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Metrics for the Evaluation of LWR Accident Tolerant Fuel

Shannon Bragg-Sitton, Ph.D.

Idaho National Laboratory, Fuel Performance & Design

U.S. DOE Advanced Fuels Campaign, Deputy National Technical Director

Email: Shannon.Bragg-Sitton@inl.gov

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OECD-NEA Expert Group on Accident Tolerant Fuels for LWRs

NEA Headquarters, Paris, France

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Accident Tolerant Fuel (ATF) Goal: Enhanced “Grace Time”

*Fuels with **enhanced accident tolerance** are those that, in comparison with the standard UO_2 – Zr system, can **tolerate loss of active cooling** in the core for a **considerably longer time period** (depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations.*

Enhanced Tolerance to Loss of Active Core Cooling

Improved Reaction Kinetics with Steam

- Decreased heat of oxidation
- Lower oxidation rate
- Reduced hydrogen production (or other combustible gases)
- Reduced hydrogen embrittlement of cladding

Improved Fuel Properties

- Lower fuel operating temperatures
- Minimized cladding internal oxidation
- Minimized fuel relocation/dispersion
- Higher fuel melt temperature

Improved Cladding Properties

- Resilience to clad fracture
- Robust geometric stability
- Thermal shock resistance
- Higher cladding melt temperature
- Minimized fuel - cladding interactions

Enhanced Retention of Fission Products

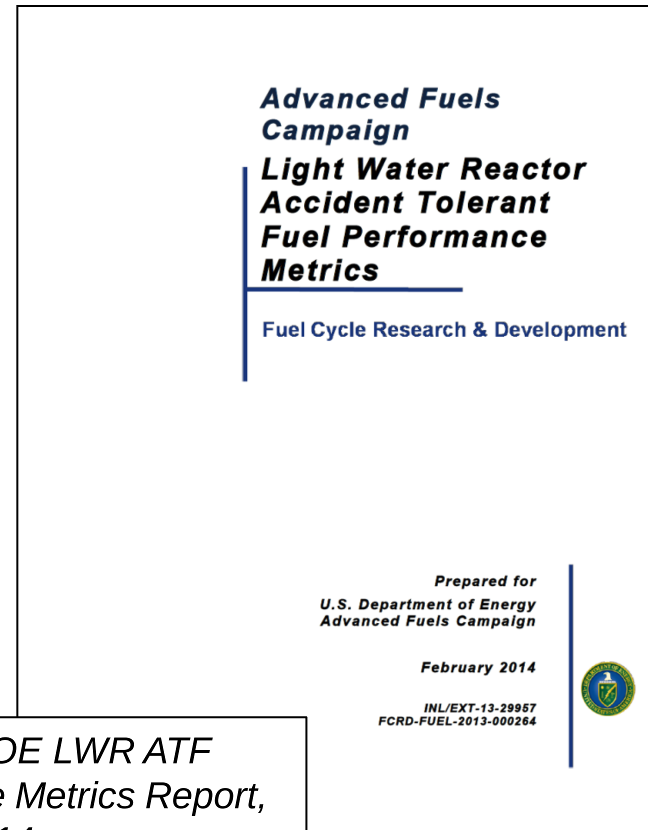
- Gaseous fission products
- Solid/liquid fission products

Metrics evaluation approach is designed to maximize improvement in <u>several interrelated areas;</u> while identifying instances in which improvement in one area could negatively impact another area.

New ATF Designs Must Meet the LWR Operations, Safety and Fuel Cycle Constraints

ATF will be evaluated over all potential "performance regimes"

- Fabrication/Manufacturability (to include Licensibility)
- Normal operations and anticipated operational occurrences (AOOs)
- Postulated accidents (Design Basis)
- Severe accidents (Beyond Design Basis)
- Used fuel storage / transport / disposition (to include potential for future reprocessing)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Light Water Reactor Accident Tolerant Fuel Performance Metrics

Fuel Cycle Research & Development

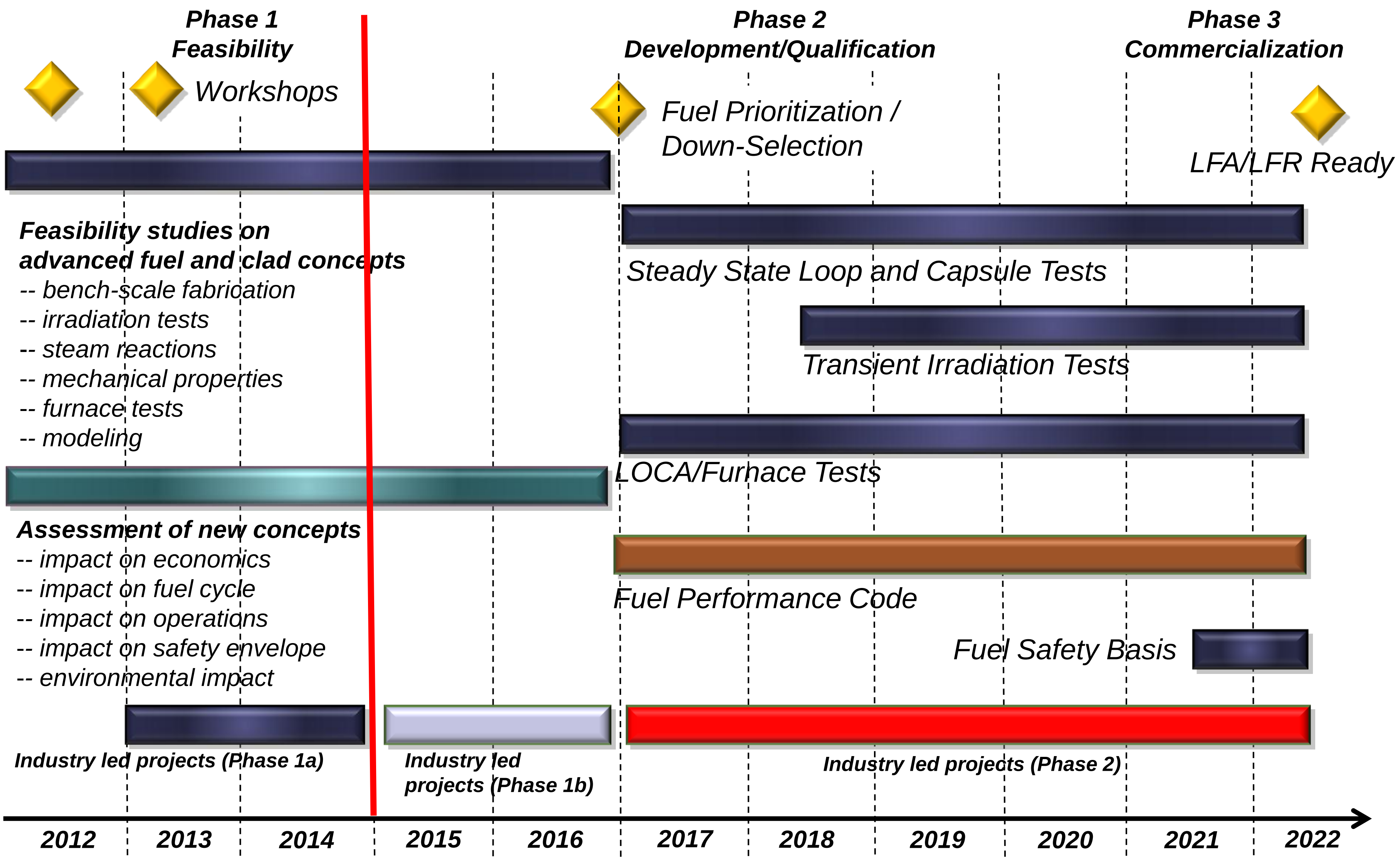
Prepared for
U.S. Department of Energy
Advanced Fuels Campaign

February 2014

INL/EXT-13-29957
FCRD-FUEL-2013-000264

See: U.S. DOE LWR ATF Performance Metrics Report, February 2014

RD&D Strategy For Enhanced Accident Tolerant Fuels – 10 Year Goal



Review Will Apply “Go / No-Go” Criteria

- The fuel design must meet current LWR constraints **without changing assembly thermal hydraulics**.
- The fuel must **maintain current cycle length and power output** at allowable enrichment levels (increased cycle length, number of fuel batches in the core management scheme, and power density may be desirable but not required).
- The fuel must have a **quantifiable benefit under accident scenarios** (e.g. longer time to onset of fuel melt) relative to the current fuel system to be deemed “accident tolerant.”
- **Reactivity feedback coefficients must be similar** in magnitude and parametric behavior to the reference UO_2 – Zr alloy system to ensure backward compatibility in existing reactors.
  - Reactivity coefficients must not reduce the safety of the reactor system or the safety margin and should fall within the existing safety envelope for UO_2 – Zr fuels.
  - In some cases the calculated moderator temperature coefficients can be slightly positive (for current fuel systems) at the beginning of life with high soluble boron concentration. It is possible that the moderator temperature coefficient may also be slightly positive for some candidate ATFs under similar conditions.
  - Reactivity coefficients that are more negative than the reference UO_2 – Zr system may be problematic if they interfere with shutdown margin or system stability.

PROPOSED ACCIDENT TOLERANT FUEL TECHNICAL EVALUATION METHODOLOGY

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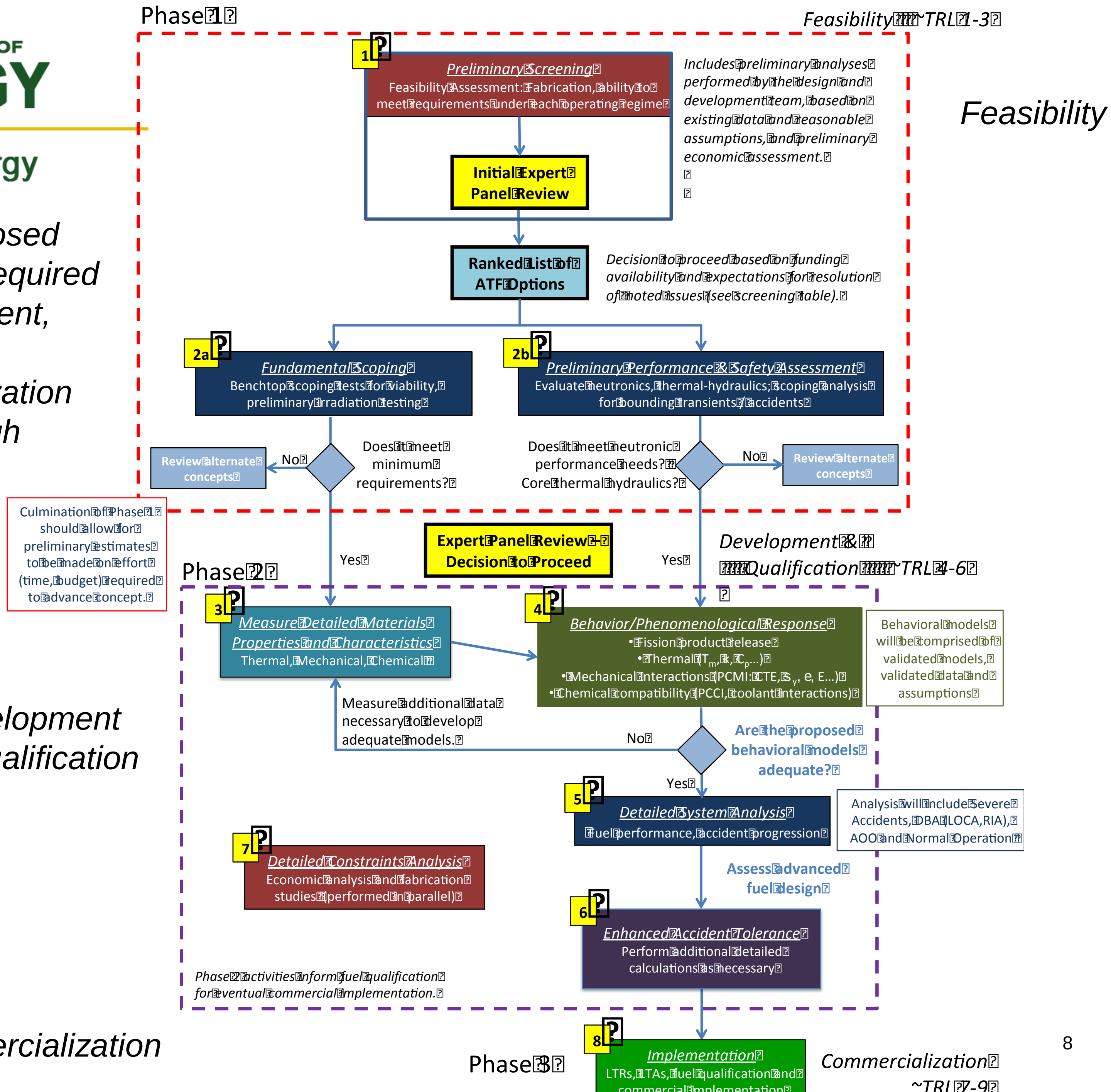
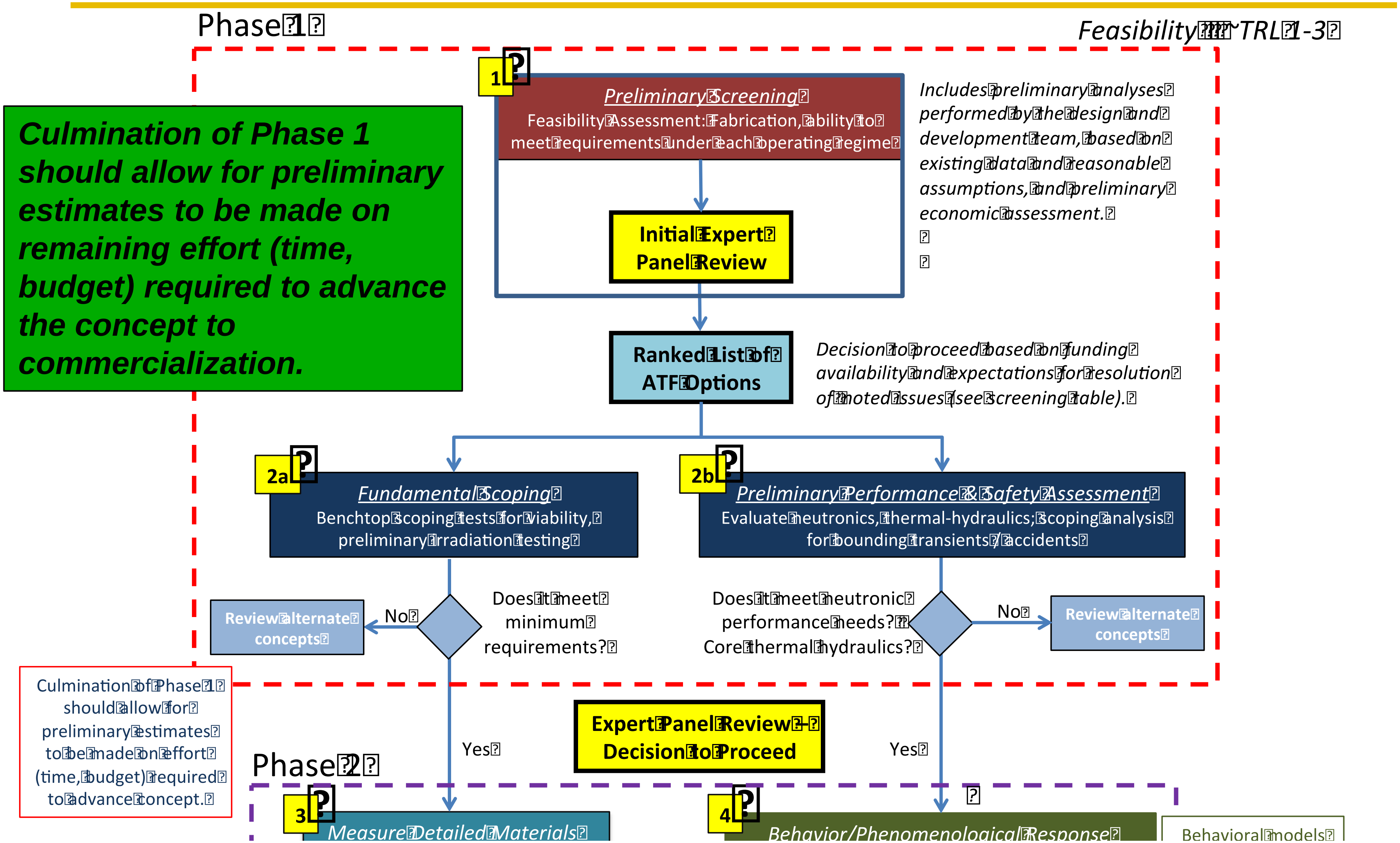
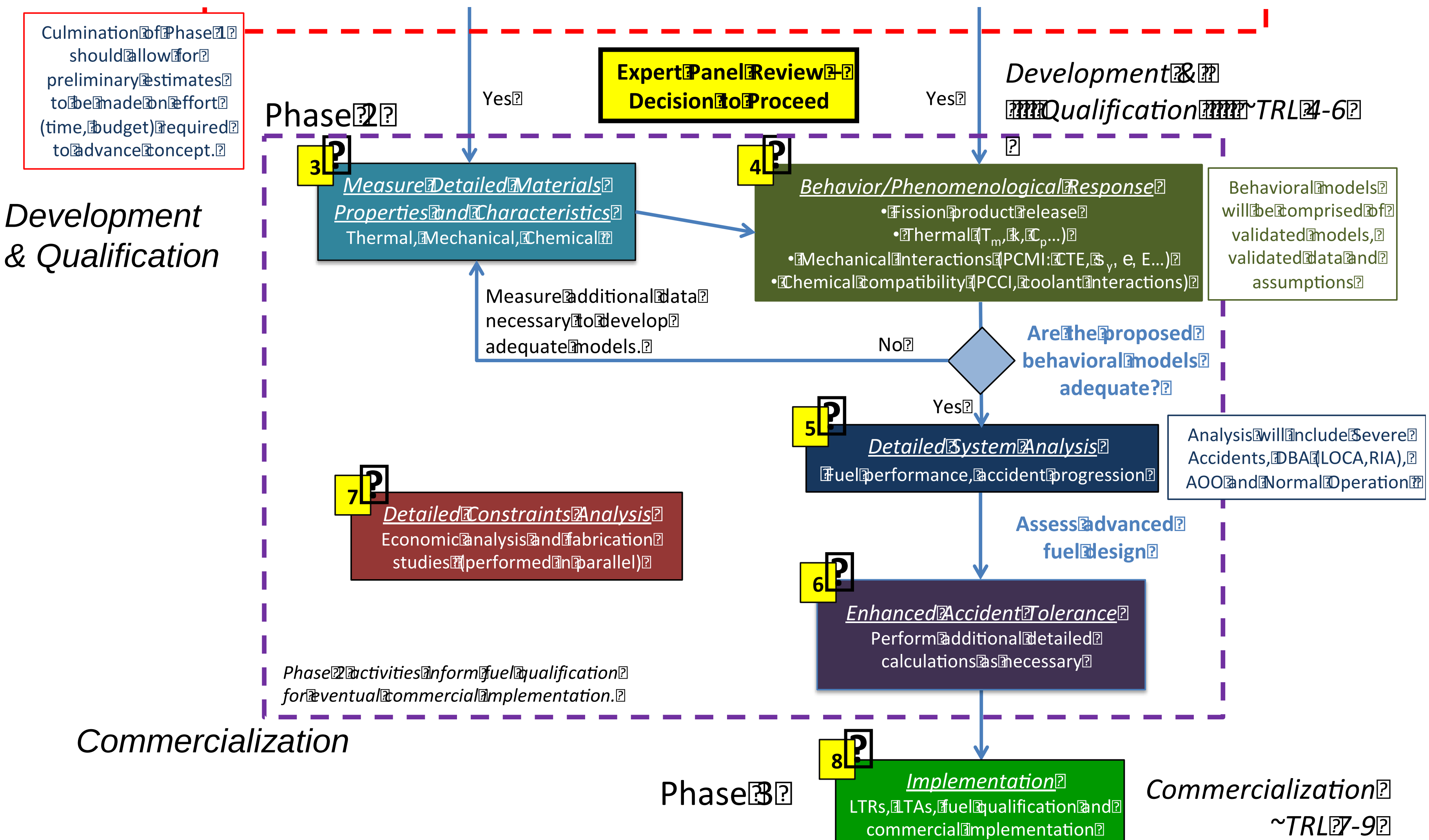
Overview of proposed flow of activities required for ATF development, evaluation, down-selection / prioritization and testing through implementation.



Feasibility Assessment Phase




Culmination of Phase 1 should allow for preliminary estimates to be made on effort (time, budget) required to advance concept.
Development & Qualification
Phase 2
Yes
Expert Panel Review – Decision to Proceed
Yes
Development & Qualification ~TRL 4-6
3
Measure Detailed Materials Properties and Characteristics
Thermal, Mechanical, Chemical
4
Behavior/Phenomenological Response
• Fission product release
• Thermal (T_m, k, C_p...)
• Mechanical interactions (PCMI: CTE, s_y, e, E...)
• Chemical compatibility (PCCI, coolant interactions)
Behavioral models will be comprised of validated models, validated data and assumptions
Measure additional data necessary to develop adequate models.
No
Are the proposed behavioral models adequate?
Yes
5
Detailed System Analysis
Fuel performance, accident progression
Analysis will include Severe Accidents, DBA (LOCA, RIA), AOO and Normal Operation
7
Detailed Constraints Analysis
Economic analysis and fabrication studies (performed in parallel)
Assess advanced fuel design
6
Enhanced Accident Tolerance
Perform additional detailed calculations as necessary
Phase 2 activities inform fuel qualification for eventual commercial implementation.
Commercialization
Phase 3
8
Implementation
LTRs, LTAs, fuel qualification and commercial implementation
Commercialization ~TRL 7-9

Expert Panel Review: Fuel Screening Attributes Assessment Table

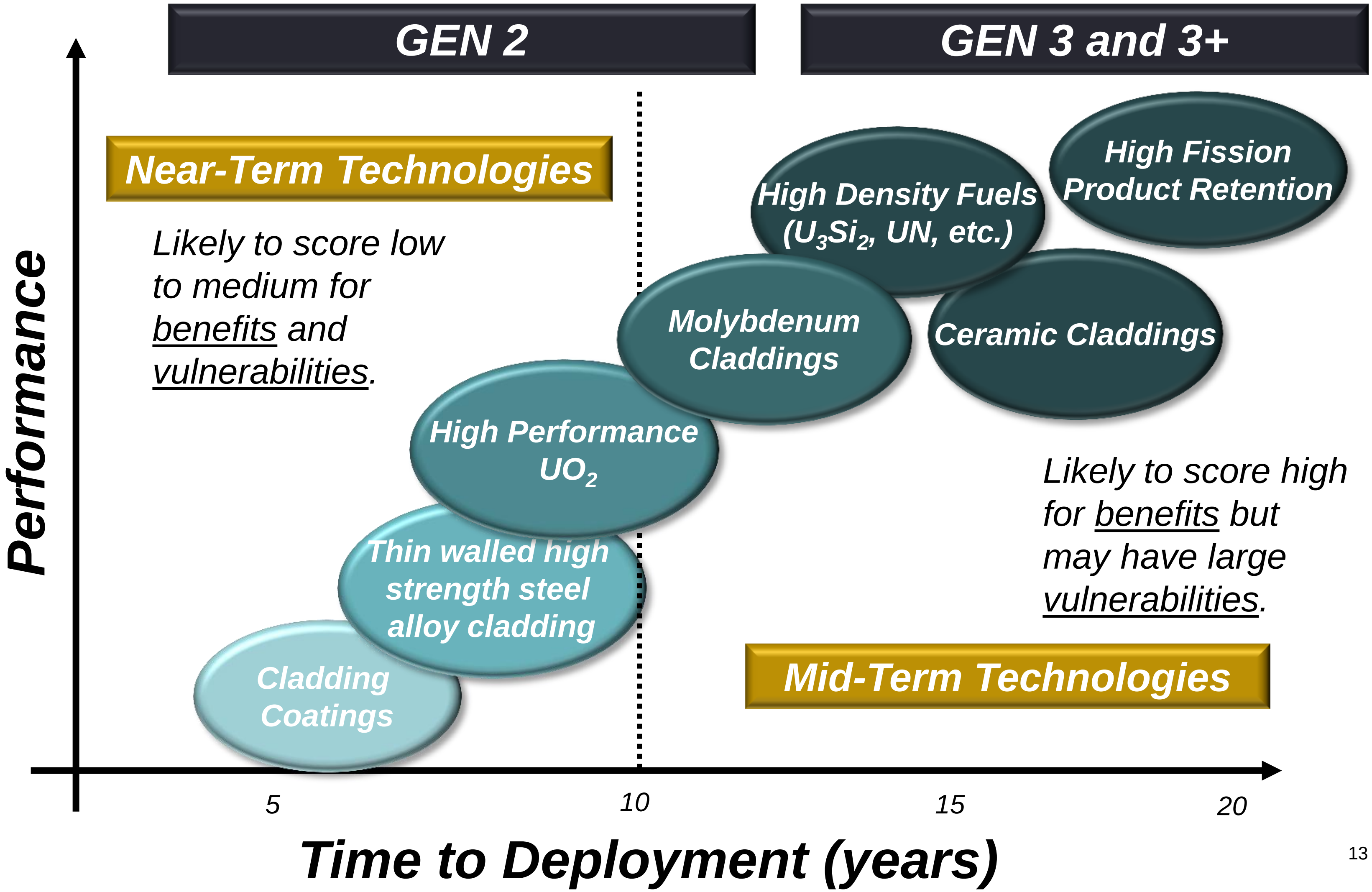
Performance Regime	Performance Attributes (For large-scale deployment)	Expert Opinion Assessment: Benefit	Expert Opinion Assessment: Vulnerability	Recommended Actions
Fabrication/ Manufacturability *Considerations:* Millions ft of clad/year Billions of pellets/year	Manageable fissile material content			
	Compatible with large scale production needs (material availability, fabrication techniques, waste, etc.)			
	Compatible with quality and uniformity standards			
Normal Operation and AOOs *Considerations:* Power ramp, ~100 W/m/min Reduced flow (departure from nucleate boiling, DNB) Flow-induced vibrations Safe shutdown - earthquake External pressure (~2500 psi) 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 and ductility			
	Thermal behavior (conductivity, specific heat, melting)			
	Chemical compatibility/ stability			
	Fission product behavior			
Postulated Accidents (Design Basis) *Considerations:* Prompt reactivity insertion Post-DNB behavior (T > 800°C) Loss of coolant conditions Steam reactions (~1000°C)	Thermal hydraulic interaction			
	Mechanical strength and ductility			
	Thermal behavior (conductivity, specific heat, melting)			
	Chemical compatibility/ stability			
	Fission product behavior			
Severe Accidents (Beyond Design Basis) *Considerations:* Thermal shock Chemical reactions Combustible gas release Long-term stability in degraded state	Mechanical strength and ductility			
	Thermal behavior (conductivity, specific heat, melting)			
	Chemical compatibility/ stability			
	Fission product behavior			
Used Fuel Storage/ Transport/ Disposition *Considerations:* Handling, placement, and drying loads	Mechanical strength and ductility			
	Thermal behavior			
	Chemical compatibility/ stability			
	Fission product behavior			

- **Evaluation of expected "benefits" and "vulnerabilities" over 5 performance regimes / life cycle stages**
  - Rank 0 – 5 for each regime.
  - 0 – equivalent to current system
  - 5 – significant benefit or vulnerability
  - Unknown property– high vulnerability
  - Recommended actions: directed by review committee to reduce vulnerabilities
- **Attributes applied to complete fuel system (fuel plus cladding)**

Concept Assessment Table: Scoring of Concepts

- **Real or perceived "Benefits" and "Vulnerabilities" will be scored *separately* to allow clear identification of risk to concept development**
  - Delineates near-term, moderate pay-off technologies and medium- to far-term, high pay-off technologies
  - Unknown behavior or properties → higher vulnerability
    - *Any identified vulnerability should have a corresponding recommended action for resolution*
- **Standard UO_2 – Zr-alloy system used as a baseline**
  - Benefit = 0, Vulnerability = 0
- **Benefits scored on a scale of zero (no change) to +5**
  - Based on what has clearly been measured OR
  - Based on what is perceived or extrapolated from existing data and analyses
- **Vulnerabilities scored on a scale of zero (no change) to -5**
  - High vulnerability may be scored if a particular behavior has not been measured or demonstrated OR
  - High vulnerability could result from a property being worse than that of UO_2 – Zr-alloy (e.g. lower melting T, higher enrichment, reduced cycle length…)

High payoff technologies may require additional development and time



Example Evaluation (Hypothetical): Fabrication / Manufacturability

Performance Attribute	Benefit	Vulnerability	Recommended Action
Manageable fissile content	2 (higher than UO_2)	0	
Compatible with large-scale production needs	0	-3 (Scale-up not yet determined; material quantities available)	Demonstrate ability to scale production.
Compatible with quality and uniformity standards	0	-2 (Reproducible quality not fully demonstrated)	Demonstrate ability to maintain standards during large-scale production.
Licensibility (includes consideration for required enrichment)	0	-4 (Requires higher enrichment to maintain cycle length)	Determine if fabrication facility and associated license can be modified to accommodate the required enrichment.

Considerations:

- *Millions ft cladding/yr, ~300 million fuel pellets per year*
- *Economics: cost of raw materials, fabrication*
- *Material availability*
- *Current fabrication plant enrichment limits*

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Example Evaluation (Hypothetical): Normal Operation and AOOs

Performance Attribute	Benefit	Vulnerability	Recommended Action
Burnup (cycle length)	0 (same as UO_2)	0	
Thermal hydraulic interaction	3 (improved)	0	
Reactivity control systems interaction	0	-2	Expected to be equivalent to current fuel; need verification
Mechanical strength / ductility (BOL, EOL)	2	-3	Good at BOL, need post-irradiation data
Thermal behavior	3 (limited data)	-3	Need additional data
Chemical compatibility (fuel, coolant), stability	0	-3	Requires demonstration under irradiation; possible coolant chemistry changes
Fission product behavior	2 (limited data)	-3	Requires long-term demonstration

***Considerations*:**

- *Overall neutronics*
- *LHGR to centerline melt*
- *Power ramp performance*
- *Reduced flow behavior*
- *Flow-induced vibrations*
- *Surface roughness effects*
- *Safe shutdown*
- *Axial growth / dimensional stability*
- *Affect of external pressure*

Example Evaluation (Hypothetical): Postulated Accidents

Performance Attribute	Benefit	Vulnerability	Recommended Action
Thermal hydraulic interaction			
Mechanical strength / ductility (BOL, EOL)			
Thermal behavior (conductivity, specific heat, melting)			
Chemical compatibility (e.g. oxidation behavior)			
Fission product behavior			
Combustible gas production			

Considerations:

- *Prompt reactivity insertion*
- *Post-DNB behavior*
- *Loss of coolant conditions*
- *Thermal shock*
- *Steam reactions (>1000^{o}C)*

Example Evaluation (Hypothetical): Severe Accidents (Beyond DBA)

Performance Attribute	Benefit	Vulnerability	Recommended Action
Mechanical strength / ductility (BOL, EOL)			
Thermal behavior (conductivity, specific heat, melting)			
Chemical compatibility (inc. high T steam reaction)			
Fission product behavior			
Combustible gas production			

Considerations:

- *Thermal shock*
- *Chemical rections*
- *Combustible gas release*
- *Long-term stability in degraded state*

Example Evaluation (Hypothetical): Used Fuel Storage / Transport /Disposition

Performance Attribute	Benefit	Vulnerability	Recommended Action
Mechanical strength / ductility			
Thermal behavior			
Chemical stability			
Fission product behavior			

***Considerations*:**

- *Handling, placement, and drying loads*
- *Future reprocessing potential*

Technical Review Committee for Concept Evaluation and Ranking

- **Review Committee Purpose:** To provide an independent assessment of the technology feasibility for near term research and development of candidate ATF design concepts and prioritization of those concepts.
- **Systematic, independent technical evaluation of each ATF concept**
  - Evaluate concept's ability to meet performance and safety goals relative to the current UO_2 – zirconium alloy system
  - Apply quantitative assessment to then allow concepts to be ranked relative to one another
- **Committee Composition:** Comprised of technology experts having knowledge and experience relevant to the technologies under review.
  - Expertise in one or more areas relevant to fuel and reactor performance: materials (metals and ceramics), neutronics, thermal-hydraulics, and severe accidents
  - It is not expected that any one reviewer would have expertise in all necessary areas
- **Results:** Concept ranking / prioritization

  Note: The committee may choose to produce two prioritized lists to
  (1) identify near-term concepts for which the 2022 Lead Fuel Rod goal may be realistic and
  (2) identify concepts that have the potential to provide significant benefit but may not fit within the 10-year development window; warrant further development investment.

Expert Review Panel Assessment

- **Sum benefit scores for each concept**
- **Sum vulnerability scores for each concept**
- **Rank / prioritize concepts –**
  - Near-term
  - Long-term (high benefit, additional R&D needs)

- **Proceed to phase 2 development efforts for a select number of concepts based on funding availability**

- **Review of concepts currently under development in the U.S. will be conducted in ~late 2016**

Thank You for Your Attention

QUESTIONS?

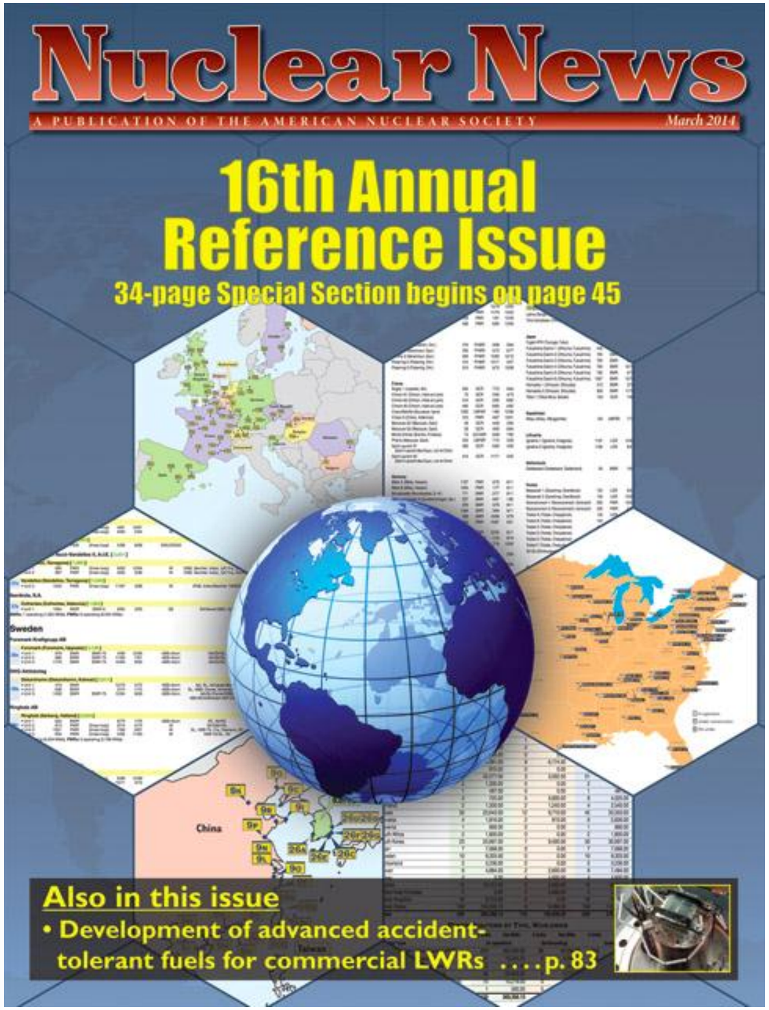
SHANNON.BRAGG-SITTON@INL.GOV

Leading ATF Design Objectives

1) Maintain or improve upon the thermal, mechanical and chemical properties observed for the current state-of-the-art fuel systems.
2) Provide "accident tolerant" improvements that increase coping time ("grace period") under severe accident scenarios.
   a. Increase the time before the onset of core melt, during which additional recovery actions can be made to halt the accident progression.
   b. Reduce the impact of a severe accident by reducing core damage frequency (CDF); maintain coolable geometry; reduce combustible gas production as well as the amount of radioactive materials potentially released.
3) Offer the capability for power uprate and increased burnup to allow an economic case to be made for adoption of the new fuel system.

Recent Publications on ATF Projects

Summary of U.S. ATF research provided in the March 2014 edition of ***Nuclear News***, the monthly publication from the American Nuclear Society.
http://www.ans.org/pubs/magazines/nn/y_2014/m_3



***Journal of Nuclear Materials* –** Special issue on accident tolerant fuels now available (Volume 448, May 2014).

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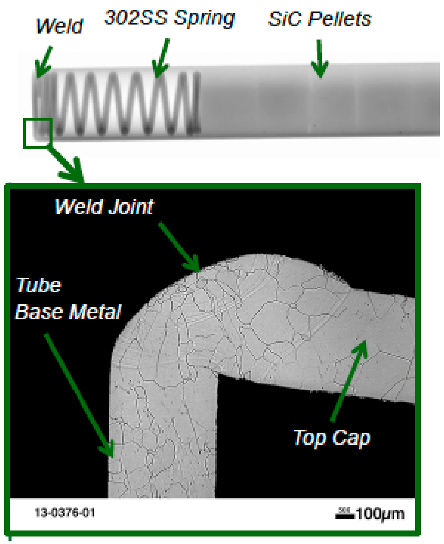
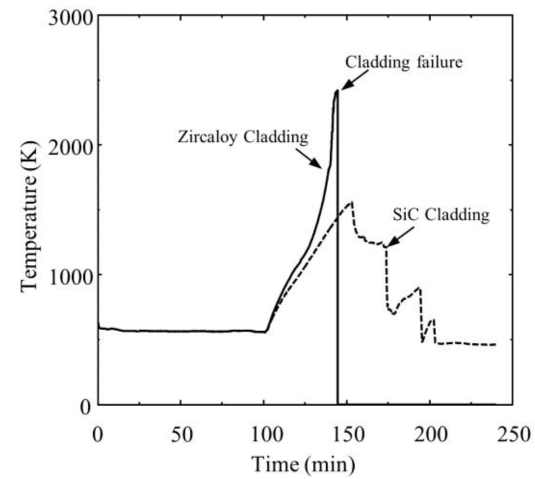
ATF cladding development efforts focus on materials with more benign steam reaction

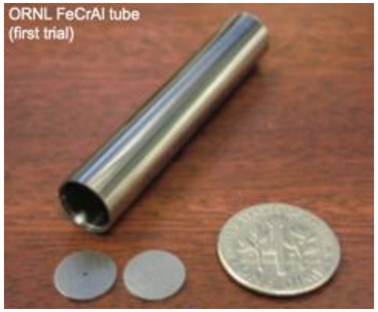
- **Advanced steels (e.g. FeCrAl)**
- **Refractory metals (e.g. Mo)**
- **Ceramic cladding (SiC)**
- **Innovative alloys with dopants**
- **Zircaloy with coating or sleeve**
  - SiC CMC
  - MAX-phase ceramics
  - Other





Comparison of MELCOR predicted cladding oxidation heating produced during a TMI-2 accident sequence.

Each concept has some pros and cons across the spectrum of operating and transient conditions of interest. A systematic analytical and experimental evaluation is being performed during the feasibility studies.



FeCrAl cladding (ORNL).

SiC cladding (GA).

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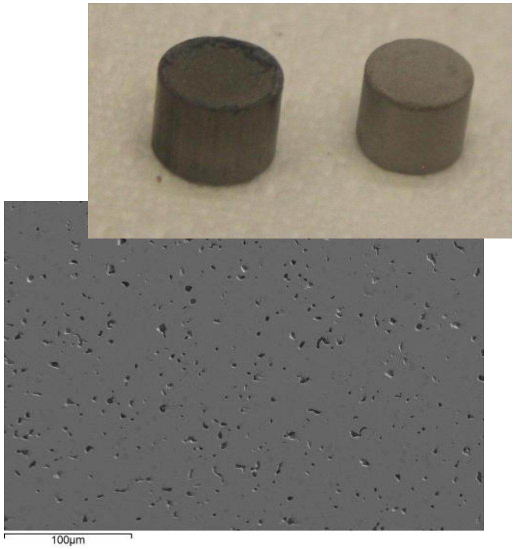
Several advanced fuel concepts are under investigation for accident tolerance

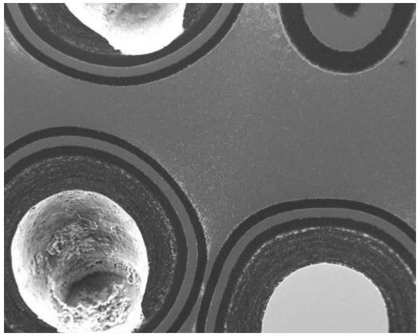
- **Higher density fuels (metal, nitride, silicide)**
  - Higher thermal conductivity
  - Higher fissile density to compensate for neutronic inefficiency of some new cladding concepts without increasing enrichment limits
- **Oxide fuels with additives**
  - Higher thermal conductivity
  - Fission product gettering
- **Microencapsulated fuels**
  - Particle fuel dispersed in a ceramic or metallic matrix



(left) Pressed and (right) Sintered Uranium Silicide Pellets (INL)

Highest achieved density: 97.8% theoretical (11.93 g/cc)

Fully Ceramic Microencapsulated Fuel (ORNL)



A systematic analytical and experimental evaluation is being performed during the feasibility studies.

The U.S. Accident Tolerant Fuel development is supported by a large part of the U.S. nuclear complex

National Laboratories

- INL Idaho National Laboratory
- Oak Ridge National Laboratory
- Brookhaven National Laboratory
- Argonne National Laboratory
- Los Alamos National Laboratory
- Pacific Northwest National Laboratory

Universities

- UF University of Florida — The Foundation for The Gator Nation
- University of Illinois — Urbana-Champaign • Chicago • Springfield
- UT The University of Tennessee — Knoxville, Chattanooga, Martin, Tullahoma, Memphis
- ATM Texas A&M University
- Georgia Tech
- MIT
- W
- M

Nuclear Industry

- GE imagination at work
- Westinghouse
- AREVA
- EPRI Electric Power Research Institute

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Summary of Major DOE-funded ATF Projects

Lead Organization	Category – Major Technology Area	Additional Collaborators
Oak Ridge National Laboratory	**Fuel:** Fully Ceramic Microencapsulated (FCM)-UO_2; FCM-UN **Cladding:** FeCrAl alloy; silicon carbide (SiC)	LANL, INL support FeCrAl weld development work
Los Alamos National Lab.	**Fuel:** Enhanced UO_2, Composite Fuels	
EPRI + LANL	**Cladding:** Advanced molybdenum alloys (multi-layer design)	ORNL
AREVA *(FOA, NEUP)*	**Fuel:** High conductivity fuel (UO_2+Cr_2O_3, +SiC) **Cladding:** Coated Zr-alloys (protective materials, MAX phase)	U. Wisconsin, U. Florida, SRNL,TVA, Duke
Westinghouse *(FOA, NEUP)*	**Fuel:** U_3Si_2, and UN+U_3Si_2 fuel **Cladding:** Coated Zr-alloy; SiC concepts	General Atomics, EWI, INL, LANL, MIT, TAMU, Southern Nuclear Operating Company
GE Global Research *(FOA)*	**Cladding:** Advanced Steel (Ferritic / Martensitic, including FeCrAl)	Global Nuclear Fuels, LANL, U. Michigan
University of Illinois *(IRP)*	**Cladding:** Modified Zr-based cladding (coating or modification of bulk cladding composition)	U. Michigan, U. Florida, INL, U. Manchester, ATI Wah Chang **UK contributions
University of Tennessee *(IRP)*	**Cladding:** Ceramic Coatings for Cladding (MAX phase; multilayer ceramic coatings)	Penn State, U. Michigan, UC Boulder, LANL, Westinghouse, Oxford, U. Manchester, U. Sheffield, U. Huddersfield, ANSTO **UK and Australian contributions

Multiple concepts will begin irradiation in the INL ATR in summer/fall 2014. Additional laboratories are providing analysis support (INL, BNL, ANL).

Key Material Properties and Behavior Characteristics – Leading ATF Design Objectives

- **Candidate fuel must maintain or improve upon:** ****Need an economic case!**
  - Thermal, mechanical and chemical properties
  - Burnup limits / cycle length
  - Operational parameters (power distribution, peaking factors, safety margins, etc.)
  - Reactivity coefficients and control parameters (shutdown margin, rod worths)
  - Handling, transportation and storage (isotopics, dose, mechanical integrity)
  - Compatibility with existing infrastructure
- **To be considered "accident tolerant", a concept must also offer <u>improved response</u> to off-normal conditions: AOOs, DBAs (RIA, LOCA, SBO) and BDBAs**
  - <u>Increased "coping time"</u> or "grace period" - time before the onset of core melt
  - Reduced impact through reduced core damage frequency (maintain coolable geometry), combustible gas production and the amount of radioactive materials potentially released
- **A very large number of properties and performance parameters must be considered in fuel development**
  - It is impossible to improve on all properties and behaviors; all behaviors are interrelated and cannot be treated independently in fuel system design
  - Define *leading design objectives* to allow for concept ranking and prioritization

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Feasibility Assessment and Down-Selection/Prioritization

- ***Feasibility studies on advanced fuel and clad concepts***
  - Bench-scale fabrication
  - Small-scale irradiation tests
  - Steam reactions
  - Mechanical and chemical properties
  - LOCA furnace tests
  - Fuel performance modeling
- ***Assessment relative to constraints***
  - Current LWR designs
  - Operational constraints
  - Economics
  - Safety performance
  - Fuel Cycle

"Metrics" are initially intended to provide guidance to the Feasibility Assessment and Down-Selection/Prioritization phase, but can continue to be applied as more data become available.

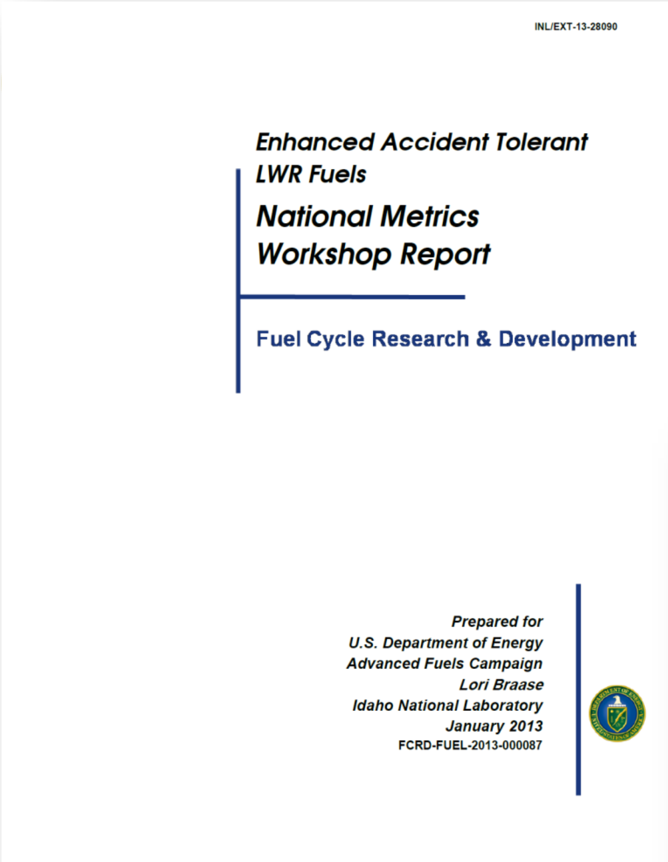
- The proposed evaluation approach allows ATF to be designed for quantitative improvement in several interrelated areas without being constrained to specific quantitative targets for each property or behavior individually.
- A broad, multi-variable evaluation approach should be capable of identifying instances for which improvement in one area could negatively impact another area.

Additional Considerations…

- Adopting a fuel technology with completely different vulnerabilities than the current fuel technology (i.e. ceramic vs. metallic cladding) would presumably require the adoption of different limiting conditions of operation.

- Ideally, a new fuel system would allow for optimization of all plant systems (e.g. emergency core cooling system, coolant chemistry control, etc.).
  - A fair comparison of technologies would require optimization of ancillary plant systems in addition to changing the fuel.

- Plant-specific optimization with the proposed new fuel system is considered to be beyond the scope of initial screening analyses intended for down-selection / prioritization of ATF concepts.
  - Note that this activity would be expected prior to deployment, at least with regard to plant operations.



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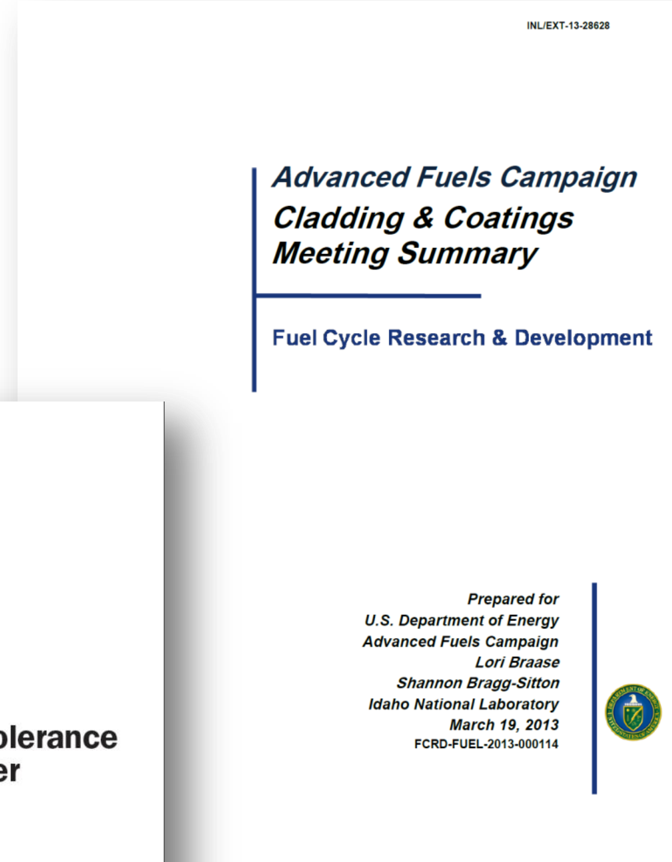
Enhanced Accident Tolerant LWR Fuels

National Metrics Workshop Report

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Advanced Fuels Campaign
Lori Braase
Idaho National Laboratory
January 2013
FCRD-FUEL-2013-000087



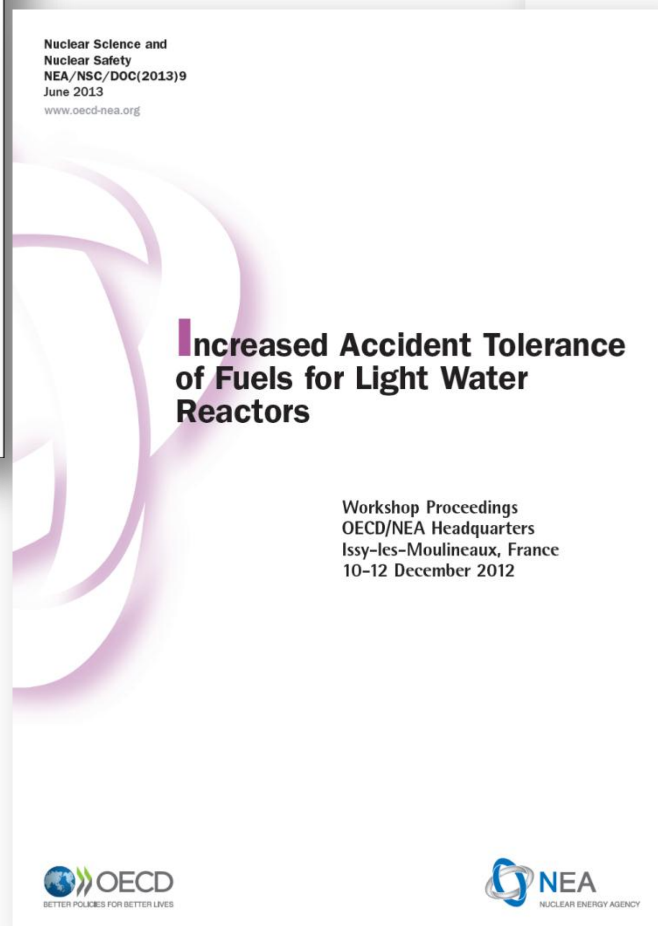
INL/EXT-13-28628

Advanced Fuels Campaign

Cladding & Coatings Meeting Summary

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Advanced Fuels Campaign
Lori Braase
Shannon Bragg-Sitton
Idaho National Laboratory
March 19, 2013
FCRD-FUEL-2013-000114



Nuclear Science and
Nuclear Safety
NEA/NSC/DOC(2013)9
June 2013
www.oecd-nea.org

Increased Accident Tolerance of Fuels for Light Water Reactors

Workshop Proceedings
OECD/NEA Headquarters
Issy-les-Moulineaux, France
10-12 December 2012

OECD BETTER POLICIES FOR BETTER LIVES
NEA NUCLEAR ENERGY AGENCY

Series of metrics meetings held to identify key accident tolerant attributes of interest and to establish international consensus on how to approach ATF design, optimization and down-selection.