Graphite Fuel Development for Nuclear Thermal Propulsion

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ANS Winter Meeting

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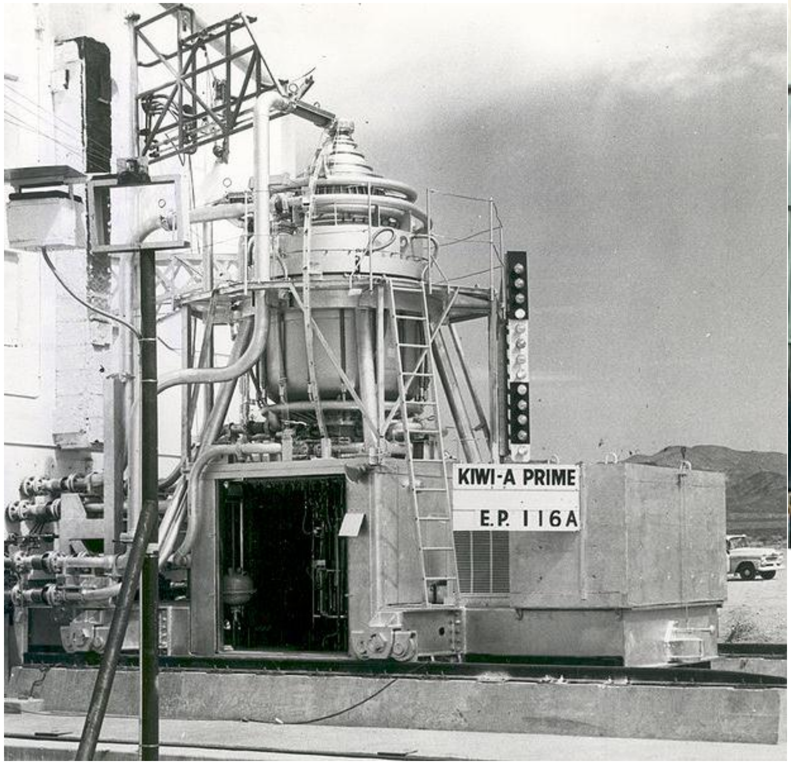
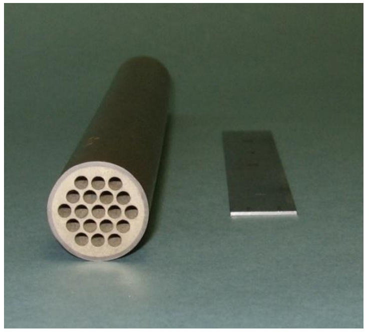


Rover KIWI-A' Reactor

NERVA Phoebus Reactor

DOE NTP Fuel Development Team

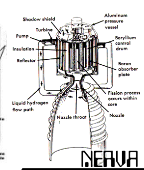
- ORNL
  - Graphite fuel, a “known” reactor-tested fuel
  - Graphite “composite” fuel, a “known” fuel with limited reactor testing
- INL, CSNR, and MSFC
  - Cermet fuels, an “advanced” fuel with some fabrication experience and limited but successful testing in TREAT

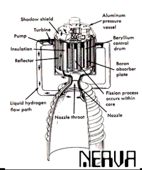


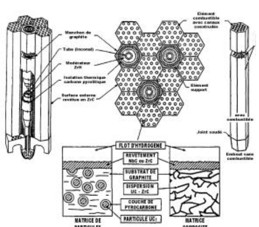
- ???
  - Carbide fuels, an “advanced” fuel with limited “knowns”

Schedule Drives Fuel Selection

If a mission is required sooner (10 years) then composite fuels might be used
If a mission is going to be later (20 years?) then advanced fuels can be developed







Flight Test

Operational

Integration

Construct Engine

Construct Fuel

Rebuild Infrastructure

2008

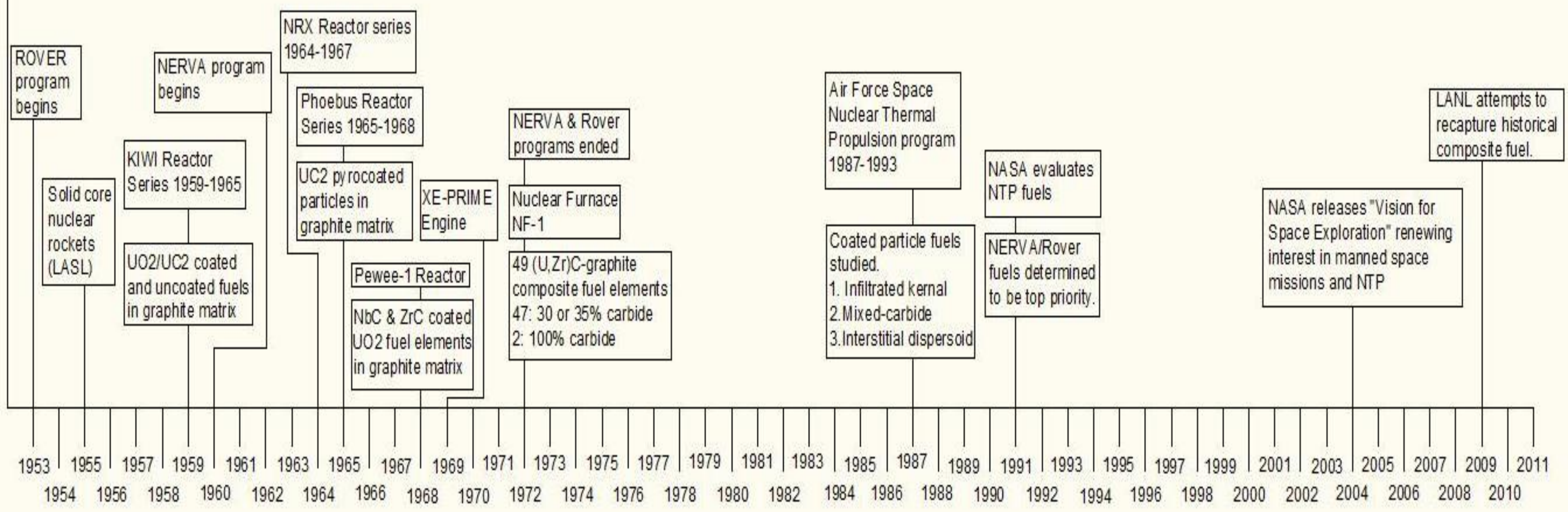
2012

2016

Overview of Graphite Fuel History

- Significant work done in 1960s and early 1970s
- Cancellations create large gaps between development efforts

• PEWEE	25 klbf
• KIWI-B	50 klbf
• NRX series	50 klbf
• Phoebus-1B	75 klbf
• Phoebus-2A	250 klbf

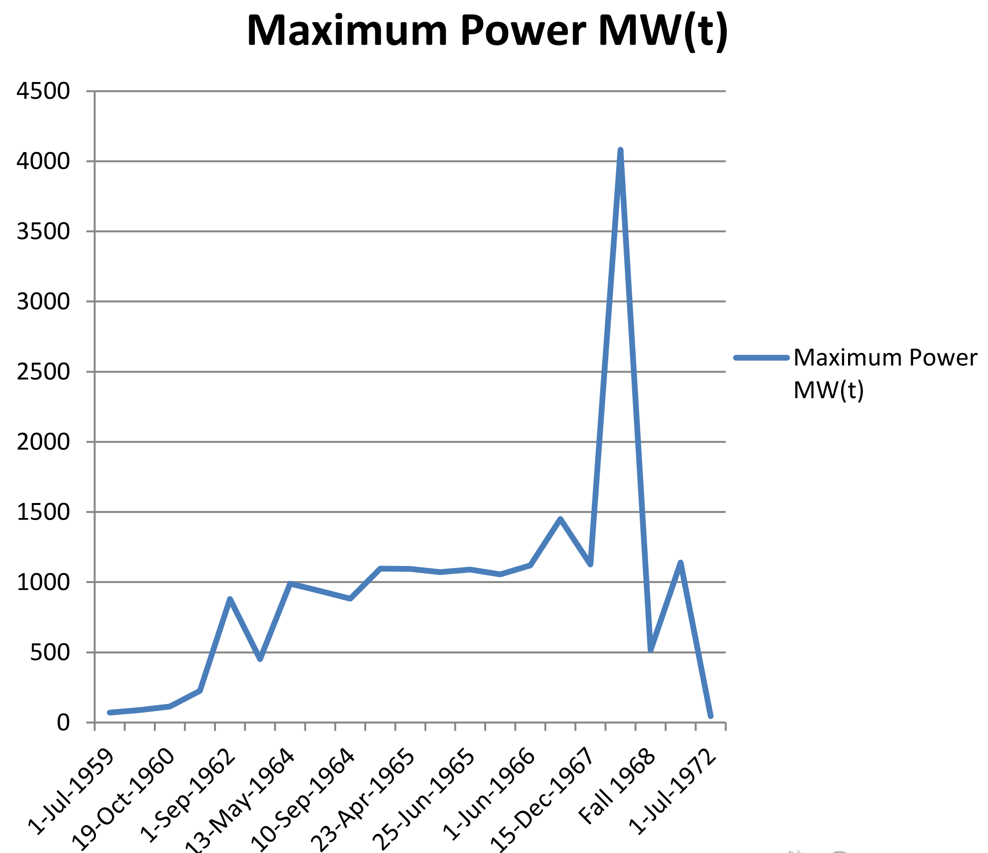


Power of Historical Reactors

NF-1 is the only reactor experience with "composite" fuel

"could withstand peak power densities of 4500–5000 MW/m³ without major difficulties and could be expected to perform satisfactorily for at least 2 hours and perhaps 4–6 hours, in a NTP reactor with T_{ex} = 2500–2800K"

Reactor	Date	Maximum Power MW(t)	Time (@ max.) seconds
KIWI-A	1-Jul-1959	70	300
KIWI-A'	8-Jul-1960	88	307
KIWI-A3	19-Oct-1960	112.5	259
KIWI-B1A	7-Dec-1961	225	36
KIWI-B1B	1-Sep-1962	880	several sec.
KIWI-B4A	30-Nov-1962	450	several sec.
KIWI-B4D	13-May-1964	990	40
KIWI-B4E	28-Aug-1964	937	480
KIWI-B4E	10-Sep-1964	882	150
NRX-A2	24-Sep-1964	1096	40
NRX-A3	23-Apr-1965	1093	210
NRX-A3	20-May-1965	1072	792
PHOEBUS-1A	25-Jun-1965	1090	630
NRX-A4/EST	1-Mar-1966	1055	1740
NRX-A5	1-Jun-1966	1120	1776
PHOEBUS-1B	23-Feb-1967	1450	1800
NRX-A6	15-Dec-1967	1125	3720
PHOEBUS-2A	26-Jun-1968	4082	750
PEWEE-1	Fall 1968	514	2400
XE-PRIME	11-Jun-1969	1140	210
NF-1	**1-Jul-1972**	**44**	**6528**



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Rover / NERVA Program Summary*

(1959-1972)

- **20 Rocket/reactors designed, built and tested at cost of ~1.4 B$ (~8.3 B$ in FY09); included construction of 3 test stands (A, C, ETS) & EMAD facility**
- **Engine sizes tested**
  - 25, 50, 75 and 250 klb_f
- **H_2 exit temperatures achieved**
  - 2,350-2,550 K (in 25 klb_f Pewee)
- **I_{sp} capability**
  - 825-850 sec (“hot bleed cycle” tested on NERVA-XE)
  - 850-875 sec (“expander cycle” chosen for NERVA flight engine)
- **Burn duration**
  - ~ 62 min (50 klb_f NRX-A6 - single burn)
  - ~ 2 hrs (50 klb_f NRX-XE: 27 restarts / accumulated burn time)

**** NERVA: Nuclear Engine for Rocket Vehicle Applications***

The NERVA Experimental Engine (XE) demonstrated 28 start-up / shut-down cycles during tests in 1969.

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A General Classification of the Various Fuel Types Considered for NTP Systems

- UO_2 (oxide)
- UN (nitride)
- UC_2 (carbide with either ZrC, NbC or TaC coatings
- UO_2 or UN in refractory metal matrix (CERMET) in refractory cladding (W, W-Re, Mo)
- UC-ZrC in graphite (composite)
- UC-ZrC-NbC solid solution ternary carbide

Pryocoated UC_2 coated particle fuel element

- Simplified heat treatment
- Reduced fuel element cracking
- KIWI-B4E
- Phoebus-1
- Phoebus-2
- PEWEE

NF-1 Reactor (advanced fuels phase)

- UC-ZrC in graphite “composite”
- UC-ZrC solid solution carbide

ROVER Reference element

- Extruded 0.75” flat-to-flat hexagonal element
  - no post-heat treatment machining required
- 52” long
  - current concepts are using shorter elements
- 19 internal coolant channels
  - web thickness is a limiting design factor
- NbC or ZrC coating
  - variable thickness along length
- 6-to-1Tie-rod support system
  - this can change
- 1.2 MW per element

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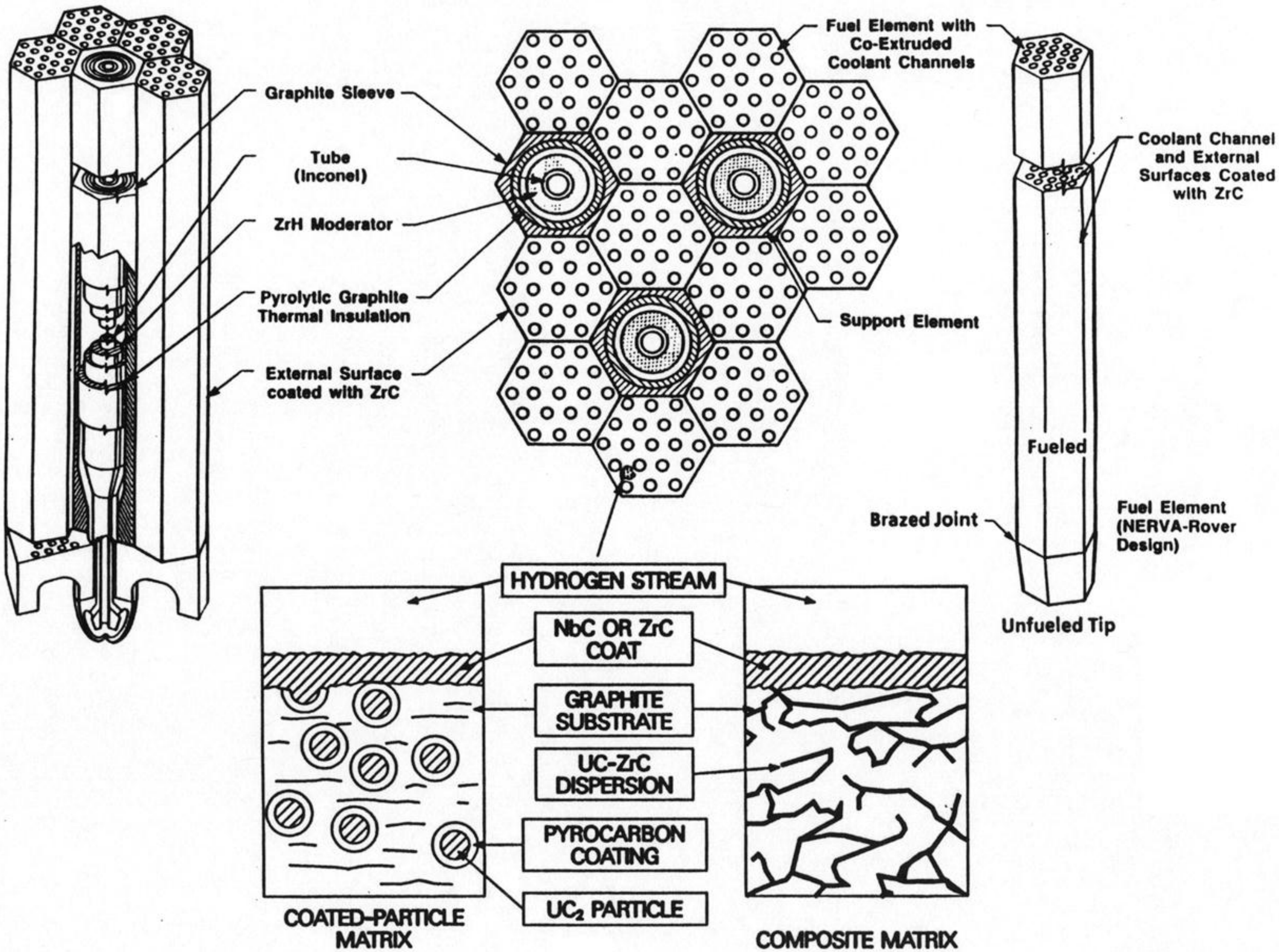
"Heritage" Rover / NERVA Composite Fuel Element and Tie Tube Bundle Arrangement



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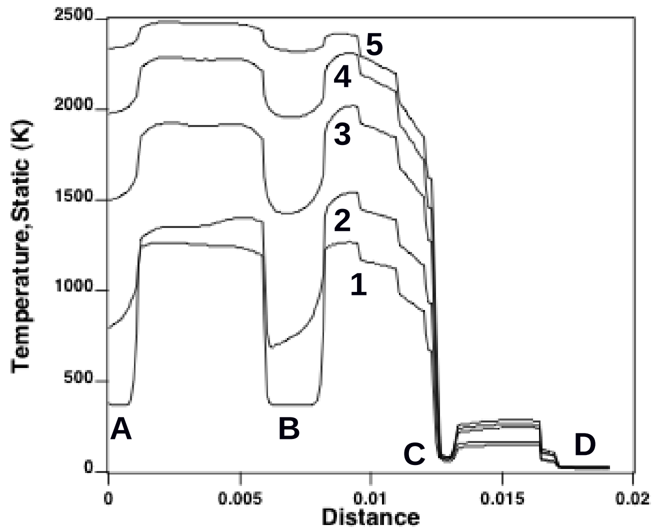
Fuel Dictates Engine Design

- **Fuel Loading**
- **Fissile loading, grams of U/cm^3**
  - **Core volume**
    - **Length of fuel to be made**
      - **Graphite offers continuous extrusion**
      - **Cermets can be made in smaller sections and joined**
  - **Amount of control drum reactivity and motion required**

- **Desirable system features**
  - **Reduce engine mass**
  - **Reduce uranium loading**
  - **Raise fuel melting temperature**
  - **Increase system performance**
  - **Increase number of thermal cycles**
  - **Minimize fission product release**

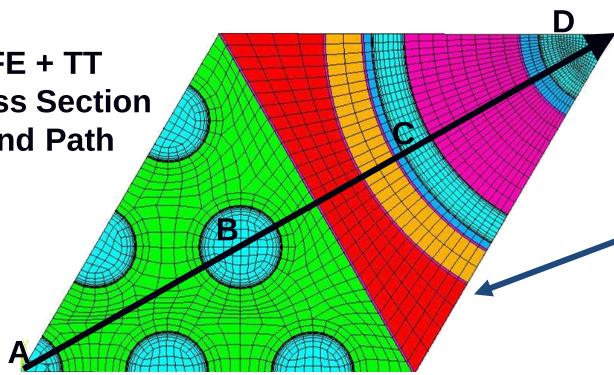
GRC / INL Integrated Neutronics-Thermal-Systems Modeling for SNRE

Temperature Distribution Across FE and TT

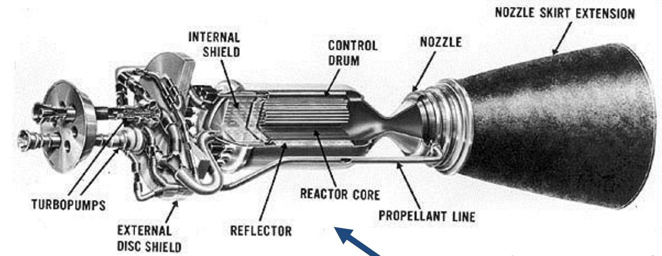


Temperature Distributions at Five Axial Stations
Numbers Indicate Cold to Hot End Stations

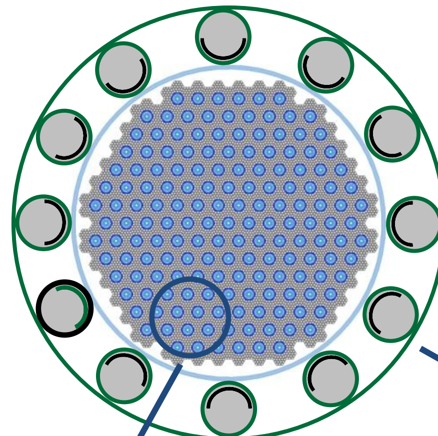
FE + TT
Cross Section
And Path



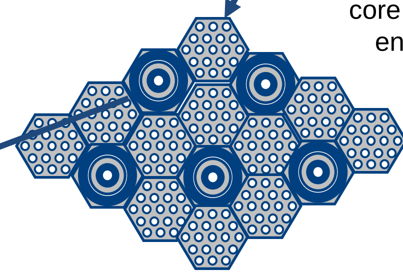
ANSYS Model



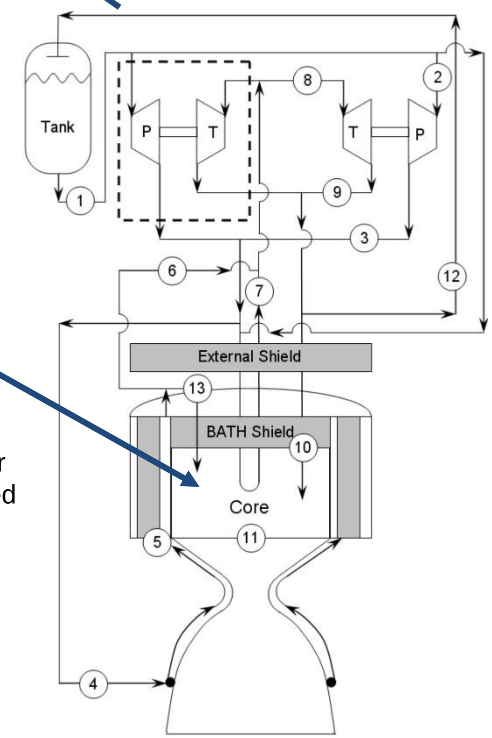
Performance, Size
& Mass estimation



MCNP neutronics for
core criticality, detailed
energy deposition,
and control
worth



Fuel Element-to-Tie Tube ratio
varies with engine thrust level



Nuclear Engine System Simulation
(NESS) code being upgraded to
use MCNP-generated data

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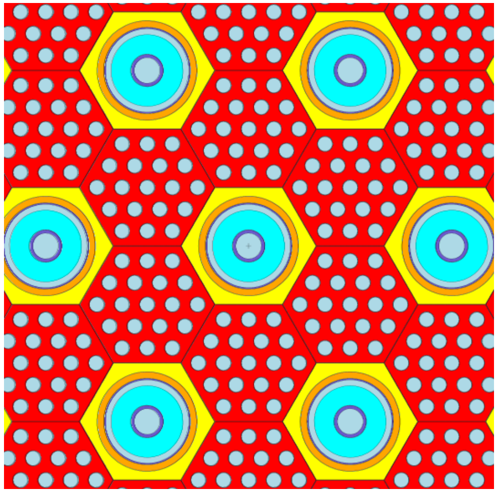
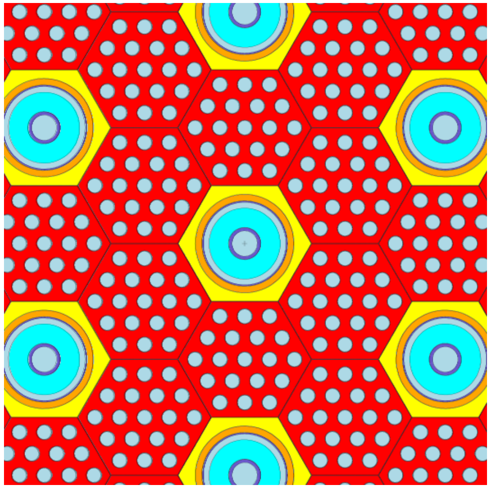
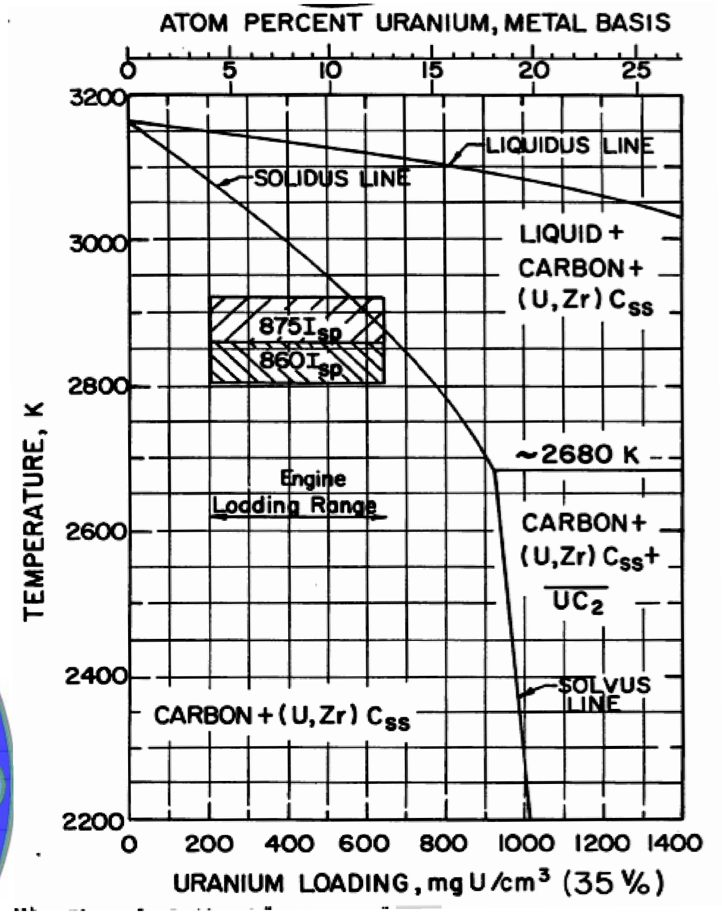
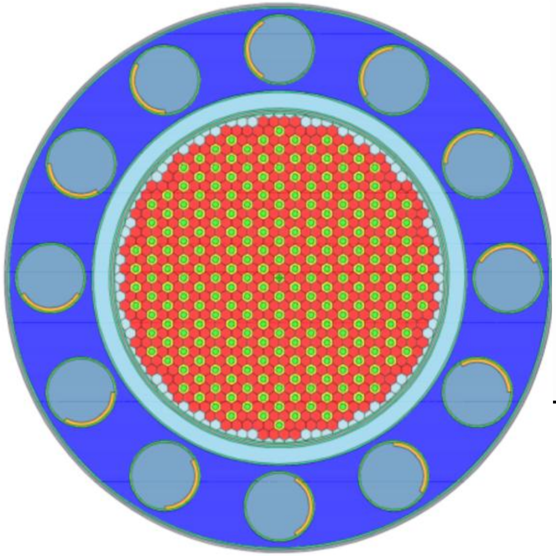
Fuel arrangements and core design

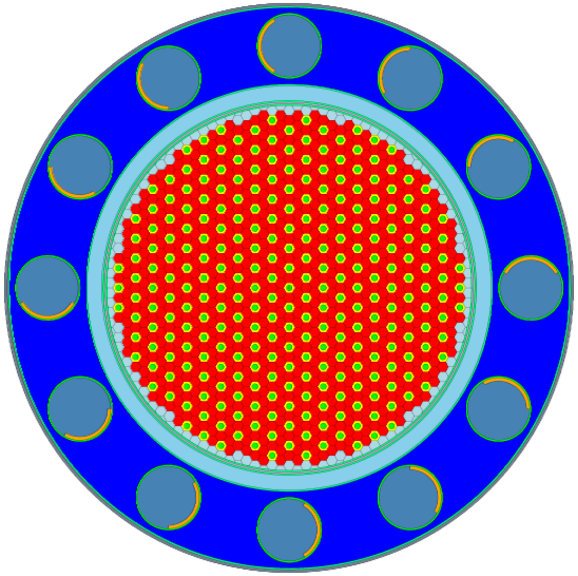
Ref: B.G. Schnitzler, 45th JPC, 2009









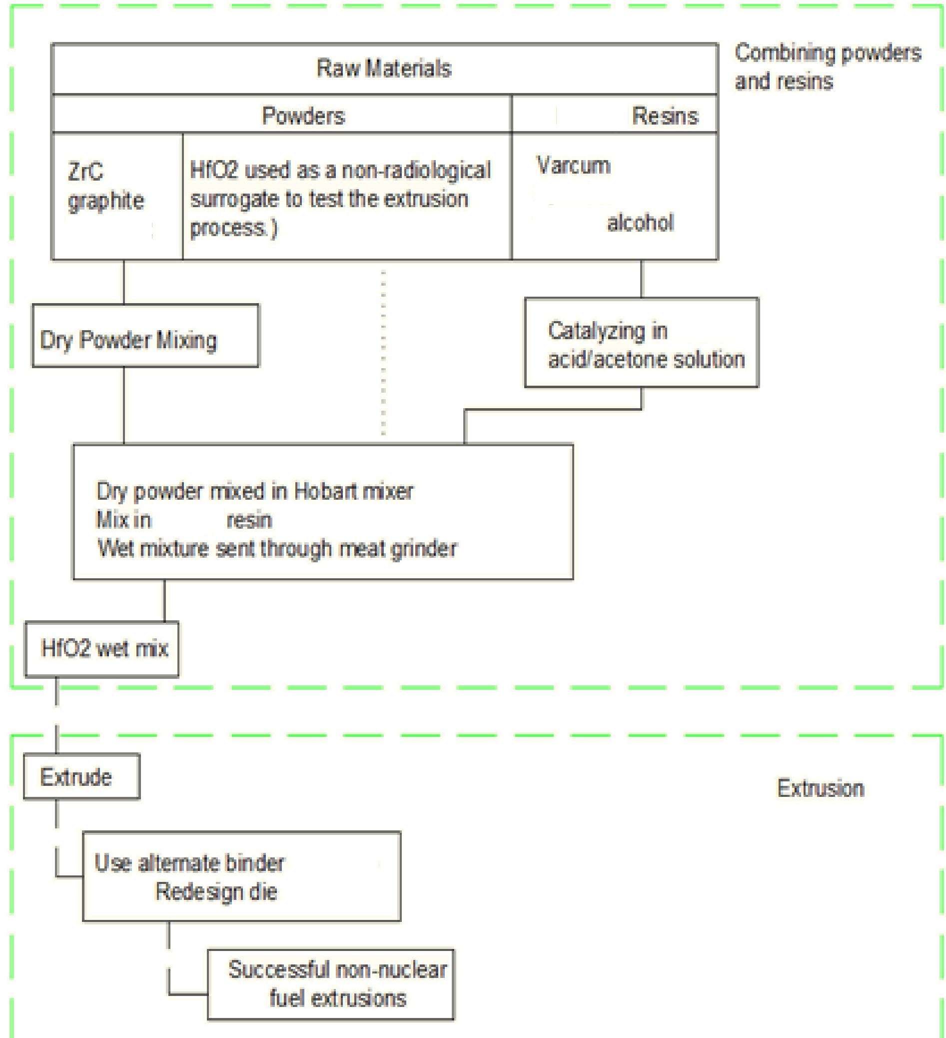


Overview of historical process to make composites

LANL used non-radiological elements to develop a "recipe" for fuel elements.

Then substituted DU for the HfO_2

We are attempting to restart processes with DU



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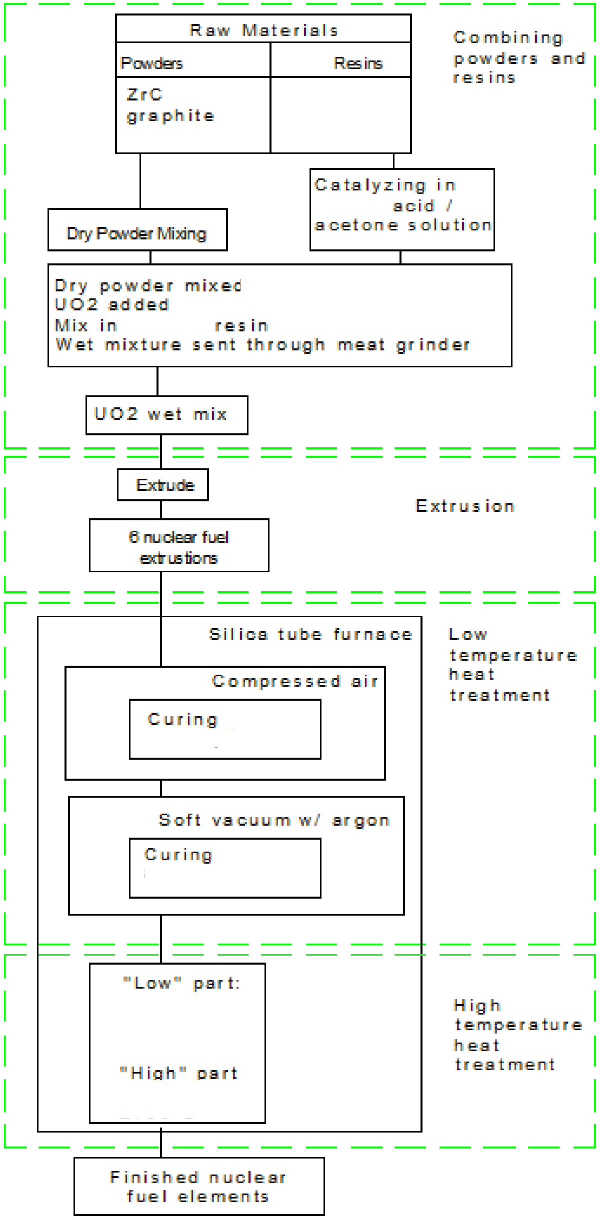
Materials required to make fuel elements

- LANL recreated old recipe using D-UO2

- Problems encountered:
  - Loss of original materials
  - Old, larger extruders and furnaces not well suited to current program needs

- **Conclusion**: Exact replication of historical fuel not feasible



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New development path

- Material substitutions are required

- This leads to the conclusion that we need an iterative, low cost capability to
  - make extrusions
  - run them through heat treatments
  - characterize them
    - Measure CTE, Thermal conductivity, strength
    - Evaluate microstructure

- After we have satisfactory fuel elements we need to be ready to coat them

For the composite fuel, we already know the general characteristics that yield good performance

Carbide Content. Vol %
U loading range. Kg/m^3
Thermal conductivity, W/m-K
Coefficient of thermal expansion, µm/m-K
Flexural strength (300K), MPa
Compressive strength (300K), MPa
Strain to fracture (300K), µm/m
Stress at fracture (300K), MPa
Elastic modulus (300K), GPa
Compressive deformation at 2800K (3.5 Mpa for 1 hour),%
Thermal stress resistance at 1700K (power density at fracture), MW/m^3

Fuels Development Approach

Recapture Fuels Fabrication Capability at Specimen Level

Produce and Characterize Fuel Specimens

Hot Hydrogen Testing of Non-Irradiated Specimens

Specimen Irradiation Testing (Without Flowing Hydrogen)

Specimen Post-Irradiation Examination (PIE)

Hot Hydrogen Testing of Irradiated Specimens

Repeat at Fuel Element (or Prototypic Element Cross-Section) Level

Composite Fuel Element Variables

- Vary
  - Uranium loading (pick one)
  - Volume fraction of carbide phase (35%)
  - Graphite constituents
  - Extrusion conditions
  - Heat treatment

Mix, extrude, heat treat
Test
Repeat

- To optimize
  - CTE mismatch
  - Strength
  - Thermal conductivity

Need to be capable of measuring these properties

When we match historical performance we will have an element we want to coat

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Processes required to get testable fuel elements

- Gather materials
- Mix powders
- Wet mix
- Extrude
- Heat treat to make an element
- get properties correct
- Coat the element
- Test prototype at MSFC

- Buy new equipment
  - Modify extruder for full length elements
  - New coater for full length elements
- Design prototypic cross section die
- Extrude longer specimen
- Heat treat to make an element
- Modify die
- Get cross-section correct
- Coat the element
- Test coated element at MSFC
- Irradiation Testing

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Important Composite Fuel Characteristics

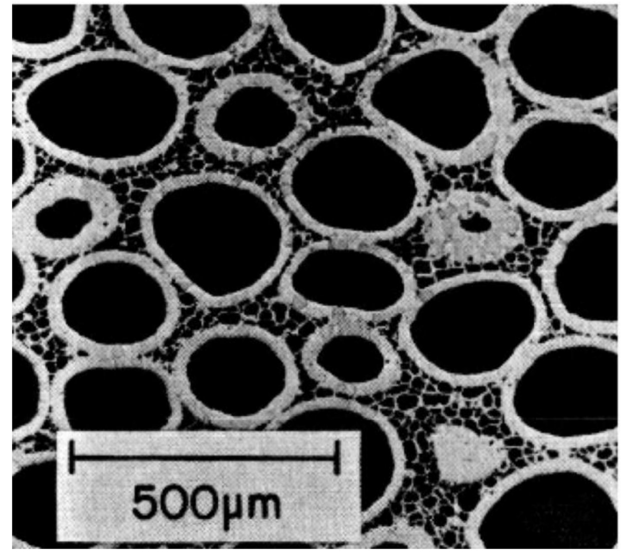
- Important to match matrix CTE to that of coating
  - ZrC CTE ~7.7 µm/m
  - Pick mixtures of graphite flour
  - Tailor extrusion conditions

- Want to get high thermal conductivity

- Want to maximize strength

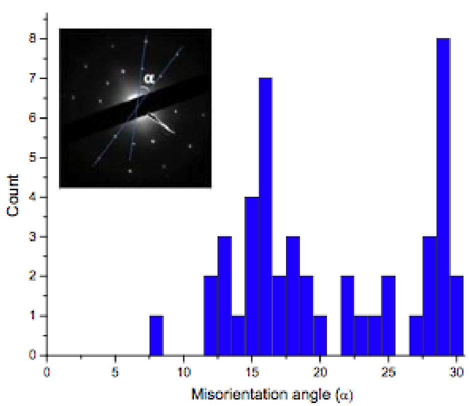
Kernels and Coatings

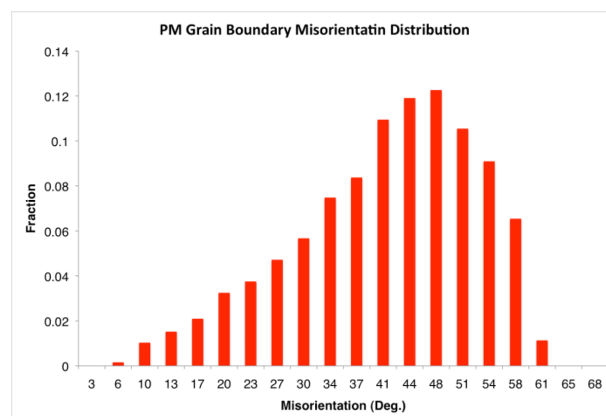
- Developing multiple methods of fabricating spherical dUO_2 microspheres
  - Establishing purity requirements
  - Establishing symmetry requirements
  - Fabricating kernels from 10 μm to 100 μm
- Investigating CVD coatings with WF_6 and WCl_6 precursors
  - WF_6 used for initial fabrication studies
  - Transitioning to WCl_6 for hot H_2 testing
  - Optimizing columnar grain structure to minimize misorientation
  - Prevents inter-particle contacts



Powder Metallurgy (PECS)

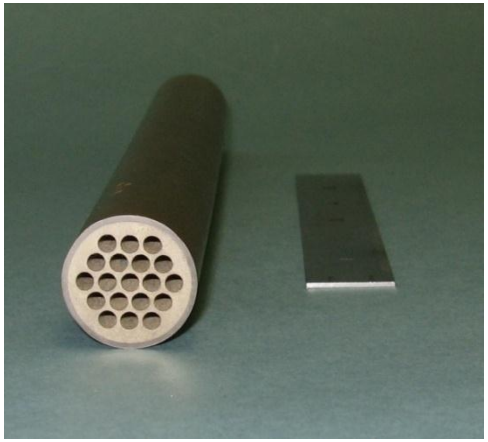
CVD

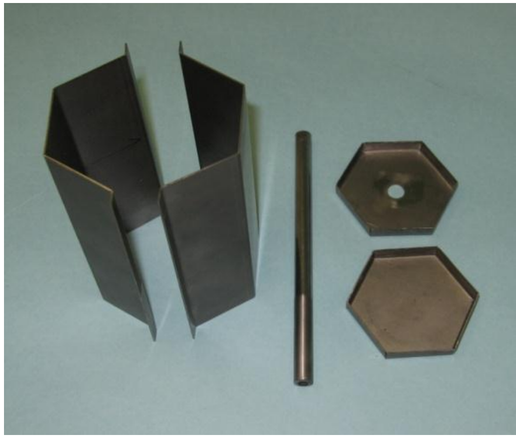




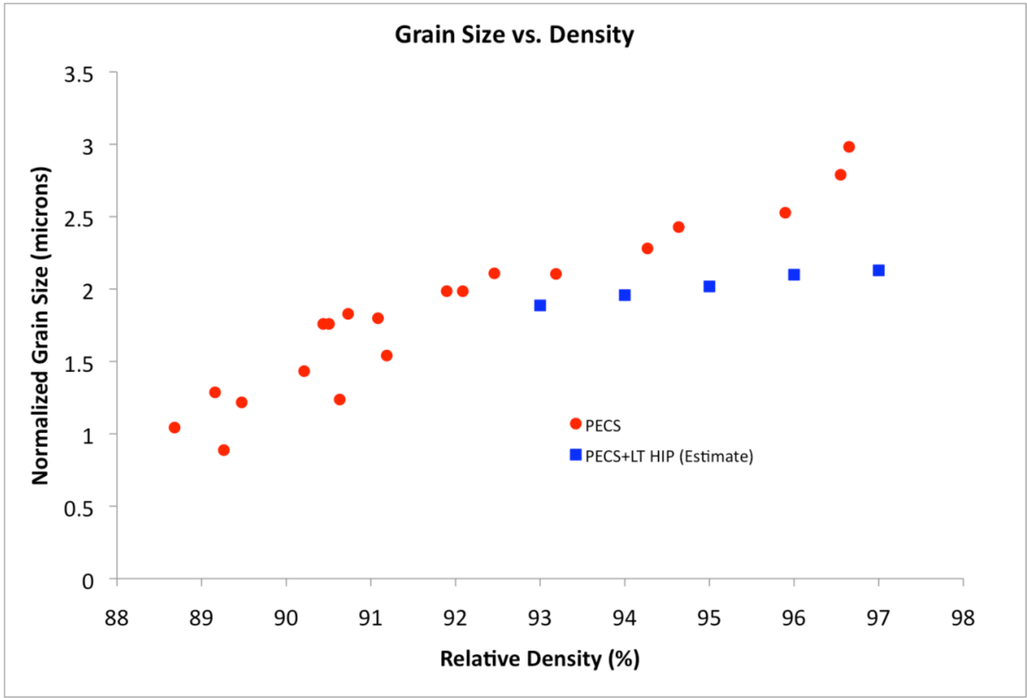
W-UO_2 Consolidation

Surrogate CERMET fuels specimens Fabricated at NASA MSFC





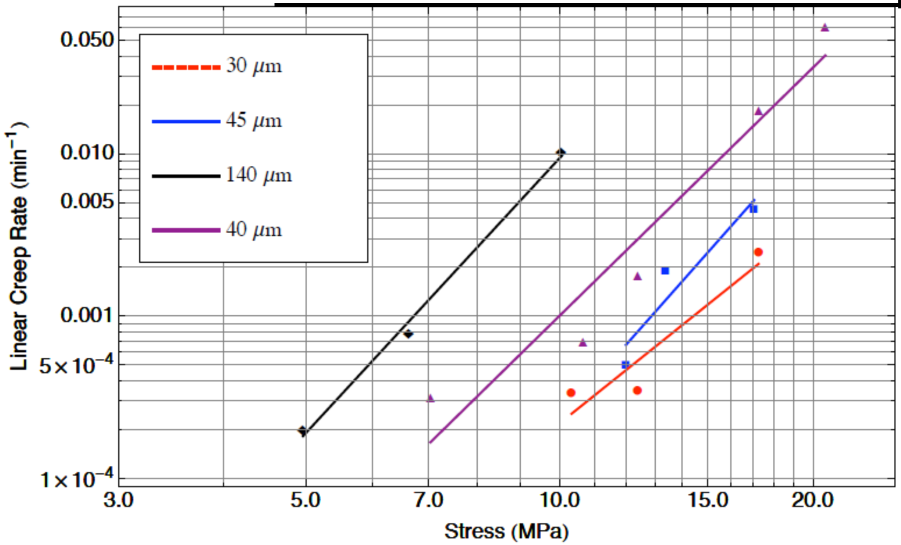
- Investigating HIP, PECS and hybridized HIP+PEC fabrication techniques
- Investigated PECS mechanisms and found them to be diffusional, not plasma based
- Must reach 98% density in the W matrix
- Working to minimize W average grain size while minimizing grain boundary misorientation
- Fabricating fuel hex segments of varying number of coolant channels and flat-to-flat dimensions by HIP and PECS techniques



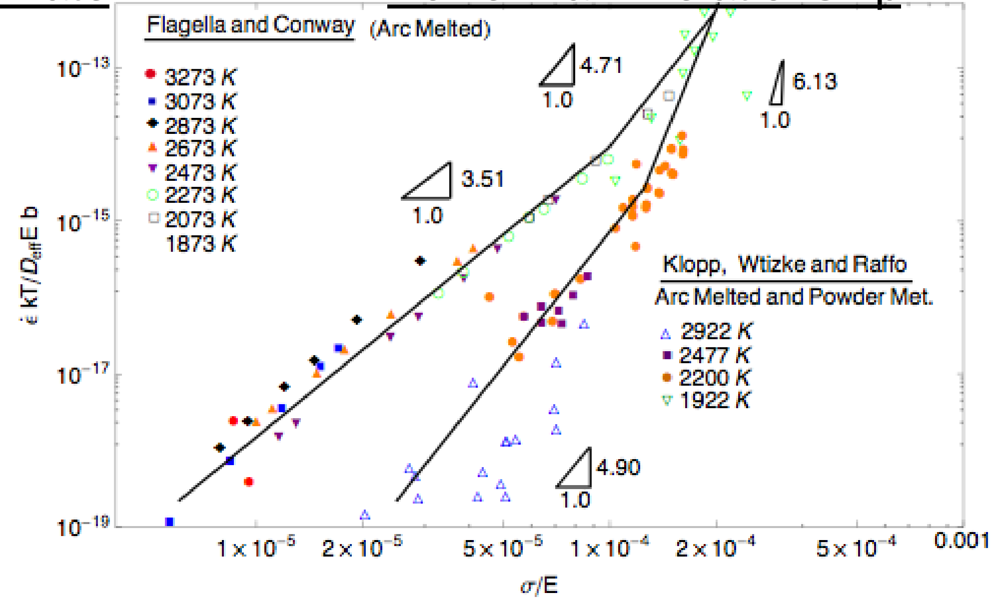
Work performed on INL/CAES PECS unit

Tungsten Creep

Effects of Grain Size on Creep Rate



Power Law Relationship



- Smaller microstructure yields a lower creep rate (opposite of most class M metals)
- PM tungsten exhibits a 3.5 power law behavior
- Arc melted tungsten exhibits a 5 power law behavior
- Working to develop a more modern creep relationship for W and W-25Re

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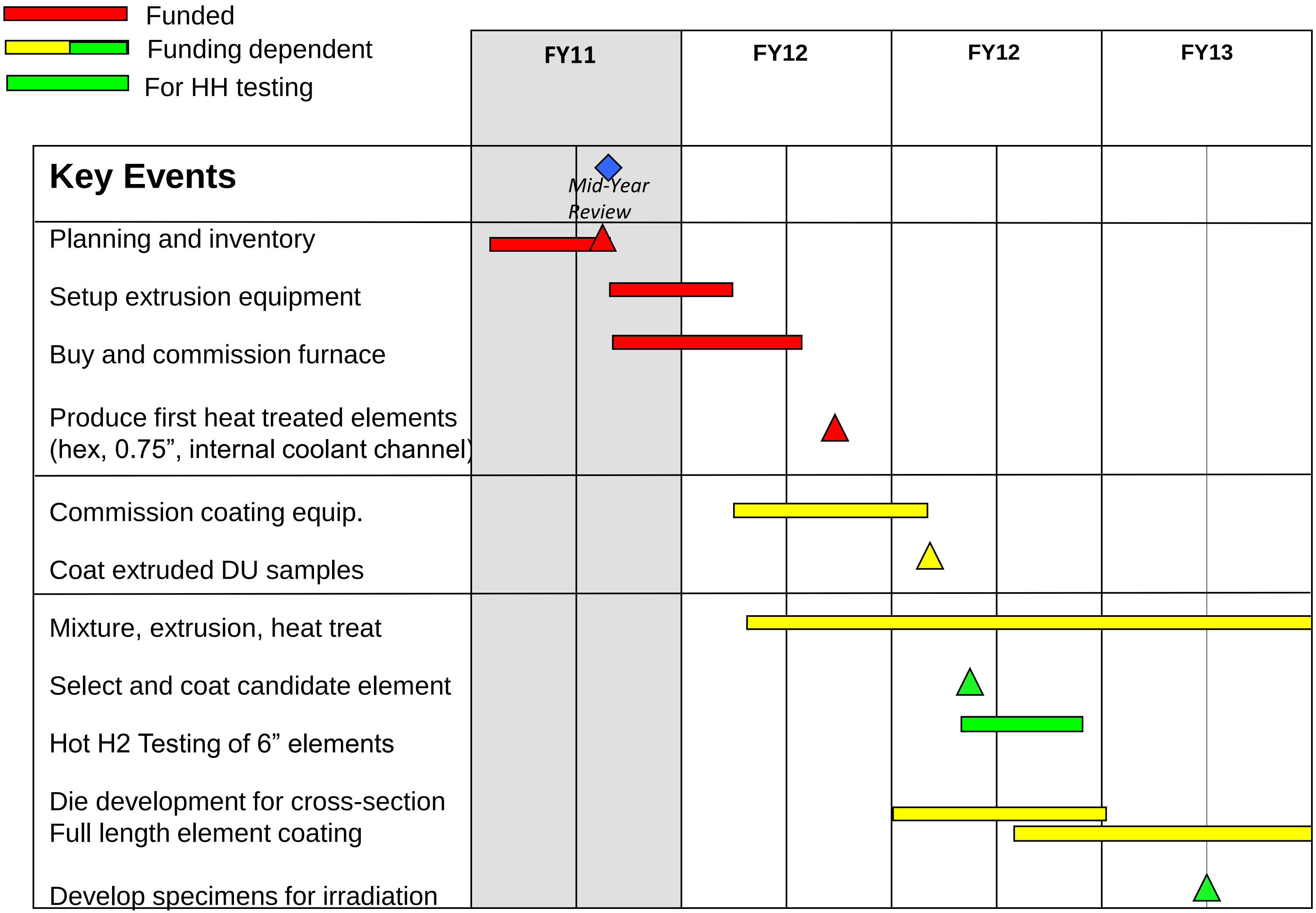
Graphite Fuel Development Schedule



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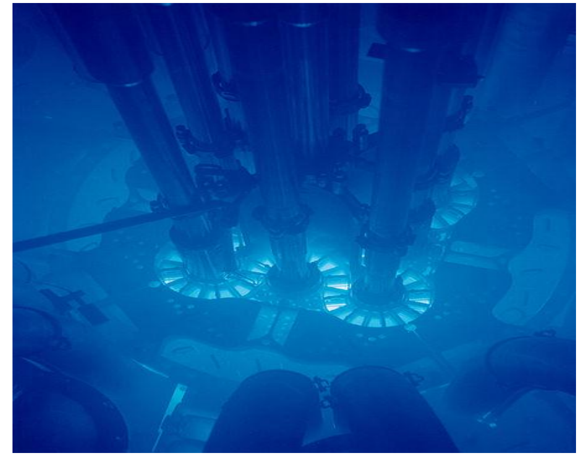
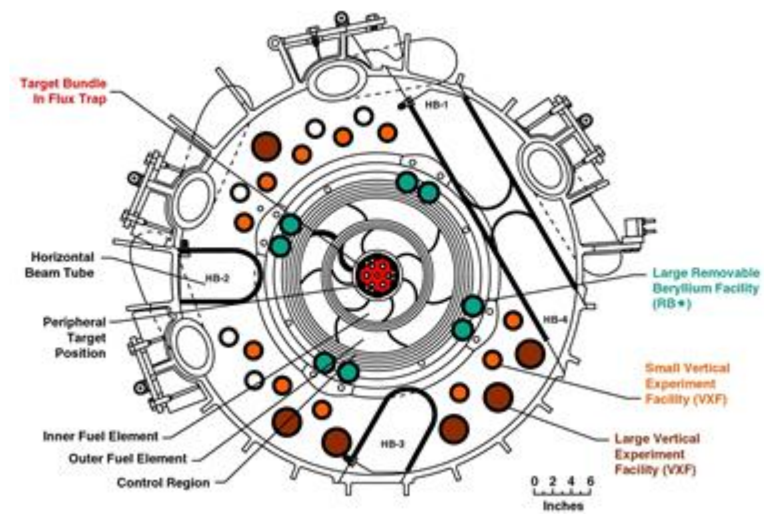
Hot H_2 Testing and Irradiation Testing

- Conduct testing as a function of time, temperature and thermal cycles
- Subscale H_2 testing of prototypic samples
- Large scale H_2 testing of elements and bundles in NTREES
- Investigate the effects of cladding damage and fuel loss
- Irradiate specimens
- Test irradiated specimens for fission product retention in hot hydrogen
- Validate assumptions for irradiated fuel performance



Advanced Test Reactor



High Flux Isotope Reactor

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Initial NTP Design Considerations for Ground / Flight Technology Demonstration Engines

- Keep it small so it's affordable

- Make it scalable to the larger size engines needed for human explorations missions

- Use similar fuel element design needed in larger engine as was done in Rover/NERVA
  - use fewer elements
  - use more shorter elements with same x-sectional geometry
    - increase length for higher power for larger thrust output

- Need to determine size and performance characteristics of <u>various engine sizes</u> with candidate fuel technology for a fair and constructive comparison

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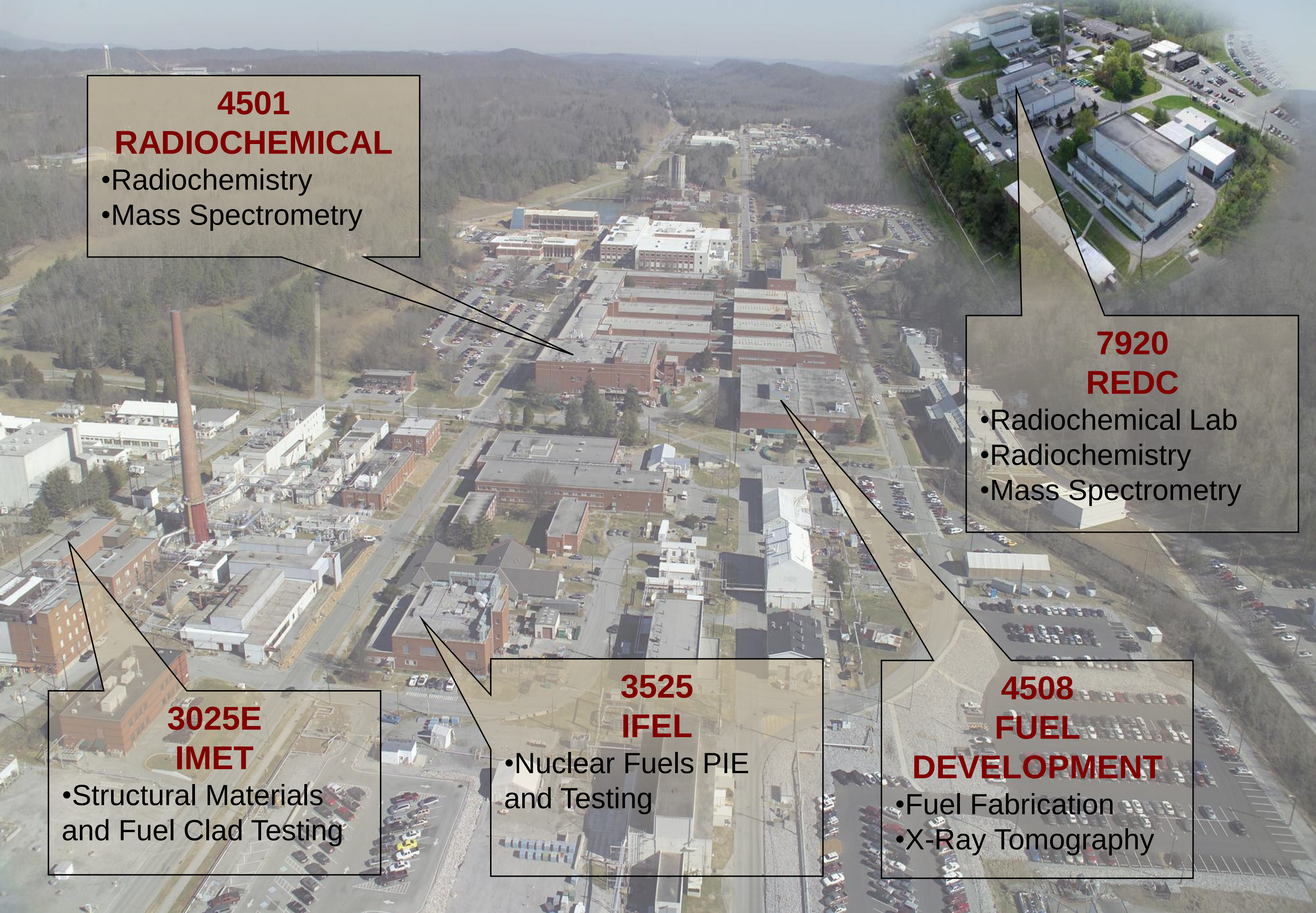
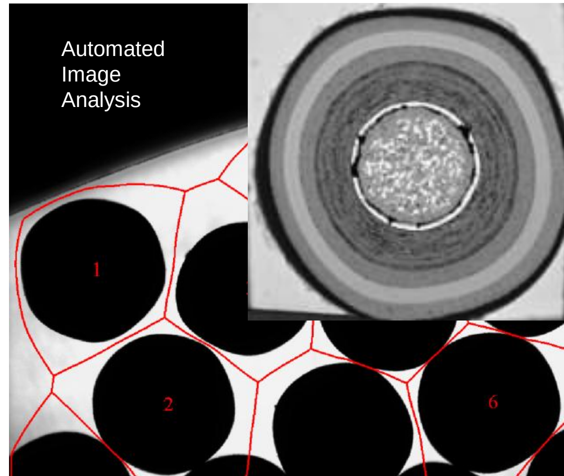
ORNL NUCLEAR FUELS COMPLEX

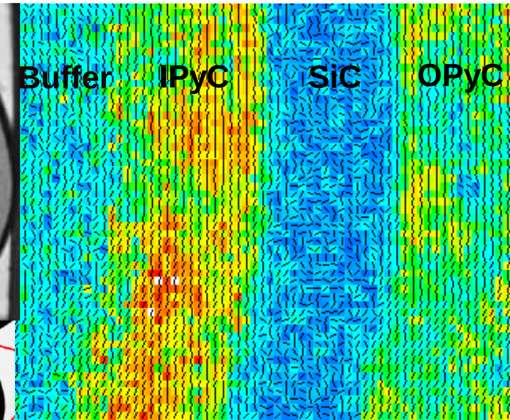


ORNL Fuel Development Capabilities

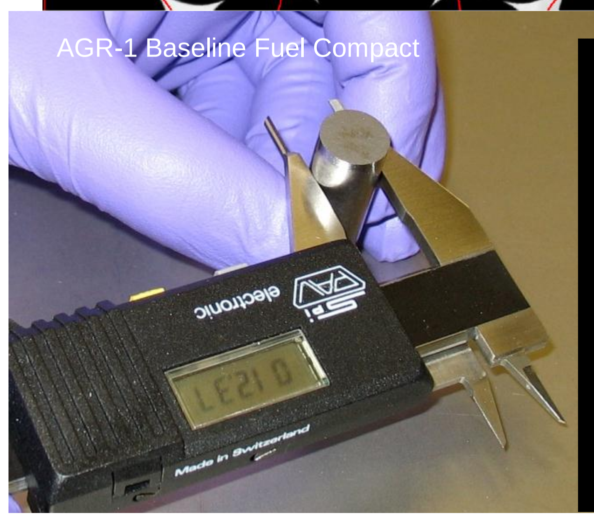
Linking Process - Properties - Performance

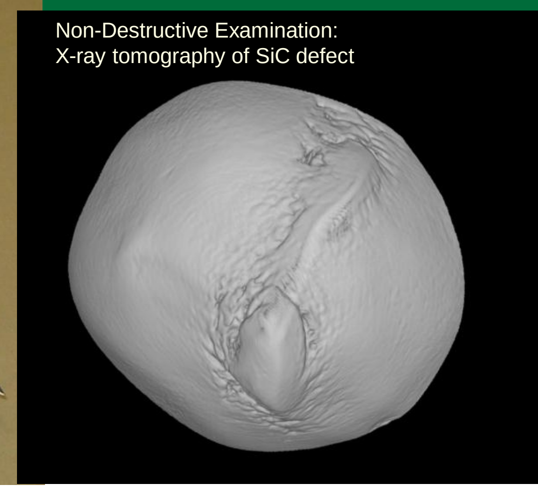
- ☑ **Kernel fabrication**
- ☑ **Particle Coating**
- ☑ **Process Modeling**
- ☑ **Characterization**
- ☑ **Compacting**
- ☑ **Extrusion**
- ☑ **Large element coating**





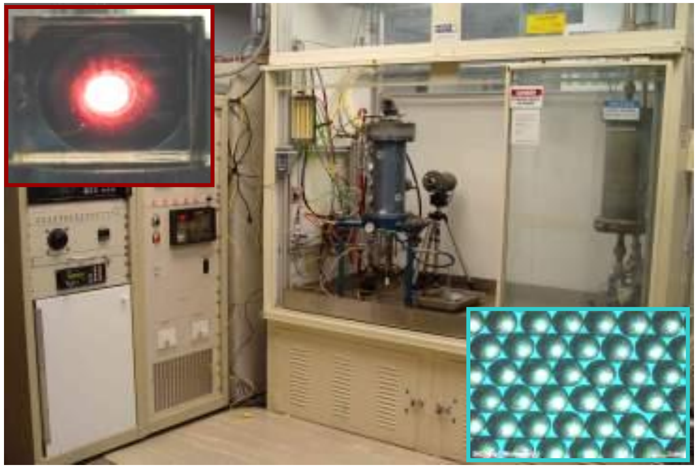
Key Performance Parameter:
PyC anisotropy - micron sized structure





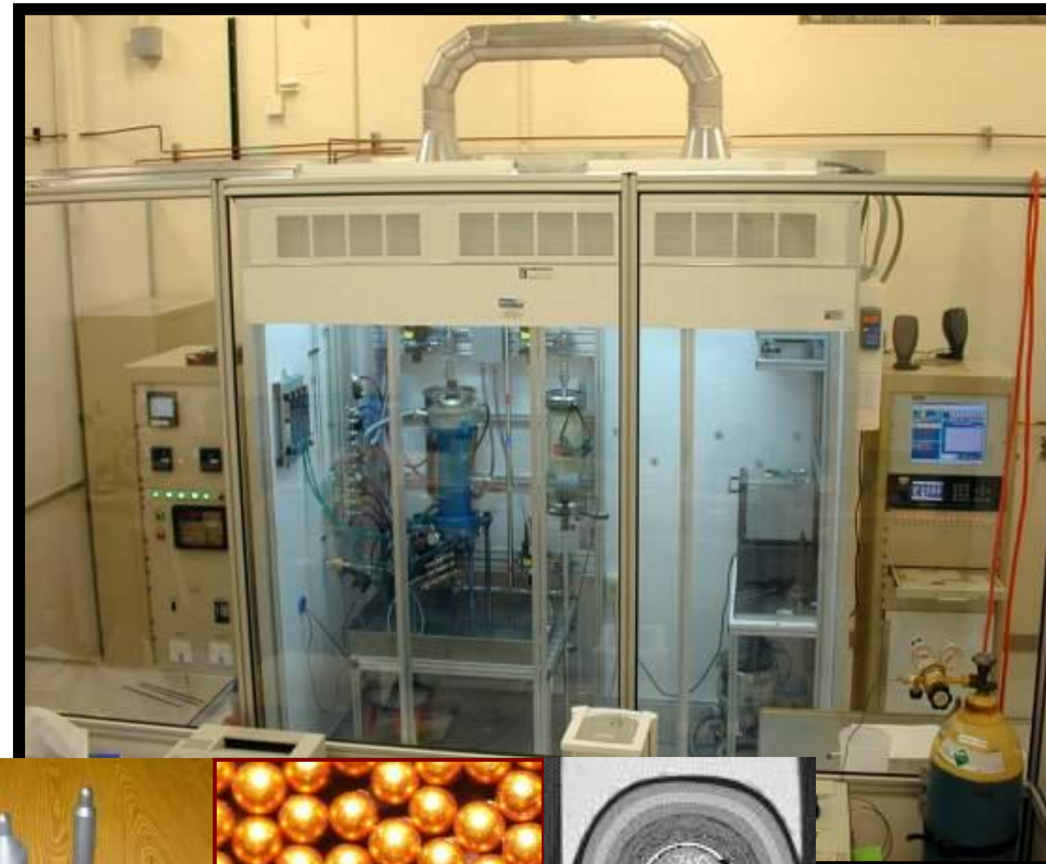
Three Coaters Support Fuel Development

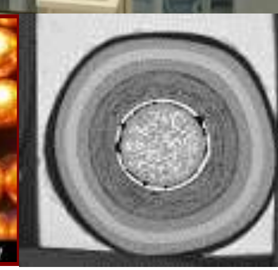
50 mm surrogate coater



100 mm surrogate coater

50 mm coater used for uranium coating





These coaters can be used for bulk specimens up to 6” in length in ZrC

Capability does not reside in the literature nor in equipment