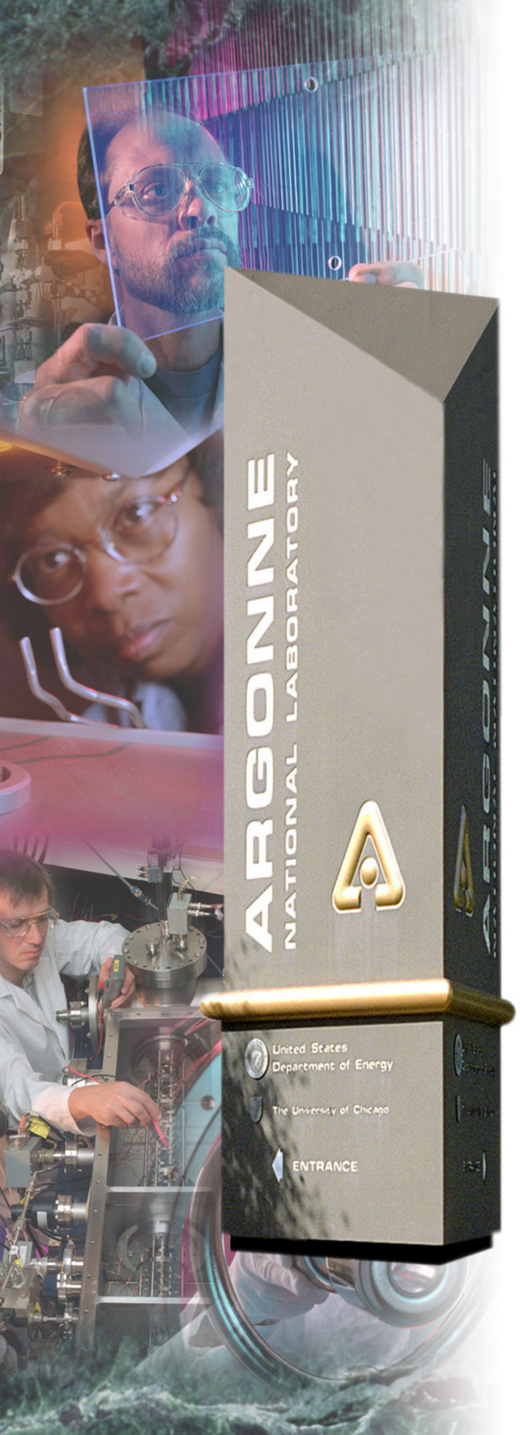

# *Comparison of Inert-Matrix Fuels for Actinide Recycling*

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*Workshop on Advanced Reactors with Innovative Fuels, Oak Ridge, TN, USA*
*February 16-18, 2005*

Office of Science
U.S. Department of Energy

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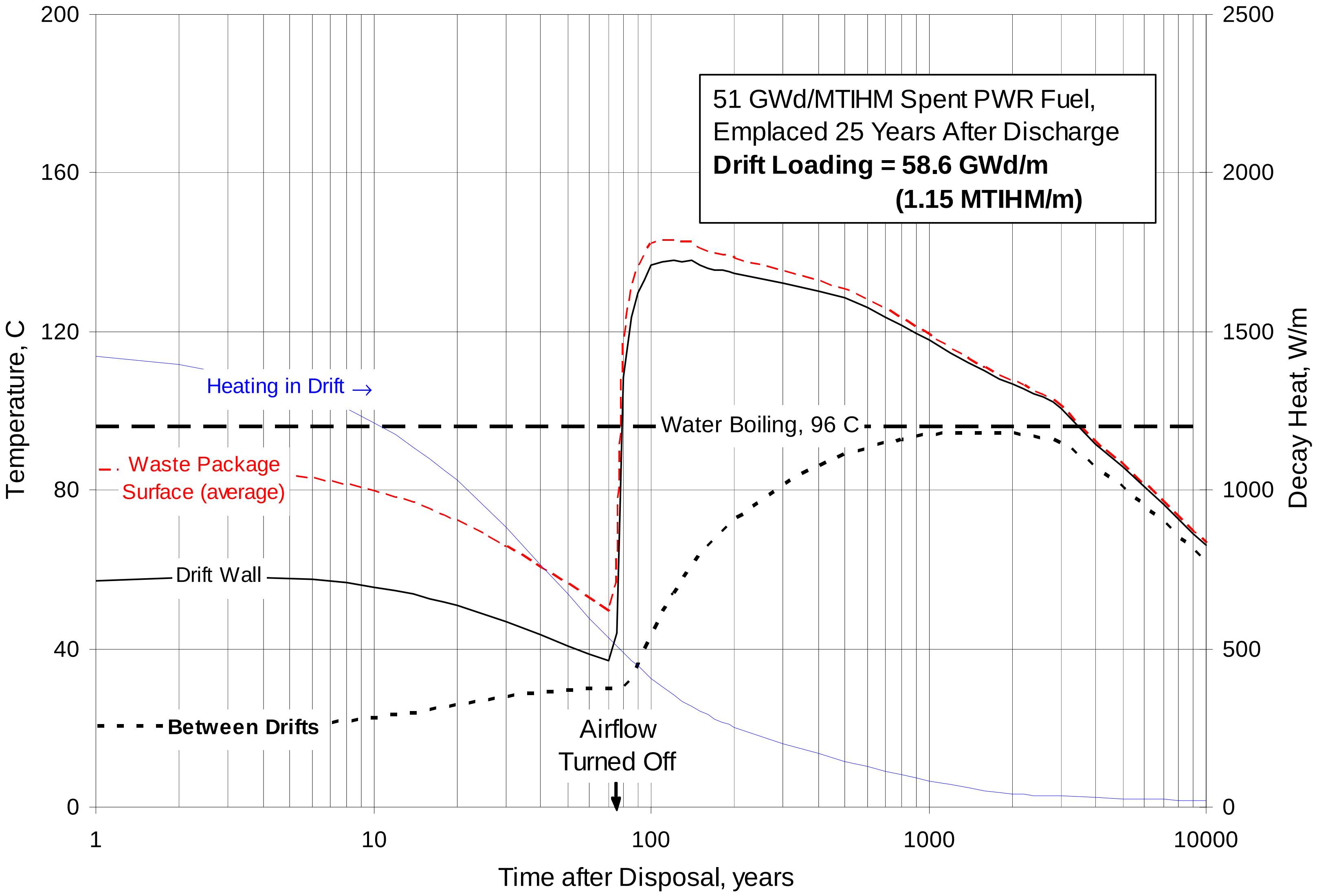
# Outline

- Background
  - Actinide management in nuclear fuel cycle
- Inert-Matrix Fuels
- Analysis Methods
- Results
  - Reactivity letdown
  - Nuclide consumption
  - Repository loading benefit
  - Reactivity coefficients
- Conclusions

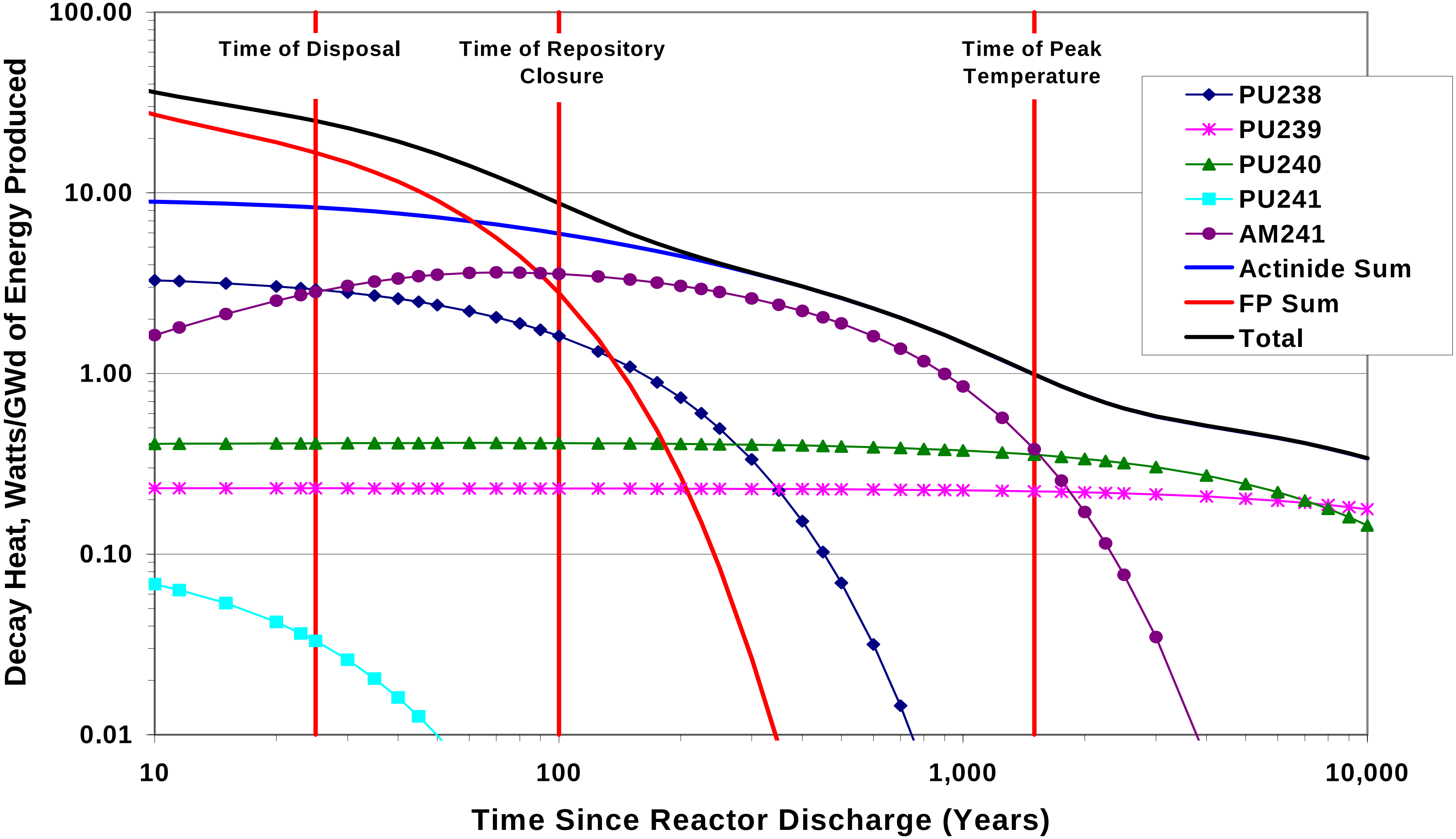
# *Actinide Management in Nuclear Fuel Cycle*

- **Advanced Fuel Cycle Initiative is investigating technologies that will enable sustainability and reduce (but not eliminate) waste management burden through *actinide management in the fuel cycle***
- **Current U. S. fuel cycle is once-through $UO_2$, directly-disposed in a geologic repository (Yucca Mountain)**
- **The drift loading for the direct disposal of typical spent PWR fuel is constrained by the peak temperature (< 96 $^{o}$C) midway between adjacent storage tunnels**
  - Rock temperature is raised by the decay energy released from the time of repository closure to the time of peak temperature
  - Dominant contributors are the actinide elements
    - *Am-241 (created by the decay of Pu-241 in storage) & other isotopes of plutonium*
    - *fission products contribute <5% to integrated decay heat*

# *Repository Transient Thermal Response: Direct Disposal of PWR Spent Fuel*



# *Contributors to Spent PWR Fuel Decay Heat*



# *Actinide Management Options*

- **Production rate of key heat-producing actinides can be reduced through advanced technologies**
  - Higher-burnup LEU
  - Actinide recycling in LWRs (MOX, IMF)
  - Higher-efficiency systems
  - Advanced systems suited for continuous recycle of actinides

| Reactor System | | Conversion efficiency | Fuel form | Burnup (GWd/MT) | Net production (kg/year/GWe) | |
|---|---|---|---|---|---|---|
| | | | | | *Pu* | $Pu^{241}+Am^{241}$ |
| **LWR** | | 33% | $UO_2$ | 50 | 221.9 | 33.7 |
| | | | | 100 | 157.0 | 25.5 |
| | | | MOX (Pu) | 45.2 | -419.7 | 84.8 |
| | | | IMF (Pu) | 510 | **-1034.2** | 39.1 |
| | | | IMF (TRU) | 510 | -871.8 | **-61.0** |
| **NGNP** | | 47% | $UC_{0.5}O_{1.5}$ | 102 | 124.6 | 27.8 |
| **LMR** | CR=0.5 | 38% | U/TRU/Zr | 118 | -358.7 | -48.6 |
| | CR=1.0 | | | | 0 | 0 |

# *Inert-Matrix Fuels*

- **Inert-matrix fuels (IMF) envisioned for weapons-grade plutonium disposition program**
- **Replace depleted-uranium matrix typical of MOX with neutronically-transparent, non-transuranic producing matrix material**
  - Eliminate in-reactor production of plutonium from uranium conversion
- **In <u>solid-solution fuels</u> (SSF) transuranics form a single phase with the inert-matrix**
- **In <u>CERCER dispersion fuels</u> ceramic fuel particles are dispersed in a ceramic material matrix**
- **In <u>CERMET dispersion fuels</u> ceramic fuel particles are dispersed in a metallic matrix**

# Inert-Matrix Fuels

| | Matrix | Advantages | Disadvantages |
|---|---|---|---|
| **SSF** | $ZrO_2$-$8.6Y_2O_3$ | - Easier fabrication | - Low thermal conductivity<br>- Poor aqueous recycle potential |
| **CERCER** | SiC | - Good thermal conductivity | - Particle volume fraction <30% for all dispersion fuels<br>- SiC reaction with Zircalloy |
| | $ZrH_{1.6}$ | - Additional moderation softens spectrum<br>- Good thermal conductivity | - Decomposition at temperatures >600oC |
| **CERMET** | Zr | - Excellent thermal conductivity<br>- Better FP retention<br>- Pyroprocess recycle potential | - Limited experimental work |

# *Evaluation of Inert-Matrix Fuel Forms*

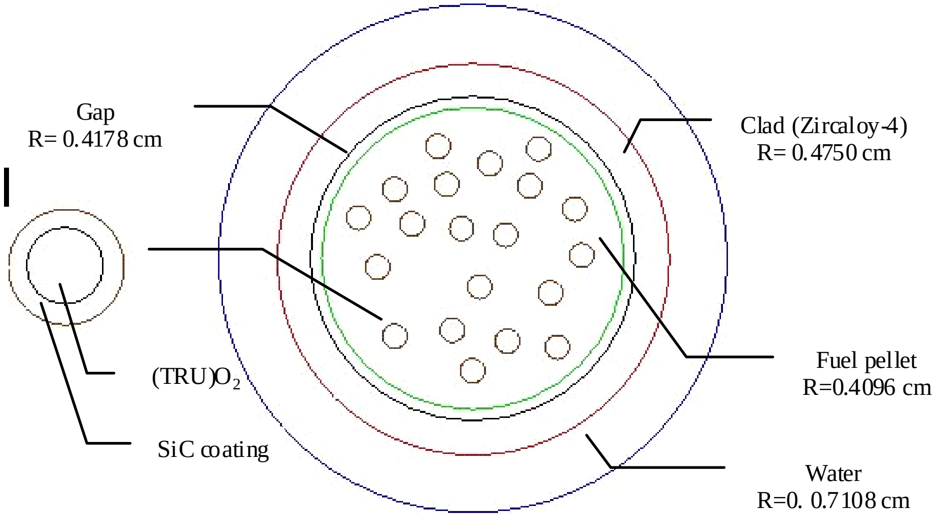
- **Systematic comparison of various inert-matrix fuel forms in LWRs**
- **Focus on Pu+Am recycling**
- **Assume assembly design parameters similar to typical PWR assembly**

| | **Dispersion Fuels with SiC-Coating** | | | **Dispersion Fuels with Nb-Coating** | | | **Solid Solution Fuel** | | |
|---|---|---|---|---|---|---|---|---|---|
| Fuel kernel diameter (μm) | 500 | | | 500 | | | N/A | | |
| Fuel particle coating thickness (μm) | **100** | | | **10** | | | N/A | | |
| **Particle volume fraction** | **10%** | **20%** | **30%** | **4.1%** | **8.2%** | **12.3%** | **N/A** | | |
| **Fuel volume fraction** | **3.6%** | **7.3%** | **10.9%** | **3.6%** | **7.3%** | **10.9%** | **3.6%** | **7.3%** | **10.9%** |
| Linear power (kW/m) | 16.1 | | | 16.1 | | | 16.1 | | |
| Specific power (W/kgHM) | 872.4 | 436.2 | 290.8 | 872.4 | 436.2 | 290.8 | 872.4 | 436.2 | 290.8 |

# Methodology

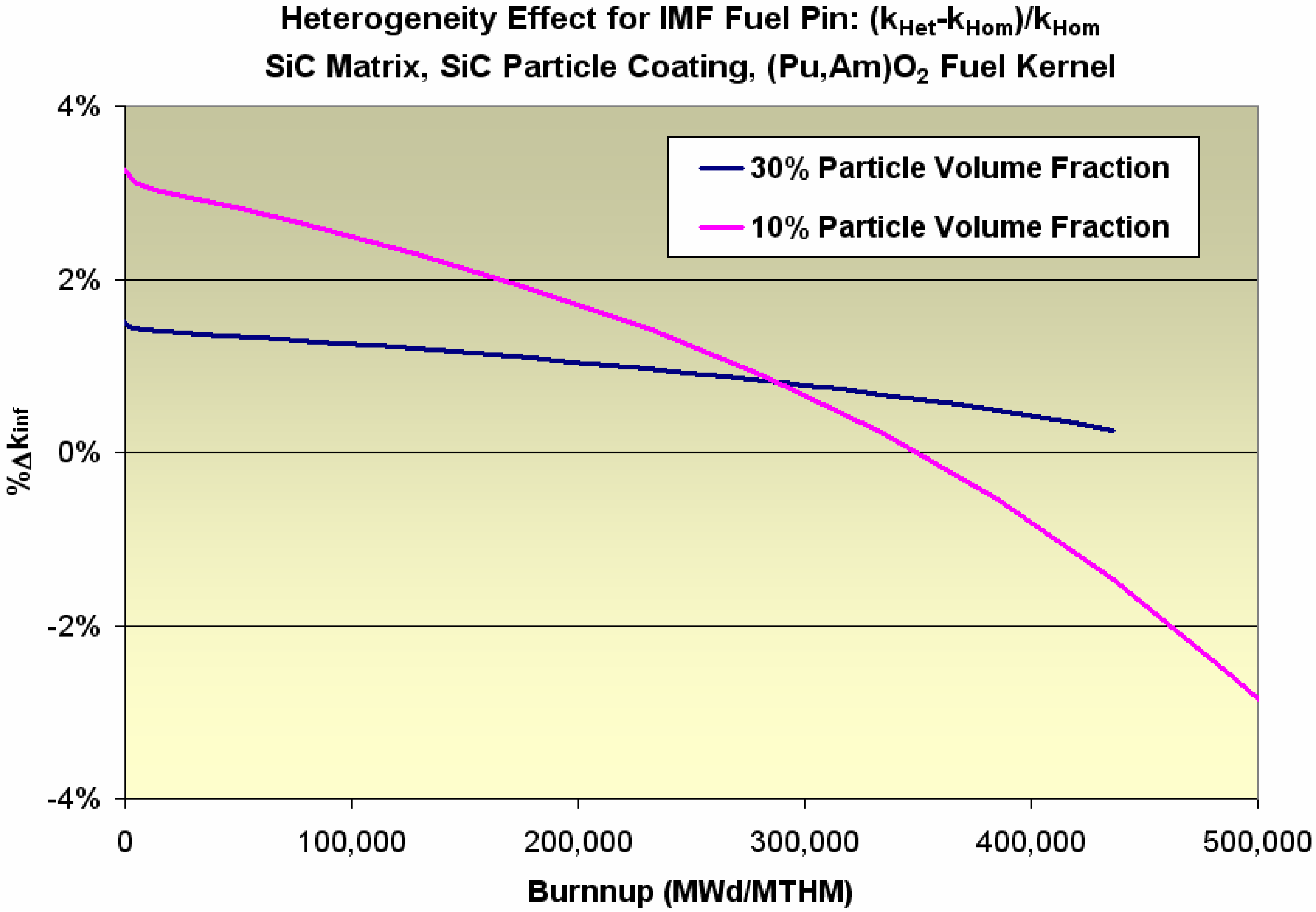
- **Calculations to be performed with WIMS8 lattice depletion code**
  - 172-group, JEF2.2-based library
  - Collision probabilities calculated for randomly distributed particles
  - Evaluate heterogeneity (self-shielding) effect

- **Heterogeneity effect for dispersion fuels ranges from 3% to 1% Δk**
  - Decreases with increasing fuel volume fraction
  - Decreases with decreasing fuel particle size
  - Not insignificant
    - *1%Δk ~ 30 full-power days*
    - *Effect on nuclide depletion*

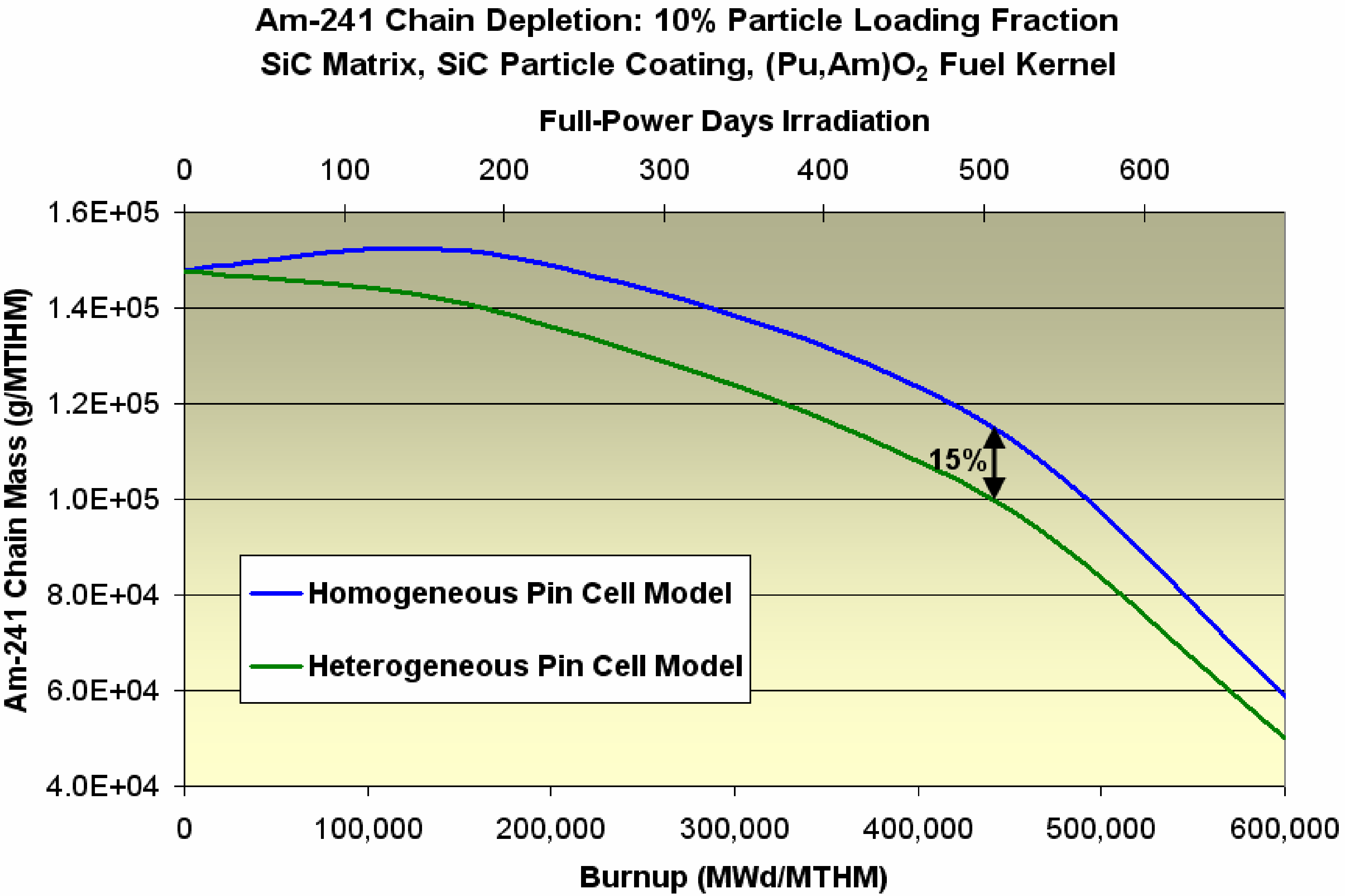


**Schematic of Cylindrical IMF Pin with Dispersion Fuel**

# *Heterogeneity Effect in Dispersion Fuels*



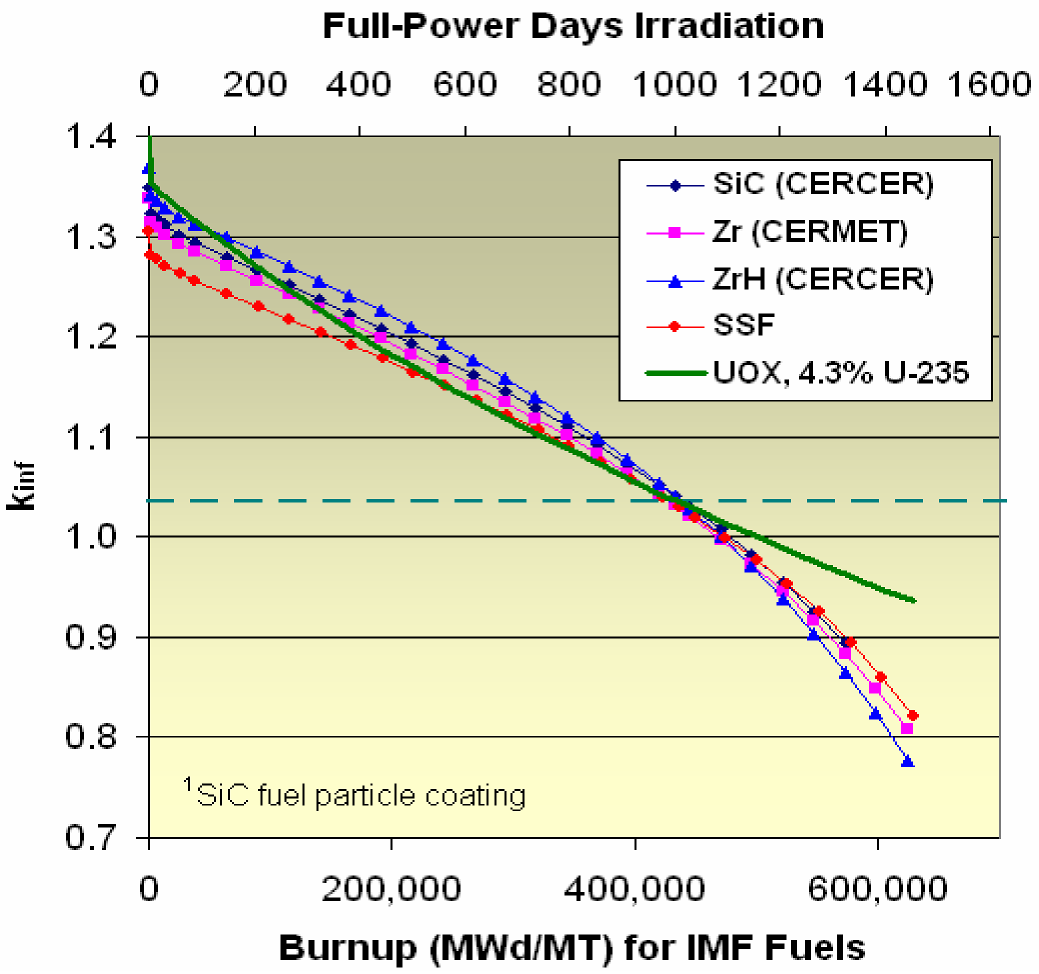
# *Heterogeneity Effect in Dispersion Fuels*



# Reactivity Letdown of IMF Fuels

- **Reactivity letdown similar to $UO_2$ through 1,000 FPD**
  - Rapid $k_{inf}$ drop-off after 1,000 FPD will yield uneven power sharing
- **ZrH has higher BOL $k_{inf}$ and greater burnup reactivity loss**
- **Burnup reactivity loss lowest for solid solution fuel**
- **Particle coating has little effect on reactivity**

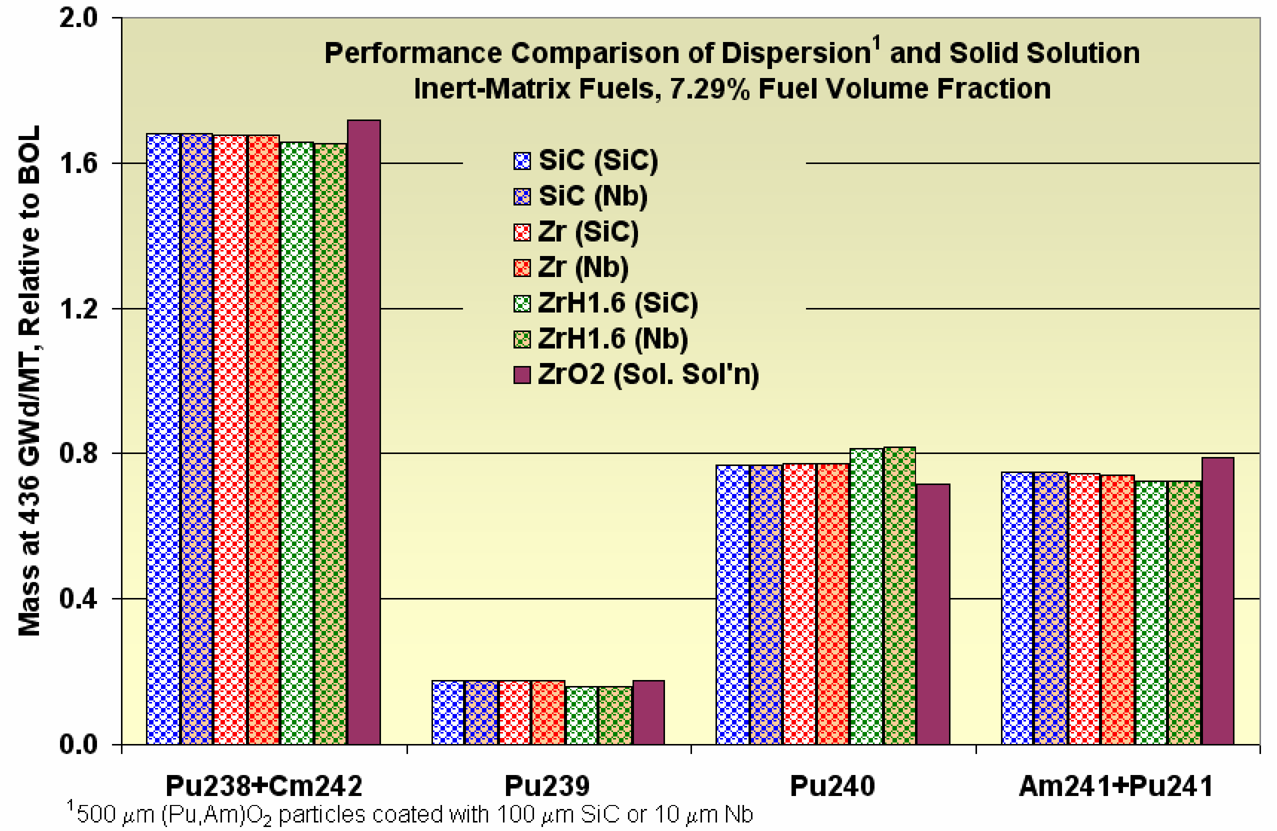
**$k_{inf}$ for Dispersion[1] and Solid Solution Inert-Matrix Fuels: 7.29% FVF**



[1] SiC fuel particle coating

# Nuclide Consumption

- Generally better in dispersion fuels
- Relatively insensitive to dispersion fuel matrix
- Even less sensitive to particle coating
- For given burnup, decreasing fuel volume fraction increases consumption



[1] 500 μm (Pu,Am)$O_2$ particles coated with 100 μm SiC or 10 μm Nb

# *Repository Loading Benefit from IMF*

- **Loading to meet repository thermal criteria estimated for “once-through then out” (OTTO) strategy**
- **Decay heat contribution from key actinides (Am-241, Pu-238, Pu-239, Pu-240) integrated from 100-1250 years after discharge; total relative to direct-disposed $UO_2$ is the estimated loading benefit**
- **Benefit for given burnup marginally better for ZrH matrix**
  - SSF provides least benefit
- **Benefit with Np recycling reduced from increased Pu-238 in waste**

**Repository Loading Benefit Estimates for IMF (7.29% FVF, 436 GWd/MT)**

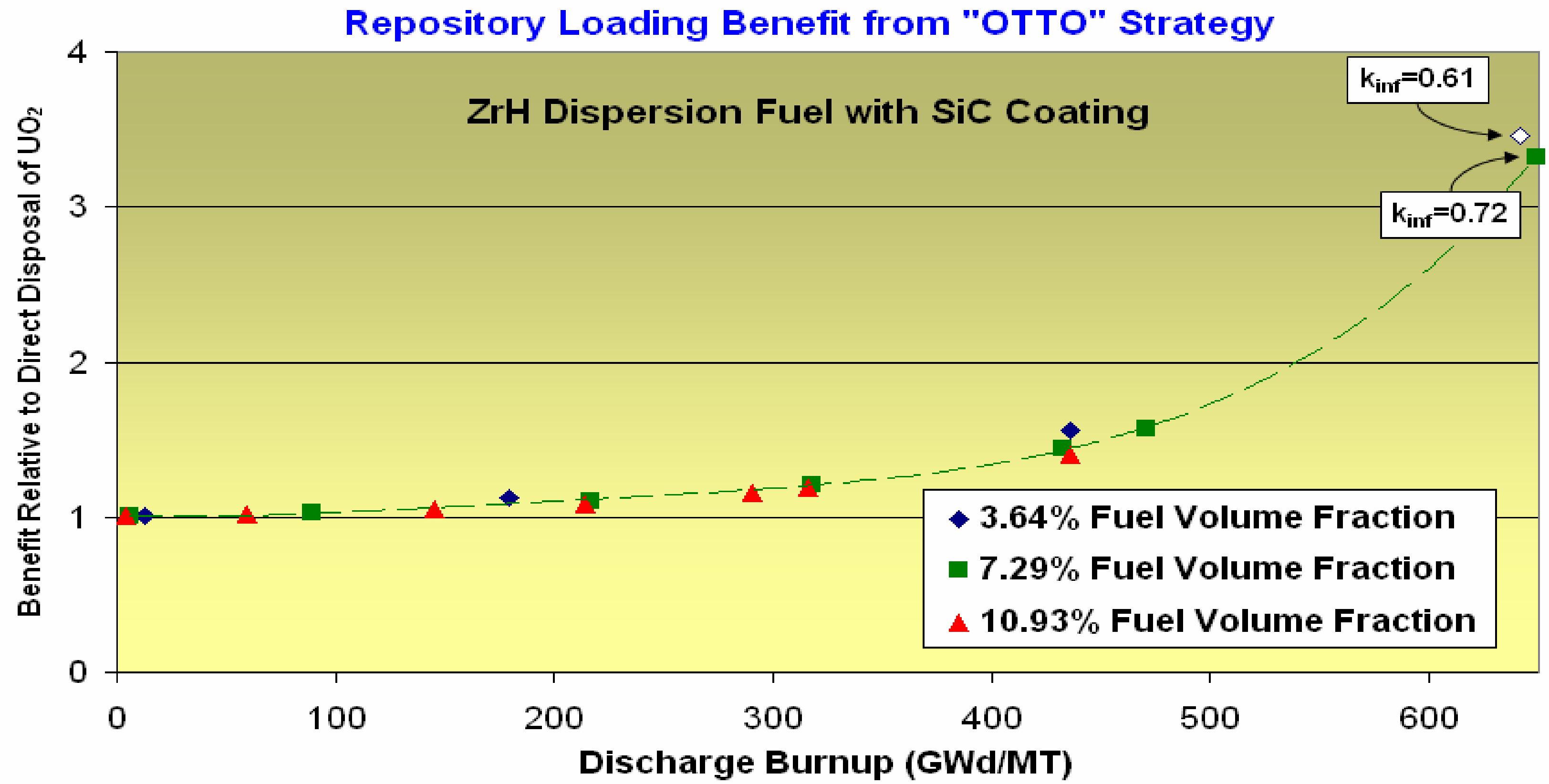
| Coating | Matrix | Loading Benefit |
|---|---|---|
| SiC | SiC | 1.418 |
| | Zr | 1.424 |
| | ZrH | **1.442** |
| Nb | SiC | 1.418 |
| | Zr | 1.425 |
| | ZrH | **1.446** |
| N/A | $(Zr,Y_{1.33})O_2$ | 1.377 |
| | $ZrO_2$, 8.87%Pu+Np+Am | 1.270 |
| | MOX, 12wt.%Pu+Am, 51 GWd/MT | 1.122 |

# *Repository Loading Benefit from "OTTO" Strategy*

| **Matrix** | **TRU V.F.** | **Decay Heat Integrated from 100-1250 Years (Watt-years/GWd)** | | | | **Loading Benefit** |
|---|---|---|---|---|---|---|
| | | **Pu238** | **Pu239** | **Pu240** | **Am241** | |
| **$UO_2$** | 4.3wt.% U-235 | 202.8 | 260.7 | 445.8 | 1,821.6 | |
| **SiC** | 3.64% | 276.2 | 36.8 | 358.1 | 1,128.2 | 1.503 |
| | 7.29% | 295.6 | 41.8 | 333.2 | 1,237.7 | 1.418 |
| | 10.93% | 308.8 | 43.5 | 320.9 | 1,247.7 | 1.409 |
| **Zr** | 3.64% | 276.1 | 36.9 | 358.8 | 1,123.7 | 1.506 |
| | 7.29% | 295.1 | 41.8 | 334.5 | 1,228.9 | 1.424 |
| | 10.93% | 308.2 | 43.6 | 322.3 | 1,237.9 | 1.416 |
| **ZrH** | 3.64% | 270.5 | 33.5 | 378.8 | 1,056.6 | **1.555** |
| | 7.29% | 291.4 | 38.4 | 345.8 | 1,199.7 | 1.442 |
| | 10.93% | 309.4 | 40.4 | 324.6 | 1,252.7 | 1.404 |
| **$(Zr,Y_{1.33})O_2$** | 3.64% | 284.2 | 38.7 | 328.1 | 1,264.5 | 1.411 |
| | 7.29% | 301.6 | 41.5 | 315.5 | 1,305.6 | 1.377 |
| | 10.93% | 313.6 | 43.9 | 311.6 | 1,295.8 | 1.377 |
| **MOX** | 12.0wt.% | 319.0 | 145.0 | 387.6 | 1,572.1 | 1.122 |

# *Repository Loading Benefit*

- **Lower fuel volume fraction in IMF increases repository benefit for “OTTO” strategy at a given discharge burnup**
- **Benefit rises sharply at higher burnup from Pu-238 consumption, but reactivity may be too low to achieve these burnup levels**



Repository Loading Benefit from "OTTO" Strategy

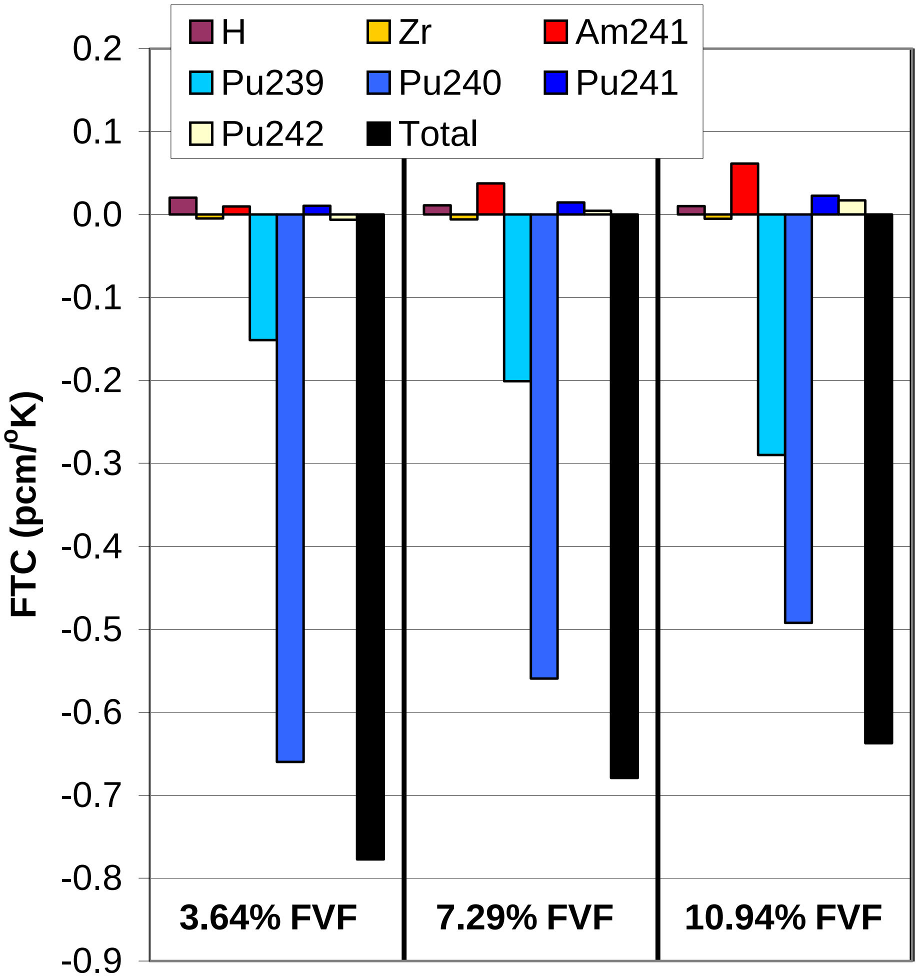
# Reactivity Coefficients

**Fuel Temperature (FTC) and Coolant Void Coefficients (CVC) at BOL**

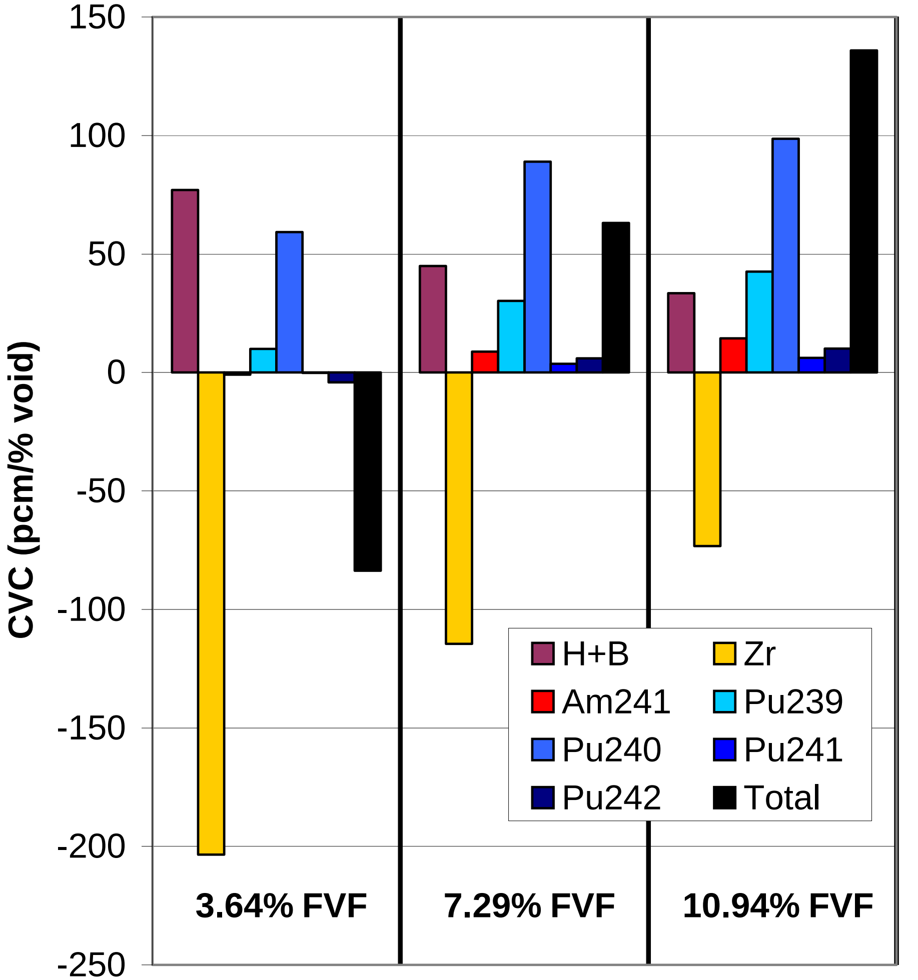
| **Fuel V.F.** | **Matrix** | **FTC ($pcm/^oK$)** | **CVC (pcm/% void)** | |
|---|---|---|---|---|
| | | | ***20% Voiding, 1500 ppm*** | ***99% Voiding, 1500 ppm*** |
| 4.3wt.% $U^{235}$ | $UO_2$ | -1.88 | -22.1 | -567.5 |
| 3.64% | SiC | -0.60 | +18.7 | +39.5 |
| | Zr | -0.53 | +8.2 | -103.8 |
| | $ZrH_{1.6}$ | -1.11 | +57.1 | +13.3 |
| | $(Zr,Y_{1.33})O_2$ | -0.76 | -27.0 | -83.6 |
| 7.29% | SiC | -0.71 | -24.2 | +117.7 |
| | Zr | -0.65 | -31.4 | +84.1 |
| | $ZrH_{1.6}$ | -1.58 | -6.8 | -32.7 |
| | $(Zr,Y_{1.33})O_2$ | -0.71 | -44.2 | +63.0 |
| 10.93% | SiC | -0.73 | -15.6 | +163.8 |
| | Zr | -0.69 | -20.8 | +162.2 |
| | $ZrH_{1.6}$ | -1.51 | -22.1 | -13.1 |
| | $(Zr,Y_{1.33})O_2$ | -0.65 | -26.3 | +135.9 |

# *Reactivity Coefficients*

**Components of Fuel Temperature Coefficient**
**$(Zr,Y)O_2$ Solid Solution Fuel**



**Components of 99% Coolant Void Coefficient**
**$(Zr,Y)O_2$ Solid Solution Fuel**



# *Conclusions*

- **Relative to direct disposal of spent $UO_2$ fuel, Pu+Am recycling in IMF provides additional benefit for repository loading**
- **For fuel forms considered, consumption of key actinides is relatively insensitive to matrix material or particle coating**
- **Repository loading benefit is marginally better for ZrH matrix**
- **Heterogeneity effect in dispersion fuels is important for transmutation modeling**
- **For given burnup, benefit is greatest with lower fuel volume fraction**
  - Loading benefit increases with fuel burnup, but higher burnup levels may not be achievable because of rapidly declining reactivity
- **Reactivity coefficients must be more closely evaluated**
  - Coolant void coefficient is positive for some cases, but addition of burnable poisons or heterogeneous core (assembly) design will yield lower values