Fuel Development and Qualification

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Current Fuel Development and Qualification Activities at INL

- **Advanced Reactors**
  - Tristructural isotropic (TRISO) Fuel for modular high temperature gas-cooled reactors
  - Metallic Fuel for sodium fast reactors including transmutation fuel
- **Light Water Reactors**
  - Accident Tolerant Fuels
- **High Performance Research Reactors**
  - LEU Plate Fuel

Fuel Development and Qualification Activities

[adapted from D.C. Crawford, D. L. Porter, S. L. Hayes, M. K. Meyer, D. A. Petti and K. Pasamehmetoglu, "An Approach to Fuel Development and Qualification," *Journal of Nuclear Materials*, 371 (2007) 232-242.]

Selection of Potential Fuel Candidates

- Early scoping studies
- Establish criteria and develop options
- Very limited knowledge at this stage

Lab Scale: Concept Definition and Feasibility

- Potential range of fuel types
- Goal is to downselect and establish a reference fuel design
- Limited knowledge at this stage
- Develop fuel performance model

Improvement and Scaleup

- Take best results from lab scale
- Scale up fabrication process to pilot or engineering scale
- Optimization of process
- Testing at this stage is sometimes termed performance demonstration
- Validation of fuel fabrication processes and specifications
- Improve fuel performance models

Qualification and Demonstration

- Test large quantities of fuel rods or particles
- Fabrication process is mature
- Statistical demonstration of performance
- Bound reactor conditions and include margin
- Validation of fuel performance models

Activities in Each Phase and Nominal Timelines: 5 to 7.5 Years for Each Phase

Fabrication

Design of Irradiation Capsule

1.5 years

Irradiation

2 - 3 years

Post-irradiation Examination

Transient/Safety Testing

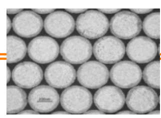
1.5 - 3 years

Specific details on timelines will depend on technology details and specific requirements of irradiation and safety testing

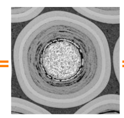
Scaling Up Kernel Production, Coating, Overcoating, and Compacting Processes to Create a Pilot Line

Lab Scale

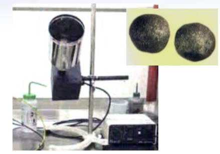
Sol-Gel Kernel Production



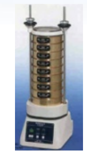
Lab Scale 2-inch CVD Coating (60 g charge)



Prepare Matrix



Overcoat and Dry

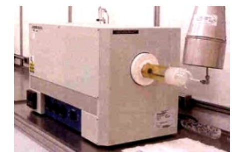


Sieve

Table

Riffle

Compact



Carbonize

Heat Treat

Engineering Scale

Kernel Forming and Drying

Industrial Scale 6-inch CVD Coating (2 kg charge)

Dry Mix and Jet Mill Matrix

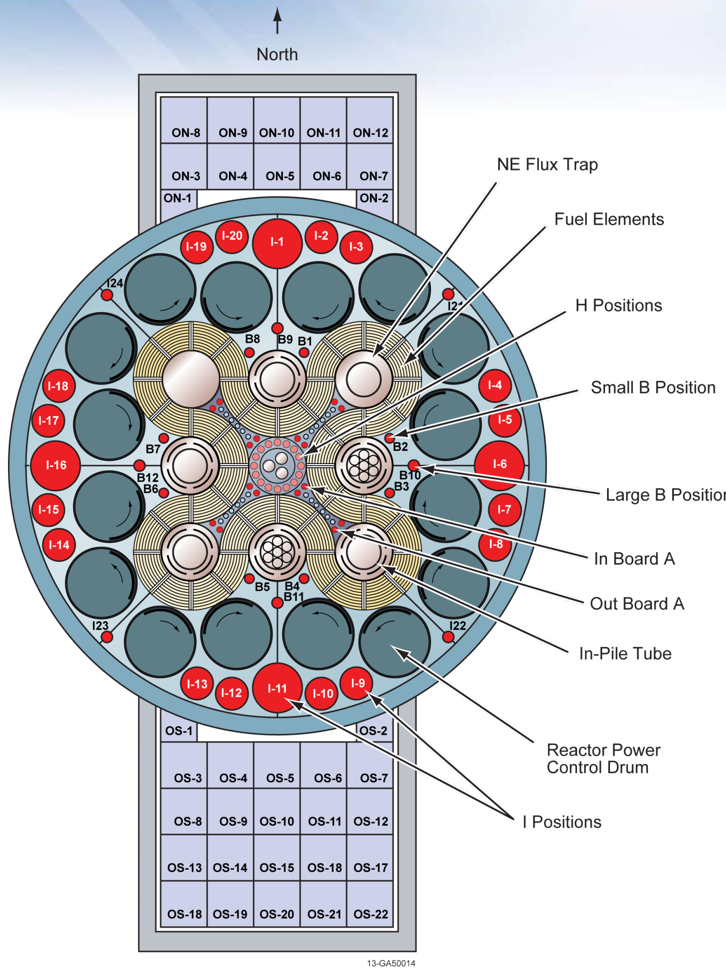
Granurex Overcoat and Dry

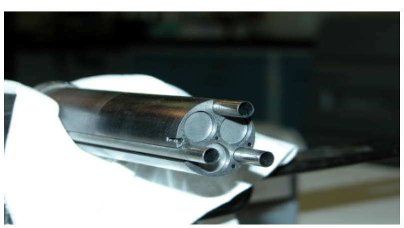
Hot Press Compact

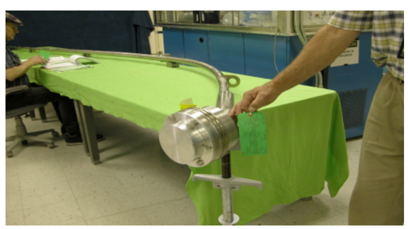
Carbonize + Heat Treat in one Sequential Process

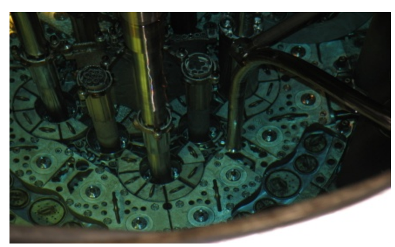
Irradiation Testing

- **Advanced Test Reactor (ATR) is the workhorse for irradiation testing in the US**
- **Small, medium and large flux volumes are available for testing**
- **A range of tests and conditions can be establishing to meet user needs:**
  - Drop in capsule
  - Instrumented lead
  - In-pile loop with controlled chemistry and flow
  - On-line fission gas monitoring



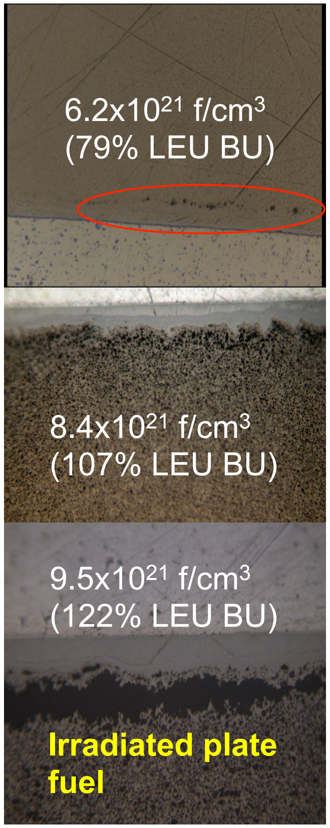


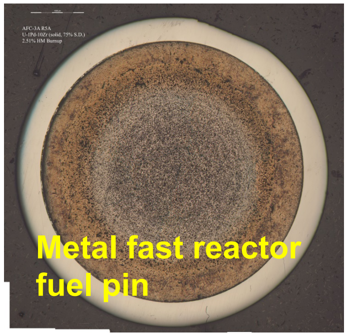


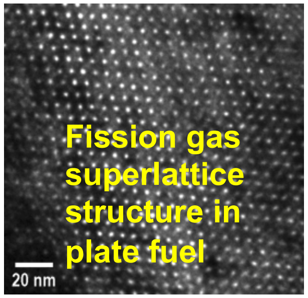


Post-irradiation Examination

- **Hot Fuel Examination Facility (HFEF) is used to examine a range of irradiated fuels using specially designed rigs and equipment to make requisite measurements**
  - Metrology and dimensional change
  - Metallography
  - Fission gas release
  - Gamma scanning
  - Radiography

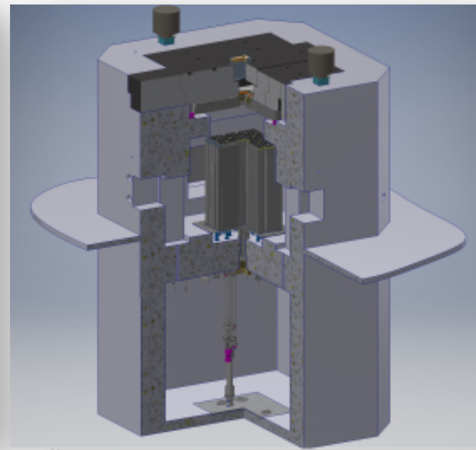


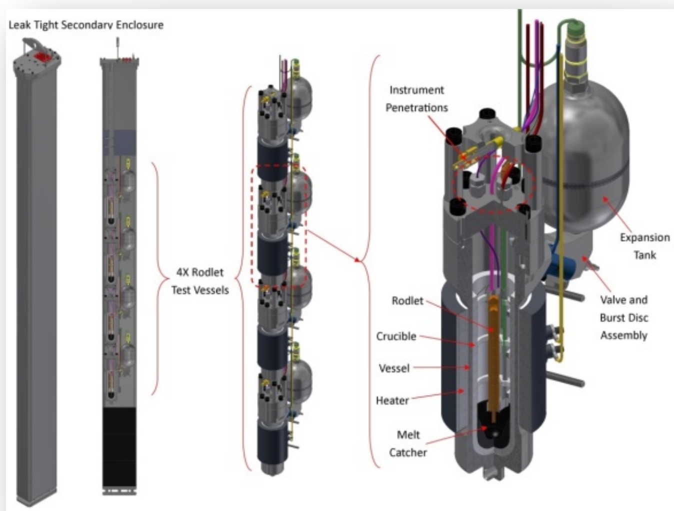


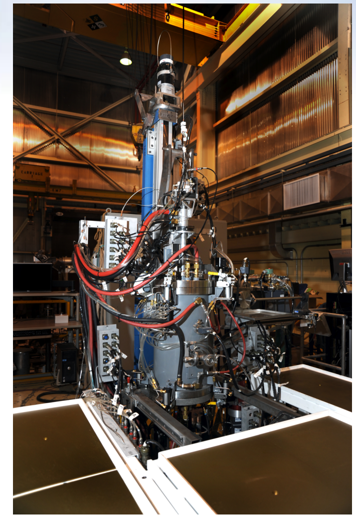


Transient and Safety Testing

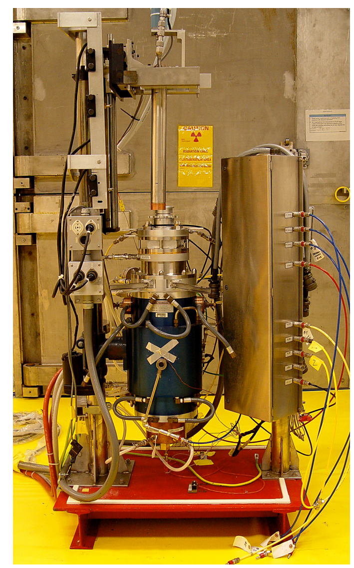
TREAT at INL





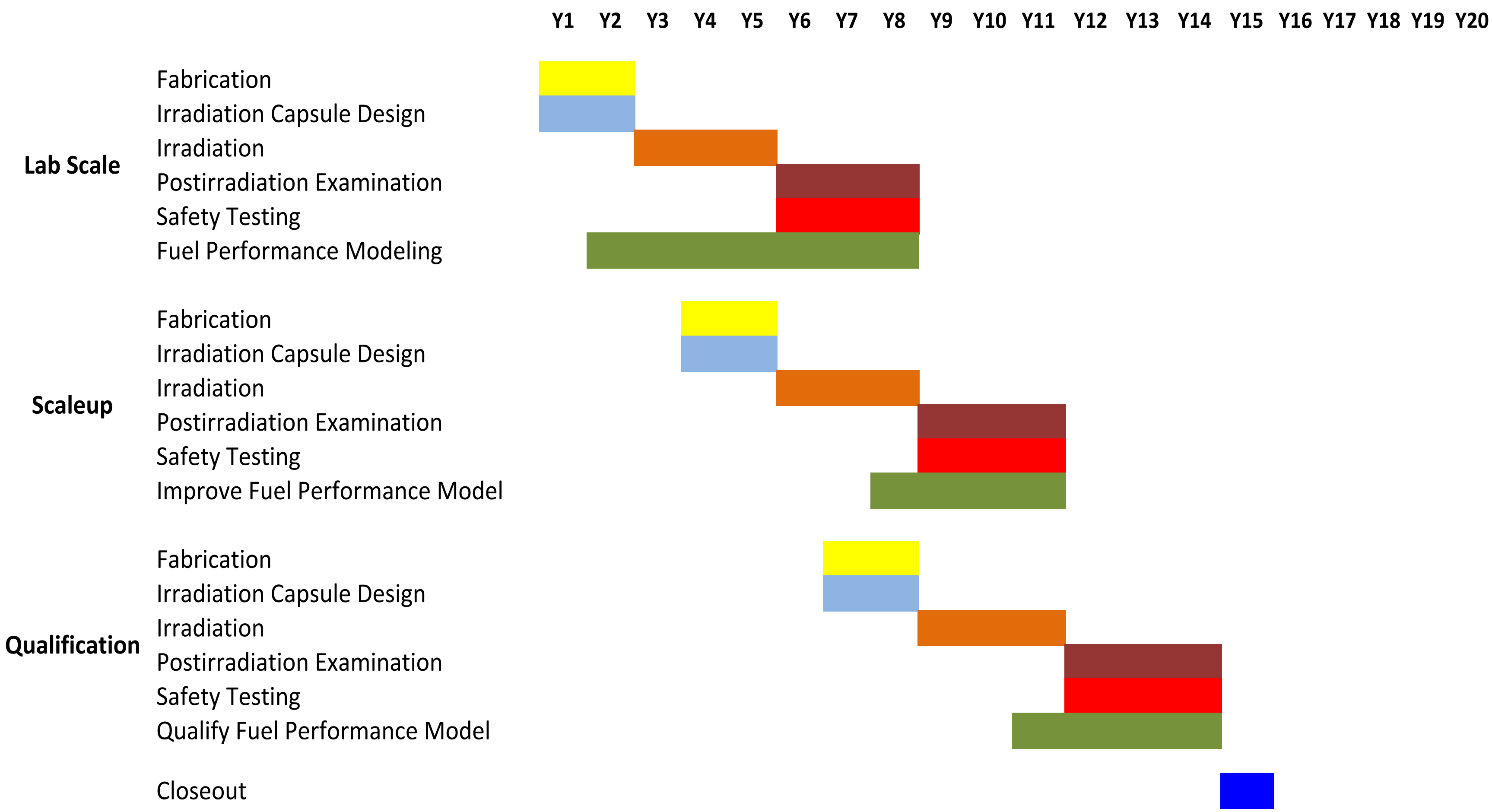


INL Furnace

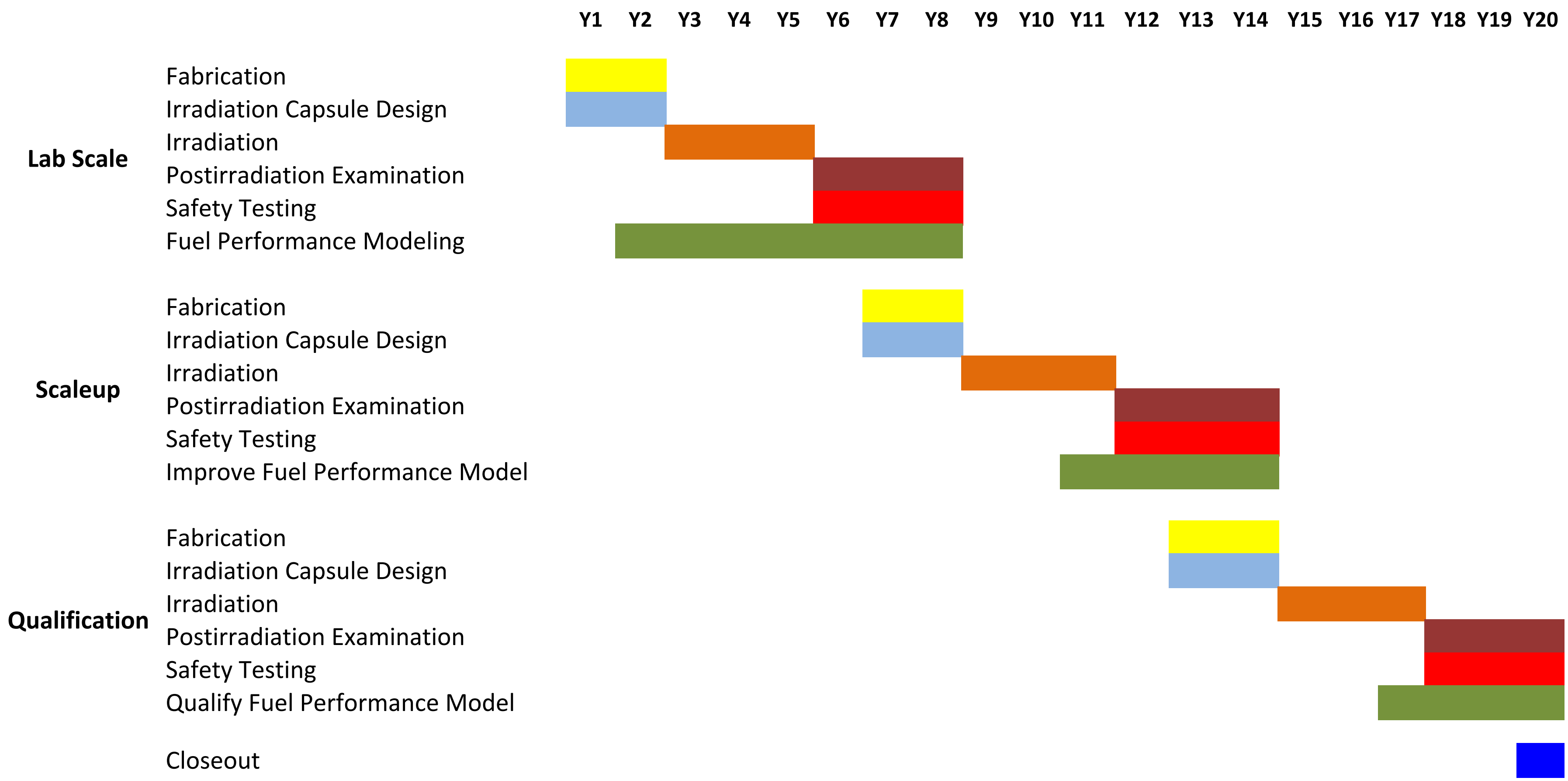


ORNL Furnace

Overall schedule to qualify fuel: High degree of confidence success oriented schedule with limited feedback between phases. No resource limitations. 15 years to qualify fuel once fuel form is established



Overall schedule to qualify fuel: Lower degree of confidence. Feedback from PIE of previous phase necessary to proceed to next phases. 20 years to qualify fuel once fuel form is established. If unanticipated results are obtained it could easily delay another 5 years.



Where is Each Fuel System on this Development Trajectory?

Selection of Potential Fuel Candidates

Lab Scale: Concept Definition and Feasibility

Improvement and Scaleup

Qualification and Demonstration

Accident Tolerant Fuels Span a range depending on specific candidate

Metallic Fuel with Transmutation additions for SFR

TRISO for modular HTGRs

Metallic Fuel for SFRs

U-Mo for Research Reactors

Accident Tolerant Fuels

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.

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

Enhanced Tolerance to Loss of Active Core Cooling

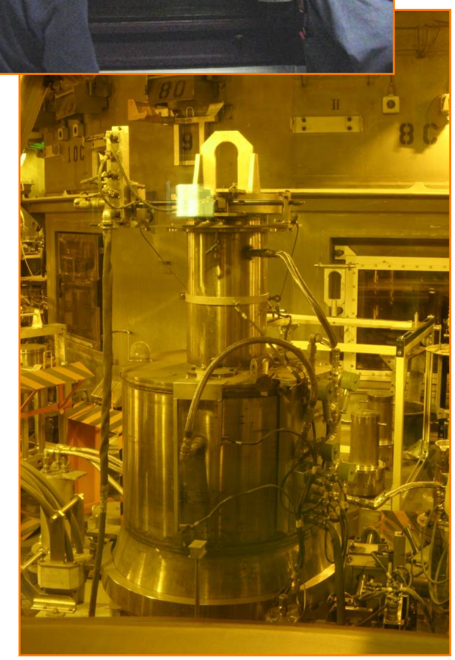
Improved Cladding Properties
- Resilience to clad fracture
- Robust geometric stability
- Thermal shock resistance
- Higher cladding melt temperature
- Minimized fuel - cladding interactions

Enhanced Retention of Fission Products
- Gaseous fission products
- Solid/liquid fission products

- Example include: SiC cladding, FeCrAl cladding, coatings on Zircaloy cladding, UO2 fuel pellets with special additives to improve thermal performance, fully ceramic matrix TRISO coated particle fuel

SFR Transmutation Fuels with Minor Actinides (MA) and Rare Earth (RE) Fission Products

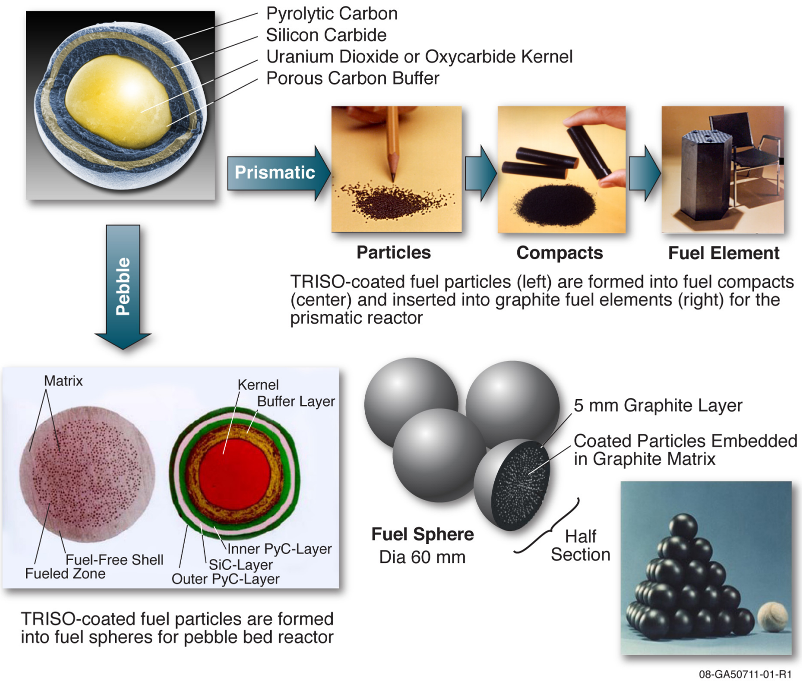
- Unique Features of SFR Transmutation Fuels
  - Pu content, which depending on conversion ratio selected may be higher than historic database (with corresponding decrease in U content)
  - Minor actinides (Am, Np, Cm) present in significant quantities
  - Rare earth fission product (La, Pr, Ce, Nd) carry-over from recycle step may be significant
- Gives Rise to Challenges and Unknowns
  - Need for remote fuel fabrication
  - Need for new fabrication methods (e.g., due to Am volatility, waste minimization, etc.)
  - Effects on fuel performance must be determined



UCO TRISO-coated Particle Fuel

- Currently uranium oxycarbide TRISO fuel is being qualified in the US
- Excellent fuel performance under normal operating conditions at high burnup (up to 20 atom%) and high temperatures (up to 1250°C)
- Excellent fuel performance under postulated accidents at high temperature (1600-1800°C)
- Key needs:
  - Characterization and understanding fission product retention/transport in TRISO coatings (SiC and pyrolytic carbon) and graphite

TRISO Fuel for High Temperature Gas-cooled Reactors

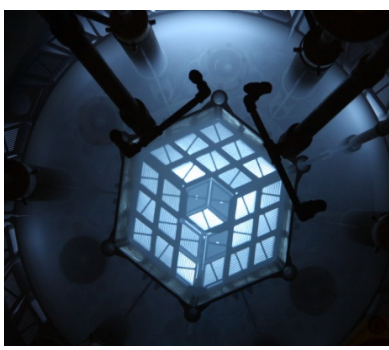


TRISO-coated fuel particles (left) are formed into fuel compacts (center) and inserted into graphite fuel elements (right) for the prismatic reactor

TRISO-coated fuel particles are formed into fuel spheres for pebble bed reactor

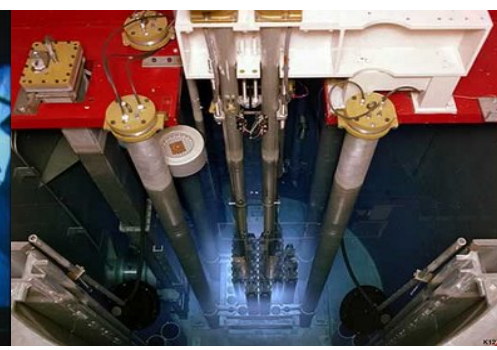
USHPRR Fuel Development Program

- **The USHPRR Project aims to eliminate more than 200 kg of HEU from commerce annually by converting five research reactors and one associated critical assembly**
- **Goal: develop LEU fuels that are:**
  - Qualified
  - Commercially available
  - Suitable
  - Acceptable
- **Single 'Base Monolithic' fuel type to allow conversion of 4 U.S. High Performance Research Reactors (MURR, NBSR, MITR, ATR) and 1 critical facility (ATR-C)**

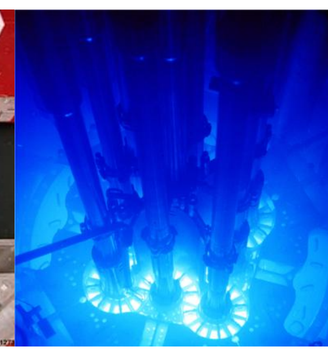


MITR

MURR



NBSR



ATR

HFIR

Summary and Conclusions

- **Fuel development and qualification programs go through four major steps**
  - Selection of potential fuel candidates
  - Lab scale concept feasibility
  - Improvement and scaleup
  - Qualification and demonstration
- **It can take 15 to 25 years to qualify a new fuel form depending on its maturity/level of confidence in the fuel form**
- **Significant efforts are required in terms of fuel fabrication scaleup, irradiation testing, post-irradiation examination and safety testing to provide the data necessary for reactor design and safety analysis**

Backups

Advanced Modeling and Simulation

- Advances in computer modeling can accelerate development and deployment of reactor systems
- Less "trial and error" experimentation
- Modeling of fuel and materials at the meso-scale is key part of this advanced modeling effort
- Validation of the models will require unique data at the meso-scale
- Microstructural evolution of fuel, cladding and structural materials under irradiation
- Fission gas evolution and transport in uranium based fuel
- Thermomechanical behavior and physiochemical interactions at fuel/clad interface
- Fission product chemistry evolution as a function of burnup and temperature