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METRICS DEVELOPMENT FOR ENHANCED ACCIDENT TOLERANT LWR FUELS

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OECD / NEA

Second Meeting on Increased Accident Tolerance of Fuels for LWRs

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Presentation Outline

- Overview of Accident Tolerant Fuels in the U.S.
- Definition of “metrics”
- Proposed evaluation methodology
- Sample calculations
- Discussion

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The Accident Tolerant Fuel effort 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

MIT

Texas A&M University

Georgia Tech

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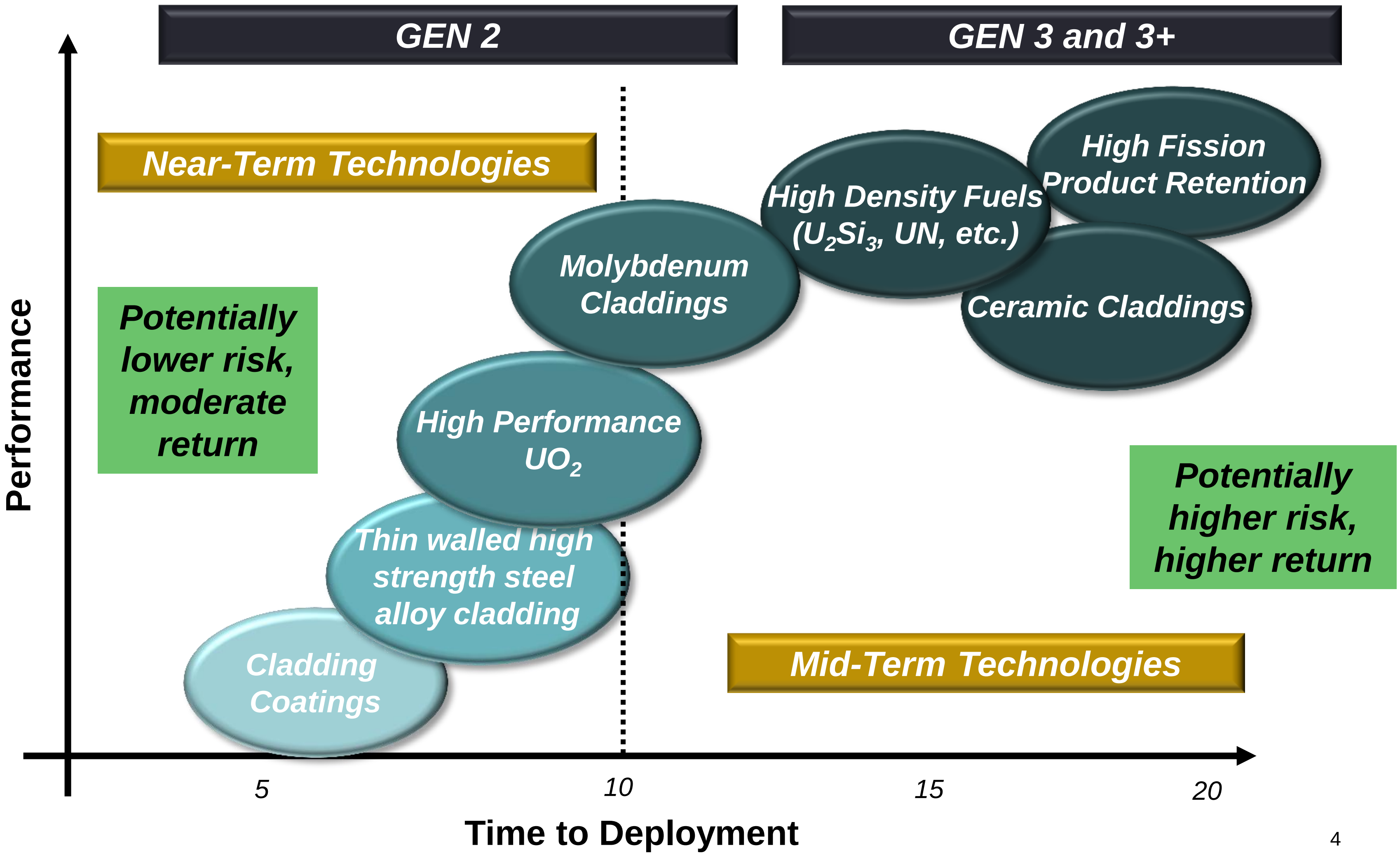
Nuclear Industry

GE imagination at work

Westinghouse

AREVA

ATF R&D Works with Industry Partners Towards Technology Selection



What do we mean by "metrics"?

Possible options:

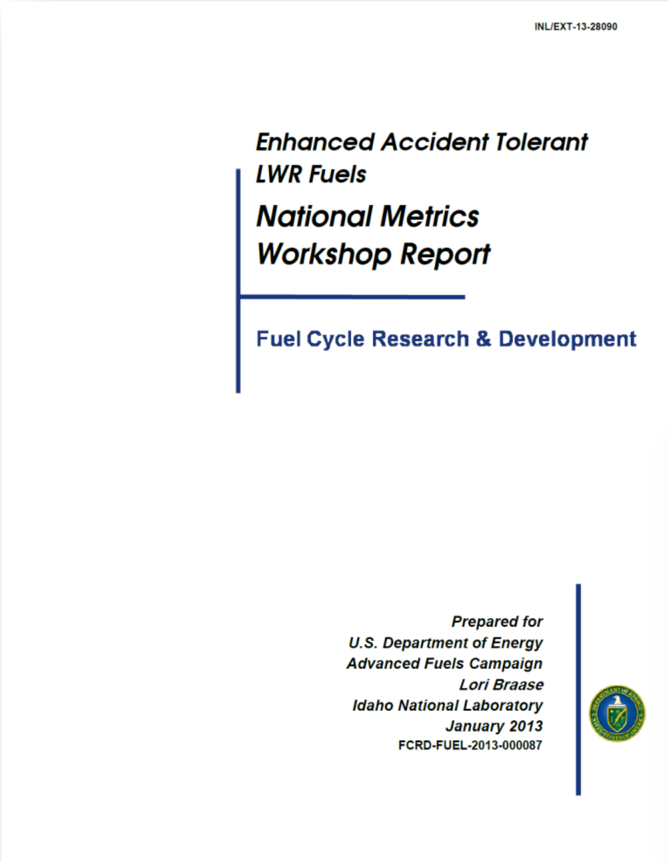
- Quantitative targets for selected properties or behaviors
- Well-defined, technically based method of evaluation to allow ranking of proposed technologies

Challenges:

- Complex interrelationship of properties and behaviors
- Different properties demonstrate different levels of importance depending on the reactor type (PWR vs. BWR) or accident scenario – cannot set a quantitative target that is universally applicable

Where we settled for accident tolerant fuel "metrics":

- A set of technical bases by which multiple concepts can be fairly evaluated against a common baseline (NOT quantitative targets for individual properties)
- A technical evaluation methodology to rank the ability of each ATF concept to meet performance and safety goals relative to the current UO_2 – zirconium alloy system and relative to one another
- The resultant ranked evaluation can inform concept down-selection, such that the most promising ATF design option(s) can continue to be developed toward qualification given budget and time constraints



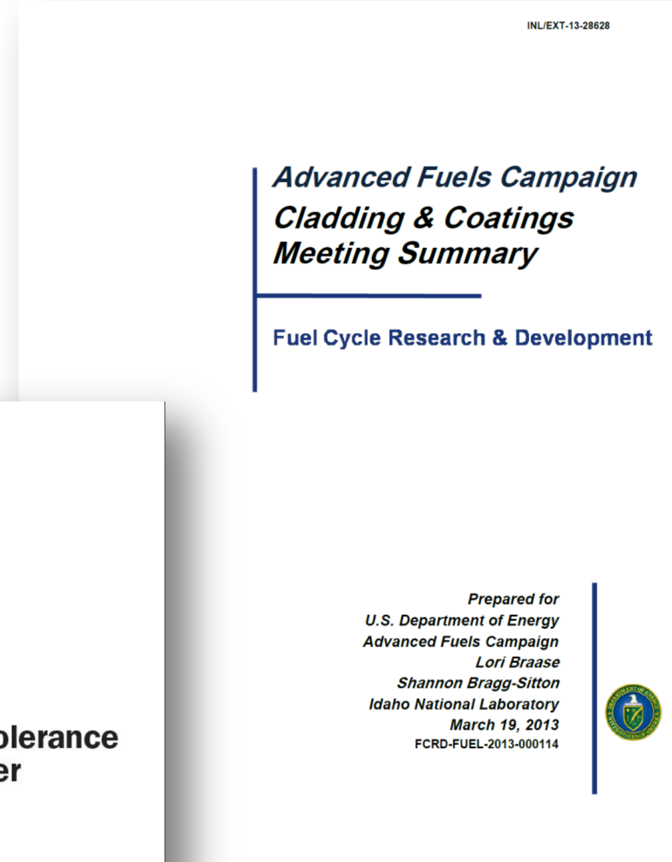
INL/EXT-13-28090

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
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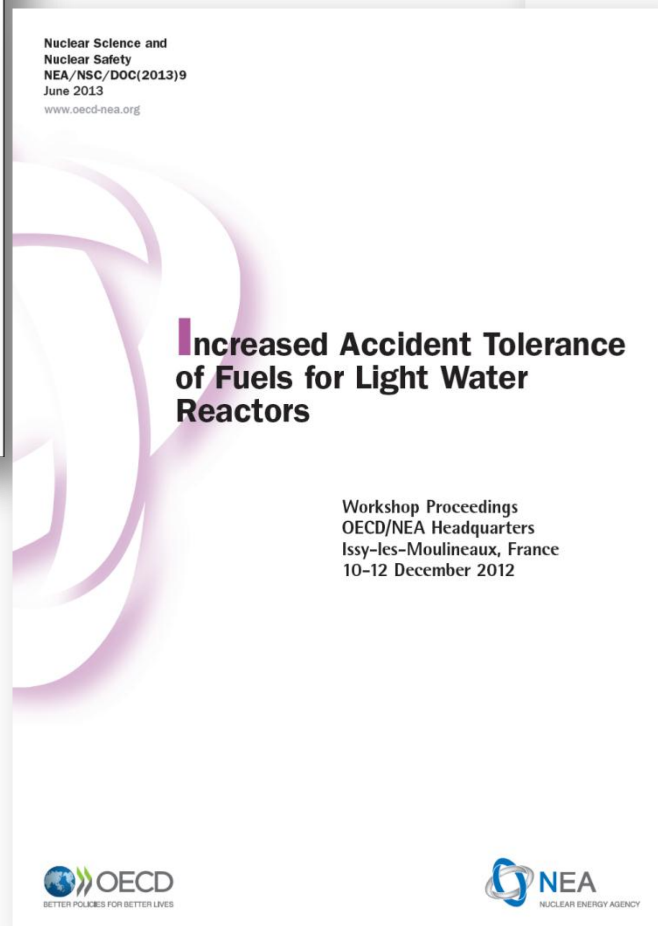
Idaho National Laboratory
March 19, 2013
FCRD-FUEL-2013-000114



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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.

Feasibility Assessment and Down-Selection

- ***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

Evaluation "metrics" currently under development are intended to provide guidance to the <u>Feasibility Assessment and Down-Selection phase</u>. These metrics will continue to be applied as more data becomes available to reduce uncertainty in performance estimates.

Feasibility Assessment and Down-Selection

- The proposed evaluation approach will allow 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.
- Some go / no-go criteria will be established:
  - Must meet current LWR constraints without changing assembly thermal-hydraulics
  - Must be expected to have a quantifiable benefit under accident scenarios
  - Reactivity coefficients CANNOT be positive; negative coefficients ranked relative to that for current system
  - Must maintain current cycle length and power output at allowable enrichment

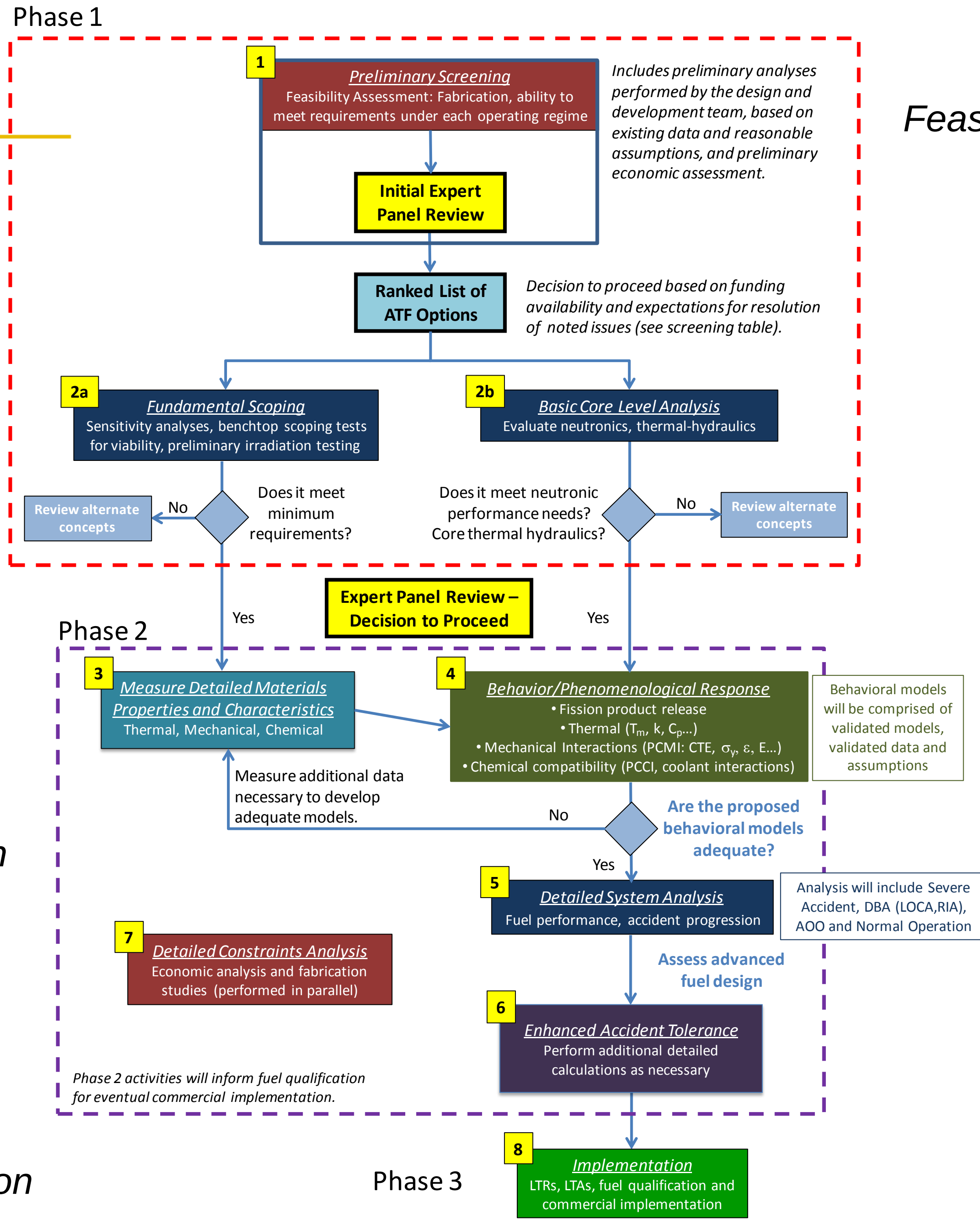
PROPOSED ACCIDENT TOLERANT FUEL TECHNICAL EVALUATION METHODOLOGY

Overview of proposed flow chart for development, evaluation, down-selection and testing of ATF concepts through implementation.

Feasibility

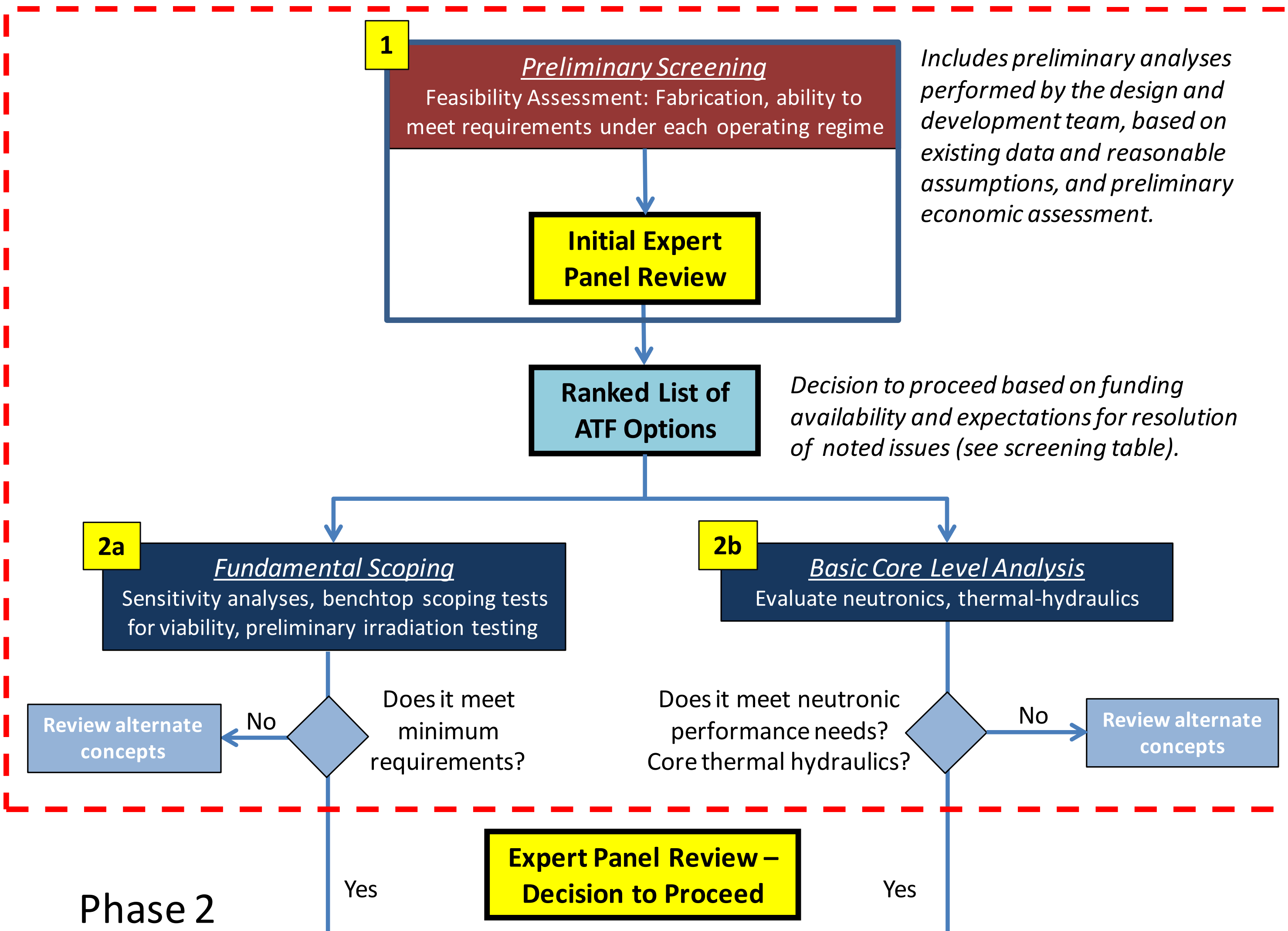
Development & Qualification

Commercialization



Feasibility Assessment Phase

Phase 1



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Expert Panel Review: 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 – raw materials, processes	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:* Overall neutronics Power ramp, ~100 W/m/min Reduced flow (departure from nucleate boiling, DNB) Flow-induced vibrations Safe shutdown - earthquake External pressure (~2750 psi, 10% above 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 and 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) Loss of coolant conditions Steam reactions (~1000°C)	Thermal hydraulic interaction			
	Mechanical strength and ductility			
	Thermal behavior (conductivity, specific heat, melting)			
	Chemical compatibility / stability (including high temperature steam interaction)			
	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 (including high temperature steam interaction)			
	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**
  - Fabrication / Manufacturability
  - Normal Operation and Anticipated Operational Occurrences
  - Postulated Accidents (Design Basis)
  - Severe Accidents (Beyond Design Basis)
  - Used Fuel Storage / Transport / Disposition
- **Attributes applied to complete fuel system (fuel plus cladding)**

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	Fission product behavior			

Rank 0 – 5 for each regime.

0 – equivalent to current system

5 – significant benefit or vulnerability

Unknown property– high vulnerability

Recommended actions would be intended to reduce vulnerabilities.

Step 1 – Preliminary Screening and Expert Panel Review

- **Purpose: Eliminate proposed designs not likely to improve upon the current UO_2 – Zr alloy fuel system and, hence, should not warrant additional investment**
- **Apply existing data and / or assumptions** to assess potential performance under normal condition and for improved safety under DBA and BDBA conditions – estimate "failure probability" [note that some scoping tests may be completed for some concepts even at this early stage]
- **Initial screening results are expected to have large uncertainty due to limited data available**
  - Uncertainty in properties / behaviors would equate to high "vulnerability" score
  - Technologies that do not depart significantly from the current UO_2-Zr alloy fuel system – expected to have a modest benefit score and low vulnerability

    → *Low risk, modest payoff, potentially near term development*
  - A relatively immature concept 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 is available

    →*High risk but potentially high payoff, requiring a longer development time*

Expert Review Panel: Specialists in materials (metals and ceramics), neutronics, thermal-hydraulics, and severe accidents

Step 2a: Fundamental Scoping Tests and Evaluations

Experimental

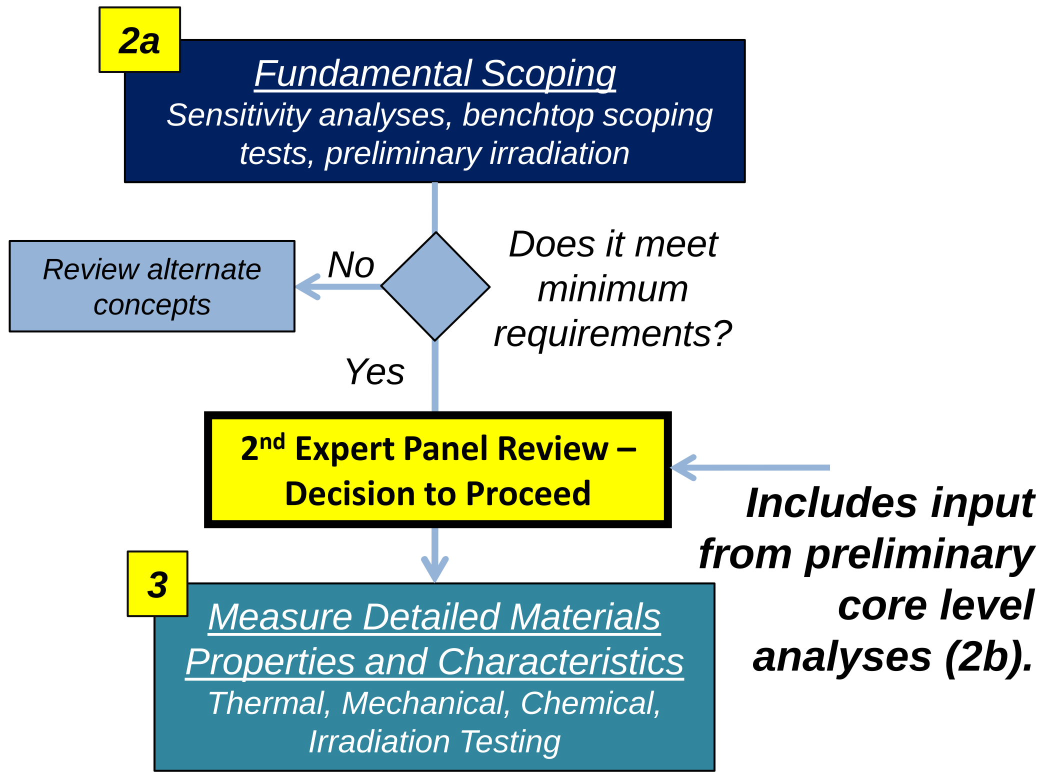
- A set of **prioritized characterization and scoping tests** is proposed to provide early indication of the accident tolerance of a specific concept
- Tests will provide some of the necessary material properties data for detailed models

Computational

- **Parametric studies / sensitivity analyses** to begin identification of key properties for a class of fuel and cladding designs
- Helps focus on properties / behaviors that will provide the greatest opportunity for improved performance

Example sensitivity studies:

- fuel thermal conductivity
- cladding oxidation rate
- cladding heat of oxidation



Prioritized Cladding Screening Tests

Prioritization based on greatest uncertainty / vulnerability for specified cladding type.

- **Metallic Cladding**
  - **Steam oxidation, post-steam ductility / strength tests**
  - Environmental testing (corrosion, irradiation assisted SCC, SCC, erosion)
  - Basic chemical compatibility at normal operating conditions
  - Irradiation environmental testing (sample coupons; determine effects on mechanical properties)
  - Mechanical testing (assuming baseline unirradiated data is already available, additional mechanical tests would not be required until after a material has passed the other screening tests identified)

- **Ceramic Cladding**
  - **Mechanical integrity tests (simple tests for hermeticity, break)**
  - Steam oxidation, post-steam ductility / strength tests
  - Basic chemical compatibility at normal operating conditions
  - Environmental testing (LWR water exposure over a range of chemistry conditions)
  - Mechanical properties measurement
  - Irradiation environmental testing (sample coupons; determine effects on mechanical properties)

- **Hybrid Cladding / Coatings on Cladding Tube**
  - **Assess coating adhesion – initial, thermal cycling, with flow (spall), wear (fretting)**
  - Based on substrate and “coating” materials and configuration, follow metallic or ceramic cladding priorities as defined above; additional details for coated cladding options include:
    - *Environmental testing w/small exposed region (autoclave)*
    - *Chemical compatibility to include coating / substrate compatibility (establish temperature limit)*

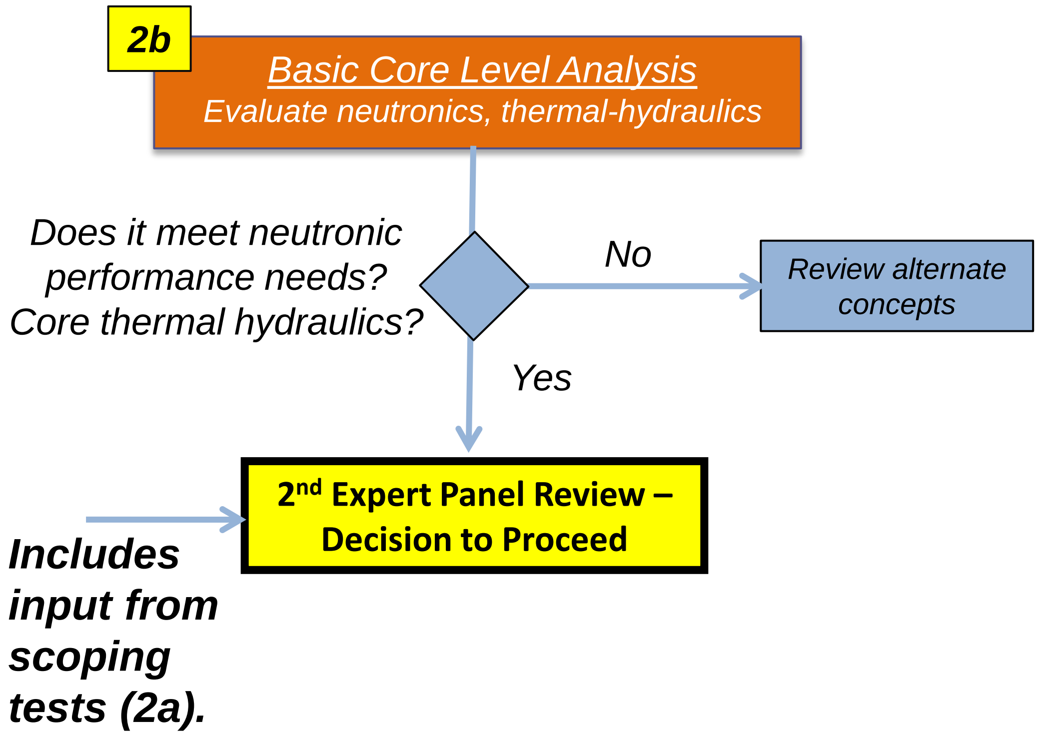
Fuel Screening Tests

- **Scoping evaluations that can be conducted on cold, clean fuel material prior to initial irradiation testing include:**
  - **Fuel – Clad Compatibility:**
    Evaluation of chemical compatibility with the proposed cladding material at temperature for an extended period of time. The fuel-cladding interaction should be mapped over a range of temperatures, from normal operating conditions to accident scenarios.
  - **Fuel – Coolant Compatibility:**
    In the event of a cladding breach, the potential interaction between the fuel and coolant (liquid water and steam) must be understood over a range of possible temperatures.
  - **Determination of Key Properties:**
    Basic pre-irradiation fuel properties should be measured, including thermal conductivity, density, etc., over a range of temperatures. These properties should again be measured following irradiation.
- **Initial Irradiation Testing:**

  Irradiation testing and post-irradiation characterization, property measurement.

Step 2b: Basic Core Level Analysis

- **Analysis to address how implementation of the concept will affect reactor performance and safety characteristics**
- **Neutronic analyses**
  - Assembly or core-level
  - Cycle length
  - Burnup
  - Fuel management schemes
  - Power peaking
  - Estimates of reactivity and control coefficients
- **Thermal-hydraulic analyses**
  - Assembly or core-level
  - Steady-state estimates of the Departure from Nucleate Boiling Ratio (DNBR) or Minimum Critical Power Ratio (MCPR)
- **Fuel performance**



Example Step 2b: Core-Level Analysis, UO_2 vs. UN (*note that UN is __not__ considered directly as an ATF and is only used here for example)*

- **Impact of the fuel design on the core power and flux distribution, reactivity coefficients, control parameters, neutronic behavior and thermal hydraulic behavior must be evaluated and understood at a given state-point and as a function of burn-up.**

***Results demonstrate potential effect of higher fuel density and thermal conductivity.*

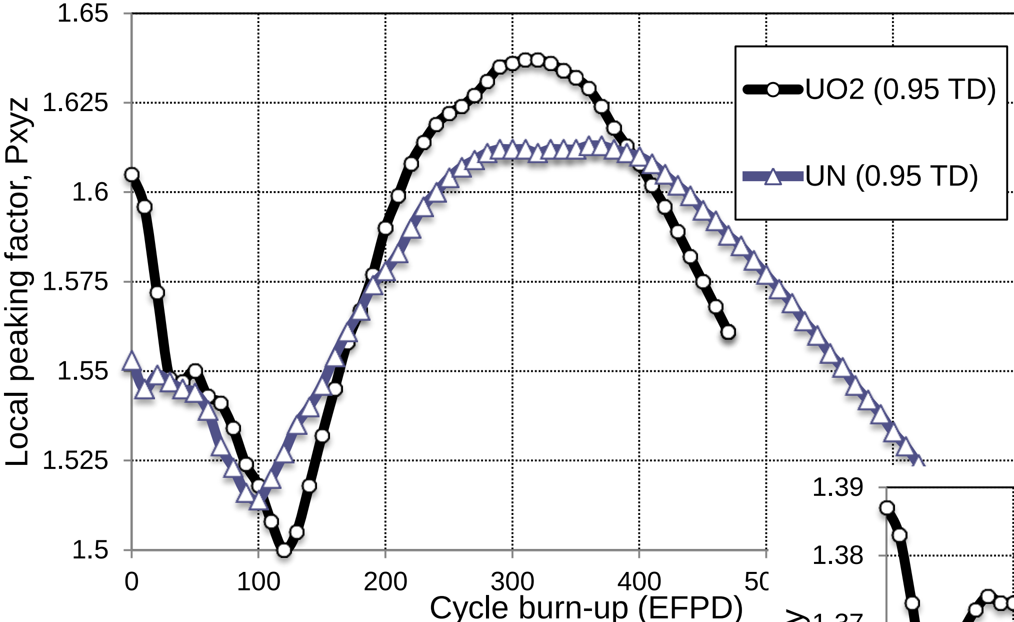
Fuel	UO_2 (0.95 TD*)	UN (0.95TD*)
Batch burn-up (GWd/t)	17.6	17.7
Discharge burn-up (GWd/t)	52.7	53.1
Cycle length (EFPD)	456	647

Evaluated option may affect cycle length and the reactor control parameters

UN near design limit: Implies that soluble boron is less effective for reactivity control, and alternative methods of reactivity control may have to be applied if this fuel were to be integrated into an existing PWR.

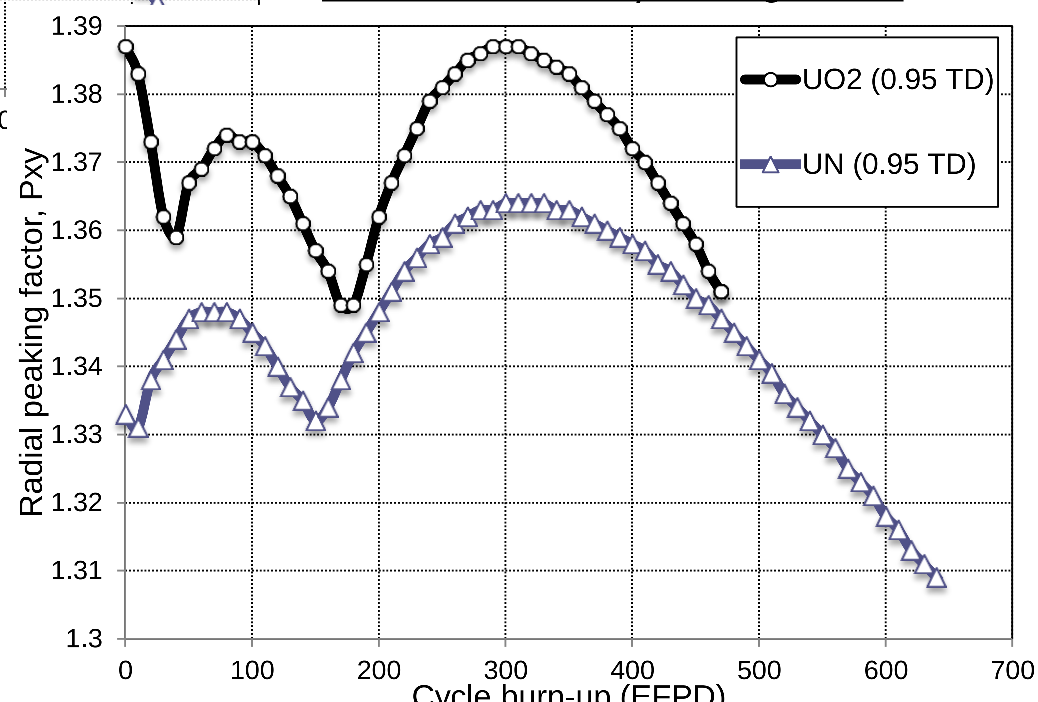
Reactivity Coefficient	Ref. Design Limit	UO_2	UN
Fuel Temperature Coefficient, pcm/K	-6.3 to -1.8	-2.7	-2.8
Moderator Temperature Coefficient, pcm/K	-72.0 to 0.0	-32.8	-32.1
Boron Coefficient, pcm/ppm	-13.5 to -5.0	-6.0	-5.0

Comparison of Peaking Factors: UO_2 vs. UN (*note that UN is <u>not</u> considered directly as an ATF and is only used here for example*)



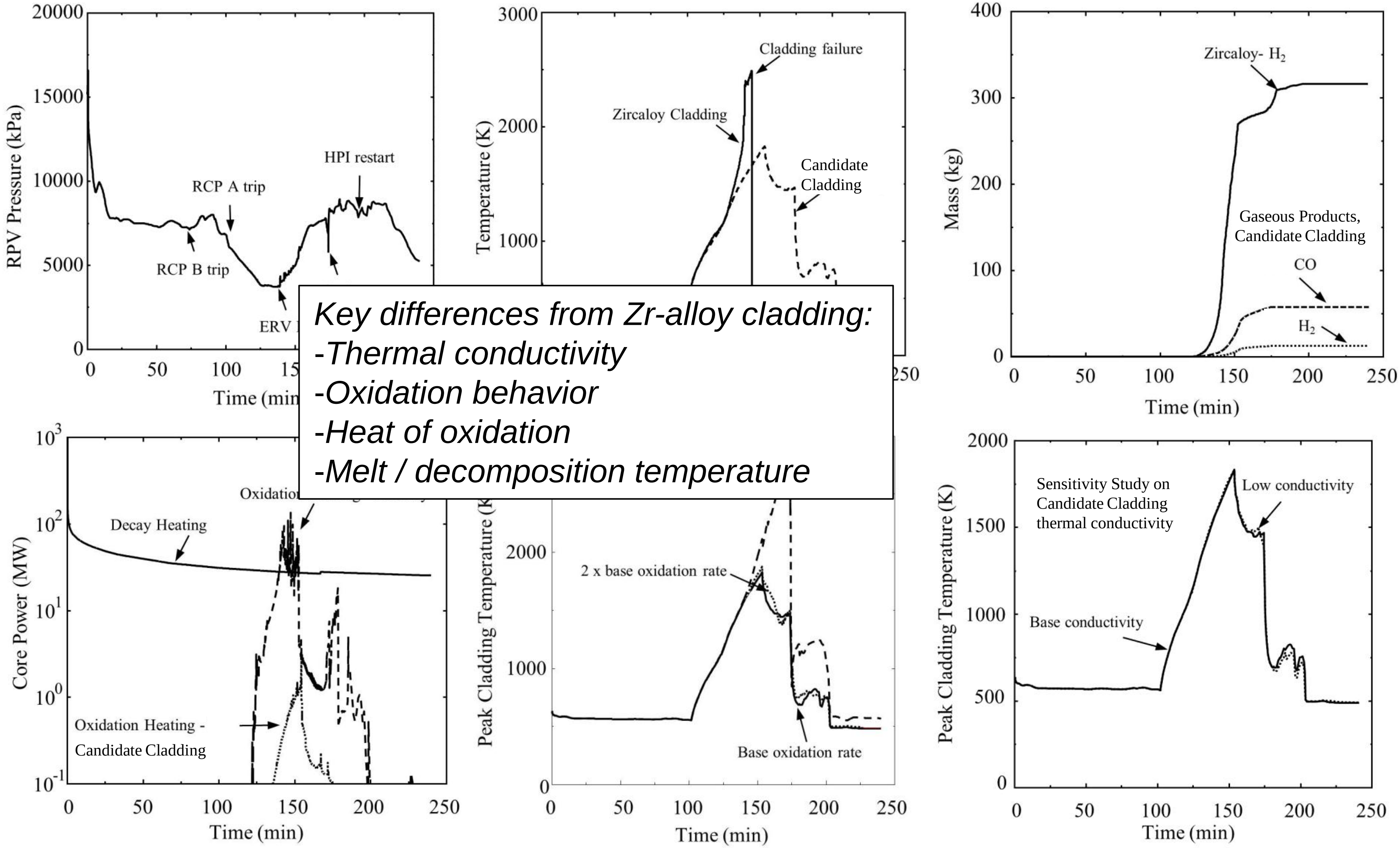
Results demonstrate potential effect of <u>higher fuel density and thermal conductivity</u>.

If UN were applicable to an LWR, results suggest that it would potentially have <u>more safety margin due to the lower peaking factor</u>.



Note that the reduced power peaking is not entirely an intrinsic property of the fuels analyzed, but is a <u>holistic impact of the fuel properties as well as the parameters applied in the analysis</u> (burnable poison loading, fuel management scheme, reactor geometry, etc.).

Preliminary Analysis of Accident Performance (Step 2b; further evaluation in Step 6) – Baseline PWR Severe Accident Analyses: MELCOR, TMI-2

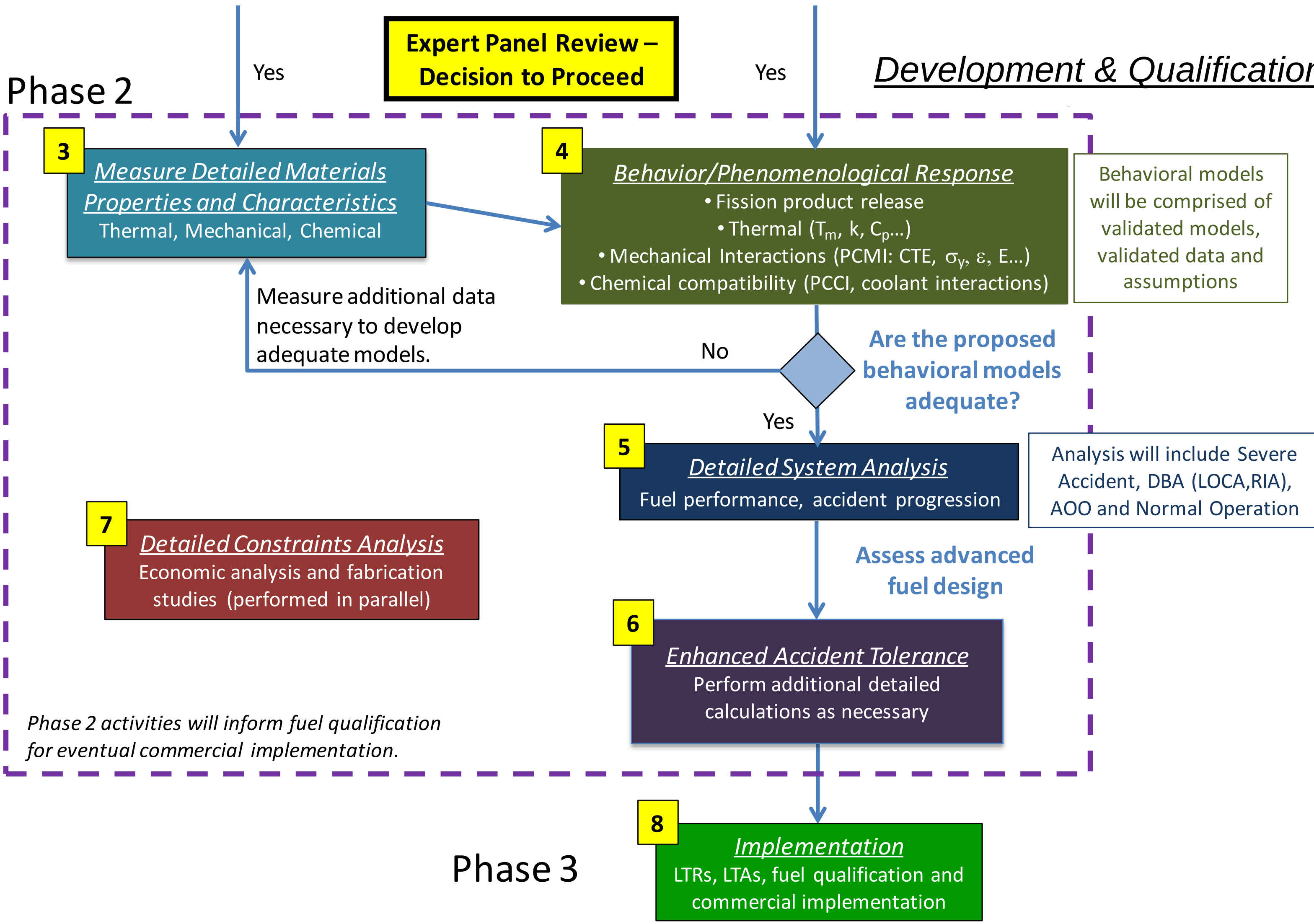


Key differences from Zr-alloy cladding:
- *Thermal conductivity*
- *Oxidation behavior*
- *Heat of oxidation*
- *Melt / decomposition temperature*

Second Expert Panel Review Commenced Following Feasibility Assessment

Further characterization and testing follows down-selection.

Development & Qualification Phase



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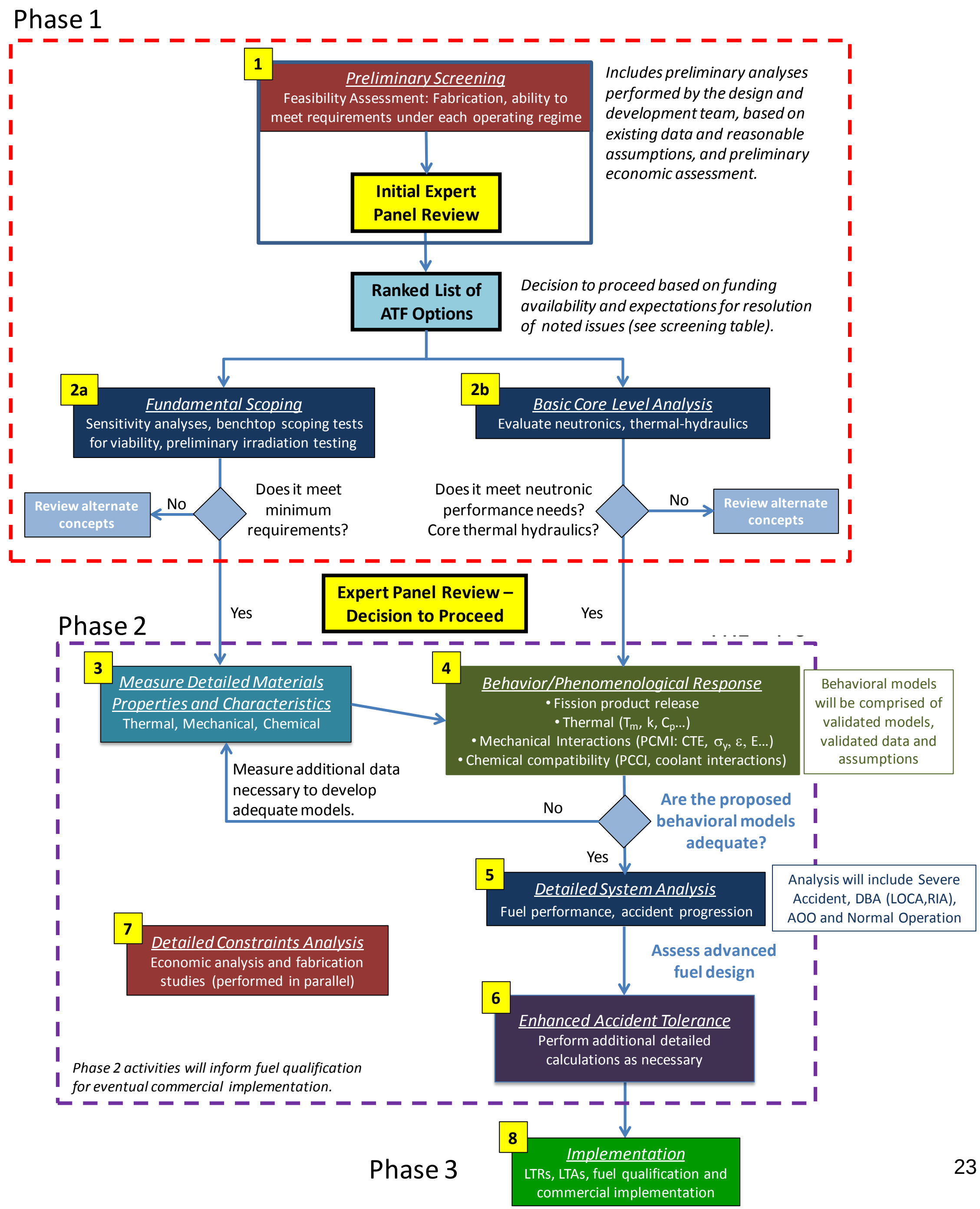
Questions?



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Key Material Properties and Behavior Characteristics – Leading ATF Design Objectives

- **Candidate fuel must maintain or improve upon:**
  - Thermal, mechanical and chemical properties
  - Burnup limits / cycle length
  - Operations 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

Need an economic case!

- **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 inter-related and cannot be treated independently in fuel system design
  - Define *leading design objectives* to allow for concept ranking and down-selection