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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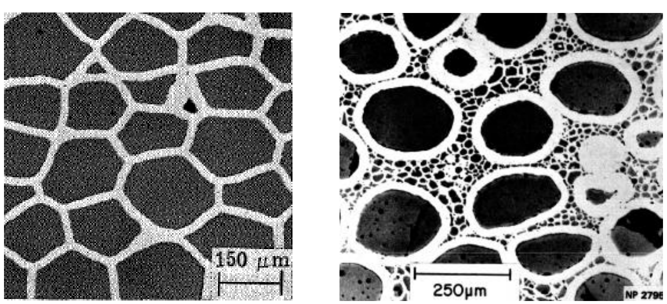
Outline

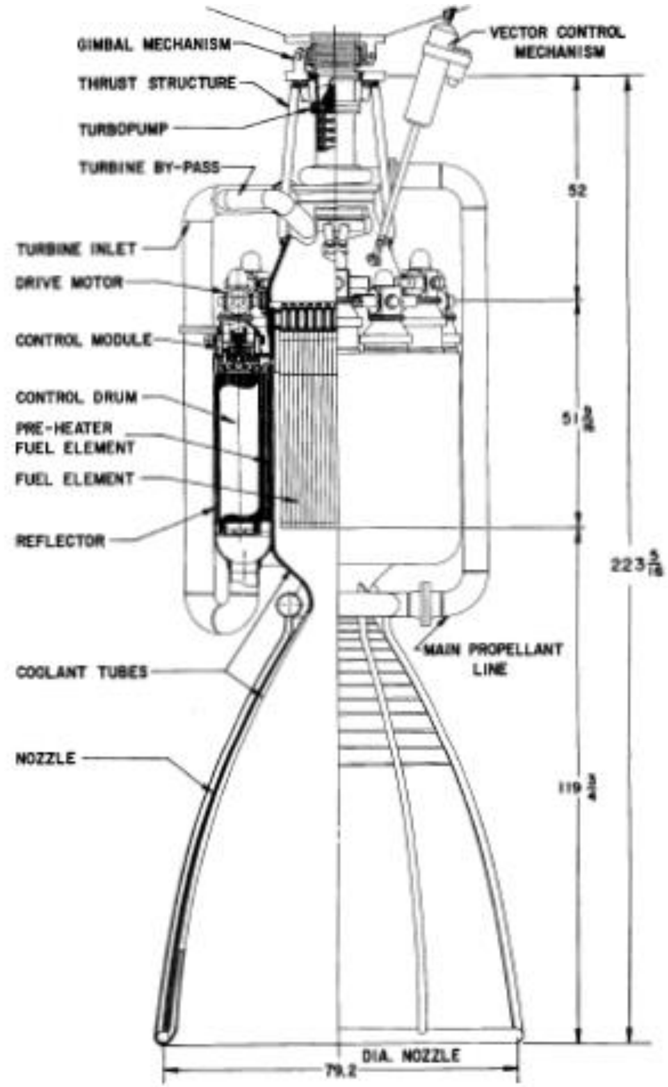
- Historical CERMET Fuel Fabrication and Test Data
- AES FY12-14 Fuel Materials Development
- Development and Qualification Approach
- AES FY15-17 Plan
  - Materials and Process Optimization
  - Hot Hydrogen Screening
  - Material Property and Irradiation Testing
  - Cost/Schedule
- Summary

CERMET Fuel Materials

- CERMET fuels consist of a metal matrix with embedded ceramic fuel particles
  - W matrix (high melting point, H2 compatibility)
  - UO2, 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, UO2 - dark phase



ANL 2000MW CERMET Engine

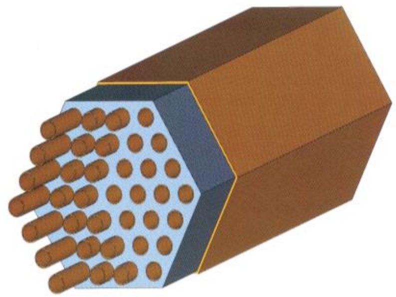
W-UO2 Materials and Process

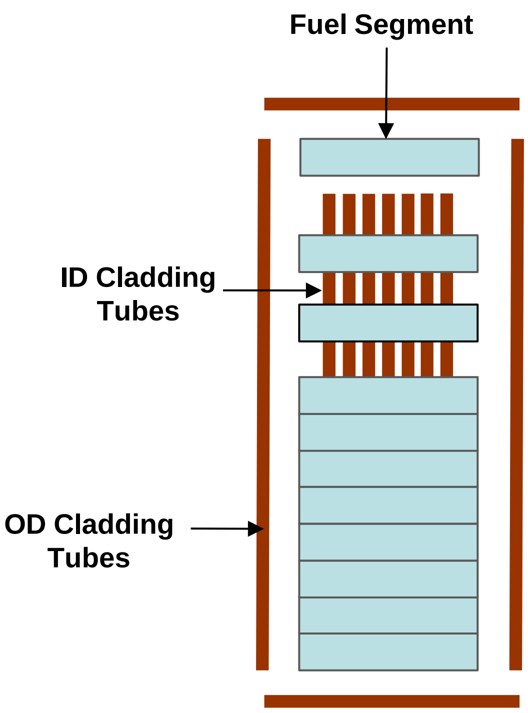
- Current work is based on ANL and GE710 Programs
  – Detailed specifications developed for GE710
  – Extensive capabilities that do not currently exist
- No qualified fuel fabrication processes
    - Key risk for NTP
    - Must recapture and certify process
- CERMET fuel loss mechanisms are known
  – Vaporization of UO2
  – Diffusion through pores and cracks
  – Differences in CTE of W matrix and UO2
  – Thermal decomposition of fuel/matrix
- Proven M&P approaches to inhibit fuel loss
  – Complete surface cladding with tungsten
  – W coated spherical UO2
  – Addition of oxide stabilizers to UO2

W-UO2 CERMET Samples fabricated during ANL Program

GE710 W-UO2 Fuel Fabrication

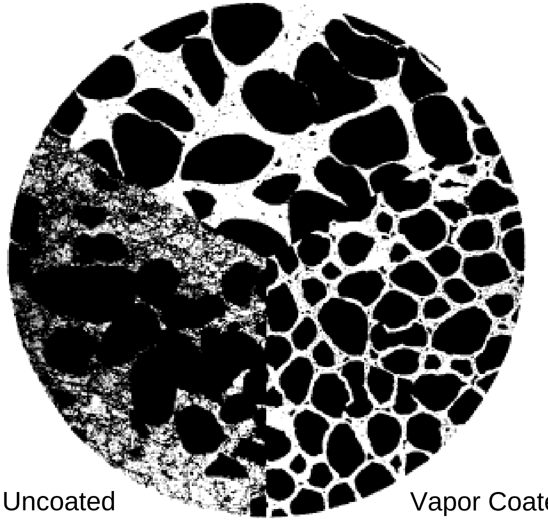
- Powder processing
  - Sieving, weighing, and blending
  - Isostatic pressing of fuel segments (wafers)
  - Hydrogen sintering (consolidation of segments)
- Fuel segment machining
  - Face grinding of fuel segments
  - Channel hole drilling
- Cladding/component fabrication
  - EDM for cladding and HIP 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



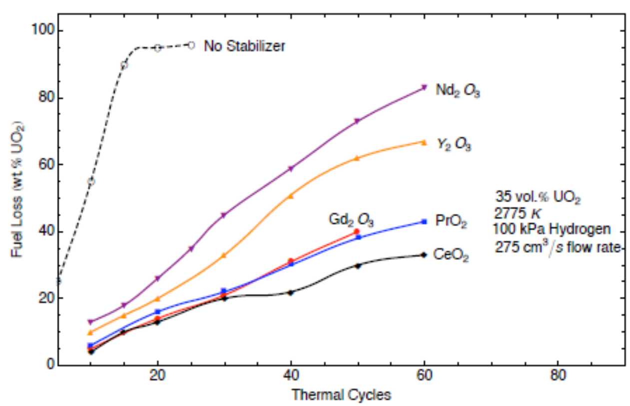


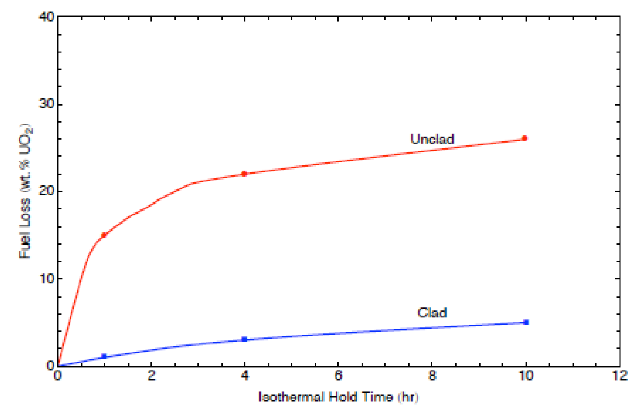
W-UO2 CERMET Test Data

- 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 UO2 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 UO2
- Addition of oxide stabilizers decrease fuel loss by preventing the reduction of UO2

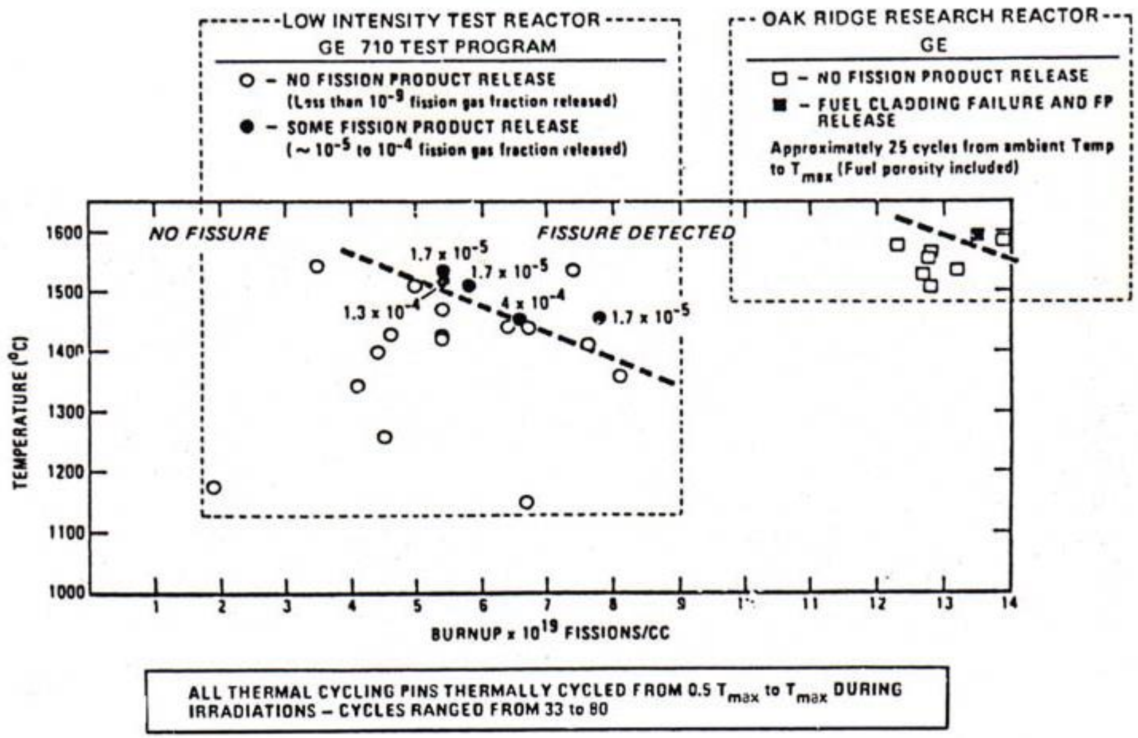


Charts courtesy of Jon Webb, “Literature Review of Historical W-UO2 Fabrication and Testing Efforts”, Idaho National Laboratories, Internal Document.





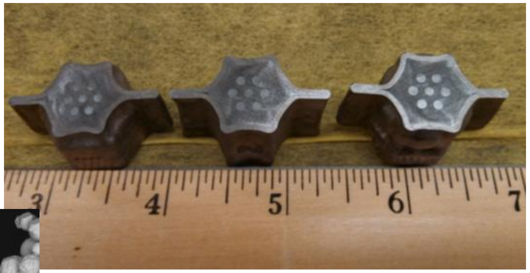
GE710 Irradiation Testing



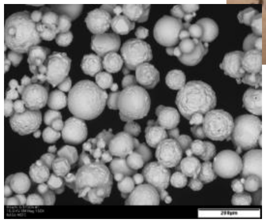
- No in-pile testing at current prototypic NTR conditions
- Majority of samples tested at low temps and longer durations
  - 1500C, 1000's of hours
- Fission gas containment to burn up levels exceeding $9x10^{19}$ fissions/cm^3
  - Equivalent to dozens of Mars missions

FY12-14 NCPS CERMET Development

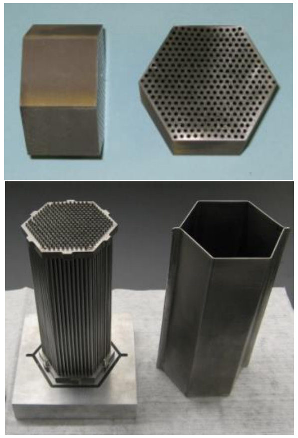
- UO2 feedstocks (ORNL sol gel, CSNR alginate)
- Powder handling (glove box sieving, blending, filling)
- CVD W coated UO2 spheres, W claddings
- Hot Isostatic Pressing (HIP)
- Post Machining (sectioning, grinding)
- Compact Fuel Element Testing (CFEET)
- Successful fab/test of W-UO2 sample

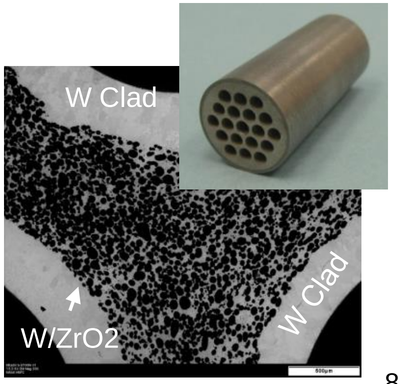


W-UO2 Samples

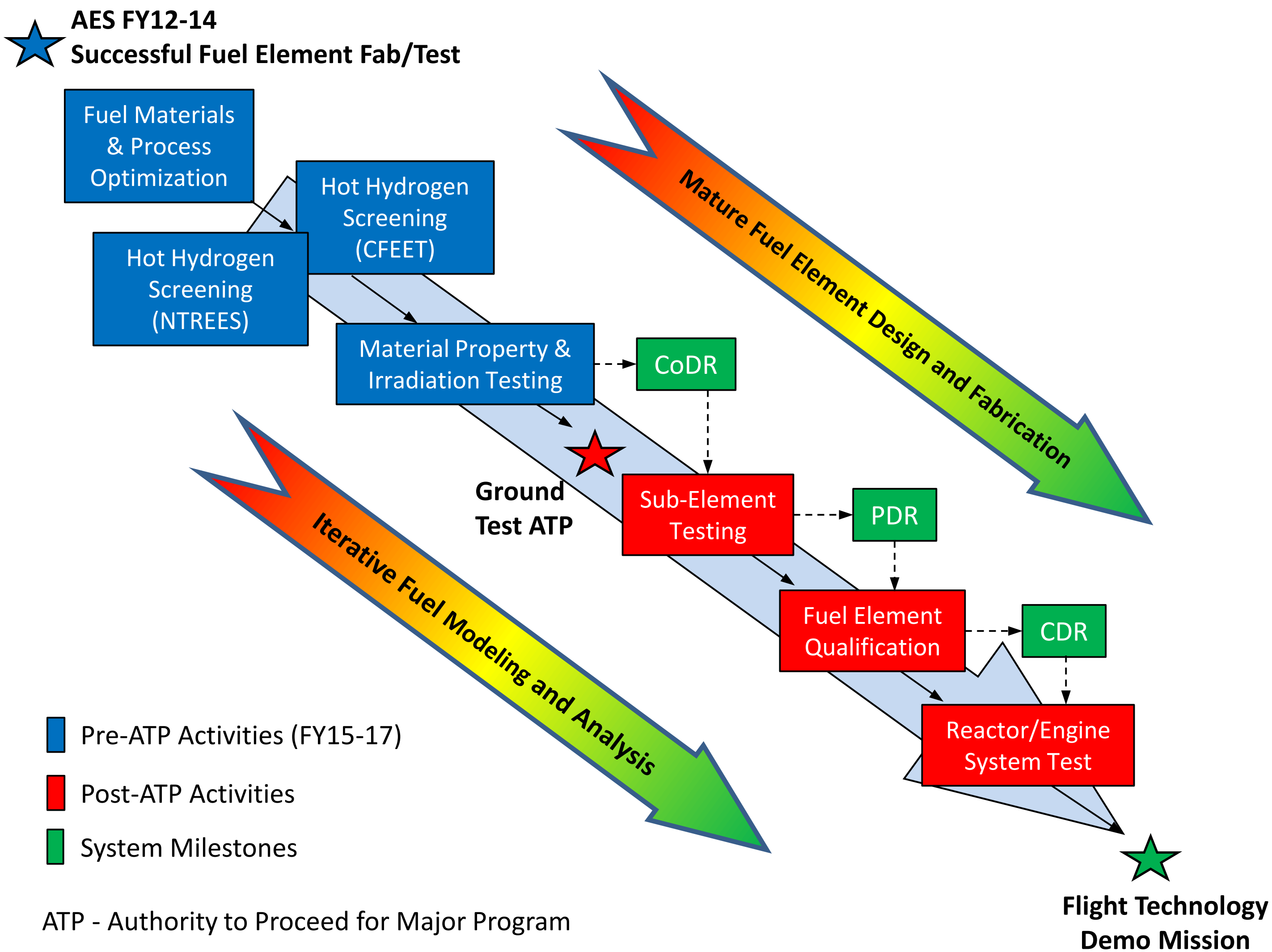


Dedicated Depleted Uranium Labs



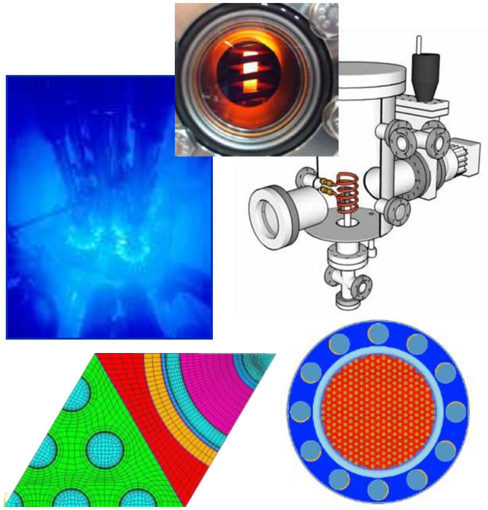


CERMET Fuel Development Path

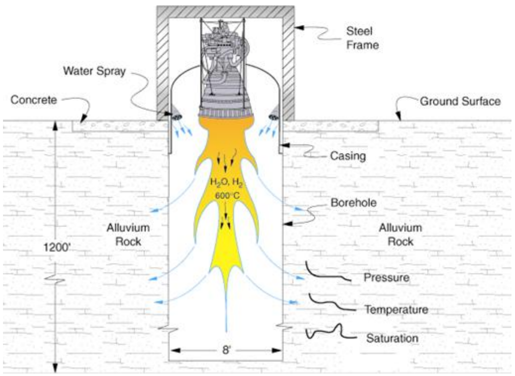


ATP - Authority to Proceed for Major Program

Fuel Development and Qualification



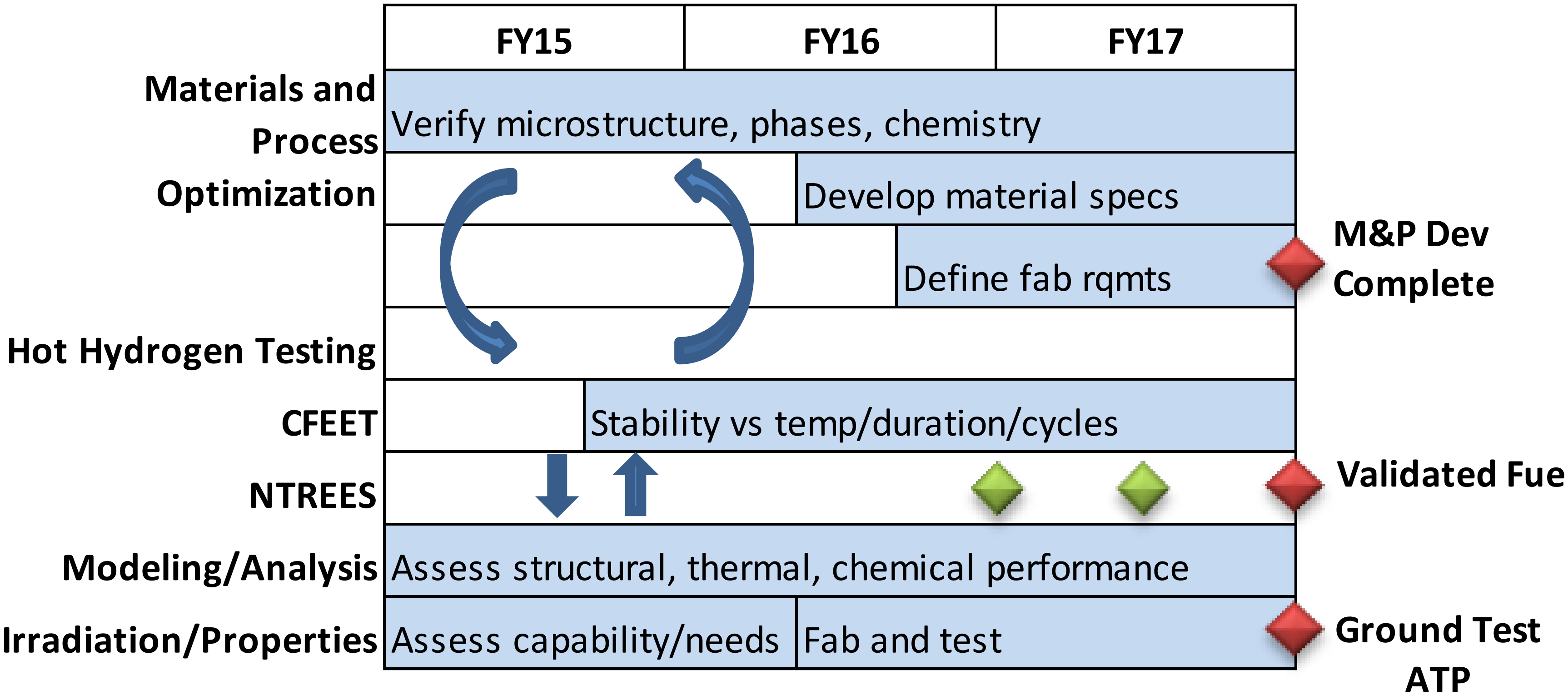
- "Certify" fuel material and fabrication process
- Separate effects testing
  - – Thermal chemical and cyclic stability in H2
  - – Irradiation for fission tolerance and retention
- Combined effects testing ($$$$)
  - – Radiation, temperature, H2, and pressure
  - – Subscale HFIR or ATR
  - – Single 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

- 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

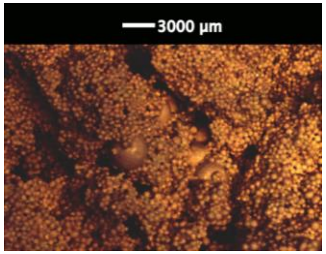
CERMET Fuel Development Timeline



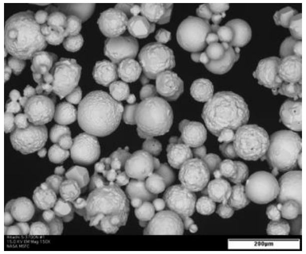
- Iterative M&P optimization and subscale H2 screening
- Continuous improvement and validation of modeling
- Validation of fuel element design and performance

CERMET Fuel Development Tasks

- UO_2 feedstock (spheres)
  - Sol Gel (ORNL)
  - Ammonium Alginate (CSNR)
  - Develop particle size constraints, yields, etc.
- W coated UO_2 (MSFC)
  - Optimize processing of various size UO_2 spheres
  - Develop production approach
- W-UO_2 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

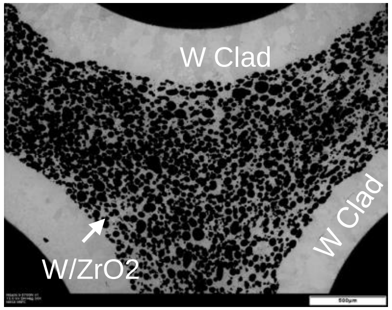


(CSNR)

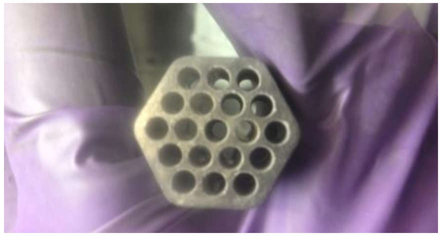


(ORNL)

UO2 Spheres



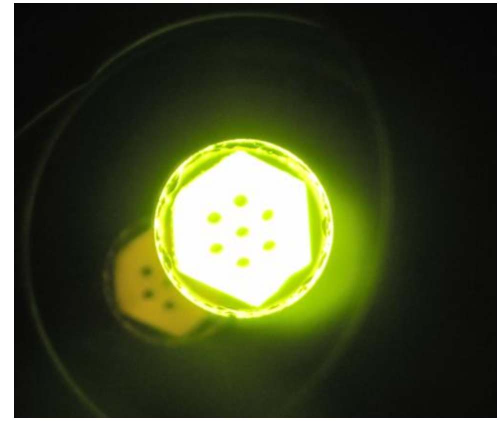
W Clad CERMET (MSFC)



UO2 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.



H2 Testing of W-UO2 sample at MSFC

FY15-17 Irradiation Testing

- 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 H2 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)

	FY15	FY16	FY17
UO2 feedstocks	850	850	850
Fuel Segment Consolidation	750	750	750
Characterization	650	650	650
Material Properties	450	600	600
Irradiation Testing	150	1150	1150
Modeling/Analysis	600	600	600
Hot Hydrogen Testing	475	625	625
Industry	500	500	500
	4425	5725	5725

	$M
Total FY15-17 CERMET	15.9
Total FY12-14 CERMET	12.3

	$M
NASA	8.2
DOE/Industry	7.7

Summary

- Materials, processing, and fuel failure mechanisms are defined from previous ANL and GE710 programs
- Demonstrated fabrication and testing of W-UO2 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

- Jim Werner – Idaho National Laboratory (INL)

Questions?