Metrics for the Evaluation of LWR Accident Tolerant Fuel

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OECD-NEA Expert Group on Accident Tolerant Fuels for LWRs
NEA Headquarters, Paris, France
Multiple contributors and reviewers have offered input to the Evaluation Metrics presented today:
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- Jon Carmack, Lori Braase, Melissa Teague, Brad Merrill, Robert Youngblood, Steve Hayes, Idaho National Laboratory
- Chris Stanek, Ken McClellan, Los Alamos National Laboratory
- Robert Montgomery, Pacific Northwest National Laboratory
- Larry Ott, Kevin Robb, Oak Ridge National Laboratory
- Mike Billone, Mitch Farmer, Argonne National Laboratory
- Mike Todosow, Nicholas Brown, Brookhaven National Laboratory
- Industry reviewers –
  • Concept development teams (AREVA, GE, Westinghouse)
  • Advisory committee to the National Technical Director (vendors, utilities)
Fuels with enhanced accident tolerance are those that, in comparison with the standard $\text{UO}_2-\text{Zr}$ 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.

**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

**Enhanced Tolerance to Loss of Active Core Cooling**

Metrics evaluation approach is designed to maximize improvement in several interrelated areas; 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)

See: U.S. DOE LWR ATF Performance Metrics Report, February 2014
RD&D Strategy For Enhanced Accident Tolerant Fuels – 10 Year Goal

Feasibility studies on advanced fuel and clad concepts
-- bench-scale fabrication
-- irradiation tests
-- steam reactions
-- mechanical properties
-- furnace tests
-- modeling

Assessment of new concepts
-- impact on economics
-- impact on fuel cycle
-- impact on operations
-- impact on safety envelope
-- environmental impact

Phase 1
Feasibility
Workshops


Phase 2
Development/Qualification
Fuel Prioritization / Down-Selection
Steady State Loop and Capsule Tests
Transient Irradiation Tests
LOCA/Furnace Tests
Fuel Performance Code
Fuel Safety Basis

Phase 3
Commercialization
LFA/LFR Ready

Industry led projects (Phase 1a)
Industry led projects (Phase 1b)
Industry led projects (Phase 2)
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
Overview of proposed flow of activities required for ATF development, evaluation, down-selection / prioritization and testing through implementation.

**Development & Qualification**

1. **Initial Expert Panel Review**
   - Includes preliminary analyses performed by the design and development team, based on existing data and reasonable assumptions, and preliminary economic assessment.

2a. **Fundamental Scoping**
   - Benchtop scoping tests for viability, preliminary irradiation testing.
   - Does it meet minimum requirements?

2b. **Preliminary Performance & Safety Assessment**
   - Evaluate neutronics, thermal-hydraulics; scoping analysis for bounding transients / accidents.
   - Does it meet neutron performance needs? Core thermal hydraulics?

3. **Measure Detailed Materials Properties and Characteristics**
   - Thermal, Mechanical, Chemical.
   - Measure additional data necessary to develop adequate models.

4. **Behavior/Phenomenological Response**
   - Fission product release
   - Thermal (F, \( T_{th} \), \( C_p \), ...)
   - Mechanical Interactions (PCMI: CTE, \( C_p \))
   - Chemical compatibility (PCC, coolant interactions)

5. **Detailed System Analysis**
   - Fuel performance, accident progression.
   - Assess advanced fuel design.

6. **Enhanced Accident Tolerance**
   - Perform additional detailed calculations as necessary.

7. **Detailed Constraints Analysis**
   - Economic analysis and fabrication studies (performed in parallel).

8. **Implementation**
   - LTRs, LTAs, fuel qualification and commercial implementation.

Culmination of Phase 1 should allow for preliminary estimates to be made on effort (time, budget) required to advance concept.
Culmination of Phase 1 should allow for preliminary estimates to be made on remaining effort (time, budget) required to advance the concept to commercialization.

Phase 1

1. Preliminary Screening
   Feasibility Assessment: Fabrication, ability to meet requirements under each operating regime
   
   Initial Expert Panel Review
   
   Ranked List of ATF Options

   Includes preliminary analyses performed by the design and development team, based on existing data and reasonable assumptions, and preliminary economic assessment.

   Decision to proceed based on funding availability and expectations for resolution of noted issues (see screening table).

2a. Fundamental Scoping
   Benchtop scoping tests for viability, preliminary irradiation testing
   
   Review alternate concepts
   
   Does it meet minimum requirements?

2b. Preliminary Performance & Safety Assessment
   Evaluate neutronics, thermal-hydraulics; scoping analysis for bounding transients / accidents
   
   Does it meet neutronic performance needs? Core thermal hydraulics?

Phase 2

3. Measure Detailed Materials
   
   Expert Panel Review – Decision to Proceed
   
   Yes

4. Behavior/Phenomenological Response
   Behavioral models

   Yes
Development & Qualification

Phase 2

3. Measure Detailed Materials Properties and Characteristics
   - Thermal, Mechanical, Chemical
   Measure additional data necessary to develop adequate models.

4. Behavior/Phenomenological Response
   - Fission product release
   - Thermal ($T_m, k, C_p...$)
   - Mechanical Interactions (PCMI: CTE, $\gamma$, E...)
   - Chemical compatibility (PCCI, coolant interactions)

Are the proposed behavioral models adequate?

5. Detailed System Analysis
   - Fuel performance, accident progression
   Assess advanced fuel design

6. Enhanced Accident Tolerance
   - Perform additional detailed calculations as necessary

7. Detailed Constraints Analysis
   - Economic analysis and fabrication studies (performed in parallel)

Phase 2 activities inform fuel qualification for eventual commercial implementation.

Culmination of Phase 1 should allow for preliminary estimates to be made on effort (time, budget) required to advance concept.

Development & Qualification ~TRL 4-6

Expert Panel Review – Decision to Proceed

Phase 3

8. Implementation
   - LTRs, LTAs, fuel qualification and commercial implementation
   ~TRL 7-9

Commercialization

Behavioral models will be comprised of validated models, validated data and assumptions.

Analysis will include Severe Accidents, DBA (LOCA, RIA), AOO and Normal Operation.

Commercialization
## Expert Panel Review: Fuel Screening

### Attributes Assessment Table

<table>
<thead>
<tr>
<th>Performance Regime</th>
<th>Performance Attributes (For large-scale deployment)</th>
<th>Expert Opinion Assessment</th>
<th>Recommended Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fabrication/Manufacturability</strong></td>
<td>Manageable fissile material content</td>
<td>Benefit</td>
<td></td>
</tr>
<tr>
<td>Considerations:</td>
<td>Compatable with large scale production needs (material availability, fabrication techniques, waste, etc.)</td>
<td>Vulnerability</td>
<td></td>
</tr>
<tr>
<td>Millions of clad/year</td>
<td></td>
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<tr>
<td>Billions of pellets/year</td>
<td></td>
<td></td>
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<tr>
<td><strong>Normal Operation and AOOs</strong></td>
<td>Utilization or Burnup (12, 18, or 24 months/cycle)</td>
<td>Benefit</td>
<td></td>
</tr>
<tr>
<td>Considerations:</td>
<td>Thermal hydraulic interaction</td>
<td>Vulnerability</td>
<td></td>
</tr>
<tr>
<td>Power ramp, ~100 W/m/min</td>
<td>Reactivity control systems interaction</td>
<td></td>
<td></td>
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<tr>
<td>Reduced flow (departure from nucleate boiling, DNB)</td>
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<td>Mechanical strength and ductility</td>
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<tr>
<td>Flow-induced vibrations</td>
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<td></td>
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<tr>
<td>Safe shutdown - earthquake</td>
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<tr>
<td>External pressure (~2500 psi)</td>
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<tr>
<td>Axial growth (less than upper nozzle gap)</td>
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<tr>
<td><strong>Postulated Accidents (Design Basis)</strong></td>
<td>Thermal hydraulic interaction</td>
<td>Benefit</td>
<td></td>
</tr>
<tr>
<td>Considerations:</td>
<td>Thermal behavior (conductivity, specific heat, melting)</td>
<td>Vulnerability</td>
<td></td>
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<tr>
<td>Prompt reactivity insertion</td>
<td></td>
<td></td>
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<tr>
<td>Post-DNB behavior (T &gt; 800°C)</td>
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<tr>
<td>Loss of coolant conditions</td>
<td></td>
<td></td>
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<tr>
<td>Steam reactions (~1000°C)</td>
<td></td>
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<tr>
<td><strong>Severe Accidents (Beyond Design Basis)</strong></td>
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<tr>
<td>Considerations:</td>
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<tr>
<td>Thermal shock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical reactions</td>
<td>Fission product behavior</td>
<td></td>
<td></td>
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<tr>
<td>Combustible gas release</td>
<td></td>
<td></td>
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<tr>
<td>Long-term stability in degraded state</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Used Fuel Storage/Transport/Disposition</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Considerations:</td>
<td></td>
<td></td>
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<tr>
<td>Handling, placement, and drying loads</td>
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</tr>
</tbody>
</table>

### 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)
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.

**Near-Term Technologies**

- Cladding Coatings
  - Likely to score low to medium for benefits and vulnerabilities.

**Mid-Term Technologies**

- Thin walled high strength steel alloy cladding
  - Likely to score high for benefits but may have large vulnerabilities.

**High Performance UO₂**

**High Density Fuels**

- (U₃Si₂, UN, etc.)

**GEN 2**

**GEN 3 and 3+**

- Ceramic Claddings
- Molybdenum Claddings
- High Fission Product Retention
Example Evaluation (Hypothetical): Fabrication / Manufacturability

<table>
<thead>
<tr>
<th>Performance Attribute</th>
<th>Benefit</th>
<th>Vulnerability</th>
<th>Recommended Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manageable fissile content</td>
<td>2 (higher than UO$_2$)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Compatible with large-scale production needs</td>
<td>0</td>
<td>-3 (Scale-up not yet determined; material quantities available)</td>
<td>Demonstrate ability to scale production.</td>
</tr>
<tr>
<td>Compatible with quality and uniformity standards</td>
<td>0</td>
<td>-2 (Reproducible quality not fully demonstrated)</td>
<td>Demonstrate ability to maintain standards during large-scale production.</td>
</tr>
<tr>
<td>Licensibility (includes consideration for required enrichment)</td>
<td>0</td>
<td>-4</td>
<td>Determine if fabrication facility and associated license can be modified to accommodate the required enrichment.</td>
</tr>
</tbody>
</table>

**Considerations:**
- **Millions ft cladding/yr, ~300 million fuel pellets per year**
- **Economics: cost of raw materials, fabrication**
- **Material availability**
- **Current fabrication plant enrichment limits**
### Example Evaluation (Hypothetical): Normal Operation and AOOs

<table>
<thead>
<tr>
<th>Performance Attribute</th>
<th>Benefit</th>
<th>Vulnerability</th>
<th>Recommended Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burnup (cycle length)</td>
<td>0 (same as UO$_2$)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Thermal hydraulic interaction</td>
<td>3 (improved)</td>
<td>0</td>
<td>Expected to be equivalent to current fuel; need verification</td>
</tr>
<tr>
<td>Reactivity control systems interaction</td>
<td>0</td>
<td>-2</td>
<td>Good at BOL, need post-irradiation data</td>
</tr>
<tr>
<td>Mechanical strength / ductility (BOL, EOL)</td>
<td>2</td>
<td>-3</td>
<td>Good at BOL, need post-irradiation data</td>
</tr>
<tr>
<td>Thermal behavior</td>
<td>3 (limited data)</td>
<td>-3</td>
<td>Need additional data</td>
</tr>
<tr>
<td>Chemical compatibility (fuel, coolant), stability</td>
<td>0</td>
<td>-3</td>
<td>Requires demonstration under irradiation; possible coolant chemistry changes</td>
</tr>
<tr>
<td>Fission product behavior</td>
<td>2 (limited data)</td>
<td>-3</td>
<td>Requires long-term demonstration</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Performance Attribute</th>
<th>Benefit</th>
<th>Vulnerability</th>
<th>Recommended Action</th>
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</thead>
<tbody>
<tr>
<td>Thermal hydraulic interaction</td>
<td></td>
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<tr>
<td>Thermal behavior (conductivity, specific heat, melting)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical compatibility (e.g. oxidation behavior)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fission product behavior</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Combustible gas production</td>
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### Considerations:
- Prompt reactivity insertion
- Post-DNB behavior
- Loss of coolant conditions
- Thermal shock
- Steam reactions (>1000°C)
### Example Evaluation (Hypothetical): Severe Accidents (Beyond DBA)

<table>
<thead>
<tr>
<th>Performance Attribute</th>
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<th>Vulnerability</th>
<th>Recommended Action</th>
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<tbody>
<tr>
<td>Mechanical strength / ductility (BOL, EOL)</td>
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<tr>
<td>Thermal behavior (conductivity, specific heat, melting)</td>
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</tr>
<tr>
<td>Chemical compatibility (inc. high T steam reaction)</td>
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<tr>
<td>Fission product behavior</td>
<td></td>
<td></td>
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**Considerations:**
- **Thermal shock**
- **Chemical reactions**
- **Combustible gas release**
- **Long-term stability in degraded state**
## Example Evaluation (Hypothetical): Used Fuel Storage / Transport /Disposition

<table>
<thead>
<tr>
<th>Performance Attribute</th>
<th>Benefit</th>
<th>Vulnerability</th>
<th>Recommended Action</th>
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<tr>
<td>Mechanical strength / ductility</td>
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<tr>
<td>Fission product behavior</td>
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</tbody>
</table>

**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 UO₂ – 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

Nuclear Energy

- 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?

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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.

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

- 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

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

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

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)
- University of Illinois
- University of Tennessee
- Texas A&M University
- Georgia Tech
- MIT

**Nuclear Industry**
- General Electric
- Westinghouse
- AREVA
- EPRI
### Summary of Major DOE-funded ATF Projects

<table>
<thead>
<tr>
<th>Lead Organization</th>
<th>Category – Major Technology Area</th>
<th>Additional Collaborators</th>
</tr>
</thead>
</table>
| 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\(_2\)O\(_3\), +SiC)                              | U. Wisconsin, U. Florida, SRNL, TVA, Duke                                                 |
|                                  | **Cladding:** Coated Zr-alloys (protective materials, MAX phase)                               |                                                                                          |
| Westinghouse (FOA, NEUP)          | **Fuel:** U\(_3\)Si\(_2\), and UN+U\(_3\)Si\(_2\) fuel                                       | General Atomics, EWI, INL, LANL, MIT, TAMU, Southern Nuclear Operating Company           |
|                                  | **Cladding:** Coated Zr-alloy; SiC concepts                                                    |                                                                                          |
| 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 |
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 improved response to off-normal conditions: AOOs, DBAs (RIA, LOCA, SBO) and BDBAs
- Increased “coping time” 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
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.
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.