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Looking Beyond Standard LWR Fuel

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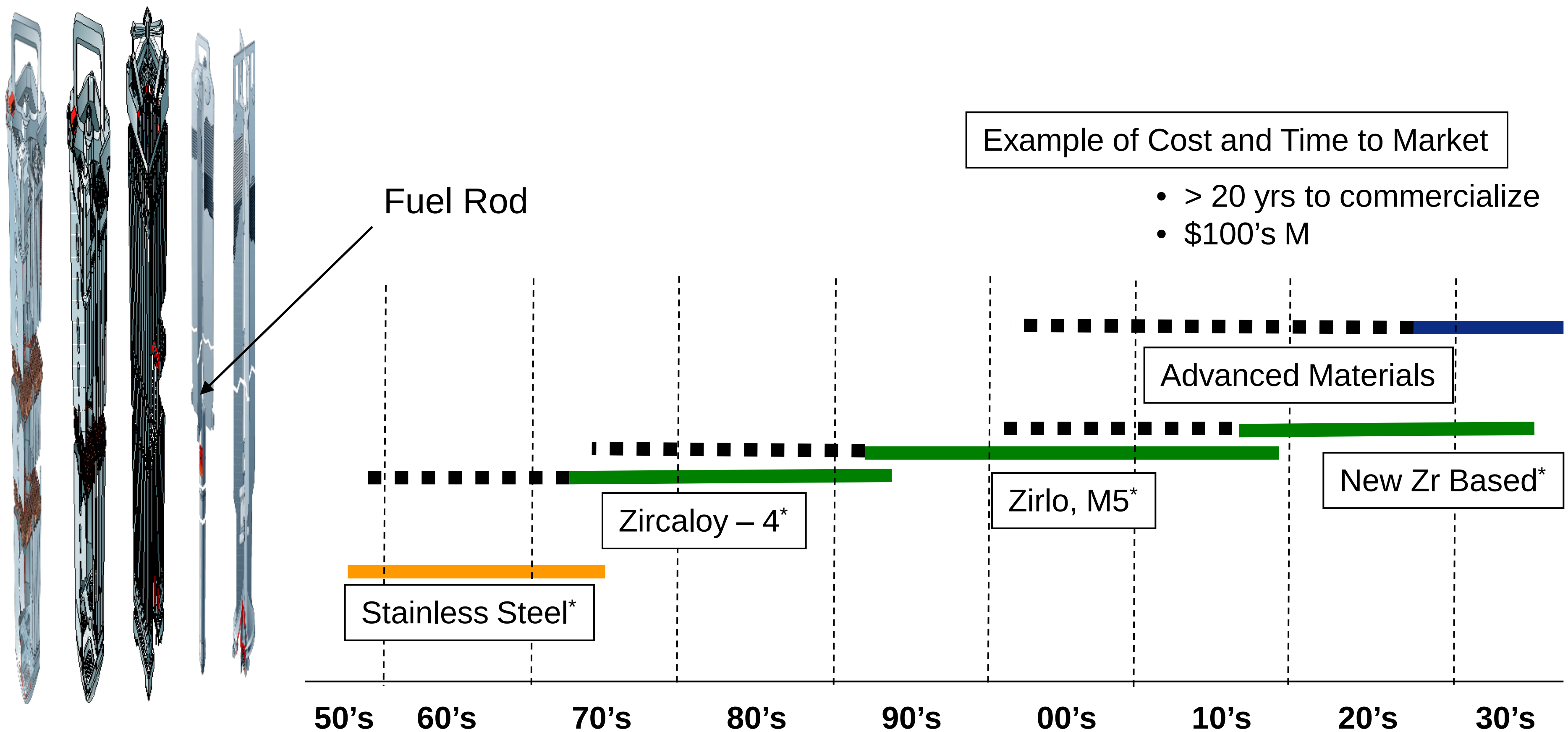
Drivers for Advanced LWR Fuels

- Lower plant operating cost
  - Increased availability
    - Failure-free fuel (resistant to debris and grid-to-rod fretting failures)
    - Longer fuel cycles (24 months… or longer)
  - Increased capacity with uprates
  - Improved asset utilization
- Lower capital costs
  - Extend life of existing plants beyond 60 years
  - Reduce the number of safety systems required

New Fuels is Not for the Faint of Heart - It takes ~20 years for even evolutionary changes



* Timeline information based on "Fuel Design and Fabrication" paper by Kyu-Tae Kim, KHNP

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Research Topics

- Longer life clads
  - Higher performance Zr alloys
  - New clads such as SiC
- Higher Density Fuel Pellets
- Higher thermal conductivity fuel (BeO addition)
- Enriched Gadolinia
- Enriched Zirconium

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Characteristics of Silicon Carbide

- retains its strength to 1500 °C and higher
- is radiation resistant (and non-parasitic), and
- is one of the hardest materials in nature.

Silicon Carbide (SiC)

- Beginning in the early 1990s, a new development: silicon carbide composites made from radiation-resistant fibers with toughness equivalent to metals.
- Irradiated to very high fast fluences in Fusion R&D programs with little loss in strength

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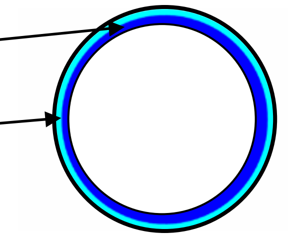
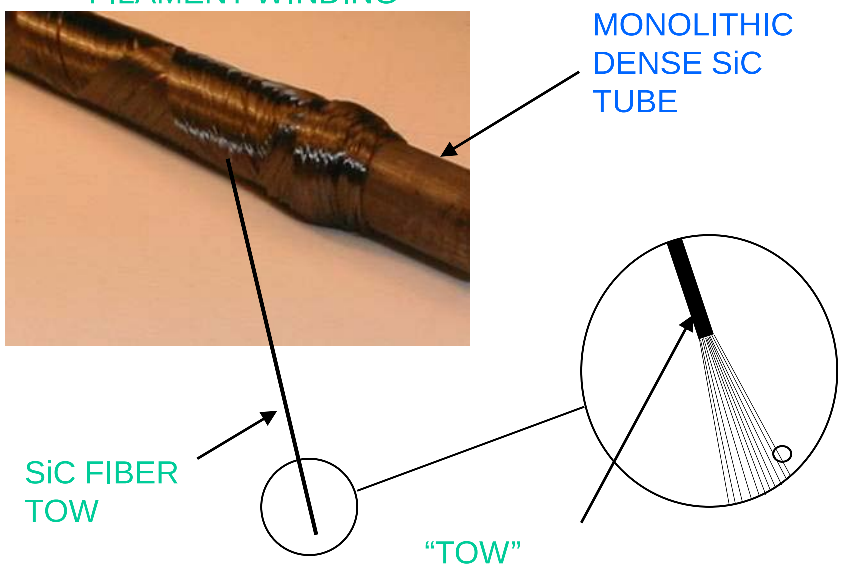
Westinghouse SiC duplex Clad

- SiC Duplex Cladding
  - Monolithic dense SiC inner layer (12-20 mils)
  - SiC/SiC composite (fiber + infiltrated SiC) layer (12-15 mils)



FILAMENT WINDING

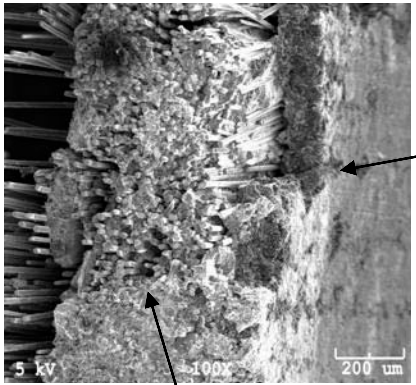


MONOLITHIC DENSE SiC TUBE

SiC FIBER TOW

“TOW” (500-1000 FIBERS)

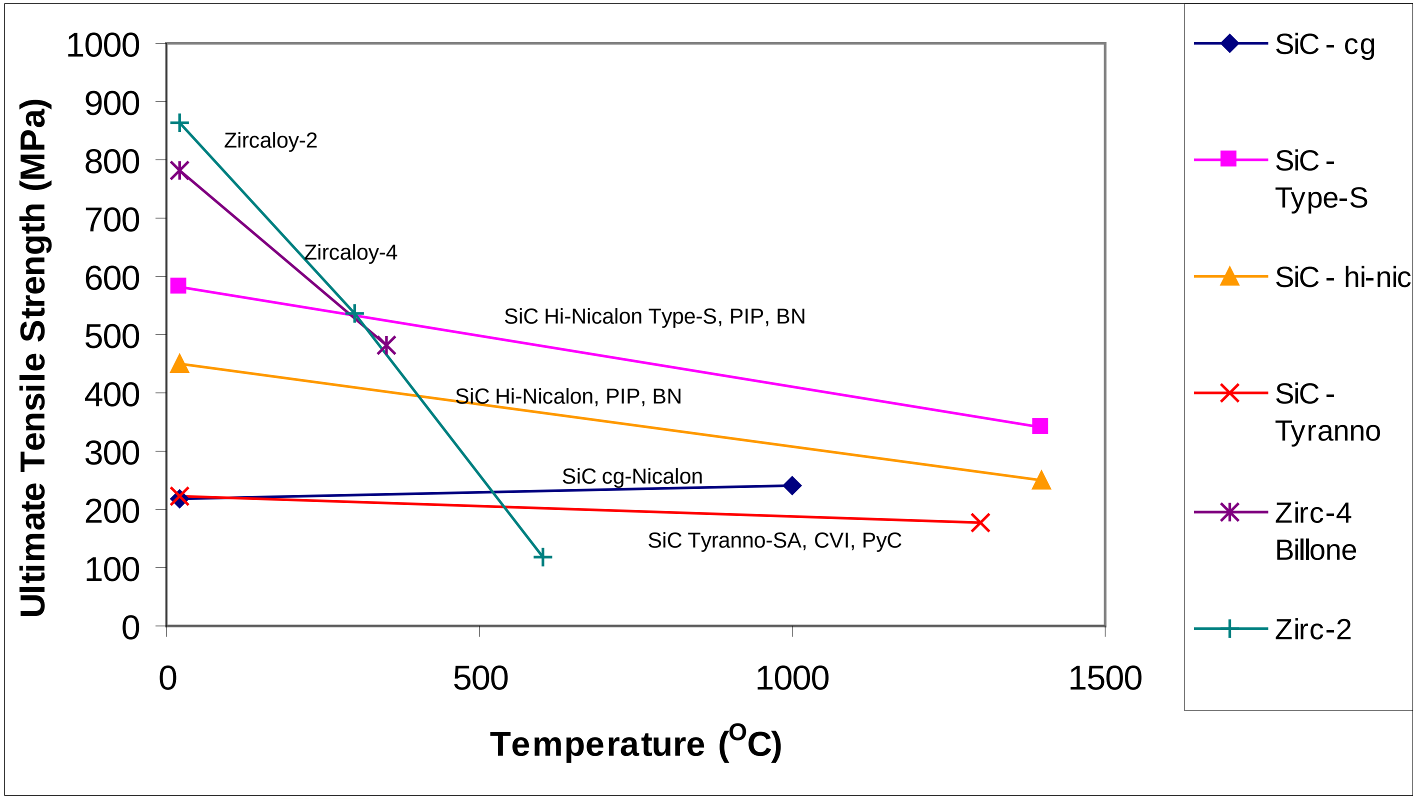
MATRIX DENSIFICATION



BARRIER LAYER

SiC_f/SiC COMPOSITE LAYER

SiC Composite Tubes Maintain Strength to Very High Temperatures



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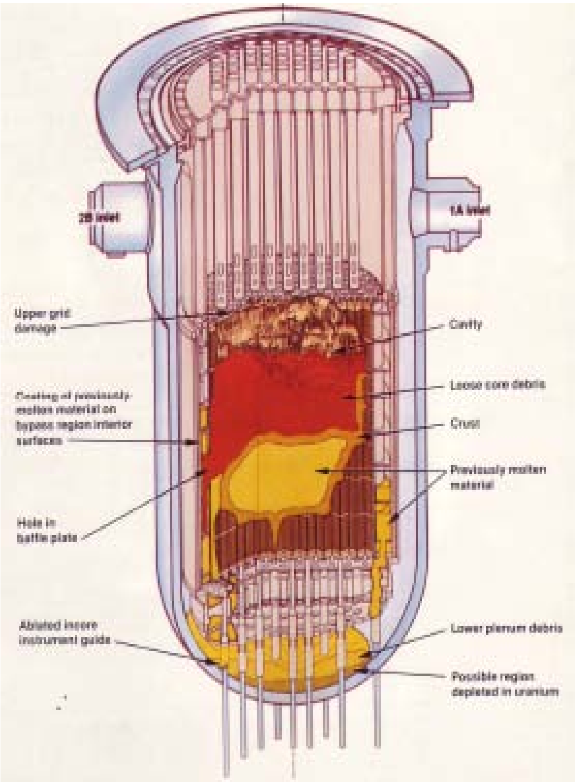
TMI-2 might have been nothing more than a minor incident if they had used SiC tubes.



TMI-2 Core End-State Configuration

- Zircaloy Cladding (used in TMI reactor)
  - Tubes ballooned at 900°C after 2 hours
  - Coolant blockage at approx 1200°C
  - Exothermic reaction of zirc with H_2O
- Silicon carbide composite cladding
  - Retains strength to >1500°C
  - No ballooning with minimal reaction
  - Very little damage – gas only

Conclusions

- Could have avoided $3B cleanup
- Could have saved a $2B asset
- Would have provided more response time for operators

Increased safety leads to greater public acceptance of Nuclear

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SiC is "Game Changing"

- One of the hardest materials known
  - Debris resistant
  - Radiation resistant
  - Significant margin increase to typical failure mechanisms
- Lower parasitic absorption cross section than Zircaloy
  - Large improvement in fuel cycle economics
- Dramatically improved performance under accident conditions
  - Anticipated to withstand LOCA, dryout and DNB without failing or oxidizing

Significant benefits in nuclear safety and operating costs

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Potential High Density Fuels

Material	Melting Point (C)	Density (gr/cm^3)	Content of uranium g/cm3	Conductivity Thermal @500°C W/m*K	XS barn/U atom	Strength	Manufacture cost/complexity
UO_2	2760	10.96	9.66	2 to 4	0.0004	Brittle	Benchmark
UN	2650	14.4	13.55	High	Low w/ N^{15}	Strong	similar UO2
U_3Si_2	~1500	12.2	11.31	High	Low	Glassy Alloy	>UO2
5w/o BeO+UO_2	2600	10.8	9.18	Moderate	Low	Brittle	similar UO2
(ZrU)Al, Si	1600	8.5		High	Low	Extrudable	metal >>UO2
ZrUH (TRIGA)	>1200°C	7.6	5.48	High	Low	Extrudable	metal >>UO2
UH-$_3$	Non stable	10.93	10.79		Low	Extrudable	>UO2
UAl_2	1590	8.1	6.60	High	Low	Extrudable	metal >>UO2
U3Si	930	15.05	14.48	28	0.0533	Glassy Alloy	>UO2

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50 MWd/kgU =~10 nvt's. UO_2 swelling ~4.2% (linear expansion) =~ 10% (volumetric)

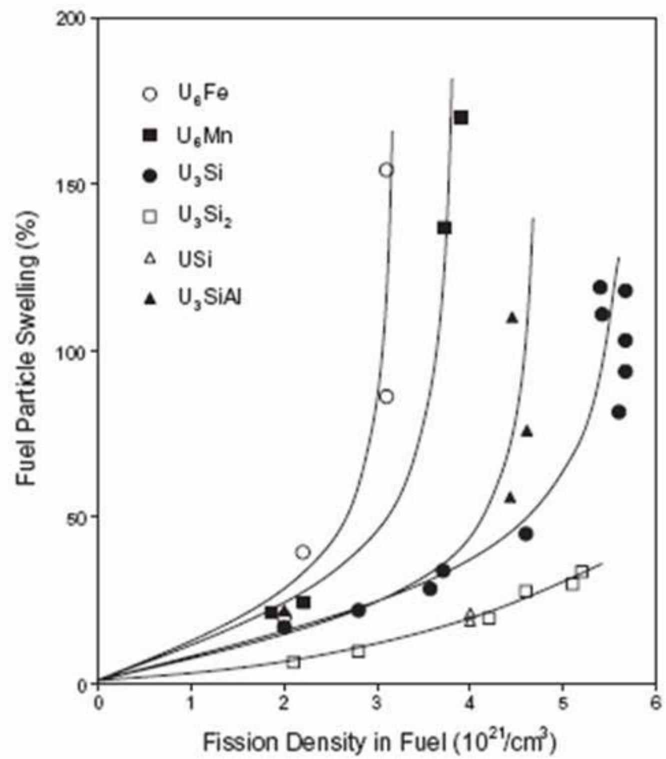

Fig. 3. Fuel particle swelling (ΔV_f) as a function of fission density. The fuel particle swelling is calculated from the mini-plate swelling.

444 URANIUM DIOXIDE: PROPERTIES AND NUCLEAR APPLICATIONS

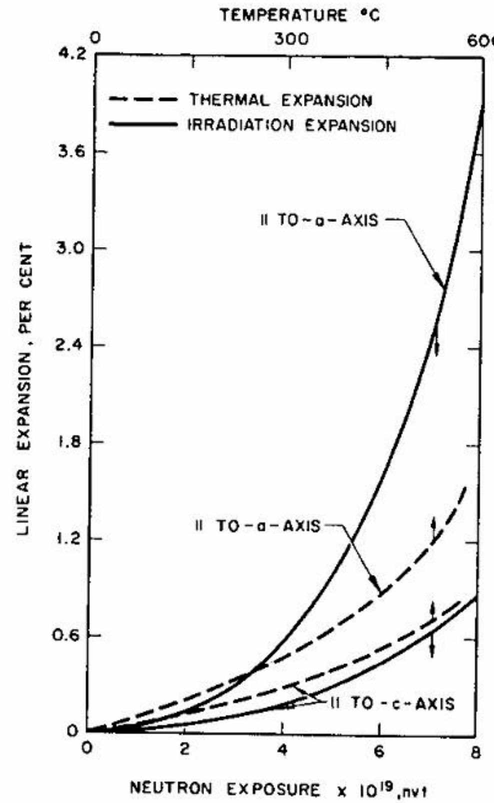

FIGURE 9.1. Lattice Expansion of Quartz Caused by Neutron Irradiation and Temperature [21].

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High Density Pellets

- UN and others
  - Can pack in more Uranium in same geometry (fuel cycle cost)
    - For instance, UN enriched to 5 w/o U-235 has as much fissile uranium as UO_2 enriched to 7 w/o U-235.
  - Allows us to overcome the 5 w/o enrichment limit to enable enough energy to be loaded for long cycles
- All have significantly better thermal properties (conductivity) which results in lower pellet temperatures
- Many have water reactivity problems
- Many may requires enrichment of anion (for instance, N15 for UN)

Remove

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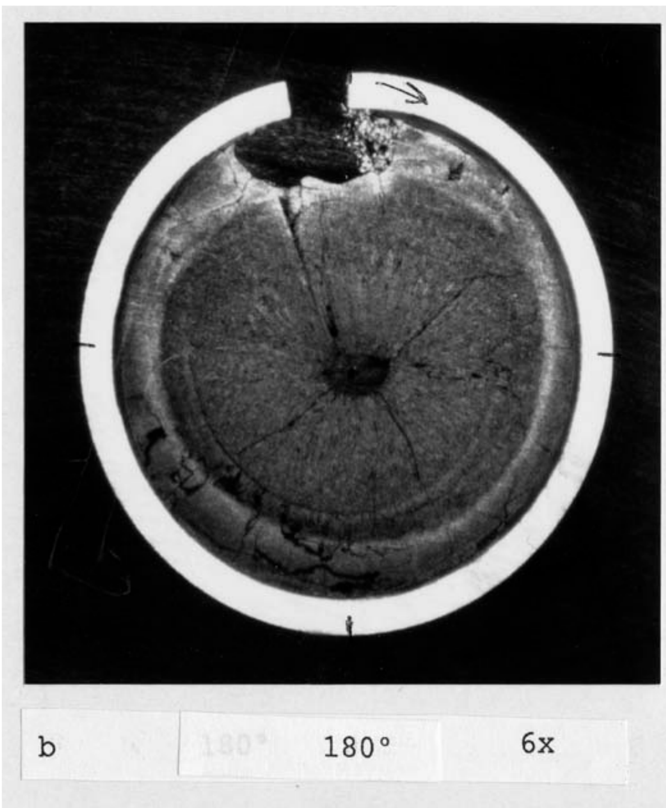
UO_2 and UN Fuel Interaction With Water
The Good and the Very Ugly

UO_2 BWR rod with a large secondary defect (long slit)



UN Pellets in short SS rod with slit 6 Hours in 300°C Water

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Revolutionary Fuel Rod – Value Proposition

- SiC enrichment savings
  - No debris failures, fretting failures or Crud Induced failures
  - Lack of corrosion concerns allows chemistry that removes CIPS constraints (in operating plants)
    - Feed 4-8 fewer assemblies (at higher enrichment)
- UN specifically useful for AP1000 users (to achieve 24 month cycles) & for upratings / 24 month cycles (at high duty) in the existing fleet
  - Cost Savings for these plants in fuel, maintenance, capacity factor improvement – significant value ($5-10M yr)

Revolutionary Fuel Rod Investment Estimates and Risks

- Development Cost and Timetable
  - ~$300 M for SiC alone
  - ~$600 M for SiC/UN
    - UN requires N15 enrichment
  - Will take around 15 - 20 years for commercial deployment
  - Financial issue - costs front end loaded while payback is 20 years out - Investment analyses all look terrible
- Risks
  - Test results could prove product not technologically feasible
    - Manage through stage gates and limited up front investment
  - Licensing risk given the significant impact on the NRC CFRs
  - Cost Benefit assessments will need more detailing before significant investments are made

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BeO Concept

- Addition of ~5% (vol) of BeO powder to UO_2 powder to coat UO_2 grains with BeO to provide continuous thermal path
- Increases thermal conductivity
- BeO also serves neutronic needs as a moderator and through a n,2n reaction as an internal neutron source to amplify the neutron generation rate of U

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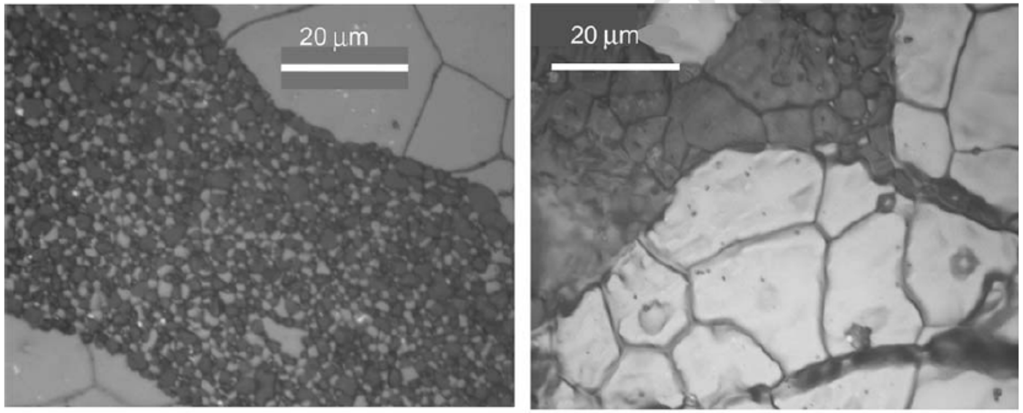
Base Case

- 4.8% BeO, 93.2% UO_2, 2% void (versus 95% UO2, 5% voids)
- Increased thermal conductivity by ~20 to 30% (reduced fuel temperature by ~10%)
- Decreased U content by ~1.9%



(a) (b)

Fig. 9. (a) Polished and thermally etched section of a co-sintered UO_2/BeO pellet fabricated from green, self-milled granules, and (b), from 'self-milled' bisqued granules. Light regions are UO_2, while dark regions are BeO. Reduction in the amount of dispersed UO_2 phase within the BeO phase using bisqued granules is observed.

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Benefits – Thermal Conductivity

- Higher thermal conductivity (20 to 30%) lowers average temperature of fuel pellet ~40 to 60°C
  - More margin during LOCA by lowering volume average temperature (~40 to 80°C)
  - Reduced fission gas release by ~30%
  - Reduced Doppler absorption (partially makes up for U loss)
- Question:

1. Are any of these items currently limiting fuel performance?

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Benefits – Neutronic and Centerline Temperature Melt Give Low Discounted IRR

- Nuetronic
  - Reduced Doppler absorption (partially makes up for U loss)
  - Neutronic benefit from the (*n*, 2*n*) reaction of ^{9}Be with fast neutrons
  - Total benefit = $840k
- Centerline Temperature
  - From BWR example, for each 1% LHGR (kW/m) operating limit increase, reduces front-end FCC by 0.1%
  - Savings would be about 1% based on 10% decrease in centerline temperature
  - Total Benefit = $540k
- Total Benefit = $1.38M or @50% to vendor, $690k profit (minus added manufacturing costs)
- Discounted (8%) IRR assuming $100M for testing, licensing and manufacturing changes @30 reloads/yr = 3%

Fuel Type	**235U Enrichment**	**Total U Loading, kg**	**Cost @$105/kgU as UF6, $130/SWU, $200/kgU fabrication**
UO_2	4.027	27820	$55,000,140
UO2-5% BeO	4.034	27290	$54,161,490 (BeO=$250/kg)

TRITON control module of SCALE 5.0 with the 238-energy group cross-section library.. Comparisons made between the currently-used UO2 fuel and BeO fuel in a 15x15 pin subassembly Babcock and Wilcox reactor

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Manufacturing Issues – No Issue

- Review of 10CFR850 [20] 116 by Solomon et al. indicates that the controls for enriched UO_2 should be adequate for BeO as well
- Under the previous 10 times higher Permissible Exposure Limit of 2 mg/m^3, the Atomic Weapons Establishment beryllium facility in Cardiff, Wales had only one case of chronic beryllium disease stemming from a non-standard event in over 36 years of operation
- Addition of BeO would present only minor technical issue during manufacture

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Added Costs

- BeO powder - $250/kg
- Blending step for BeO and UO_2
- High sintering temperature – new furnaces, longer sintering times
- Testing and Licensing – Estimate is $70M
- Customer acceptance – not likely an issue since no negative effects apparent

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Enriched Gadolinium - Overview

- Gd occurs naturally as seven isotopes but only Gd155 and Gd157 provide the neutron absorption needed for core design – these make up only 30% of the total
- The other isotopes result in parasitic absorption resulting in shortened fuel cycles and therefore lost uranium utilization
- Use of Gd enriched in the two odd isotopes significantly improves the performance of gad as a burnable absorber – getting much closer to the performance of ZrB_2 IFBA
- Separation method is technically challenging since no volatile Gd compound (volatile) known

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Enriched Gadolinium - Value

- An enriched Gd product would be extremely attractive to BWR customers and non-IFBA using PWR customers, due to the significant savings in Fuel cycle costs
- Estimates range from ~$33k/kg for Gd155+Gd157 to ~$45k/kg for pure Gd157

Enriched Zirconium - Overview

- Zr occurs naturally as five isotopes (90, 91, 92, 94, and 96) with Zr91 and Zr92 having very high neutron absorption cross-sections – these make up only 28% of the total
- The other isotopes have much lower parasitic absorption
- Separation method is technically challenging because high temperatures (~300°C to 400°C) are required for $ZrCl_4$ volatility
- Cl has two isotopes

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Enriched Zirconium - Value

- An enriched Zr product would be extremely attractive to LWR fuel customers due to the significant savings in fuel cycle costs
- Estimates range from ~$330/kg for pure Zr90 to ~$260/kg for no Zr91+Zr92

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Industry Needs for Revolutionary Fuel Rod Investment

- More streamlined approach to testing and licensing
- Access to test data from national labs
- Significant aid for testing
  - Test reactor access
  - PIE facilities
  - Timely access to test facilities
  - Modeling of test results
- IP protection agreements

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