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Advanced Fuels Campaign Light Water Reactor Accident Tolerant Fuel Performance Metrics Executive Summary

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Advanced Fuels Campaign
LWR Accident Tolerant Fuel Performance Metrics

Shannon Bragg-Sitton
Brad Merrill
Melissa Teague
Idaho National Laboratory

Larry Ott, Kevin Robb
Oak Ridge National Laboratory

Mitch Farmer, Mike Billone
Argonne National Laboratory

Robert Montgomery
Pacific Northwest National Laboratory

Chris Stanek
Los Alamos National Laboratory

Michael Todosow, Nicholas Brown
Brookhaven National Laboratory

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Idaho National Laboratory
Advanced Fuels Campaign
Idaho Falls, ID 83415

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Prepared by:
Shannon Bragg-Sitton, INL

Reviewed by:
Advanced Fuels Campaign Technical Leads:
Steven Hayes, INL
Rory Kennedy, INL
Stuart Maloy, LANL
Ken McClellan, LANL
Lance Snead, ORNL
Cetin Unal, LANL

Approved by:

W. Jon Carmack, INL AFC National Technical Director	Date

Advanced Fuels Campaign:
Enhanced LWR Accident Tolerant Fuel Performance Metrics

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. As a result, continual improvement of technology, including advanced materials and nuclear fuels, remains central to industry's success. Decades of research combined with continual operation have produced steady advancements in technology and yielded an extensive base of data, experience, and knowledge on light water reactor (LWR) fuel performance under both normal and accident conditions. In 2011, following the Great East Japan Earthquake, resulting tsunami, and 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 the U.S. Congress, the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) initiated an Accident Tolerant Fuel (ATF) Development program. Prior to the events at Fukushima, the emphasis in the fuel development activities was on improving nuclear fuel performance in terms of increased burnup for waste minimization, increased power density for power upgrades, and increased fuel reliability.

The current nuclear power industry is based on mature technology and has an excellent safety and operational record. Except for a few extremely rare events, the current UO_2 – zirconium alloy fuel system meets all performance and safety requirements while keeping nuclear energy an economically competitive clean-energy alternative for the United States. Any new fuel concept must be compliant with and evaluated against current design, operational, economic, and safety requirements. The overall fuel cycle must also be considered, especially for concepts that represent a significant departure from the current technology.

After the March 2011 events at Fukushima, enhancing the accident tolerance of LWRs became a topic of discussion within the U.S. and internationally. In the Consolidated Appropriations Act, 2012, Conference Report 112-75, the U.S. Congress directed DOE-NE to give "priority to developing enhanced fuels and cladding for light water reactors to improve safety in the event of accidents in the reactor or spent fuel pools." As a result, the pre-decisional draft roadmap, "Development of Light Water Reactor Fuels with Enhanced Accident Tolerance - Report to Congress," was written; the document has not yet been issued pending Administration approval.

The draft accident tolerant fuel roadmap focuses on the development of advanced LWR fuels with enhanced accident tolerance. Fuels with enhanced accident tolerance are those that, in comparison with the standard UO_2 – zirconium alloy system currently used by the nuclear industry, can tolerate loss of active cooling in the reactor core for a considerably longer time period during design-basis and beyond design-basis events (depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations and operational transients. The Fuel Cycle Research & Development (FCRD) Advanced Fuels Campaign (AFC) research, development and demonstration (RD&D) effort currently focuses on applications in currently operating reactors or reactors with design certifications. New fuel concepts will be evaluated with respect to the accident scenarios and specific plant designs for LWRs and fuel fabrication facilities. The candidate advanced fuel concepts must also be evaluated within the context of other potential improvements being developed to enhance overall safety (e.g., access to emergency cooling water, additional battery power, etc.) to fully characterize the impact of the candidate fuels on reactor operations. Overall safety assessments should be performed to the extent possible in the Phase I feasibility studies; these evaluations will be enhanced as more data becomes available in subsequent phases of development.

The accident tolerant fuels (ATF) development effort adopts a three-phase approach to commercialization (Figure ES-1). Phase 1 includes feasibility assessment and down-selection during which fuel concepts will be developed, tested, and evaluated. Feasibility assessments of the new concepts will be performed to reduce the number of concepts for further development. These assessments include: laboratory scale experiments, e.g., fabrication, preliminary irradiation, material properties measurements; fuel performance code updates; and analytical assessment of economic, operational, safety, fuel cycle, and environmental impacts. In Phase 2, the fabrication process will expand to industrial scale for lead test rods (LTRs) and lead test assemblies (LTAs). Finally, Phase 3 establishes commercial fabrication capabilities. 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, TRL 4-6 to "proof-of-principle," and TRL 7-9 to "proof-of-performance" (Carmack and Pasamehmetoglu 2008). The draft evaluation methodology presented in this document focuses on Phase 1 assessment and down-selection, but it also establishes the framework necessary to move a new fuel concept through further development and analysis in Phase 2.

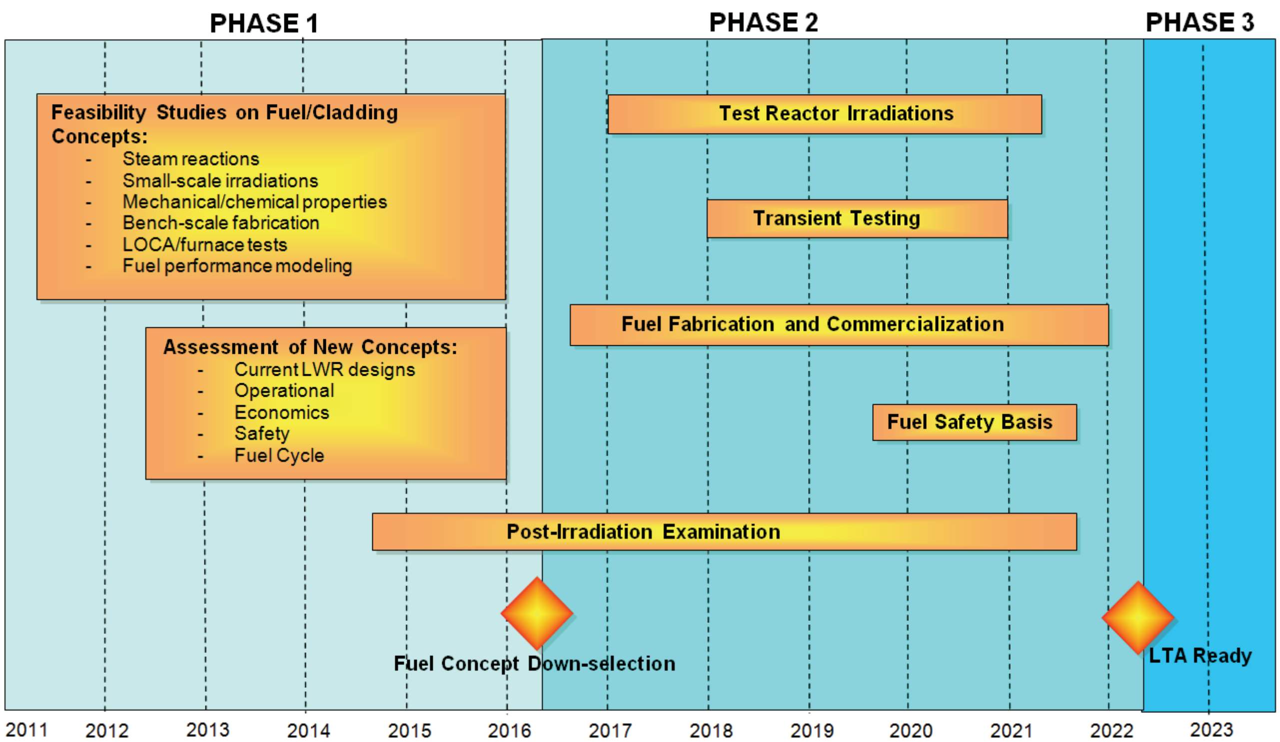

Figure ES-1. Research, development, and demonstration strategy for enhanced accident tolerant fuel development; an estimated timeline for each phase is included.

Qualitative attributes for fuels with enhanced accident tolerance include improved reaction kinetics with steam, resulting in slower hydrogen generation rate (or generation of other combustible gases), while maintaining acceptable cladding and fuel thermo-mechanical properties, fuel-clad interactions, and fission-product behavior. These attributes provide qualitative guidance for parameters that must be considered in the development of fuels and cladding with enhanced accident tolerance. A common set of technical metrics will 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 accident tolerant fuel options. A series of national and international meetings were held in FY2013 to begin establishing a consensus on how to approach ATF design, optimization and evaluation for down-selection (Braase 2013; Braase and Bragg-Sitton 2013; OECD/NEA 2013). Each of these meetings provided expert direction on an appropriate set of enhanced accident tolerant fuel 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 begun to define a technical evaluation approach for accident tolerant fuels. Preliminary analyses have been conducted on a handful of ATF concepts, and sensitivity analyses have been performed for key performance parameters, including fuel thermal conductivity, cladding thermal conductivity, and cladding oxidation rate. Sensitivity analyses provide early insight to the key parameters to be used for cladding and fuel optimization, while more detailed analyses allow evaluation of currently proposed concepts based on the available property and performance data.

An assessment of the potential beneficial impact or unintended negative consequences of candidate ATF concepts must address the obvious “fuel-specific” characteristics of the concept but, perhaps more importantly, the assessment must address how implementation of the concept will affect reactor performance and safety characteristics. This assessment would include neutronics and thermal-hydraulics analyses to ensure that the reactor would operate as intended with the candidate fuel system. Coupled thermal hydraulic-neutronic analysis of candidate ATFs is essential for understanding the synergistic impact of the thermal properties and reactivity feedback.

Industry, academia and the DOE national laboratories are currently investigating multiple ATF concepts. The proposed technical evaluation methodology will be applied to gauge the ability of each of these concepts to meet performance and safety goals relative to the current UO_2 – zirconium alloy system and relative to one another. This ranked evaluation 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.

The steps described in Figure ES-2 (numbered 1 – 8) address the full scope of activities that need to be considered in evaluating the feasibility of candidate ATFs. Carrying out all the indicated steps can require significant investment of time and resources. However, the fidelity or level of detail involved depends on the stage of evolution/development of a concept. During the “screening” stage (Step 1), the level of detail associated with analyses will be limited, based on the current state of knowledge for the selected concept. The level of detail may range from literature reviews and expert judgment through limited experiments and computational analyses. The goal is to have sufficient confidence in the results of the assessment (with a reasonable investment of time and resources) that identified changes relative to the reference UO_2 – zirconium alloy fuel system are known well enough to proceed with continued development of the concept, or conclude that the concept should be modified or abandoned. For further description of the corresponding fuel technology readiness level related to Figure ES-2, see Appendix B: Technology Readiness Levels of the *Advanced Fuels Campaign Execution Plan (Draft)*, INL-EXT-10-18954, Rev. 3, June 2013 (INL 2013).

The design / development team for a candidate fuel system would be expected to rely on preliminary analyses and scoping studies performed as a part of the initial technology selection to complete the candidate fuel screening table (Table ES-1). The attributes defined in the table correspond to a complete fuel system (fuel plus cladding) over the full fuel life cycle (fabrication – operation – used fuel management). Table ES-1 is designed to identify “Benefits” and “Vulnerabilities” for each concept. The candidate fuel system should be ranked within each category on a scale of 0 to 5, where “0” indicates no notable change from the current UO_2 – zirconium alloy system and “5” indicates either a significant benefit relative to the current system or a significant vulnerability. If a specific property or behavior is not yet known (or not known conclusively), this would correspond to higher vulnerability. For attributes that are currently unknown or assumed, recommended actions should then be noted by the review panel. If a decision is made to continue development to Steps 2a, 2b despite these noted vulnerabilities, these recommended actions should be resolved before convening the second expert review panel that would be tasked with ranking the remaining candidate technologies (shown between Phase 1 [Steps 1, 2a, 2b] and Phase 2 [Steps 3-7]) based on both perceived benefits and remaining vulnerabilities. Concepts that are further in their development may have already completed elements listed in items 2a and 2b prior to the initial expert panel review, while others may have larger uncertainties associated with the expected fuel system behavior. The former case would have fewer recommended actions, while the latter may have more recommended actions necessary to reduce uncertainty in the performance estimates.

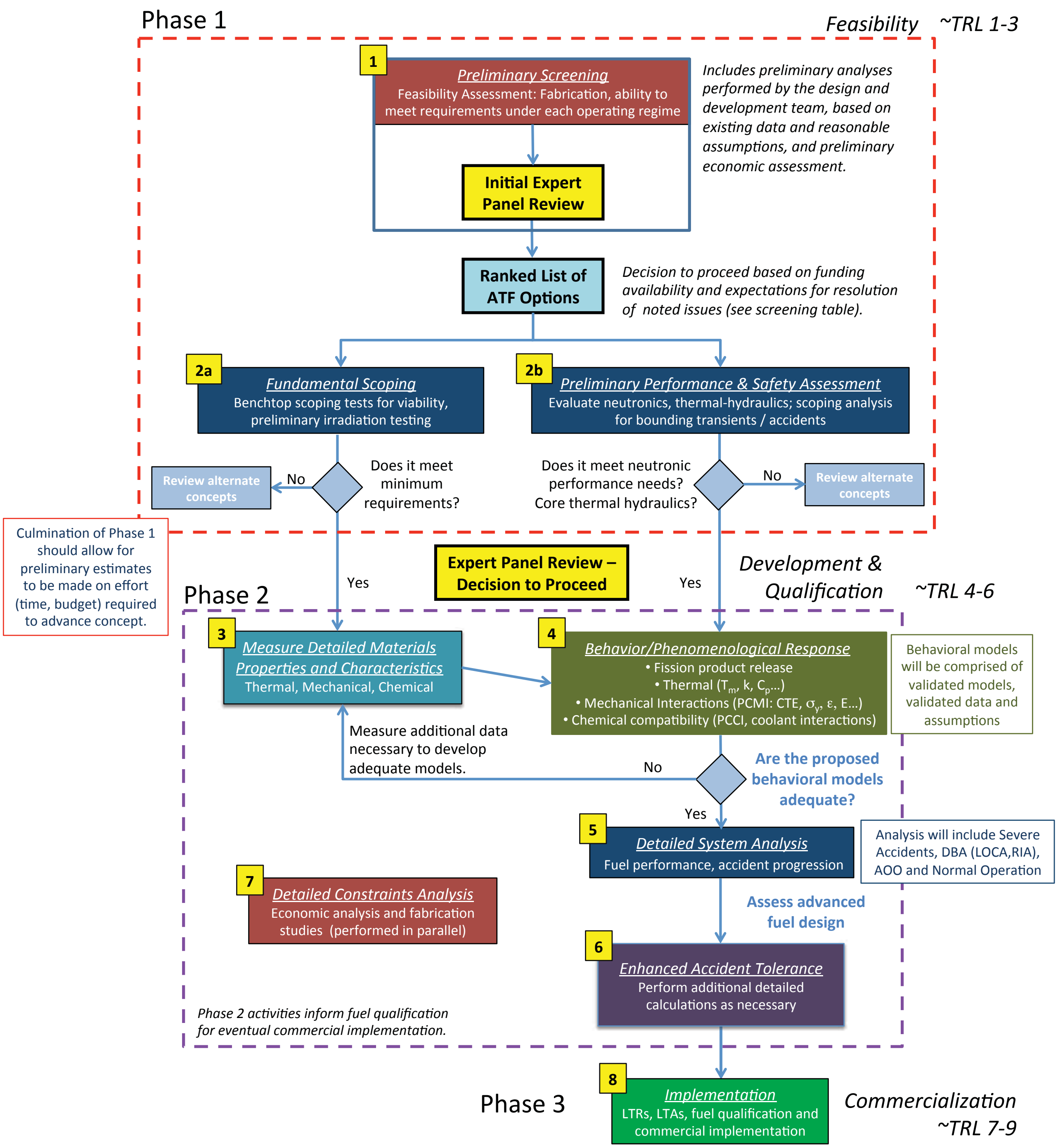

Figure ES-2. Proposed Accident Tolerant Fuel evaluation methodology. Preliminary concept down-selection would occur within Step 1 (see step numbers 1-8 noted), with secondary down-selection occurring at the end of Phase 1 prior to detailed tests and behavior model development.

Table ES-1. Candidate Fuel Screening Attributes Assessment Table

Performance Regime	Performance Attributes (For large-scale deployment)	Expert Opinion Assessment		Recommended Actions
		Benefit	Vulnerability	
Fabrication/Manufacturability *Considerations:* Millions ft of clad/year ~300 million pellets/year Economics - cost of raw materials and fabrication process Current fabrication plant enrichment limits	Manageable fissile material content			
	Compatible with large-scale production needs (material availability, fabrication techniques, waste, etc.)			
	Compatible with quality and uniformity standards			
	Licensibility			
Normal Operation and AOOs *Considerations:* Overall neutronics Linear Heat Generation Rate (LHGR) to centerline melt Power ramp, ~100 W/m/min Reduced flow (departure from nucleate boiling, DNB) Flow-induced vibrations Surface roughness effects Safe shutdown - earthquake External pressure (~2750 psi, 10% above PWR design pressure) Axial growth (less than upper nozzle gap)	Utilization or Burnup (12, 18, or 24 month/cycle)			
	Thermal hydraulic interaction			
	Reactivity control systems interaction			
	Mechanical strength, ductility (beginning of life and after irradiation)			
	Thermal behavior (conductivity, specific heat, melting)			
	Chemical compatibility (fuel-cladding) / stability			
	Chemical compatibility with and impact on coolant chemistry			
	Fission product behavior			
Postulated Accidents (Design Basis) *Considerations:* Prompt reactivity insertion Post-DNB behavior (T > 800°C for $Zr\text{-}UO_2$ system) Loss of coolant conditions Thermal shock Steam reactions (~1000°C +)	Thermal hydraulic interaction			
	Mechanical strength and ductility			
	Thermal behavior (conductivity, specific heat, melting)			
	Chemical compatibility/ stability (e.g. oxidation behavior)			
	Fission product behavior			
	Combustible gas production			
Severe Accidents (Beyond Design Basis) *Considerations:* Thermal shock Chemical reactions Combustible gas release Long-term stability in degraded state	Mechanical strength, ductility			
	Thermal behavior (conductivity, specific heat, melting)			
	Chemical compatibility/ stability (including high temperature steam interaction)			
	Fission product behavior			
	Combustible gas production			
Used Fuel Storage/ Transport/ Disposition *Considerations:* Handling, placement, and drying loads; future reprocessing potential	Mechanical strength, ductility			
	Thermal behavior			
	Chemical stability			
	Fission product behavior			

The independent Initial Expert Panel Review will be tasked with reviewing input (currently available data and analysis results) provided by each of the design teams and using this information to make a qualitative assessment of the relative benefits or vulnerabilities associated with the candidate design for each "Performance Attribute" relative to the specified "Performance Regimes:"

1. Fabrication / Manufacturability (to include Licensibility)
2. Normal Operation and Anticipated Operational Occurrences (AOOs)
3. Postulated Accidents (Design Basis)
4. Severe Accidents (Beyond Design Basis)
5. Used Fuel Storage / Transport / Disposition (to include potential for future reprocessing)

Upon completion of Table ES-1, the scores in the "benefits" and "vulnerabilities" columns should be tallied. The scores in each of these columns 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, modest payoff, but could potentially be developed in the near term for commercial demonstration. On the contrary, 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. For example, candidate ceramic cladding may score very well due to its ability to operate to very high temperature and minimal interaction with steam, but challenges in fabricating a hermetic fully ceramic cladding in the lengths necessary for LWR application may result in high vulnerability scores and a large number of recommended actions. A concept scored with a high benefit and high vulnerability 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 same screening table (Table ES-1) can be applied in both the initial and secondary expert panel reviews. The level of uncertainty in each of the performance attributes would be expected to decrease at each evaluation stage, allowing quantitative estimates for some of the behaviors of interest as more property data become available. To continue with the above example of a high risk, potentially high payoff technology, the vulnerability score and number of recommended actions would be expected to decrease significantly between these reviews to allow a more informed decision to proceed (or not proceed). Note that there is also provision for "off-ramps" prior to a secondary expert review should a concept design or specific material demonstrate that it cannot meet the minimum performance requirements during the fundamental scoping tests (Step 2a) or core level analysis (Step 2b).

The convened expert review panel would be comprised of technology experts selected based on their knowledge of the technologies under review. This review panel should include experts specializing in materials (metals and ceramics), neutronics, thermal-hydraulics, and severe accidents. The totaled "benefits" and "vulnerabilities" scores for each technology will result in a ranked, prioritized list of candidate technologies. The review panel may choose to develop two ranked lists, one for near-term technologies, fitting within the defined 10-year development window, and a second for longer term technologies that appear to have a significant benefit at this early development stage but are unlikely to meet the defined development timeframe. The number of technologies selected to proceed for additional testing and development will be dependent on budget availability. It is anticipated that a few technologies will continue development beyond the first expert panel review, but only one or two would proceed beyond the second panel review. Upon completion of Phase 2, a lead test rod or assembly would be fabricated for industry testing in a currently operating light water reactor.

Braase 2013. L. A. Braase, *Enhanced Accident Tolerant LWR Fuels National Metrics Workshop Report*, INL/EXT-13-28090, Idaho National Laboratory, January.

Braase and Bragg-Sitton 2013. L. A. Braase and S. M. Bragg-Sitton, *Advanced Fuels Campaign Cladding & Coatings Meeting Summary*, INL/EXT-13-28628, Idaho National Laboratory, March.

Carmack and Pasamehmetoglu 2008. W.J. Carmack, K.O. Pasamehmetoglu, *Definition of Technology Readiness Levels for Transmutation Fuel Development*, INL/EXT-08-13780, Idaho National Laboratory, prepared for the U.D. Department of Energy Transmutation Fuel Campaign, January.

OECD/NEA 2013. Increased Accident Tolerance of Fuels for Light Water Reactors, Workshop Proceedings, OECD/NEA Headquarters, 10-12 Dec 2012, NEA/NSC/DOC(2013)9, June.