# Fast Reactor Physics - 2
# Reactivity Feedbacks and Fuel Cycle

Robert N. Hill
Program Leader – Advanced Nuclear Energy R&D
Nuclear Engineering Division
Argonne National Laboratory

NRC Fast Reactor Technology Training Curriculum
White Flint, MD
March 26, 2019

# Outline

- Fast Reactor Reactivity Feedbacks
  - Delayed Neutron Fraction
  - Geometric Expansion Coefficients
  - Doppler Coefficient
  - Coolant Density/Void Coefficient

- Fuel Cycle Implications
  - Breeder vs. Burner Configurations
  - Conventional Advanced Fuel Recycle Options
  - "Traveling Wave" Concepts

# Fast Spectrum Physics Distinctions

- Combination of increased fission/absorption and increased number of neutrons/fission yields more excess neutrons from Pu-239
  - Enables "breeding" of fissile material
- In a fast spectrum, U-238 capture is more prominent
  - Higher enrichment (TRU/HM) is required (neutron balance)
  - Enhances internal conversion
- Reduced parasitic capture and improved neutron balance
  - Allows the use of conventional stainless steel structures
  - Slow loss of reactivity with burnup
    - Less fission product capture and more internal conversion
- The lower absorption cross section of all materials leads to a much longer neutron diffusion length (10-20 cm, as compared to 2 cm in LWR)
  - Neutron leakage is increased (>20% in typical designs, reactivity coefficient)
  - Reflector effects are more important
  - Heterogeneity effects are relatively unimportant

# Whole-Core Reactivity Coefficients for Different Size Fast Reactors

| | unit | 250 MWt ABTR | 1000 MWt ABR | 3500 MWt US-Europe |
|---|---|---|---|---|
| Effective delayed neutron fraction | | 0.0033 | 0.00334 | 0.0035 |
| Prompt neutron lifetime | Ms | 0.33 | 0.38 | 0.32 |
| Radial expansion coefficient | ¢/◦ C | -0.43 | -0.38 | -0.21 |
| Axial expansion coefficient | ¢/◦ C | -0.05 | -0.05 | -0.07 |
| Sodium density coefficient | ¢/◦ C | 0.03 | 0.13 | 0.18 |
| Doppler coefficient | ¢/◦ C | -0.10 | -0.13 | -0.13 |
| Sodium void worth | $ | 1.10 | 4.93 | 7.29* (4.98) |
| Sodium voided Doppler coefficient | ¢/◦ C | -0.07 | -0.09 | -0.09 |

- Power coefficient is quite negative
  - More negative at smaller size because of radial expansion coefficient
  - Sodium density coefficient also more positive at larger size
- Physics underlying each coefficient will be explained

# Delayed Neutron Fraction

- Hummel and Okrent – *Reactivity Coefficients in Large Fast Power Reactors, ANS, 1970* is a good reference for underlying physics
- Delayed neutron fraction dominated by key fission isotopes
  - Low (0.2%) for Pu-239
  - High (1.5%) for U-238
  - Between 0.3-0.5% for higher plutonium isotopes
  - Particularly low (<0.2%) for minor actinides
- Net result is 0.3-0.4% for conventional compositions
  - Slightly lower burner designs (~0.2% for pure burner)
- Higher for U-235 enriched systems (LWRs)
  - Delayed neutron fraction for U-235 is ~0.67%

- *Delayed neutron fraction is an indicator of sensitivity*
  - At low values, response to small changes in the reactivity is magnified and power can change more quickly
  - Feedback effects can be favorable or not depending on the transient

# Geometric Expansion Coefficients

Whole-core coefficients are computed by eigenvalue difference for a small change in each dimension

- Radial expansion – uniform expansion of grid plate by 1%
  - Reduction of fuel/structure densities by 1%
  - This allows more axial leakage in particular
- Axial expansion – uniform expansion of fuel by 1%
  - Reduction of fuel density by 1%
  - Allows more radial leakage
  - Also, effectively inserts the control rods which remain stationary
  - In some cases, fuel assumed bound to clad for axial expansion
- These feedbacks are very important for fast reactor transient behavior
  - Tied to different material temperatures (load pads, grid plate, fuel)
  - Thus, timing will be different

# Neutron Balances of Radial and Axial Expansions

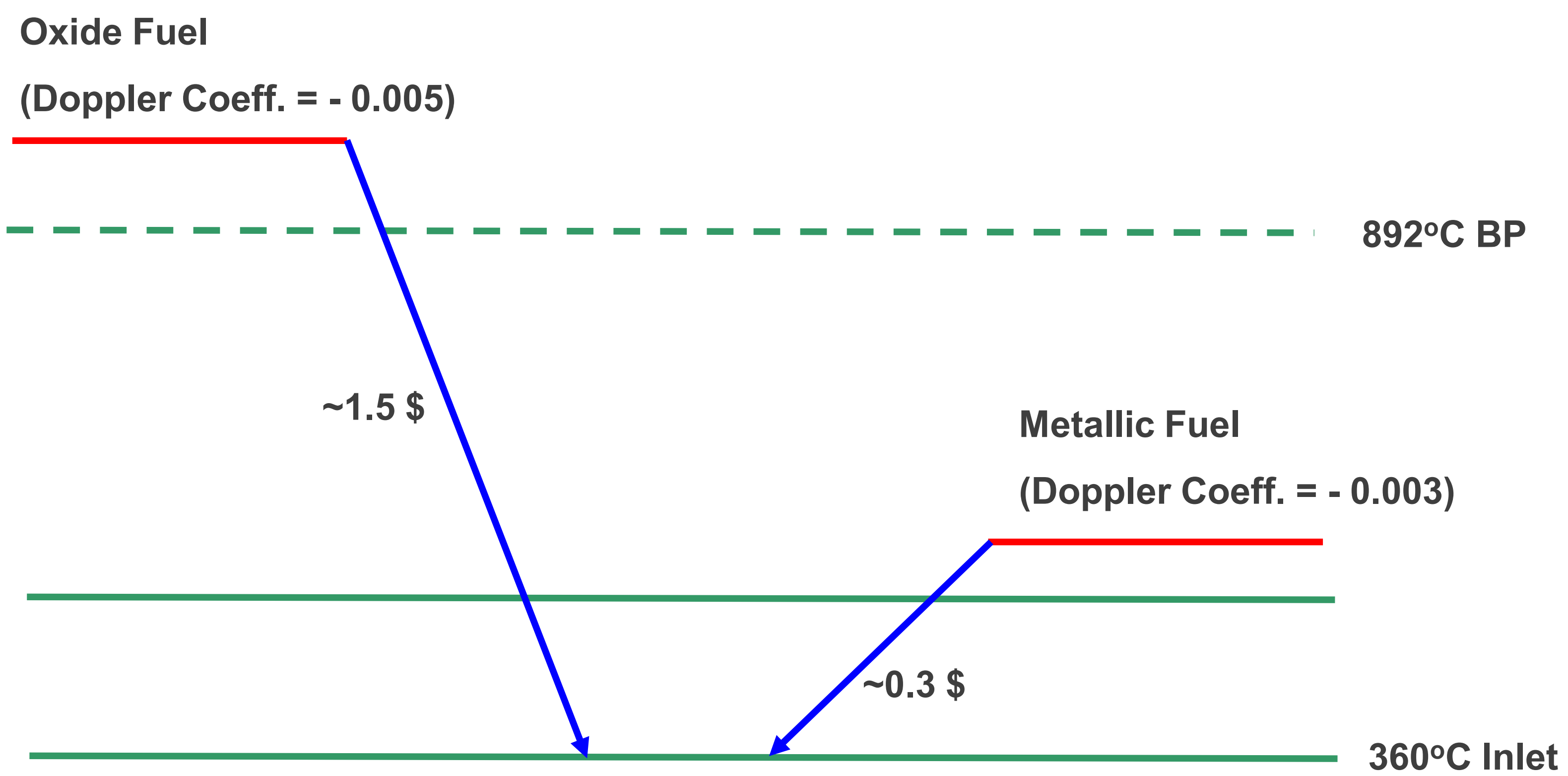
| | Base Case | Radial Expansion | | Axial Expansion | |
|---|---|---|---|---|---|
| | balance | balance | Δρ (%) | balance | Δρ (%) |
| Fission source | 100.00 | 100.00 | | 100.00 | |
| (n,2n) source | 0.18 | 0.18 | | 0.18 | |
| Absorption | 68.89 | 68.93 | -0.04 | 68.93 | -0.05 |
| Leakage | 31.54 | 32.16 | -0.63 | 31.61 | -0.07 |
| Radial | 17.49 | 17.72 | -0.23 | 17.59 | **-0.10** |
| Axial | 14.05 | 14.45 | **-0.40** | 14.02 | 0.03 |
| Sum | | | -0.67 | | -0.12 |

- To first order, radial expansion is an axial leakage effect, and
- Axial expansion is a radial leakage effect!
- Because the height is the short dimension (more axial than radial leakage), the radial expansion coefficient is more negative
- Axial absorption effect can be magnified by effective control rod insertion

# Doppler Coefficient

- Doppler coefficient arises primarily from U-238 resonance broadening
  - Enhanced by high U-238 content
    - Reduced Doppler for high enrichment burner concepts
  - Self-shielding effect more pronounced at low energies (keV range)
    - Doppler enhanced by spectral softening
    - Voided Doppler is smaller from spectral shift
- Temperature dependence in fast spectrum is different than LWR
  - Doppler range from $1/T^{1/2}$ for large to $1/T^{3/2}$ for small resonances
  - For typical FR, an approximate 1/T dependence observed
- There is also a structural Doppler reactivity effect (~1/3 fuel Doppler)
  - However, tied to temperature of steel, not fuel (different timing)
- Doppler feedback is not helpful in all transients
  - For example, when trying to cool the fuel to shutdown condition (e.g., ULOF), it is a positive feedback
  - Conversely prompt negative feedback in UTOP transient

# Reactivity Swing for Power Reduction



# Coolant Density Coefficient

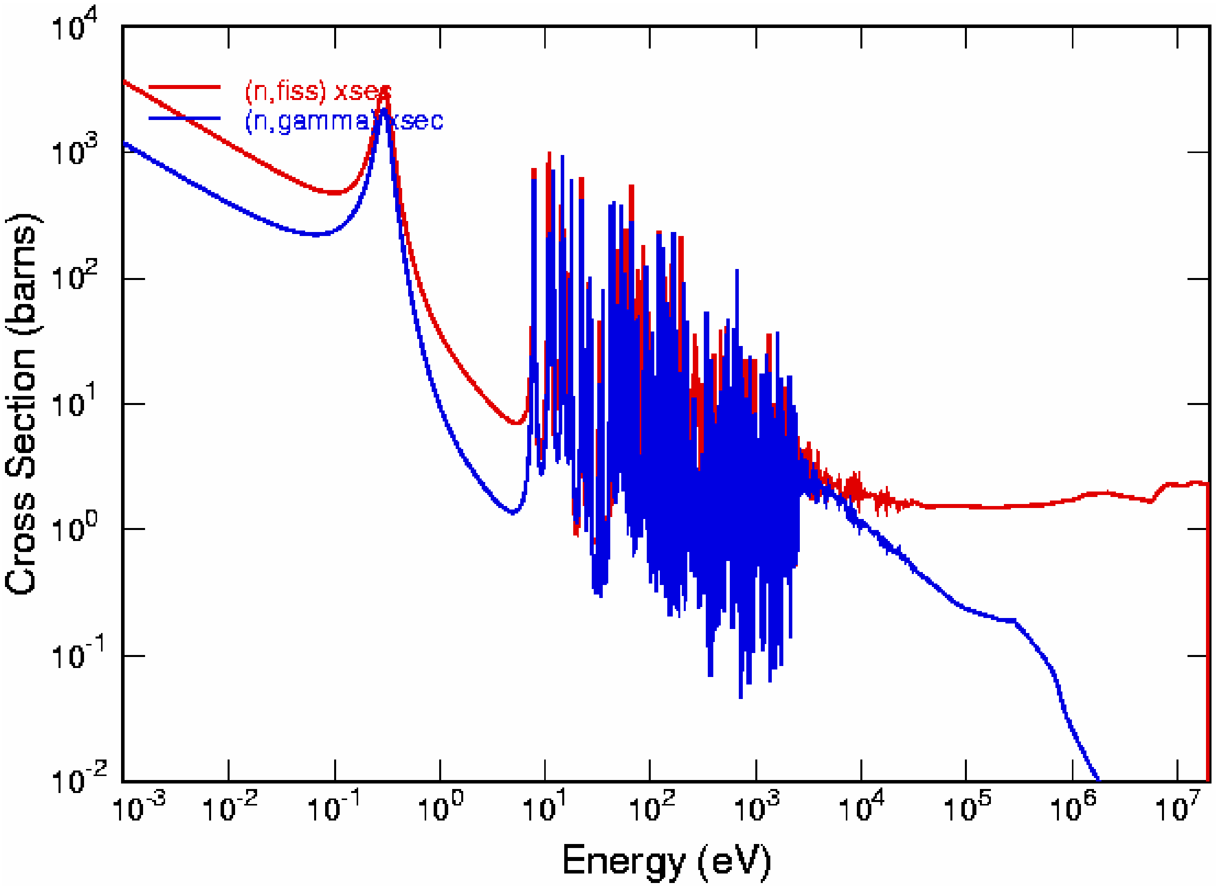
Coolant density coefficient computed by first-order perturbation theory to evaluate small density (temperature variation) impacts

- Spectral effect
  - Reduced moderation as sodium density decreases
  - In fast regime, this is a positive reactivity effect
    - From Pu-239 excess neutrons and threshold fission effects
- Leakage effect
  - Sodium density decrease allows more neutron leakage
  - This is a negative reactivity effect in the peripheral regions
- Capture effect
  - Sodium density decrease results in less sodium capture
  - This is a relatively minor effect

Void worth is evaluated using exact perturbation theory to account for shift in flux distribution and change in cross sections for voided condition

- In general, 10% more positive than the first-order density worth

# Spectral Variation of Neutron Cross Sections: Pu-239




- Fission and capture cross section >100X higher in thermal range
- Sharp decrease in capture cross section at high energy

# Sodium Void Worth by Components ($)

| | | Capture | Spectral | Leakage | Total |
|---|---|---|---|---|---|
| **1000 MWt ABR (startup metal core)** | BOC | 0.5 | 9.1 | -5.2 | 4.4 |
| | EOC | 0.5 | 9.9 | -5.5 | 4.9 |
| **250 MWt ABTR (startup metal core)** | BOC | 0.4 | 6.4 | -5.8 | 1.0 |
| | EOC | 0.4 | 6.6 | -5.8 | 1.1 |

- Flowing sodium completely voided in ALL active and above-core regions
- Void worth tends to increase with core size
- However, difficult to conceive transient situations that reach boiling
  - Low pressure system
  - >300$^{o}$C margin to boiling
  - Other feedbacks are negative to get to voiding!
- Extensive report on void worth reduction – Khalil and Hill, NSE, 109 (1995)

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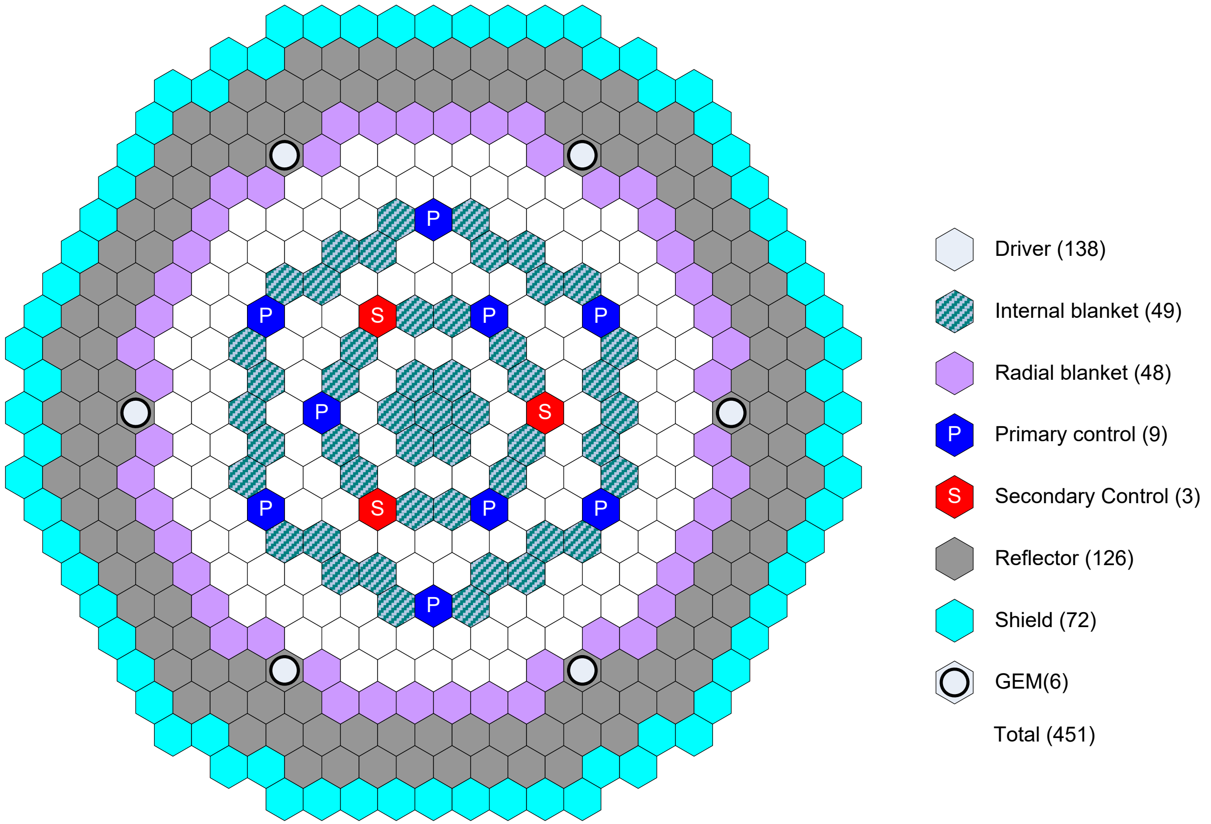
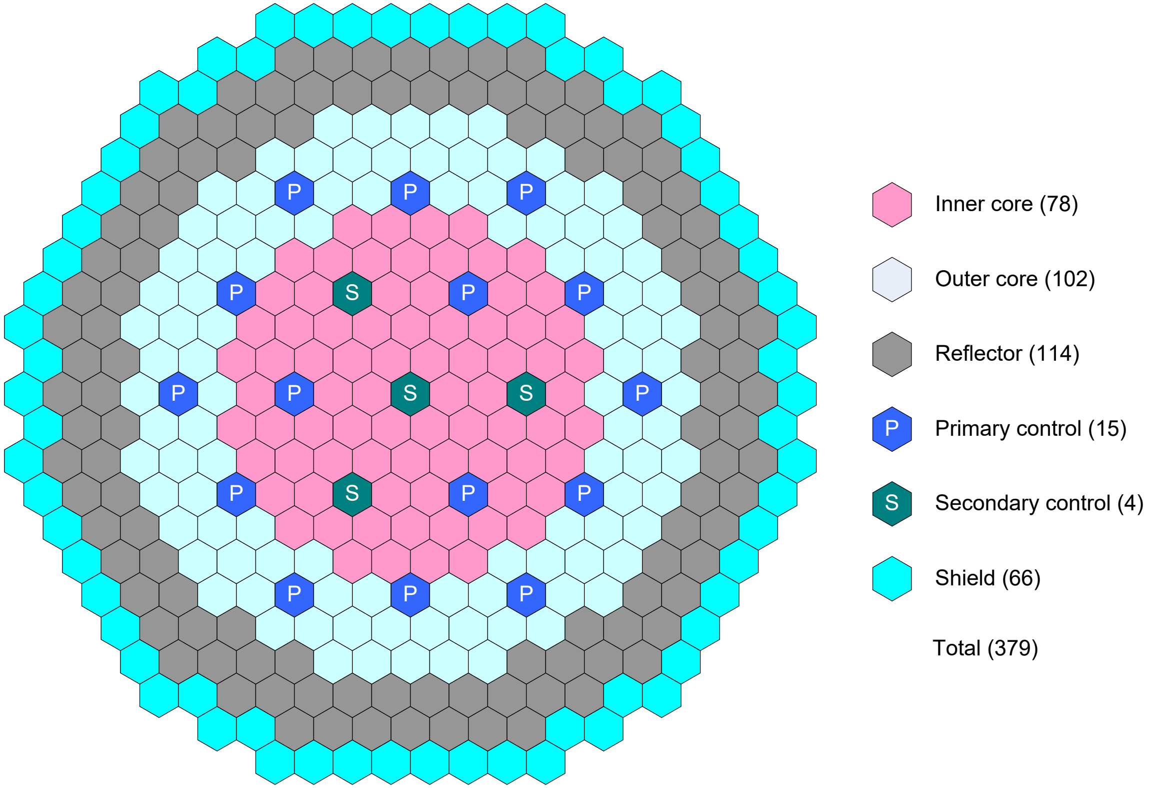
# Conventional 1000 MWt SuperPRISM (Metal Core)




- Internal and external blankets allocated
  - Result in conversion ratio of ~1
- Only 12 control rod locations with very low burnup reactivity losses
- Blanket, two row reflector, and boron carbide for radial shielding

# Burner 1000 MWt Preliminary ABR Burner Design



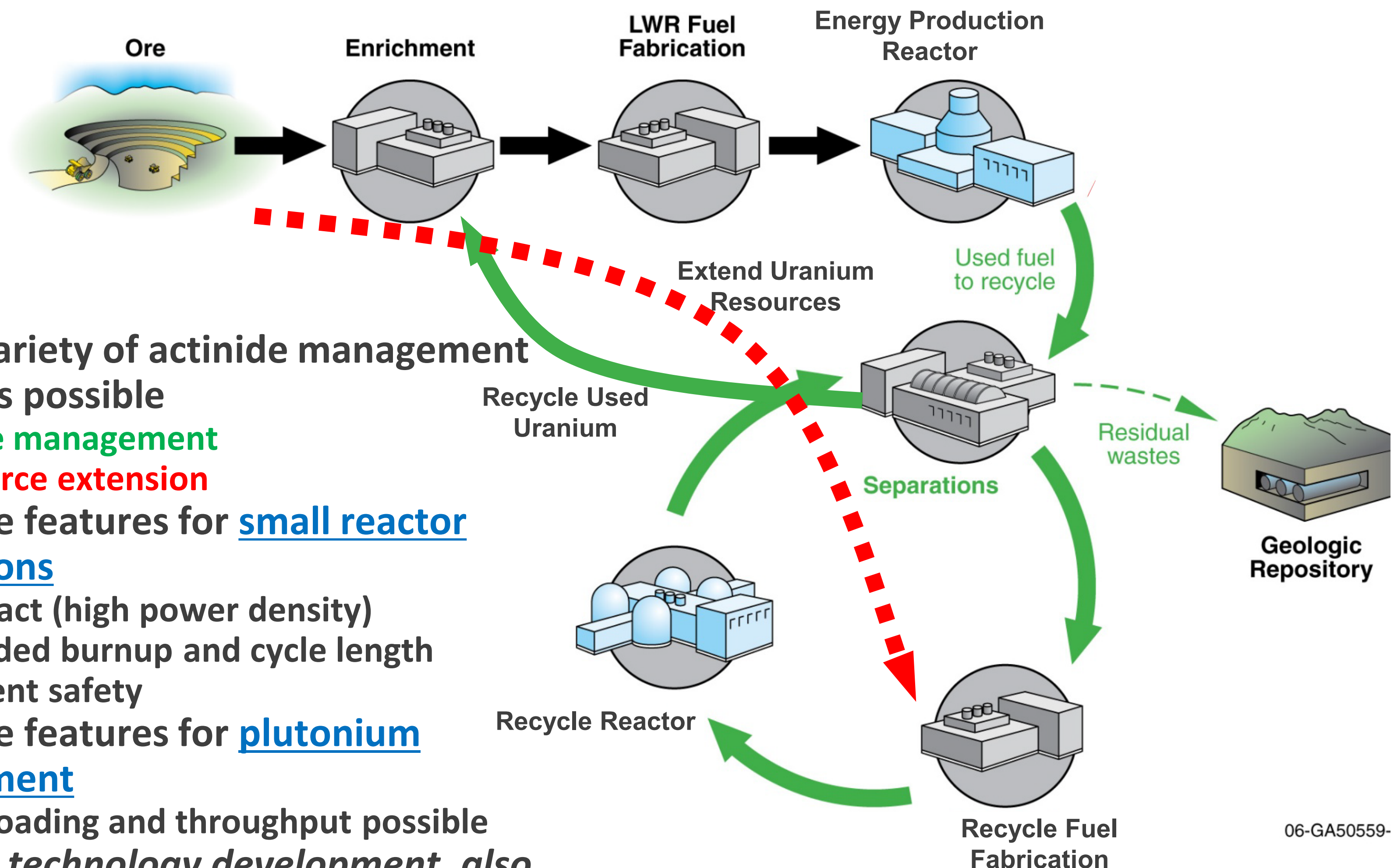

- Two enrichment zones to reduce radial power peaking
- No blankets allocated for conversion ratio < 1
- Additional (20) control rod locations for burnup reactivity losses
- Similar radial shield configuration

# Neutron Balance

| | | PWR | SFR | |
|---|---|---|---|---|
| | | | CR=1.0 | CR=0.5 |
| **U-235 or TRU enrichment, %** | | **4.2** | **13.9** | **33.3** |
| Source | fission | 100.0% | 99.8% | 99.9% |
| | (n,2n) | | 0.2% | 0.1% |
| Loss | leakage | 3.5% | **22.9%** | **28.7%** |
| | radial | 3.0% | 12.3% | 16.6% |
| | axial | 0.4% | 10.6% | 12.1% |
| | absorption | 96.5% | 77.1% | 71.3% |
| | fuel | 76.7% | 71.8% | 62.2% |
| | (U-238 capture) | (27.2%) | (31.6%) | (17.1%) |
| | coolant | **3.4%** | 0.1% | 0.1% |
| | structure | 0.6% | 3.7% | 3.7% |
| | fission product | **6.8%** | 1.5% | 2.4% |
| | control | 9.0% | 0.0% | 2.9% |

- Conversion ratio defined as ratio of TRU production/TRU destruction
  - Slightly different than traditional breeding ratio with fissile focus

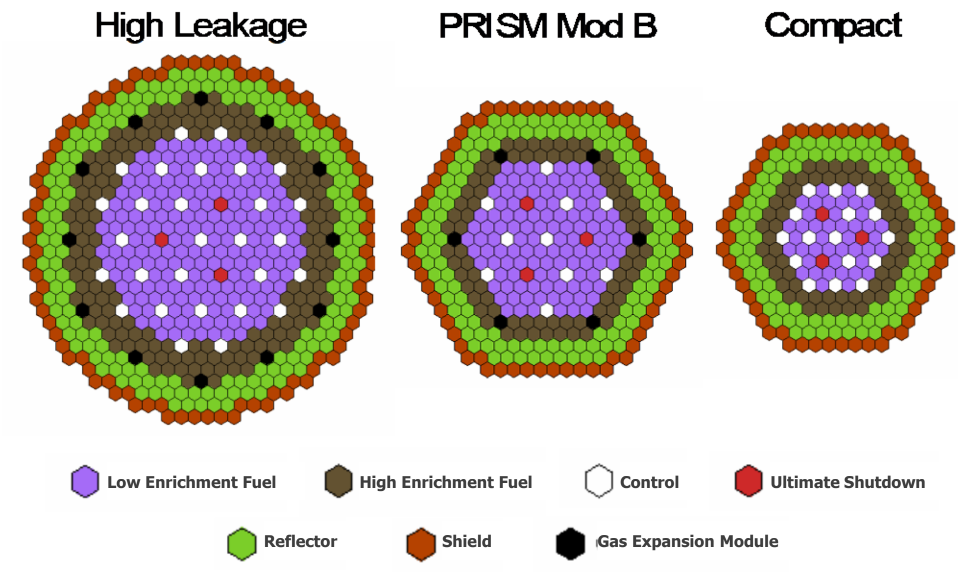
# Actinide Management in Fast Reactors




- A wide variety of actinide management strategies possible
  - Waste management
  - Resource extension
- Favorable features for small reactor applications
  - Compact (high power density)
  - Extended burnup and cycle length
  - Inherent safety
- Favorable features for plutonium management
  - High loading and throughput possible
- *With key technology development, also intended for electricity, heat production, or other energy product missions*

# Fast Reactors are Flexible for Actinide Management

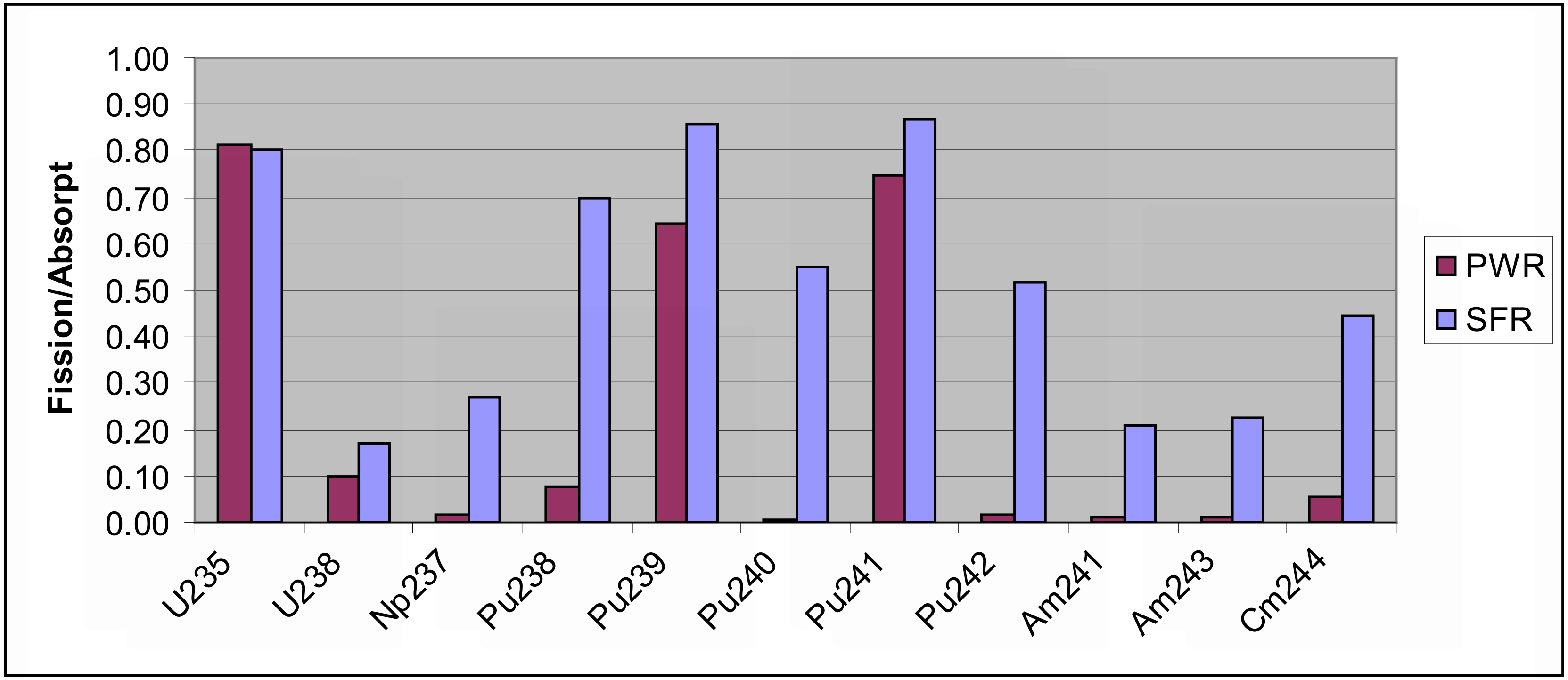
- **Can be configured as modest breeders (CR≥1) to moderate burners (CR≥0.5) with conventional technology**
- **Low conversion ratio designs (CR<0.5) have been investigated for transmutation applications**
  - High enrichment fuels are required (~50% TRU/HM for CR=0.25)
  - Non-uranium fuel would be needed to achieve CR=0
- **Safety performance will change at low uranium content (e.g., reactivity losses, reduced Doppler coefficient)**
  - Detailed safety analysis conducted for CR=0.25 SFR system
  - Inherent safety behavior is not compromised
- **Compact low conversion ratio design COE is similar to reference system**
  - High leakage configuration increases cost by 20%
  - Fuel cost and capacity factor differences are important



# Transmutation Approach for Improved Waste Management

- **Long-term heat, radiotoxicity, and dose are all dominated by the Pu-241 to Am-241 to Np-237 decay chain**
- **Destruction of the transuranics (TRU) is targeted to eliminate the problematic isotopes**
- **Some form of separations is necessary to extract transuranic elements for consumption elsewhere**
- **The transuranic (TRU) inventory is <u>reduced</u> by fission**
  - Commonly referred to as 'actinide burning'
  - Transmutation by neutron irradiation
  - Additional fission products are produced
- **In the interim, the TRU inventory is contained in the fuel cycle**

# Impact of Energy Spectrum on Fuel Cycle (Transmutation) Performance




- Fissile isotopes are likely to fission in both thermal/fast spectrum
  - Fission fraction is higher in fast spectrum
- Significant (up to 50%) fission of fertile isotopes in fast spectrum

**Net result is more excess neutrons and less higher actinide generation in FR**

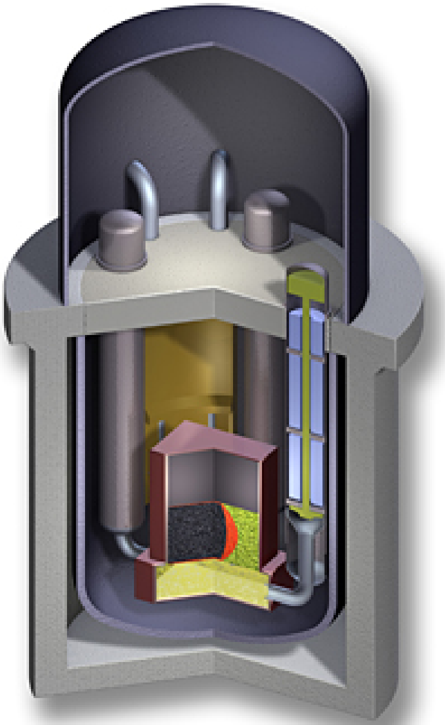
# Fuel Cycle Implications of Reactor Physics

The reactor spectral differences lead to fuel cycle strategies:

- **Thermal reactors** typically configured for <u>once-through (open) fuel cycle</u>
  - They can operate on low enriched uranium (LEU)
  - They require an external fissile feed (neutron balance)
  - Higher actinides must be managed to allow recycle
    - Separation of higher elements – still a disposal issue
    - Extended cooling time for curium decay
- **Fast reactors** are typically intended for <u>modified open or full recycle</u> with uranium conversion and resource extension
  - Higher actinide generation is suppressed
  - Neutron balance is favorable for recycled TRU
    - No external fissile material is required
    - Can enhance U-238 conversion for traditional breeding
    - Can limit U-238 conversion for burning

# Fast Spectrum Breed and Burn Principles

- **Enriched U-235 (or Pu-239) starter core would be surrounded by a blanket of fertile fuel**
- **Enriched fuel would produce neutrons that generate power and convert fertile fuel to fissionable fuel**
- **Irradiated fertile fuel would replace enriched fuel after original U-235 (or Pu-239) is burned and new Pu 239 is formed**
- **Use of "Standard Breeders" exploit this physics in conjunction with reprocessing**
  - Complete U-238 conversion and fission, with the uranium utilization limited only by losses
- **Breed and Burn concepts promote conversion, but minimize reprocessing (modified open)**
  - Once fertile zone dominates, once-through uranium utilization at the fuel burnup limit

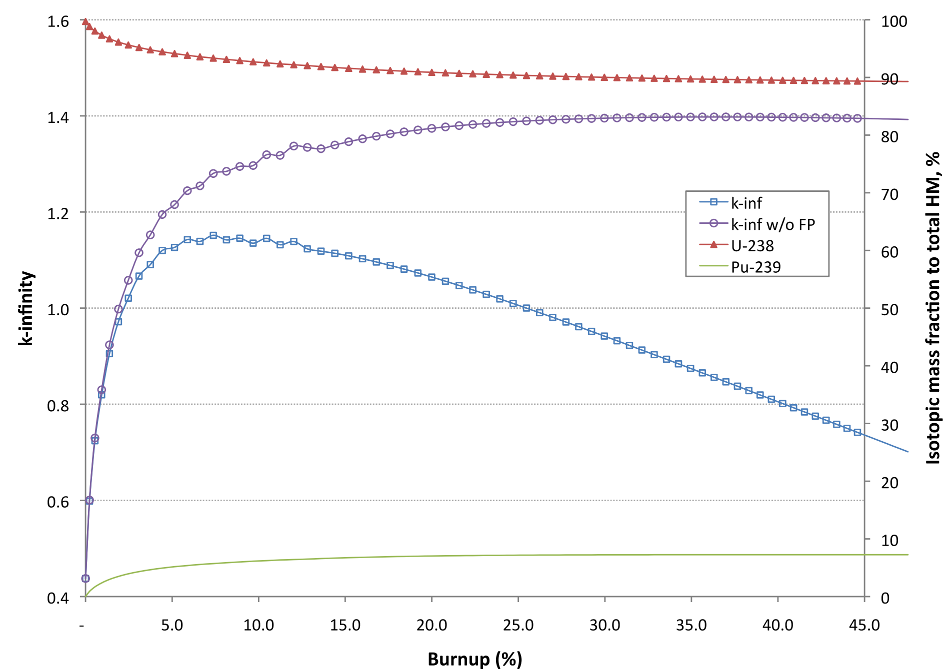


Travelling Wave Concept

# "Traveling Wave" Concept

- **Concepts employ a fast neutron spectrum and run on depleted uranium**
  - DU is converted to Pu during reactor operation
  - Fissile material (enriched-U or Pu) is required <u>only</u> in the first core, to initiate the conversion
- **Traveling wave reactor a particular variant**
  - Fission wave propagates from fissile "starter" through the adjacent DU zone

## $K_{inf}$ vs. burnup in a fast spectrum




## History of Concept

**1958** Saveli M. Feinberg proposes a "breed-burn" reactor in which unenriched fuel is moved around the core to sustain fission

**1979** Michael J. Driscoll and others at MIT further evaluate breed-burn reactor ideas

**1988** Lev Feoktistov works on the concept in Russia and publishes an analysis of a concept of a physically safe reactor

**1996** Edward Teller, Lowell Wood (now at Intellectual Ventures), and others at Lawrence Livermore Lab detail ways to make breed-burn waves travel through a stationary fuel supply

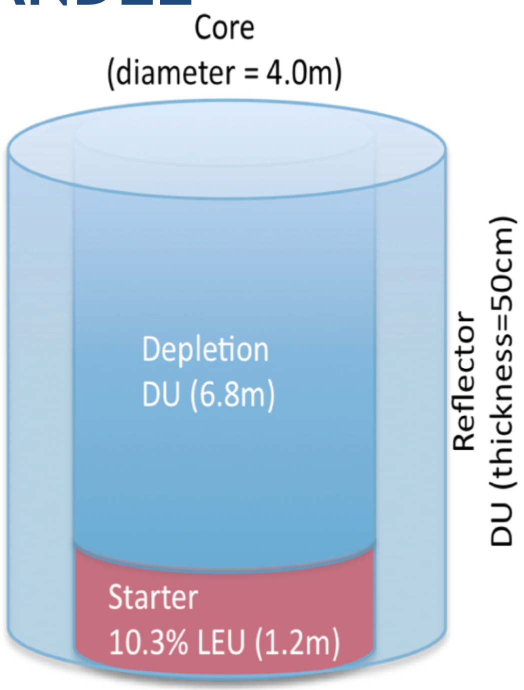
**2000** Hugo van Dam publishes mathematical analyses of waves of fission moving inside nuclear fuels

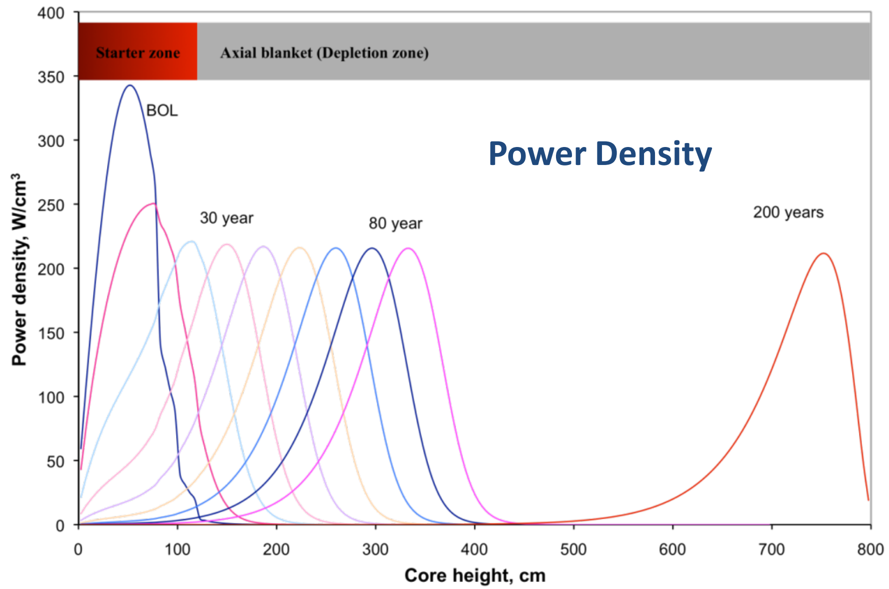
**2001** Hiroshi Sekimoto begins a series of conceptual studies of various kinds of TWRs

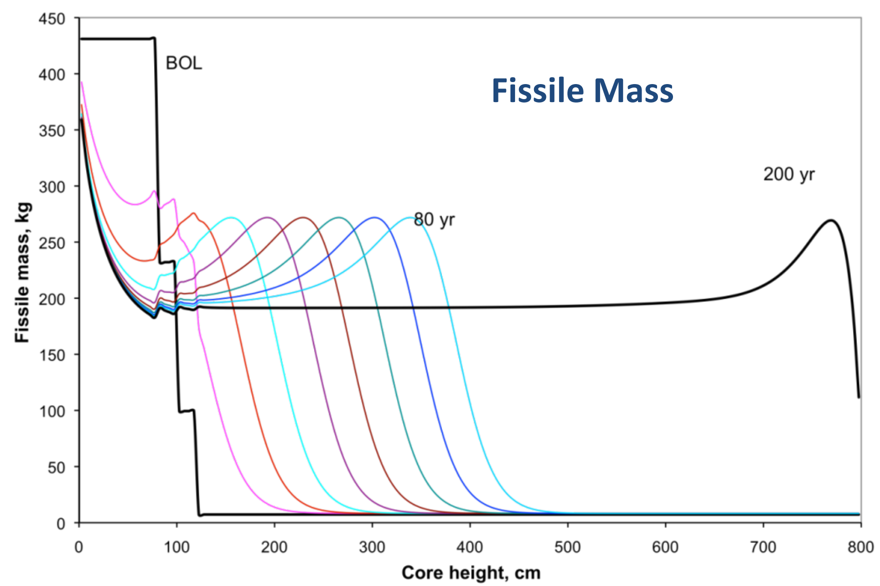
**Early 2000s** Sergii Fomin and N. Shul'ga study the burning wave in fast reactors in the Ukraine

**2006** Intellectual Ventures begins detailed physics and engineering studies of the feasibility, cost, and features of various TWR designs

# CANDLE




- Fissioning zone propagates from starter thru DU region
- In principle, reactor operation can be extended in proportion to height of the DU region

# Uranium Utilization

## Once-through systems

| | PWR-50GWd/t | PWR-100GWd/t | VHTR | Fast Burner |
|---|---|---|---|---|
| Burnup, % | 5 | 10 | 10.5 | 22.3 |
| Enrichment, % | 4.2 | 8.5 | 14.0 | 12.5 |
| Utilization, % | 0.6 | 0.6 | 0.4 | 0.8 |

## Recycling Systems

<table>
<tr><th rowspan="2"></th><th colspan="2">LWR</th><th colspan="2">LWR-Fast Burner</th><th>Fast</th></tr>
<tr><th>UOX</th><th>MOX</th><th>LWR-UOX</th><th>Fast Burner</th><th>Converter</th></tr>
<tr><td>Power sharing, %</td><td>90</td><td>10</td><td>57</td><td>43</td><td>100</td></tr>
<tr><td>Burnup, %</td><td>5</td><td>10</td><td>5</td><td>9</td><td>-</td></tr>
<tr><td>Enrichment, %</td><td>4.2</td><td>-</td><td>4.2</td><td>12.5</td><td>-</td></tr>
<tr><td>Utilization, %</td><td colspan="2">0.7</td><td colspan="2">1.4</td><td>~99</td></tr>
</table>

**Is it possible to improve U utilization significantly …**

- **without recycle?**
- **with limited recycle?**

# Physics Performance of Breed & Burn Concepts

| | Conventional SFR | CANDLE | CBZ | MB3 |
|---|---|---|---|---|
| Fissile enrichment of starter, % | 15 | 10.3 | 12.2 | 6.2 |
| Excess reactivity (max / min), %Δk | 2/0.5 | 3.2 / 0.8 | 3.9 / 0.5 | 3.1 / 0.6 |
| Ave. power density (BOC/EOC), W/cc | | | | |
| – Fissile (starter) region | 350 | 197 / 0.6 | 171 / 48 | 177 / ------ |
| – Fertile (DU) region | 50 - 100 | 0.2 / 27.2 | 2.8/ 63.3 | 5.5 / 96.1 |
| Power peaking factor | | | | |
| – Fissile region | 1.5 | 2.45 | 1.49 | 1.84 |
| – Fertile region | 4 | 30.1 | 6.84 | 4.61 |
| Avg. discharge burnup (GWd/t) | | | | |
| – Fissile fuel | 100 | 362 | 316 | ---- |
| – Fertile fuel | 30 | 248 | 198 | 277 |
| Peak fast fluence, $x10^{23}$ neutrons/cm2 | | | | |
| – Fissile fuel | 3.5 | 40.3 | 22.1 | 23.4 |
| – Fertile fuel | 2.0 | 41.9 | 21.6 | 21.7 |

- For postulated B&B concepts, fuel burnup to 20-30%
- However, much higher neutron damage must be tolerated

# Summary and Conclusions

- **Fast reactor physics are quite different from thermal reactor behavior**
  - Better neutron balance (flexible actinide management)
  - Higher enrichment required to compensate U-238 capture
  - Neutron leakage is increased
- **Reactivity coefficients were discussed**
  - Expansion coefficients prominent because of high leakage
  - Negative power coefficient
  - Positive sodium density (and void coefficient)
  - Overall favorable inherent performance (for complete set of feedbacks) has been demonstrated
- **Typical fast reactor configurations and fuel cycles were identified**
  - Range from conventional blanketed breeder, to moderate burner with no blankets, to low conversion ratio (high enrichment) options
  - Fuel recycle strategies for waste management and resource extension
  - Innovative "breed and burn" once-through concepts

# Questions?