Physics of Breed and Burn Nuclear Reactors

Reactor Physics Summer School

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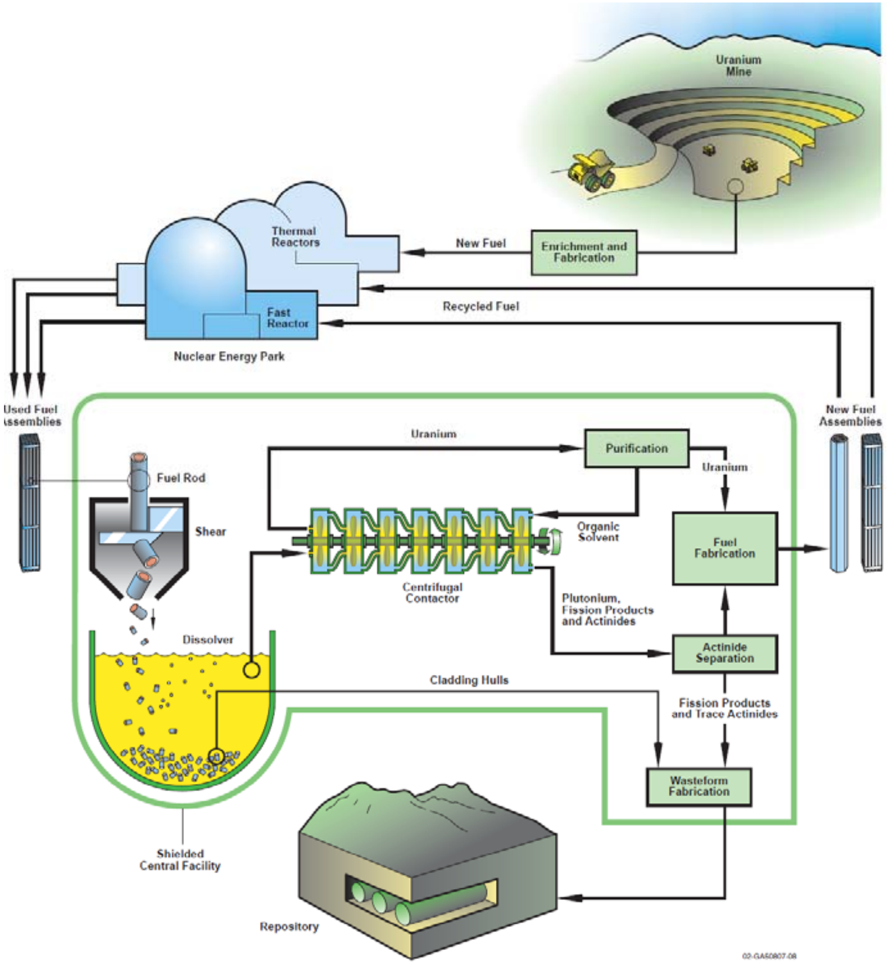
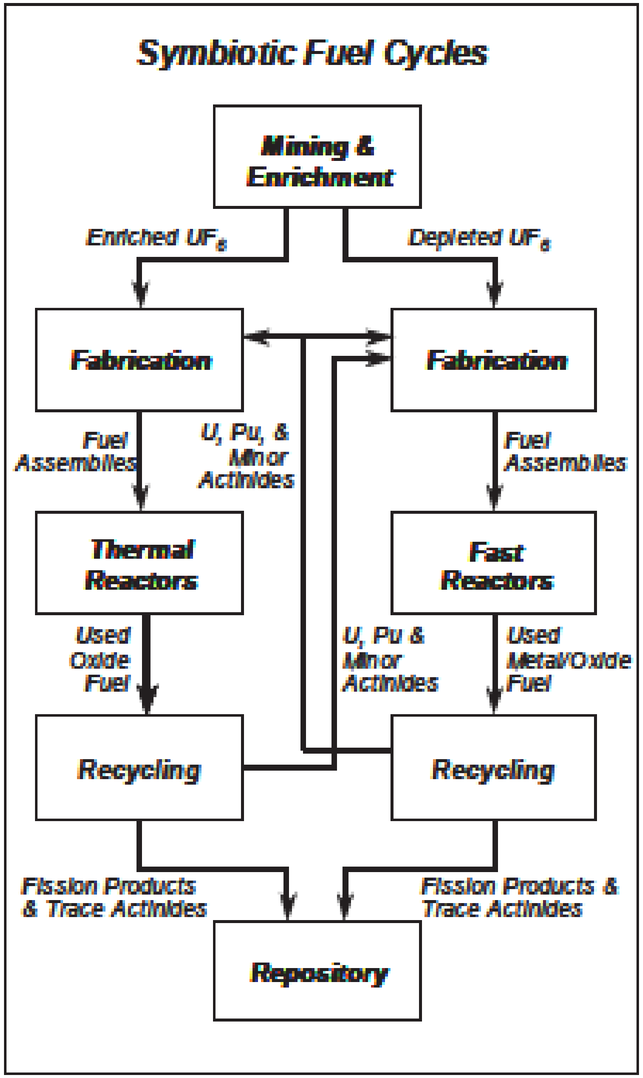
Outline

- What is a Breed & Burn (B&B) reactor
- Brief history
- The CANDLE reactor
    - Concept description
    - Practical implementation considerations
- The TerraPower “standing wave” reactor concept
- Minimum burnup required for B&B mode of operation
- Sensitivity of minimum required burnup to
    - Core composition
    - Fuel type
    - Core dimensions
    - Reactivity control requirements
- Minimum attainable doubling time
- Spawning mode of operation and its implications

What is a B&B reactor?

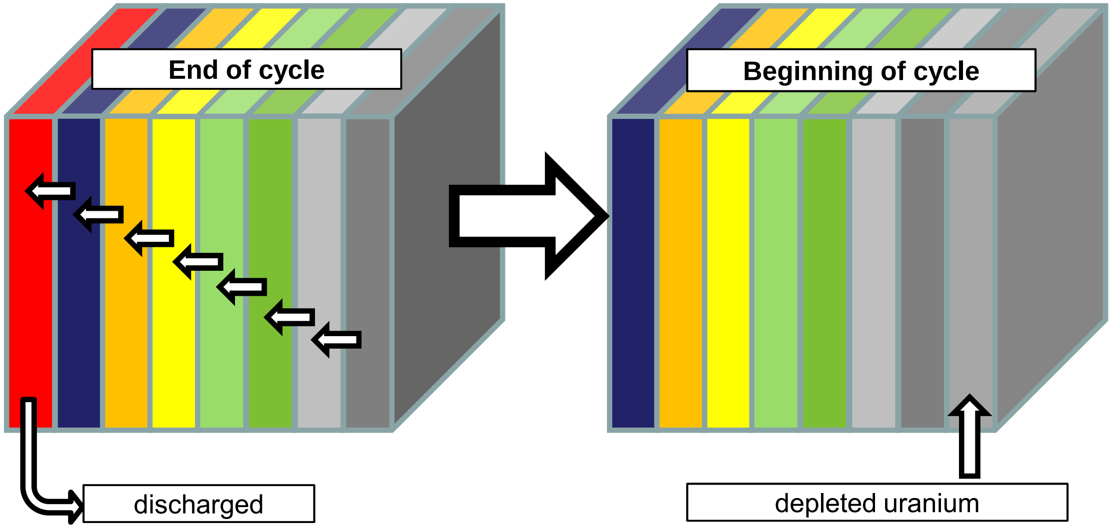
- Conventional breeder reactors are designed to recycle the plutonium (Pu) and Minor Actinides (MA) once the fuel reaches its radiation-damage limit





What is a B&B reactor?

- Breed & Burn reactors are designed to “burn” (fission) part of the Pu (MA) bred without separating the Pu (MA) from the fuel
- They operate on the once-through fuel cycle or (option being studied at UCB) – “reconditioning” the fuel that reached its radiation damage limit without separation of actinides and solid fission products.



Brief History

- First proposed by S.M. Feynberg and E.P. Kunegin, Proc. 2nd UN Inter. Conf., 1958

More recently by

- G.J. Fischer et al., “The Fast-Mixed Spectrum Reactor Interim Report,” Brookhaven National Laboratory Report BNL-50976, January 1979
- Edward Teller, Lowell Wood et al. (Proc. of the Frontiers in Physics Symposium, American Physical Society and the American Association of Physics Teachers Texas Meeting, Lubbock, Texas, USA, 1995).); Recently re-evaluated by TerraPower.
- Georgy Toshinsky – LMFBR Operation in the Nuclear Cycle Without Fuel Processing, Advanced Reactor Safety Topical Mtg., Orlando, FA, 1997
- Hiroshi Sekimoto – the CANDLE reactor concept, Proceeding of PHYSOR 2000, Pittsburgh, May 7-11, 2000.

The CANDLE reactor concept

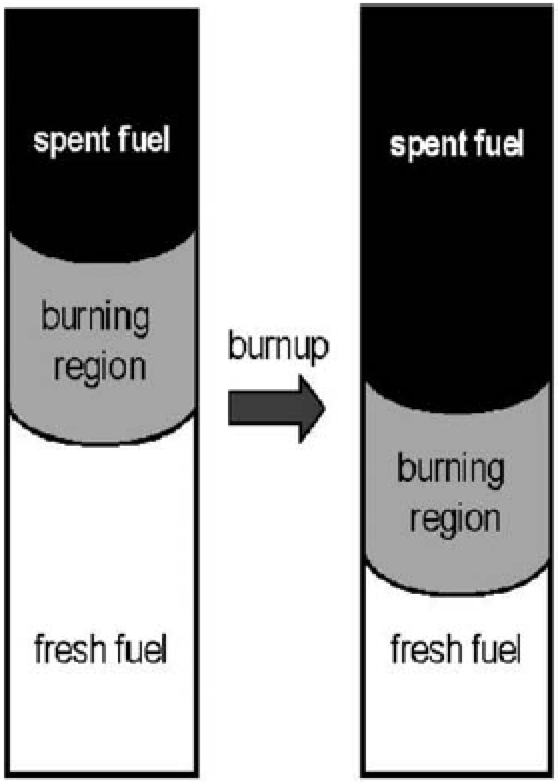


Fig. 1. CANDLE burnup strategy.

CANDLE: Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy production

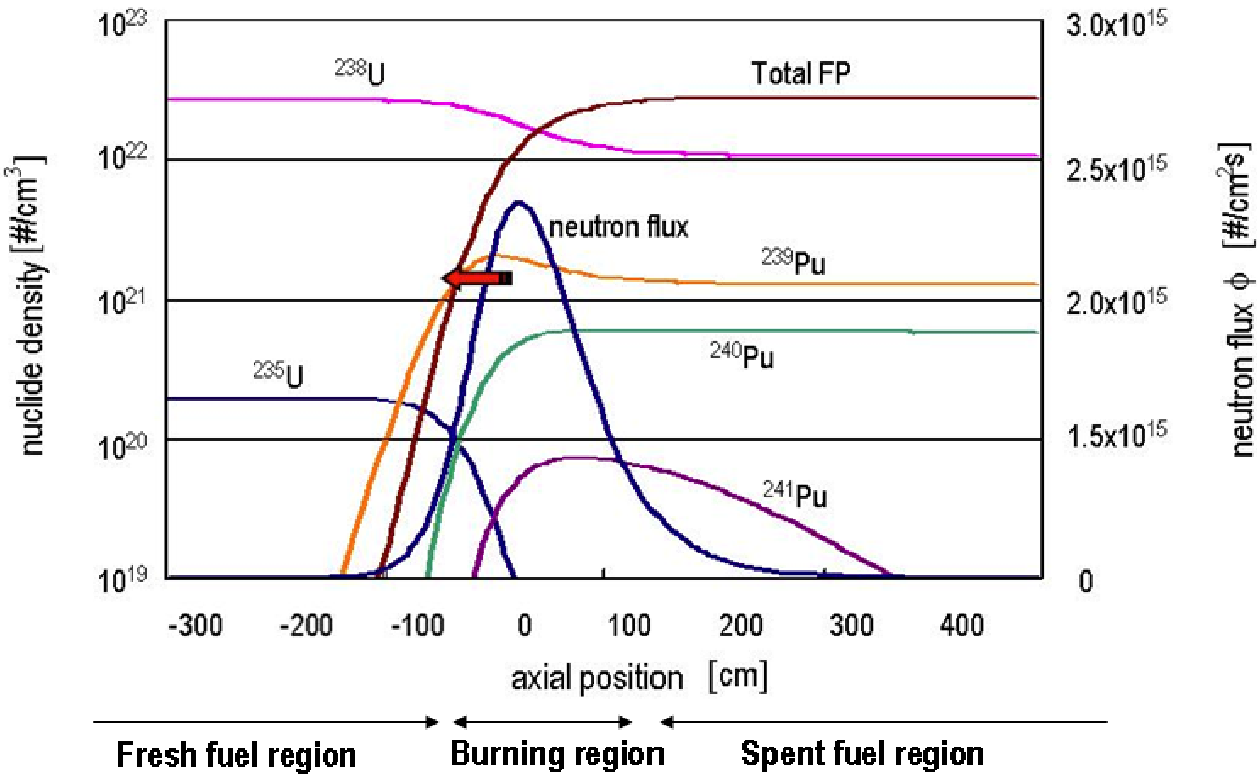
Conceived by Prof. Hiroshi Sekimoto of the Tokyo Institute of Technology (UCB NE Alumnus)

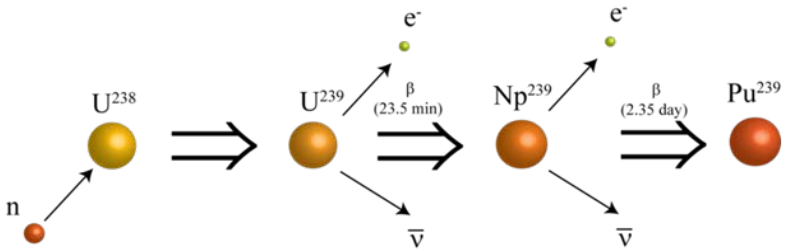
- Start with elongated depleted (natural) uranium core
- Load fissile fuel (enriched uranium or Pu from LWR UNF or TRU from LWR UNF) in one side (or center) of the core in the amount needed to establish a chain reaction
- Design the core to have a high breeding ratio – requires a hard neutron spectrum → liquid metal (gas ???) coolant

Principles of propagating fission “wave”

pertaining to the CANDLE reactor concept

(from Prof. Sekimoto’s publication)

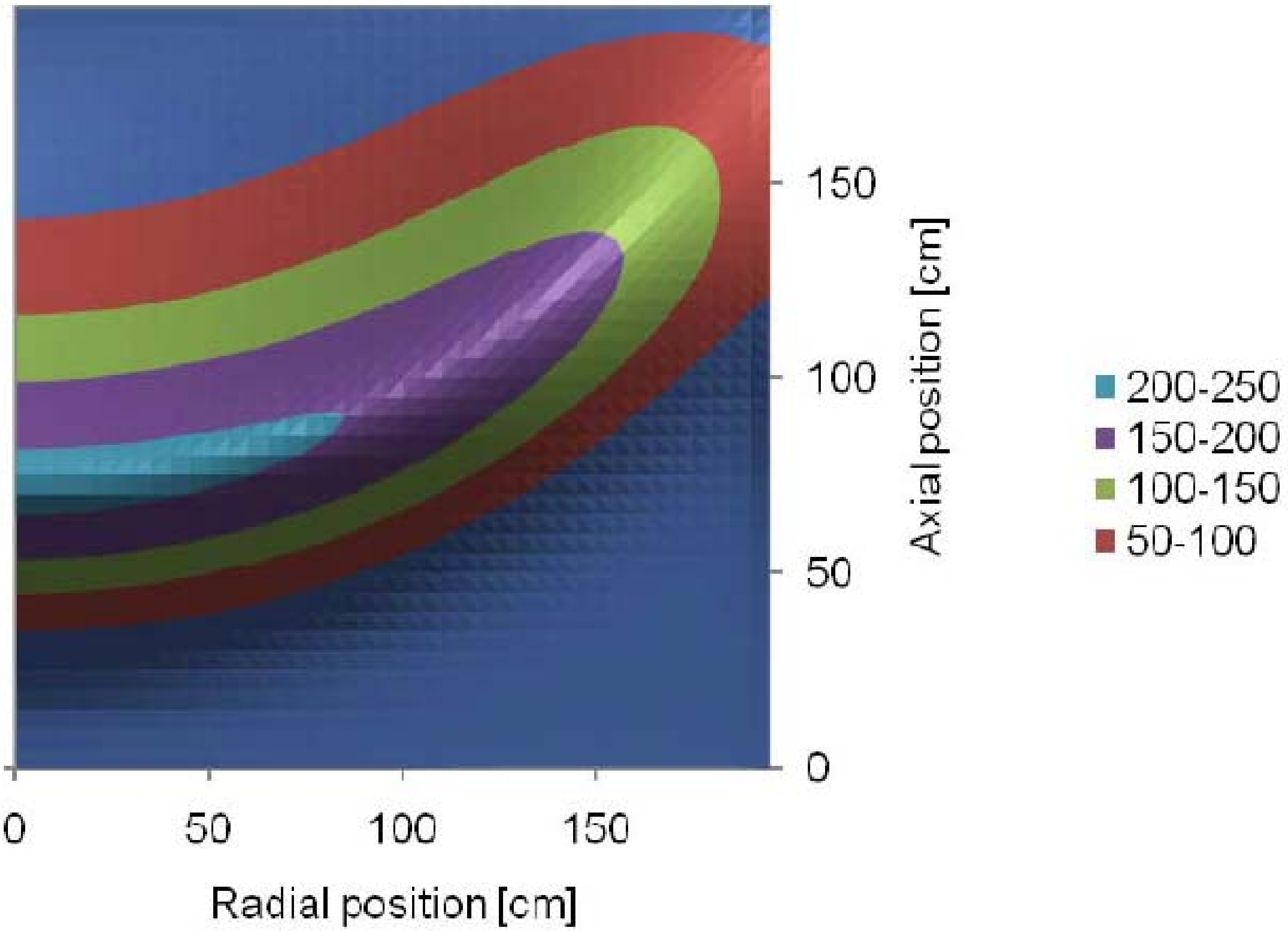




Typical power-density (w/cc) distribution of propagating fission "wave"

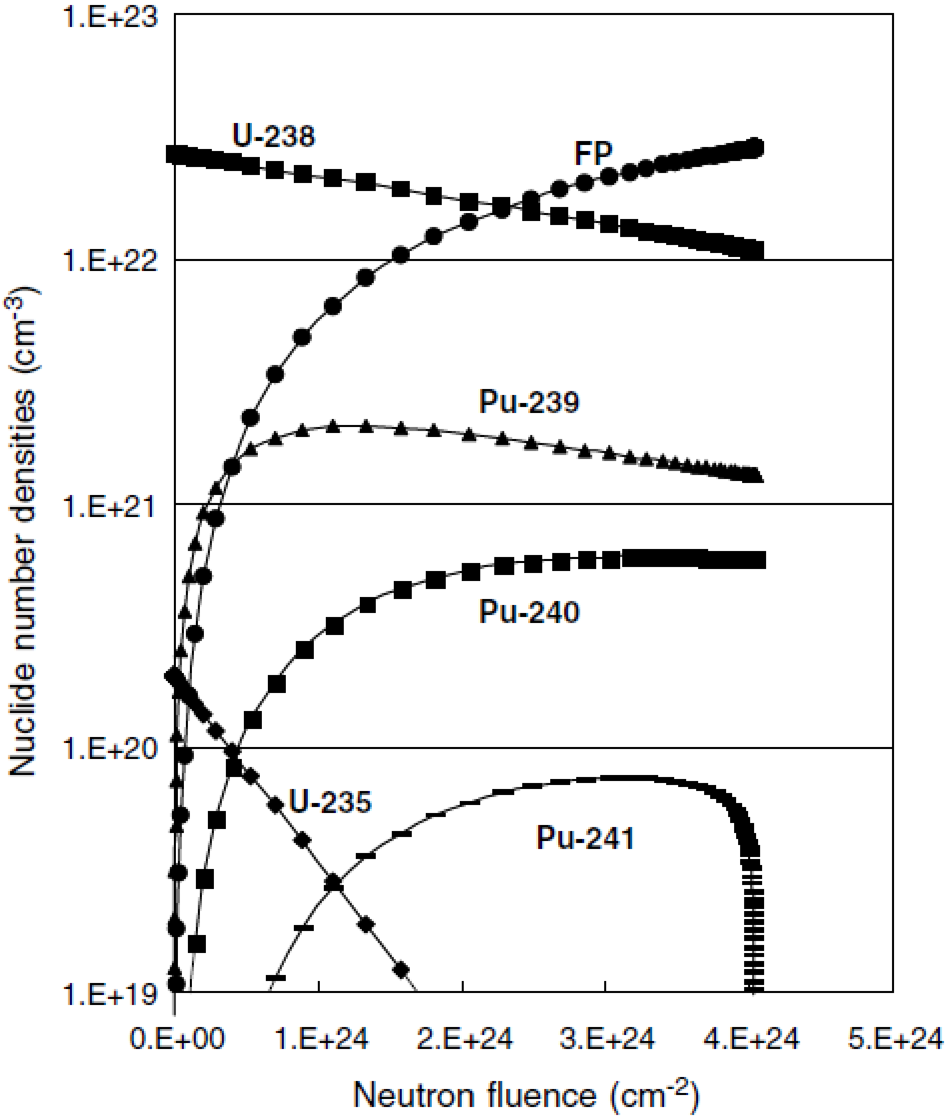
pertaining to the CANDLE reactor concept

(from Prof. Sekimoto's publication)



Isotopic evolution in CANDLE

From Sekimoto et al.



At a given location in the core

Fission products concentration becomes very high (resulting in a significant loss of neutrons)

Neutron balance evolution in CANDLE

From Sekimoto et al.

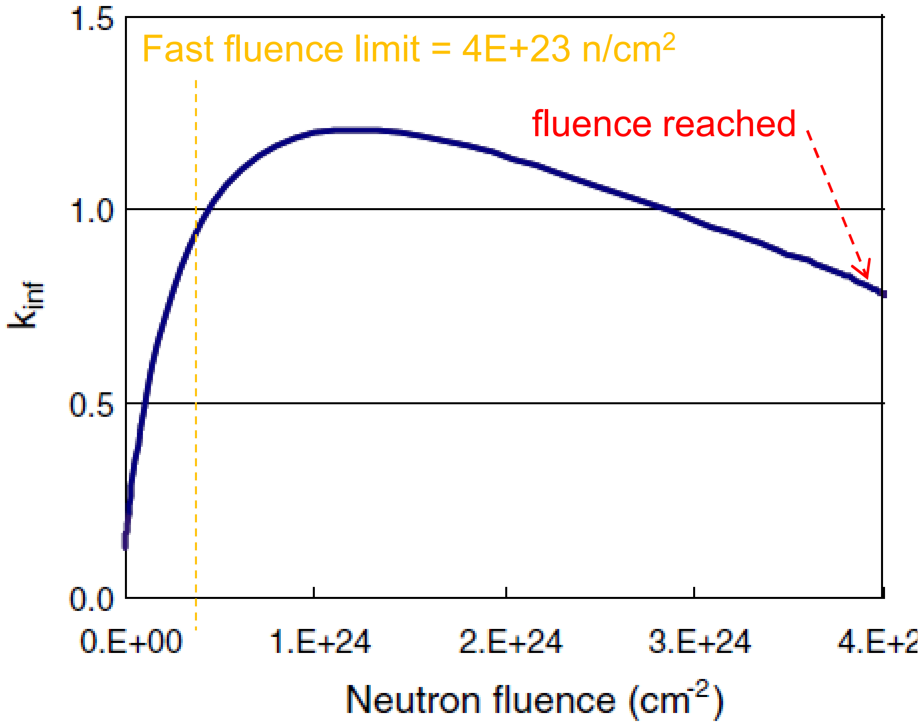


Fig. 3. Change of k_{inf} along neutron fluence.

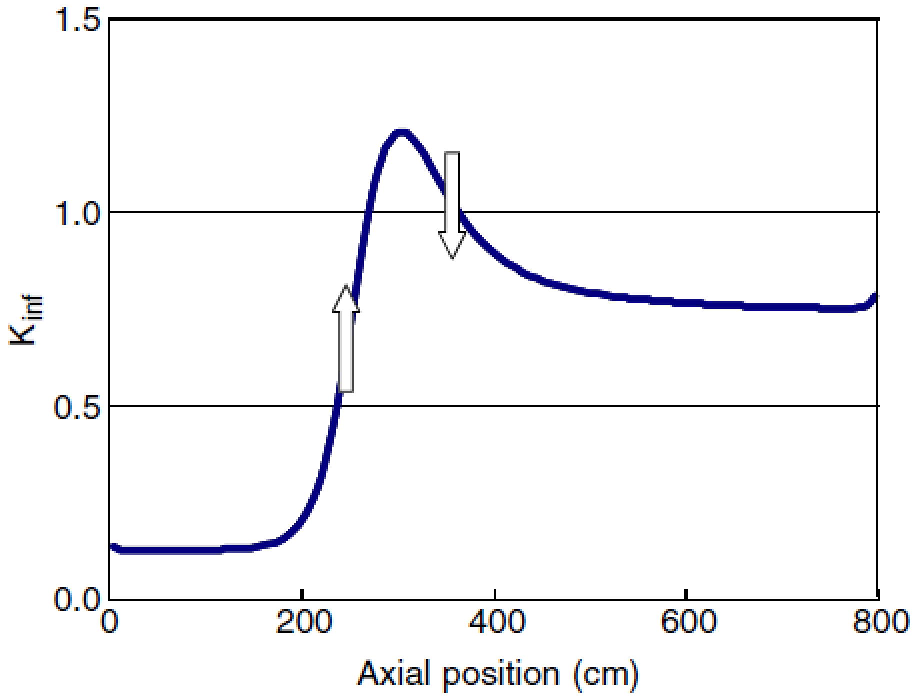


Fig. 4. Change of k_{inf} along core axis.

Evolution of k_∞ with total neutron fluence (time or burnup) at a given location in the CANDLE core

Variation of k_∞ as a function of axial location along CANDLE core axis – a snapshot in time

Practical implementation issues for CANDLE type cores

- Average burnup of left-over fuel is ~40% -- beyond proven technology (for example - *clad materials were qualified for up to ~10% burnup (200 dpa on clad))*
- Coolant friction loss through the core is very high due to very long core and tight lattice pitch -- this will limit coolant flow rate and, hence, core power density

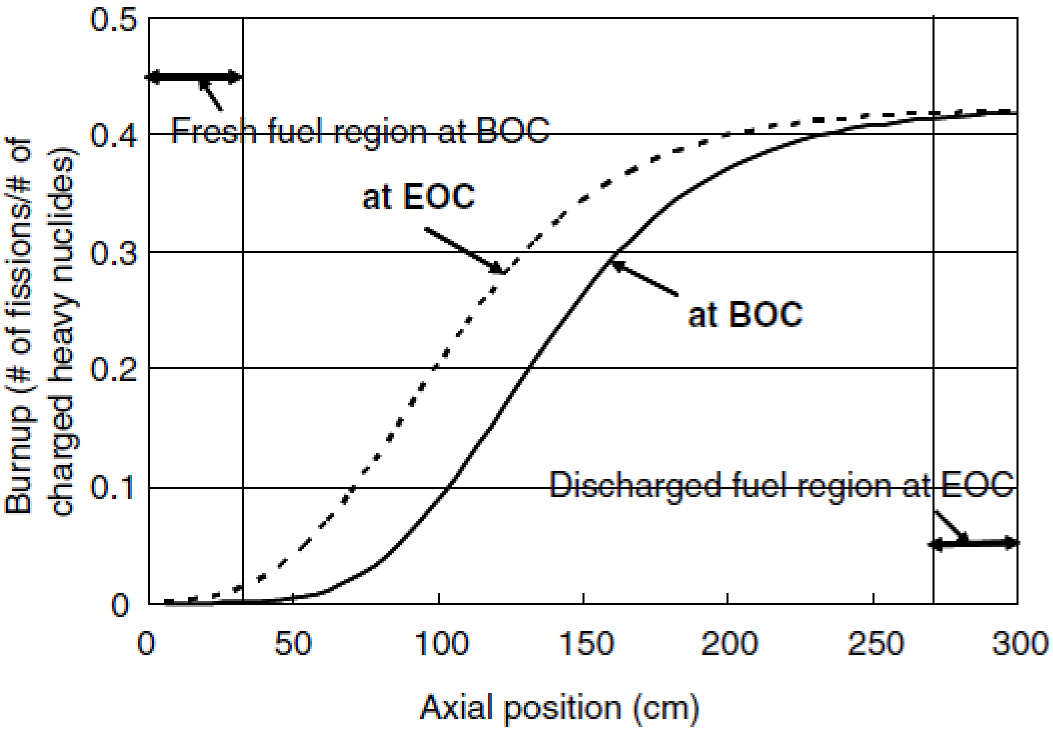
  This drawback can possibly be alleviated using a “stacked” core scheme (see below)

Practical implementation issue of CANDLE type cores:

Very high burnup

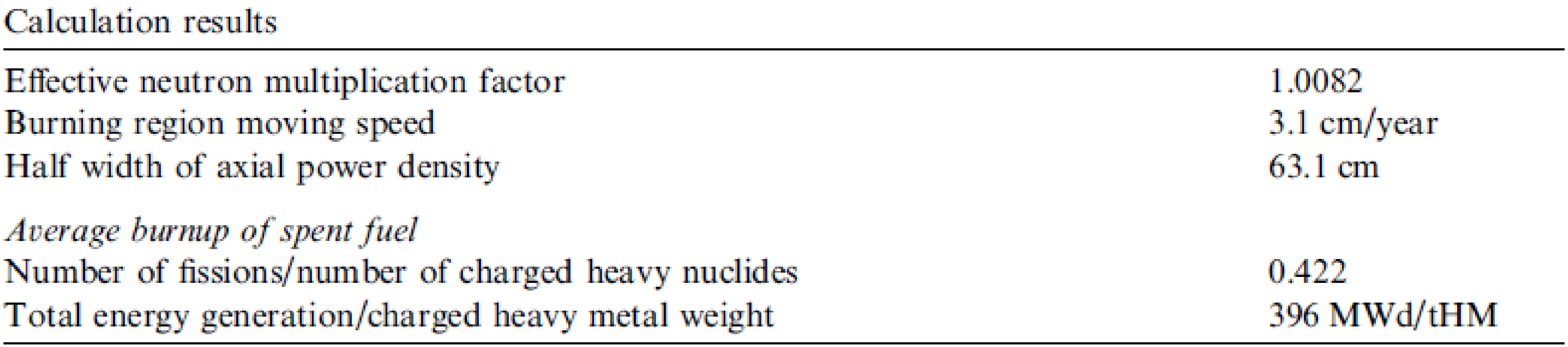
Could be alleviated by fuel “reconditioning” (removing gaseous fission products and replacing clad)

Burnup required for wave propagation



From Sekimoto et al. CANDLE

- Accumulated burnup ~ 400 GWD/tHM
- This is much beyond presently accepted value as the integrity of the fuel rods that is constrained by
  - radiation damage to the clad
  - gaseous fission products pressure buildup inside the fuel rod
  - fuel swelling causing clad stressing and straining



Calculation results	
Effective neutron multiplication factor	1.0082
Burning region moving speed	3.1 cm/year
Half width of axial power density	63.1 cm
Average burnup of spent fuel	
Number of fissions/number of charged heavy nuclides	0.422
Total energy generation/charged heavy metal weight	396 MWd/tHM

Practical implementation problems of CANDLE type cores

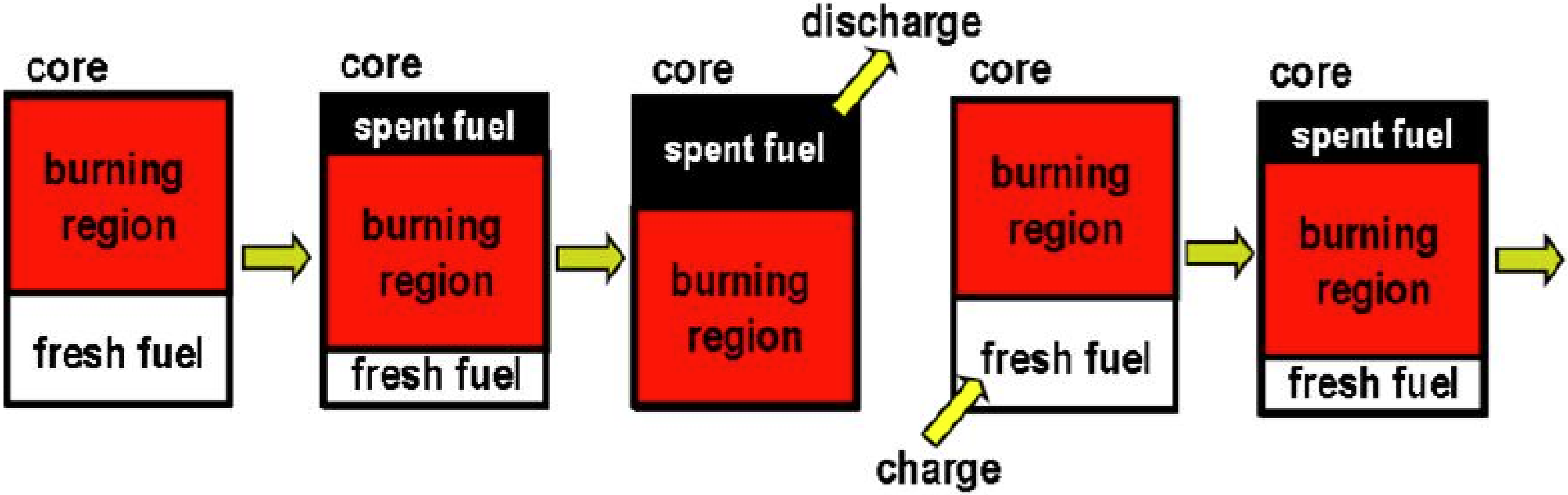
High coolant pressure loss

Could be alleviated by reducing core height using fuel axial staggering

A more practical embodiment of a CANDLE core

pertaining to the CANDLE reactor concept

(from Prof. Sekimoto’s publication)



Looks complicated (stacking fuel axially) and neutron wasteful (high leakage probability)

Why do we need a tight lattice pitch?

Fast (hard) spectrum is preferable

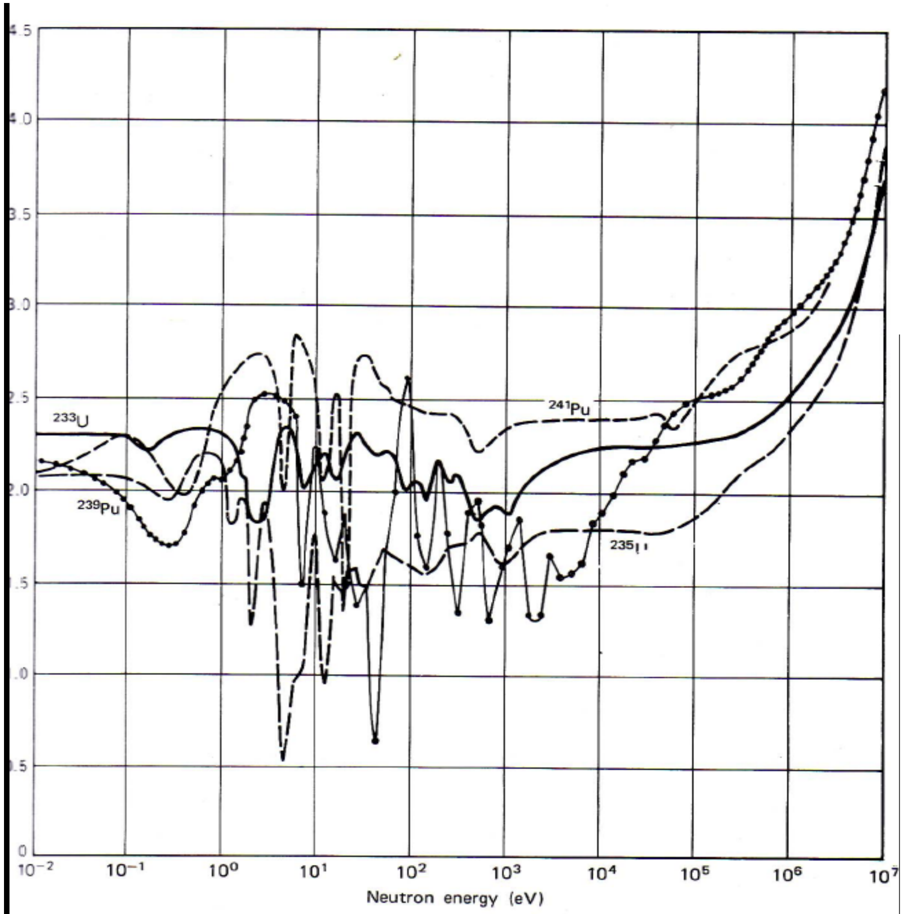
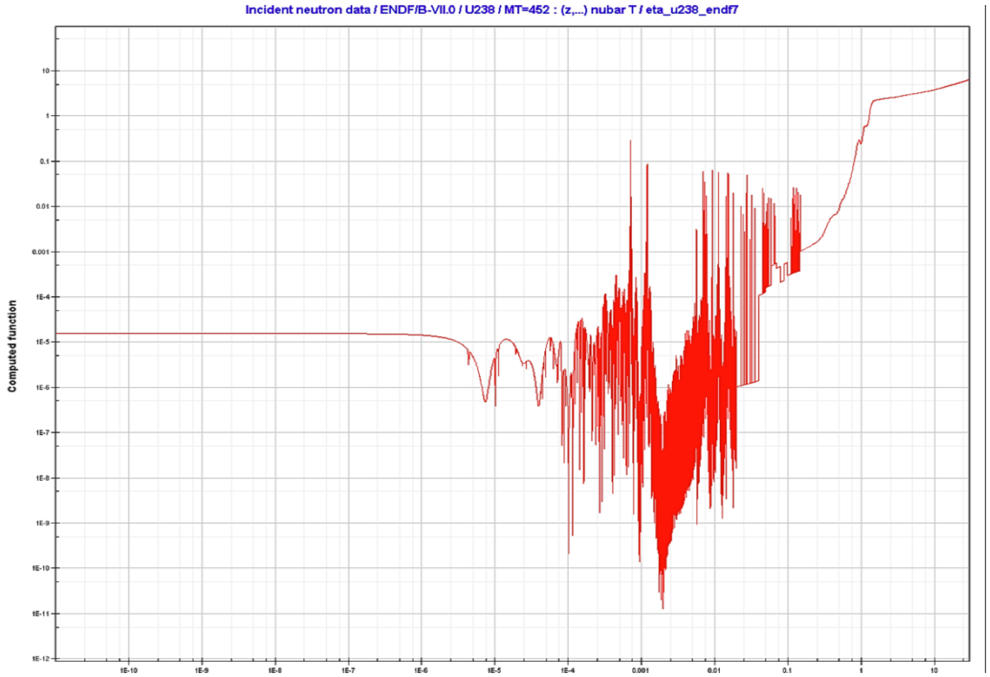


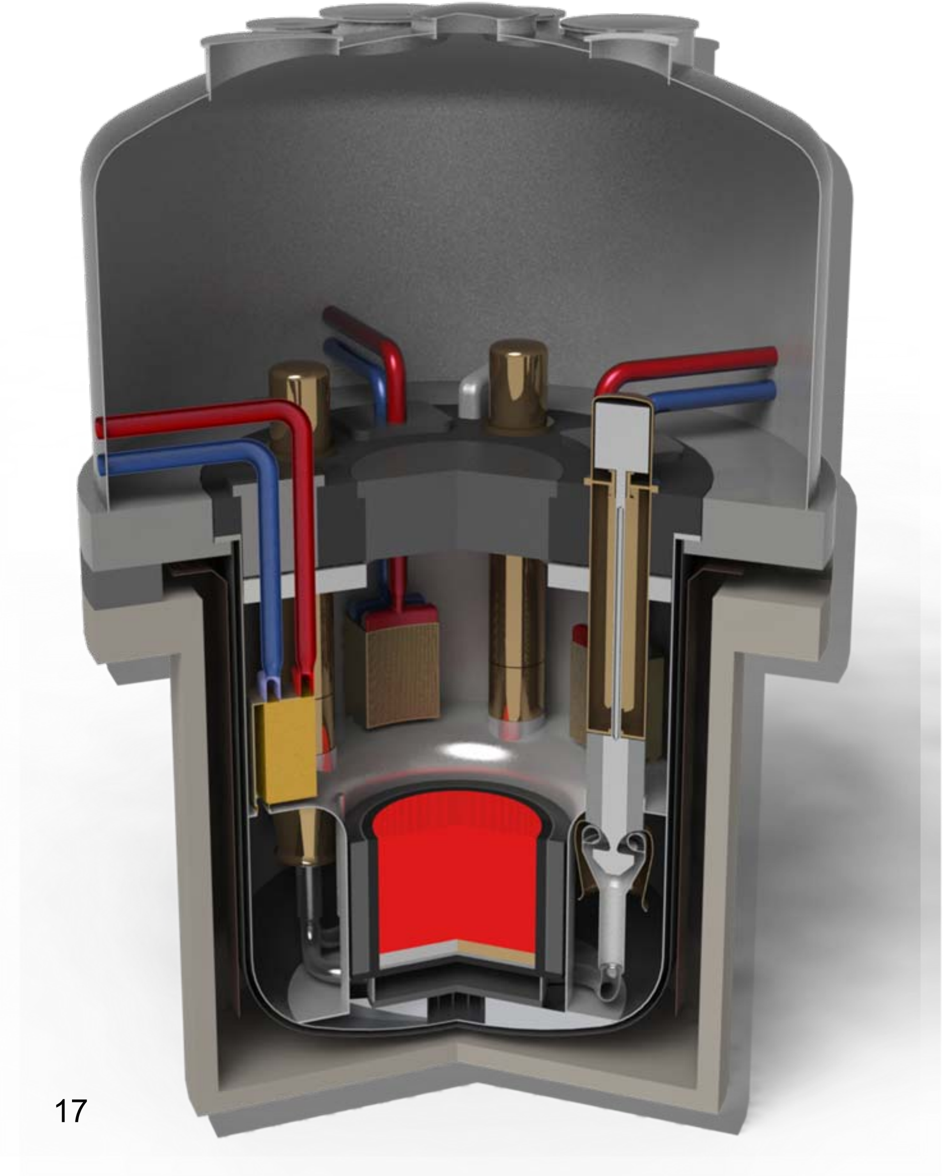
FIGURE 2-25. Variation of η with energy for ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu.

- $\eta \equiv \nu\, \Sigma_f / \Sigma_a$ is the highest
- ^{238}U is the best fertile fuel – high σ_f at large E



The TerraPower “standing wave” core concept (TP ICAPP 2010)

Cylindrical Standing-Wave Reactor



- Core is of a more conventional geometry
- Wave is stationary
  in the lab frame;
  fuel is moved radially
- Power density is typical of a fast reactor through entire life

Typical layout of a large TP Core

(TP ICAPP 2010)

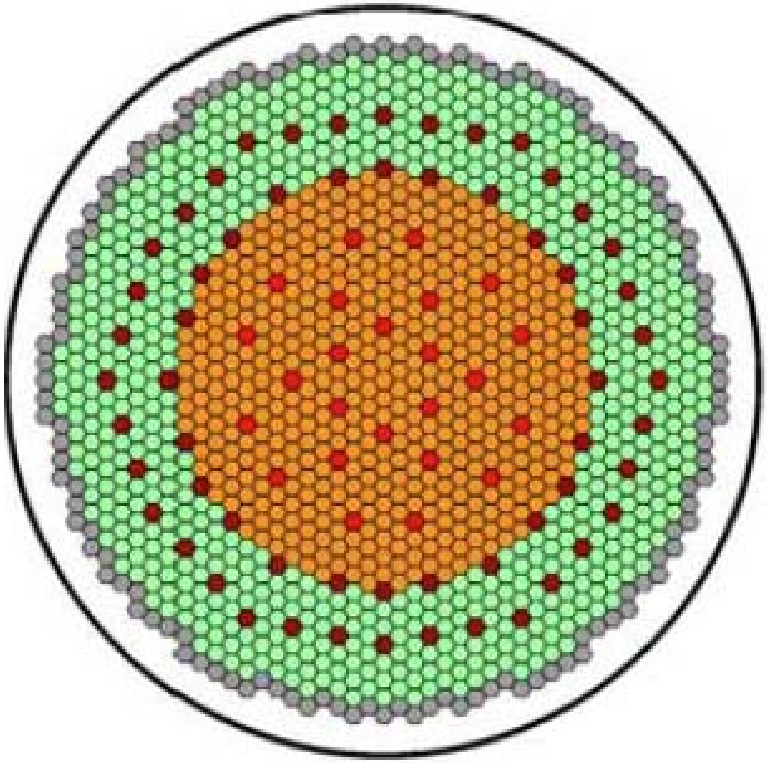
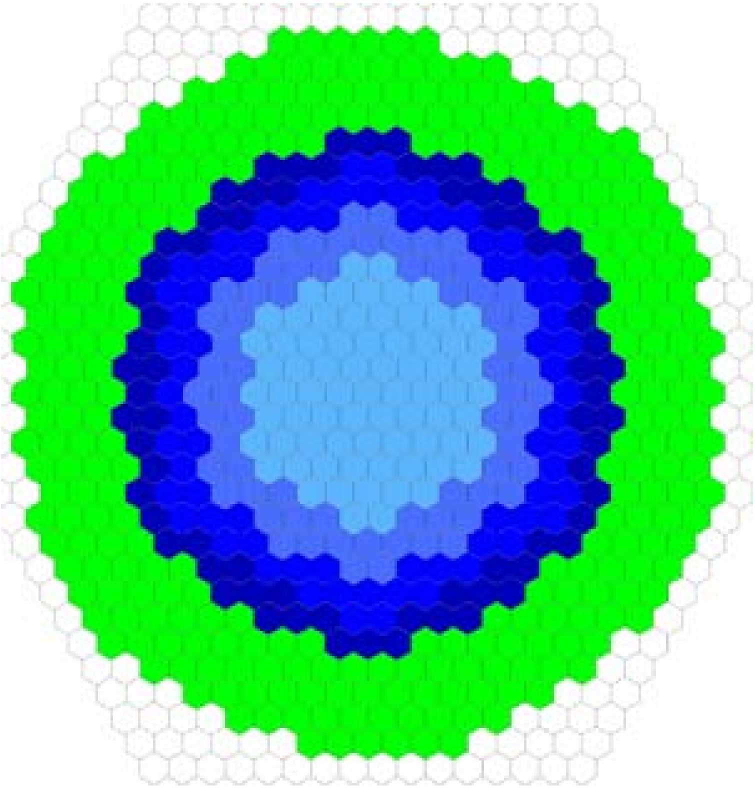
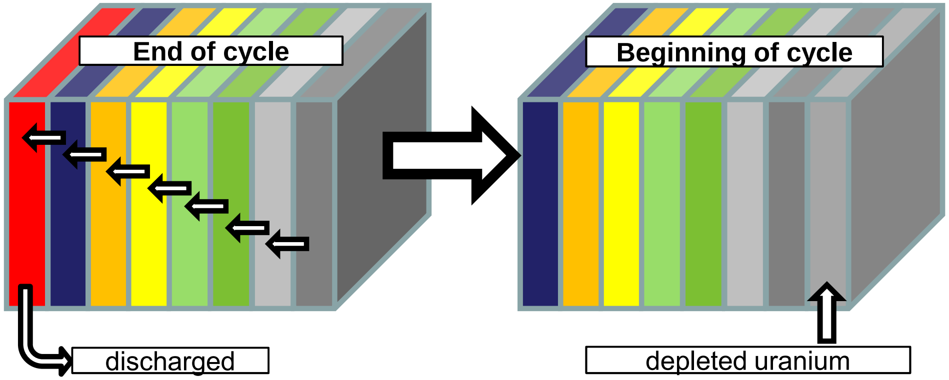


Fig. 2. BOL Core face map (Orange – ACZ, Green FCZ, Red – Movable Control and Safety Assemblies, Brown – FCZ absorber assemblies at EOL, Grey-shield assemblies

Example: UCB initial B&B core layout and fuel management scheme

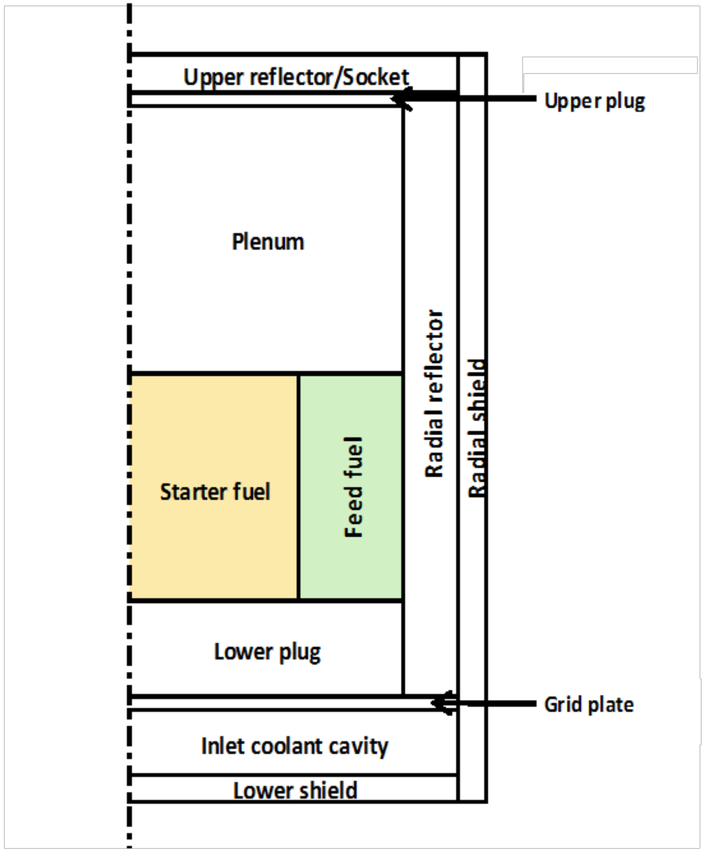


- Starter (blue) volume = blanket (green) volume
- TRU wt% progressively increases across 4 equal volume radial zones -- 6.6, 11.7, 12.2 to 15.3wt%
- Shuffling scheme is shifting inward, using 8 equal volume radial zones



Core examined at UCB

- Core considered is that described in Florent Heidet and Ehud Greenspan PHYSOR-2010 paper: “Breed-and-burn Depleted Uranium In Fast Reactors Without Actinides Separation” (See dimensions next slide)



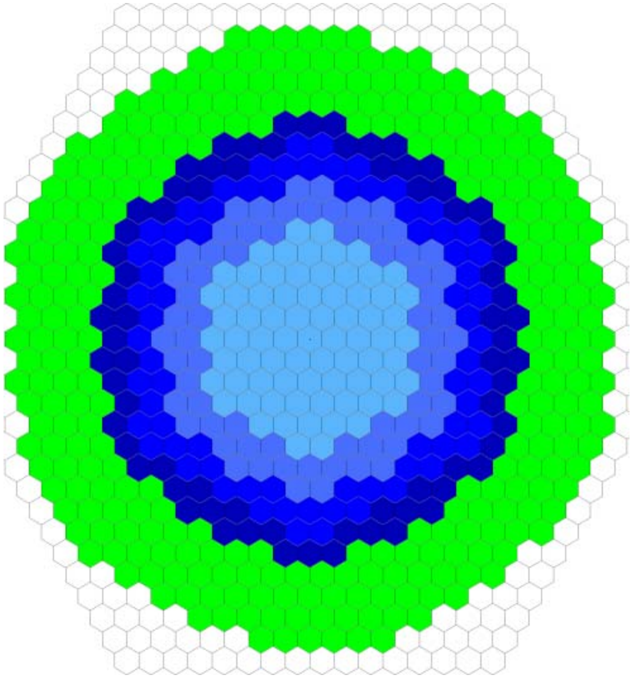
Core examined (2)

Dimensions, composition and temperature of the modeled breed & burn core

Region	Height (cm)	Thickness (cm)	Material (Volume %)	Temp. [K]
Upper reflector	34.93	242.2	50% HT9- 50% Na	783
Upper end plug	2.54	201.36	22% HT9 - 78% Na	783
Plenum	250	201.36	22% HT9 - 28% Na	783
Seed	209.36	142.38	37.5% Fuel - 22% HT9 - 28% Na – 12.5% Na (gap)	800
Blanket	209.36	58.98	37.5% Fuel - 22% HT9 - 28% Na – 12.5% Na (gap)	800
Lower end plug	90.42	201.36	22% HT9 - 78% Na	628
Grid plate	5.18	242.2	50% HT9 - 50% Na	628
Coolant inlet	60	242.2	22% HT9 - 78% Na	628
Lower shield	20	242.2	43.1% B_4C - 29.7% HT9 - 27.2% Na	628
Radial reflector	552.32	40.84	50% HT9 - 50% Na	628
Radial shield	672.43	20.5	43.1% B_4C - 29.7% HT9 - 27.2% Na	628

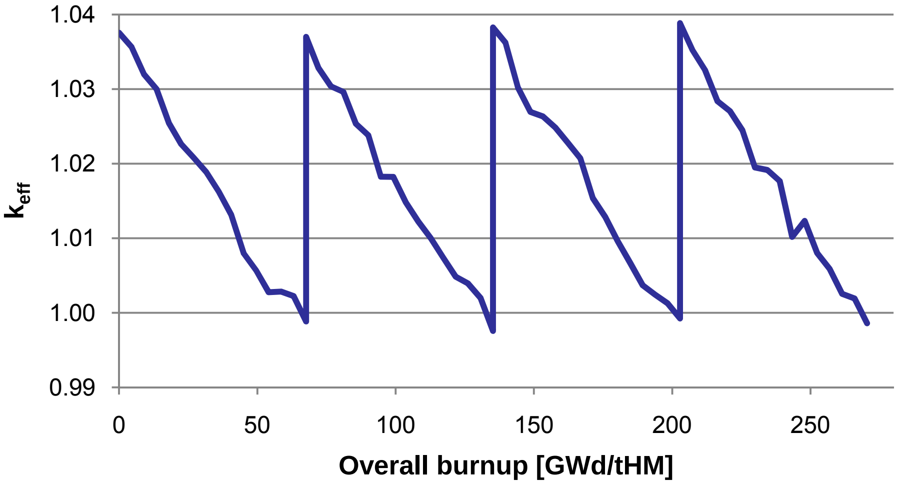
Model and constraints

- Neutronics and depletion codes used:
  - MCNP5 version 1.40
  - ORIGEN2.2
  - MOCUP
- The core is modeled with MCNP5:
  - **8 radial depletion zones**
  - 3 axial depletion zones
  - All zones have same volume
  - **Four different** TRU or ^{235}U **enrichments** in the initial seed (blue zones)



- Constraints
  - Sustainable B&B mode of operation
  - Max. power density will not exceed 450 W/cm^3 (IAEA database)
  - HT-9 cladding [proven/expected]:
    - Maximum DPA: 200/400
    - Maximum fast fluence: 4.0E+23/ 8.0E+23 n/cm^2

Attainable equilibrium burnup is ~50%

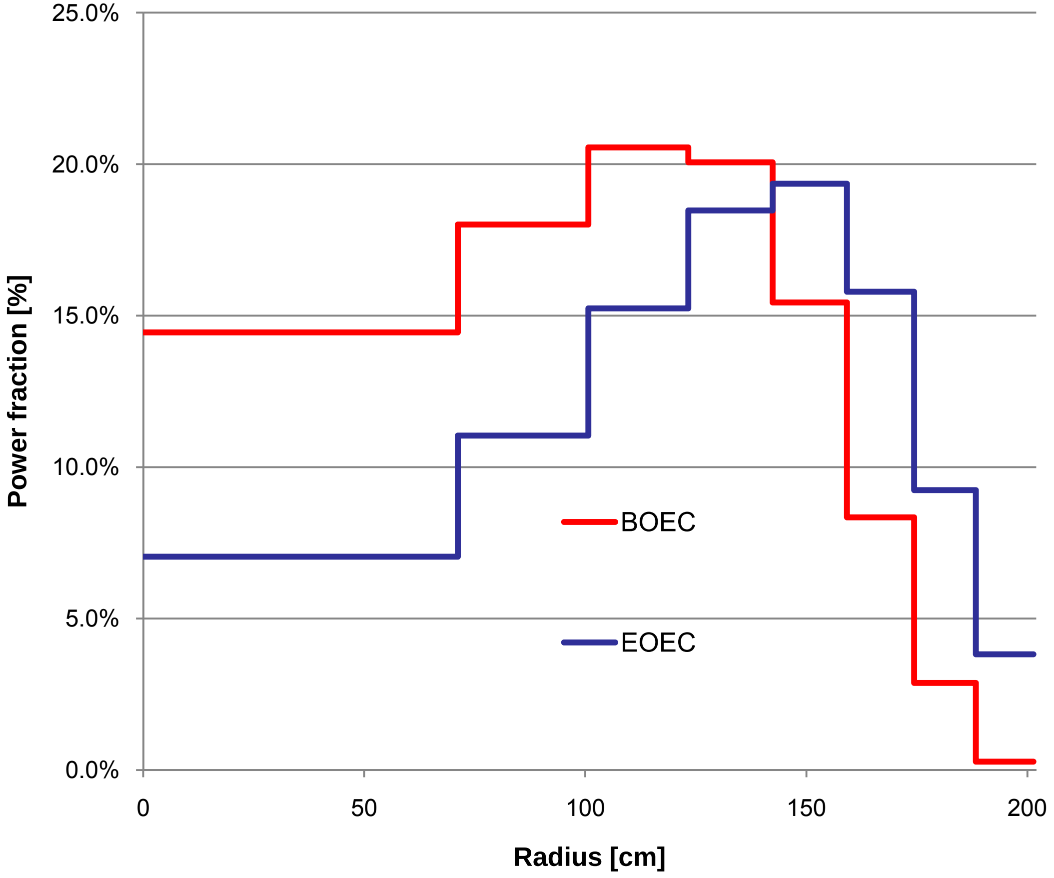


- Melt refining process* is applied when fuel reaches 20% (10%) BU
- Seed is let running as long as k_{eff} >1.0
- Seed discharge BU ~ 50%
- Fuel shuffling starts thereafter
- Equilibrium discharge BU ~55%

***The melt-refining process** assumed for reconditioning the metallic fuel:

- Fuel clad is removed
- Volatile and gaseous fission products (FP) are released
- Some of the solid FP are oxidized with a zirconia crucible: 100% of Br, Kr, Rb, Cs, I, Xe and Cs and 95% of Sr, Y, Te, Ba, Th, Am and RE are removed
- Fuel is recast with depleted U makeup, reclad and loaded back to the core

Resulting radial power distribution at equilibrium; average neutron leakage probability ~7%



Minimum burnup required to establish a sustainable breed & burn operation

- Perform a time-dependent neutron balance for a unit volume of core starting with fresh feed fuel (depleted uranium, thorium or other feed composition):
- # of fission neutrons generated per unit volume per unit burnup (in FIMA*) is

$$\Sigma_i [\nu^i \Sigma_f^i N^i \Phi] / \Sigma_i [\Sigma_f^i N^i \Phi]$$

- # of neutrons absorbed per unit volume per unit burnup (in FIMA) is

$$\Sigma_i [\Sigma_a^i N^i] / \Sigma_i [\Sigma_f^i N^i]$$

- # of net number of neutrons generated per unit volume as a function of burnup (in FIMA) is

$$\int d(BU) \{\Sigma_i [\nu^i \Sigma_f^i N^i] / \Sigma_i [\Sigma_f^i N^i] - \Sigma_i [\Sigma_a^i N^i] / \Sigma_i [\Sigma_f^i N^i]\} =$$

$$\int d(BU)\, \underline{\nu}(BU) \{ 1 - 1/k_\infty(BU) \}$$

Where $\underline{\nu}(BU) = \Sigma_i [\nu^i \Sigma_f^i N^i] / \Sigma_i [\Sigma_f^i N^i]$ and $k_\infty = \Sigma_i [\nu^i \Sigma_f^i N^i] / \Sigma_i [\Sigma_a^i N^i]$

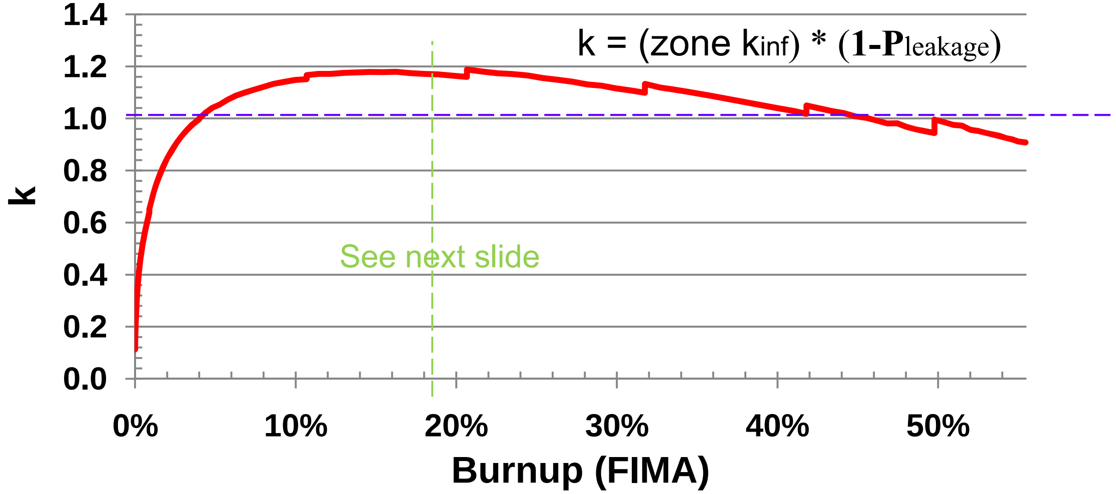
- Minimum required burnup corresponds to that burnup for which

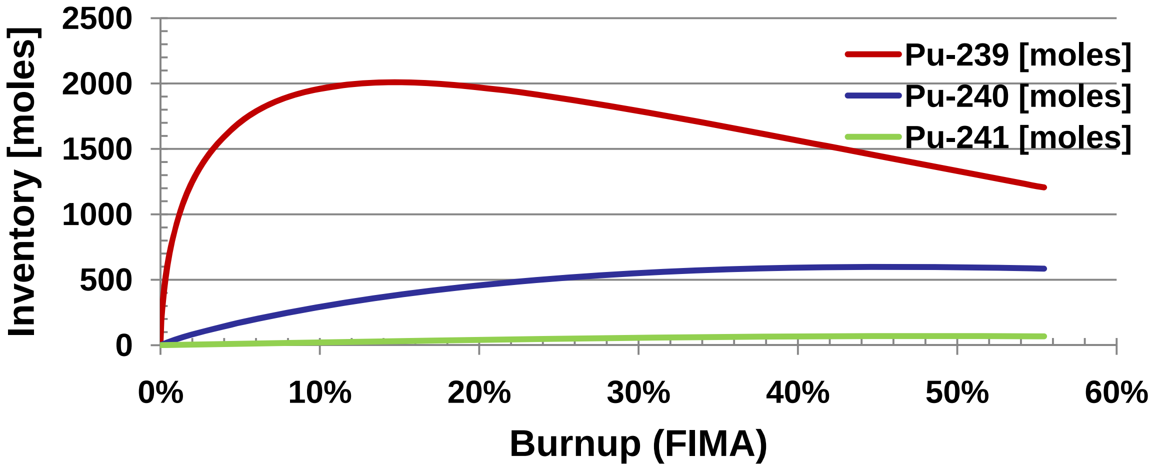
$$\int d(BU)\, \underline{\nu}(BU) \{ 1 - 1/k_\infty(BU) \} = 0$$

*FIMA = Fissions per Initial heavy-Metal Atom

Equilibrium core k & Pu evolution

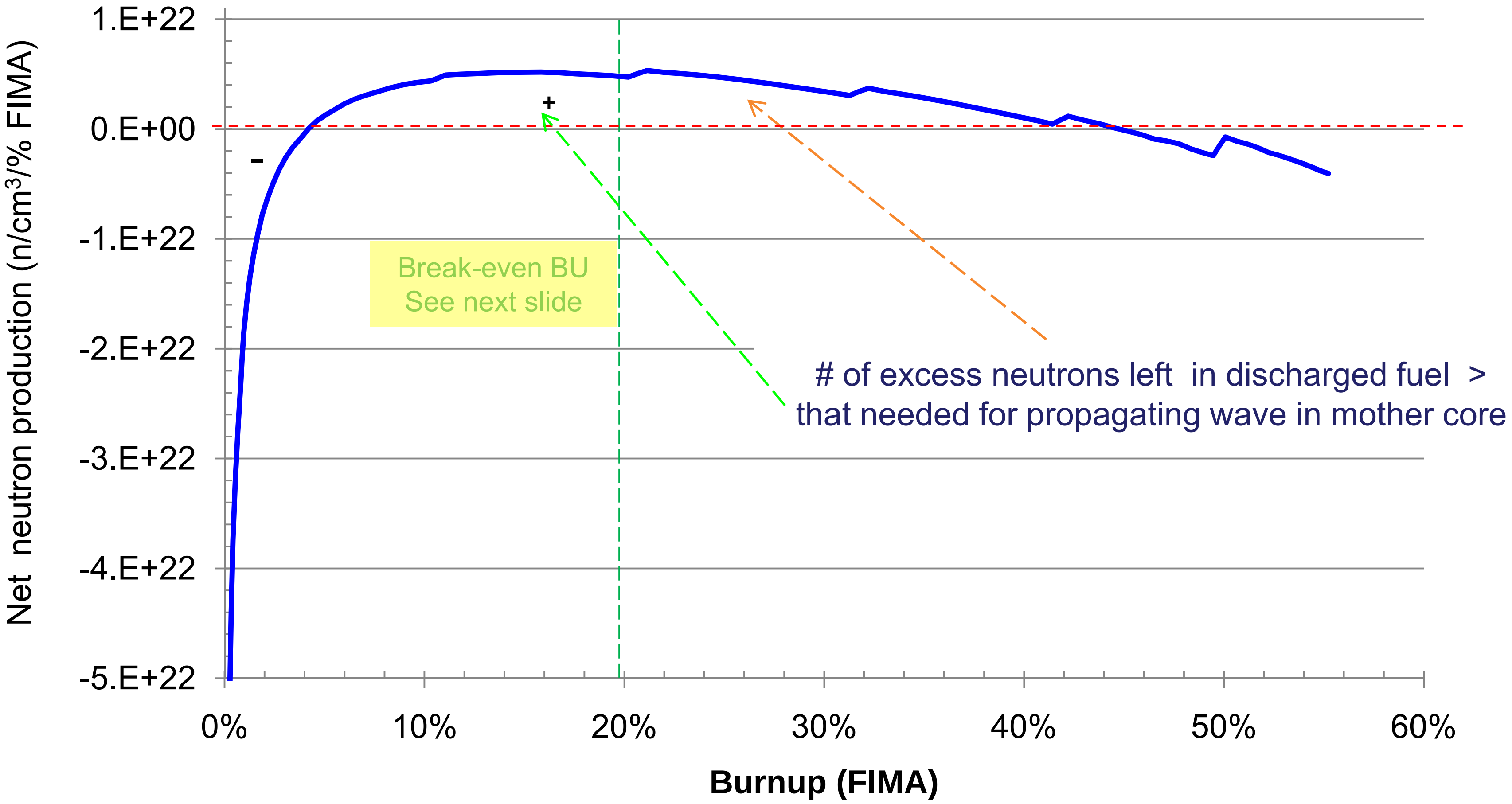
Heidet (UCB) analysis





Equilibrium core neutron balance evolution

Following a depleted U feed fuel as it moves through the equilibrium core until discharge



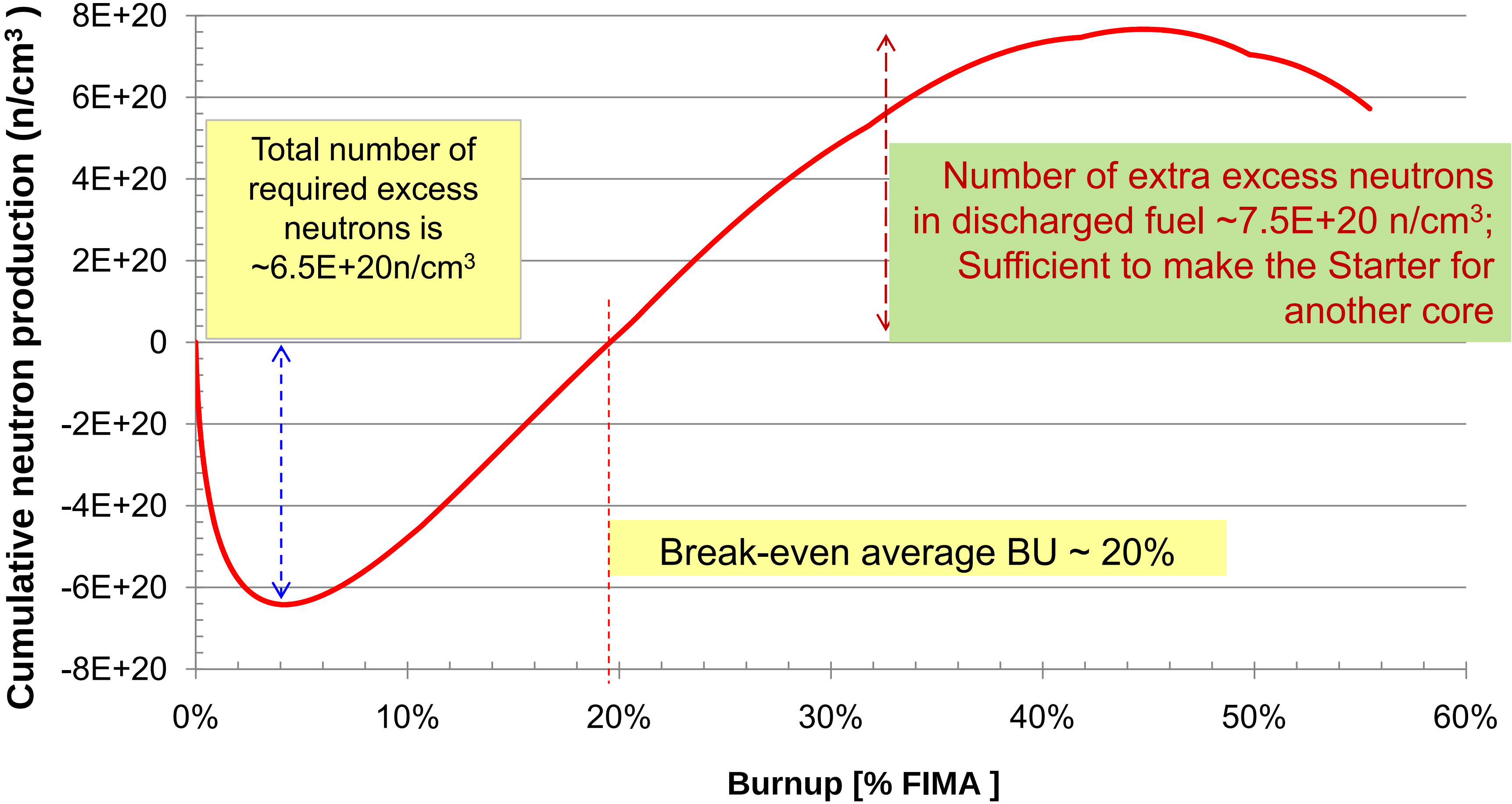
Break-even BU
See next slide

# of excess neutrons left in discharged fuel > that needed for propagating wave in mother core

Equilibrium core neutron balance

Finding 1: Minimum burnup required for establishing a sustained breed & burn core is ~20%

Finding 2: There are more excess neutrons (~7.5E+20 n/cm^3) left in fuel discharged at ~20% average BU than required for establishing a propagating wave (~6.5E+20 n/cm^3)



Total number of required excess neutrons is ~6.5E+20n/cm^3

Number of extra excess neutrons in discharged fuel ~7.5E+20 n/cm^3; Sufficient to make the Starter for another core

Break-even average BU ~ 20%

Neutron balance analysis conclusions

- The minimum burnup required for establishing a Breed & Burn mode of operation in the UCB core examined (LP=4.4%; BU reactivity swing=2%) is ~**19.5%** (Using full core analysis getting 19.4%)
- There is sufficient excess reactivity left in the fuel discharged at the minimum required burnup (defined above) to enable the discharged fuel to serve as the Starter for a new core (i.e., to establish a B&B mode of operation in a new core)

Questions:

(1) How sensitive is the minimum required BU to core design

(2) How long does it take to accumulate fuel (initially loaded into an equilibrium core as a depleted uranium feed) at 19.5% FIMA in quantity required for the “Starter” of a new B&B core? This time will be referred to as the “Doubling Time”

Sensitivity of minimum required BU to core design

Minimum required burnup is very sensitive to core design:

- Core composition
    - Fuel volume fraction
    - Uranium (HM) loading
    - Fuel type
    - Structural material and volume fraction
    - Coolant material and volume fraction
- Core dimensions – smaller core have larger leakage probability
- Reactivity control requirements – want to minimize fraction of neutrons that needs be captured in reactivity control elements

Want to minimize neutron loss and make the neutron spectrum as hard as practical

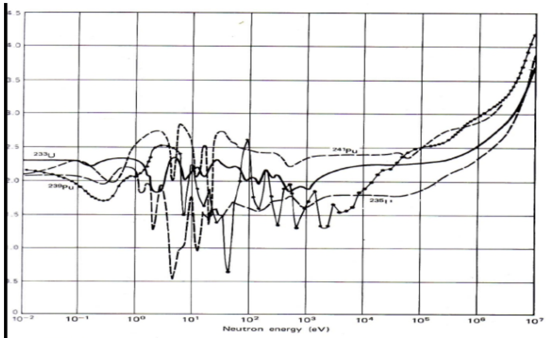
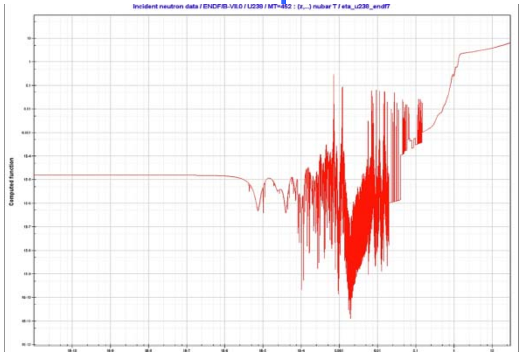


FIGURE 2-25. Variation of η with energy for ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu.



∞ medium analysis for different fuel types (k_{eq} = 1.01); no structure/coolant; from R. Petroski PHYSOR-2010

- Depleted uranium (0.3% U-235)
- **No structure, no coolant**
- Low-alloy metal fuels offer the best performance
- Thorium is viable, but performs poorly
- U_3Si_2 is the best ceramic fuel option, while unenriched nitride cannot sustain B&B operation

	Density (g/cc)	**HM dens. (g/cc)**	**Melting point (°C)**	**Min Burnup required (%)**	**HT-9 DPA required**	**Fast flu. ($/cm^2$ s)**
Metal fuels						
U-2Zr	18.3	17.9	1160	**6.8%**	195	4.83E+23
U-2Mo	18.5	18.1	1135	**7.1%**	202	5.01E+23
U-4Zr-2Nb	17.3	16.3	1135	**7.9%**	216	5.36E+23
U-10Zr	16.0	14.4	1240	**8.0%**	213	5.26E+23
U-7Nb	17.0	15.8	1160	**9.7%**	256	6.35E+23
U-9Mo	17.0	15.5	1135	**9.9%**	255	6.31E+23
Th	11.7	11.7	1842	**19.1%**	479	1.19E+24
Ceramic/ compound fuels						
U_3Si_2	12.2	11.3	1650	**8.2%**	204	4.85E+23
UP	10.2	9.0	2600	**10.4%**	243	5.94E+23
$U^{15}N$	14.3	13.5	2650	**10.6%**	214	4.63E+23
UC	13.6	12.9	2400	**11.8%**	223	4.70E+23
UAl_2	8.1	6.6	1590	**12.8%**	236	5.23E+23
UO_2	10.9	9.6	2750	**15.8%**	256	5.11E+23
UCO	12.3	11.0	2400	**17.9%**	274	5.42E+23
US	10.9	9.7	2475	**18.3%**	390	8.79E+23
UTe	10.4	6.8	1740	**19.6%**	441	1.12E+24
USe	11.3	8.5	--	**20.9%**	429	1.05E+24
UN	14.3	13.5	2650	**N/A**	N/A	N/A

Doubling time estimation; equilibrium core – Assumptions

200 GWD/tHM	Minimum average discharge BU for wave to propagate
130 W/cc	Average core power density
0.5	Fuel volume fraction in core
15.85 g/cc	Nominal fuel density
0.9	HM wt fraction
0.75	Smear density
0.9	Capacity factor
2 y	Time for cooling discharged fuel and re-fabricating new fuel, including loading the initial core of a new reactor; measured from discharge of last batch required for the new igniter
0.5	Fraction of new reactor core volume taken by the igniter (as of our PHYSOR-2010 paper 3 GWe core)

Doubling time estimation -- Analysis

Equilibrium core:

- 5.35 g/cc HM average density in core (=15.85*0.9*0.5*0.75)
- 24.3 MW/tHM Average specific power (=130/5.35)

Time to discharge half of the equilibrium core volume (to be used as igniter):

- 4115 EFPD (=200,000*0.5/24.3)
- 11.25 EFPY (=4115/365)
- 12.5 y Net doubling time -- accounting for capacity factor (=11.25/0.9)
- 14.5 y Gross doubling time – including cooling and re-fabrication time

Spawning mode of operation of B&B reactors and deployment scenario

- Fuel is discharged at the minimum sustainable burnup (~200GWd/tHM)

- After reconditioning it is used as a “starter” for a new B&B reactor

- All generations of B&B reactors are assumed to work at the minimum sustainable burnup

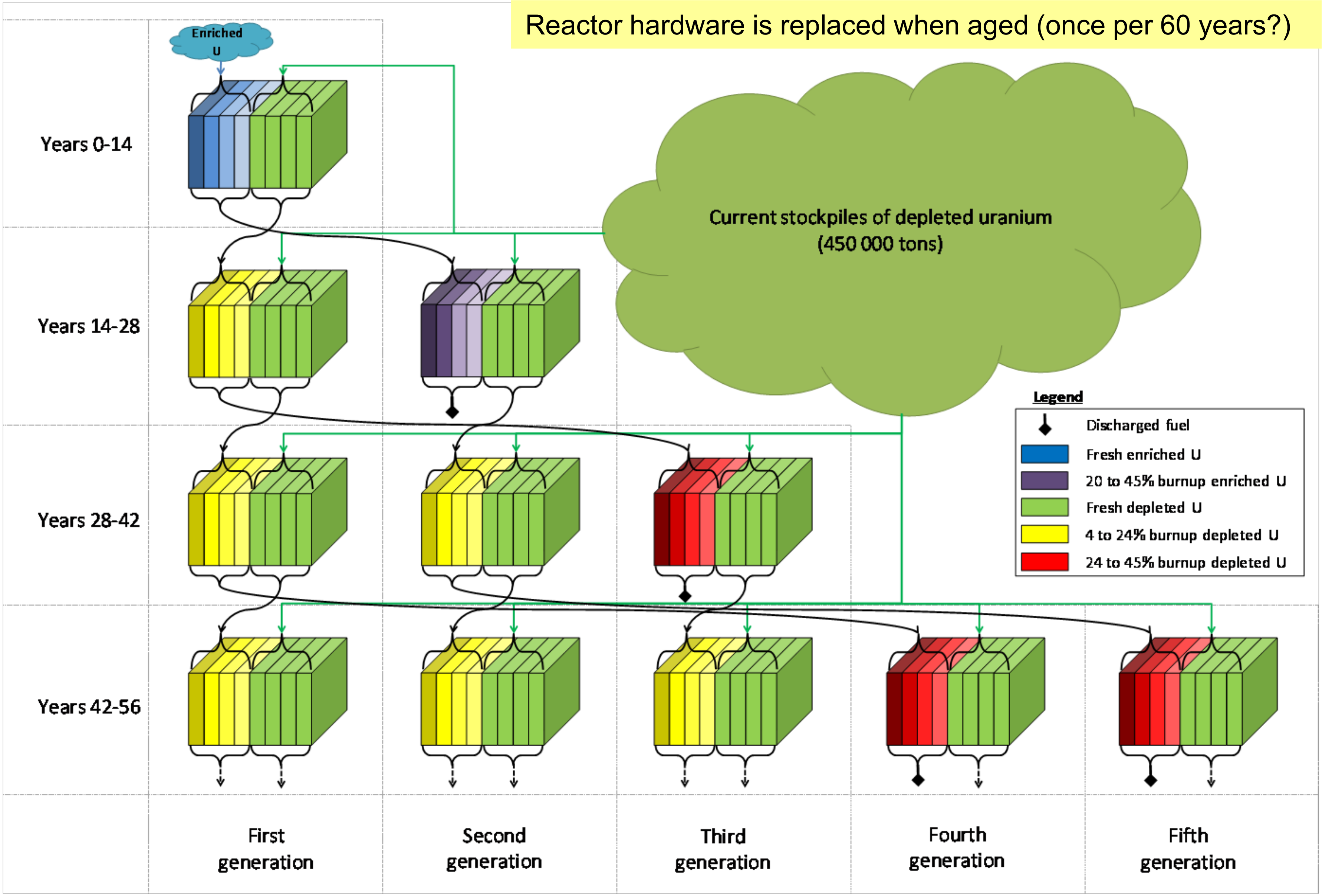
- The B&B core effective doubling time is assumed to be 14 years

- The US LWR capacity (86 GWe) is assumed constant until 2030 where it starts decreasing, replaced by B&B reactors

- Capacity factor of 0.9 is assumed

Spawning schematics of B&B reactors

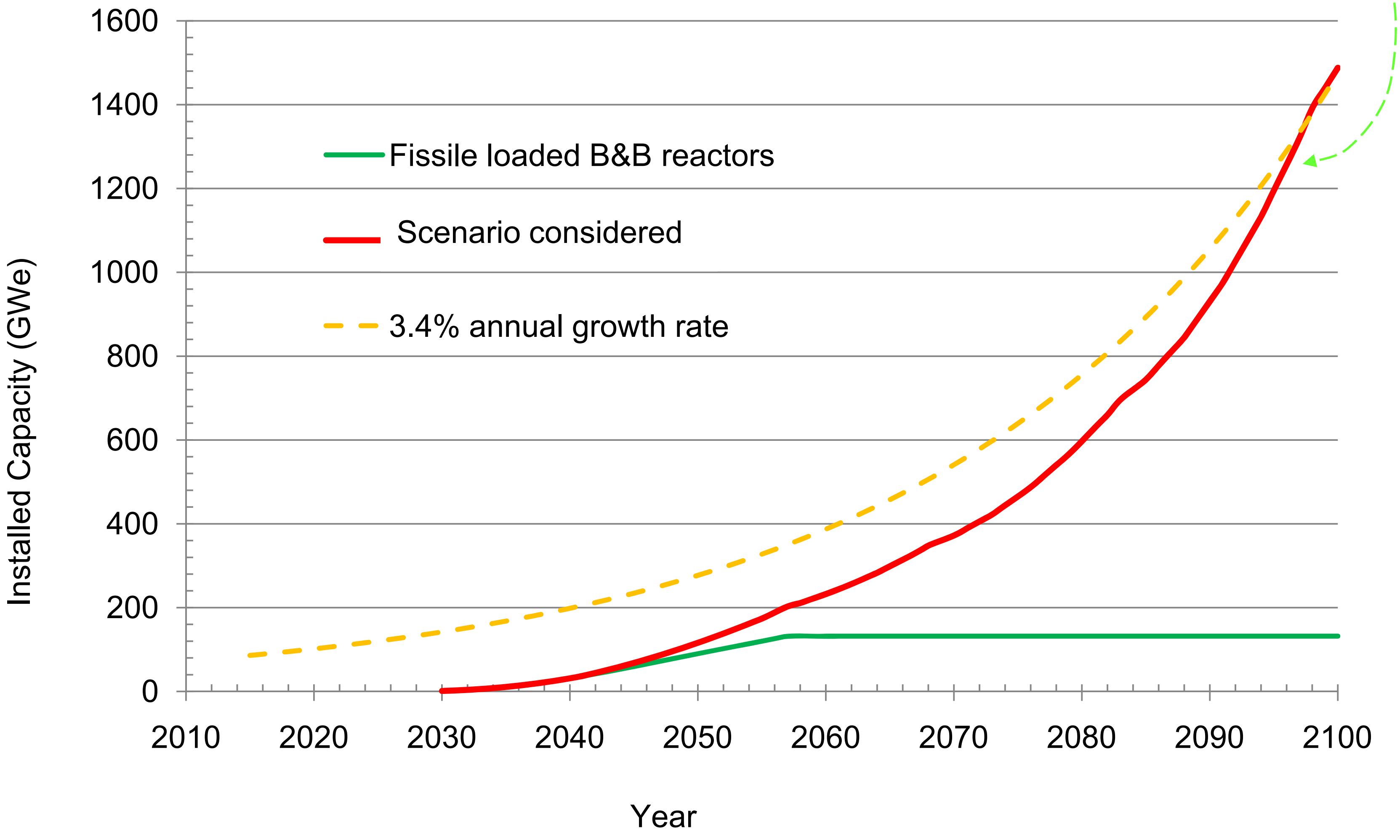
Reactor hardware is replaced when aged (once per 60 years?)



US nuclear electricity capacity growth rate with all spawning B&B reactors

B&B capacity growth rate in later part of century ~4.3% per year

Actual doubling time is ~14 years rather than 16 years assumed.



Implications of successful development of B&B reactors

Estimated Uranium Utilization Limits and Energy Value of Depleted Uranium

Mode of operation	Uranium utilization	Relative U utilization(d)	No. of years at present supply(e)
Light Water Reactors (LWRs) - reference	0.6%	1	0
Breed and burn, no fuel reconditioning(a)	20%	40	800
Breed and burn, with fuel reconditioning(b)	50%	100	2000
Fast reactor with continuous recycling(c)	>95%	>190	3900

(a) The approach being pursued by TerraPower; it assumes a successful development of advanced fuel designs capable of withstanding at least 20% average burnup.

(b) More than one reconditioning steps will be required to obtain the high fuel utilization value.

(c) This is the traditional fast reactor approach in which fuel is reprocessed many times (every 10% burnup or so). It assumes cleanup of most fission products at each recycle; depleted uranium is added at each pass; there is no limit to the number of fuel recycles.

(d) Relative to LWRs; assuming that fast reactors convert thermal energy into electricity at 20% higher efficiency than LWRs.

(e) Number of years the TWRs could supply electricity at present day total annual consumption rate (4200 million MW_eh per year; from all sources) if they are to be fueled only with the depleted uranium stockpiles (“waste”) that will be accumulated in the US from the fueling of LWRs (~1.3×10^6 tons) and TWRs (~0.5×10^6 tons) until end of deployment of first generation of TWR reactors – estimated close to 1.8 million tons.

Conclusions on B&B reactors promise

- Successful development of the breed-and-burn reactors and associated fuel re-reconditioning technologies could provide a great measure of energy security and energy cost stability

- No enriched uranium and no enrichment services will be required to support this fleet beyond the completion of the deployment of the 1st generation of B&B reactors – possibly by 2060

- The energy value of the depleted uranium stockpiles (“waste”) that will be accumulated in the US from the fueling of LWRs and B&B reactors until end of deployment of first generation of B&B reactors is equivalent, when used in the B&B fast reactors, to at least 8 and possibly up to 20 centuries of the total 2010 supply of electricity in the USA

- This prospect justifies addressing the difficult technological issues that need be solved before B&B reactors and fuel reconditioning could become commercial