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Light Water Reactor Fuels R&D to Support Nuclear Power Plant Power Uprates

Advanced Fuels Campaign

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SUMMARY

In response to Executive Order (EO) 14302, which directs the Department of Energy (DOE) to prioritize the restart, uprate, and construction of large nuclear power plants (NPPs) with a goal of achieving 5-gigawatt (GW) of uprates and initiating 10 GW of new construction by 2030, this study examines the critical role of light water reactor (LWR) fuel technology in meeting these objectives. Economic challenges remain the primary barrier to the deployment of new large LWRs, with high capital costs and extended construction timelines. However, uprating the thermal power output of existing LWRs has emerged as a cost-competitive alternative. Yet, these uprates are constrained by the limitations of current nuclear fuel technology, particularly as higher core power densities can compromise fuel integrity, accelerate fuel depletion, and negatively impact reactor economics and longevity.

To address these challenges, this work emphasizes the need for advanced LWR fuel technologies that enable significant thermal power uprates while maintaining economically viable operating cycles (1.5-2 years) and batch fractions (34-46%). Such innovations would not only allow existing reactors to achieve higher power output but also improve the economic case for new builds and restarts by reducing operating costs, increasing capacity factors, and extending reactor lifespans. By overcoming these technical and economic barriers, advanced LWR fuel technology can catalyze the deployment of large NPPs, aligning with the strategic goals outlined in EO 14302 and supporting the broader transition to a low-carbon energy future.

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ACRONYMS

AFC	Advanced Fuels Campaign
ATF	Accident Tolerant Fuel
ATR	Advanced Test Reactor
B&W	Babcock & Wilcox
BWR	Boiling Water Reactor
DNB	Departure from Nucleate Boiling
DOE	Department of Energy
EO	Executive Order
FY	Fiscal year
GW	Gigawatt
H/HM	Hydrogen-to-Heavy Metal ratio
HBU	High burnup
HFIR	High Flux Isotope Reactor
HM	Heavy Metal
INL	Idaho National Laboratory
K	Reactivity factor (criticality value)
LEU	Low-enriched uranium
LHGR	Linear Heat Generation Rate
LOCA	Loss of Coolant Accident
LOFT	Loss of Flow Test
LWR	Light Water Reactor
MITR	Massachusetts Institute of Technology Nuclear Research Reactor
MW	Megawatt
NE	Office of Nuclear Energy
NGF	Next Generation Fuels
NRC	Nuclear Regulatory Commission
NPP	Nuclear Power Plant
OD	Outer Diameter
ORNL	Oak Ridge National Laboratory
PBF	Power Burst Facility
PCI	Pellet cladding interaction
PCS	Primary Coolant System
PWR	Pressurized Water Reactor
R&D	Research and Development
SAFDL	Specified and Accepted Fuel Design Limits
SPERT	Special Power Excursion Reactor Test
SWU	Separative work units
t@T	Time at temperature
TREAT	Transient Reactor Test Facility
U.S.	United States

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1. INTRODUCTION

Executive Order (EO) 14302 section 4 directs the Department of Energy (DOE) to prioritize support for the restart, uprate, and construction of large nuclear power plants (NPPs). Section 4(a) of the order gives a goal to achieve 5 gigawatts (GW) of power uprates by 2030 and to have construction underway of 10+ GWs more (or10 new large plants) by 2030. Section 4(c) of the order directs the department to prioritize funding in this area toward technologies with a high degree of technological maturity, financial backing, and potential for near term deployment [1]. The nuclear fuel technology elements of this mission are in alignment with the Accident Tolerant Fuels (ATF) program that is being executed by DOE Office of Nuclear Energy's (NE) Advanced Fuels Campaign (AFC).

All large nuclear reactors (800 MWe and greater) currently deployed, those with current Nuclear Regulatory Commission (NRC) design licenses as well as those pursuing NRC design licenses, are light water cooled and moderated. Additionally, a significant percentage of the small and medium sized nuclear reactor designs are also based on light water reactor (LWR) technology (e.g., BWRX, AP-300, VOYGR). Advanced (non-water moderated/cooled) reactors represent an emerging and exciting new opportunity which are also prioritized by the current administration (EO 14299) [2]. However, given the smaller power outputs of these reactors and the time needed for them to achieve commercial deployment, meeting the administrations goals with respect to EO 14302 will require a significant expansion of LWR technology.

Economic barriers remain the principal obstacle for the deployment of additional LWR technology. The installation of a new large LWR can cost ~$10,000,000 per megawatt (MW) and take 6-8 years for construction. However, recent analysis has shown that uprating the thermal power output of an existing LWRs can be orders of magnitude lower cost with timelines closer to 1-2 years [3]. However, the power output of a large LWR cannot be indefinitely increased. Eventually, the power density, and thus the thermal power output of a large reactor begins to be limited by the fuel assemblies themselves. Higher core power densities can challenge the fuel's structural integrity with high thermal loads and can more quickly deplete the fuel assemblies.

Designing LWR cores with power densities much greater than ~110 kW/l without changes to the fuel assemblies themselves would require plants to develop core designs with either much shorter operating cycles (~1 year) or excessively higher reload or batch fractions (> 50%). Shorter operating cycles and high batch fractions will both significantly drive up the operating cost and decrease the overall energy output of a NPP by lowering the plant's capacity factor and/or excessively increasing the fuel cost. Flatter, higher leakage core designs also accelerate pressure vessel embrittlement shortening the overall life of the NPP.

Thus, it should be the aim of new light water reactor fuel technology to enable significant thermal power uprates of large NPPs while maintaining the plant's operating cycle of 1.5 years to 2 years and batch fractions between 34% and 50%.

The achievement of this new nuclear fuel technology goal would not only enable larger uprates for those plants which are currently power density limited, but would also provide economic incentives for other plants, including new builds and restarts, by enabling longer fuel cycles and/or lower batch fractions in those NPPs. By offering NPPs the ability to either uprate their thermal power, increase their capacity factor, and/or decrease their operating costs, the economic inertia for restarting and building out new large, light water reactor based NPPs can be overcome.

2. BACKGROUND

LWR reactor fuel rods consist of UO_2 pellets encased in a zirconium alloy sheath or cladding tube. The UO_2 pellets are stoichiometric, near fully dense, solid pellets, often with dish and chamfers and enrichments currently up to 4.95% U-235. The zirconium alloy cladding tubes are generally 98%+ zirconium metal with approximately 1% additions of niobium or tin and smaller concentrations of iron, chrome, and sometimes nickel. The tubes are produced via numerous cold working and annealing steps followed by a final heat treatment producing either a fully recrystallized or a stress relieved microstructure [4]. Fuel rods are arranged into fuel assemblies in a square lattice array. Boiling water reactor (BWR) assemblies are approximately 13 cm square, surrounded by channel boxes with cruciform control blades passing between the assemblies. Pressurized water reactor (PWR) assemblies are larger, between 20 cm to 21.5 cm square, with several of the fuel rod lattice positions containing control rod guide tubes where control rods can be inserted into the assemblies.

Fuel assembly geometry changes are a principal way that fuel assembly thermal margins have been improved historically. Fuel assemblies have evolved to have a greater number of smaller diameter fuel pins. This way the thermal power of the assembly can be increased while individual pin powers are constant or decreased. For BWRs this is achieved more easily as the control blades in these plants pass between the fuel assemblies. BWR fuel assemblies have evolved from 8x8 arrays all the way to 11x11 arrays. However, for PWRs the control rod guide tubes are integrated inside the fuel assemblies and a change in the array would necessitate a change in the control rods and the reactor vessel penetrations that they pass through. Thus, for PWRs the assembly changes have been linked to evolutions in the design of the reactors themselves. Early 2-loop Westinghouse and Combustion Engineering plants contained 14x14 arrays. Babcock & Wilcox (B&W) plants increased the array size to 15x15, which are also found in some latter Westinghouse 3-loop plants. Modern high-power density Combustion Engineering System 80 plants contain 16x16 arrays. The latest 4-loop and AP-1000 Westinghouse plants contain 17x17 arrays. The fuel pins in the 17x17 PWR arrays and those in the 11x11 BWR arrays are quite similar in size each being ~9.5mm in outer diameter (OD) with an ~0.57mm cladding wall thickness containing fuel pellets that are ~8.2mm in OD. To date, no PWR NPP has changed its array size [5].

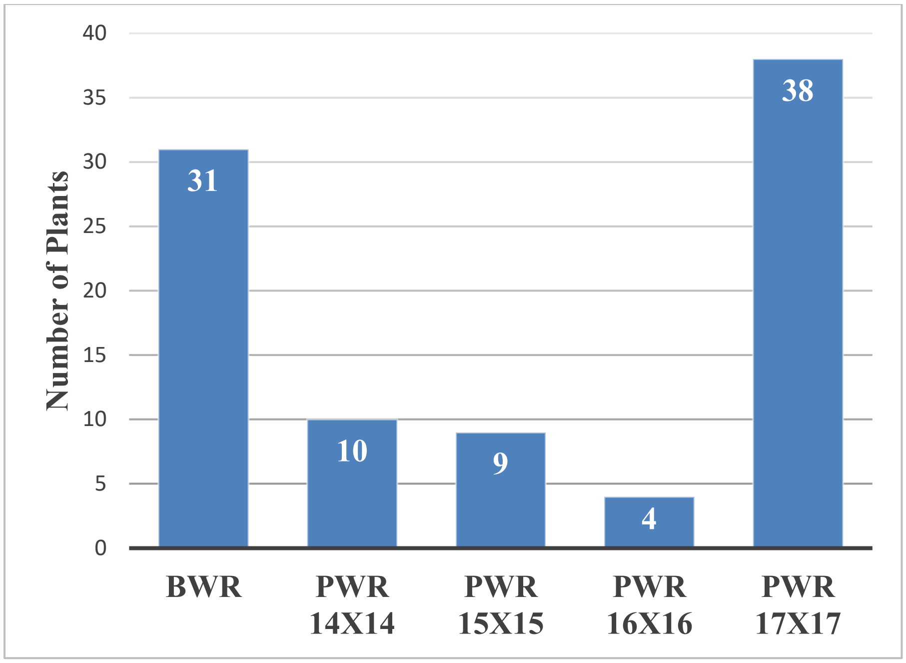


Figure 1. Make Up of U.S. Nuclear Fleet by Fuel Assembly Type.

Optimizations in fuel rod technology have focused on achieving high density fuel pellets with precise dimensions (to increase fissile loading without increased enrichment), and cladding technologies which have high corrosion resistance, better creep strength, and lower irradiation growth (to extend service life and increase operating envelope). Recent development from the DOE's AFC ATF program have developed doped fuel pellets with near theoretical densities (~98%), and with large grain sizes to improve fission gas retention and softer pellet cladding contact [6] as well as increase uranium loading. Coated claddings with improved resilience to oxygen embrittlement in high temperature steam conditions have also been developed under the ATF program [7]. These improvements in the LWR fuel industry have been paired with initiatives to increase the enrichment limits (~6-10%), and rod average burnup (~75MWd/kgU) of the fuel as well as demonstrating tolerance for high temperature (up to ~800°C) exposure limits (colloquially identified as cladding time at temperature [t@T] limits) to replace thermal hydraulic margins which prevent the onset of a boiling crisis [8][9]. These ATF improvements with their corresponding design limit increases represent the first meaningful step in increasing the power output of LWR fuel assemblies.

Relative to the capital investments associated with plant power up rates and new reactor construction, LWR fuels are relatively inexpensive and are regularly replaced in the reactor cores every 1.5 years to 2 years. The combination of natural uranium ore and enrichment services make up nearly 80% of the fuel assembly cost [10]. Increasing the enrichment by 20% (e.g. from 5% to 6%) requires a roughly 20% increase in natural uranium feed as well as an approximate 20% increase in enrichment capacity (measured in separative work units [SWU]). Thus, a good first order approximation for the cost differences in LWR fuel assembly designs is the amount and enrichment of the uranium in the fuel assemblies.

2.1. Fuel Cycle Considerations

The reactivity of a fuel assembly is determined by calculating the criticality value (k) of an infinite array of fuel assemblies k_∞. Assuming an overall core leakage value of 0.035 $\Delta k/k$, fuel assemblies with k_∞ values greater than 1.035 are considered to have excess reactivity and contribute to the sustained nuclear reaction, while assemblies with k_∞ values less than 1.035 suppress the sustained nuclear reaction. LWRs have a negative breeding ratio, meaning that as fissile U-235 atoms in the fuel pellets are fissioned, only limited amounts of the fertile U-238 atoms are converted to fissile Pu-239. Thus, the k_∞ values of fuel assemblies decrease with exposure, with the depletion rate being proportional to the assembly power and time.

This depletion necessitates a refueling outage every 1.5 years to 2 years where a percentage of the core is replaced with fresh assemblies. This percentage is called the batch fraction. The more excess reactivity that is initially loaded into an LWR core, the higher the power level that can be sustained for a given cycle length. The excess reactivity available at the start of an operating cycle depends both on the number of fresh fuel assemblies and the enrichment of the fresh assemblies. The amount of excess reactivity that can be loaded into a LWR core is limited by the NPP's required shutdown margin which is the amount of subcriticality a plant is required to maintain with all the control rods inserted except for the highest worth control rod. Maintaining high core thermal powers for meaningful cycle lengths without impacting shutdown margin often requires the use of burnable poisons in the fuel assemblies which limit their initial excess reactivity but 'burn-out'(e.g., are depleted as they are converted by neutron absorption and transmutation) over time.

The total energy output (or exposure) of a LWR fuel assembly across all its irradiation cycles is often given relative to the fuel assemblies heavy metal mass and is referred to as the burnup. Burnup is a useful metric for determining how much of the energy available in the fuel is utilized over its life. The relationship between core thermal power, assembly average burnup, assembly mass, batch fraction, and cycle length is given in equation 1 below. Increasing core power requires either increasing the fuel assembly heavy metal (HM) mass, the burnup, or batch fraction or else decreasing the cycle length.

$$TP = \frac{m * n * BU}{t} \tag{1}$$

TP = Reactor Thermal Power (MW)
m = Assembly Mass Heavy Metal Mass (kgU)
n = Number of Fuel Assemblies Replaced Each Cycle
BU = Assembly Average Burnup (MWd/kgU)
t = Cycle length (days)

Individual fuel assembly discharge burnups can vary as the specific discharge burnup of a fuel assembly depends on its placement in the core over its life. The variation of assembly discharge burnups increases as the batch fraction increases. With batch fractions greater than 50% some fuel assemblies would only be irradiated for one cycle, and no assembly would be irradiated for more than two cycles. This would lead to undesirably poor fuel assembly and uranium utilization with numerous plant consequences.

Burnup limits are generally expressed as a rod average burnup and sometimes as a peak pellet burnup. Current burnup limits for existing fuels are 62 MWd/kgU, however increases to 75 MWd/kgU are being pursued in the ATF program. Factors limiting burnup more generally have to do with the overall irradiation and environmental degradation of the fuel rods than with burnup itself. Phenomena such as cladding corrosion (and associated hydrogen pickup), fuel rod growth, and fuel rod internal pressure are some examples of what can be limiting. These phenomena often become particularly important in accident analysis as it must be shown that the performance of degraded rods in design basis accidents does not challenge plant safety criteria or subsequent storage safety criteria.

2.2. Thermal Power Considerations

In addition to the fuel cycle considerations the structural integrity of the fuel rods within the assemblies must also be considered. The thermal power limits of fuel rods are referred to as linear heat generation rate (LHGR) limits. LHGR limits are also sometimes derived from plant safety limits but more often are derived from the fuel vendors specified and accepted fuel design limits (SAFDL). SAFDLs are meant to prevent fuel rod failure and damage during normal operations and anticipated plant operational occurrences. Failure and damage to fuel rods in a nuclear reactor is almost always associated with the overheating of either the fuel pellets themselves or the cladding which encases the fuel pellets. Overheating of the fuel rods can occur due to a variety of phenomena which are linked to the material properties of the fuel rods themselves, their degree of exposure or degradation the rods have experienced, and the thermal hydraulic boundary conditions.

A NPPs primary coolant system (PCS) is responsible for keeping the fuel rods adequately cooled. When the PCS remains as a subcooled liquid or in nucleate boiling, heat transfer properties of the system are sufficient to keep cladding temperatures only slightly above (or maximum 100° C greater than) that of the liquid itself, regardless of fuel rod heating rate. If, however, due to excessive heat fluxes or inadequate coolant flows, the liquid water evaporates on the fuel cladding surface, due either to a departure from nucleate boiling (DNB) or dry out condition, the heat transfer begins to rapidly degrade resulting in excessive cladding temperatures. Cladding strength and corrosion resistance decrease rapidly with increasing temperature resulting in damage or failure. The current convention of the nuclear industry is to preclude heat flux and coolant flow conditions which result in DNB and dry out although some efforts are underway to allow short durations in these conditions through the development of a cladding t@T limit below the alpha/alpha + beta transition temperature for tin-based alloys which is around 800° C.

While cladding overheating can directly result in fuel rod damage and is primarily linked to plant thermal hydraulic conditions, fuel pellet overheating can also lead to damage and failure of the fuel rod indirectly via over stressing or straining the cladding even if the cladding remains cool. Overheating of fuel pellets is less dependent on plant thermal hydraulic conditions but more related to the fuel pellets' own heating rate and degree of exposure. Oxide fuel pellets have a low thermal conductivity and can expand significantly as its temperature increases. Additionally, oxide pellets accumulate fission gases in its ceramic matrix which can drive additional swelling or be released to the fuel rod plenum resulting in excessively high rod internal pressures. Oxide pellet swelling and off gassing increases with both temperature and exposure resulting in lower thermal (LHGR) limits for the fuel rods as their exposure increases.

3. FUEL TECHNOLOGY ALTERNATIVES

According to the EO the fuel technology pursued should have a high degree of technical maturity and potential for near term deployment. Additional requirements come from an analysis of the fuel cycle and thermal power considerations described above. The new fuel technology will be required to have either more uranium mass or be able to reach higher burnups to support the higher power levels while maintaining cycle length and batch fractions. Supporting these burnups and cycle lengths will also require the fuel to maintain higher reactivity levels. Increasing the initial excess reactivity will likely be limited by the available shutdown margin. However, it will be desired for the fuel to deplete more slowly or to maintain a k_∞ value greater than ~1.035 up to a higher exposure level. Slowing this depletion can be achieved either through embedding higher burnable poison levels in the fuel rods or through hardening of the neutron spectrum so that more Pu-239 is produced.

Burnable poisons such as gadolinia, europia, and boron coatings have the advantage of already being in commercial development. However, the use of burnable poisons removes uranium mass from the fuel assemblies which places further upward pressure on required burnup increases. Additionally, and often more problematic is that these existing burnable poisons often have significant impacts on fuel rod thermal performance, negatively impacting LHGR limits which are required to increase in a power uprate scenario. Hardening the spectrum of a LWR would require decreasing the hydrogen to heavy metal (H/HM) ratio of the plant by either removing water or adding uranium. Uranium increases could be achieved through the development of a higher density fuel form or through changes to the assembly lattice geometry, the latter of which has a higher potential for near-term deployment.

3.1. Enhanced Accident Tolerant Fuels

Following the March 2011 Great Tohoku Earthquake and subsequent tsunami's impact on the Japanese coastline and, in particular, the Fukushima Daiichi Nuclear Power Plant, enhancing the accident tolerance of LWRs become a topic of serious discussion. In 2012, the U.S. Senate directed DOE-NE to create a research and development (R&D) plan to deliver nuclear fuel technology with enhanced accident tolerance. As mentioned earlier coated claddings and doped fuel pellets emerged as leading near-term candidates. The program was later amended in 2019 and again in 2024 to include technologies that improved economic incentives to accelerate deployment including high burnup (HBU), increased enrichment (low-enriched uranium [LEU]+), and t@T. These were designated as enhanced ATF.

Dramatic progress was made through cooperative research agreements between DOE and the U.S. fuel suppliers that leveraged the national laboratory expertise and facilities to progress through multiple technology development phases including (Phase 1) concept development and screening in test reactors, completed in 2016, and (Phase 2) concept development and lead test rod demonstration in commercial reactors, completed in 2025. All enhanced ATF products including coated claddings, doped fuel pellets, as well as the enhanced economic features of HBU, LEU+, and t@T are anticipated to have achieved complete deployment by the end of Phase 3 in 2029.

ATF technologies are inherently designed to increase fuel rod robustness, allowing for higher thermal power densities and burnups. The doped fuel pellets should provide enhanced fission gas retention and lower pellet cladding interaction stresses. The coated cladding provides improved resilience to waterside corrosion and high temperature steam oxidation particularly above the alpha/alpha + beta transition temperature of 800° C and below the Cr/Zr eutectic temperature of ~1300° C. However, these coatings currently only exist for PWR water environments. BWR reactors have the advantage of having inherently lower cladding temperatures during dry out events and fuel developers for BWRs have the advantage of being able to more easily increase the array size of their fuel bundles. However, development of a BWR coating would be advantageous and could likely be achieved by the mid 2030's.

3.2. Enlarged Annular Fuel

Annular fuel pellets with a larger OD so that the fuel area is maintained or slightly increased, relative to current designs have the potential to significantly aid fuel assembly power density increases. If possible, adding heavy metal (uranium) to the fuel assemblies has the combined benefit of increasing the overall energy that can be released at a given burnup and increasing the exposure at which the assembly's reactivity is greater than 1.035 due to the harder neutron spectrum. Figure 2 below shows the dramatic benefit of a 20% increase in HM mass in an LWR fuel assembly. Infinite reactivity at the beginning of irradiation is lower (increasing shutdown margin) even when the enrichment is increased from 5% to 6%. Even with less initial excess reactivity the enlarged fuel pellets stay above the 1.035 k_∞ threshold for up to a higher level of energy release with an even greater benefit when the enrichment is increased from 5% to 6%.

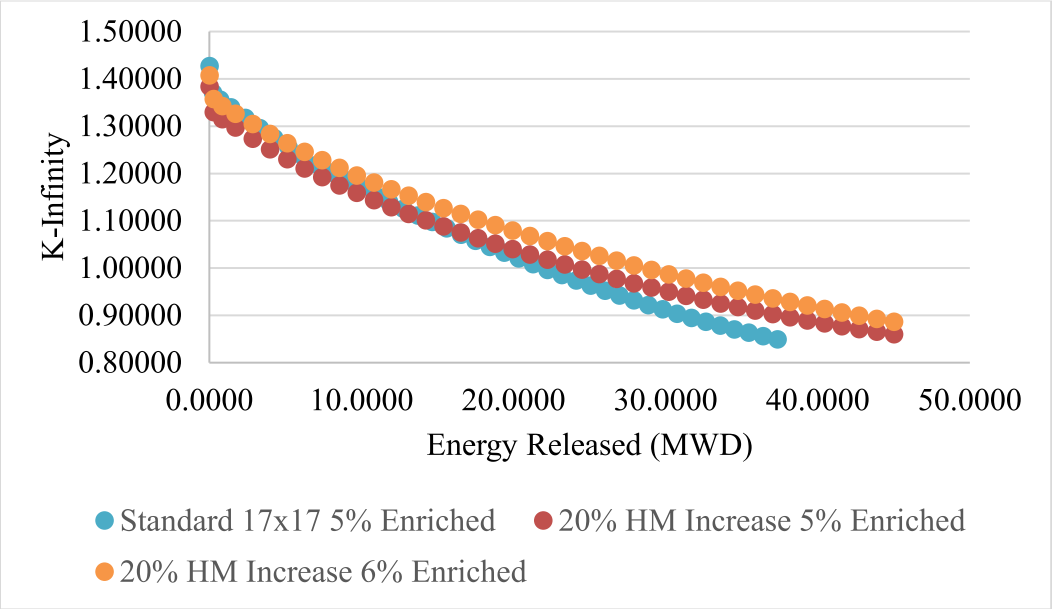


Figure 2. Infinite Lattice Reactivity of an Enlarged 17x17 Assembly.

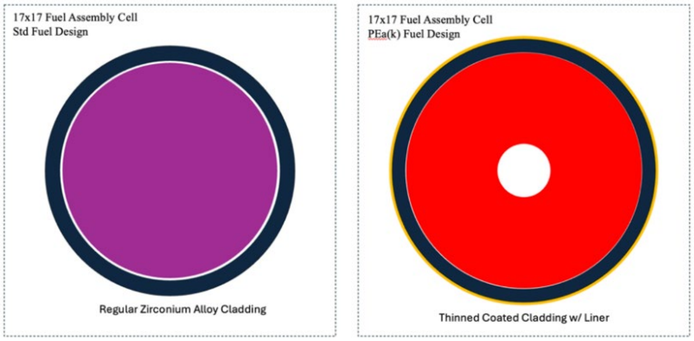
A 20% increase in heavy metal mass with annular fuel pellets likely requires unacceptably high cladding OD increases bringing fuel pins in too close of contact and unacceptable decreases to flow area. However, 10% increases may be achievable for only smaller increases in cladding OD. Assuming a minimum pellet cladding gap of 25 microns a range of potential fuel annulus sizes, cladding thicknesses, and cladding ODs are presented in Table 1.

Table 1. Possible Cladding OD to Achieve a 10% Increase in Fuel Loading

Pellet Annulus (mm)	**Cladding Thickness (mm)**									
	0.57	**0.55**	**0.53**	**0.51**	**0.49**	**0.47**	**0.45**	**0.43**	**0.41**	**0.39**
0	9.79	9.75	9.71	9.67	9.63	9.59	9.55	9.51	9.47	9.43
0.5	9.80	9.76	9.72	9.68	9.64	9.60	9.56	9.52	9.48	9.44
1	9.85	9.81	9.77	9.73	9.69	9.65	9.61	9.57	9.53	9.49
1.5	9.92	9.88	9.84	9.80	9.76	9.72	9.68	9.64	9.60	9.56
2	10.02	9.98	9.94	9.90	9.86	9.82	9.78	9.74	9.70	9.66
2.5	10.15	10.11	10.07	10.03	9.99	9.95	9.91	9.87	9.83	9.79
3	10.30	10.26	10.22	10.18	10.14	10.10	10.06	10.02	9.98	9.94
3.5	10.48	10.44	10.40	10.36	10.32	10.28	10.24	10.20	10.16	10.12

Switching from solid to annular fuel pellets can dramatically lower fuel temperatures for only a minimal trade off in loss of fuel area. Assuming a standard fuel pellet OD of 8.2mm or heat transfer distance of 4.1mm radially, adding a 2.2mm annulus shortens the heat transfer distance to a 3mm radius while removing only 3.8mm^2 of fuel. Achieving this same thermal margin improvement with solid pellets (decreasing pellet OD) would require a loss of 24.5mm^2 of fuel. Likewise, small increases in pellet OD can add significantly to the fuel area. Increasing the fuel pellet OD can be achieved via decreasing the pellet cladding gap, decreasing the cladding thickness, or increasing the cladding OD. Modern fuel pellet manufacturing processes can create pellets with extremely high precision such that it is feasible to assume the current ~80-micron gap sizes could be reduced to ~25 microns without meaningfully impacting fuel rod fabricability. A reduction in gap size combined also with a reduction in cladding thickness, and very high density doped-UO_2 pellets result in almost immediate closure of the pellet cladding gap which also helps lower fuel temperature. Immediate closure of the pellet cladding gap also eliminates the need to backfill the fuel rods with He gas to facilitate early heat conduction across the pellet cladding gap. Lower starting plenum pressures allow more margin for fission gas release before cladding lift off occurs.

Reducing the cladding thickness and pellet cladding gap will come with thermal mechanical challenges however, Increased pellet cladding interaction (PCI) will be a principal consideration. However, PCI stresses in the cladding can also be mitigated by using annular pellets which can expand/swell in two radial directions. A cladding liner can also be considered to further alleviate PCI stresses. Efforts to increase the cladding OD while maintaining array size decreases the available flow area. Decreases in flow area will result in higher pressure drops over the core, which for a given pump power will decrease the volumetric flow rate and result in higher coolant temperature increases with lower margin to a DNB or dry out event. The power uprate itself will also affect DNB margin. Thinner cladding with a larger OD also presents corrosion challenges in both steady state and accident scenarios. For a given amount of corrosion with a set amount of hydrogen (steady state) or oxygen (accident) absorption, the smaller cladding mass will lead to higher concentrations of brittle hydride and oxide phases. Also, cladding stresses will be higher for given pressure differentials resulting in a greater number of burst rods in depressurization loss of coolant accidents (LOCA). The use of coated claddings materials will be employed to mitigate these challenges. A case study for a PWR fuel rod with its outer diameter increased to 10mm with a 500-micron wall thickness and 2mm annulus is considered in Figure 3 below.



	Std	PEa(k)	Δ%
Water Area (mm²)	87.88	80.22	↓8.65%
Cladding Area (mm²)	15.99	14.92	↓6.7%
Fuel Area (mm²)	52.81	59.07	↑11.85%
Gas Area (mm²)	2.08	3.14	↑51%

Figure 3. Enlarged Annular Fuel Design Alternative with 10% Higher Fuel Loading.

Initial fuel performance simulations comparing standard fuel designs to the enlarged annular fuel design were conducted. The standard design is called the solid standard case and is run at 180 W/cm out to ~55 MWd/kgU. The enlarged annular case is run at a higher linear heat rate of 210 W/cm out to 60 MWd/kgU. Fuel performance simulations were conducted using the BISON fuel performance code [11]. Results show overall comparable fuel temperatures in both cases and even slightly lower temperatures for the enlarged annular fuel despite its higher heat rate. These temperatures translate to comparable fission gas releases. The larger internal volume in the annular fuel case and lower initial pressure, results in much lower plenum pressures in the enlarged annular fuel than in the standard fuel case. Cladding stress is only higher in the enlarged annular case at the beginning of life and is compressive due to the high-pressure differential and recovers soon after contact is made with the annular pellets. Cladding strains are larger in the enlarged annular case due to the higher PCI.

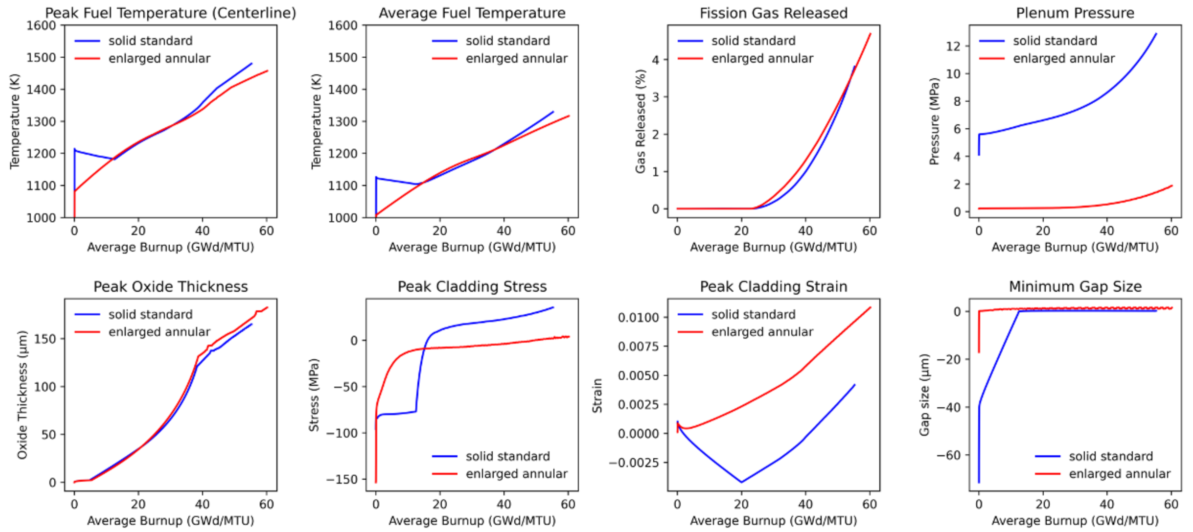


Figure 4. BISON Fuel Performance Simulations Showing Ability of Enlarged Annular Fuel to Operate at Higher Linear Powers.

3.3. Next Generation Fuel Development

Advanced material technologies such as silicon carbide claddings, advanced stainless steels, and non-oxide fuel pellets such as nitrides, or metallic uranium forms are being developed by AFC as part of its Next Generation Fuels (NGF) initiative. While these technologies have development timelines beyond the goals of the EO on power uprates their development has a high potential payoff and could lead to significant power density increases in LWR fuels. Thus, they will continue to be developed and reviewed by AFC as part of NGF.

4. R&D Facilities and Stakeholder Engagement

AFC can support the full lifecycle needs of the LWR community through both 1) maintaining critical experimental infrastructure required for cross-cutting R&D, most notably world-class irradiation testing and post irradiation examination capabilities, and 2) engaging with stakeholder communities for near-term (<2 years), mid-term (5-10 years) and long-term (>10 years) technology development and deployment missions.

The near-term technology objectives will be supported through R&D conducted under the near-term ATF program. In this program, AFC will assist the three U.S. fuel suppliers with completing development of nearly mature ATF technologies for LWRs, including coated cladding and doped fuel technology. These technologies have been the focus of several successive cooperative research projects awarded by DOE to the U.S. fuel suppliers since 2016. A final Phase 3 award is anticipated in fiscal year (FY) 2026 that will support completion of the DOE sponsored R&D program elements. Subsequent deployment will be driven by industrial forces, primarily economic advantages achieved through adoption of the new fuel systems.

Success with near term objectives will set the stage for even greater performance and production increases in the existing LWR fleet. Harvesting the benefits of the developed enhanced ATF technologies including the potential incorporation of enlarged annular fuel pellets, can be pursed in the medium-term. These benefits will also impact the economic drivers to build ten new LWR power plants called for in section 4a) of EO 14302. Industry-led analysis has suggested that plants have the potential to support as much as 20% uprates when additional fuel technology improvements are combined with other physical plant modifications. This opportunity for much larger uprates is a target mission for the AFCATF mid-term support effort. As the deployment timelines are longer, an open-source program that supports technology development of a pre-industrial program accessible to all U.S. fuel suppliers and, thus, utilities would be most impactful. AFC will collaborate with the industrial stakeholder community to identify promising technology options and co-develop an R&D plan that leads promising technologies to a subsequent industrialization phase that will be facilitated by technology transfer initiatives as necessary.

Long-term R&D is necessary to identify, evaluate, and mature technologies with the potential to dramatically enhance the landscape, often referred to as transformational or disruptive technologies. The NGF branch of AFC is focused on high-risk research activities that support bold, innovative concept development that is outside typical stakeholder direction and is aimed at achieving significant technological breakthroughs. For LWRs, this could include dramatic improvements to the fissile management, plant safety, economics, and waste management. Nucleation and identification of novel concepts of this type requires engagement with a broad community of technologists including nuclear and non-nuclear industrial innovators, national laboratory researchers, and university researchers. AFC will be a nexus for the nuclear fuels and materials community and will endeavor to facilitate idea formulation and evaluation.

Fuel technology R&D is built on the foundation of a robust experimental testbed that delivers the unique environmental conditions relevant to nuclear fuels and the state-of-the-art examination capabilities necessary to characterize their response. Development, deployment, and operation of these specialized facilities is typically beyond the means of the commercial industry and thus form the core of the national laboratory system model. The U.S. pioneered this model which was instrumental in the emergence of the U.S. commercial nuclear industry. During the 1960's to 1980's U.S. national laboratories operated a number of test reactors and hot cell facilities dedicated to fuels and materials testing for LWRs. These included materials test reactors, such as the Advanced Test Reactor (ATR) and its predecessors (Materials Test Reactor and Engineering Test Reactor) for steady-state fuel performance research, and transient testing reactors, such as the Transient Reactor Test (TREAT), Special Power Excursion Reactor Test (SPERT), Loss of Flow Test (LOFT) and Power Burst (PBF) Facilities and a diverse family of hot cells dispersed throughout the DOE complex. As growth in the U.S. commercial fleet slowed in the 1990's, much of this infrastructure was repurposed and closed and the intellectual center of nuclear fuels and material research supporting LWRs moved abroad to Europe and Russia.

One of the key objectives of the ATF program was to revitalize the national infrastructure to once again infuse the industry with a wave of innovative technologies that would improve overall performance. The scope and timeframe for this effort were significantly expanded and accelerated in response to closure of the Halden Reactor in Norway, which effectively left Russia at the center of LWR research in a period when collaboration was deemed impossible. A national strategy was thus developed based on coordinated use of Idaho National Laboratory's (INL) ATR, Oak Ridge National Laboratory's (ORNL) High Flux Isotope Reactor (HFIR), and the Massachusetts Institute of Technology Nuclear Research Reactor (MITR) for steady-state testing and the INL's TREAT for transient testing as well as the large- and small-scale hot cell facilities located INL and ORNL.

Combined, this network of facilities functionally forms the basis for a National Center of Excellence in LWR Nuclear Fuels and Materials[a]. The AFC program's foundational mission is to develop, maintain, and strategically deploy this testbed in support of the near-term, mid-term, and long-term missions outlined previously. This testbed will revolve around two water loops in ATR (one each supporting PWR

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[a] National Center for Nuclear Fuels and Materials Development to be modeled after the recently announced National Center for Used Fuel Research

and BWR conditions), transient testing in dedicated water devices at TREAT, separate effects testing in ATR, HFIR, and MITR, and hot cell testing/examinations at INL and ORNL.

5. CONCLUSIONS AND RECOMMEDATIONS

New LWR fuel technology is being developed to support power uprates as well as fuel cycle and operating cost benefits for existing LWR based NPPs in support of EO 14302. AFC is working to develop technology over the near-, mid-, and long-term to enable sustained power uprates and economic incentives for new deployment. AFC has, through the ATF program, developed a strong LWR test bed and a meaningful stakeholder network to achieve these goals. A summary of the key features of LWR fuels and fuel features with desired performance benefits is included below.

Coated zircaloy based claddings have largely been developed under the ATF program for PWRs and will be developed for BWRs. Coated cladding reduce the oxidation and hydrogen pickup during normal service conditions and provide marginal enhancements to cladding strength. This will help offset penalties associated with thinning the cladding wall. The principal benefit of coated claddings will be expansion of t@T limits from ~800° C (alpha/alpha + beta transition temperature) up to 1300° C (Cr/Zr eutectic temperature).

Doped/high density UO_2 pellets have been developed for PWR and BWRs under the ATF program and allow for maximizing fuel density and improving fission gas retention to help aid fuel cycle economics and burnup extensions.

Thin claddings with reduced pellet cladding gaps will allow for the addition of uranium metal that is removed from the lattice when annular fuel is incorporated. Even small reductions in cladding thickness and pellet cladding gap can allow meaningful increases in fuel area. Small pellet cladding gaps may require the incorporation of cladding liners to offset PCI stresses.

Enlarged annular fuel pellets will have equivalent of slightly higher fuel areas with lower heat transfer distances providing equivalent or better fuel depletion with greatly expanded power density margins resulting from lower fuel operating temperatures and lower fission gas release.

The combination of these enhancements should allow for meaningful power density increases enabling significant thermal power uprates of large NPPs while maintaining the plant’s operating cycle of 1.5 years to 2 years and batch fractions between 34% and 50%.

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Timeline for the ATF Program

2011

- **March:** Fukushima Daiichi nuclear disaster highlights the need for accident-tolerant nuclear fuels (ATF).
- **Senate Report 112-75:** Senate requests a report from the Department of Energy (DOE) on plans for accident-tolerant fuel development.

2012

- **H.R. Conference Report 112-331:** Congress provides funding to the DOE Office of Nuclear Energy (DOE-NE) to initiate R&D for ATF.
- **Phase 1 (FY2012–FY2016):** Program launched under DOE-NE with competitive awards for industry-led R&D.
    - **Award Recipients:** Westinghouse Electric Company (WEC), General Electric (GE), and Framatome (then AREVA NP).
    - Focus: Identify material candidates and conduct testing in material test reactors.

2015

- **March:** DOE submits a Report to Congress detailing the ATF development plan, structured into three phases.
- **Phase 1 Completion:** Initial research on material candidates completed.

2017

- **Phase 2 Begins (FY2017–FY2025):** Focus shifts to development and qualification testing.
    - Includes ATF Lead Test Assembly (LTA) irradiations, commercial-scale testing, and post-irradiation examinations (PIE).
    - Major facilities include INL/ATR, INL/TREAT, ORNL/HFIR, and ORNL/SATS.

2019

- **Public Law 115-439:** Expands program scope to include Low Enriched Uranium Plus (LEU+) and higher burnups (HBU) for enhanced fuel performance. Described as Enhanced ATF (EATF).

2024

- **Public Law 118-67:** Redefines "Advanced Nuclear Fuel" (ANF) to include EATF.

2025

- **Phase 2 Completion:**
    - First ATF LTA demonstrations in commercial reactor complete and PIE initiated.
    - Insertion of EATF LTAs in commercial reactor completed.
- **Executive Order 14302 Sec. 4a:** Directs DOE to collaborate with industry to achieve 5GW of LWR power uprates by 2028.

2026

- **Phase 3 Begins (FY2026–FY2030):** Focus on applying EATF technologies to achieve uprates.
    - Objective: Deploy HBU, LEU+, t@T, and ATF to deliver power uprates.
    - Challenge: Complete research activities needed to inform utilities, fuel suppliers, and regulator operations and licensing actions.

2028 (Anticipated)

- **Achieve Power Uprates:** Industrial deployment of EATF technologies in the U.S. commercial nuclear fleet to deliver 5GW in power uprates.

2030 (Anticipated)

- **Phase 3 Completion:** Identify new fuel technologies capable of supporting 20% uprates in the U.S. commercial nuclear fleet.