Feasibility Studies on Once Through Subcritical Cores driven by Accelerator Spallation Neutron Source

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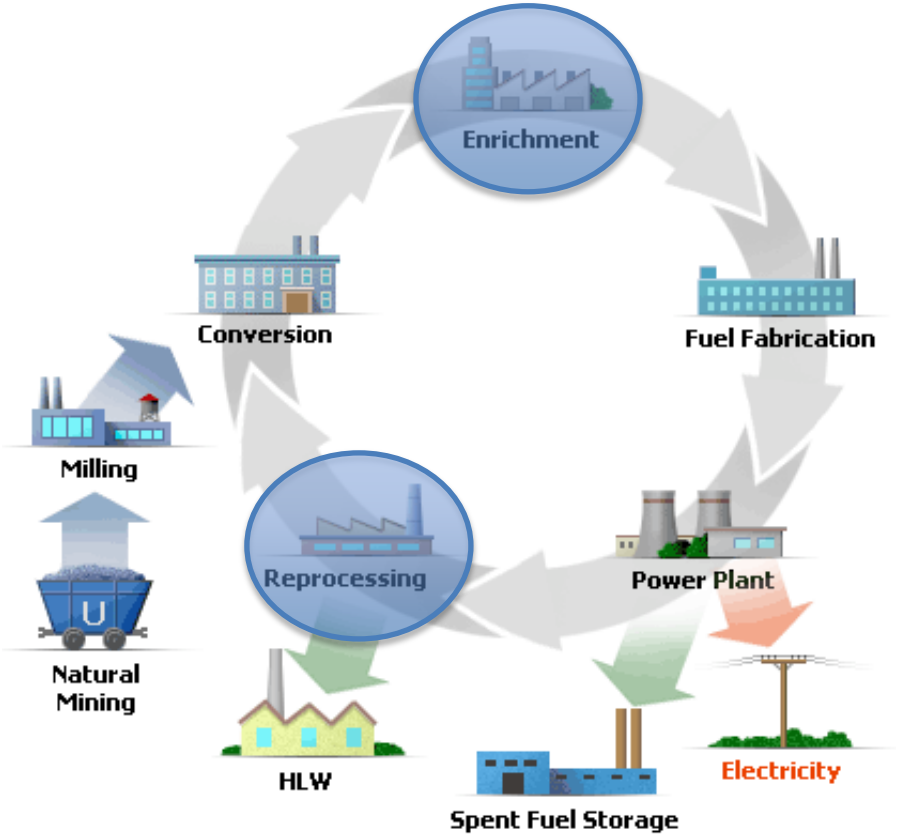
Contents

- Motivation
- Pebblebed Based ADS
- Energy Multiplier Module Based ADS
- Breed & Burn Based ADS

Motivation: Eliminating need for enrichment and reprocessing

- LLNL developed the enrichment-free, reprocessing-free, subcritical fuel cycle concept for the fusion-fission hybrid variant of LIFE.
- A subcritical fission blanket could be driven by a spallation neutron source rather than a fusion source.

This fuel cycle would eliminate critical points of the nuclear fuel cycle with respect to weapons proliferation



Kramer, "Neutron Transport and Nuclear Burnup Analysis for LIFE " Fusion Science and Technology (2009)
"Nuclear Industry Fundamentals" Nuclear Opportunities Fund. Web. 25 Mar. 2010 <www.investnuclear.com/ni_fundamentals>

Project Goal:

- Assess the feasibility of once-through, un-enriched, no chemical-reprocessing, nuclear fuel cycles using a spallation neutron source to drive a subcritical fission blanket
  - Investigate several once-through reactor variants
  - For each subcritical blanket variant try to identify a fairly optimized fuel and reactor design
  - Calculate the energy multiplication of each system

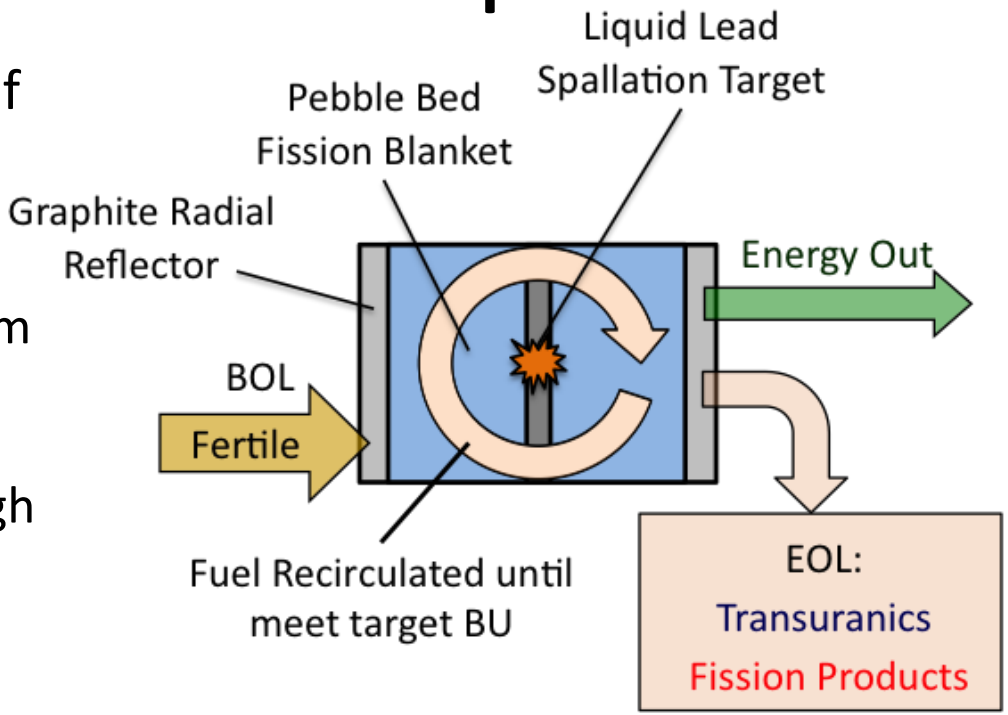
Systems Investigated

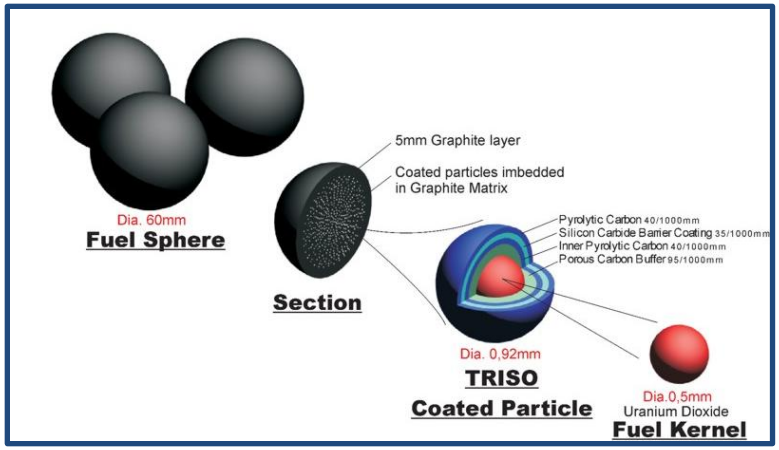
	System	Fuel	Fuel Form	Moderator	Coolant
Thermal	FHR	Th/NU	high temp. particle fuel	Graphite	Liquid Salt
Thermal	PBMR	Th/NU	high temp. particle fuel	Graphite	Helium
Fast	EM2	DU	sphere pack	-	Helium
Fast	B&B	UNF	metallic	-	Sodium

- Fast and Thermal Spectrum fuel cycles were investigated with a variety of fuel forms and coolants

Pebble Bed: Concept

- Large continuously fueled bed of Pebble Fuel surrounding an accelerator driven neutron source.
  - Outer Radius of Pebblebed 2.4m to minimize radial leakage
  - Fuel pebbles are well mixed
  - Robust particle fuel enables high burnups
  - High burnups are required to breed fissile fuel
- Coolants:
  - Liquid Fluoride Salt: *high volumetric heat capacity, operates at atmospheric pressure*
  - Helium: *neutron economy*





Thermal Systems: Neutronics Model

- MCNP5 used for neutron transport
- ORIGEN for depletion analysis
- Coupled with a custom utility, BEAU, developed to analyze continuously fueled nuclear systems.
- Assumptions:
  - Axially infinite model
  - Equilibrium core modeled assuming time-averaged, *equilibrium*, fuel composition
  - MCNP5 is run in source driven mode assuming a spallation neutron spectrum
  - Power produced in fission blanket is derivative of the neutron source

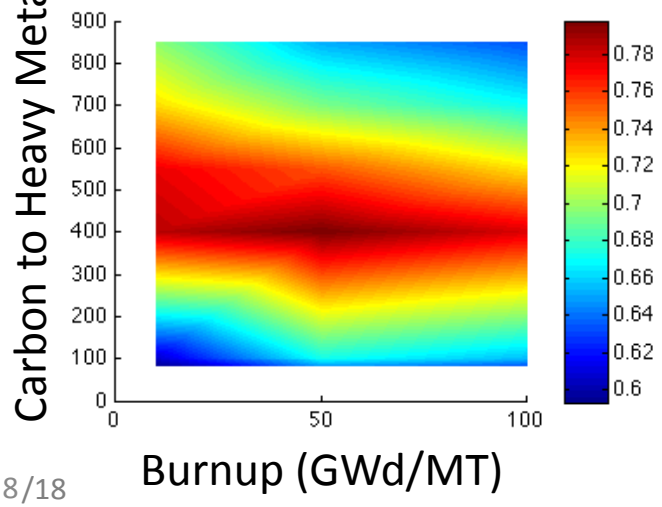
Cisneros, "Pebble Bed Reactor Depletion Analysis with Multiple Fuel Types" ANS summer meeting (2011)

Thermal System: Optimization

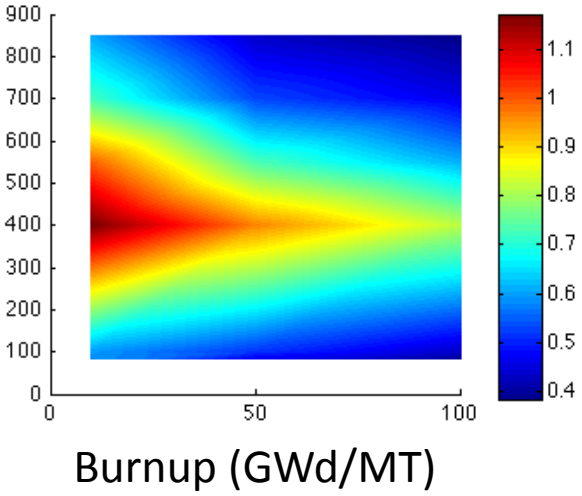
- Two design variables for each fuel/ coolant variant are neutron spectrum and discharge burnup.
  - Neutron spectrum controlled by the fuel to moderator ratio, carbon to heavy metal ratio (C/HM), which is adjusted by changing the packing fraction of the fuel particles in the pebbles.
  - The discharge burnup is controlled by selecting a cycle length to impose a target burnup.
- Parametric studies were performed for each fuel/coolant variant to maximize the energy multiplication of the system.

$$Electricity\ Gain = \frac{Electric\ Power\ ADS}{Electric\ Power\ Proton\ Bream}$$

k-infinity: NU/HE system



Electric Energy Gain: NU/HE system



k-infinity

Coolant	Fuel: Th	Fuel: NU
Flibe	0.877	0.749
Helium	0.877	0.785

Electricity Gain

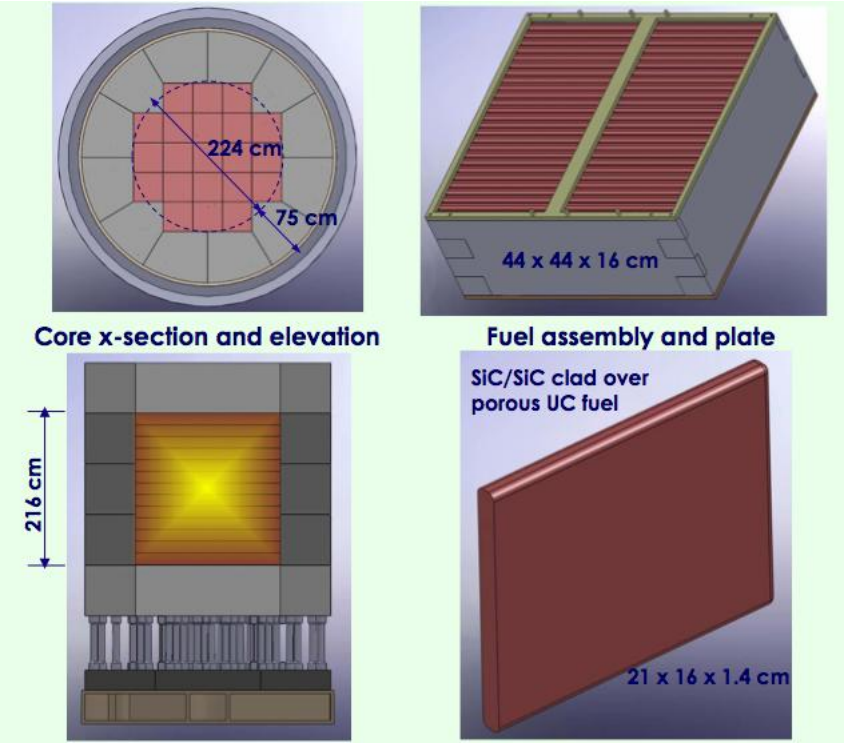
Coolant	Fuel: Th	Fuel: NU
Flibe	1.65	0.71
Helium	1.69	1.17

Thermal Systems: Conclusions

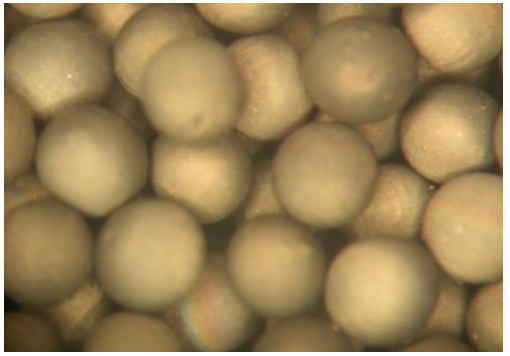
- Additional optimization work was performed to increase burnup with no significant gains in excess power or k-effective
  - Burnup segregation
  - Alternative Shuffling Schemes
  - Increased Cooling Time
- The once-through fuel cycles analyzed in this study do not multiply energy well enough to merit further studies

Fast Systems: EM2 Concept

- General Atomics is proposing a new advanced gas-cooled, fast-spectrum reactor concept, the Energy Multiplier Module (EM^2)
- EM^2 is based on technology developed for the GT-MHR
- Uses sphere pack UC fuel form to allow for venting of volatile FP



UC particle formation

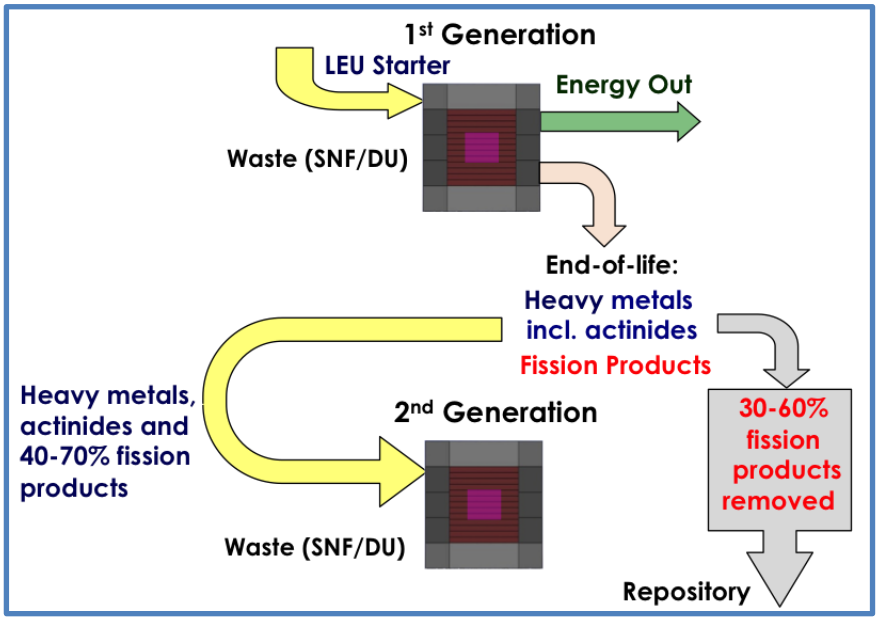


Early development of SiC composite wrap fuel plate sample at GA

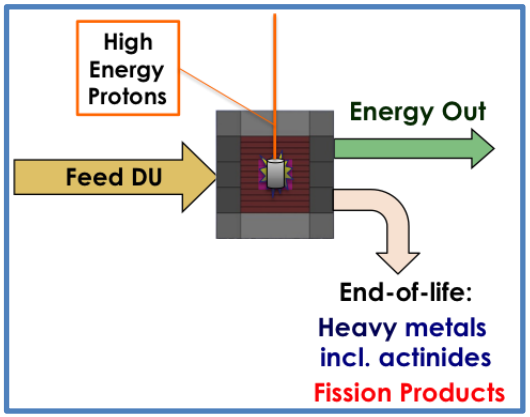
Schleicher "Change the Game for Nuclear Energy" Presentation at UC Berkeley (2010)

EM2: Fuel Cycles

Critical – EM^2 Fuel Cycle



ADS Driven – EM^2 Fuel Cycle



Schleicher "Change the Game for Nuclear Energy" Presentation at UC Berkeley (2010)

- A critical EM^2 requires a starter composed of either EU or TRU/DU
- A spallation neutron source could allow this system to operate without fissile fuel supply
- EM2 requires 30% FP removal every 15% FIMA – UCB aims to eliminate reprocessing the fuel entirely

EM^2: Neutronics Model

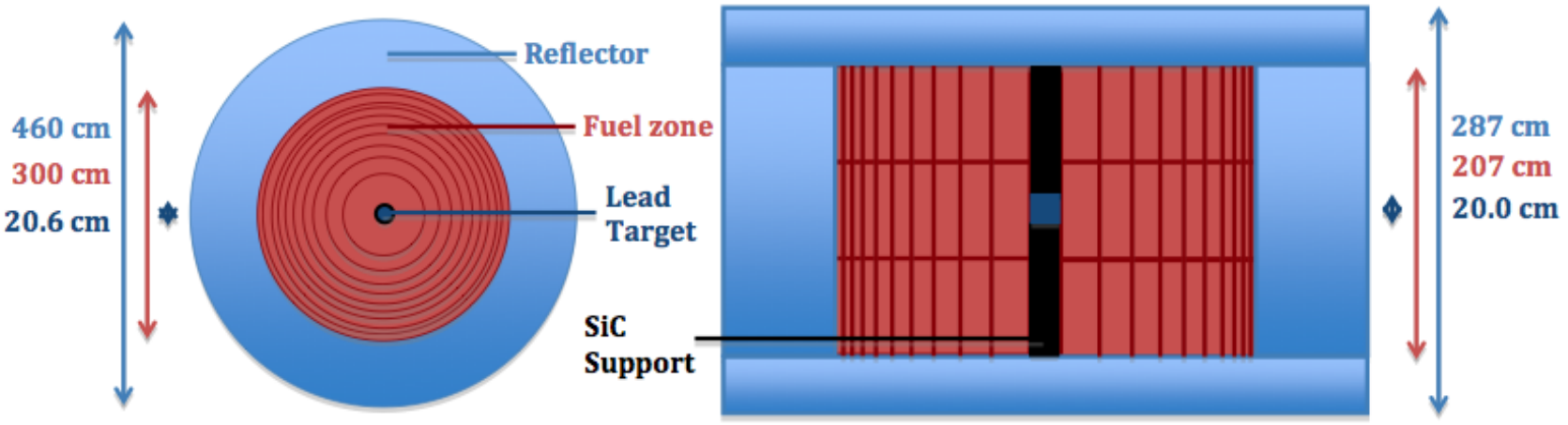
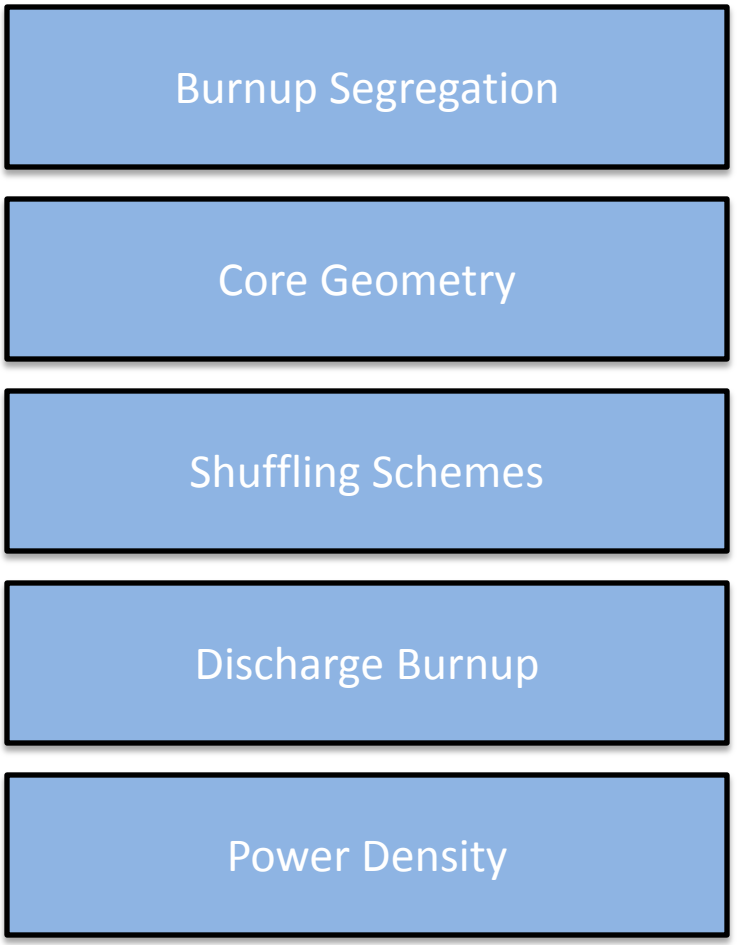


Figure 22 - Detailed geometry of the cylindrical core with the spallation neutron source: XY view (left) and YZ view (right)

- MCNP5 used for neutron transport
- ORIGEN for depletion analysis coupled by MOCUP
- Used spallation neutron spectrum for neutron source in lead target

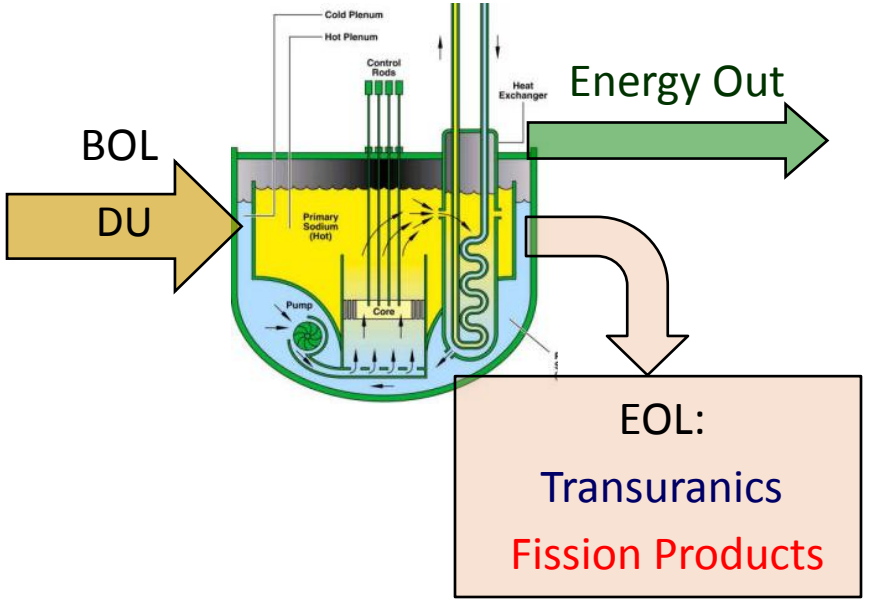
EM^2: Optimization and Results

- Optimization Studies for the EM^2 focused around
  - Effect of burnup segregation
  - Geometry of the EM^2 core
  - Alternative Shuffling Schemes
  - Sensitivity to discharge burnup
  - Power density
- A system with an *electricity gain* of 3.01 was identified for a finite cylindrical system, however the theoretical limit of the system is close to 4.52 – the *electricity gain* for a minimum leakage system (spherical system).



Fast Systems: Breed & Burn

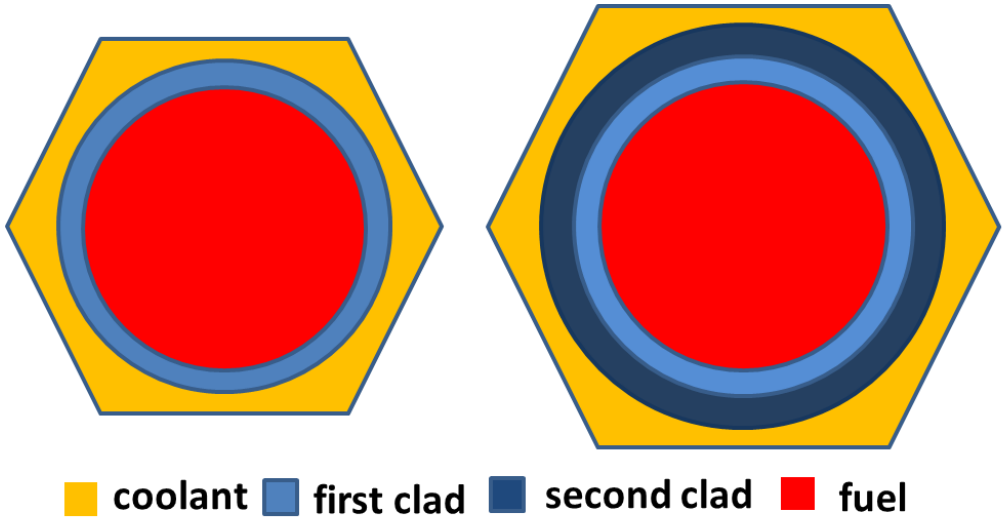
- Breed & Burn Reactor:
  - Coolant: Sodium
  - Fuel Form: Metallic Pins, 10w% Zr
  - Fuel Clad: HT-9
  - Feed Fuel: Depleted Uranium
  - Burnup: 20% FIMA



- A Breed & Burn reactor is a high-burnup fast reactor developed by Terra Power LLC and also studied at UCB.
- DU is fed into the Breed & Burn and transuranics are bred and fissioned in the fuel until the clad reaches a radiation damage limit at which time the fuel must be discharged.

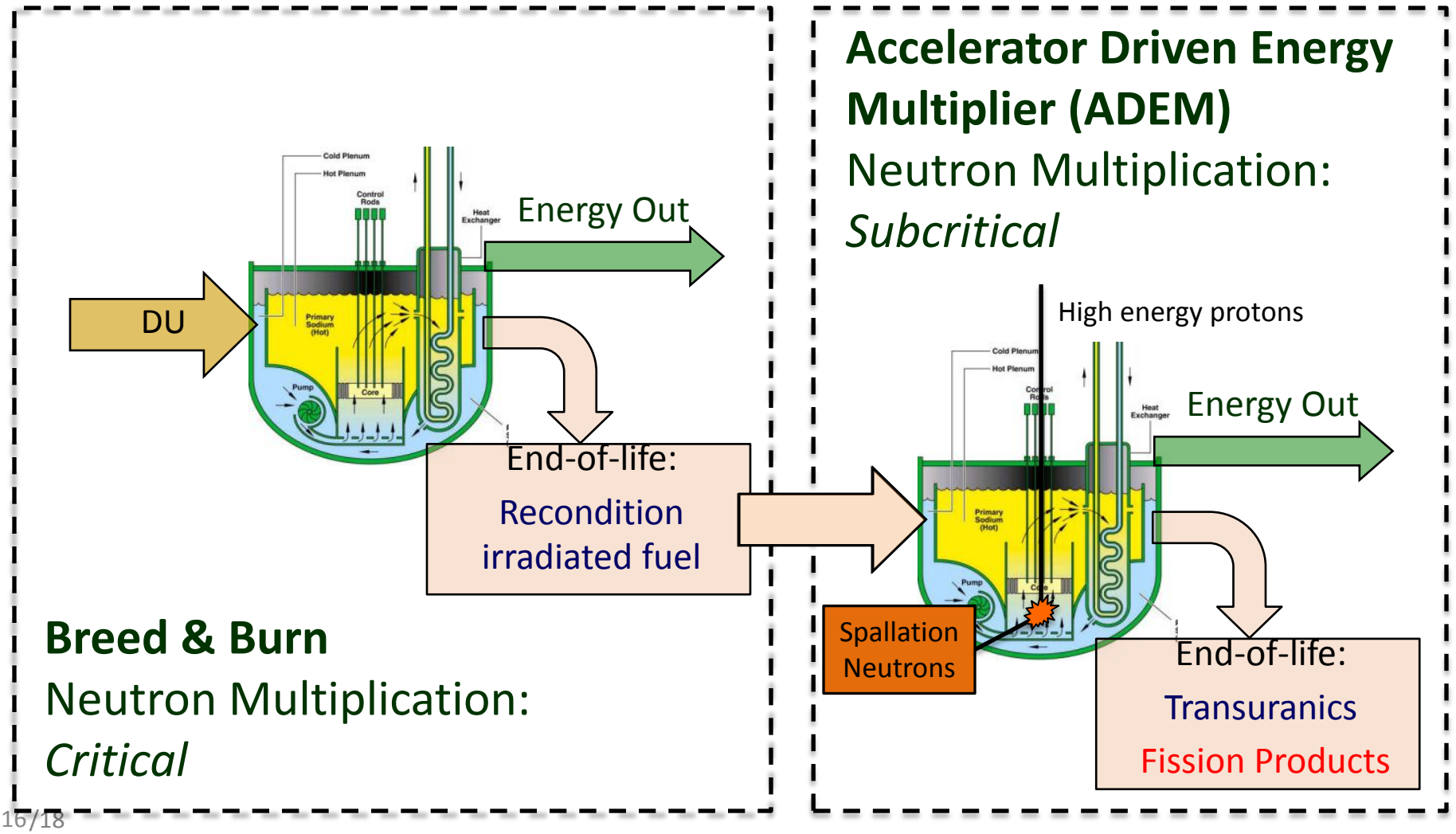
Breed & Burn: Recondition Fuel

- Physical Reconditioning:
  - Gaseous fission products are vented
  - New clad is implemented over original cladding



- Second clad provides mechanical integrity for another irradiation campaign
- Reconditioning is only physical processing – no additional proliferation concerns
- However, second clad reduces k_∞

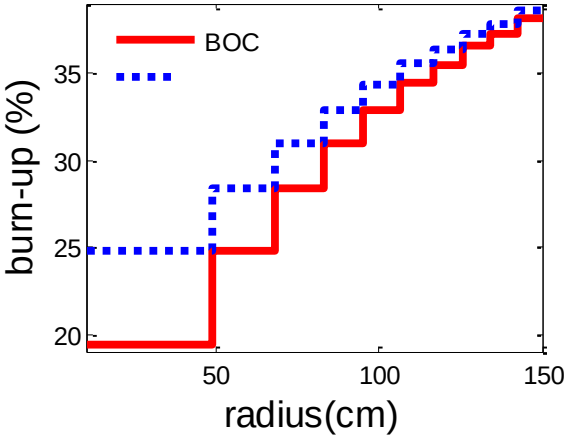
Breed & Burn: Two Tiered Fuel Cycle



Breed & Burn: Results

- ADEM core utilizes 10 depletion zones and an in to out shuffling scheme
- Preliminary neutronics and depletion calculations predict that the fuel can be driven to a final burnup of 39.5% FIMA

Burnup Distribution for Constant Coolant Area



P/D: 1.122

	BOC	EOC
Burnup (% FIMA)	20	35
K-effective	.966	.959
Electricity Gain	6.4	5

P/D: 1.078

	BOC	EOC
Burnup (% FIMA)	20	39.5
K-effective	.980	.965
Electricity Gain	10	6

Di Sanzo, "An Accelerator Driven Energy Multiplier for Doubling Uranium Ore Utilization" Accelerator Applications 2011

Conclusions

- Spallation neutron sources enabled power multiplication in subcritical fission blankets without enrichment or chemical reprocessing.
- Fast spectrum fission blankets performed significantly better than thermal spectrum fission blankets with respect to electricity gain.
- Comparing the two fast-spectrum systems analyzed the spallation neutron source to drive a B&B fission blanket for an additional 20% FIMA is an intriguing application of ADS system.
  - This system achieved a significant electricity multiplication factor
  - This B&B system increases natural uranium utilization by a factor of ~40 relative to the once-through LWR fuel cycle, and the ADEMs fuel cycle further increases the uranium utilizaiton by a factor of 2!
  - Therefore, this system warrants further investigation