SAFETY AND ECONOMIC BENEFITS OF ACCIDENT TOLERANT FUEL

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Advanced fuels such as Accident Tolerant Fuels (ATF) have the potential to improve the safety and economic performance of commercial nuclear reactors as well as provide additional operational flexibility for responding to variations in system energy demand.

Due to the current state of the industry, particularly in the United States, the timing of the deployment of new advanced nuclear fuel concepts, such as ATF, will be a critical aspect in its adoption by the industry. In particular, because the costs associated with the development, testing, and licensing of advanced fuels will need to be amortized over the remaining life of the plants it will be imperative to deploy these technologies on a much faster time scale than has traditionally occurred for new fuel designs. Because nuclear power plant (NPP) owner/operator decisions and investments related to extended plant operating lifetimes (i. e. second license renewal) are made many years in advance, the benefits of ATF need to be obtained within the next 5 years or so for them to factor into these decisions. Additionally, 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.

To support this goal, the Electric Power Research Institute (EPRI) performed a preliminary assessment of the technical and regulatory challenges that exist across the entire fuel cycle with a focus on licensing and full core deployment of ATF concepts.

BACKGROUND

Over the past decade, ATFs have been researched, designed, and developed to tolerate a loss of active cooling in the reactor core for a longer time period than traditional fuel designs, while maintaining and improving fuel and plant performance during normal operation. ATF designs may provide more resilient performance during hypothetical accident scenarios while supporting more efficient normal operations including the capability for better plant integration with renewable generation sources. Technically, ATF concepts were designed to reduce cladding oxidation kinetics and hydrogen generation rates while improving cladding thermomechanical properties and performance, among others, during hypothetical accident conditions.

In the wake of the 2011 Fukushima Daichi accident, the priority of accelerating the research and development of ATF technologies was recognized by the U.S. Congress, U.S. Department of Energy (DOE), and the nuclear industry. As a result, the U.S. DOE initiated a 10-year program with the goal of inserting test rods with enhanced accident tolerance into a commercial reactor by 2022. With strong support from the nuclear industry, significant milestones were completed over the last 18 months, four years earlier than the ATF implementation goals set by the U.S. Congress. These milestones include the insertion of Global Nuclear Fuel's (GNF) IronClad and ARMOR ATF concepts into Southern Nuclear Operating Company's (SNOC) Plant Hatch in February 2018. The ARMOR lead test assembly (LTA) contained segmented rods to simplify future fuel inspection activities. The ARMOR LTA was the first ATF deployment in a commercial NPP which contained fuel pellets. Furthermore, SNOC loaded Framatome's PROtec ATF design into the Alvin W. Vogtle Electric Generating Plant's Unit 2 in March 2019. This was the world's first full-length ATF implementation. Later in 2019, Westinghouse and GNF inserted their Encore™ and ARMOR/IronClad ATF concepts into Exelon's Byron Unit 2 and Clinton Power Station, respectively.

In addition, several countries have also developed ATF programs, as well as, joint international ATF programs through the Organization for Economic Co-operation and Development-Nuclear Energy Agency (OECD-NEA), the International Atomic Energy Agency (IAEA), and European Atomic Energy Community

SEGURIDAD Y BENEFICIOS ECONÓMICOS DEL COMBUSTIBLE CON ALTA RESISTENCIA A ACCIDENTES

Los combustibles avanzados, como los de alta resistencia a accidentes (ATF), tienen la capacidad de mejorar la seguridad y el rendimiento económico de los reactores nucleares comerciales, así como proporcionar flexibilidad operativa para responder a las variaciones en la demanda de energía de la red.

Debido al estado actual de la industria, particularmente en los Estados Unidos, el momento de implantación de nuevos conceptos de combustible nuclear avanzado, como el ATF, será un aspecto crítico en su adopción por parte de la industria. En particular, teniendo en cuenta que los costes asociados con el desarrollo, las pruebas y la licencia de combustibles avanzados deberán amortizarse durante la vida útil restante de las plantas, será imperativo implementar estas tecnologías en una escala de tiempo mucho más reducida que la que tradicionalmente se ha empleado para los nuevos diseños de combustible. Además, la investigación, el desarrollo, el licenciamiento y la implantación de combustibles nucleares avanzados requieren de una inversión y colaboración importante entre los suministradores de combustible, las empresas de servicios públicos, las autoridades reguladoras y otras agencias gubernamentales.

Para respaldar este objetivo, el Instituto de Investigación de Energía Eléctrica (EPRI) realizó una evaluación preliminar de los desafíos técnicos y normativos que existen en todo el ciclo del combustible, enfocados a la licencia y el despliegue completo de los conceptos de ATF.

(Euratom). For Spain, a dialogue has started on ATF research and potential adoption in Spanish commercial NPP through the Spanish Nuclear Fission Technology Platform CEIDEN that includes utilities, government, universities, and fuel vendor stakeholders.

CHALLENGES

Today, low natural gas prices combined with increasingly competitive renewable energy sources in the United States have placed significant stress on the current nuclear fleet. This situation has resulted in the premature closure of a number of operating NPP and is providing an ongoing challenge to the continued operation of a number of other plants from a purely economic basis. For nuclear plants to remain a feasible generation option, new technologies need to be implemented to improve their economic competitiveness. Specific advanced fuel technologies have the potential to offer multifunctional performance improvements over current fuel designs through improved safety under accident conditions (the fundamental objective of ATF), enhanced fuel reliability, efficiency, and performance during normal operations, and overall increased economic benefits with optimized fuel cycles.

For any new fuel technology to be economically feasible, substantial safety and economic benefits likely will be required to justify this investment. EPRI's preliminary qualitative study also evaluated challenges related to use of enrichments both above and below 5% by weight. This assessment is summarized in Figure 1 with green indicating relatively short implementation timeframes on the order of about 5 years, yellow for mid-term, and red for longer term timeframes. For the safety and economic benefits column, green means substantial benefits whereas yellow indicates moderate benefits.

ATF Business Case Development:

To provide broad applicability for these new designs, coordinate activities and provide input for developers and other stakeholders across the industry, the U.S. industry formed the ATF Working Group. Coordinated by the Nuclear Energy Institute (NEI), this group includes representatives from EPRI, NEI, DOE, fuel suppliers, nuclear power utilities, and various other industry experts. The U.S. Nuclear Regulatory Commission (NRC) has also developed a "Project Plan to Prepare the U.S. NRC for Efficient and Effective Licensing of Accident Tolerant Fuels," which highlights their preparatory activities for conducting safety reviews of vendor submittals.

In order to facilitate widespread industry adoption, the following criteria were developed by the industry for ATF designs:

- Acceptable neutron absorption cross sections to ensure adequate operational and economic performance.
- Amenable to fabrication and configurations suitable for the current LWR fleet.
- Sufficient supply of raw materials to supply the operational needs of the global LWR fleets.
- Compatibility with current LWR coolants under normal operating conditions.
- Ability to meet the existing design, operational, reliability and licensing requirements.

ATF concepts under active development are categorized as near-term or longer-term based on their anticipated timeline to full core deployment. Near-term concepts can use the current licensing structure with current regulations and regulatory guidance to allow for licensing of these ATF concepts. These near-term concepts are expected to be commercially viable for full core deployment by the mid-2020's. Longer-term concepts are still being developed and tested. These design concepts may also require the development and adoption of a revised regulatory framework. As a result, these concepts are expected to take a longer period of time to develop and license prior to full-core deployment in operating commercial reactors.

ATF adoption by commercial reactor operators will ultimately be a business decision. A critical metric for the industry decision-makers is ATF deployment timeframes. The sooner these ATF concepts can be deployed, the sooner the safety and economic benefits may be realized over the remaining life of the plants. Ideally, ATF would increase plant safety while potentially reducing operational costs and increasing plant efficiencies. The research, development, licensing, and deployment of advanced nuclear fuels represents a substantial investment and collaboration among fuel suppliers, operating utilities, research institutions, regulatory authorities, and other governmental agencies. For any new fuel technology to be economically feasible, substantial safety and economic benefits are 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

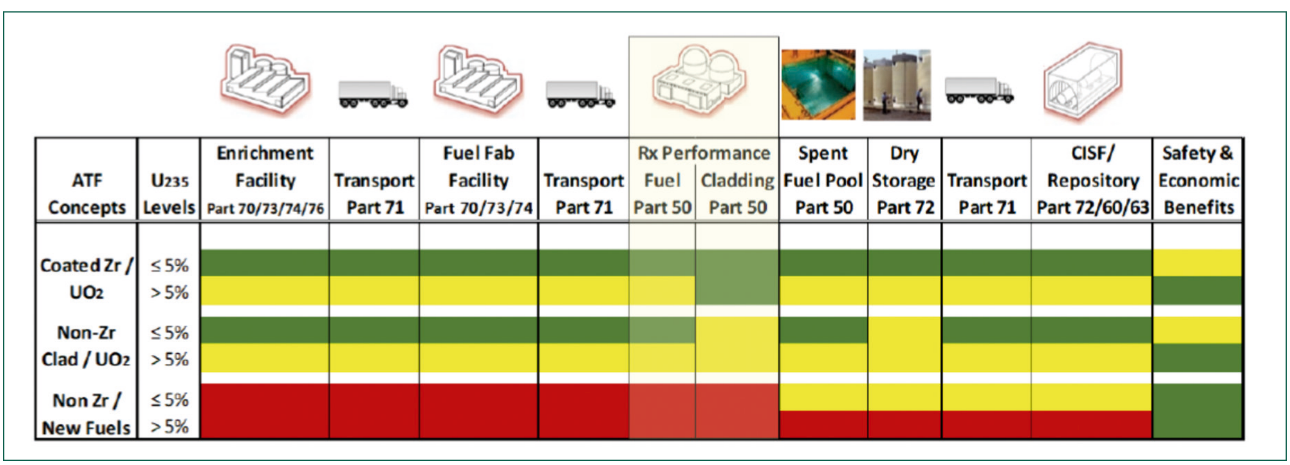

Figure 1. Technical and regulatory challenges existing across the entire fuel cycle for ATF deployment.

normal and accident conditions and deploy these fuels by the early to mid-2020s. As a result, EPRI has conducted research and developed an evaluation of potential safety and economic benefits of ATF technologies including the implementation of higher uranium enrichments and discharge burnups.

It should be noted that the term "safety benefits" identifies an increase in safety, i.e., margin gain, over the performance of standard Zirconium-/Uranium Dioxide-based (Zr/UO_2) fuels.

ATF VALUE

EPRI has been collaborating with key governmental, regulatory and commercial stakeholders and conducting research on advanced fuels with greater reliability, safety, cost savings, efficiencies and performance for the past 30 years.

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. In 2017, EPRI's performed an initial assessment of potential expected ATF performance. This work was done to assess and quantify the various safety enhancements offered by ATF and summarized in Figure 2. The performance of each ATF concept was evaluated for a number of postulated accidents. Safety analyses for key accident sequences were performed and the ATF results were compared with those for the same sequences calculated using current $Zr\text{-}UO_2$ fuel designs.

Following this initial assessment, EPRI performed research for additional accident scenarios, fuel cycle optimization (i.e., increased enrichment and discharge burnups) assessments, and exploration of additional benefits not previously studied. These efforts identified three major areas of potential economic benefits: a) increased fuel reliability, b) more efficient fuel cycles that could also reduce the amount of generated waste, and c) more robust fuel performance leading to improved operational flexibilities. These potential economic benefits could provide improved safety with substantial cost reductions and/or plant operational performance enhancements.

The EPRI analyses were performed collaboratively with a broad and diverse group of stakeholders from industry, academia, EPRI, fuel vendors, and national laboratories. These analyses provided ATF stakeholders with a comprehensive and independent assessment of the potential safety and economic benefits afforded by ATF deployment. EPRI's initial results conclude that:

- For accident scenarios where reactor cooling is lost for an extended period of time, ATF increased the time available to cope with the accident by approximately 1-2 hours before the onset of core damage.
- Core damage was further delayed with some ATF concepts by several additional hours. Without mitigation, this results in the system depressurizing from the failure of the hot leg (e.g., hot leg creep rupture). Additional core cooling can occur from the subsequent accumulator injection in the cold leg, further delaying core damage. This scenario applies to certain Pressurized Water Reactor (PWR) Station Black Out (SBO) events.
- For an evaluation of the Three Mile Island Unit 2 accident, using EPRI's Modular Accident Analysis Program (MAAP) software, ATF may have been able to prevent, or at the very least, reduce core damage for this event (see Figures 3 and 4).
- ATF could reduce the core damage frequency (CDF) by approximately 10% – 15% where no additional mitigation actions are credited and approximately 15% – 20% in cases where additional mitigation actions are credited, according to preliminary probability risk assessment (PRA) evaluations.

This initial EPRI research concluded that ATF may have the potential to provide multifunctional performance advantages over standard Zr/UO_2 fuels by providing increased operational safety margins while also providing enhanced fuel reliability, fuel cycle optimizations, and a reduction of spent nuclear fuel. This led to an expanded research effort, building upon initial ATF analyses, to include crediting severe accident mitigation strategies as well as conducting standard safety analyses, fuel cycle optimizations (including enrichment and discharge burnups increases), and identification of plant specific benefits not previously captured. EPRI's subsequent analyses concluded that:

- ATF may provide additional coping time to allow for the successful deployment of severe accident mitigation equipment, with greater confidence, to successfully mitigate severe accidents.

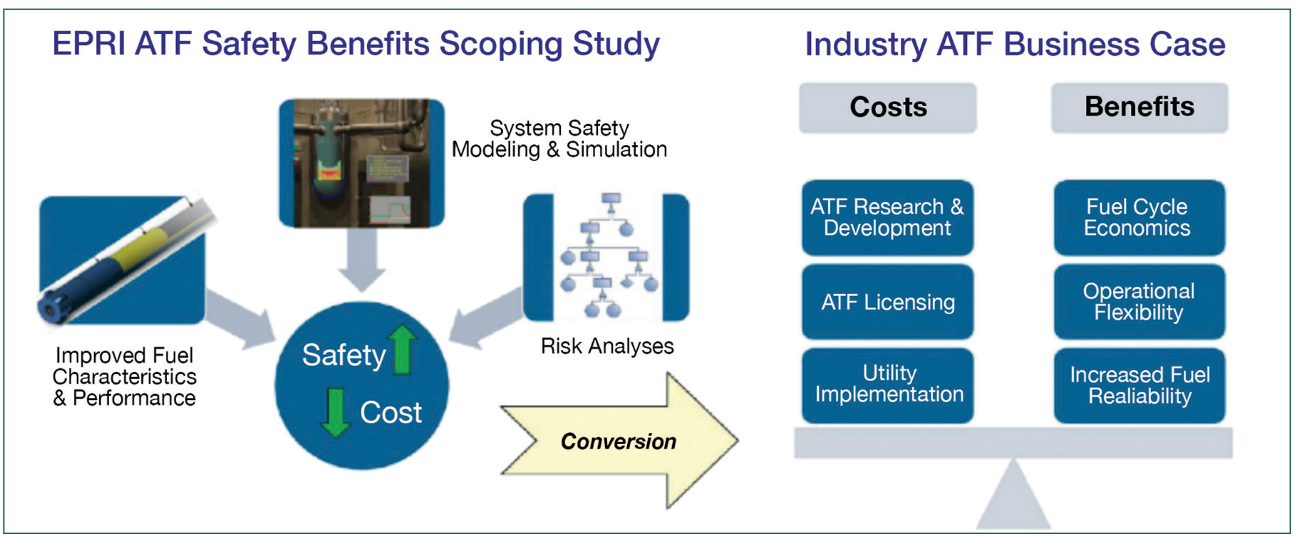

Figure 2. EPRI ATF Valuation 1.0 analysis for conversion into the Industry ATF Business Case for evaluation of safety and economic benefits.

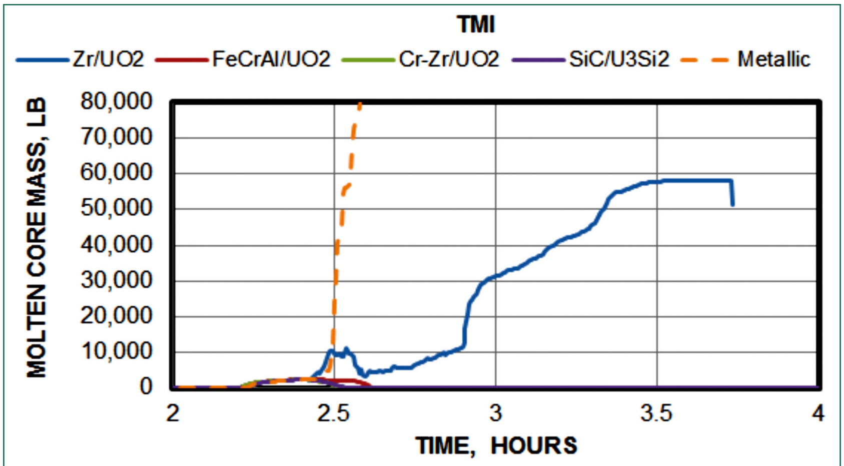

Figure 3. TMI-2 benchmark results for Molten Core Mass, lb.

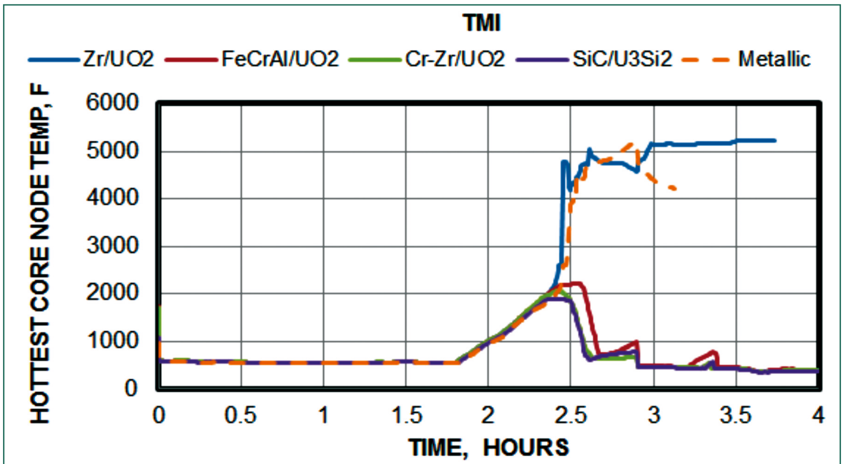

Figure 4. TMI-2 benchmark results for Hottest Local Core Temperature, degrees F.

- For PWR loss of flow events limited by departure from nucleate boiling (DNB), analysis results for coated Zr-alloy cladding with doped UO_2 and standard Zr/UO_2 fuel systems are effectively the same. However, these results also show that if the current DNB acceptance criteria is replaced by a cladding strength-based failure mechanism, then opportunities to alter plant operation strategies and increase core design flexibility could be realized to support economic gains.
- PWR loss of coolant accident (LOCA) assessments have shown safety margin improvements with the implementation of coated cladding and doped UO_2 pellets. The additional safety margins are found through the use of pellets with higher thermal conductivity which result in lower pellet operating temperatures. Furthermore, reductions in the maximum local oxidation (MLO) can be achieved as a result of ATF cladding concepts with reduced clad-steam oxidation kinetics. Lastly, these performance benefits could support delays in Emergency Core Cooling System (ECCS), but additional research is required to confirm.
- LOCA assessments show margin improvements enabled by coated Zr-alloy cladding concepts by reducing the amount of hydrogen generated and oxide thicknesses, therefore, increasing cladding ductility and increasing resilience under LOCA conditions.
- Coated Zr-alloy cladding concepts could support modest peaking factor increases to support PWR fuel cycle optimization.
- Boiling Water Reactor (BWR) ATF concepts meet licensing requirements for safety analyses where boiling transition is permitted. ATF increases the capability of the fuel to withstand short periods of dryout during which boiling transition occurs. This would allow lowering the critical power ratio (CPR) operating limit which in turn could be used to support reducing fuel cycle cost.
- BWR ATF concepts can meet ECCS LOCA licensing requirements with substantial reductions in ECCS injection flow.
- Utilizing ATF safety margins, operation and maintenance costs can be reduced through the utilization of additional CPR margins, relaxing scram requirements, removal of the End of Cycle Recirculation Pump Trip function, and/or by allowing operation at lower core flow within the current licensed operating domain.

CONCLUSION

ATF technology concepts have the potential to provide increased safety margins over standard Zr/UO_2 fuels while also providing enhanced fuel reliability, improved economics through optimized fuel cycles, and reduced high-level waste generation. These ATF concepts may enable the realization of additional economic benefits from increased enrichments, higher discharge burnups, and higher resiliency for more efficient operations and cost savings.

While EPRI is not developing specific ATF technologies, it is informing public and private stakeholders with key safety, economic, and operational technical analyses to support strategic decision-making for ATF implementation. The adoption of ATF design concepts is on track for initial implementation within the U.S. fleet in the early 2020s. In addition to the economic and operational benefits, ATF may enable the current regulatory limits for discharge burnups to be extended. Coupled with an incremental increase in uranium enrichment would allow for more efficient core designs and operations, leading to additional cost savings to the industry and society. New design concepts may also provide a foundation for additional longer-term improvements that will support the existing fleet through the balance of its operating life, and potentially lead to the next generation of reactors. EPRI is committed to supporting the evaluation of these technologies through its independent research and technical expertise. ■

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