Fast Reactor Physics - 2
Reactivity Feedbacks and Fuel Cycle

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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 <u>more excess neutrons</u> from Pu-239
  - Enables "breeding" of fissile material
- In a fast spectrum, U-238 capture is more prominent
  - <u>Higher enrichment</u> (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)
  - <u>Neutron leakage is increased</u> (>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

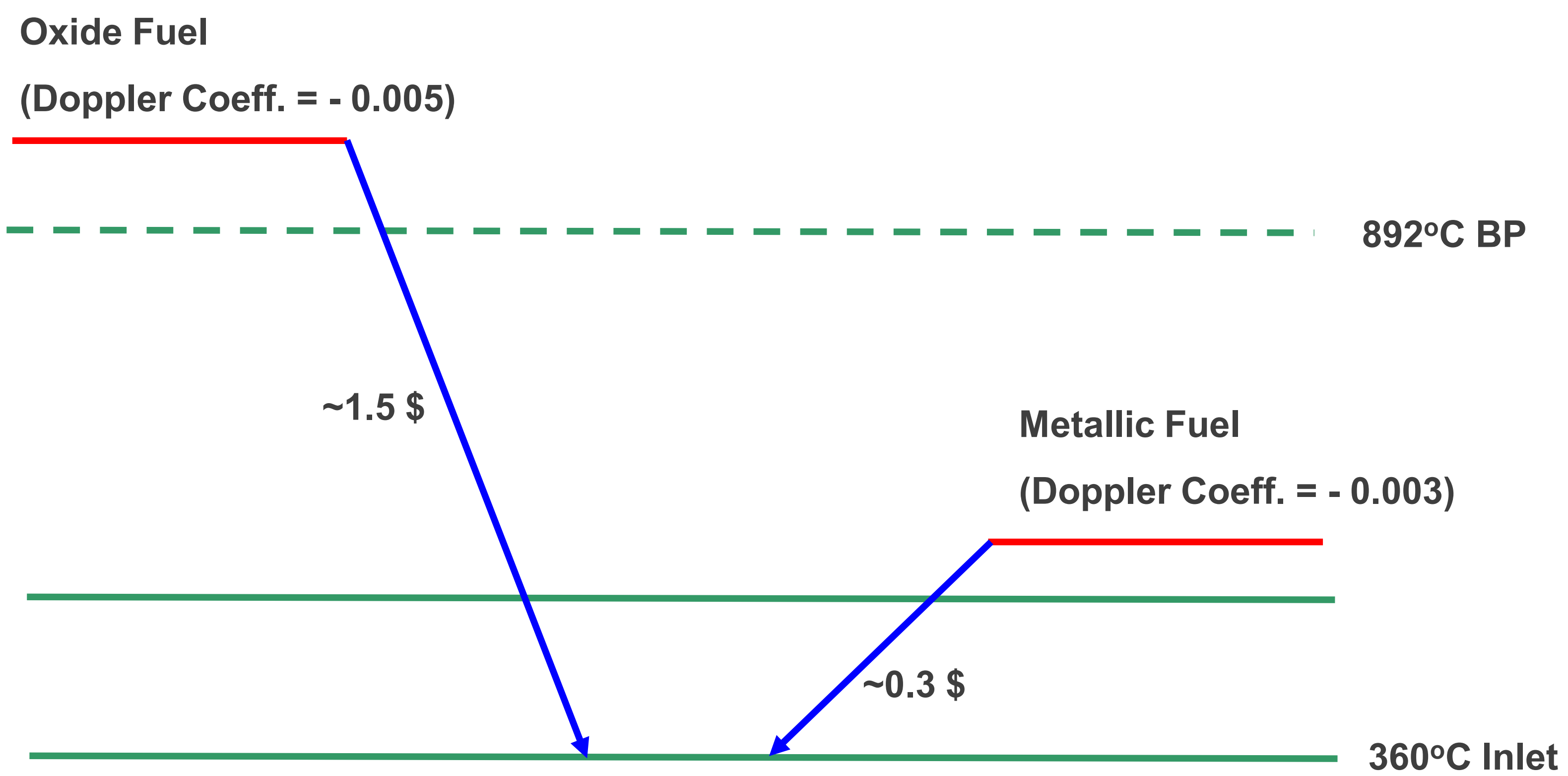
	Base Case	Radial Expansion		Axial Expansion	
	balance	balance	Δρ (%)	balance	Δρ (%)
Fission source	100.00	100.00		100.00	
(n,2n) source	0.18	0.18		0.18	
Absorption	68.89	68.93	-0.04	68.93	-0.05
Leakage	31.54	32.16	-0.63	31.61	-0.07
Radial	17.49	17.72	-0.23	17.59	**-0.10**
Axial	14.05	14.45	**-0.40**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

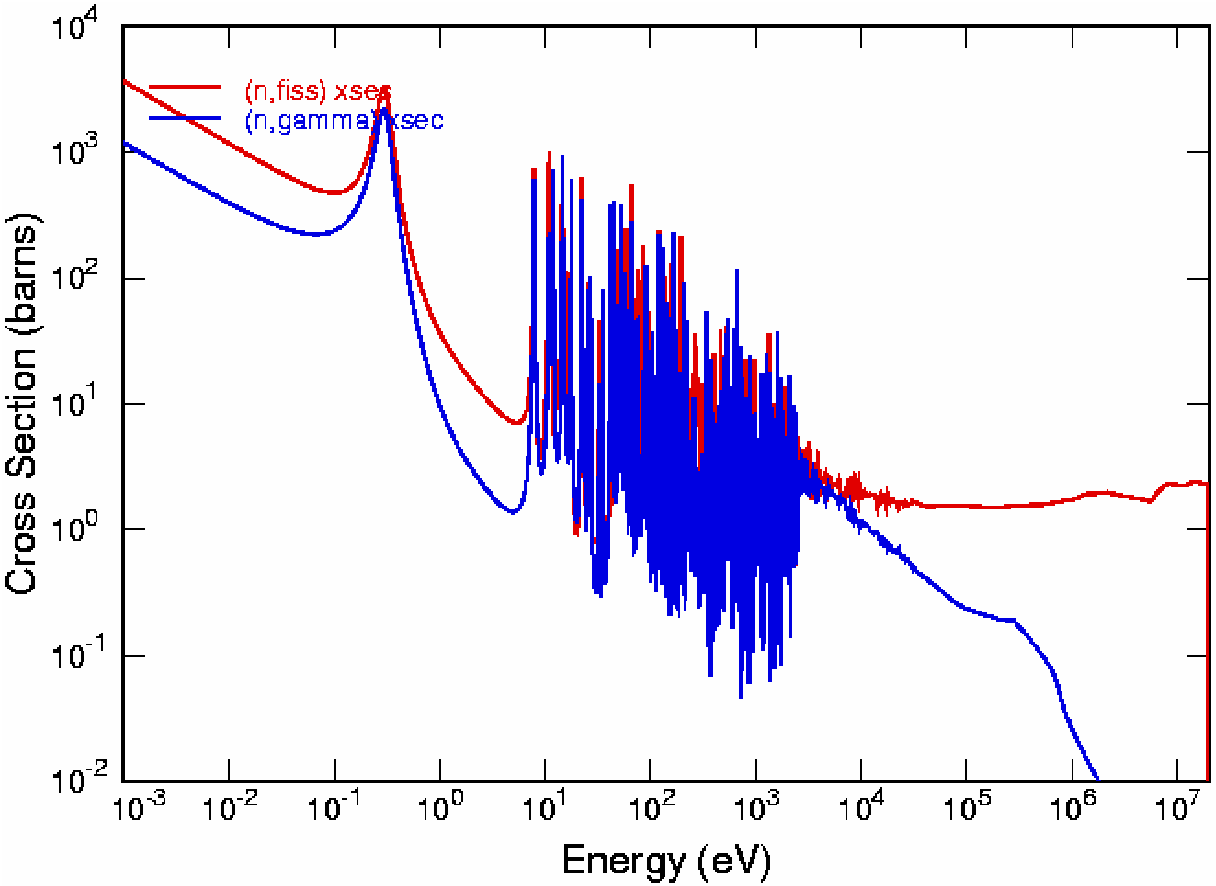
Coolant density coefficient computed by first-order perturbation theory to evaluate small density (temperature variation) impacts

- 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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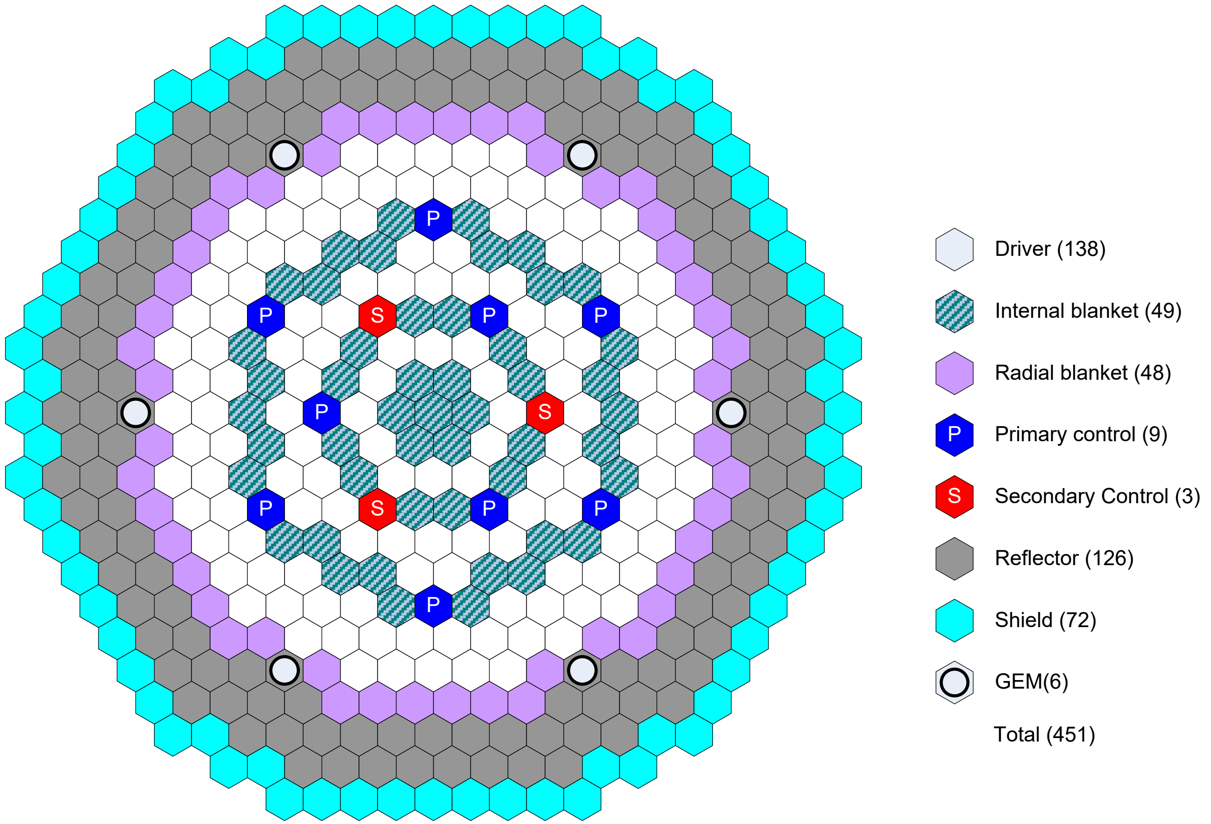
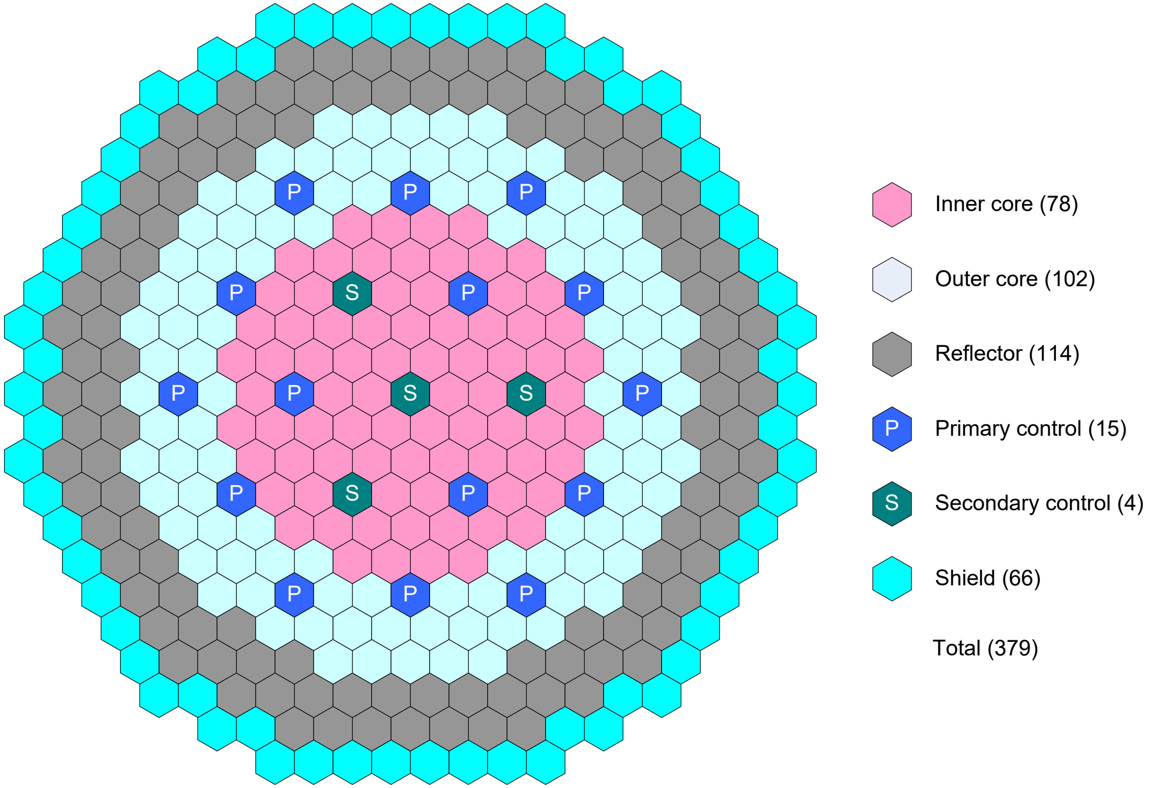
Conventional 1000 MWt SuperPRISM (Metal Core)



- 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



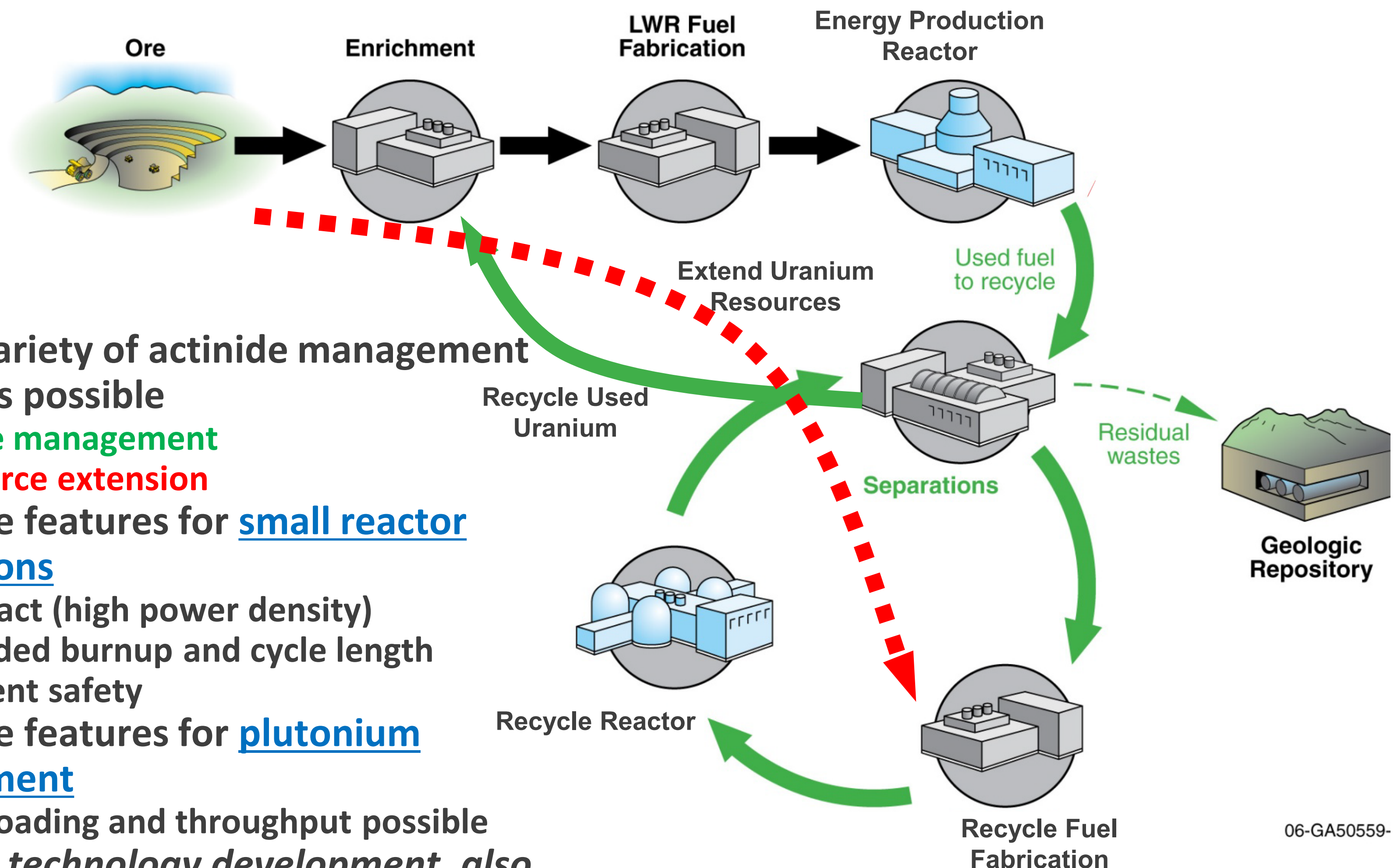
- Two enrichment zones to reduce radial power peaking
- No blankets allocated for conversion ratio < 1
- Additional (20) control rod locations for burnup reactivity losses
- Similar radial shield configuration

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

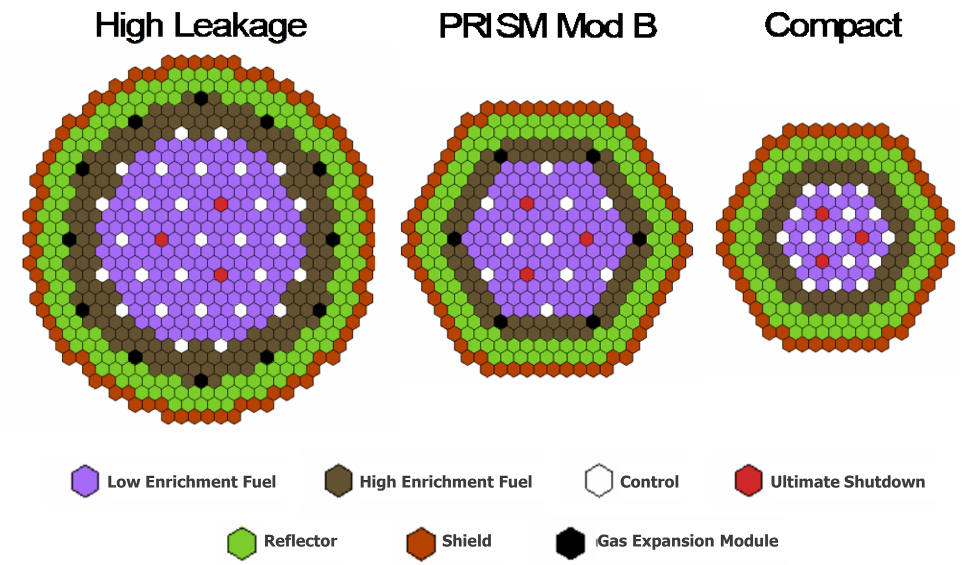
Actinide Management in Fast Reactors



- 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

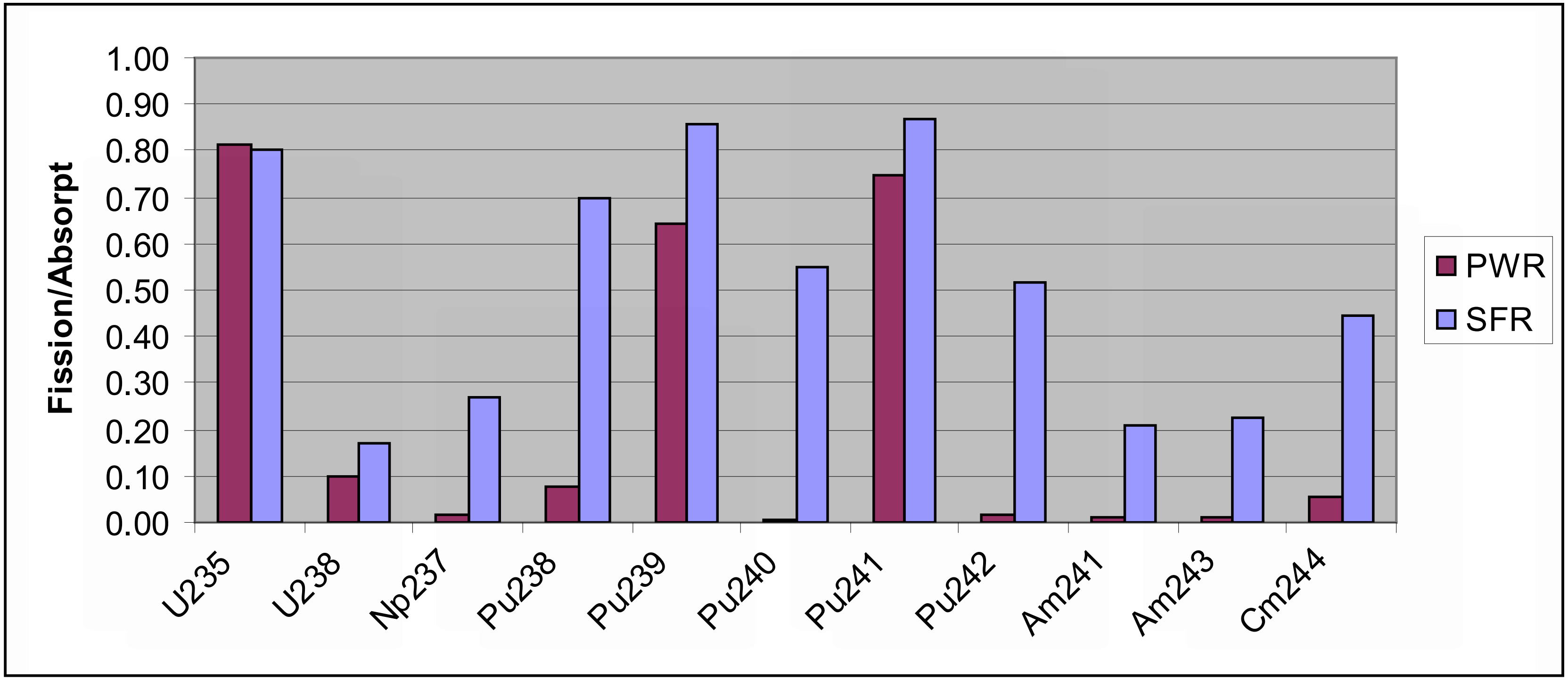
- **Can be configured as modest breeders (CR≥1) to moderate burners (CR≥0.5) with conventional technology**
- **Low conversion ratio designs (CR<0.5) have been investigated for transmutation applications**
  - High enrichment fuels are required (~50% TRU/HM for CR=0.25)
  - Non-uranium fuel would be 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 reduced 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

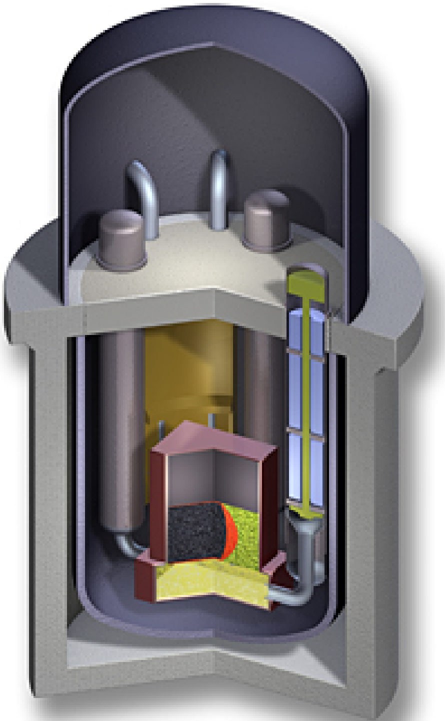
Fuel Cycle Implications of Reactor Physics

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

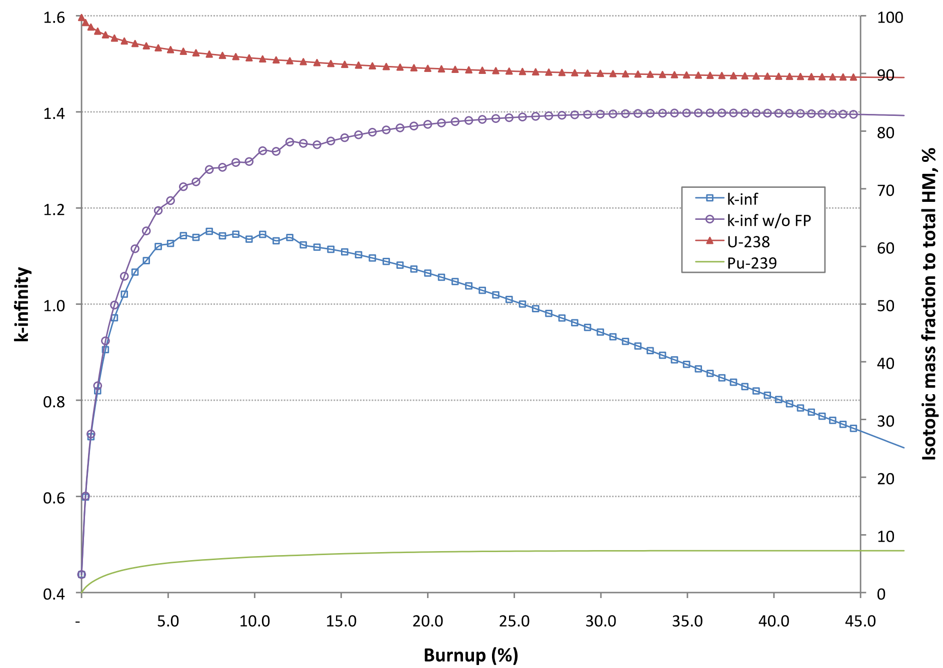


Travelling Wave Concept

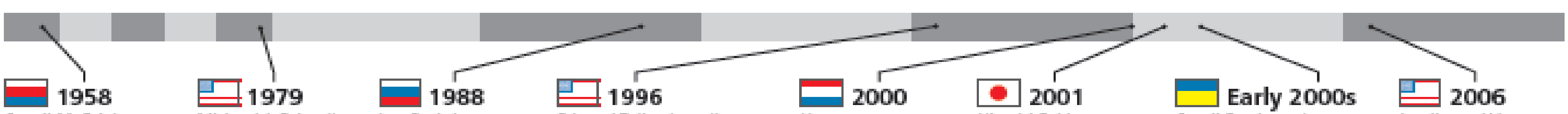
“Traveling Wave” Concept

- **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

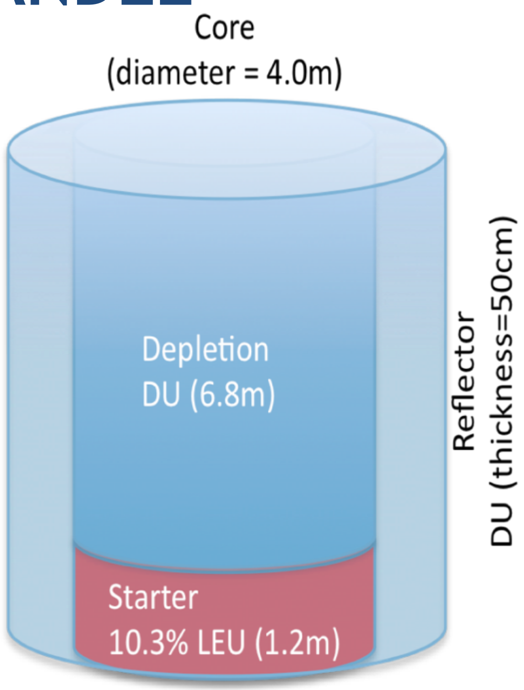
2000 Hugo van Dam publishes mathematical analyses of waves of fission moving inside nuclear fuels

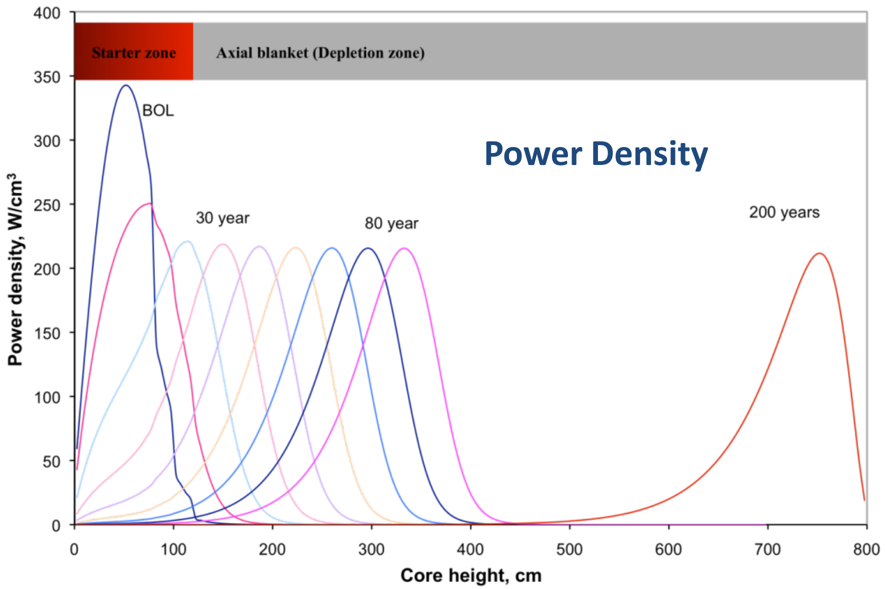
2001 Hiroshi Sekimoto begins a series of conceptual studies of various kinds of TWRs

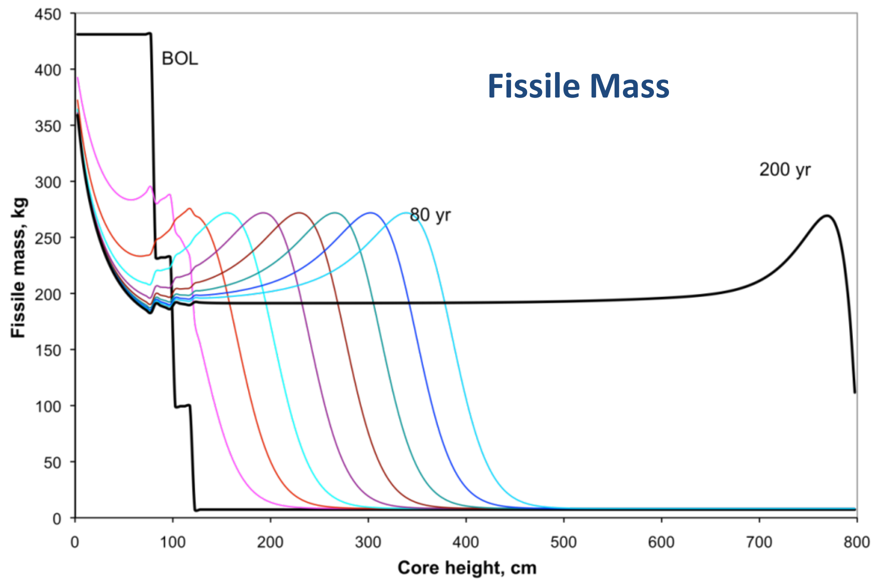
Early 2000s Sergii Fomin and N. Shul'ga study the burning wave in fast reactors in the Ukraine

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

	LWR		LWR-Fast Burner		Fast
	UOX	MOX	LWR-UOX	Fast Burner	Converter
Power sharing, %	90	10	57	43	100
Burnup, %	5	10	5	9	-
Enrichment, %	4.2	-	4.2	12.5	-
Utilization, %	0.7		1.4		~99

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?