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Safety and Economic Benefits of Accident Tolerant Fuel

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Revision Table

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NEI Project Lead: Aladar Csontos

NEI Project Support: Frances Pimentel, Senior Project Manager, Engineering and Risk

<u>Dominion Energy</u>
John Harrell

<u>Electric Power Research Institute</u>
Nathan Capps
Fred Smith
Bob Hall

<u>Framatome</u>
Bret Boman
Jeffrey Reed
Gary Peters

<u>JENSEN HUGHES, Inc</u>
Stephen Hess

<u>Westinghouse Electric Company</u>
Zeses Karoutas
Michael Shockling
Edward Lahoda

<u>Duke Energy Corporation</u>
Robert Rishel

<u>Exelon Corporation</u>
Bill Gassmann

<u>GE – Hitachi / Global Nuclear Fuel</u>
Fran Bolger

<u>Southern Nuclear Operating Company</u>
Susan Hoxie-Key
Owen Scott
John Williams
Johnathan Chavers

Disclaimer

This document was developed by the NEI[1] Accident Tolerant Fuel (ATF) Safety Benefits Task Force to provide an overview of potential benefits of ATF concepts. This evaluation is based on public information only. All figures regarding benefits or costs are based on non-proprietary, general industry knowledge and are intended to reflect only an “order-of-magnitude” illustration. They are not intended to predict results in particular situations or for particular facilities.

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[1] The Nuclear Energy Institute (NEI) is the organization responsible for establishing unified industry policy on behalf of its members related to matters affecting the nuclear energy industry, including the regulatory aspects of generic operational and technical issues. NEI's members include entities licensed to operate commercial nuclear power plants in the United States, nuclear plant designers, major architect/engineering firms, fuel cycle facilities, nuclear materials licensees, and other organizations and entities involved in the nuclear energy industry.

Executive Summary

After the accident at the Fukushima Daiichi Nuclear Power Plant, every aspect of nuclear plant operations was studied, including the existing uranium dioxide fuel pellets enveloped by zirconium-based alloys. The development of advanced fuel design concepts (Accident Tolerant Fuels [ATF]) was made a higher priority and accelerated by combining recent operating experience with worldwide research and development. In response to the U.S. Department of Energy (DOE) mandate from Congress, the DOE and industry have partnered to develop and deploy fuel technologies that enhance accident tolerance and provide operational resiliency while enabling sustained economic performance through minimizing cost and improving efficiency. These ATF concepts exhibit more robust fuel performance characteristics resulting in enhanced accident tolerance. Under the leadership of the Nuclear Energy Institute, the industry undertook an analysis of advanced fuel concepts, including the participation of fuel manufacturers, reactor licensees, the Electric Power Research Institute (EPRI), and others. The ATF Working Group was formed to assess the potential safety and economic benefits of ATF products and to determine how to accelerate the licensing of these ATF products for earlier deployment. The ATF Working Group along with the EPRI technical evaluations clearly demonstrated the potential safety and economic benefits to utilities resulting from the deployment of ATF products.

It is important to recognize that the transition to more robust fuel is not necessary to ensure high levels of safety for nuclear power plants. The nuclear fuel products used today in the 93 operating U.S. nuclear power reactors meet all regulatory requirements and have an excellent safety record. Accident Tolerant Fuels are the latest innovation the nuclear industry is undertaking to continue to improve safety and reduce operating costs. The improved material response of ATF provides additional margin during postulated accidents, operational transients, and normal operation; this increased margin reduces the likelihood of fuel failure. In addition, more robust fuels offer a number of economic advantages as well as the additional safety margin as described herein. These economic advantages have expanded recently with the passage of the Inflation Reduction Act in 2022 which provided federal tax incentives for clean energy production and investment at existing nuclear power plants. The additional safety and performance margins afforded by ATF could facilitate and expand the potential for power uprates to generate more clean energy thereby sustaining existing plants for longer operations.

Early and widespread adoption of ATF products is predicated on an economic business case that overcomes the costs associated with a new fuel product being inserted into a reactor. Engineers undertake extensive analysis, manufacturers change their manufacturing processes, and regulators must additionally conclude that the new fuel product will perform safely under both normal and unlikely plant operating conditions. These activities represent significant investments. Thus, before vendors, licensees and regulators embark on these activities, the costs and benefits need to be fairly established and the new fuel product's economic viability confirmed.

The economic benefits of ATF concepts are predicated upon the capacity of the new fuel product to support a wider range of operating conditions, and the ability to translate that wider range of allowable operating conditions into plant equipment and operating strategies that ensure safety and reduce operating costs. If an advanced fuel product could delay the onset of core damage following the failure of the core cooling system and all of its associated backup systems, more time would be available for operators to implement strategies to cool the core, thereby reducing the likelihood of core damage. Specifically, the use of ATF at the Three Mile Island Nuclear Power Plant more than 40 years ago would have reduced oxidation and therefore resulted in a reduction of the core damage or potentially prevented the core damage from occurring.

The analyses identified the following potential benefits for ATF products. The applicability and magnitude of each benefit would depend upon plant-specific conditions.

- **Improved Accident Performance**
  By improving robustness to various failure mechanisms and by generating less combustible gas during postulated accident scenarios, overall accident performance is improved.

- **Increased Fuel Cycle Flexibility**
  By enabling an increase in the allowable burnup, and by improving thermal margins, key limitations in core design can be ameliorated. This will enable plants to optimize fuel loading and/or cycle length to minimize fuel costs. Plants previously unable to economically transition to 24-month cycles may become able to do so with implementation of higher allowable burnup and higher enrichments. This will reduce the frequency of plant refueling outages, further reducing worker exposure and outage costs.

- **Improved Fuel Economic Performance**
  By reducing batch loading sizes or by extending cycle lengths, fewer assemblies would be used to produce the same amount of electricity. This reduces the amount of fuel that needs dry storage and disposal and billions of dollars would be saved on the back end of the fuel cycle (i.e., spent fuel treatments).

- **Improved Ability for Flexible Plant Electrical Output**
  Improved fuel robustness will improve a plant’s ability to respond to changing conditions on the grid (e.g., accommodate time-varying wind and solar electric output).

- **Reduced Susceptibility to Crud and Improved Tolerance of Aggressive Water Chemistry**
  By improving resistance to mineral deposits on the fuel cladding and by accommodating more aggressive water chemistry to reduce the inventory of minerals in the coolant, crud buildup can be reduced. The reduction of crud buildup will enable some plants to achieve greater fuel efficiency, reducing plant operating costs.

- **Increased Time Available for Mechanical Systems and Human Operators to React**
  Increased time for systems and operators to react during an event mitigates the likelihood of core damage accidents.

- **Improved Fuel Cladding Surface Robustness**
  By utilizing more robust materials, the cladding is protected and the risk of damage from debris and grid-to-rod fretting is reduced.

- **Reduced Duration of Shut-Downs for Refueling**
  More robust fuel will enable the fuel handling speed to be increased, reducing the time needed to prepare the core for the next cycle.

ATF products may offer improvements to nuclear plant safety while enabling the potential for fuel cycle cost improvements that result in improved economics. Additionally, the plant equipment and operating strategy changes allowed by the performance of ATF products may result in savings in Operation & Maintenance (O&M) and/or capital costs. Individual operators will need to gauge the applicability of the new fuel options to their own circumstances.

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1 INTRODUCTION

After the accident at the Fukushima Daiichi Nuclear Power Plant every aspect of nuclear plant operation was studied including the existing uranium dioxide fuel pellets enveloped by zirconium-based alloy tubes (cladding). Advanced fuel design concepts (Accident Tolerant Fuels [ATF]) were accelerated by combining recent operating experience with worldwide research and development. Advances in materials science have made it possible to make reactor fuels that are more robust and durable. ATF is defined as a reactor fuel product that exhibits improved material response when compared to traditional uranium dioxide fuel cladding enveloped by zirconium-based alloys (UO_2-Zr) while providing the capability to maintain or exceed fuel performance during normal operations, operational transients, and design-basis accidents.

Several ATF designs are being developed to enhance safety. These ATF concepts have been categorized as either near-term or long-term based on the anticipated implementation time to full core deployment. Near-term concepts include those that maintain the existing UO_2-Zr fuel design or that use previously-used iron-based cladding materials with relatively minor changes. Longer-term, or subsequent concepts, significantly change the fuel system by replacing the fuel pellet and/or cladding with materials that have not previously been reviewed and approved for use in commercial nuclear reactors; thus, these concepts are anticipated to need more modeling and testing to support their licensing and deployment.

In December 2016, NEI formed an industry working group to accelerate industry efforts for ATF deployment. A key effort was to develop information on ATF performance and to use the data to evaluate whether safety margins gained by using the new fuel might be used to also achieve cost reductions through operational and regulatory improvements. The working group established the NEI Safety Benefits Task Force (SBTF) to perform this work. The SBTF is comprised of utility representatives, nuclear fuel vendors, the Electric Power Research Institute (EPRI), and other technical/engineering organizations that provide services to nuclear utilities.

This report documents the activities of the SBTF through 2023. In 2017, the U.S. industry studied the potential enhanced safety margins and benefits associated with ATF concepts that are undergoing development. The enhanced safety margins associated with the ATF concepts were assessed in relation to the existing UO_2-Zr fuel system. Scoping evaluations conducted by EPRI indicated that safety benefits would be achieved from adoption of ATF by operating plants. This work was expanded in 2018 to broaden the scope of events analyzed to obtain a more complete understanding of both the safety and economic benefits that could be provided by ATF.

2 PURPOSE

This SBTF report identifies and quantifies the safety and economic benefits associated with various ATF concepts in different scenarios. The economic viability of ATF was investigated in a comprehensive safety benefits evaluation published by EPRI, “Accident Tolerant Fuel Valuation: Safety and Economic Benefits.”[2] The EPRI report contains detailed information regarding the quantitative technical evaluation that was performed for ATF.

Development, licensing, and deployment of ATF represent a substantial investment among fuel vendors, operating utilities, regulatory authorities, and other governmental agencies. ATF research intends to

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[2] Accident Tolerant Fuel Valuation: Safety and Economic Benefits: EPRI, Palo Alto, CA: March 2019. 3002015091

quantify the safety benefits, and to evaluate whether or not the additional safety margins provided could also yield an economic benefit for the commercial light water reactors. For ATF to be economically feasible, credited safety benefits may be necessary to provide economic incentives for nuclear power plants to transition from UO_2-Zr. The results are intended to support ATF business cases.

To maximize the economic benefit to utilities, given the remaining licensed lifetime of the existing fleet, ATF should be developed and deployed with urgency. The future sustainability of the commercial light water reactor fleet depends on industry’s ability to innovate at a pace which will allow the plants to remain economically competitive with other rapidly advancing energy technologies.

3 ATF CONCEPTS DESCRIPTION

As stated previously, ATF is defined as fuel that exhibits improved material response during postulated design basis accidents and severe accidents when compared to the traditional fuel system comprised of uranium dioxide fuel pellets contained within zirconium-based alloy cladding. Another primary ATF design characteristic is the capability to maintain or exceed current fuel performance during normal operations and operational transients. As the development of the various ATF concepts has progressed, it has become evident that improved fuel performance can be utilized to derive an economic benefit in many areas of nuclear power plant design and operation. This section discusses the various proposed U.S. ATF concepts and the associated basis for this improved fuel performance.

3.1 ATF Fuel Concepts

The primary ATF fuel types under consideration at present in the U.S. include doped uranium dioxide fuel and high-density fuels. These ATF fuel concepts would replace the uranium dioxide fuel pellets in the traditional fuel system currently used in existing plants.

Doped Uranium Dioxide

Doped uranium dioxide fuel pellets are fabricated with the addition of small amounts of dopants such as alumina and/or chromia to improve the pellet grain structure and improve mechanical behavior. The improved pellet grain structure can also increase uranium density and therefore improve fuel economics. The additives promote densification and diffusion during sintering. Doped UO_2 fuel contains several attributes which can potentially improve its viscoplastic behavior and economic performance relative to standard UO_2. Doped fuel has improved creep properties and cracking patterns, and thus features softer pellet-clad-mechanical interaction (PCMI) and correspondingly softer PCMI contact pressure. This softer contact improves stress, strain, and fuel conditioning margins. Doped fuel also features lower steady state and transient fission gas release and rod internal pressure, which reduces LOCA cladding burst probability and can also limit dispersal.

Higher Density Pellets

Non-UO_2 fuels such as U_3Si_2, $U^{15}N$, $U^{11}B_2$, and UC contain several unique attributes which can improve economic performance over the standard UO_2 fuel system. One primary benefit is the greater uranium density in these non- UO_2 compounds. For example, uranium silicide has 17% higher uranium density than uranium dioxide and a thermal conductivity 5 to 10 times higher than uranium dioxide. Uranium nitride has approximately a 40% increase uranium density and a similar increase in thermal conductivity as U_3Si_2 with a melting point that is as high as UO_2. Because of a uranium and U-235 density much greater than UO_2, these non- UO_2 fuels can mitigate or eliminate the need for enrichment greater than 5%, potentially producing large fuel cost savings and can provide additional fuel savings by allowing fewer assemblies to be loaded for typical fuel cycles. These non- UO_2 fuels typically have significantly higher thermal conductivity, which allows for a lower fuel temperature and lower stored energy during full power operation, which in turn improves transient, AOO, and LOCA performance since the cladding temperature increase during the event will be lessened. Due to the thermal conductivity improvement, transient and LOCA fuel rod ballooning and burst can be significantly reduced or eliminated, thus increasing PCT and cladding oxidation margins. Increased thermal conductivity along with increased U-235 density also allows for significant power uprates while maintaining cycle length and reducing issues such as centerline melt during transients. Another benefit of non- UO_2 fuels is reduced fission gas release, which in conjunction with improved conductivity and reduced stored energy can also help address rod internal pressure concerns and LOCA induced Fuel Fragmentation Relocation and Dispersal (FFRD).

Metallic Fuel

Metallic fuels include variants on uranium/zirconium alloys that are metallurgically bonded during fabrication and depart from existing cylindrical pellet-cladding technology. The main advantages include improved fuel rod integrity and thermal conductivity that result in lower fuel temperatures. The metallurgical bond between the fuel and cladding and lack of spacer grids can reduce the potential for localized fuel failures and fission product releases that are possible with current pellet-in-cladding designs under normal and design basis accidents, such as LOCAs. This concept would replace both the current uranium dioxide fuel pellet as well as the current zirconium-based alloy cladding material.

3.2 ATF Cladding Concepts

The primary ATF cladding types under consideration in the U.S. include coated zirconium alloys, advanced steels, and silicon carbide. These ATF cladding concepts would replace the current zirconium-based alloy cladding materials in the traditional fuel system currently used in existing plants.

Coated Cladding

The coated cladding ATF concept consists of a thin metallic or ceramic coating applied to the standard zirconium alloy cladding surface. The coating tends to improve the fuel robustness (resistance to failure during normal operation) and corrosion resistance. The principal safety advantage is reduced oxidation during postulated accident conditions that improves fuel safety margins and reduces the risk associated with hydrogen generation. For Cr-coated zirconium alloy cladding, many economic benefits have been identified. Numerous different LOCA tests have demonstrated that thermomechanical properties such as strength and creep time to rupture are improved relative to standard cladding, with corresponding significant decreases in balloon size and rupture opening. Ballooning has also been observed to occur at higher temperatures than in standard cladding. The higher temperature creep resistance, reduced oxidation, and higher burst temperatures lower the amount of deformation and the probability of burst during a postulated LOCA. Post-quench ductility is also improved. High burnup oxidation and hydrogen pickup are also reduced, resulting in improved material properties. With respect to CHF/boiling transition, the addition of Cr coating improves oxidation as well as cladding high temperature creep properties that can result in a significant improvement of survival time during DNB conditions which may allow the industry to move to a Time at Temperature criterion. Coated cladding experiences lower corrosion, hydrogen pickup, and hydrogen embrittlement, which can improve fuel licensing limit operational margin and enable higher burnup operation. Additionally, coated cladding has been shown to be more resistant to grid-to-rod and debris fretting, which can wear through the cladding. The harder and more resilient coated cladding could reduce operational costs through the avoidance of leaker rods.

Advanced Steel Cladding

Advanced steel cladding consists of variants of iron-based alloys such as iron/chromium/aluminum. Its main advantages are resistance to corrosion, improved strength and improved wear performance. These alloys have been used in high temperature industrial applications for many years (e.g., furnace tubes).

Testing performed as part of the ATF program shows improved oxidation performance under normal and postulated accident conditions. These ferritic iron-based alloys are predicted to substantially reduce hydrogen generation during postulated accidents. Fuel rod cladding made from advanced steel clad has been demonstrated to have several thermomechanical benefits when compared to standard cladding. Under normal operational states, the mechanical strength of advanced steel alloys is observed to be superior to the mechanical strength of zircaloy. Tensile testing of various advanced steel alloy tubes at temperatures representative of reactor operation indicated significantly improved properties over Zircaloy-2 in terms of ultimate tensile strength, yield strength, and Young's Modulus. Plastic yielding (ballooning) and perforation characteristics are demonstrated to be similar to or better than zircaloy. Analyses also indicate that cladding wall thickness can be reduced below that of standard fuel sufficient to allow for increased uranium loading, enabling overall cost neutrality compared with Zircaloy-2 due to parasitic neutron absorption in the advanced steel.

Silicon Carbide Cladding

Monolithic or composite silicon carbide cladding is a leading non-metallic cladding variant. It has the potential to tolerate temperatures far greater than current cladding material limits, providing severe accident improvements as well as margin for postulated accident scenarios. These improvements are dependent on the accident sequence and progression. Additional benefits from silicon carbide cladding include extremely low oxidation rates with the potential to dramatically reduce post-accident hydrogen production. Its high strength is expected to maintain a higher level of integrity during design-basis events, retaining fission products well into beyond-design-basis accident scenarios. Fuel rod cladding made from ceramic composites of silicon carbide has numerous attributes which can improve fuel cycle economics. These include improved physical/chemical properties, improved high temperature properties, irradiation resistance, capability for greater critical heat flux, and reduced parasitic neutron absorption.

3.3 Improved Fuel Performance

ATF cladding and fuel variants have several attributes which can address the most significant challenges to nuclear fuel reliability. ATF can reduce the risk of loss of the fuel rod cladding fission product barrier due to grid-to-rod fretting, debris fretting and corrosion, which are three of the most prevalent fuel reliability risks in the industry that impact economic performance during normal operation. Prevention of fretting and corrosion related fuel defects represents a significant economic benefit for the industry, and improved corrosion performance will also permit operation in more economically favorable water chemistry operating regimes.

The improved fuel performance of the ATF fuel and cladding types could be utilized to derive an economic benefit in many areas of nuclear power plant design and operation. For example, there are numerous benefits in the areas of fuel cycle economics and operational flexibility.

- In an ideal reactor, all of the neutrons generated by the fission events would be used to create additional chain reactions. This is not realistic as many of the materials will absorb neutrons. ATF concepts with some parasitic neutron absorption coupled with increased uranium density can produce an improvement in fuel cycle economics.

- Improved thermal conductivity can improve margin to fuel licensing limits.

- Improved pellet and cladding properties result in a more robust and durable fuel and reduce the potential for fission gas release.

- The more robust cladding variants have higher mechanical strength and hardness, and improved corrosion performance. These properties improve both safety margins and allow for more flexible design.

For Cr-coated zirconium alloy cladding, the improved hardness and wear behavior will result in increased wear resistance during normal operation. Cladding corrosion performance can also be improved as lower levels of oxide and lower levels of crud buildup are observed compared to standard zirconium alloys. Overall oxidation rates and weight gain, hydrogen pickup, and hydride formation also have been observed which compare favorably to zirconium alloy. Similarly, advanced steel cladding is very protective against debris fretting and corrosion during normal operation and has improved properties in those areas over standard zirconium alloy. Initial studies have also shown that silicon carbide can have an improved wear resistance and fretting performance, dependent upon the method of fabrication. In general, for many ATF cladding variants, modification to fabrication techniques or the proposed use of thin coatings may additionally improve fretting and corrosion performance.

Other benefits are noted during transient and accident scenarios such as improved cladding strength and a reduction in steam oxidation at high temperatures. One of the primary design goals of accident tolerant fuel is to resist fuel damage and to improve performance and coping time during severe accidents. Accident coping time is generally defined as the time lapse between the departure from normal operation and the point at which significant fuel damage occurs. This improved severe accident coping time will delay major amounts of fuel damage and loss of geometry and allow for greater opportunity for reactor core cooling to be reestablished. All ATF fuel and cladding variants increase severe accident coping time relative to standard UO_2 fuel/zirconium alloy cladding using the mechanisms described below.

- Cr-coated zirconium alloy cladding exhibits much slower high temperature steam oxidation kinetics, with a corresponding reduction in reaction heat, and a reduction in exothermic zirconium oxidation and hydrogen release; and with significant delays also in oxidation time and ballooning time. Ballooning temperature is also observed to increase. Cr-coated cladding is experimentally observed to maintain its integrity to a greater degree upon quenching and to exhibit a significant increase in critical oxidation time before post-quench loss of ductility and brittle behavior.

- Fuel rod cladding made from advanced steel clad also exhibits improved coping time and performance during severe accidents. This includes reduced reaction heat and hydrogen generation, and overall improved reaction kinetics. Post quench ductility is improved and the ability to maintain a post-accident coolable geometry is enhanced.

- Fuel rod cladding made from ceramic composites of silicon carbide has several enhanced accident tolerance physical/chemical and high temperature properties when compared to metallic cladding materials. Silicon carbide exhibits high temperature oxidation resistance and high temperature strength and can maintain a coolable geometry at high accident temperatures. Experiments have demonstrated that silicon carbide high temperature steam accident oxidation coping time is extended with no ballooning and negligible corrosion rates; thus, preserving damage tolerance and BDBA safety margin. Quenching behavior is also very good with minimal post quench cracking or spallation observed.

- Non- UO_2 fuels typically have significantly higher thermal conductivity, which allows for a lower fuel temperature and lower stored energy during full power operation, which can in turn improve severe accident tolerance. Oxidation, fission gas release, and burst characteristics during an accident are improved.

Studies of the Fukushima accident have shown that additional coping time, coupled with additional mitigating actions such as FLEX injection, might have significantly delayed or possibly prevented core damage from occurring. There are many areas of fuel and reactor design and operation where this safety increase can be translated into an economic benefit. By leveraging the improvements in performance, benefits can be derived in the areas of risk-informed regulations, plant equipment engineering, and flexible plant operations.

4 ATF SAFETY AND ECONOMIC BENEFITS

Accident tolerant fuel will benefit both the safety and economics of current operating plants. Work sponsored by the NEI ATF SBTF has examined the potential for ATF to benefit fuel cycle economics, to enhance fuel performance during routine plant operations and events that could challenge fuel integrity, and to provide opportunities to leverage ATF performance to relieve plant operating constraints. Section 4 provides a brief overview of analyses sponsored by the ATF SBTF and the results obtained.

Accident tolerant fuel and cladding variants have been conclusively demonstrated in the literature to significantly improve many of the characteristics necessary to derive economic benefits in fuel cycle economics and reactor operation. These ATF characteristics improve cladding resistance to high levels of stress and strain, improve LOCA performance via reduced cladding oxidation and reduced/eliminated fuel rod burst and fuel dispersal, and improve resistance to damage during events which result in departure from nucleate boiling. Of note is that these more robust fuel types can be used to justify higher exposure limits than standard fuel, which then in turn allows for the possibility of economic utilization of increased U-235 enrichments. The ability to support flexible operations such as load following is also improved as the fuel rod is better able to accommodate larger severity, magnitude, and duration of power changes.

The safety and economic benefits from the ATF fuel and cladding concepts described in Section 3 are categorized as either Fuel Cycle Benefits or Plant Performance Benefits; the distinction being whether the safety and economic benefits originating from the fuel performance properties of the ATF concepts are realized as part of the fuel cycle (fabrication, the fuel in the core during operation, and disposal) or occur in other aspects of plant operation.

These benefits are further classified by how the associated benefit would be realized.

- Benefits can be realized by utilities without regulator interaction
- Benefits can be realized by utilities with regulator interaction on a generic basis
- Benefits can be realized by utilities with regulator interaction on a plant-specific basis

Each ATF concept has specific benefits associated with it, and each plant is unique in its ability to realize the benefits. The specific benefits for a particular plant will be a subset of all the benefits described in this report, depending on plant specifics. These subsets of benefits may fall into one or both categories, and one or more of the classifications.

4.1 Fuel Cycle Benefits

The improved fuel performance aspects of ATF products will enable utilities to realize fuel cycle benefits. Fuel costs comprise approximately 20-25% of a nuclear power plant's total generating costs. The cost of this fuel is directly impacted by the efficiency of a core design developed to meet the plant's energy objectives. As noted in Section 3, ATF products have fuel performance benefits. These benefits can be realized in core design efficiency and fuel reliability and are expanded upon below.

Increased Cycle Length and Burnup, and Reduced Batch Sizes

Cycle length and discharge burnup provides the largest opportunity to significantly impact plant operating costs and strategies. Furthermore, cycle length affects the plant's total energy production, fuel costs, and outage costs. Most early plant designs were assumed to operate with 12-month intervals between refueling outages. However, many United States plants have extended their nominal cycle lengths to 18- or 24-months, while many European and Asian nuclear plants continue to operate with 12- to 15-month cycles. Extending operating cycles would reduce the number of times the nuclear plant would need to shut down for refueling over the course of its operating life, reducing worker exposure and outage costs.

The increased uranium density in the fuel pellets provided by some ATF concepts enables more efficient fuel usage, decreasing the number of fresh fuel assemblies needed to achieve a specific energy output. This can reduce fuel costs and the number of assemblies that enter the back end of the fuel cycle (i.e., storage and disposal). This will lower worker dose and utility costs.

ATF products can enable increased burnup and enrichment because these concepts provide enhanced performance during postulated accidents that are expected to be a limiting factor in high burnup applications. A sufficiently increased allowable discharge burnup would allow nuclear power plants to utilize some fuel assemblies for a longer time in the core, resulting in a more efficient use of the fuel. As a result, fewer fresh fuel assemblies would be required for each cycle. This would reduce the component costs of fuel including fabrication, conversion, and mining. These smaller batch sizes also could enable over a billion dollars in savings for the back end of the fuel cycle over the life of the reactor fleet.

While virtually all U.S. BWR reactors operate on a 24-month fuel cycle, only about 20% of the PWR plants can operate economically on a 24-month fuel cycle with the current burnup and enrichment limits. Increased burnup provided by ATF concepts coupled with increased enrichment would remove a key limitation in core design resulting in additional fuel cycle flexibility that could permit many PWRs to operate economically on a 24-month cycles.

The net savings for the fleet, assuming all PWR and BWR plants not currently operating on a 24-month cycle switch to a 24-month cycle, is $3.1 B or an average annual saving of $1.5M per reactor per year assuming the reactors have a 60-year operating life. Additionally, the number of dry casks needed to store spent fuel would be reduced by ~500 casks. If operation continues for an 80-year operating life, the net savings increases to $12.5B or an annual savings of ~$2.3M per reactor per year, and the number of dry casks needed to store spent fuel is reduced by ~1800. Additional details are described in the NEI White Paper, "The Economic Benefits and Challenges with Utilizing Increased Enrichment and Fuel Burnup for Light-Water Reactors."

Departure from Nucleate Boiling (DNB) and Critical Power Ratio (CPR) Margin

ATF concepts can provide plants more operating margin by allowing operation under more challenging conditions. The operating region would be expanded to include operation with departure from nucleate boiling (DNB) and critical power ratio (CPR) conditions for a limited amount of time. This additional margin extends the time without predicted fuel cladding failures during operating transient scenarios, thereby providing additional margin to plant operating limits. This benefit could allow for more efficient use of the fuel and could further reduce fuel costs or provide additional operational flexibility.

Crud and Aggressive Water Chemistry

The buildup of crud deposits on nuclear fuel rods creates operational issues, constraints on core designs, and may have been a factor in some recent fuel cladding failures. ATF cladding concepts may be more resistant to crud buildup. Furthermore, some ATF products can tolerate aggressive water chemistries due to cladding materials more resistant to mineral deposition. The aggressive water chemistries reduce the inventory of minerals in the coolant that cause crud buildup, potentially easing constraints on some PWR core designs allowing more efficient fuel and plant performance.

Fuel Reliability

The more robust ATF concepts would increase fuel reliability resulting in fewer fuel failures, reduced corrosion, and reduced exposure to plant workers.

BWR Non-zircaloy Fuel Channels

Non-zircaloy fuel assembly channels made of materials such as silicon carbide represent an opportunity for economic improvement for BWRs. Fuel channels represent a significant percentage of the zircaloy in a BWR core, and the reduced parasitic neutron absorption in SiC can translate into fuel cost savings. Additionally, other potential economic benefits exist, such as the potential for reduced channel distortion, the possibility to reuse channels for an extended lifetime, and greatly improved high temperature steam oxidation.

4.2 Plant Performance Benefits

4.2.1 Accident Performance

A variety of ATF concepts have been designed to improve performance during unlikely severe accidents, such as the Three Mile Island and Fukushima Daiichi events, as well as hypothetical design basis accident scenarios whose consideration is required by regulatory bodies worldwide. In addition, ATF concepts maintain or exceed normal reactor operational performance when compared to current fuel concepts. These characteristics provide a safety incentive for widespread adoption of ATF.

To assess and quantify ATF's enhanced safety benefits, a variety of domestic and international ATF stakeholders completed independent studies of ATF performance for severe accidents, licensing basis analyses, and normal operational benefits. Evaluations indicate that if ATF had been in use during an extended loss of power event with the loss of ultimate heat sink, similar to the conditions at the Fukushima Daiichi Nuclear Power Plant, operators would have had an additional 1 to 3 hours to cool the core and prevent core damage.

This additional time can allow operators to deploy equipment, such as Flexible Coping Strategies (FLEX), to possibly prevent or limit core damage. For the Three Mile Island event, the severe accident analyses indicated that specific ATF concepts would have reduced oxidation and therefore resulted in a reduction of the core damage or potentially prevented the core damage from occurring during that event. Overall, preliminary plant Probabilistic Risk Assessments (PRA) indicated that the additional coping time provided by the ATF concepts could reduce core damage frequencies (CDF), a measure of risk, by approximately 5%-20%.

ATF's enhanced mechanical strength at elevated temperatures, improved oxidation resistance, and reduced hydrogen production could directly benefit the plant licensing basis. The plant licensing basis analyses indicated that ATF would be capable of providing enhanced safety margins by permitting nuclear power plants to achieve operational performance improvements. Economic gains could be realized by both leveraging ATF's ability to operate above the existing thermal and mechanical limits and ATF could allow for the replacement of the current thermal criterion with one more appropriately based on mechanical limits. Such modifications to the licensing basis would permit plant operational changes, thereby enabling improved fuel efficiency and plant economics.

Furthermore, the additional safety margins provided by ATF could support relaxation of the requirements for some standby safety systems. These extensions would reduce operating restrictions, and maintenance costs.

4.2.2 Operational Flexibility

The deployment of ATF concepts provides an opportunity to increase safety while reducing operational costs and increasing plant efficiencies.

<u>Reduced Outage Durations</u>

More robust ATF concepts could enable improvements in fuel handling such as reducing the need for fuel cleaning activities and surveillance during outages. This improved operational flexibility during outages helps reduce the outage duration, reducing worker dose, making nuclear power plants more economical.

Load Follow and Faster Start-Up

Another operational benefit from the improved fuel performance aspects of some ATF concepts is the enabling of higher ramp rates that will allow for more load-follow capabilities and faster start-up times. Additionally, these enhanced thermal-mechanical margins improve the performance of the fuel during normal operation by allowing plants to modify their operational strategies; thereby supporting more efficient plants and improved grid resilience.

4.2.3 Expanded Potential for Power Uprates

The industry is seeking to expand the potential for power uprates at existing facilities.[3] ATF with higher enrichments could provide further safety and operational performance margins to enable initial and additional power uprates at existing plants.[4] The Inflation Reduction Act of 2022 provided substantial tax incentives for clean energy production and investment. With the net-zero emission goals of the upcoming decades, there is a consensus and recognition of the essential role that nuclear energy has in reaching greenhouse gas emission reduction targets. The tax provisions in the Inflation Reduction Act include a production tax credit for existing nuclear power plants and technology-neutral credits for new and expanded production from and investment in clean energy facilities such as power uprates at existing nuclear power plants.

5 HIGH BURNUP AND HIGH ENRICHMENT SAFETY AND ENVIRONMENTAL BENEFITS

ATF products can enable increased burnup and enrichment because these concepts provide enhanced performance during postulated accidents that are expected to be a limiting factor in high burnup applications. In the NEI White Paper, “The Economic Benefits and Challenges with Utilizing Increased Enrichment and Fuel Burnup for Light-Water Reactors,”[5] the use of high burnup with the corresponding increase in fuel enrichment demonstrated a reduction in the fuel reload batch size needed for a plant to achieve its energy production requirements. This reduction in fuel reload batch size corresponds to a reduced amount of high-level waste generated to produce this energy. The reduction in high-level waste inventory provides a number of safety and environmental benefits. For example, fewer dry storage casks with lower dose rates per cask, based on the same cask heat loads, are required. Also, site occupational dose is reduced due to the reduction in the number of dry storage cask loading campaigns along with a reduction in the site boundary dose to the public due to fewer casks being stored on site. With fewer storage casks required to be used, the risk of a cask handling and transportation accident is also reduced. Additionally, the dose during the eventual transportation to a repository will also be reduced.

The reduction in fuel reload batch size also reduces the risk of transportation of new fuel to the site and new fuel handling events during on-site movement and storage. Application of higher burnup fuel requires less uranium ore, so the environmental impact of mining is also reduced. Conversion services requirements are also reduced while enrichment services are increased, however, both conversion and enrichment services provide little direct material interaction with workers or the open environment. The

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[3] NEI Report, “The Future of Nuclear Power, 2023 Baseline Survey,” 2023.

[4] Top Fuel 2022 Technical Report, “Achieving Sizable Power-Uprate for Existing Fleet Through LEU+ and ATF,” Koroush Shirvan, Dept. of Nuclear Science and Engineering- MIT and Al Csontos – NEI.

[5] NEI White Paper, “The Economic Benefits and Challenges with Utilizing Increased Enrichment and Fuel Burnup for Light‐Water Reactors,” February 2019.

overall environmental impact of higher burnup and enrichment is currently being evaluated by the NRC, but similar previous evaluations did not identify any material negative environmental impact.

Increasing burnup will increase the decay heat of a discharged fuel assembly, requiring longer cooling time in the SFP prior to transfer to dry storage. Increased enrichment offsets a portion of the decay heat increase. In addition, fewer high burnup assemblies will be discharged to the SFP over time. Taking these offsetting factors into account, initial scoping calculations indicate maximum SFP decay heat will increase on the order of a few percent.[6] This value includes the effect of a modest increase in the number of fuel assemblies in the SFP requiring additional cooling time before dry storage.

Similarly, increased burnup increases the neutron and gamma dose rate from the fuel to be placed into dry storage. As with decay heat, increased enrichment reduces the neutron dose rate. Longer cooling time required to meet dry storage decay heat requirements reduces both contributors to dose.

A dose rate scoping calculation for a typical canister and concrete overpack system compared storage of HBU fuel from 24-month cycles to fuel from non-HBU 18-month cycles.[7] HBU fuel reduced the external total dose rate during normal storage on the order of 10% per canister. A lower gamma contribution more than offset the increased neutron contribution for this system. When combined with the volume reduction due to discharging fewer fuel assemblies (fewer canisters needed), an overall net reduction in dry storage system radiation dose is achieved.

As previously discussed, higher burnup and enrichment designs provide opportunities to extend cycle lengths for a majority of the PWR fleet. This reduces the number of outages and reduces occupation dose for outage workers as well as reduces the risk of outage related events. The economic advantages of higher burnup and higher enrichment fuel provides additional economic margin for plants that may be subject to early shutdown due to economic performance. Supporting the continued operation of these plants provides continued low carbon emitting electrical generation, consistent with national and international environmental objectives.

6 POTENTIAL FUTURE BENEFITS

The Safety Benefits Task Force identified other areas for potential safety and economic benefits based on engineering judgment and the collective understanding of the current state of the technology. It remains reasonable to assume that eventual economic benefit will be derived in some of these areas, listed below, even though no detailed and documented investigation has been performed to date.

These benefit areas can be revisited as new technical information becomes available or the regulatory predictability for the benefit area is clarified.

1. Operational Flexibility - Core Offload Earlier after Cycle Shutdown
2. Operational Flexibility - Increased Fuel Handling Speeds
3. Risk Related Regulations - Fire Watch Reduction (NFPA 805) and Maintenance Rule, Reduced Regulatory-Driven Plant Modifications, 10 CFR 50.69 Scope Expansion, Additional Risk Informed

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[6] EPRI Report 3002027535, “Scoping Calculation of the Impact of Increased Burnup Limits on Pressurized Water Reactor Spent Fuel Pool Inventory Management,” 2023.

[7] EPRI Report 3002027535, “Scoping Calculation of the Impact of Increased Burnup Limits on Pressurized Water Reactor Spent Fuel Pool Inventory Management,” 2023.

Surveillance Frequency Changes, EQ HELB Savings, Significance Determination Process (Reduced Safety Significance)

4. Station Operations and Emergency Preparedness - Reduction in Emergency Planning Zone (EPZ), Reduction in Security Footprint, Cyber Security Reduction, Eliminate Technical Support Center, Longer Emergency Preparedness (EP) Response Times
5. Plant Equipment - Eliminate Accumulator / Core Flood Tank (CFT) / Safety Injection Tank (SIT) (ECCS Passive Injection) Testing, Eliminate Emergency Diesel Generator (EDG) Fast Start, Eliminate Automatic Containment Spray, Eliminate TS Requirements on Hydrogen Control Equipment, De-Inert Mark I/II Containment (BWR), Eliminate Control Room Habitability Equipment, Eliminate Standby Gas/Secondary Containment (BWR)
6. Time at Temperature – Coated cladding provides additional protection of the cladding at DNB and Dryout conditions. This could provide additional benefits in margin for selected PWR and BWR transients.

7 CONCLUSIONS

To maximize the benefit for the environment, consumers, and plant operators, any decision to pursue ATF products will need to be made urgently. The future sustainability of the commercial light water reactor fleet depends on industry’s ability to innovate at a pace which will allow the plants to remain economically competitive with other rapidly advancing energy technologies.

Each ATF concept has specific associated benefits and all the benefits noted below may not be applicable to every ATF concept. Moreover, each plant has been highly optimized by owners/operators based on plant-specific circumstances. Therefore, the benefits attainable from ATF implementation will be largely plant-specific; however, the ATF benefits can be inferred.

The analyses identified the following potential benefits for ATF products. These potential benefits are a buffet of options, whether a specific benefit would be of value to a specific plant would depend on the plant-specific conditions.

- **Improved Accident Performance**
  By improving robustness to various failure mechanisms and by generating less combustible gas during postulated accident scenarios, overall accident performance is improved.

- **Increased Fuel Cycle Flexibility**
  By enabling an increase in the allowable burnup, and by improving thermal margins, key limitations in core design can be ameliorated. This will enable plants to optimize fuel loading and/or cycle length to minimize fuel costs. Plants previously unable to economically transition to 24-month cycles may become able to do so with implementation of higher allowable burnup and higher enrichments. This will reduce the frequency of plant refueling outages, further reducing worker exposure and outage costs.

- **Improved Fuel Economic Performance**
  By reducing batch loading sizes or by extending cycle lengths, fewer assemblies would be used to produce the same amount of electricity. This reduces the amount of fuel that needs disposal and billions of dollars would be saved on the back end of the fuel cycle (i.e., spent fuel treatments).

- **Improved Ability for Flexible Plant Electrical Output**
  Improved fuel robustness will improve a plant's ability to respond to changing conditions on the grid (e.g., accommodate time-varying wind and solar electric output).

- **Reduced Susceptibility to Crud and Improved Tolerance of Aggressive Water Chemistry**
  By improving resistance to mineral deposits on the fuel cladding and by accommodating more aggressive water chemistry to reduce the inventory of minerals in the coolant, crud buildup can be reduced. The reduction of crud buildup will enable some plants to achieve greater fuel efficiency, reducing plant operating costs.

- **Increased Time Available for Mechanical Systems and Human Operators to React**
  Increased time for systems and operators to react during an event mitigates the likelihood of core damaging accidents.

- **Improved Fuel Cladding Surface Robustness**
  By utilizing more robust materials, the cladding is protected and the risk of damage from debris and grid-to-rod fretting is reduced.

- **Reduced Duration of Shut-Downs for Refueling**
  More robust fuel will enable the fuel handling speed to be increased, reducing the time needed to prepare the core for the next cycle.

Figure 1 illustrates how the benefits discussed throughout this report ultimately combine to support the future sustainability of the commercial light water reactor fleet. The industry's ability to innovate will allow the plants to remain economically competitive with other rapidly advancing energy technologies.

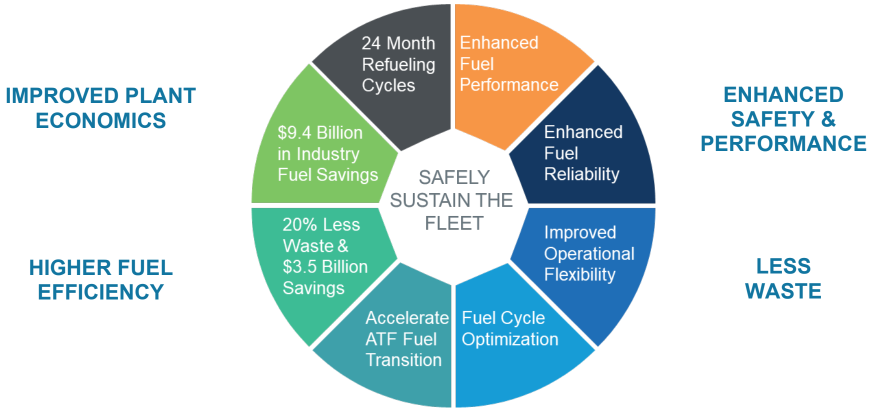

Figure 1: Illustration of incorporation of ATF design concepts safely sustaining the nuclear fleet.

Development, licensing, and deployment of ATF will represent a substantial investment among fuel vendors, utilities, regulatory authorities, and other government agencies. However, the potential safety and economic benefits of ATF represent an opportunity for the nuclear industry to innovate to continue to improve safety while reducing operating costs in order for the industry to remain economically viable.

Incorporation of ATF design concepts described above with higher burnup fuel designs and increased enrichment has the potential to extend the value of increased enrichments and fuel burnup levels by optimizing fuel design thermal limits, improving corrosion resistance of the fuel cladding, and improving the fuel reliability over current designs.

As discussed in Section 5, High Burnup and High Enrichment Safety and Environmental Benefits, the referenced economic analysis showed that all the scenarios yielded positive economic benefits for the U.S. nuclear fleet. The use of higher burnup fuel designs results in a reduction in high level waste and the corresponding investment in dry cask storage systems. Additionally, most PWRs could increase their operating schedule flexibility potentially resulting in fewer refueling outages and increased energy production; however, these benefits are plant dependent and were not credited in the economic analysis. Fuel management benefits are dominated by fuel fabrication savings for utilities. Estimated fuel fabrication price increases were included in the analysis; however, the actual increases are subject to commercial negotiations.

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