Development of advanced accident-tolerant fuels for commercial LWRs

By Shannon Bragg-Sitton

Post-Fukushima, the focus for advanced fuels is on fuel system behavior under design-basis accident and severe-accident conditions, along with improved performance under normal operating conditions.

The safe, reliable, and economic operation of the nation's nuclear power reactor fleet has always been a top priority for the United States' nuclear industry. Continual improvement of technology, including advanced materials and nuclear fuels, remains central to the industry's success. Decades of research combined with continual operation have produced steady advancements in technology and have yielded an extensive base of data, experience, and knowledge on light-water reactor fuel performance under both normal and accident conditions. Thanks to efforts by both the U.S. government and private companies, nuclear technologies have advanced over time to optimize economic operations at nuclear power plants while ensuring safety.

One of the missions of the Department of Energy's Office of Nuclear Energy (NE) is to develop nuclear fuels and claddings with enhanced accident tolerance. In 2011, following the earthquake and tsunami in Japan and the subsequent damage to the Fukushima Daiichi nuclear power plant complex, enhancing the accident tolerance of LWRs became a topic of serious discussion. As a result of direction from Congress, NE initiated accident-tolerant fuel (ATF) development as a primary component of the Fuel Cycle Research and Development (FCRD) Advanced Fuels Campaign.

Prior to the accident at Fukushima, the emphasis of advanced LWR fuel development was on improving nuclear fuel performance in terms of increased burnup for waste minimization, increased power density for power upgrades, and increased fuel reliability. Fukushima highlighted some undesirable performance characteristics of the standard fuel system during severe accidents, including accelerated hydrogen production under certain circumstances. Thus, fuel system behavior under design-basis accident and severe-accident conditions became the primary focus for advanced fuels, along with striving for improved performance under normal operating conditions to ensure that proposed new fuels will be economically viable.

The goal of the ATF development effort is to demonstrate performance with a lead test rod (LTR) or lead test assembly (LTA) irradiation in a commercial power reactor by 2022. Research and development activities are being conducted at multiple national laboratories and universities and within the industry, with support from the DOE program.

Current LWR fuel standard

The U.S. commercial fleet produces electricity in LWRs using a standard uranium dioxide –zirconium (UO_2-Zr) alloy fuel system. The design and development of an advanced fuel demonstrating enhanced accident tolerance first requires an understanding of the performance of the current state-of-the-art fuel system under the various system operating regimes. Decades of industry research and operational experience have produced an extensive database supporting the performance of LWR fuel during normal power operations and during postulated accident conditions. The nuclear power industry is focused on continuous improvement and reliable operation and deploys design enhancements to the fuel system as they become available. Typically these are small incremental improvements to the current fuel system design, which has been optimized over decades. U.S. boiling water reactors currently use Zircaloy-2, while pressurized water reactors previously used Zircaloy-4 and have now transitioned to zirconium-niobium (Zr-Nb) cladding (M5 and ZIRLO), with M5 and ZIRLO demonstrating improved corrosion behavior relative to Zircaloy-4.

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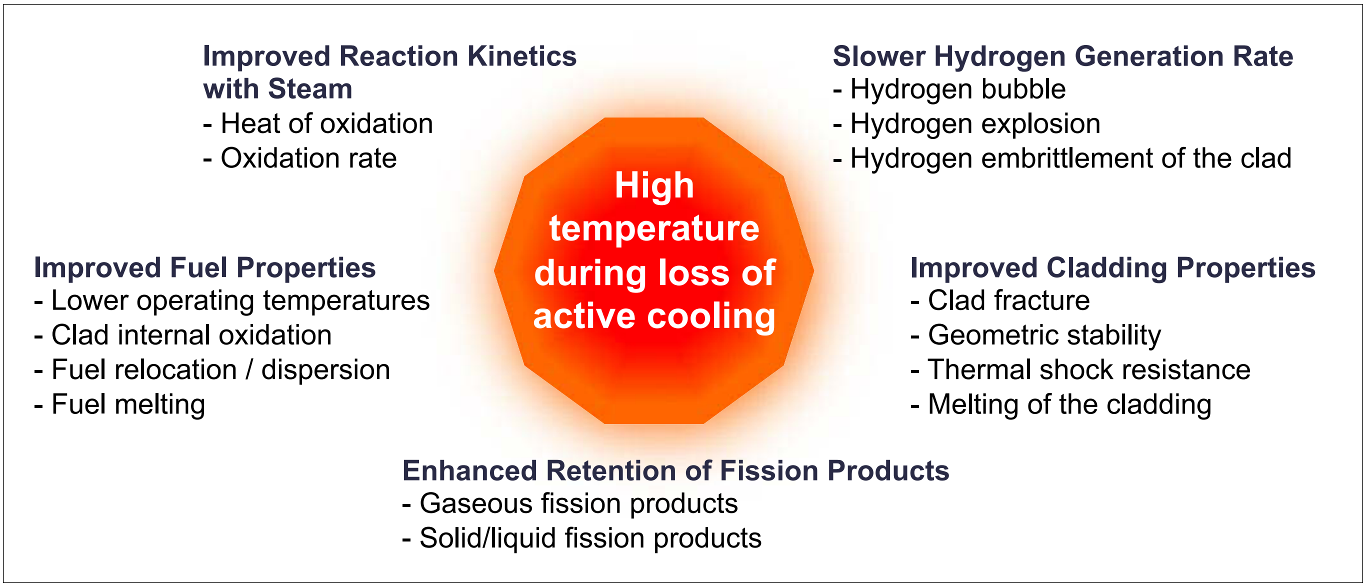

Fig. 1. Major issues that need to be addressed in establishing accident-tolerant fuel attributes

ATF design goals, constraints

The overall goal of the Advanced Fuels Campaign is to identify alternative fuel system technologies to enhance the safety, competitiveness, and economics of the U.S. commercial power reactor fleet. The development of an enhanced fuel system supports the sustainability of the U.S. nuclear fleet.

The development of fuels with enhanced accident tolerance necessarily begins with the definition of down-selection requirements during a concept feasibility assessment. In short, fuels with enhanced accident tolerance will tolerate the loss of active cooling in the core for a considerably longer period of time and to higher temperatures than the current fuel system while maintaining or improving fuel performance during normal operations. As summarized in Fig. 1 and defined relative to the current state-of-the-art system, key requirements for advanced fuels can be broken into three main subcategories:

1) *Nuclear Fuel Cladding*—Slower reaction kinetics with steam (for example, reaction rate and heat of oxidation), slower hydrogen (or other combustible gas) generation rate, and good cladding thermo-mechanical properties.

2) *Nuclear Fuel*—Enhanced thermo-mechanical properties, and enhanced fission product retention.

3) *Constraints*—Backward compatible with current fuel fabrication facilities, fuel handling equipment, and LWR designs; improved operational and safety envelope (normal, anticipated conditions, and representative accident scenarios); and minimal economic impacts.

Advanced nuclear fuel and cladding must maintain, at a minimum, the level of performance and safety margin associated with the current industry standard fuel system. To warrant the additional costs associated with the development, licensing, and implementation of a new fuel technology, advanced fuel options must not just meet these performance levels but must exceed them by providing for the possibility of power uprates, increased fuel burnup, reduced number of assemblies per reload, and increased cycle length (reduced outage frequency), as well as significantly enhanced safety performance under off-normal conditions.

Any new fuel concept proposed for enhanced accident tolerance under rare events must also be compliant with and evaluated against current design, operational, economic, and safety requirements. The complete fuel cycle must be considered, especially for concepts that represent a significant departure from the current technology. Candidate advanced fuel concepts should also be evaluated in the context of other potential plant-level improvements—such as access to emergency cooling water and additional battery power—that are being developed to enhance overall safety to fully characterize the impact of the candidate fuels on reactor operations.

The constraints associated with commercial nuclear fuel development and deployment are as follows (also see Fig. 2):

■ *Backward compatibility*—Regardless of whether the actual deployment target is a current or future reactor, the fuel is likely to be fabricated in existing fuel fabrication facilities and qualified and initially demonstrated in existing commercial reactors. Proposed fuel concepts should not require modifications to the fabrication plant or host reactor for demonstration irradiation. This backward-compatibility constraint encompasses existing fuel handling equipment, fuel rod or assembly geometry, and co-resident fuel in the reactor.

■ *Operations*—A new fuel system must maintain or extend plant operating cycles, reactor power output, and reactor control. To maintain current operational levels, some proposed fuel system concepts may require higher fuel enrichment. While the impact of higher enrichments is fairly well understood from a technical perspective, regulatory, equipment, and fuel performance issues would have to be addressed for both the fuel fabrication facility and the operating plant.

■ *Safety*—The safety and performance of a proposed new fuel system must be assessed relative to that of the UO$_2$–Zr alloy system under normal, operational transient, design-basis accident, and beyond design-basis conditions. During the current feasibility assessment phase, specific emphasis is being placed on long-term station blackout, loss-of-coolant accidents (LOCA), and reactivity insertion accidents.

■ *Front end of the nuclear fuel cycle*—The impact of new fuels and cladding on the front end of the nuclear fuel cycle must be assessed within the framework of current and future regulations and policies. For instance, if an advanced stainless steel cladding were to replace Zr-based alloys and maintain the same wall thickness, the required fuel enrichment would increase by 1 to 2 percent (referred to as the uranium-235 penalty). Some concepts could require even greater increases in enrichment. In addition to the economic penalty associated with fuel enrichment activities, higher enrichment would result in lower uranium utilization, would have a major impact on operations at current enrichment and fuel fabrication plants, and would require changes to operating licenses.

■ *Back end of the nuclear fuel cycle*—A new fuel system could also have an impact on the back end of the nuclear fuel cycle. The storage (wet and dry) and repository performance of the fuel (assuming a once-through fuel cycle) must not be degraded; otherwise,

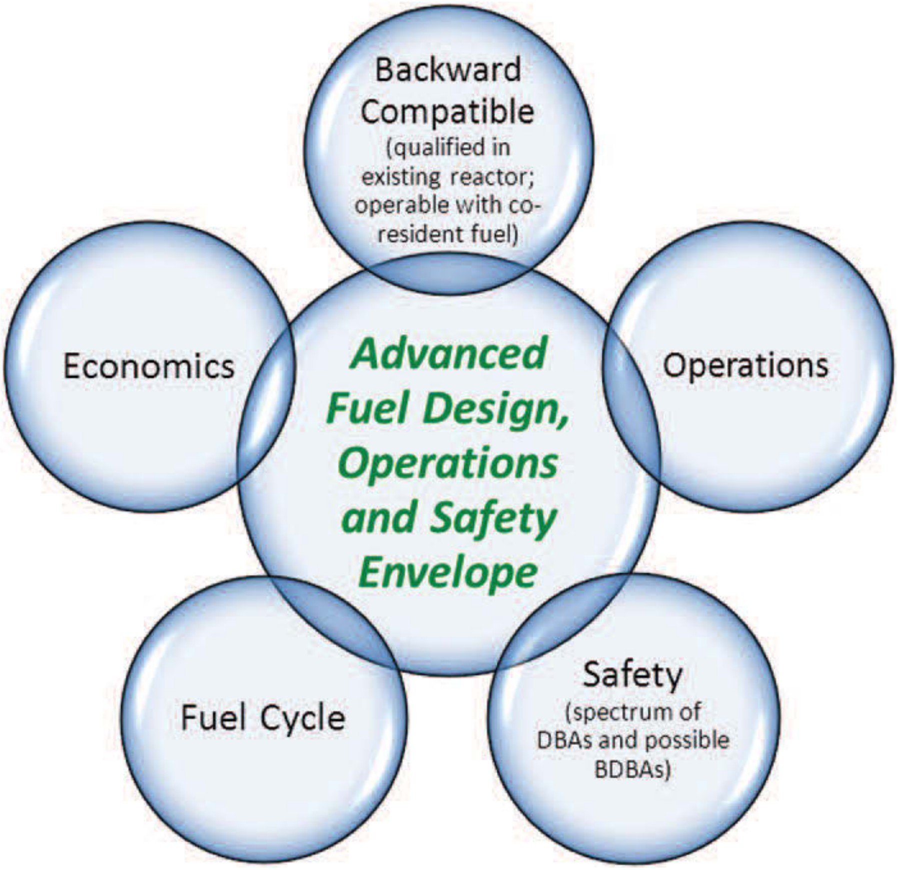

Fig. 2. Considerations that constrain new fuel designs

engineering solutions must be augmented during storage and disposal. Over the long term, U.S. policy changes to make the transition to a closed fuel cycle that would include reprocessing and recycling would require an evaluation of the impact of the new fuel form on reprocessing, which in turn would require licensing modifications, in addition to changes in operational procedures and handling equipment. An assessment of the impact of a new fuel on potential future fuel cycles will be coordinated with the FCRD Separations and Waste Forms Campaign and the Fuel Cycle Options Campaign.

■ *Economics*—Economics is a key constraint for industry adoption of a new fuel. After decades of optimization, the UO_2-Zr alloy fuel system is a streamlined technology that accounts for a relatively small percentage of the overall nuclear electricity production cost. It is important to carefully and completely assess the economic impact of a proposed new technology and to determine how much additional fuel cost the utilities will accept, given that the plants operate within all regulatory requirements with currently available fuel. Higher burnup (extended cycle with reduced waste and reduced refueling cost) and higher power densities (power upgrades) could mitigate some of the expected additional costs. While focusing on enhanced safety, it is imperative to maintain enhanced performance goals as an economic consideration.

ATF development activities

With the assistance of the nuclear energy community, the FCRD Advanced Fuels Campaign has embarked on an aggressive schedule for the development of enhanced accident-tolerant LWR fuel system candidates. The program is in the early phases of R&D and is currently supporting the investigation of a number of candidate technologies that may improve the fuel system.

The ATF development effort has adopted a three-phase approach to commercialization, with the approximate fiscal year time frame given in parentheses:

Phase 1: Feasibility Assessment and Down-Selection—In the current phase, fuel concepts are developed, tested, and evaluated. Feasibility assessments of the new concepts performed to identify promising concepts include lab-scale experiments, such as fabrication, preliminary irradiation, and material property measurements; fuel performance code updates; and analytical assessment of economic, operational, safety, fuel cycle, and environmental impacts. (FY 2012–FY 2016)

Phase 2: Development and Qualification—Prototypic fuel rodlets will be irradiated in a test reactor at LWR conditions to provide the data required for the lead test rods/lead test assemblies. The fabrication process will expand to industrial scale for LTRs/LTAs. (FY 2016–FY 2022)

Phase 3: Commercialization—Region-sized reloads are tested to verify the performance observed for the LTRs and LTAs and to provide additional data for final licensing of the product. Commercial fabrication capabilities are established. (FY 2022 and beyond)

Each development phase roughly corresponds to the technology readiness levels (TRL) defined for nuclear fuel development, where TRL 1–3 corresponds to the "proof-of-concept" stage (Phase 1), TRL 4–6 to "proof-of-principle" (Phase 2), and TRL 7–9 to "proof-of-performance" (Phase 3).

Currently, three campaign-directed efforts in the development of ATF concepts are under way, each being led by a national laboratory. Additional research activities are being conducted by three industry-led funding opportunity announcement research projects and two Nuclear Energy University Programs integrated research projects (IRP). The ATF concepts that are currently being investigated are summarized below.

While the research teams are developing and evaluating fuel and cladding concepts that could be used in an existing commercial LWR, the Georgia Institute of Technology was awarded a separate IRP to begin the development of an accident-tolerant reactor concept that could incorporate an ATF concept from one of the other teams. The work at Georgia Tech is funded through a different branch of NE that is focused on next-generation reactor development, but work is coordinated with the ATF development teams under FCRD. The Georgia Tech team includes the following university, industry, and national laboratory collaborators: the University of Michigan, Virginia Polytechnic Institute and State University, the University of Tennessee, the University of Idaho, Morehouse College, Polytechnic University of Milan (Italy), and the University of Cambridge (United Kingdom); Westinghouse Electric Company and Southern Nuclear Operating Company; and Idaho National Laboratory (INL).

Georgia Tech's Integral Inherently Safe Light Water Reactor concept would be a high-power (about 1,000 MWe) LWR with inherent safety features. Enabling innovations include the use of high power density technologies and components and a compact core design achieved by using a nonoxide fuel form with improved heat removal capability. It is likely that this reactor concept would adopt the leading ATF design developed by one of the fuel development teams. These features would allow increased core power density while also improving core safety performance and response under transient and accident scenarios. A novel steam generating system is proposed that is based on very compact printed-circuit heat exchangers that allow this power level to be compatible with an integral configuration.

Campaign-directed efforts

The campaign-directed efforts are summarized below. Concepts that have matured

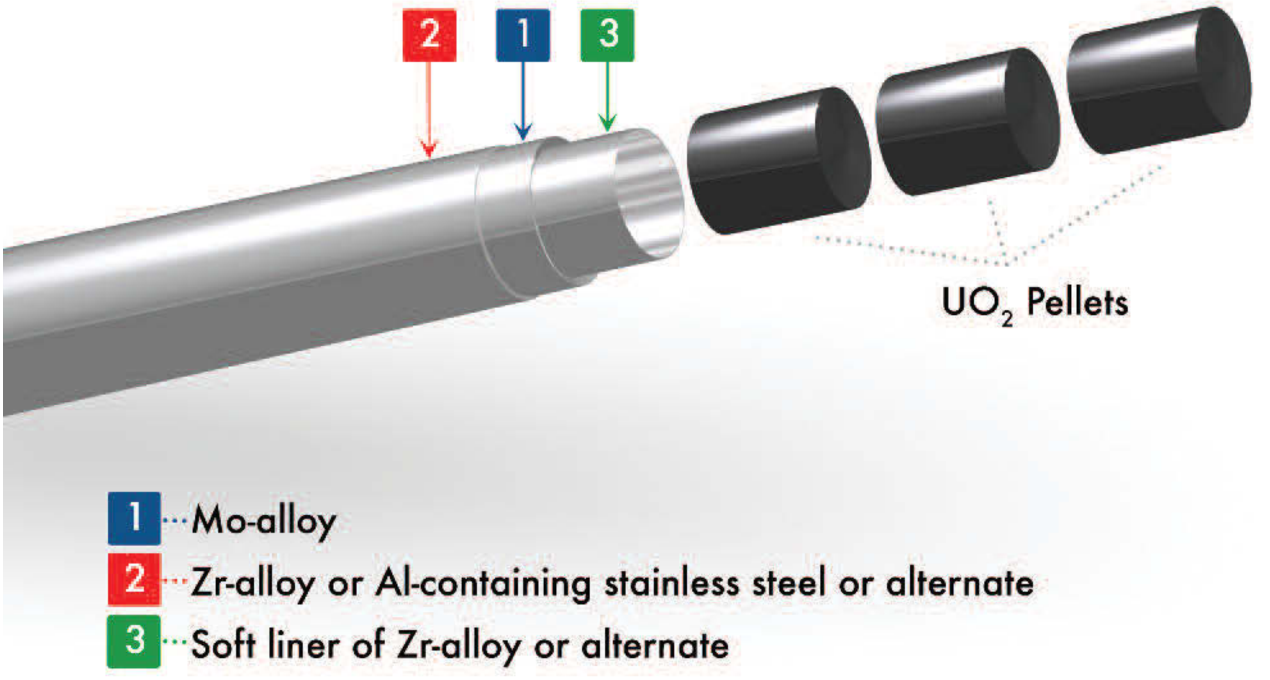

Fig. 3. Duplex and triplex molybdenum cladding concept

to the point of irradiation testing will be sent to INL for final assembly and integration into an irradiation capsule.

Los Alamos National Laboratory

Los Alamos National Laboratory (LANL), in New Mexico, leads the development of high-density ceramic fuels and is also a key contributor in the development of advanced, corrosion-resistant metallic alloys—such as iron-chromium-aluminum (FeCrAl) and molybdenum (Mo)—that could be used as cladding in a number of other ATF concepts. Mo cladding development is conducted via collaboration with the Electric Power Research Institute (EPRI), and FeCrAl development is conducted via collaboration with Oak Ridge National Laboratory, as discussed below.

Advanced Mo alloys with improved ductility and improved corrosion and oxidation resistance are being fabricated into thin-wall tubes (about 0.2 mm) for out-of-pile testing, including exposure to a steam environment at temperatures up to 1200 °C, and in-pile testing. Fine-grained, high-purity Mo can be formed directly into thin-walled tubing using the fluidized bed chemical vapor deposition process. The advantages of Mo include high melting point (2600 °C), excellent high-temperature strength and creep resistance, and good ductility at low temperatures. One drawback, however, is oxidation at high temperatures. EPRI, therefore, is developing coated Mo cladding to improve high-temperature oxidation resistance.

EPRI's cladding design incorporates high-strength, thin-wall Mo alloy as the core structure. In a duplex structure, the outer surface of the Mo alloy is bonded with a thin layer made of Zr-alloy or Al-containing stainless steel for protection from corrosion under normal operating conditions and from steam oxidation under accident conditions by forming stable ZrO_2 or Al_2O_3. A soft Zr-alloy layer may be included on the inner surface to increase the toughness of the composite cladding. The duplex and triplex cladding design is illustrated in Fig. 3.

In addition to developing improved cladding materials for accident conditions, LANL is investigating improvements in the fuel material that will support the ATF objectives. Research within the ceramic fuels technologies area includes taking an evolutionary path based on UO_2 fuels, and taking a revolutionary path based on composite fuels.

Exploratory work has been undertaken to study the performance benefits that may be realized through minor modifications to reference UO_2 that would be largely transparent to fuel fabricators, operators, and licensing requirements (an evolutionary path). Three criteria were developed to assess these evolutionary options. First, improved fracture toughness and plasticity could relieve fuel pellet cracking and missing surfaces that not only introduce uncertainties during reactor startup and operation but also provide free surfaces that accelerate fission product and transuranic release during a full breach. Second, enhanced thermal conductivity would provide clear benefits to normal operation, as well as some advantages during LOCAs and reactivity insertion accidents under certain conditions. Third, enhanced oxidation resistance would increase coping time before fuel pulverization occurs and would also enhance stability during wet or dry storage of used fuel.

A second approach to the development of ATF is the exploration of advanced composite systems (a revolutionary path) with the potential to improve the accident performance of LWR fuels, as well as offer benefits to normal operation. Composite fuels have been of interest for many decades, as a wide range of both ceramic and metallic alloys can be envisioned that would surpass the performance of traditional LWR fuels. When systems are explored within the constraint of use in existing commercial LWRs, however, the practical limit on U-235 enrichment creates significant challenges in the introduction of nonfissile second phases. Any inert second phase incorporated in a proposed fuel must be limited to extremely low volume fractions to maintain reactor performance at less than 5 percent enrichment. It is difficult for such concepts to achieve improvement in any of the critical metrics, such as thermal conductivity, mechanical properties, or thermochemical stability, when limited in such a way. One potential composite fuel approach is the use of uranium-bearing second phases. A range of ceramic/ceramic candidate composite systems with at least one high uranium-density phase are undergoing initial assessment using a combination of thermodynamic analysis, thermochemical and thermophysical property review, material compatibility screening experiments, and assembly-level neutronic analysis.

Oak Ridge National Laboratory

Oak Ridge National Laboratory (ORNL) has proposed and leads the development of a high-temperature, oxidation-resistant steel cladding—for example, a nuclear-grade FeCrAl alloy—and a microencapsulated (TRISO-based) fuel.

While advanced steels have historically been used for LWR fuel cladding, their use was supplanted not only due to the excellent neutronics of Zircaloy, but also by the dominance of the Naval Reactors–led Zircaloy industry. While the performance of the early-generation stainless steel cladding used in reactors such as Yankee Rowe (annealed 304L) rivaled that of Zircaloy alloys, the LOCA performance of 304L was not exceptional. The emphasis of the current high-temperature, oxidation-resistant steel cladding program exploits nearly a half-century of improvements in steel development while carrying out the supporting analysis to show the efficacy of this approach toward improving coping time in various accident scenarios.

In the early development phase, a suite of model alloys was postulated based on computational thermodynamics and then fabricated and tested using the FCRD Severe Accident Test Station to determine the material response to steam attack. These tests helped identify a compositional range with remarkable resistance to steam attack up to 1475 °C, essentially consuming 10–20 microns of material in 24 hours at 1200 °C through the formation of a protective surface oxide. This result contrasts with Zircaloy, which would be entirely consumed under these conditions, producing considerable heat and hydrogen in the process. With the model compositions identified, new engineering-grade alloys have been fabricated. These alloys possess very small and stable grains (on the order of tens of microns) with strength more than twice that of commercial Zircaloy. Moreover, these alloys do not sacrifice ductility at the expense of increased strength. In parallel with the continued alloy development, supporting initiatives in the area of irradiation performance, welding, and core accident modeling are ongoing.

The second accident-tolerant technology being developed at ORNL focuses on the enhanced retention of fission products. Specifically, the fully ceramic microencapsulated fuel builds on the renewed success of the Next Generation Nuclear Plant (NGNP) program to produce high-quality TRISO fuel, seeking to apply TRISO particles at LWR conditions. The clear advantage of this fuel is the formidable barrier to fission product release offered by the silicon carbide (SiC) shell of the TRISO particle. These particles also are compacted in a dense, high-conductivity, and radiation-resistant SiC matrix that serves as a secondary boundary to fission product release. Since the concept was first put forth, significant development and analysis have been conducted. To date, fuel development hurdles, such as the ability to achieve a robust high TRISO–density compact fuel, demonstration of the radiation stability of fuel constituents, and preliminary core analyses have been encouraging. Next-step development tasks are under way, including the fabrication of the uranium nitride (UN) kernel fuel that is required to achieve adequate fissile density, continued study of compacting scale-up, and full-core analysis.

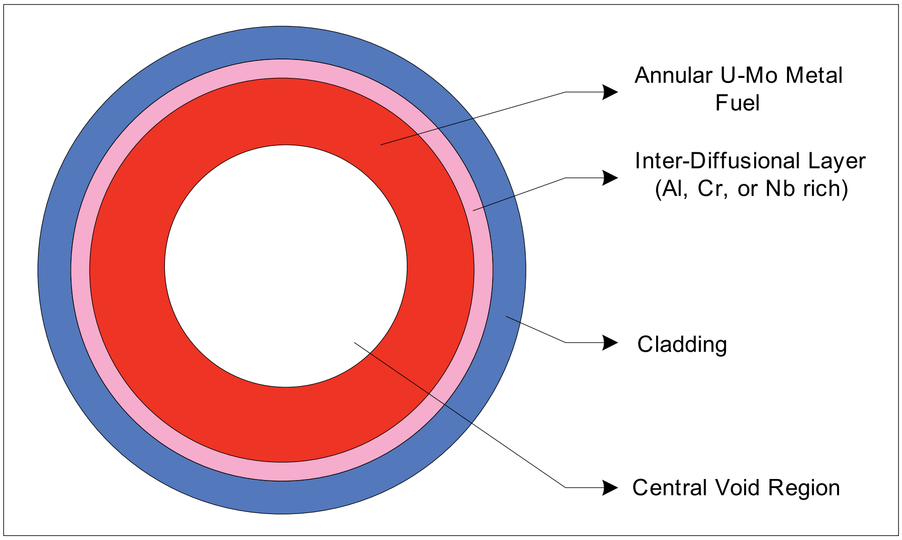

Fig. 4. Triple-layer co-extruded U-Mo metal fuel system

Pacific Northwest National Laboratory

Pacific Northwest National Laboratory (PNNL) leads the development of the LWR U-Mo fuel concept. Similar to the development of metal fuel for liquid-metal reactors, the objective of this effort is to develop a metal fuel with improved performance for LWRs. Specific characteristics of such a fuel would include higher linear heat rates, higher power densities, and higher burnups. In addition, cladding materials with improved accident tolerance are being incorporated into this fuel system. The basic program is structured around a co-extruded U-Mo metal fuel material with selected elements added to improve corrosion resistance. The overall program consists of the following three parts:

- *Co-extrusion development*—Using the co-extrusion experience from the production reactors on the Hanford Site, PNNL is exploring a triple co-extruded fuel system. The system consists of an annular U-Mo fuel slug surrounded by an anticorrosion layer, such as niobium, and accident-tolerant cladding, such as the FeCrAl alloy MA-956 (see Fig. 4).
- *Corrosion-reducing trace elements*—Again, using experience from earlier metal fuel programs, PNNL is exploring the use of anticorrosion coatings on the U-Mo fuel to reduce or mitigate possible corrosion. Coating materials under investigation include niobium, aluminum, chromium, and vanadium. These elements may be used in various combinations as coatings or may be incorporated as low-concentration elements in the U-Mo fuel metal itself.
- *Cladding tubing fabrication development*—Applying experience from the cladding suppliers on the Hanford Site, PNNL is developing the processes for forming cladding materials that may be more difficult to fabricate but may exhibit accident-tolerant attributes. For example, the fabrication of MA-956 cladding tubing was recently successful. PNNL performed this extrusion and tubing down-sizing in support of the LANL ATF test described earlier.

Industry, university-led efforts

The industry and university teams are developing and evaluating both advanced cladding and advanced fuel concepts. Following are brief introductions to each team and the key concepts of interest.

Areva

The enhanced ATF concept under development by Areva is being designed to improve performance under both normal and beyond design-basis conditions while ensuring that the cost of the ATF remains competitive with the current fuel design. The Areva team consists of Areva, the team leader, providing technical guidance related to fuel manufacture and fuel requirements; the University of Florida, developing fuel pellets; the University of Wisconsin and Savannah River National Laboratory, providing cladding coatings; and Duke Energy and the Tennessee Valley Authority, providing utility consultation.

The ATF technology concepts being considered by the Areva team include the following:

- Chromia doping in the fuel pellet to reduce fission gas generation, improve load-following characteristics, increase uranium density, improve wash-out characteristics in rod failure, and lock up cesium into the fuel matrix.
- SiC fibers in the fuel pellet to improve thermal heat transfer in normal conditions to increase fuel efficiency, improve margin

in an accident condition, and lock up iodine into the fuel matrix.

- Coatings on the existing Zr-alloy cladding to reduce hydrogen pickup, mitigate hydride reorientation in the cladding, and increase coping time during accident conditions.

General Electric

The objective of the General Electric Global Research and Global Nuclear Fuels team, which currently includes the University of Michigan and LANL, is to investigate the replacement of Zr-alloy cladding with advanced steels, such as FeCrAl alloys, which offer a number of benefits in beyond design-basis accident conditions. Improved properties under normal conditions may provide sufficient benefit to mitigate the increased neutron absorption characteristics of these materials.

Samples of commercial and experimental alloys have been successfully tested over different lengths of time in 100 percent superheated steam from 600 °C to 1475 °C. Results to date indicate that the best candidate new alloys—including APMT and Alloy 33—have several orders of magnitude improvement over the current zirconium-based alloys in reaction kinetics with steam. Similarly, these advanced steels have been tested to demonstrate superior mechanical properties under both normal operating conditions and accident conditions. Ferritic steels are also highly resistant to irradiation damage and environmentally assisted cracking under normal operating conditions. Irradiation testing in a research reactor will be conducted in the near future.

Westinghouse

The objective of the Westinghouse Electric Company team is to develop an ATF with improved economics during normal operation and the containment of all fuel fission products to the fuel during a beyond design-basis accident. The partners in this consortium and their focus areas are Westinghouse, developing concept fuel, determining research needs, licensing approach and cost, and evaluating the overall economics of ATF; General Atomics, developing SiC cladding; EWI (formerly the Edison Welding Institute), developing hot-spray coatings on Zr-alloy cladding; the University of Wisconsin, developing cold-spray coatings on Zr-alloy cladding; LANL, manufacture of UN fuel; INL, manufacture of uranium silicide (U_3Si_2) fuel; Texas A&M University, manufacture and testing of waterproofed UN fuel; the Massachusetts Institute of Technology, providing steam oxidation, quenching, and reactor testing of ATF cladding candidates; and Southern Nuclear Operating Company, licensing and economics of ATF from the customer's perspective.

Fuel development has progressed for both fuel types of interest. Results to date have indicated that manufacture of waterproofed UN using U_3Si_2 is feasible, with the achievement of densities approaching 90 percent. U_3Si_2 has been successfully manufactured into pellets of about 94 percent of theoretical density. Cladding development has had limited success to date. Zr alloys coated with Ti_2AlC and NanoSteel have not produced any significant increase in accident tolerance. Samples of SiC cladding have been successfully manufactured and tested in an autoclave at accelerated conditions (425 °C). High-temperature (greater than 1200 °C) steam tests and irradiation in a research reactor will follow. Finally, a full development and testing program has been laid out, and the expected economics of the various options have been determined.

University of Illinois (cladding only)

The University of Illinois IRP team, which includes partners at the University of Michigan, the University of Florida, INL, and ATI Wah Chang, is investigating two solution pathways toward improved ATF cladding. An additional partner, the University of Manchester, is funded by the Research Councils U.K. Energy Program. Both pathways are based on the modification of monolithic Zircaloy cladding to inhibit the rapid oxidation that occurs during elevated-temperature steam exposure and involve either a coating or a low-concentration bulk additive.

Two significant achievements to date are the irradiation of a set of coated samples by high-energy protons to mimic fast neutron damage and the demonstration of delayed oxidation induced by a coating during 700 °C steam exposure. Figure 5 shows the coated samples mounted prior to proton irradiation. The proton irradiation was performed at the University of Michigan to 2.3 displacements per atom (dpa). The samples were Zircaloy-2 with FeCrAl coatings of varying composition, ranging from 4000 to 7000 Å thick. These samples will be used in four-point bending tests, high-temperature steam exposure, and autoclave testing. Similar films are planned for irradiation in the INL Advanced Test Reactor to similar dpa values; a comparison of proton and neutron irradiation will be useful.

Oxidation mass gain versus time for uncoated polished Zircaloy-2, for Zircaloy-2–4 (FeCrAl:54/28/18), and for Zircaloy-2–7 (FeCrAl:61/5/34) specimens during 700 °C steam exposure are shown in Fig. 6. The delayed onset of oxidation in the Al-rich specimen (Zircaloy-2–7) is clear from the mass gain measured as a function of time, which shows an oxidation delay of approximately 180 minutes.

University of Tennessee (cladding only)

The University of Tennessee—along with Pennsylvania State University, the University of Colorado, the University of Michigan, LANL, Westinghouse Electric Company, Oxford University, the University of Manchester, the University of Sheffield, the University of Huddersfield, and the Australian Nuclear Science and Technology Organization—is working to develop surface modifications of Zr-alloy cladding by applying ceramic coatings. Ceramic Coatings for Clad (The C3 Project) involves coating zirconium alloys with various architectures of ceramic coatings, including nitrides, oxides, and carbides, using various coating techniques such as cathodic arc vapor deposition, magnetron sputtering, thermal spray, pulsed liquid injection, and ion beam–assisted vapor deposition.

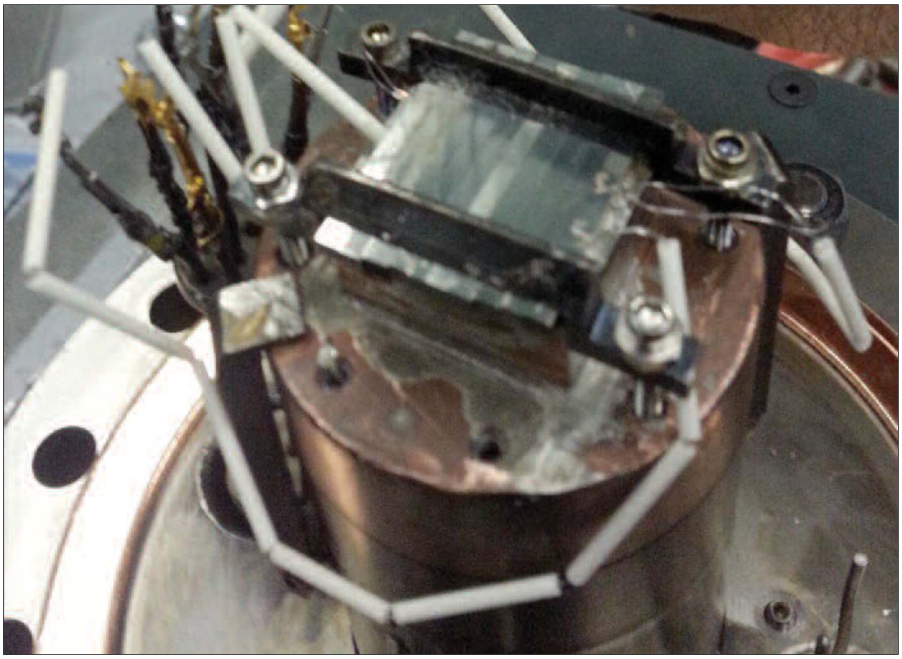

Fig. 5. At the University of Michigan, Zircaloy-2 samples with FeCrAl coatings of varying composition prior to 1-MeV proton irradiation. Samples were irradiated to 2.3 dpa at 360 °C.

Ceramic-coated cladding is expected to improve performance as compared to conventional Zr-alloy cladding in the following respects:

- During normal service, the ceramic coating should decrease cladding oxidation and hydrogen pickup (the latter leads to hydriding and embrittlement).
- During a reactor transient, such as a LOCA, the ceramic coating should significantly delay oxidation of the Zr-alloy cladding, thus reducing the amount of hydrogen generated and the oxygen ingress into the cladding.

The most significant work to date on this project has involved fabricating titanium nitride and titanium aluminum nitride coatings on Zr-alloy substrates. Three-day corrosion tests performed in 2013 in static 350 °C water demonstrated that certain nitride coatings exhibit significantly less weight gain than bare Zr-alloy samples. The lower weight gain of the nitride-coated samples is due to a substantial reduction in corrosion-induced oxidation of the Zr-alloy substrates, as compared to uncoated Zr-alloy samples. Work is under way to develop a better understanding of this improved corrosion behavior for ceramic-coated cladding, and higher-temperature corrosion experiments, which better simulate accident conditions, are currently in progress.

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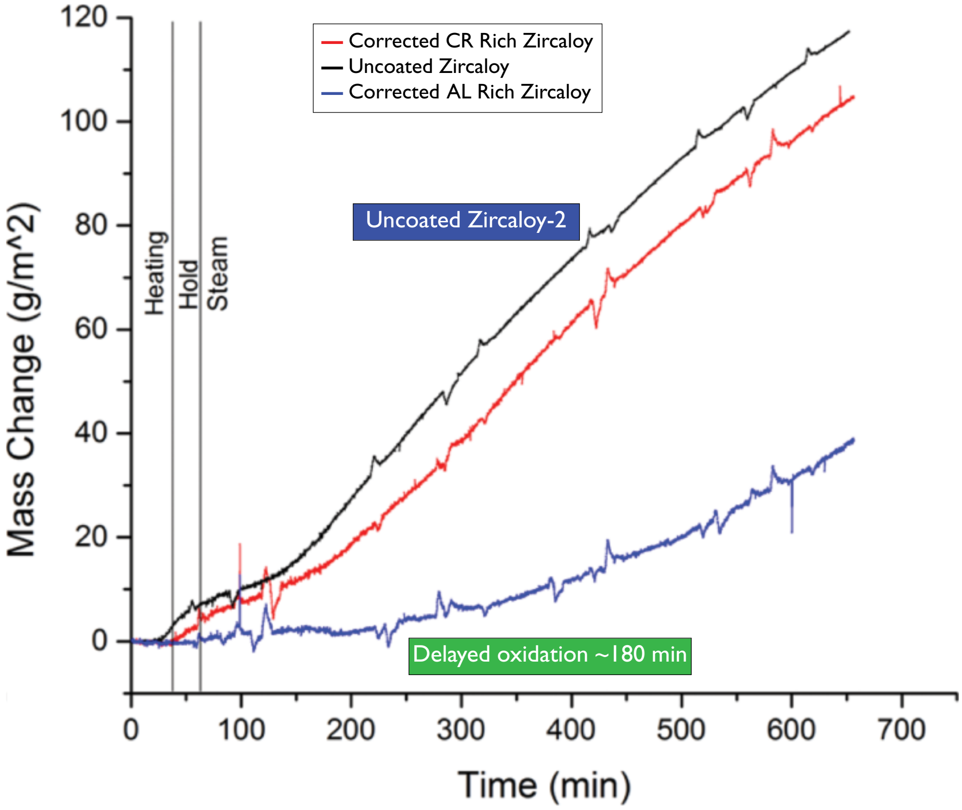

Fig. 6. Weight gain measurements in 700 °C steam for two approximately 4000-Å-thick FeCrAl coatings (red and blue lines) and uncoated Zircaloy-2 (black line); one FeCrAl coating delayed oxidation in steam by about 180 minutes.

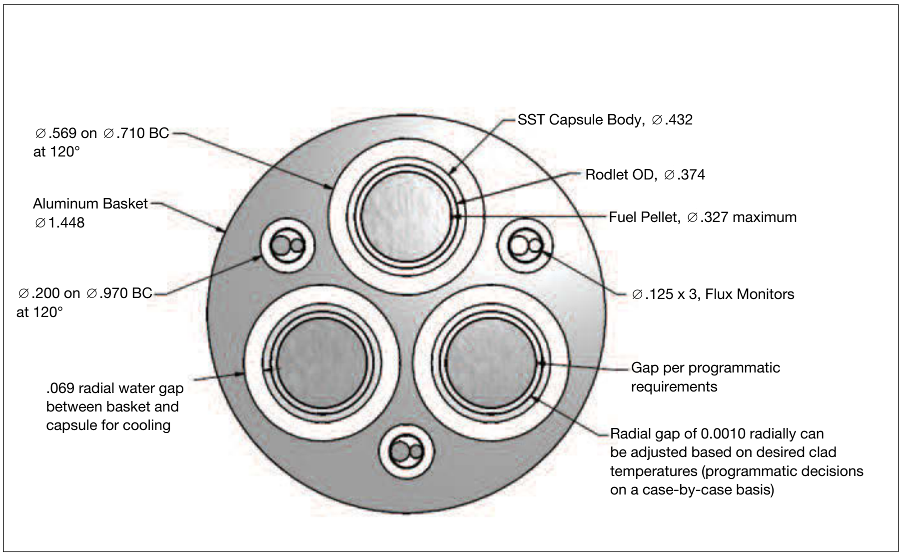

Fig. 7. Cross section of existing basket assembly to be adapted for ATF-1; multiple capsules will be stacked in each radial capsule position (dimensions in inches).

ATF irradiation testing

An irradiation test plan has been drafted for ATF concepts to progress from feasibility experiments under normal operating conditions to integral demonstrations under accident conditions to support the LTR/LTA program and eventual qualification of an ATF concept.

The initial irradiation series, referred to as ATF-1, will utilize drop-in capsules in the INL Advanced Test Reactor (ATR) to investigate the performance of a variety of proposed ATF concepts under normal LWR operating conditions. The ATF-1 capsules are filled with an inert gas and are designed to isolate fuel rodlets from the ATR primary coolant during irradiation. Hence, the test rodlet cladding will not be in contact with water coolant during irradiation. This test series is intended to investigate the irradiation behavior of new fuels and their interaction with the cladding. Resultant data on fuel behavior and fuel-cladding interaction will inform down-selection to one or more promising concepts prior to irradiation tests. Figure 7 shows the cross-section of the irradiation basket that houses the irradiation capsules, and Fig. 8 shows a schematic of the irradiation capsule assembly. It is currently anticipated that the post-irradiation examination and characterization activities will be conducted at INL.

The follow-on irradiation test series will include loop testing in the ATR (ATF-2) and transient testing (ATF-3 and -4). ATF-2 will utilize the pressurized water loop in the INL ATR, such that the ATF fuel rods will be in direct contact with high-pressure water coolant with active chemistry control to mimic the conditions of PWR coolant. The most promising concept(s) would then proceed to ATF-3. ATF-3 would include transient testing of rods, possibly in the INL TREAT facility, to investigate performance under reactivity insertion accident scenarios. The final step in this test series would be transient testing of a subset of LTRs, possibly in TREAT, while LTRs or LTAs are irradiated in a commercial LWR.

ATF evaluation metrics

Qualitative attributes for fuels with enhanced accident tolerance, such as improved reaction kinetics with steam resulting in slower hydrogen generation rate, provide guidance for the design and development of fuels and cladding with enhanced accident tolerance. A common set of technical evaluation metrics should be established to aid in the optimization and down-selection of candidate designs on a more quantitative basis.

Metrics describe a set of technical bases by which multiple concepts can be fairly evaluated against a common baseline and against one another. In some cases, this may equate to a specific quantitative target value for selected properties or behaviors. Metrics can also describe a clear technical methodology for evaluation that can be used to rank two or more concepts. Because of the complex multiphysics behavior of nuclear fuel and the large set of performance requirements that must be met, the latter definition is adopted for the current evaluation of candidate ATF options.

A series of national and international meetings was held in FY 2013 to begin establishing a consensus on how to approach ATF design, optimization, and evaluation for down-selection. Each of these meetings provided qualitative direction on an appropriate set of enhanced ATF attributes, metrics, and associated screening evaluations for different classes of fuel and cladding material.

Beginning with the qualitative guidance on ATF metrics, a small team from across the DOE laboratories has defined an ATF technical evaluation approach. An assessment of the potential beneficial impact or unintended negative consequences of candidate ATF concepts will address the obvious "fuel-specific" characteristics of the concept. The assessment will also address how implementation of the concept will affect reactor performance and safety characteristics. This includes neutronics and thermal-hydraulics analyses to ensure that the reactor will operate as intended with the candidate fuel system. Coupled thermal-hydraulic/neutronic analysis of candidate

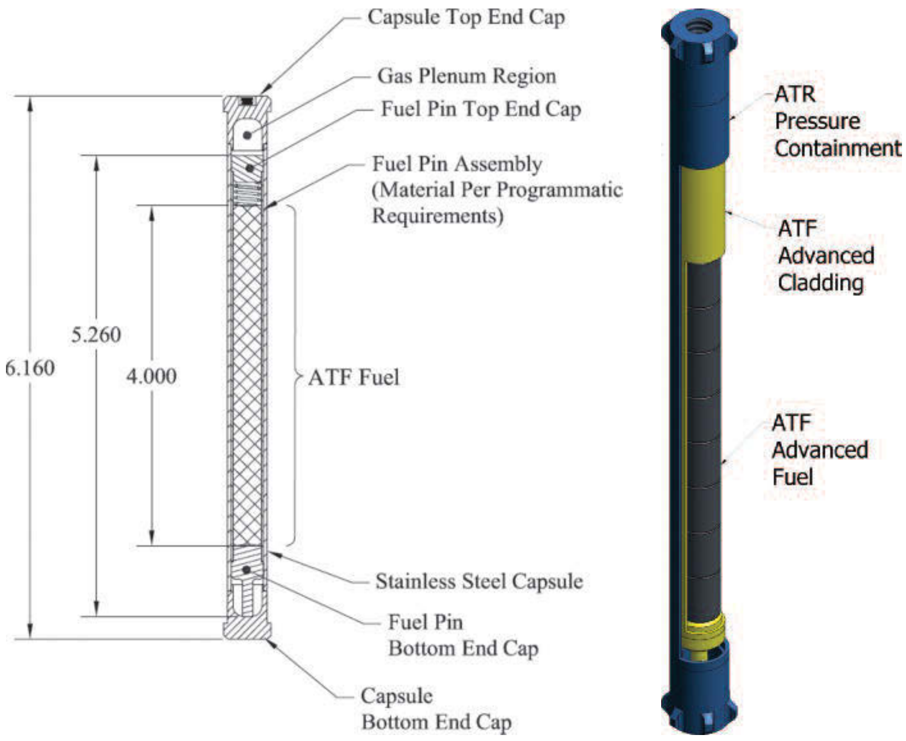

Fig. 8. ATF-1 capsule assembly overview and associated schematic (dimensions in inches)

ATFs is essential for understanding the synergistic impact of the thermal properties and reactivity feedback.

An independent expert panel review team will be established to review the ATF concepts under development. This team will be composed of technology experts selected based on their knowledge of the technologies under review, including materials (metals and ceramics), neutronics, thermal-hydraulics, and severe accidents.

The expert panel will be tasked with reviewing input (currently available data and analysis results) provided by each of the ATF design teams. This information will be applied to assess the relative benefits or vulnerabilities (with corresponding numerical scores for each) associated with the candidate design for a number of performance attributes across relevant performance regimes, including the following:

1. Fabrication/manufacturability (to include licensability).
2. Normal operation and anticipated operational occurrences.
3. Postulated accidents (design basis).
4. Severe accidents (beyond design basis).
5. Used fuel storage/transport/disposition (to include potential for future reprocessing).

The economics of manufacture and operation, from both the utility and vendor perspectives, will be considered within each appropriate operational regime (namely, within topics 1, 2, and 5 above) in scoring the fuel and cladding design. Numerical "benefits" and "vulnerability" scores provide an indication of both development stage and expected performance benefits.

Technologies that do not depart significantly from the current UO_2-Zr alloy fuel system might be expected to have a modest benefit score and low vulnerability. This candidate technology would be considered low risk and modest payoff, but could potentially be developed in the near term for commercial demonstration. A relatively immature concept that is a significant departure from the current UO_2-Zr system may have a high vulnerability score due to the existing technology or data gaps, while simultaneously scoring well in the benefits column based on the limited data that are available. A concept with high benefit and high vulnerability scores would be considered high risk but potentially high payoff, requiring a longer period of time for development relative to technologies that are nearer to the current UO_2-Zr system.

The proposed technical evaluation methodology will result in a ranked list of candidate ATF designs. Down-selection using this list will enable the continued development of the most promising ATF design options given budget and time constraints, with a goal of inserting one (or possibly two) concepts as an LTR or LTA in a commercial LWR by 2022. NN