Safety and economic benefits of accident tolerant fuel

The deployment of ATF could lead to increased safety margins, optimized fuel cycles, and a reduction in high-level waste while enabling higher enrichment and burnup limits.

By Aladar Csontos and Fred Smith

Accident tolerant fuel (ATF) is designed to withstand a loss of active cooling in a reactor core for a longer time period than conventional fuel designs and to maintain and improve fuel and plant performance during normal operation. ATF designs provide more resilient performance during hypothetical accident scenarios and support more efficient normal operations, including the capability for better plant integration with renewable generation sources.

In the wake of the 2011 Fukushima Daiichi accident, the U.S. Congress, the Department of Energy, and the nuclear industry recognized that accelerating the research and development of ATF technologies must be a priority. As a result, the 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 have been reached over the past 18 months, four years earlier than the ATF implementation goals set by Congress. These milestones include the insertion of Global Nuclear Fuel's (GNF) IronClad and ARMOR ATF lead test assemblies (LTA) into Southern Nuclear Operating Company's Hatch plant in February 2018. The loading of the ARMOR LTAs, which contained segmented rods to simplify future fuel inspection activities, was the first deployment of pellet-containing ATF in a commercial nuclear power plant. In March 2019, Southern loaded the world's first full-length ATF fuel rods—featuring Framatome's PROtec design—into Vogtle-2. Later this year, Westinghouse and GNF plan to insert their EnCore and ARMOR/IronClad ATF LTAs into Exelon's Byron-2 and Clinton reactors, respectively.

In addition, several countries have developed ATF programs and joint international ATF programs through the OECD Nuclear Energy Agency, the International Atomic Energy Agency, and the European Atomic Energy Community (Euratom).

To ensure broad applicability of these new fuel designs, coordinate activities, and provide input for developers and other stakeholders, the U.S. nuclear industry formed the ATF Working Group. Coordinated by the Nuclear Energy Institute, this group includes representatives from NEI, the DOE, fuel suppliers, the Electric Power Research Institute (EPRI), nuclear power utilities, and various other industry experts. Also, the Nuclear Regulatory Commission has released its *Project Plan to Prepare the U.S. Nuclear Regulatory Commission for Efficient and Effective Licensing of Accident Tolerant Fuels*, which outlines its activities in preparation for conducting safety reviews of vendor submittals.

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

- Acceptable neutron absorption cross sections to ensure adequate operational and economic performance.
- Amenability to fabrication and configurations suitable for the current light-water reactor fleet.
- A sufficient supply of raw materials to meet the operational needs of the global LWR fleets.
- Compatibility with current LWR coolants under normal operating conditions.
- Capability to meet 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 be licensed using the current licensing structure, regulations, and regulatory guidance. These near-term concepts are expected to be commercially viable for full-core deployment by the mid-2020s. Longer-term concepts are still being developed and tested. These design concepts may require the development and adoption of a revised regulatory framework. As a result, they 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 industry decision-makers is ATF deployment time frames. The sooner these ATF concepts

---

Aladar Csontos (<acsontos@epri.com>) is Technical Executive for Fuel and Chemistry at the Electric Power Research Institute, and Fred Smith (<fsmith@epri.com>) is Technical Executive for the EPRI Fuel Reliability Program. The work represented in this article was performed as part of the EPRI Fuel Reliability Program.

can be deployed, the sooner their 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. It should be noted that the term “safety benefits” signifies an increase in safety—a margin gain—over the performance of standard zirconium/uranium dioxide–based (Zr/UO_2) fuels.

The research, development, licensing, and deployment of advanced nuclear fuels represent 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 widespread implementation of the new technologies. These benefits may include increased safety margins, enhanced fuel reliability, improved economics, optimized fuel cycle operational strategies, and reduced waste generation, among others. Over the past year, the U.S. nuclear industry has been aggressively pursuing ATF concepts with the goal of deploying the fuels by the early to mid-2020s. As a result, EPRI has developed an evaluation of potential safety and economic benefits of ATF technologies, including the implementation of higher uranium enrichments and discharge burnups.

ATF value

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

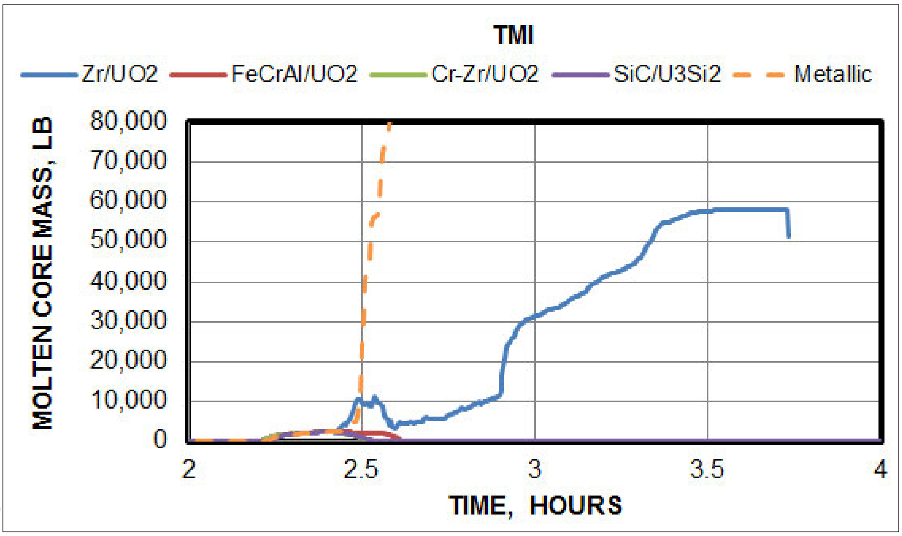
The early adoption of ATF by commercial reactor owners and operators is predicated on the need to assess the potential benefits from ATF with the associated implementation costs. In 2017, EPRI performed an initial assessment of potential expected ATF performance. This work was done to assess and quantify the various safety enhancements offered by ATF. 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/UO_2 fuel designs.

Following this initial assessment, EPRI performed research on additional accident scenarios, conducted fuel cycle optimization assessments (increased enrichment and discharge burnup), and explored additional benefits not previously studied. These efforts identified three major areas of potential economic benefits: (1) increased fuel reliability, (2) more efficient fuel cycles that could reduce the amount of waste generated, and (3) more robust fuel performance leading to improved operational flexibilities. These potential economic benefits could provide substantial cost reductions and/or plant operational performance enhancements.

The EPRI analyses were performed collaboratively with a broad range of industry stakeholders, and the results were scrutinized by the same diverse group. 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 findings include the following:

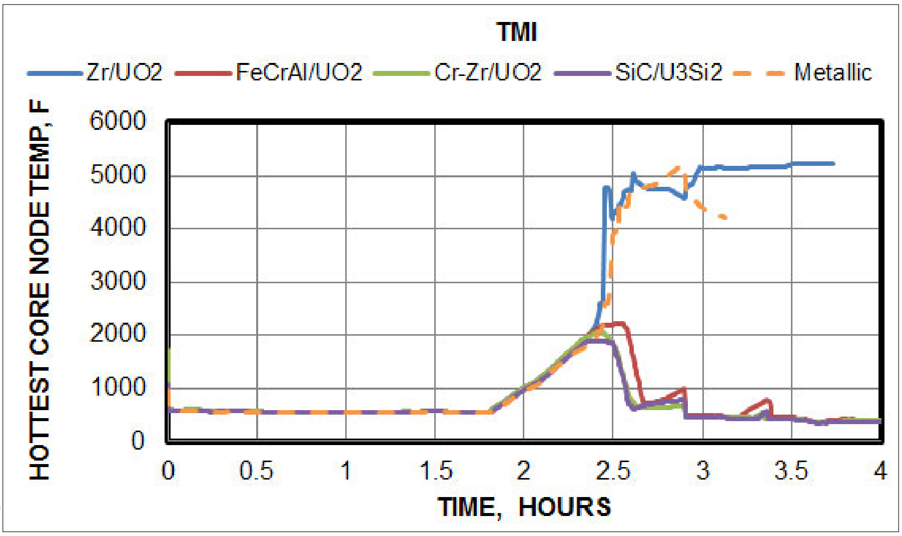
- For accident scenarios where reactor cooling is lost for an extended period of time, ATF increased the time available to cope with the accident by about one to two hours before the onset of core damage.
- Core damage was further delayed by several hours with some ATF concepts. Without mitigation, the system depressurizes from the failure of the hot leg (i.e., hot leg creep rupture). Additional core cooling can occur from a subsequent accumulator injection in the cold leg, further delaying core damage. This scenario applies to certain pressurized water reactor station blackout events.
- Based on an evaluation of the Three Mile Island-2 accident using EPRI’s Modular Accident Analysis Program software, ATF may have been able to prevent, or at the very least reduce, core damage for that event (see Figs. 1 and 2).
- ATF could reduce the core damage frequency by about 10–15 percent in cases where no additional mitigation actions are credited, and by about 15–20 percent where additional mitigation actions are credited, according to preliminary probability risk assessment evaluations.

EPRI’s initial research concluded that ATF may have the potential to provide



Graph: EPRI

Fig. 1: TMI-2 benchmark results for molten core mass, in pounds (lb).



Graph: EPRI

Fig. 2: TMI-2 benchmark results for hottest local core temperature, in °F.

multifunctional performance advantages over standard Zr/UO_2 fuels by increasing operational safety margins while also providing enhanced fuel reliability, fuel cycle optimization, and a reduction of spent nuclear fuel. This led to an expanded research effort, built on initial ATF analyses, to include crediting severe accident mitigation strategies, conducting standard safety analyses, assessing fuel cycle optimizations (including enrichment and discharge burnup increases), and identifying plant-specific benefits not previously captured. EPRI's subsequent analyses concluded the following:

- ATF can provide additional coping time to allow for the deployment of severe accident mitigation equipment.
- For PWR loss-of-flow events limited by a 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 are 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 results in lower pellet operating temperatures. Furthermore, reductions in the maximum local oxidation can be achieved as a result of ATF cladding concepts with reduced clad-steam oxidation kinetics. These performance benefits could support delays in emergency core cooling system (ECCS) initiation, but additional research is required to confirm that possibility.
- LOCA assessments show margin improvements enabled by coated Zr-alloy cladding concepts by reducing the amount of hydrogen generated and the oxide thicknesses, thereby increasing cladding ductility and resilience under LOCA conditions.
- Coated Zr-alloy cladding concepts could support modest peaking factor increases to support PWR fuel cycle optimization.
- Boiling water reactor 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 costs.
- BWR ATF concepts can meet ECCS LOCA licensing requirements with substantial reductions in ECCS injection flow.
- ATF safety margins can enable operation and maintenance cost reductions through utilizing additional CPR margins, relaxing scram requirements, removing the end-of-cycle recirculation pump trip function, and/or allowing operation at lower core flow within current licensed operating limits.

Fuel enrichment and burnup

It is likely that ATF fuel will be more expensive than current fuel designs. Fuel costs currently account for approximately 20 percent of a commercial LWR's total generating costs. Few other individual cost components have such a large impact on the economics of the nuclear fleet. A plant's fuel costs depend on two factors: the price of the fuel components (uranium feed, conversion, enrichment, and fabrication) and the efficiency of the core design. Fuel component costs are driven by supply and demand, and in the long run are outside the control of individual utilities. The efficiency of a core design determines the quantity of nuclear material needed to meet a plant's energy objectives. While a utility can improve the efficiency of the core design, this efficiency is ultimately limited by the specific constraints of the core design. Initial research into current fuel management practices has shown that 99 percent of the variation in fuel cycle efficiency is attributable to variations in uranium enrichment and discharge burnup. Many sites are currently constrained by existing regulatory limits on one or both of these parameters.

In 2018, EPRI completed an analysis of the potential benefits and challenges associated with increasing the current fuel enrichment and burnup limits. Fuel enrichments of up to 6–7 percent U-235 (the current limit is 5 percent) are anticipated. Revising these limits impacts a large portion of the nuclear fuel cycle, as well as the licensing bases for plant operators and fuel suppliers and the back end of the fuel cycle. While there are economic advantages to making these changes, they require long-term capital investments and regulatory changes.

Increasing the fuel burnup limit also requires addressing a number of fuel mechanical design and reliability considerations. These include, but are not limited to, rod internal pressure, cladding corrosion and hydrogen pickup, rod and assembly growth, and cladding strain. While demonstrating acceptable fuel performance that satisfies all these design criteria represents a significant effort, it does not present an insurmountable technical challenge. The fuel suppliers have developed, or are developing, advanced materials or design features to address these considerations. Also, some of the features of new ATF designs may provide additional safety performance margins in these areas.

However, issues related to fuel fragmentation, relocation, and dispersal (FFRD) during postulated design basis accidents remain a significant research challenge. FFRD is postulated to occur if a high-burnup fuel rod balloons and bursts during a design basis accident, such as a LOCA. If sufficient fission gas is present in the pellet, it may cause the pellet to fragment. Pellet fragments may relocate into the balloon volume and potentially disperse into the coolant through the burst area. FFRD has been observed in some test reactor experiments under simulated LWR conditions. EPRI, with support from the DOE and in collaboration with the NRC's Office of Nuclear Regulatory Research, is conducting separate effect tests that may potentially result in a full integrated test in 2022 using the restarted Transient Reactor Test Facility at Idaho National Laboratory. This integral test will be performed under prototypical LWR conditions, which combine realistic fuel temperature profiles, appropriate linear power densities, and fission gas distributions appropriate to high-burnup fuel. This test is expected to advance the understanding of FFRD to support potential extensions of existing burnup limits. Previous test results for BWR designs have shown less susceptibility to FFRD concerns, and tests on BWR fuel are not planned, since the onset of FFRD is expected to occur outside the targeted burnup levels.

Separately, fuel burnup limits, designed to avoid cladding burst, are also being pursued. Some international regulators have already licensed plants to higher burnup levels using this approach.

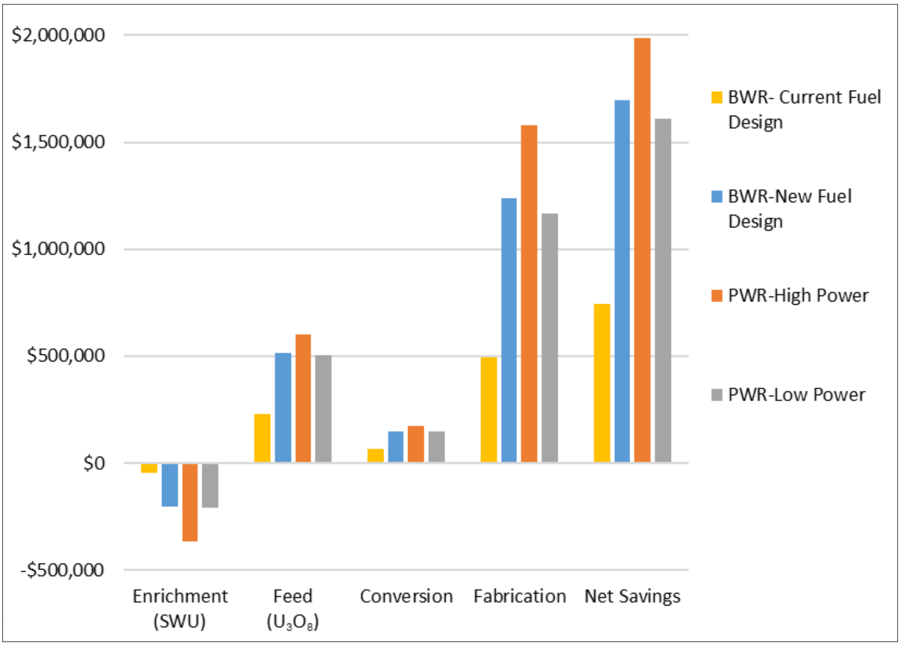
The largest technical challenge to increasing the enrichment limit is related to controls and analysis to maintain criticality safety margins for fuel enrichment and fabrication facilities, as well as storage and transportation systems. The transportation of enriched UF_6 from the enrichment facility to the fuel fabricator may require the development of new Type 30B transportation packages. New packages are currently being developed by at least one transport package supplier.

Fuel designed with higher enrichments will also include higher concentrations of fixed neutron absorbers to control in-reactor reactivity and power peaking. This is expected to largely offset the challenges for fuel storage and transportation. In addition, fuel with higher enrichments will operate to higher burnups, which also tends to offset criticality issues. New criticality analysis must be performed using updated assumptions consistent with the expected fuel design changes. The strategy of using a higher concentration of fixed absorbers is generally expected to be effective. Some sites, however, have limited design or storage flexibility and will elect not to adopt higher enrichment fuel designs. While relicensing any fuel system to meet modern criticality analysis standards poses regulatory challenges, these are considered by industry to be manageable with the current technology and regulatory guidance.

Some generic analysis methods may be affected by fuel burnup limit increases. These include accident source terms and decay heat correlations. A full review of the industry's existing experimental data and associated fuel modeling is needed to determine whether sufficient margin exists in the current limits to support higher burnups.

New dry cask designs will be required to address fuel criticality, decay heat, and site boundary dose limits for the exclusion area and low-population zone. These changes to the design and licensing bases for dry cask systems do not pose a significant technical challenge. Higher burnup designs will allow longer cooling times for the same spent fuel pool storage capacity. This increase in cooling time will partially offset the increase in heat load due to higher burnup. New cask designs, currently being qualified to higher heat load limits, are expected to provide the capability to address these higher heat loads.

To evaluate the benefits of new enrichment and burnup limits, fuel management studies were performed for both PWR and BWR systems. The results of these studies are illustrated in Fig. 3. For all cases, enrichment expenses increased slightly, and U_3O_8 feed stock costs were reduced. Most of the savings come from fabrication, because fewer fabricated assemblies are needed for new reload batches. This results in savings that are relatively insensitive to future feed or enrichment prices, but fuel fabrication costs are expected to increase to address the impact of these changes on fuel suppliers.



Graph: EPRI

Fig. 3: Annual fuel cost savings by component for 1,000 MWe plant.