

# *Affordable Development and Optimization of CERMET Fuels for NTP Ground Testing*

*Nuclear Cryogenic Propulsion Stage (NCPS)  
Advanced Exploration System (AES) Project*



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**Nuclear and Emerging  
Technologies for Space (NETS)  
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# Outline

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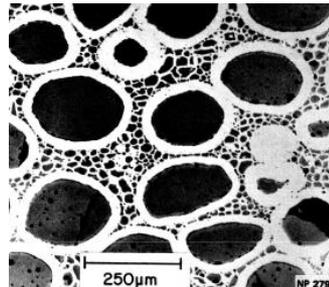
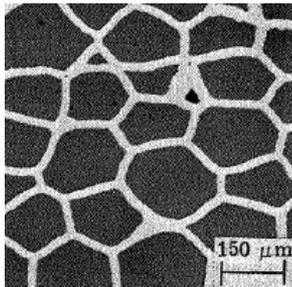
- Historical CERMET Fuel Fabrication and Test Data
- AES FY12-14 Fuel Materials Development
- Development and Qualification Approach
- AES FY15-17 Plan
  - Materials and Process Optimization
  - Hot Hydrogen Screening
  - Material Property and Irradiation Testing
  - Cost/Schedule
- Summary



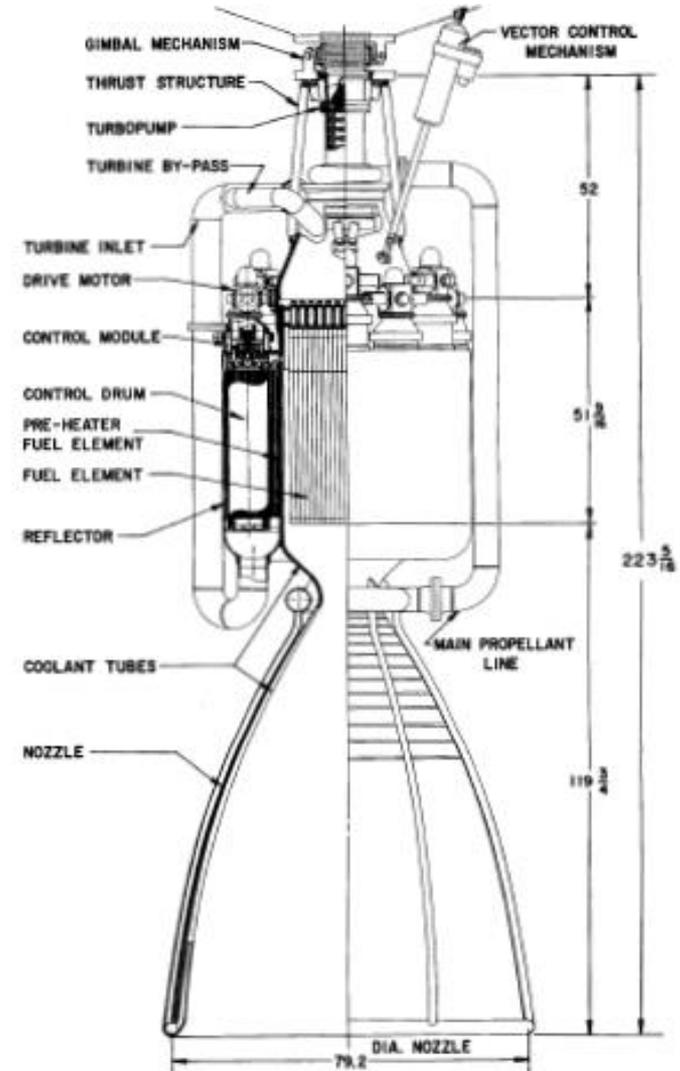


# CERMET Fuel Materials

- CERMET fuels consist of a metal matrix with embedded ceramic fuel particles
  - W matrix (high melting point, H<sub>2</sub> compatibility)
  - UO<sub>2</sub>, UN, (U,Zr)CN fuel particles
- Developed in 1960's as an alternate to graphite based fuels
  - Long operating life (>10 hrs, 2500 C)
  - Multiple restart capability at high specific impulse (800-900 sec)
- Improved fission product retention
- Metal phase improves toughness



W - light phase, UO<sub>2</sub> - dark phase



ANL 2000MW CERMET Engine



# W-UO<sub>2</sub> Materials and Process

- Current work is based on ANL and GE710 Programs
  - Detailed specifications developed for GE710
  - Extensive capabilities that do not currently exist
- No qualified fuel fabrication processes
  - Key risk for NTP
  - Must recapture and certify process
- CERMET fuel loss mechanisms are known
  - Vaporization of UO<sub>2</sub>
  - Diffusion through pores and cracks
  - Differences in CTE of W matrix and UO<sub>2</sub>
  - Thermal decomposition of fuel/matrix
- Proven M&P approaches to inhibit fuel loss
  - Complete surface cladding with tungsten
  - W coated spherical UO<sub>2</sub>
  - Addition of oxide stabilizers to UO<sub>2</sub>

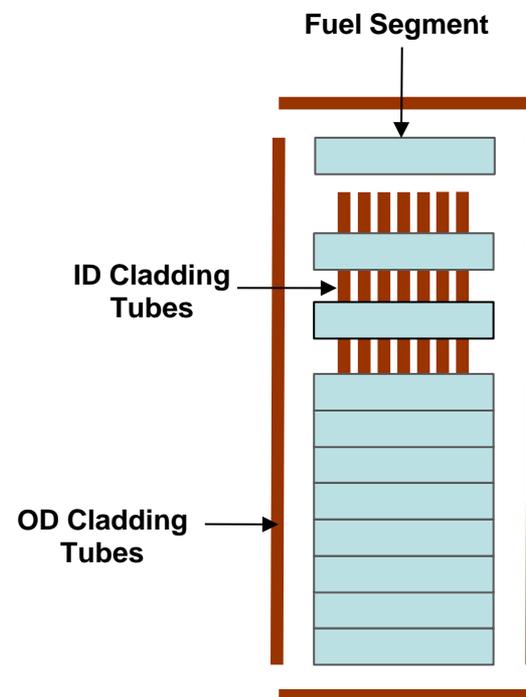
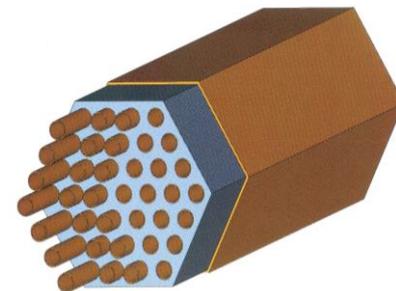


W-UO<sub>2</sub> CERMET Samples  
fabricated during ANL Program



# GE710 W-UO<sub>2</sub> Fuel Fabrication

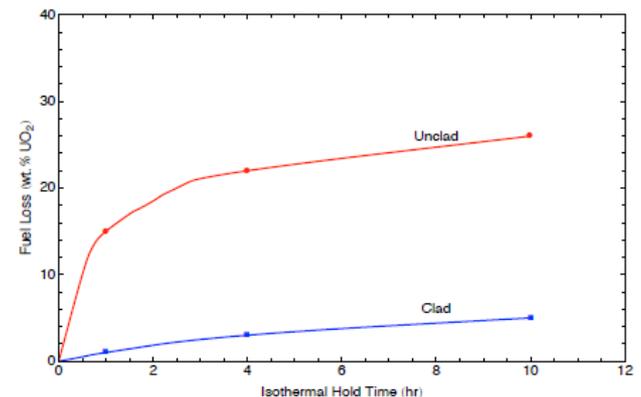
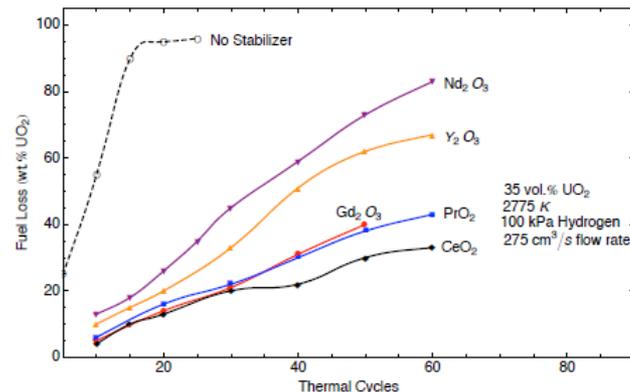
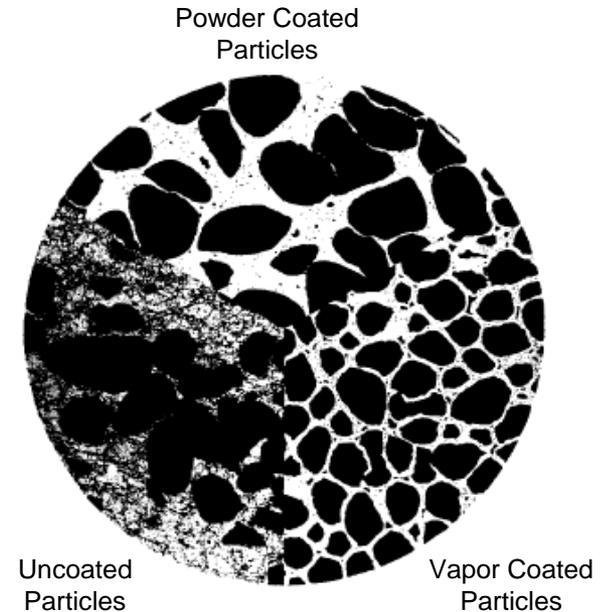
- Powder processing
  - Sieving, weighing, and blending
  - Isostatic pressing of fuel segments (wafers)
  - Hydrogen sintering (consolidation of segments)
- Fuel segment machining
  - Face grinding of fuel segments
  - Channel hole drilling
- Cladding/component fabrication
  - EDM for cladding and HIP can components
  - End plates, inner/outer cladding tubes
- Assembly and bonding process
  - Stacking of fuel segments
  - Insertion of cladding tubes
  - E-beam welding of HIP cans
  - HIP bonding of integrated assembly
- Successfully fabricated and tested numerous elements





# W-UO<sub>2</sub> CERMET Test Data

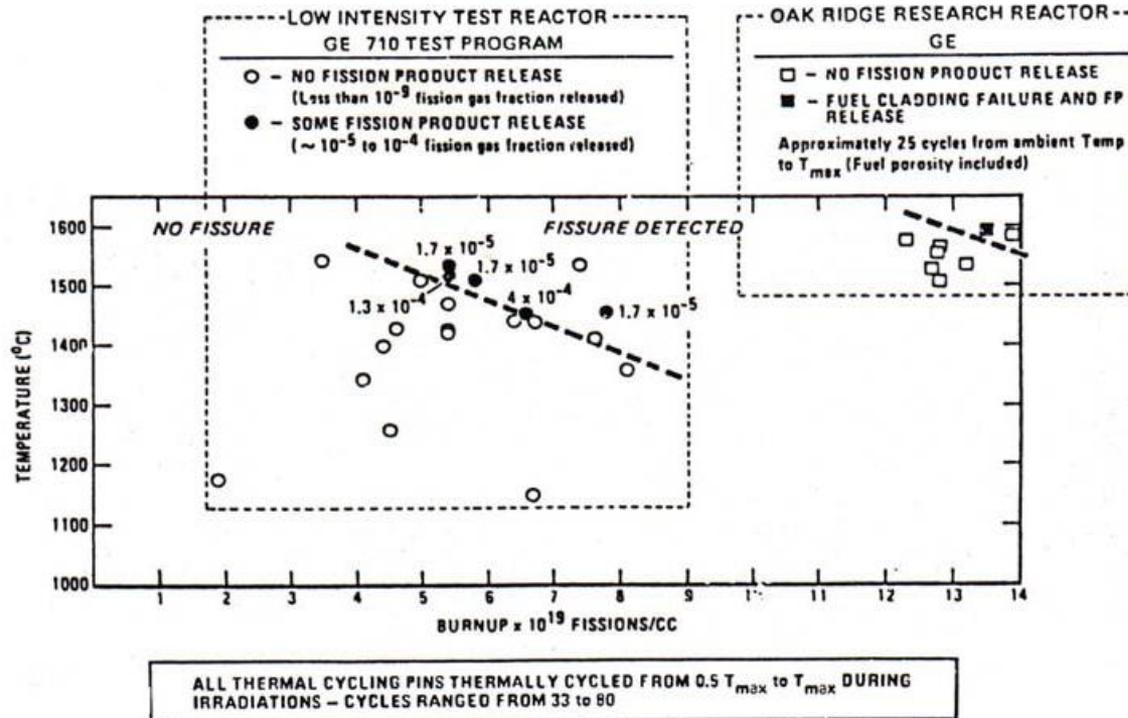
- Limited data available with a large variation in starting materials, processing, and testing
- Surface claddings enhance fuel retention and thermal cyclic life
  - 27 wt% loss in unclad vs. 3 wt% for clad samples
- Particle coatings shown to improve UO<sub>2</sub> distribution and provide continuous W matrix
  - 23 wt% loss at 2500 C for 2 hours vs. 0.8 wt% loss of samples with W coated UO<sub>2</sub>
- Addition of oxide stabilizers decrease fuel loss by preventing the reduction of UO<sub>2</sub>



Charts courtesy of Jon Webb, "Literature Review of Historical W-UO<sub>2</sub> Fabrication and Testing Efforts", Idaho National Laboratories, Internal Document.



# GE710 Irradiation Testing



- No in-pile testing at current prototypic NTR conditions
- Majority of samples tested at low temps and longer durations
  - 1500C, 1000's of hours
- Fission gas containment to burn up levels exceeding  $9 \times 10^{19}$  fissions/cm<sup>3</sup>
  - Equivalent to dozens of Mars missions

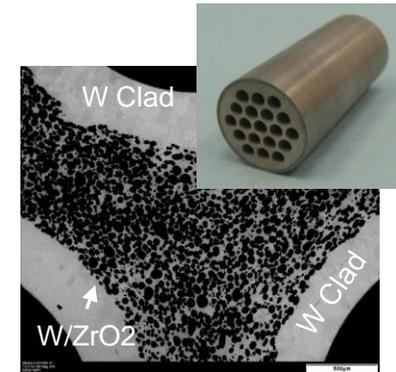
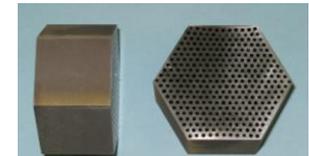
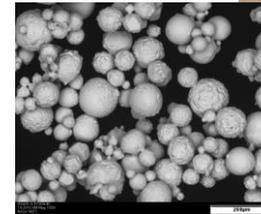


# FY12-14 NCPS CERMET Development

- UO<sub>2</sub> feedstocks (ORNL sol gel, CSNR alginate)
- Powder handling (glove box sieving, blending, filling)
- CVD W coated UO<sub>2</sub> spheres, W claddings
- Hot Isostatic Pressing (HIP)
- Post Machining (sectioning, grinding)
- Compact Fuel Element Testing (CFEET)
- Successful fab/test of W-UO<sub>2</sub> sample



W-UO<sub>2</sub> Samples



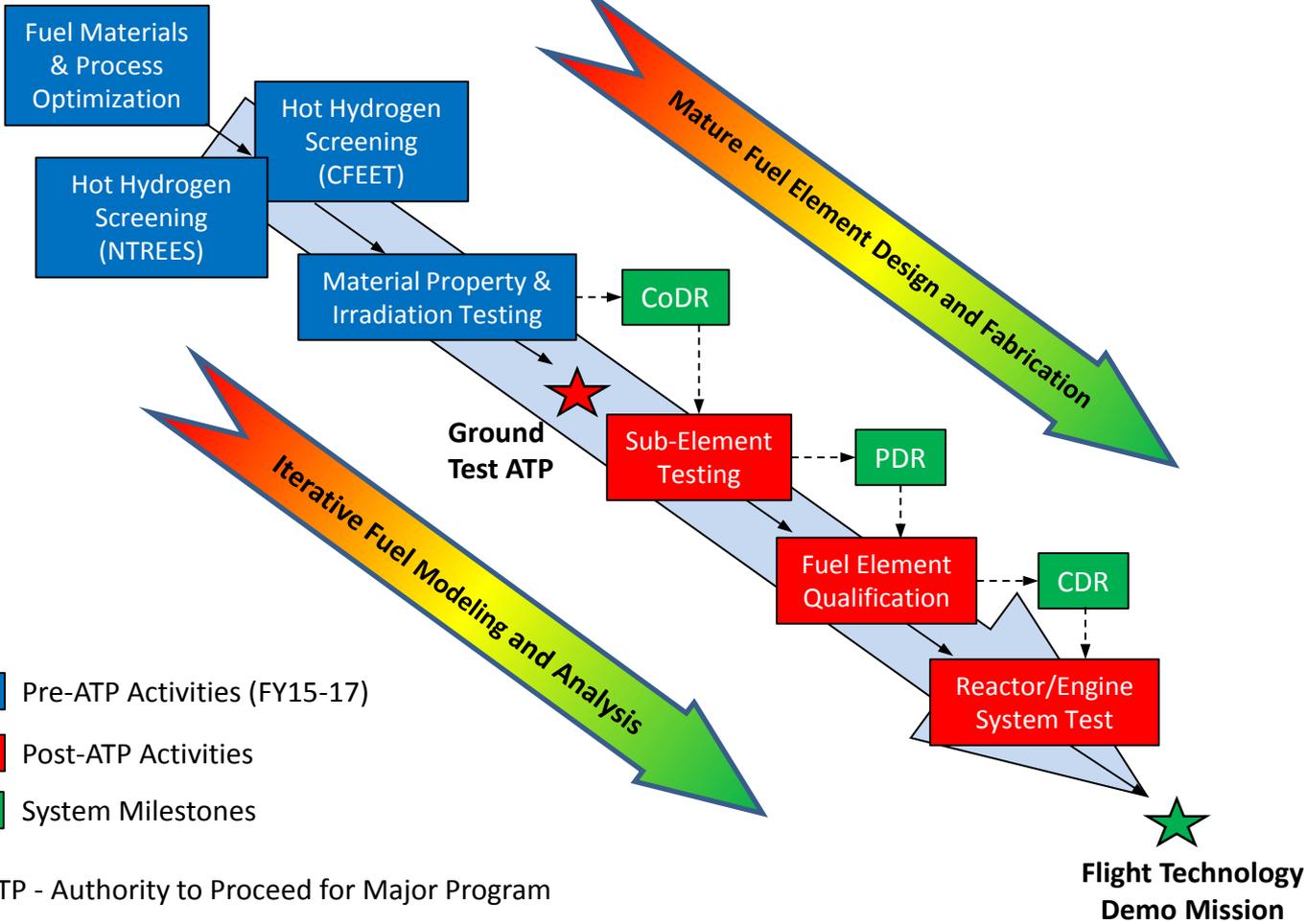
Dedicated Depleted Uranium Labs





# CERMET Fuel Development Path

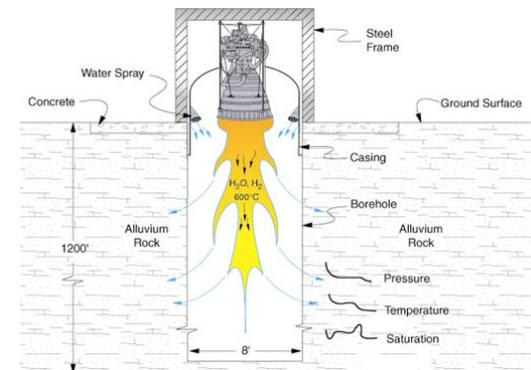
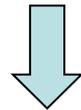
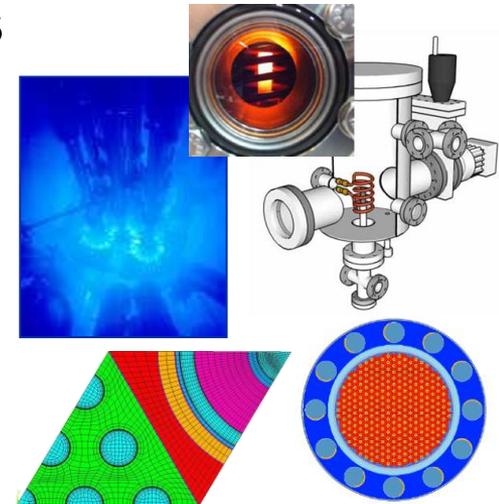
★ AES FY12-14  
Successful Fuel Element Fab/Test





# Fuel Development and Qualification

- “Certify” fuel material and fabrication process
- Separate effects testing
  - Thermal chemical and cyclic stability in H<sub>2</sub>
  - Irradiation for fission tolerance and retention
- Combined effects testing (\$\$\$\$)
  - Radiation, temperature, H<sub>2</sub>, and pressure
  - Subscale HFIR or ATR
  - Single element and/or bundle in ATR
  - Nuclear Furnace?
- High cost for prototypic testing
- Affordable option-separate effects and fuel modeling to eliminate combined effects?
  - What are the risks for engine ground test?





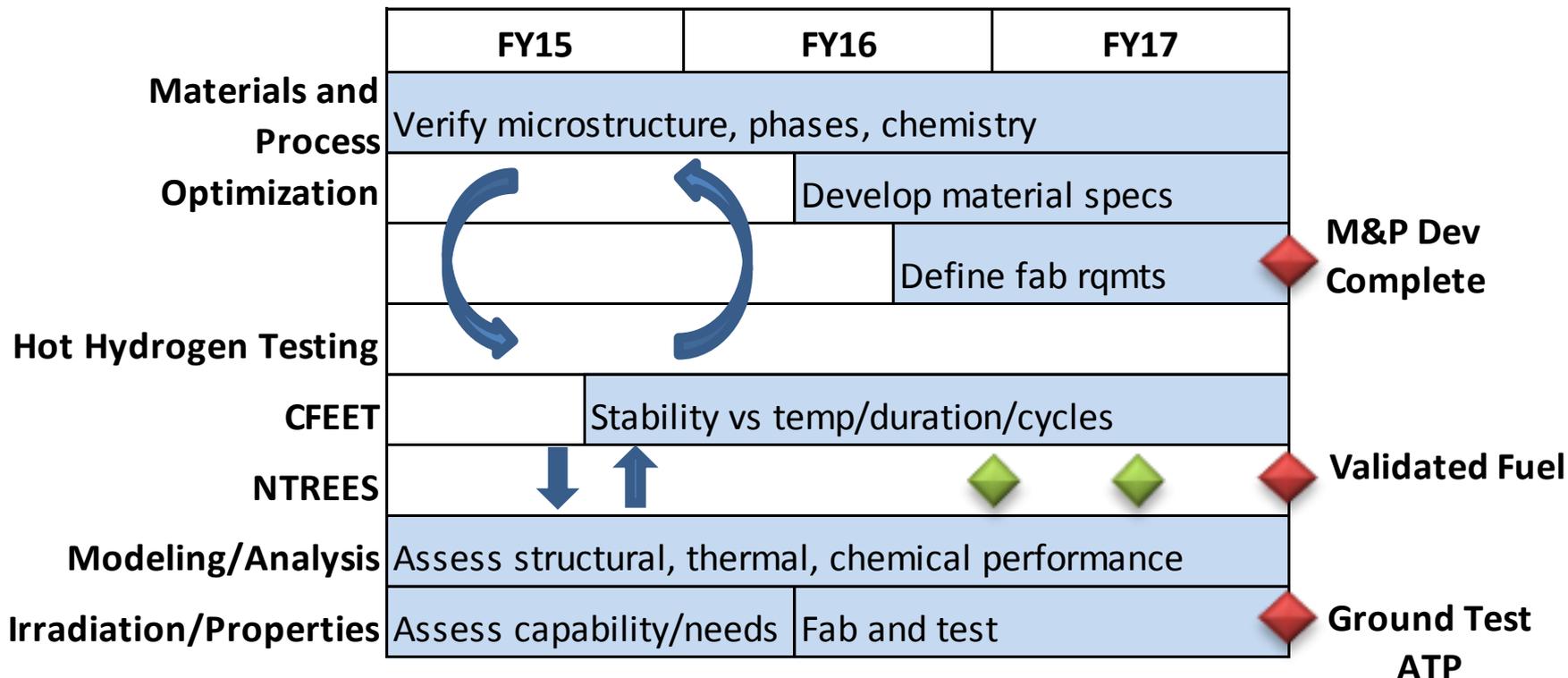
## FY15-17 Development and Optimization

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- Goal is to mature fuel for future ground test program
  - Enable qualification and production in FY17-20??
  - Develop basis for performance, production cost and schedule
- Complete M&P development and characterization
  - Understand processing-microstructure-property relationships
  - Extensive subscale screening in H2
  - Baseline materials, properties, and specifications
  - Demonstrate prototypical performance of fuel
- Most of the capabilities currently exist to meet FY15-17 goals
  - May require upgrades for LEU (HEU facility does not exist for fuel fab)
- Limited material properties and irradiation screening
- Testing and modeling to anchor designs & performance
  - Structural, thermal, chemical, and neutronics
  - Separate effects testing to validate



# CERMET Fuel Development Timeline

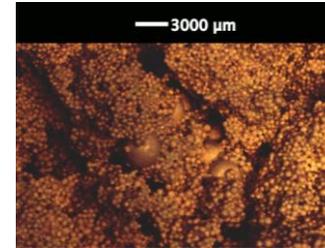


- Iterative M&P optimization and subscale H2 screening
- Continuous improvement and validation of modeling
- Validation of fuel element design and performance

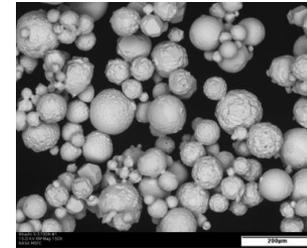


# CERMET Fuel Development Tasks

- UO<sub>2</sub> feedstock (spheres)
  - Sol Gel (ORNL)
  - Ammonium Alginate (CSNR)
  - Develop particle size constraints, yields, etc.
- W coated UO<sub>2</sub> (MSFC)
  - Optimize processing of various size UO<sub>2</sub> spheres
  - Develop production approach
- W-UO<sub>2</sub> fuel segment consolidation
  - Hot Isostatic Press (MSFC)
    - Full length net shape consolidation
    - Integral claddings
  - Spark Plasma Sintering (CSNR)
    - Similar to GE710 but improved consolidation
    - Stacked and bonded segments/claddings
    - Net shape fabrication of cooling channels

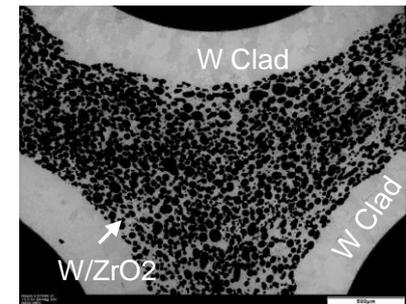


(CSNR)



(ORNL)

UO<sub>2</sub> Spheres



W Clad CERMET (MSFC)

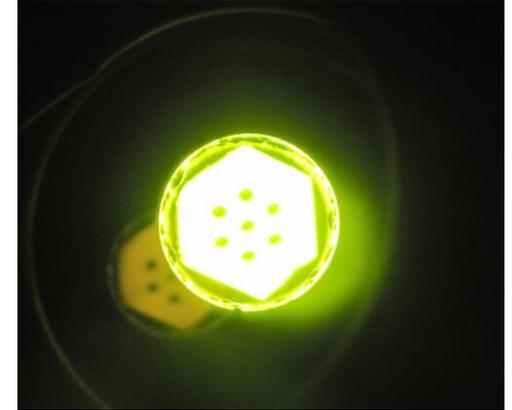


UO<sub>2</sub> CERMET (CSNR)



# CERMET Fuel Development Tasks

- Hot hydrogen testing (MSFC)
  - Subscale screening in CFEET
  - Full length validation in NTREES
- Material characterization (MSFC, INL)
  - Consolidated microstructure, phases, density
  - Chemistry
  - Fuel loss and migration
- Material properties (MSFC, INL, Industry)
  - Thermal expansion, conductivity (diffusivity, specific heat)
  - Tensile, modulus, bend ductility
- Production facility study (NASA, INL, Industry)
  - Process needs, location, facility requirements, etc.



H<sub>2</sub> Testing of W-UO<sub>2</sub> sample at MSFC



# FY15-17 Irradiation Testing

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- Irradiation may not be a key driver in fuel failure/design
  - GE710 fuel “qualified” for 100 hours at 2148 C with minimal testing
  - Must be verified to understand risk
  - Combined effects testing required at some point for qualification
- Irradiation testing (ORNL, INL, or University)
  - LEU or HEU? (need fission heating)
  - Subject samples to nuclear environment
  - Evaluate fission product tolerance and containment
  - Dimensional stability and swelling
  - Perform post test metallographic evaluation
- Limitations
  - Temperature, pressure, and H<sub>2</sub> environment
  - How much can we really learn?
- Goal is to develop basis for future qualification



# Cost/Risks

- **Costs**

- Costs comparable to current AES effort
- More funding for DOE and Industry participation
- Characterization capability does not exist at NASA

- **Risks**

- RF heating/NTREES may not work for validating fuel element
- Monolithic designs not feasible (may require segmented design)
- LEU/HEU required for irradiation testing (no fabrication facility)

	<u>FY15</u>	<u>FY16</u>	<u>FY17</u>	
<b>UO2 feedstocks</b>	850	850	850	
<b>Fuel Segment Consolidation</b>	750	750	750	<u>\$M</u>
<b>Characterization</b>	650	650	650	<b>Total FY15-17 CERMET</b> 15.9
<b>Material Properties</b>	450	600	600	<b>Total FY12-14 CERMET</b> 12.3
<b>Irradiation Testing</b>	150	1150	1150	
<b>Modeling/Analysis</b>	600	600	600	<u>\$M</u>
<b>Hot Hydrogen Testing</b>	475	625	625	<b>NASA</b> 8.2
<b>Industry</b>	500	500	500	<b>DOE/Industry</b> 7.7
	<u>4425</u>	<u>5725</u>	<u>5725</u>	



# Summary

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- Materials, processing, and fuel failure mechanisms are defined from previous ANL and GE710 programs
- Demonstrated fabrication and testing of W-UO<sub>2</sub> samples during current AES FY12-14 effort
  - Developed critical capabilities and technologies
- AES FY15-17 CERMET development and optimization
  - Optimize materials and processes, hot hydrogen screening, irradiation and material properties testing to form basis of ground test program
- What makes this affordable?
  - Existing facilities/capabilities to complete optimization
  - Limited testing to validate fuel and obtain critical irradiation/property data
  - Exploratory irradiation testing
    - Defer expensive in-pile testing until qualification approach is clear
  - Separate effects testing and modeling to evaluate the need for combined effects testing in prototypic reactor conditions



## Acknowledgements

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- Jim Werner – Idaho National Laboratory (INL)

Questions?