Idaho National Laboratory

High Burnup Fuels

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GCEP Fission Workshop
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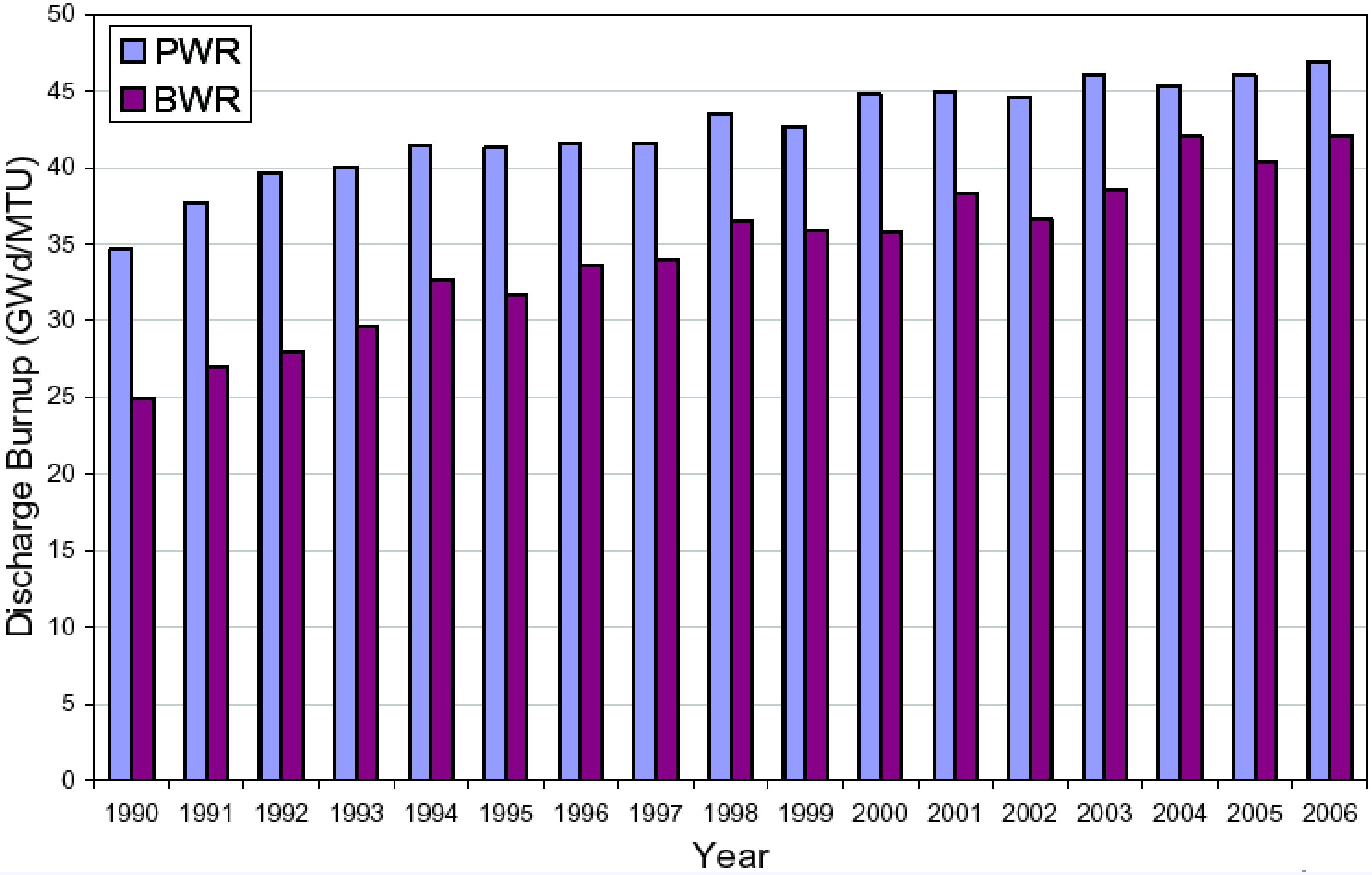
Massachusetts Institute of Technology

Focus: LWR Fuel

- Current LWR fuel technology
- Example of potential high burnup fuel technology

Average LWR Discharge Burnup



Source: EPRI

LWR Fuel Failures

Currently dominated by ‘external’ factors:

- PWRs
  - Grid to rod fretting
  - Corrosion/crud
  - Debris fretting
  - Fabrication defects
  - Pellet cladding interaction (PCI)/ Stress corrosion cracking
  - Axial offset anomaly
  - Unknown causes

- BWRs
  - Crud/corrosion
  - Debris fretting
  - PCI (non-barrier fuel)
  - Unknown causes

PWR Failure Rates

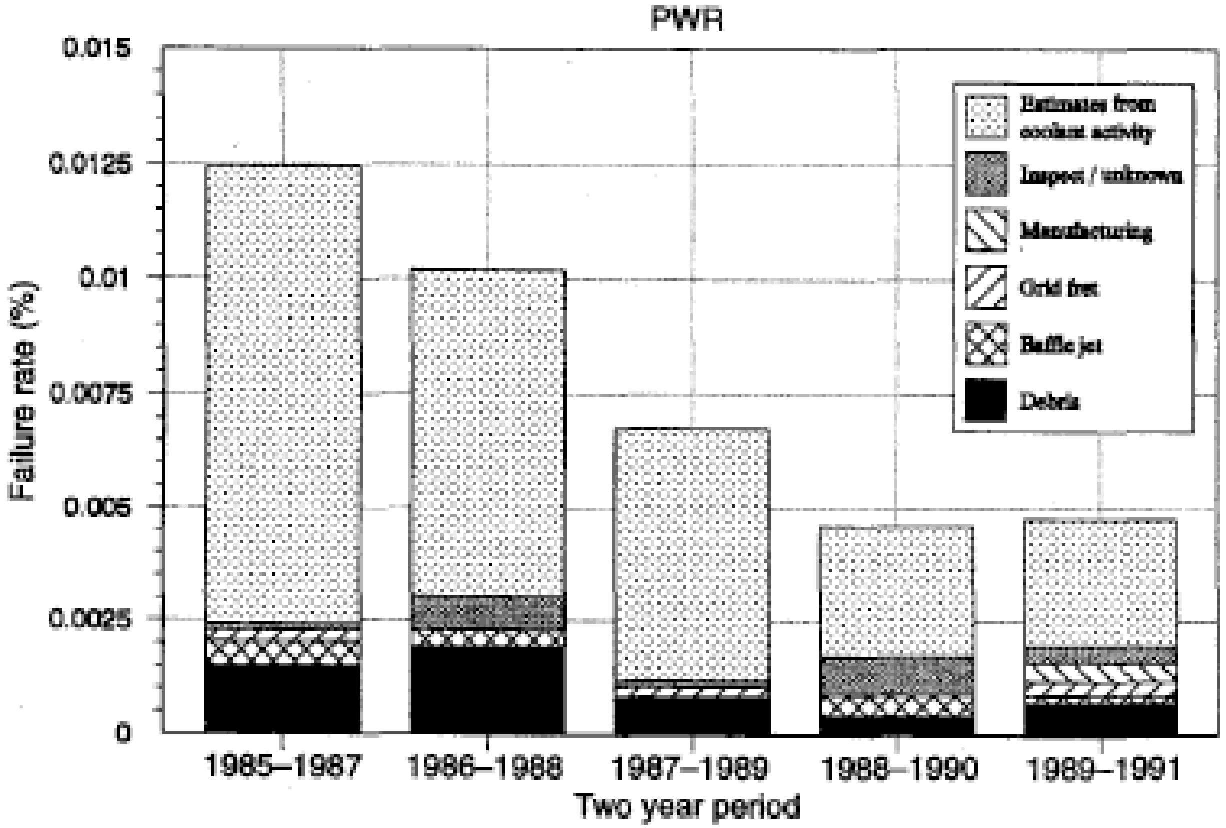


FIG. 3.1. Fuel failure rates in US BWRs and PWRs, Stoller evaluation [3.6]. (CILC — crud induced localized corrosion.)

Source: IAEA Technical report #388

Current Situation

- **U.S. industry goal of zero fuel defects by 2010**
  - **Emphasis on fuel *reliability***
  - **Implies conservative limits on burnup for current fuel systems**
  - **May limit operational flexibility**
- **Improved cladding materials available**
- **Burnup increases are leveling off in U.S.**
  - **PWR ~ 47 GWd/t**
  - **BWR ~ 42 GWd/t**
- **Increasing fuel costs driven by uranium market may tilt equation in favor of higher burnup**
- **Competitive market in in 1990's squeezed vendor R&D funding**

LWR Fuel Burnup Limits

- **Potential limiting factors:**
  - Pellet cladding interaction
  - Rod pressure
  - Hydrogen pickup (cladding embrittlement)
  - Corrosion (oxide layer)

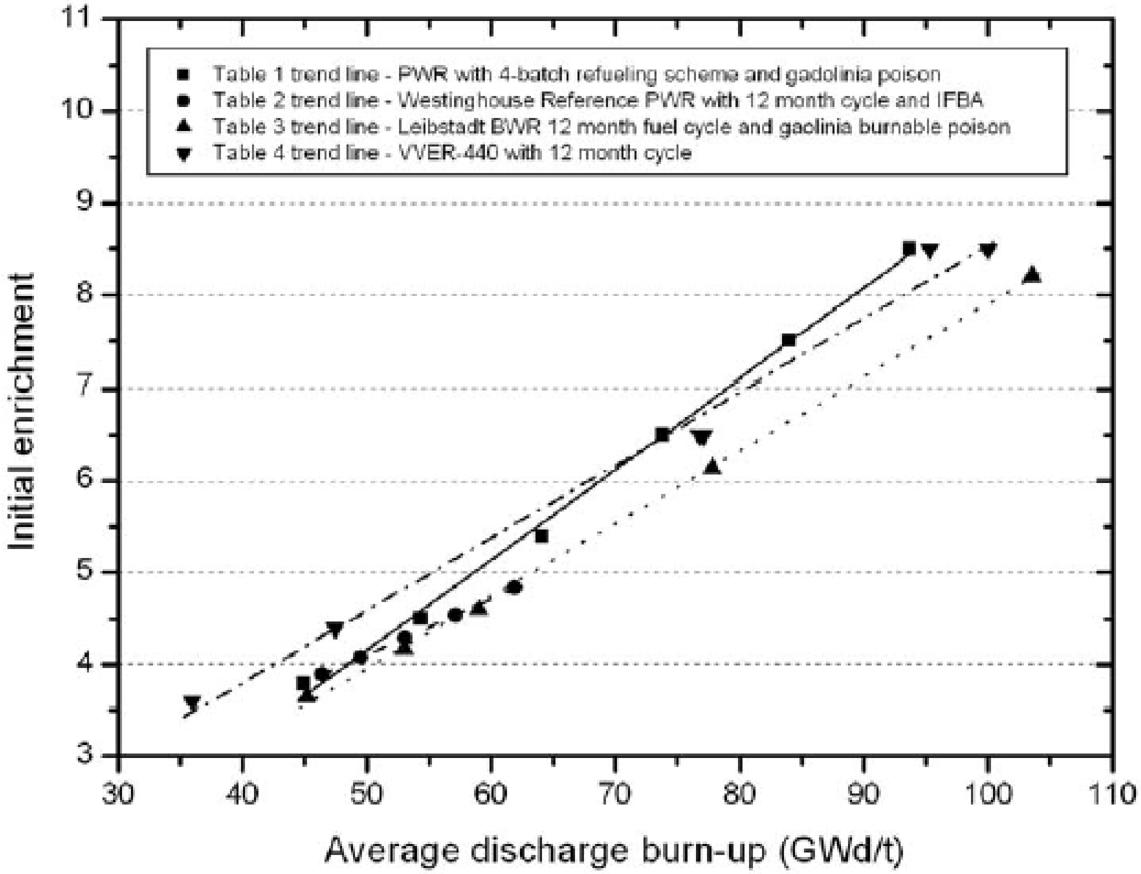
- **What is the burnup limit?**
  - At least one example of 100 GWd/t
  - May be able to tweak current UO_2 pellet fuel system to > 75 GWd/t
  - More importantly, what are the margins?

Development Needed for High Burnup

- Fuel performance
  - Fission gas release
  - Swelling/PCI
  - Cladding behavior
  - Off-normal behavior not well known (RIA, ATWS, LOCA)
- Criticality limits
  - Enrichment plants
  - Fuel fabrication plants
  - Reactor storage racks
- Spent fuel
  - Storage (62 GWd/t)
  - Transportation (45 GWd/t)
  - Cladding properties

Enrichment

Figure 1. Initial enrichment versus average discharge burn-up trend lines corresponding to Tables 1, 2, 3 and 4

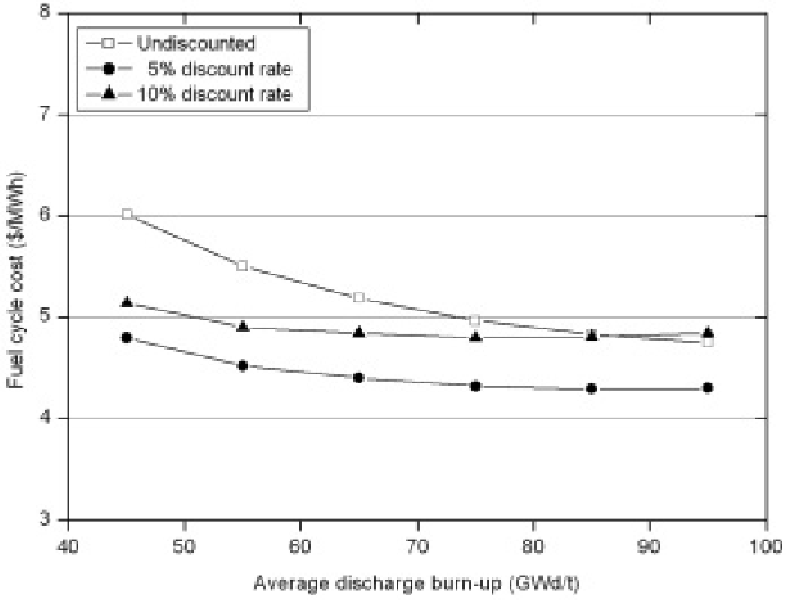


- Depending on the assumptions, enrichment > 5% required for > 60 GWd/T

OECD/NEA (2006)

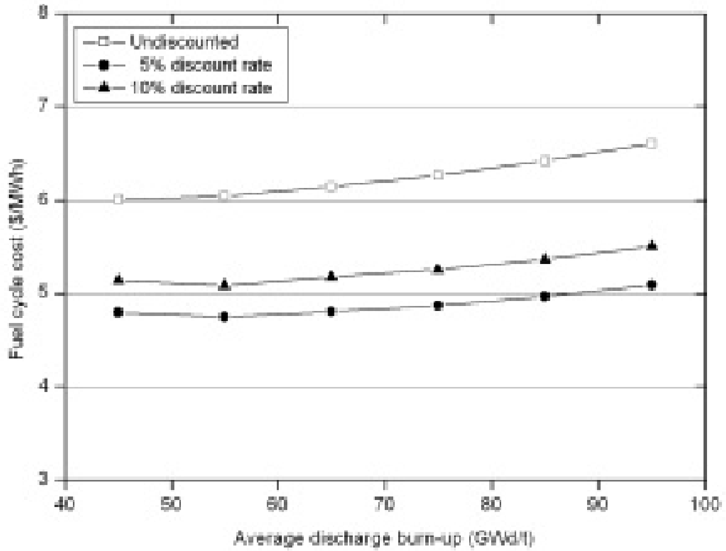
Economics

Figure 25. FCE fuel cycle levelised cost versus average discharge burn-up and discount rate – optimistic initial enrichment/burn-up relation and burn-up-independent unit costs



- Depending on the assumptions, fuel cycle costs estimates tend not to do not decrease with burnup beyond 55 – 70 GWd/t

Figure 27. FCE fuel cycle levelised cost versus average discharge burn-up and discount rate – optimistic initial enrichment/burn-up relation and burn-up-dependent unit costs



OECD/NEA (2006)

Why Bother?

- There are currently less than 100 fuel failures per year in the U.S.
  - BWR + PWR, 2004-2006
  - Failure rates are stable/declining?
- Most are the result of mechanical design, water chemistry, and debris
- No broad, clear economic incentive for higher burnup
  - No change to back end cost in U.S.
  - Enrichment > 5% beyond 60 GWd/t
  - Fuel cost ~ 20% of operating cost, insensitive
  - Fuel development is expensive

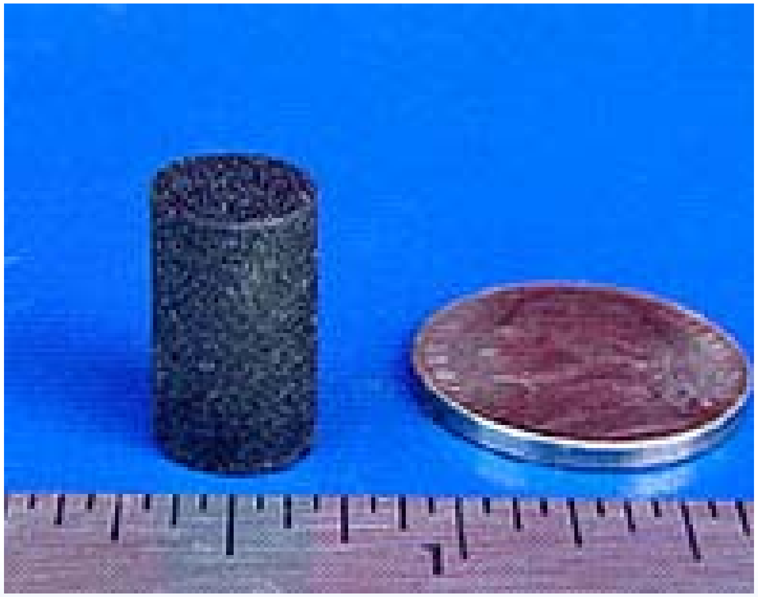
Robust Fuel

- Emphasis on fuel reliability may point toward development of *robust* fuel
  - High reliability
  - High burnup capability
  - Flexible plant operation
  - Improved safety margins

- A few possibilities:
  - Dispersion fuel
  - Coated particle fuel
  - SiC clad fuel

Example: Dispersion Fuel

- Microspheres of a fissionable material
  (UO_2, UN, UC, PuO_2, PuN, ThO_2, etc..)
- Embedded within a continuous matrix material
  (Zr, Al, Mo, Nb, SiC, Zircaloy, Stainless Steel, Graphite, Al_2O_3)
- Clad compatible with coolant, matrix and fuel



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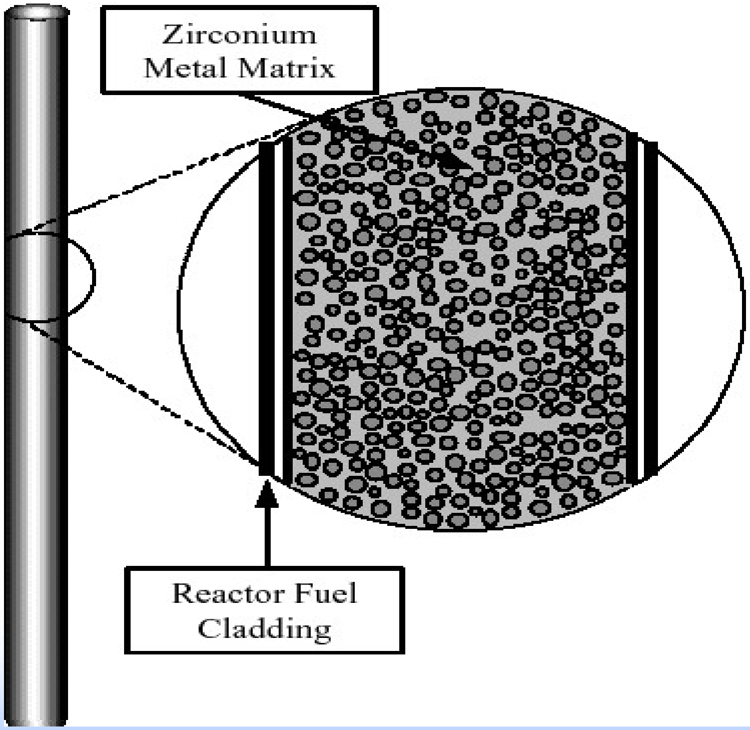
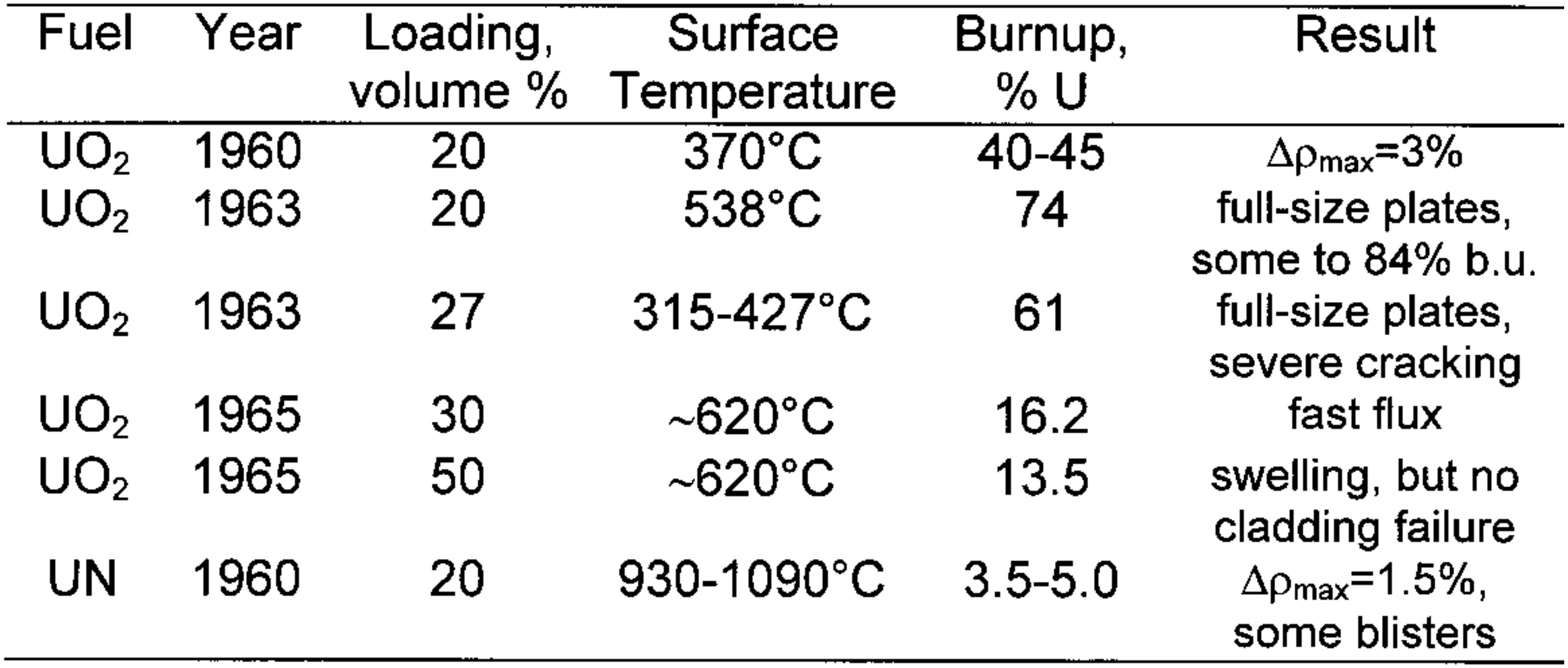


Dispersion Fuel Performance

(stainless steel matrix)



Fuel	Year	Loading, volume %	Surface Temperature	Burnup, % U	Result
UO_2	1960	20	370°C	40-45	$\Delta\rho_{max}$=3%
UO_2	1963	20	538°C	74	full-size plates, some to 84% b.u.
UO_2	1963	27	315-427°C	61	full-size plates, severe cracking
UO_2	1965	30	~620°C	16.2	fast flux
UO_2	1965	50	~620°C	13.5	swelling, but no cladding failure
UN	1960	20	930-1090°C	3.5-5.0	$\Delta\rho_{max}$=1.5%, some blisters

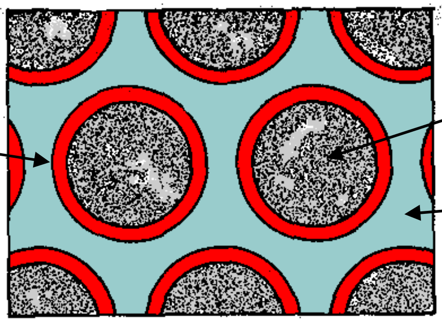
- Heavy metal burnup of 93% enriched fuel
- Plate-type fuel
- Data from UKAEA reports
- Performance depends on microstructure and temperature

Metal matrix dispersion fuels

- **Benefits**
  - Large database on similar fuels
    - Research reactor fuel, early R&D on steel matrix
  - Low failure consequence
  - Cold fuel - can operate at high power density if required
  - Fabrication of pins uses fast, simple technique (extrusion)
  - Should be capable of very high burnup
- **Issues**
  - No data on Zr matrix fuel, experimental work required
  - Lower uranium density requires higher enrichment
  - Large amount of zirconium – impact on recycle
  - Commercial sector acceptance of novel fuel
  - Behavior during accident conditions unknown

Dispersion Fuel

Ideal microstructure

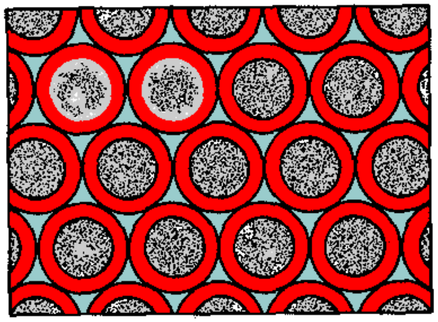


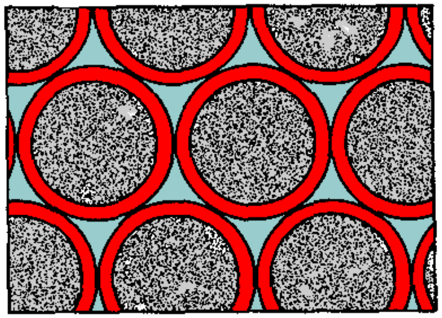
Fission fragment damage zone

Fuel particle

Matrix

Small particle size leads to overlapping damage zones





High volume loading leads to overlapping damage zones

The volume of undamaged matrix depends on fuel volume fraction (V_f), fuel particle size (D), and fission fragment range in the matrix (λ_m).

$$V_{(m)} = - \frac{V_{(f)}}{1 - V_{(f)}} \left[\left(1 + \frac{1}{D/2 \ \lambda_m} \right)^3 - 1 \right]$$

Microstructure

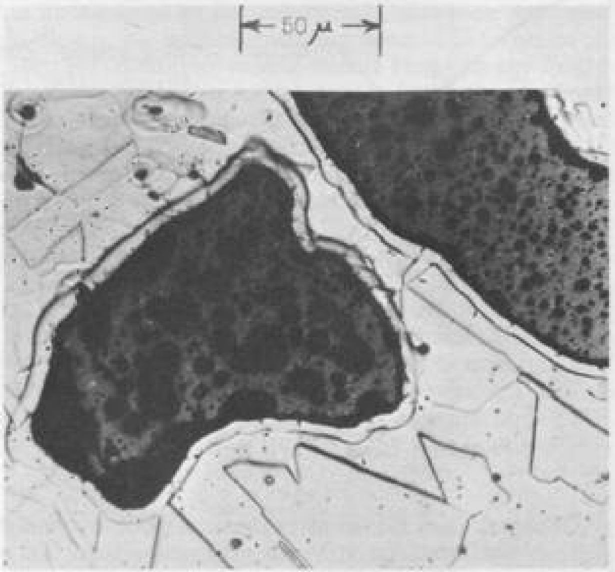
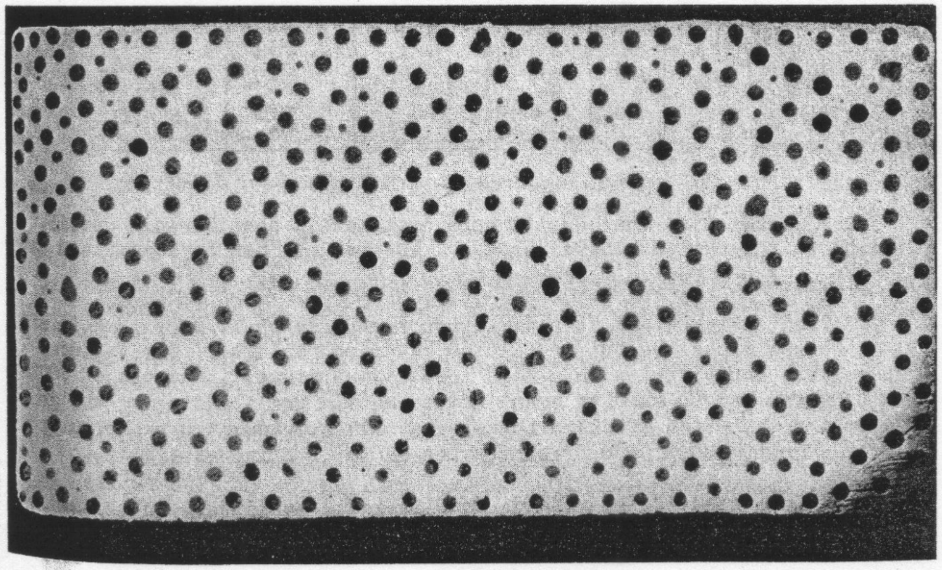


Figure 3. Zone of Fission Fragment Damage [3] in Stainless Steel Matrix Around Uranium Dioxide Particles

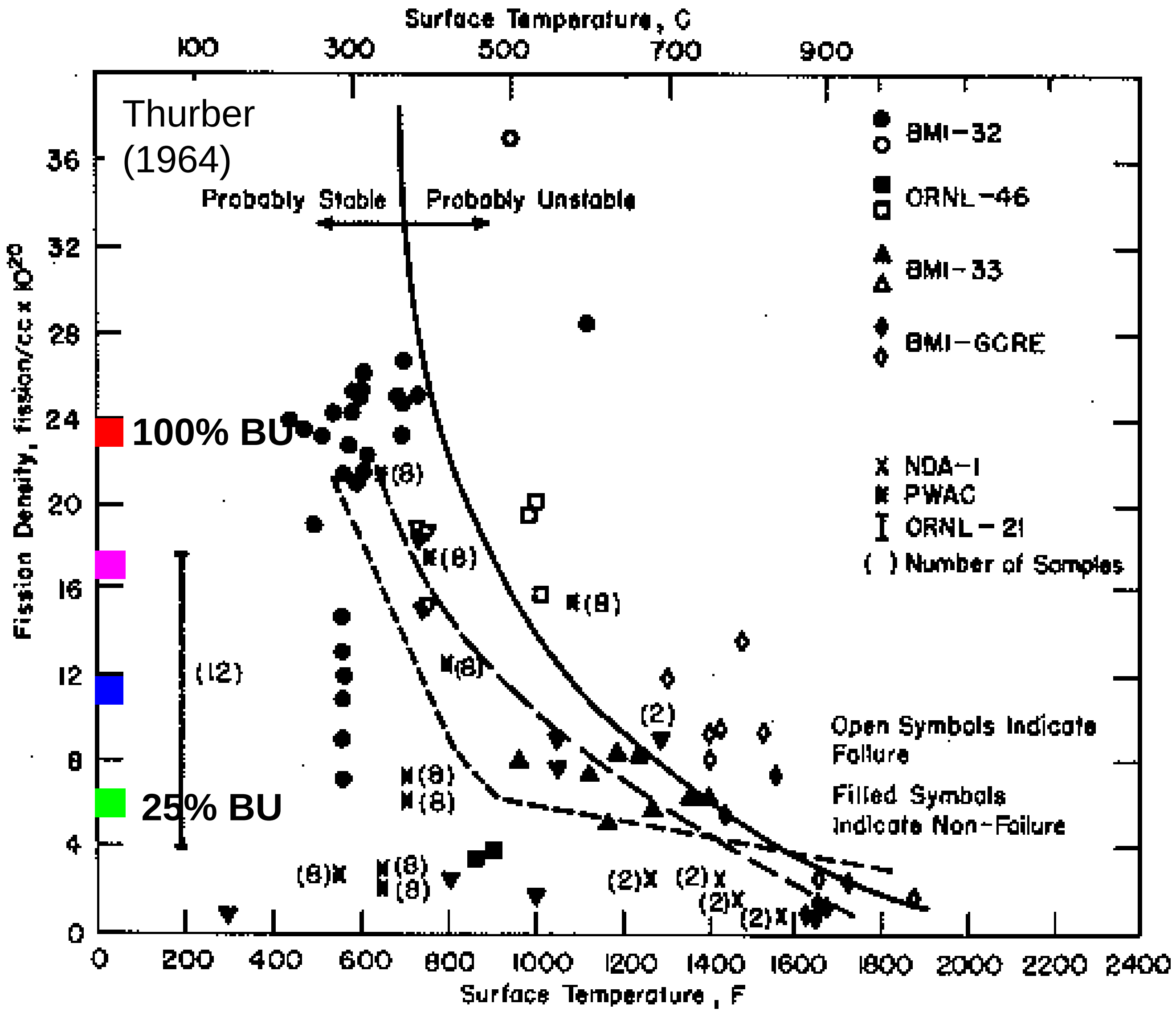


20 v/o UO_2-stainless-steel cermet. UO_2 particle size ~ 350 μm. (Magnification × 5)

Fission fragment damage zone in irradiated fuel

Fuel performance is depends strongly on microstructure

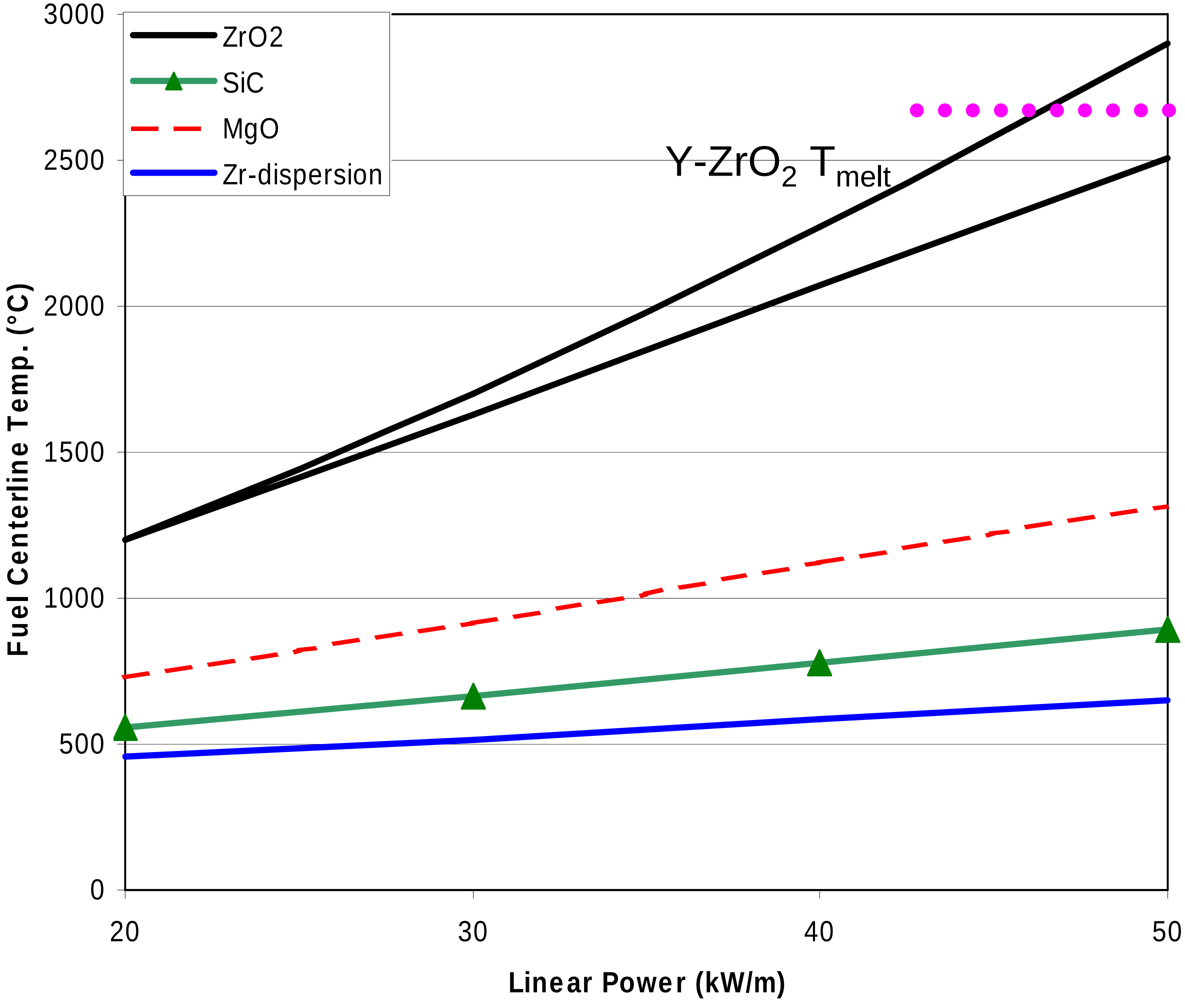
Dispersion Fuel Performance


Thurber (1964)

Example: 16 v/o dispersion of 76 wt% PuO_2 in solid solution with ZrO_2, Y_2O_3, and Eu_2O_3.

Plate-type fuels typically fail by ‘pillowing’ – rods offer more restraint but higher fuel centerline temperatures.

Fuel Centerline Temperatures



Standard 17x17 PWR rod geometry:

Clad OD = 0.914 cm

Clad ID = 0.886 cm

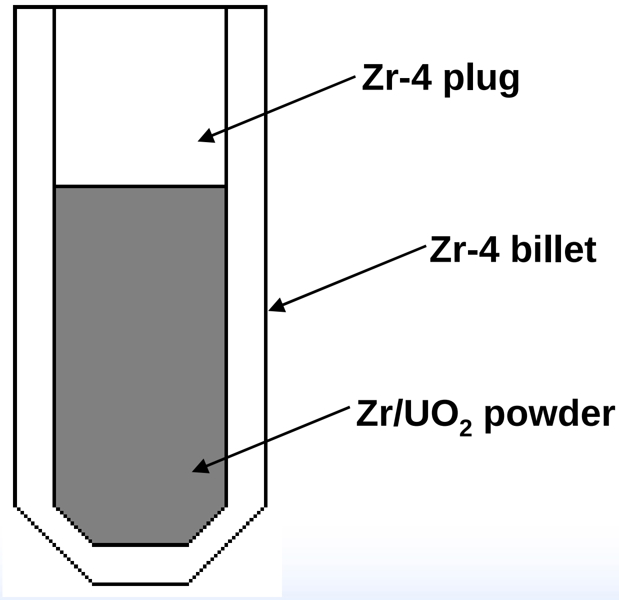
Fuel OD = 0.784 cm

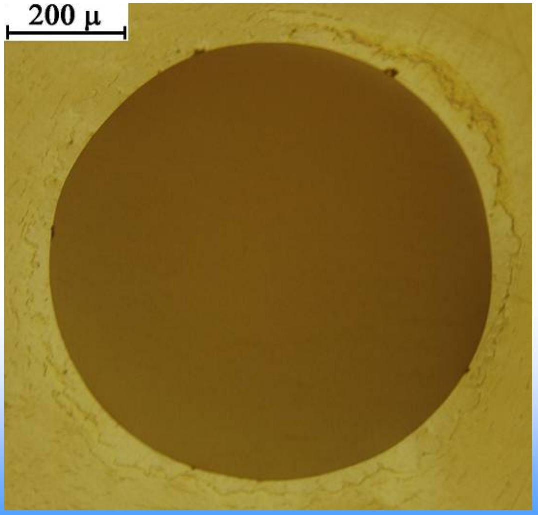
$T_{coolant}$ = 305°C

16 vol.% SiC, MgO, Zr matrix dispersions. Best guess at λ_T.

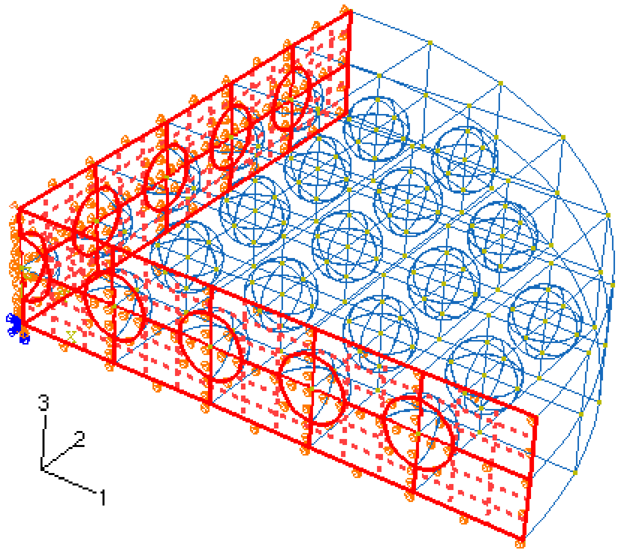
Fabrication

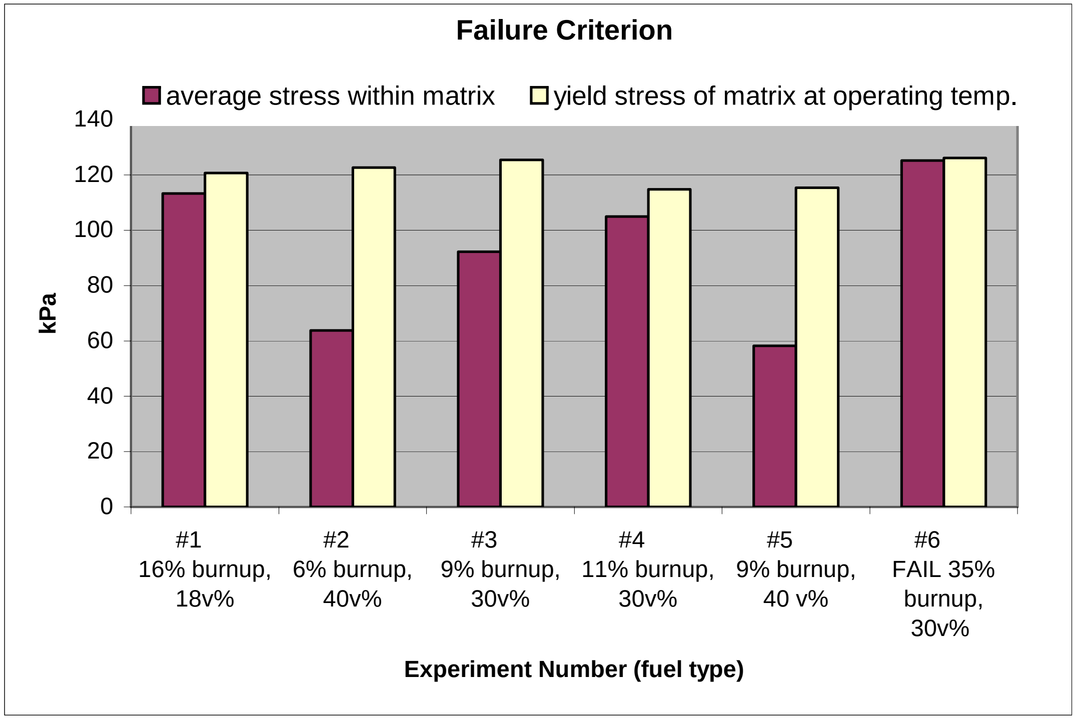
- Nb coated ZrO_2 microspheres
- One-step extrusion of billets at 700-800°C
- Can incorporate burnable poisons in microspheres or matrix





Dispersion Fuel Model





- **Finite element model used to calculate matrix stress**
- **Validated against fuel swelling data**
- **Limited data available for validation of failure criteria**

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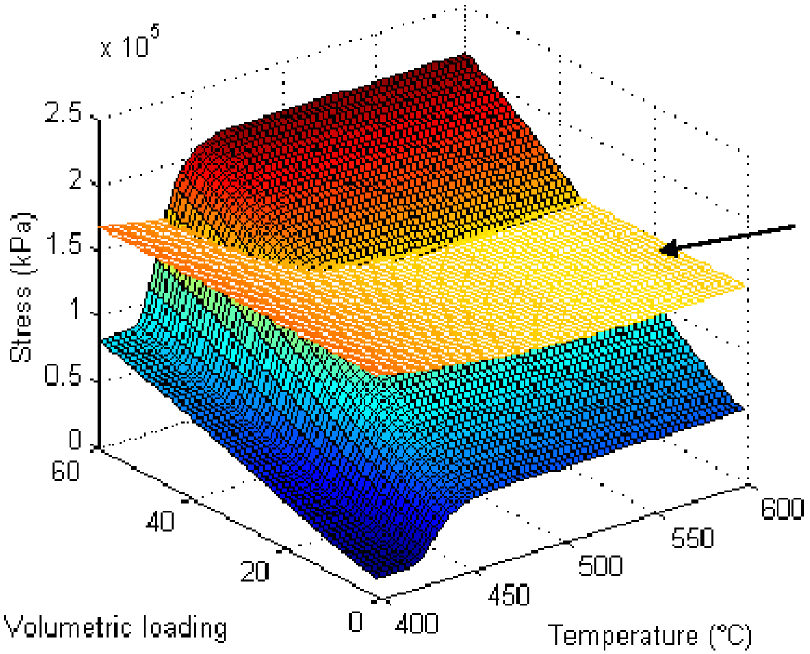
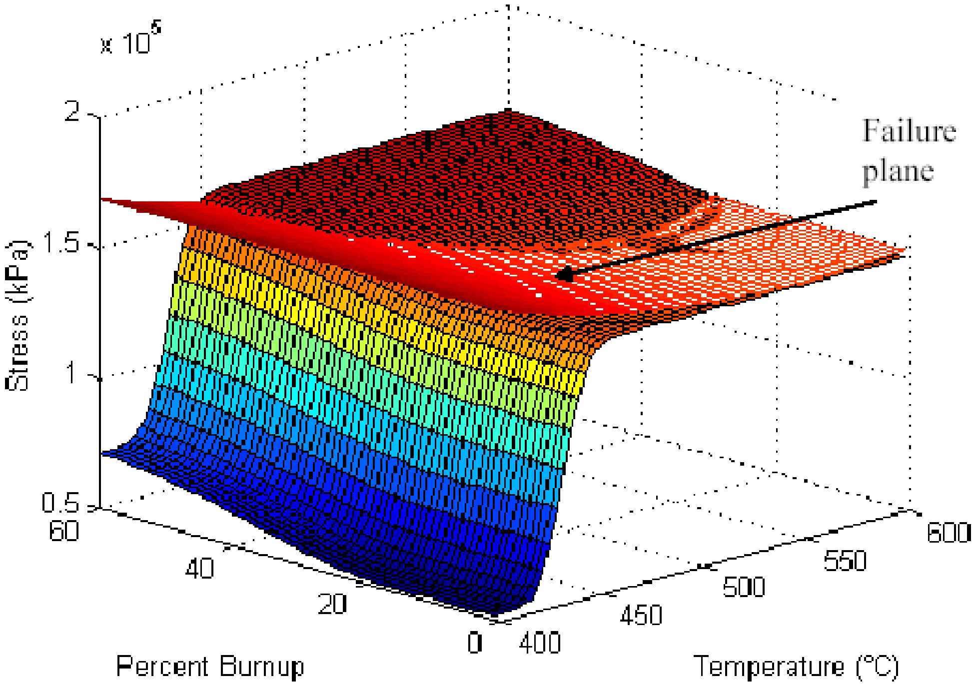
Lee Van Duyn M.S. Thesis, Georgia Tech (2003)

Zr-matrix Dispersion Fuel Failure Surfaces





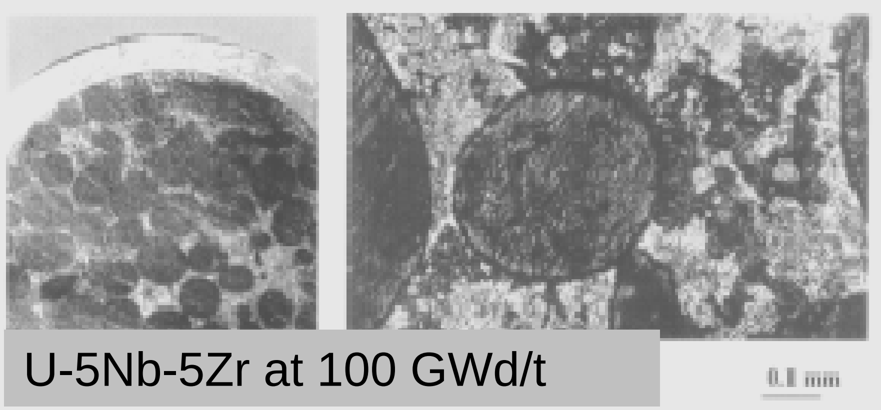
Lee Van Duyn M.S. Thesis, Georgia Tech (2003)

Fuel Parameters

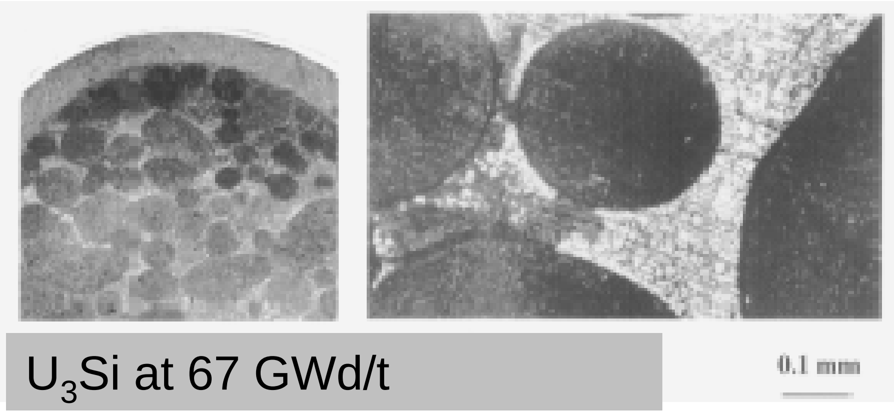
- Strategy depends on fissile material and ‘mission’
  - Uranium or plutonium
  - Deep burning of WG plutonium
- Uranium
  - Enrichment limit of 20% ^{235}U
  - High UO_2 fuel volume loading desirable to increase ^{235}U density
  - Fabrication limit 45 ~ 50 volume percent
  - Burnup potential of ~25% HM in UO_2 particles at T_s = 440°C
  - Uranium enrichment of <20% probably burnup limiting
  - Example: 170 GWd/t at 50% volume loading ~ 85 GWd/t in UO_2 pellet fuel
  - Economic case is marginal, within about 15% of pellet fuel

Increasing Uranium Density

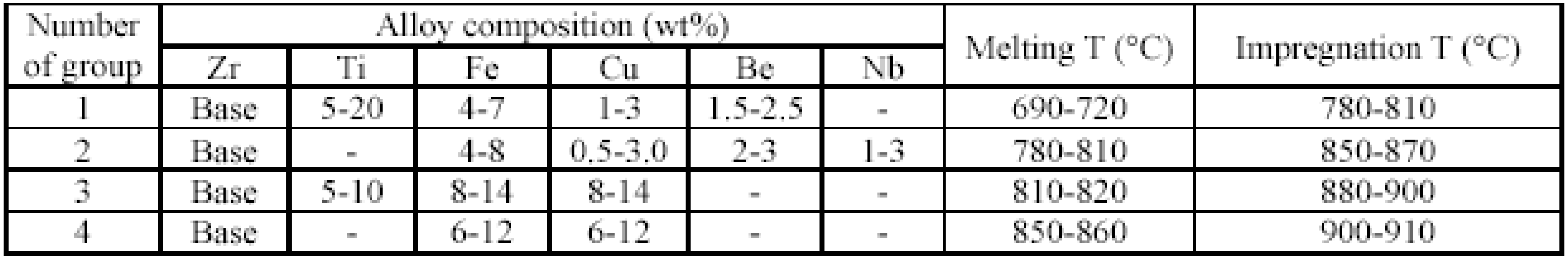
- U alloys have ~50% increase in uranium density relative to UO_2
- Zr alloy matrix, capillary impregnation (U-Mo stringers on extrusion)
- Russian fabrication and irradiation testing results at (350 - 500°C)
- U.S. RERTR program has irradiated > 100 U-Mo/Al specimens



U-5Nb-5Zr at 100 GWd/t



U_3Si at 67 GWd/t



Number of group	Alloy composition (wt%)						Melting T (°C)	Impregnation T (°C)
	Zr	Ti	Fe	Cu	Be	Nb		
1	Base	5-20	4-7	1-3	1.5-2.5	-	690-720	780-810
2	Base	-	4-8	0.5-3.0	2-3	1-3	780-810	850-870
3	Base	5-10	8-14	8-14	-	-	810-820	880-900
4	Base	-	6-12	6-12	-	-	850-860	900-910

Tab 1: Alloy compositions, melting and impregnation temperatures (T)

A. Savchenko, Bochvar Institute (2007)

Plutonium Burning

- **Volume loading likely to be limited by initial reactivity or moderator void coefficient to < 25%**
- **Potential for very high burnup**
- **Good potential for deep burning WG plutonium**
- **Burnable poison can be incorporated in the particles or matrix**
  - **Probably a combination of Gd and Er or Eu**

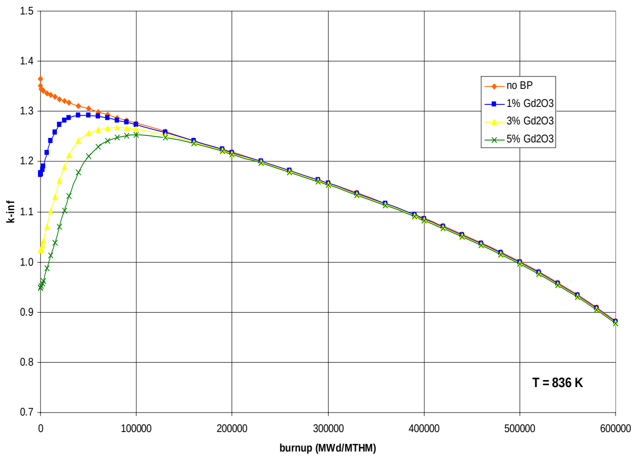


Figure 3. k-inf plotted versus burnup for various concentrations of Gadolinia

Gadolinia

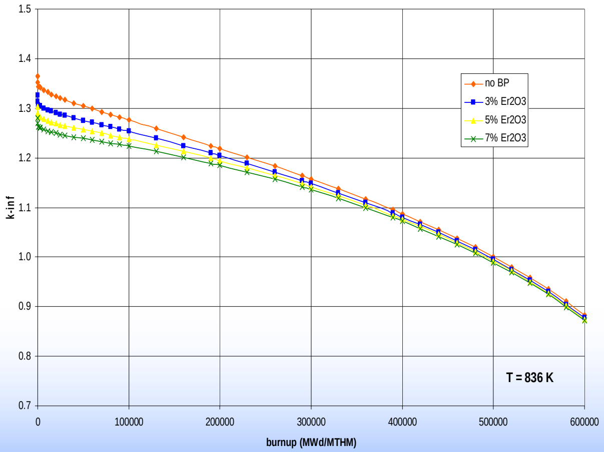


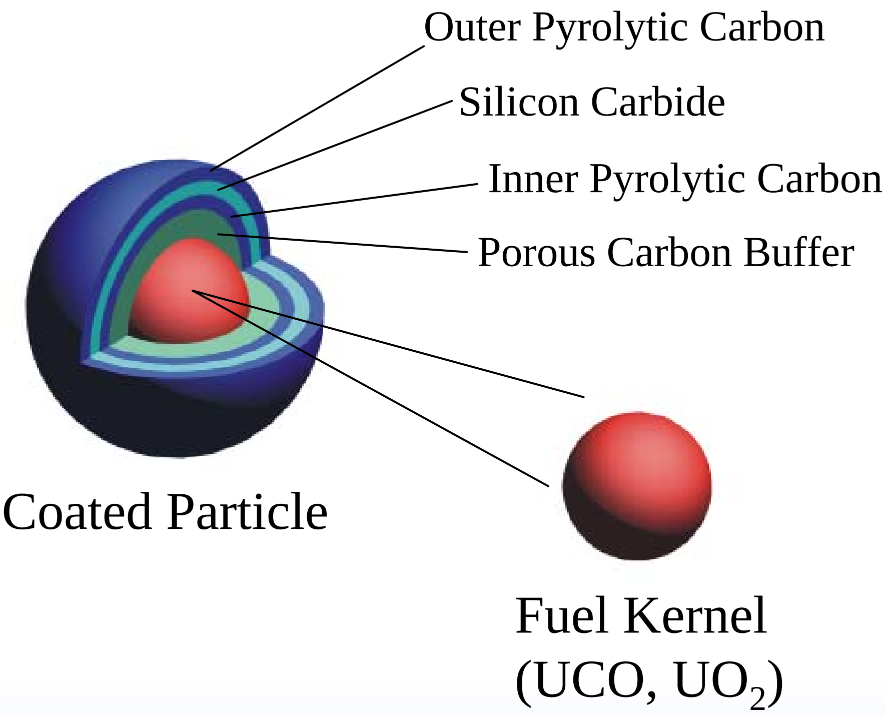
Figure 5. k-inf plotted versus burnup for various concentrations of Erbia

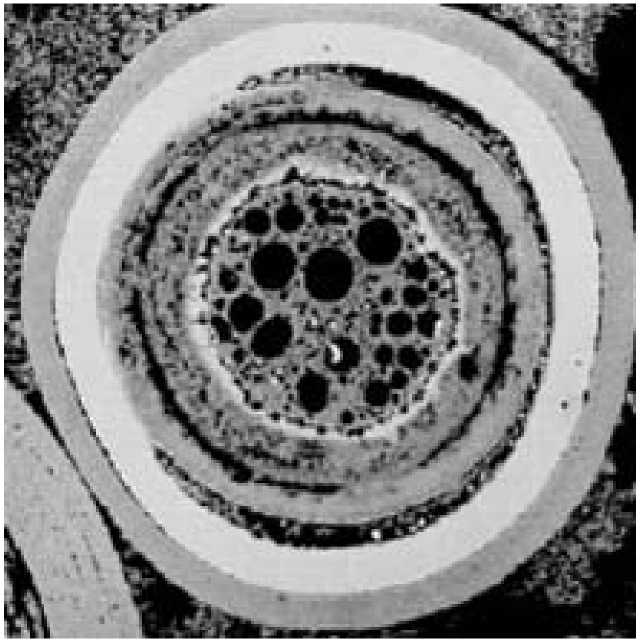
Erbia

Bill Ivans, UF (2004)

Coated Particle Fuel

- **TRISO fuel is extremely robust, but has the same (or larger) U density problem**





Summary

- There is still some room for improvement in burnup performance of current LWR fuels
- Dispersion fuel systems may offer:
  - Increased reliability
  - Lower failure consequence
  - More operational flexibility (load following?)
- New nuclear infrastructure required beyond ~ 65 GWd/T
  - Enrichment (?)
  - Fabrication
- Large fuel development/qualification effort
  - Start with low cost ‘scoping’ R&D
- Economic advantage does not appear to be great, primarily due to enrichment/density tradeoff
  - May be improved with higher density particles