - Minimized fuel restructuring/relocation/dispersal to reduce accident impacts
  - Similar neutron parasitic absorption to maintain current fuel cycle economics
  - Higher fuel burnup capability to improve fuel cycle economics
  - Improved PCI performance via more compliant fuel pellets and improved fission gas retention
  - Improved the fuel pellet mechanical properties to reduce ramp rate restrictions at startup and during flexible operations

Since the initiation of the U.S. Department of Energy (DOE) funded ATF development program, a number of ATF cladding concepts have been investigated. These concepts range from adding a protective exterior coating to the cladding to replacing the current zirconium-based alloy cladding system with completely new materials. Examples of alternative claddings include:

- Ferritic stainless-steel (SS) alloys (e.g., FeCrAl), and
- Silicon carbide (SiC) based systems.

These concepts are being pursued with the intention that they could be developed, tested, matured, and commercialized within a relatively short period of time. In addition to replacement of zirconium-based alloy cladding, coated claddings, in which a thin layer of material is deposited onto the outer surface of zirconium-based alloy cladding, are being investigated. It is thought that the coated cladding concepts will not challenge the current U.S. licensing process, therefore, expediting the development of these concepts may have near-term benefits.

In addition to ATF cladding concepts, alternative fuel concepts have been proposed as well. These concepts are being investigated to either add dopants to the current UO_2 pellet matrix, replacing the existing UO_2 fuel pellet with a new material, and/or develop an exotic geometry capable of improving the fuel performance during an accident. One example is an advanced metallic fuel consisting of Zr-U metal. This fuel utilizes a multi-lobed helical geometry used to dramatically increase the fuel rod surface area. The combination of the high thermal conductivity of the metallic fuel and large surface area in contact with the reactor coolant result in an increase in heat transfer as compared to current fuel designs. The concepts under consideration are:

The concepts currently under investigation are:

- Uranium silicide (U_3Si_2) and
- Integrated uranium-zirconium metal fuel

1.2 Current Nuclear Fuels Paradigm

Currently, low natural gas prices, increasingly competitive renewable energy sources, social and political pressures, and high operating costs have placed significant stresses on the current nuclear fleet, risking this reliable, carbon-free, baseload electricity generation source. For nuclear plants to remain a feasible technology option, new technologies need to be implemented to improve the competitiveness of nuclear power. Advanced fuels have the potential to improve the economic performance of nuclear reactors as well as providing additionally operational flexibility for responding to variation in system energy demand. Specific advanced fuel technologies have the potential to offer multifunctional performance improvements over current fuel designs through improved safety under accident conditions, enhanced fuel reliability, efficiency, and performance during normal operations, and overall increased economic benefits with optimized fuel cycles.

Timing is a significant factor in the deployment of new advanced nuclear fuel concepts, such as ATF, to support the existing fleet of operating light water reactors. The development cost for advanced fuels would be amortized over the remaining life of the plants and therefore the unit cost of generation. Additionally, implementing these designs on a faster time scale, than traditionally employed, will provide safety benefits over a longer operating period. Therefore, accelerated design-to-deployment timeframes of advanced fuel concepts are vital. This is a significant challenge due to the typically long research, development, and demonstration (RD&D) and regulatory approval timeframes. Since the 1970s, the fuel development cycle included significant delays from conceptual design to commercial fleet-wide deployment. For example, the development to deployment of MOX fuels and advanced zirconium-based alloy claddings with small additions of Niobium, such as optimized ZIRLO™ and M5™, spanned 20 ± 5 years [1-3]. While the nuclear fuel industry has refined the fuel development process significantly through parallel development and testing approaches, further acceleration of the fuel development process may be limited by irradiation test data acquisition to support regulatory approvals. For example, a three-year irradiation period of a lead test fuel assembly in a commercial reactor will likely require 5+ years followed by post-irradiation examination (PIE), testing and analysis. Since the experience with fuel qualification largely assumes compatibility with existing fuel and core designs with incremental modifications and invariant geometry, significant departures from the current fuel and core component paradigms may require substantial RD&D efforts.

The research, development, licensing, and deployment of advanced nuclear fuels represents a substantial investment and collaboration among fuel vendors, operating utilities, regulatory authorities, and other governmental agencies. Coated cladding and doped UO_2 concepts offer minor to significant departures from current Zr-UO_2 fuel designs. For any new fuel technology to be economically feasible, substantial safety and economic benefits may be required to justify the adoption and wide-spread implementation of the new technologies, e.g., increased safety margins, enhanced fuel reliability, improved economic benefits, optimized fuel cycle operational strategies, reduced waste generation, etc.

Over the past year, the U.S. nuclear industry has been aggressively pursuing ATF concepts with the goal to improve performance during normal and accident conditions and deploy these fuels by the early to mid-2020s. In light of this goal, EPRI conducted an assessment on the technical and regulatory challenges that exist across the entire fuel cycle with the specific focus on licensing and full core deployment of ATF concepts as well as assessing the challenges with enrichments above and below 5% by weight. This assessment has been illustrated in Figure 1-1.

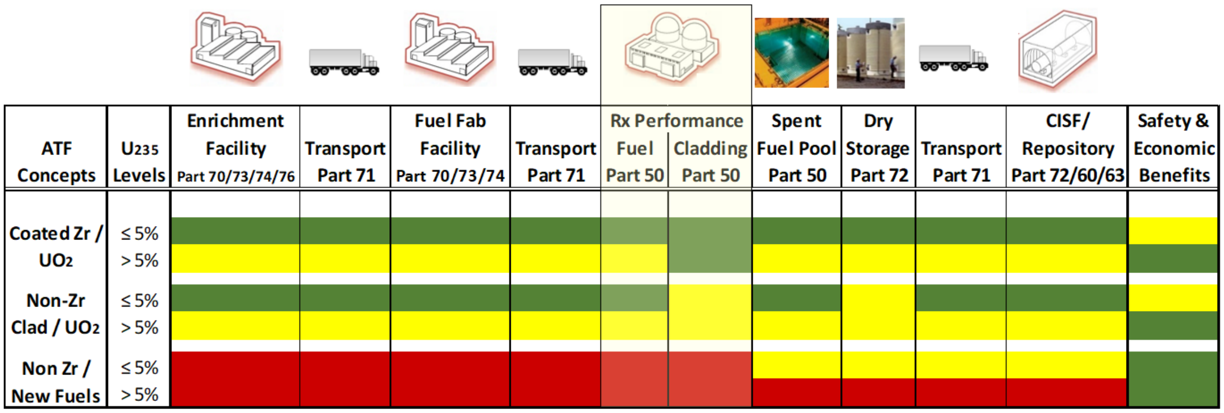

Figure 1-1
Illustrating the technical and regulatory challenges existing across the entire fuel cycle

1.3 Industry Needs and Business Case Development

Existing light water reactors use conventional nuclear fuel comprised of sintered and pressed uranium oxide (UO_2) or mixed uranium-plutonium oxide (MOX) pellets encapsulated within tubes of zirconium-based alloy cladding and arrayed in fuel assembly bundles. Enrichments for typical fuel rods are between 3-5 wt.% ^{235}U, specifically designed to optimize the operational performance of a reactor. Decades of RD&D accompanied by over 60 years of commercial and test reactor operational experience has steadily generated technological advancements as well as an extensive operational base of both material response and performance. As a result, the current licensed fuel designs have been highly optimized to provide excellent performance and reliability during normal reactor operation. Furthermore, these fuel designs also meet all technical regulatory requirements for postulated design basis accidents (DBAs) and anticipated operational occurrences (AOOs). Additionally, these designs are expected to meet public safety objectives during design bases events when modern severe accident procedures are employed. As a result, current fuel designs have undergone extensive operational and safety optimizations, and for a utility to move to a more advanced fuels concept, advanced fuels will likely need to demonstrate significant safety and economic improvements.

Over the past year, the U.S. industry has been studying the potential enhanced safety margins and benefits associated with specific ATF concepts. The enhanced safety margins associated with the ATF concepts were assessed in relation to the existing Zr-UO_2 fuel system. This EPRI Safety Benefits Scoping Study or otherwise known as ATF Valuation 1.0 provided the analytical results indicating enhanced safety benefits and were provided to a utility committee to determine the potential hard dollar economic benefits as seen in Figure 1-2. This ATF business case assessment from the EPRI ATF Valuation 1.0 study was documented in NEI 17-08 [Rev A]. Ideally, ATF would provide concomitant safety and economic benefits through reduced operating costs.

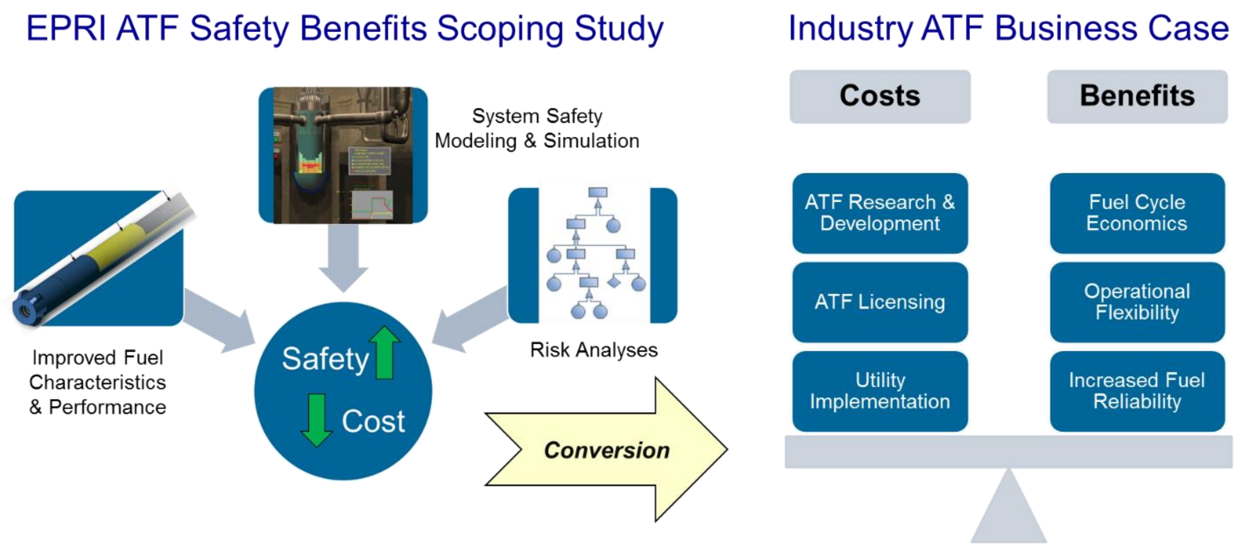

Figure 1-2
EPRI safety benefits analysis conversion into the Industry ATF Business Case for potential concomitant safety and economic benefits of ATF

An important consideration for the business case development is to obtain relevant information required to develop informed options leading to realistic decisions. Since ATF is still in the relatively early stages of development, the assessment of the potential safety and economic benefits through ATF Valuation 1.0 and 2.0 has just begun. As such, reliance on limited experimental data and expert judgements were needed to complete these assessments. EPRI developed a large collaborative team of ATF stakeholders including fuel vendors, U.S. utilities, Nuclear Energy Institute (NEI), DOE National Labs, academia, and R&D organizations to provide technical input to the analyses described in this report. As ATF concepts mature, it is anticipated that this collaboration will expand in scope as well as engage the Nuclear Regulatory Commission (NRC) and international members.

2
VALUATION 1.0

ATF Valuation 1.0 was an assessment of ATF system performance based on available ATF material properties and fuel performance data. The early adoption of ATF by commercial reactor owners/operators is predicated on the need to assess the potential benefits from ATF with the associated implementation costs. ATF Valuation 1.0 was the initial step to assess and quantify the various safety enhancements offered by ATF. For the initial ATF safety impacts assessment, the performance of each ATF concept was evaluated for a number of postulated accidents. These assessments consisted of performing safety analyses for critical accident sequences and comparing the ATF results against those obtained for the same events calculated using current fuel designs. At this stage of development, there are significant uncertainties associated with the proposed ATF concepts, and therefore, the outcomes from the safety analyses and resultant benefits assessments likewise possess significant uncertainties as well.

The following design basis, other regulated events, and beyond design basis accident sequences were evaluated, further illustrated in Figure 2-1.

- BWR Large Break Loss of Coolant Accident (LB-LOCA)
- BWR Short-Term Station Blackout (ST-SBO) and Long-Term Station Blackout (LT-SBO)
- PWR Short-Term Station Blackout (ST-SBO) and Long-Term Station Blackout (LT-SBO)
- Loss of Feed Water (PWR) and Turbine Trip (BWR)
- Three-Mile Island and the Fukushima Accidents

BDBA Scenarios and other Regulated Events:	Fuel:	UO_2	UO_2	UO_2	Cr-Doped UO_2	U_3Si_2	UO_2	U_3Si_2	U-Zr 50/50 w/o
	Clad:	Zr	FeCrAl	Cr-Coated Zr	Cr-Coated Zr	Zr	SiC	SiC	Zr
SBO	PWR	√	√	√	√	√	√	√	√
	BWR	√	√	√	√	√	√	√	√
Fukushima	BWR	√	√	√	√	√	√	√	√
TMI	PWR	√	√	√	√	√	√	√	√
DBA/AOO Scenarios:									
LB LOCA	PWR	√	√	√	√	√	√	√	√
	BWR	√	√	√	√	√	√	√	√
SB LOCA	PWR	√	√	√	√	√	√	√	√
	BWR	√	√	√	√	√	√	√	√
LOFW	PWR	√	√	√	√	√	√	√	√
Turbine Trip	BWR	√	√	√	√	√	√	√	√

Figure 2-1
ATF Valuation 1.0 cases by specific ATF concepts

2.1 Preliminary Valuation 1.0 Results

In addition to the impact of various ATF designs on plant response during these events, a representative plant probabilistic risk assessment was evaluated to obtain initial estimates of the potential reduction in plant risk as a result of adoption of ATF. The result of most interest were with regards to the Three Mile Island benchmark case.

The Three Mile Island Unit 2 (TMI-2) accident resulted in the most significant core damage event in the history of US nuclear power plant operation. On March 28th, 1979, the reactor core partially melted, due to a combination of equipment malfunctions, design issues, and operator errors. As such, TMI-2 offers a series of unique events which can be used to understand the core degradation phenomena during a severe accident. This accident has been extensively analyzed. Since the TMI-2 accident serves as a primary validation benchmark for the MAAP code, key elements for the accident progression are provided in the code documentation. Although not all aspects of the TMI-2 accident scenario are known, studies suggest that the core water level dropped below the top of active fuel (TAF) between 1:54am and 2:00am. During this time, hydrogen generation occurs from the exothermic reaction of zirconium-based alloy and steam, resulting in a significant increase in containment radiation levels at 2:20am. At this time, core temperatures were around 1200K – 1300K.

The oxidation characteristics of zirconium-based alloy in the typical UO_2/Zr fuel design are significantly different than the oxidation characteristics of the proposed ATF materials. In order to understand how these proposed ATF materials will react to an accident similar to TMI-2, accident analysis using MAAP5.05 Beta was used substituting zirconium-based alloy's thermal properties and oxidation kinetics with those of the ATF fuels. Specifically, properties and oxidation kinetics were modeled with MAAP5.05 Beta for SiC, FeCrAl, and Cr-coated Zr. The U-Zr metallic fuel has a Zr cladding with a fuel rod design that may allow 40% more cladding surface area. Thus, for the MAAP5.05 Beta model of the metallic fuel, standard zirconium-based alloy properties and oxidation kinetics models are used, and the cladding surface is increased by 40%.

Results from MAAP5.05 Beta simulations indicate a significant reduction in core damage for the TMI-2 event when cladding materials such as SiC, FeCrAl, or Cr-coated Zr are used as opposed to zirconium-based alloy. Additionally, because of the increased zirconium-based alloy cladding surface area and lower melt temperature of the U-Zr metallic fuel (relative to UO_2 fuel), core damage for the metallic fuel is predicted to occur earlier as well as more extensive than standard UO_2/Zr fuel designs. However, an important caveat in this analysis is the uncertainty to whether the operators would have been provided sufficient information to allow them to take the same actions at the same time if the fuel consisted of ATF materials.

ATF Valuation 1.0 major conclusions include and to be further expanded on in the full report in the future:

1. For accidents in which all core cooling is lost for an extended period of time, ATF technologies that only replace the zirconium-based alloy cladding may result in, ~ 1-2 hour, increase the coping time from the initiation of the loss of cooling until the onset of core damage.
2. ATF concepts that also replace the UO_2 fuel matrix will likely provide additional benefits; however, further analyses are required to incorporate results from ongoing material property testing in order to better quantify the benefits. Parametric studies of the heat capacities necessary to provide significant additional time, ~12-24 hours, to core melt during SBO sequences indicate that such material properties would require an order of magnitude increase as compared to current UO_2 / Zr fuel systems. The ATF materials currently under development are not likely to possess these properties.

3. In certain PWR SBO events, core damage was delayed by several additional hours due other induced failures in the reactor coolant system. These results indicate that more detailed ATF evaluations of the impact on the failure of other components are potentially required as these failure mechanisms may become limiting in a plant's ability to maintain a coolable core geometry and provide adequate core cooling. Additionally, the ATF concepts' thermal-mechanical properties, generally, have not yet been reported; thus, representing a significant gap in the state of knowledge.
4. Assessment of the impact of various ATF concepts on the design basis margin in a large break loss of coolant accident indicate that ATF concepts that replace the zirconium-based alloy cladding alone may result in minor margin improvement. However, analyses indicate that more advanced ATF designs in which the UO_2 fuel matrix is replaced by new materials may achieve significant improvements in margin. These ATF approaches may have the potential to provide significant safety benefits for design basis accident sequences while simultaneously supporting significant economic enhancements.
5. A representative BWR probabilistic risk assessment was evaluated to estimate the impact of ATF by providing additional time to implement mitigation actions during SBO sequences. This assessment found ~10% – 15% reduction in core damage frequency in cases where no FLEX actions were credited and ~15% – 20% reduction in core damage frequency in cases where credit for FLEX actions was taken.

It should be reemphasized that there are large uncertainties associated with all proposed ATF concepts, and it is essential to recognize the possible implications during decision making relative to the development and eventual adoption of ATF.

3

NEAR-TERM ATF GAP ANALYSIS

The goal for the Near-Term Accident Tolerant Fuel Gap Analysis was to identify any potential gaps that may impact the technical licensing/regulatory criteria and full core deployment of coatings and doped fuel pellets. The analysis assessed four aspects related to the fuel system and fuel system response to system transients:

- Material Data and Model Gaps
- Technical Regulatory Gaps
- Fuel Performance Gaps
- System Performance Gaps

The purpose of each aspect was to isolate and evaluate licensing/regulatory-specific technical requirements, whether experimental data, fuel performance analyses, and reactor system simulations, that may be needed to demonstrate the following: “(1) the fuel system is not damaged under normal operation and Anticipated Operational Occurrences (AOOs), (2) the fuel system damage is never so severe as to prevent control rod insertion when required, and (3) core coolability is always maintained” as stated in Section 4.2 of the Standard Review Plan (SRP). Furthermore, a systematic review assessed the applicability of the existing fuel design basis for doped UO_2 pellets and coated claddings to operate above 62 GWd/tU as well as to support increasing the fuel pellet enrichment to ensure current technical licensing/regulatory criteria are satisfactory and applicable to protect the fuel system at the targeted burnups and enrichments. The gap analysis results are summarized below and full described in a future EPRI report (3002014022).

3.1 Material Data Gaps

The near-term ATF concepts may have a few barriers in the licensing/regulatory process that could be overcome with modeling and test data. The largest needs are associated with the coated cladding concept. For this concept, material data is required for the coating. Since the parent cladding material is not expected to change, no additional experimental data seems to be warranted. Additionally, the coating will likely need to remain bonded to the zirconium-based alloy substrate throughout the entire irradiation process and, potentially, during all design basis accidents. In the event that the coating spalls off, the remaining cladding has already been approved by the regulator; therefore, no major negative effects are expected to occur, provided the coating does not impact the underlying material. However, the biggest barrier for coated cladding and doped UO_2 concepts would be to demonstrate that the ATF concept performs better than current fuel rod technologies. This could be demonstrated by gathering an extensive database targeting the various phenomena of interest.

3.2 Technical Regulatory Gaps

Section 4.2 of the SRP [4] was used as a guide to assure that all technical licensing/regulatory requirements for the fuel system are reviewed with respect to the near-term ATF concepts. The objective is to evaluate that, as a result of new materials, extended burnup operation, and increased pellet enrichment, the fuel system is not damaged under normal operation and anticipated operational occurrences (AOOs), fuel system damage is never so severe as to prevent control rod insertion when required, and that core coolability is always maintained. To meet the stated objectives, this review addresses the following three categories as described in SRP Section 4.2:

- Fuel System Damage (criteria most applicable to normal operation and AOOs);
- Fuel Rod Failure (criteria that apply to normal operation, AOOs, and postulated accidents) and;
- Fuel Coolability (criteria for postulated accidents).

As a result, it was determined that the current fuel design limits can appropriately address the effects of coated claddings and doped pellets within the design process, however, mechanical property data applicable to the target burnup level may be required.

3.3 Fuel Performance Gaps

Critical issues, i.e., those characteristics that may require additional experimental data and/or modeling to address because of their significance to in-core performance and/or the lack of available information, have been identified as part of the fuel performance gap analysis. Specific to advanced fuel performance codes, it may be warranted to explicitly model the coating and its interface with the zirconium-based alloy substrate to evaluate the impacts of the coating-cladding interface; however, licensing fuel performance codes may need to incorporate the effect of coating and/or spallation into the coolability methodology/calculations by generating test data assessing the coating-cladding interface under various scenarios. Furthermore, experimental data may be needed to validate the doped fuel and coated cladding behavioral and materials property models. In regard to doped UO_2, fuel material creep and plasticity, melting temperature, and fission gas release are deemed critical issues. Similarly, for coated cladding, the critical characteristics to be addressed include adherence and stability of the coating from the substrate, surface roughness, and cladding temperature (i.e., melting temperature). While the limited available information suggests that additional margin can be gained with the implementation of these near-term ATF concepts, additional data may be needed to demonstrate this. This test data, including those from lead test rod irradiations in-core to burnups exceeding current licensing/regulatory limits, may need to: a) address the identified critical issues, b) confirm acceptable performance during normal operation, AOOs, and Design Basis Accidents (DBAs) and c) validate behavioral/material properties models.

3.4 Systems Performance

Performance metrics were developed for integrated system level evaluations of ATF under all anticipated plant conditions including: (1) normal power operation, (2) AOO events specified in the plant safety analyses, (3) DBA events evaluated in plant safety analyses and incorporated in the plant design and licensing bases, (4) other regulated events, and (5) Beyond Design Basis Accident (BDBA) events that can result in severe accident conditions leading to fuel failure.

These metrics are intended to provide a consensus set that permits the various ATF stakeholders to evaluate the anticipated performance of different ATF concepts to the broad spectrum of plant operational regimes in a manner that is structured and consistent. They may also provide useful information to decision-makers to allocate funds and resources to permit the efficient and cost-effective development, licensing, and deployment of ATF across the fleet of operating nuclear power plants.

Furthermore, a systematic review of the technical licensing/regulatory requirements for increased pellet enrichment, >5 wt. % UO_2, and extended burnup operation determined that while it may be critical that additional data be collected and used to update existing fuel performance material and behavioral models, these two features alone do not seem to introduce new phenomena. Because the near-term ATF concepts do not introduce any fundamentally new phenomena, it is concluded that current methodologies are appropriate for modeling steady-state and transient/accident scenarios. The current criteria may be technically sufficient to meet the Specific Acceptable Fuel Design Limits required by General Design Criteria (GDC) 10 provided sufficient experimental data demonstrates compliance. However, going beyond 5 wt. % enrichment and >62 GWd/tU burnup will likely require additional testing.

3.5 Coating Spallation

Throughout the gap analysis, coating spallation is identified as the leading research focus area to expedite licensing and full core deployment of the coated cladding concept. The coating may be expected to adhere to the cladding, e.g., no spallation, for all normal operating conditions, including AOOs. DBAs, such as Reactivity Insertion Accident (RIA) and Loss of Coolant Accident (LOCA), have a higher potential for spallation to occur due to substantial localized cladding deformation. Depending on the coating, the coating could become activated during the irradiation process, and once it has spalled off, it can increase coolant radioactivity and overall radiological consequence. Furthermore, in sufficient quantities the spalled coating could block coolant flow effecting long term cooling and affect head loss and capture within fuel assemblies and Emergency Core Cooling System (ECCS) components. In the event of spalling during a DBA, the spalled coating may need to be accounted for in the accident source term methodology, calculations required to determine that the core geometry remains amenable to cooling, as well as the addition of the coating to the debris source term does not result in substantial head loss as discussed in GSI-191 (or GL 04-02 for PWRs) and GL 96-03 (for BWRs). Furthermore, the spalled fuel rods would need to maintain sufficient ductility to satisfy current 10 CFR 50.46 criteria.

4
VALUATION 2.0

ATF Valuation 2.0 builds upon the ATF Valuation 1.0 analysis and includes additional BDBAs, DBAs, other regulated events and AOO safety cases, fuel cycle optimization (increased enrichment and discharge burnups) assessments, and identification of additional benefits not previously captured in ATF Valuation 1.0. For example, the potential economic benefits that could be accrued from ATF could result in substantial cost reductions or plant performance enhancements including the following:

- Fuel cycle economics including the potential for improving the core design efficiencies, core operational thermal margins, capability to support (additional) power uprates, extension for lead rod burnup (beyond the current 62 GWD/MTU limit), and fuel reliability (i.e. reduced number of in-service fuel failures)
- Operational flexibility (particularly the potential to provide enhanced reactor maneuvering and “load following” capability)
- Utilize risk-informed regulatory initiatives to expand the application of benefits (specifically focused on improving the flexibility for implementing alternative treatments of plant structures, systems, and components)
- Reduce the regulatory burden including potential cost savings associated with the significance determination process evaluations and elimination or decreased requirements associated with plant structures, systems, and components that no longer provide a significant contribution to mitigating plant risk due to the deployment of the advanced fuels

These assessments indicated that the combined risk, safety, and economic benefits of advanced fuel designs would provide significant value to the commercial operating fleet and the public. These added benefits manifest in the forms of increased plant safety and performance resulting in lower cost carbon free electricity production. Mid-2020s Deployment of these technologies is essential for commercial utilities to achieve the full safety and economic benefits within a timeframe that would allow the technology to be used by the existing fleet to support a second license renewal period. The specific technical activities include:

- Perform assessments of fuel reliability and performance during normal operation and for select AOOs/ DBAs/ other regulated events / BDBA events with an objective to identify and quantify:
  - Fuel cycle performance and economic improvements
  - Improved operational flexibility
  - Enhanced fuel reliability and performance

These technical activities are being performed in a similar collaborative manner as ATF Valuation 1.0, which will include key stakeholders including the nuclear operating utilities, fuel vendors, DOE, NRC, academia, and national laboratories.

4.1 Fuel Cycle Optimization – Enrichment and Discharge Burnup:

Optimizing fuel cycle economics with advanced fuel concepts requires a reevaluation of the traditional regulatory 5.0 wt. % ^{235}U fuel enrichment and 62 GWd/MTU discharge burnup limits. The cycle length (interval between refueling outages) and discharge burnup significantly affects light water reactors operating costs. The choice of cycle length affects total energy production, fuel costs, and outage costs for a nuclear power plant. Most plants were originally designed assuming operation with 12-month intervals between refueling. In the United States, most light water reactors have extended their cycle lengths (nominal) to 18 or 24-months, while many European and Asian nuclear plants continue to operate with 12 to 15-month cycles. Increasing cycle length can increase energy production and reduce outage costs by reducing the number of refueling outages during the operating lifetime of a plant. This comes at the expense of increased fuel costs, but, less overall operating fuel and spent fuel for storage and disposal.

The fuel discharge burnup also affects the nuclear fuel costs for a commercial reactor. Increasing discharge burnup allows for more regions or batches of fuel to reside in the core at the same time, which tends to utilize the fuel more efficiently. Fewer new fuel assemblies are required each cycle resulting in lower fuel fabrication and storage costs. As a means of further optimization, increased fuel burnup requires the use of higher enrichment fuel. While this increases enrichment costs, the impact is compensated by the creation and fission of additional plutonium. A key note to make is, increasing fuel burnup may also require additional separate effects test (e.g., test data), advanced fuel assembly designs, and/or new materials capable of withstanding the higher fuel assembly duty.

The EPRI conducted a study on the issue of fuel cycle optimization in 2002 [3] and considered fuel enrichments greater than 5 wt. % ^{235}U to achieve higher discharge burnup levels. The report concluded that fuel costs continued to decline with increasing average batch discharge burnups. Since that study was conducted, fuel vendors have developed more advanced fuel designs, and several have adopted a dry UF_6-to-UO_2 conversion process. A dry process reduces the criticality safety impact, potentially reducing the significant one-time costs associated with modifying fuel manufacturing facilities to allow for production of fuel enriched in excess of 5 wt. % ^{235}U. Additionally, pressurized water reactor coolant chemistry restrictions are now employed to improve fuel reliability. These restrictions are not fully considered in the 2002 reports. The expected operating life of the plant is a significant economic factor to consider when evaluating the impact of increased fuel enrichments and discharge burnups. As a result, EPRI is reevaluating the cost benefit analyses for optimized fuel cycles with greater than 5 wt. % ^{235}U and discharge burnups greater than 62 GWd/MTU.

4.2 ATF as an Enabling Capability for Multifunctional Benefits:

Advanced nuclear fuels have the potential to provide multifunctional performance advantages over conventional Zr/UO_2 fuels with increased safety margins for beyond design basis accidents, other regulated events, DBAs, and AOOs while providing enhanced fuel reliability, improved economics through optimized fuel cycles, and reduced high-level waste generation. Current enhanced ATF concepts may enable the realization of the concomitant benefits from increased enrichments, higher discharge burnups, fuel additives, and crud resistance for more efficient operations. For example, the improved thermal-mechanical properties from ATF coatings may reduce cladding oxidation and hydrogen pick as compared to conventional Zr/UO_2 fuels during normal operation and DBAs. Reduced oxidation and hydrogen pickup may lead to further increased safety margins when coupled with coatings engineered to provide an increased resistance to crud deposition. These improved margins may then lead to more optimized fuel cycle designs, thereby improving plant economics along with enhanced safety. Due to the current state of the global nuclear industry and long timescales for fuel innovations, the future of advanced fuel concepts may not be tied to incremental improvements in performance, but, in coupled multifunctional performance gains.

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SUMMARY

EPRI is currently in the process of developing a safety and economic benefits case as well as providing a technical basis to inform the licensing and full core deployment of ATF. These will be documented in future reports and includes:

- Valuation 1.0: Evaluation of the Safety and Risk Benefits Associated with ATF Concepts

  This evaluation addresses the severe accidents that have occurred to date, other hypothetical BDBAs, severe DBAs, as well as other regulated events. The purpose of this evaluation was to determine the enhanced safety benefits presented by the ATF concepts and how the benefits can be used for our risk informed analyses. The results of this study demonstrated the proposed ATF concepts can improve the overall coping time by a small amount, ~1-2 hours. However, the biggest success is with regard to the TMI-2 accident. MAAP5.05 results indicated that ATF concepts significantly reduced the core damage by eliminating the exothermic Zr-steam reaction.

- Near-Term ATF Gap Analysis (EPRI report 3002014022, targeted for publication: July 2018)

  The “Near-Term Accident Tolerant Fuel Gap Analysis” documented a gap analysis performed assessed four groups related to the fuel system and fuel system response to system transients with the specific focus on licensing and full core deployment:

  - Material Data and Model Gaps
  - Regulatory Gaps
  - Fuel Performance Gaps
  - System Performance Gaps

  From this analysis, it was determined that separate affects data, similar to that for new zirconium-based alloy cladding concepts will likely be required. Furthermore, the current licensing/regulatory criteria was demand acceptable and relevant to the near-term ATF concepts, and current fuel performance codes and methods are adequate for these concepts. Note: for the fuel performance codes, the fuel codes may be required to validate the code following the implementation of any new material models. The larges concern for the near-term ATF is with regards to the delamination of the coating. The coating will likely be expected not to spall under normal operating conditions, however, the coating could be allowed to spall in the event of DBA. In the event of spalling during a DBA, the spalled coating may be accounted for in the accident source term methodology, all calculations required to determine that the core geometry remains amenable to cooling, as well as the addition of the coating to the sump screen debris source term does not result in substantial head loss across the sump screen as discussed in GSI-191 or GL 96-03. Furthermore, the User may need to demonstrate, through test data, that the spalled fuel rods maintain sufficient ductility to satisfy current 10 CFR 50.46 criteria.

- Valuation 2.0

  ATF Valuation 2.0 is follow on work derived from the ATF Valuation 1.0 analysis and includes additional BDBAs, DBAs, other regulated events and AOO safety cases, fuel cycle optimization (increased enrichment and discharge burnups) assessments, and identification of additional benefits not previously captured in ATF Valuation 1.0. As this work is ongoing, key conclusions are not ready to be reported.

These future reports as discussed above will provide the nuclear industry information needed to make informed business and technical decisions as the development of ATF concepts continue. Furthermore, these reports could be used to inform the ATF stakeholders as to what data might be necessary to show enhanced safety to support an economic business case.

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