Adaptation of Pb-Bi Cooled, Metal Fuel Subcritical Reactor for Use with a Tokamak Fusion Neutron Source

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Study Objectives

- Develop a nuclear design concept for a sub-critical transmutation reactor driven by a D-T tokamak fusion neutron source.

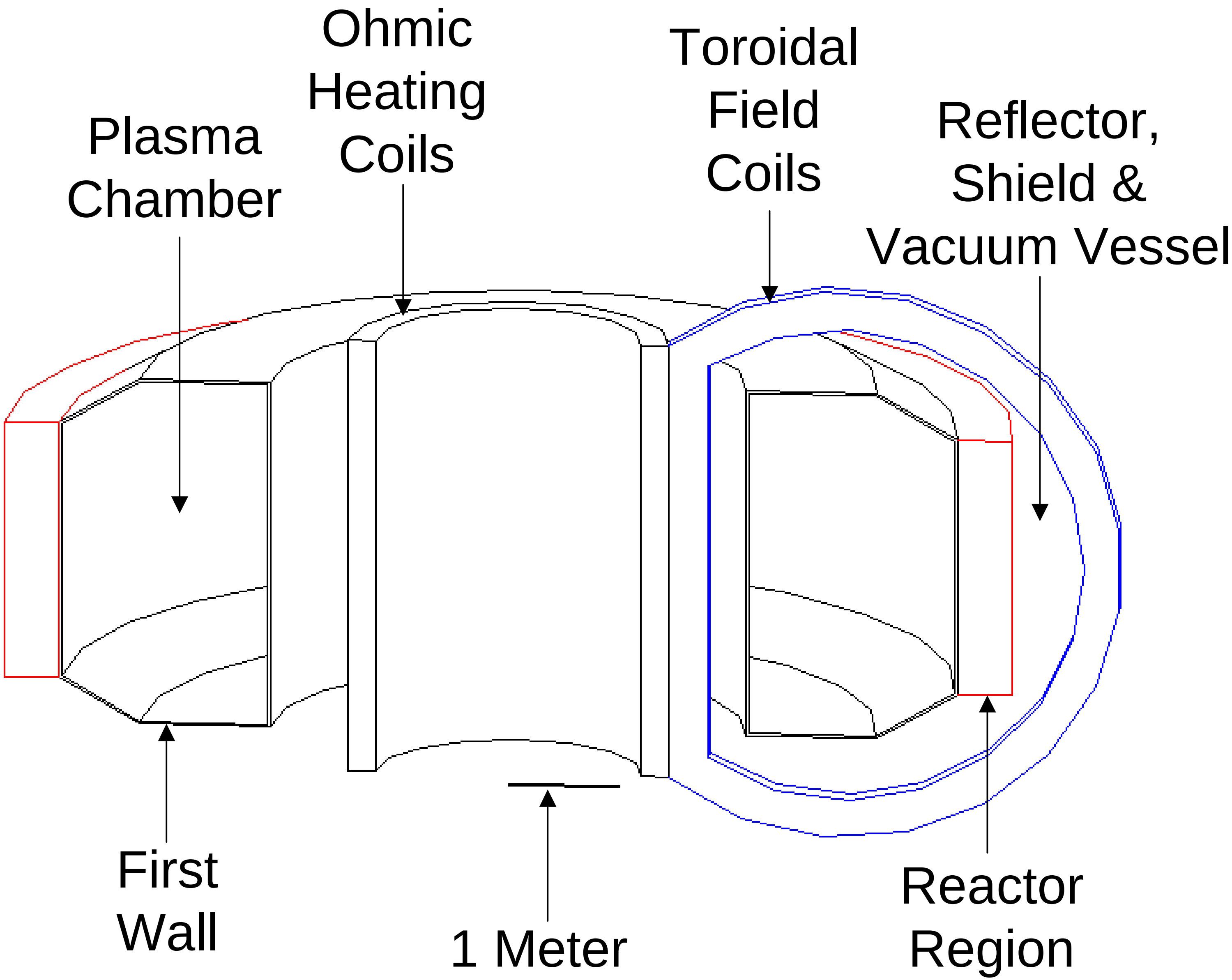
- Adapt nuclear technology being developed for ATW to identify a transmutation blanket.

- Analyze the performance of a tokamak transmutation facility.

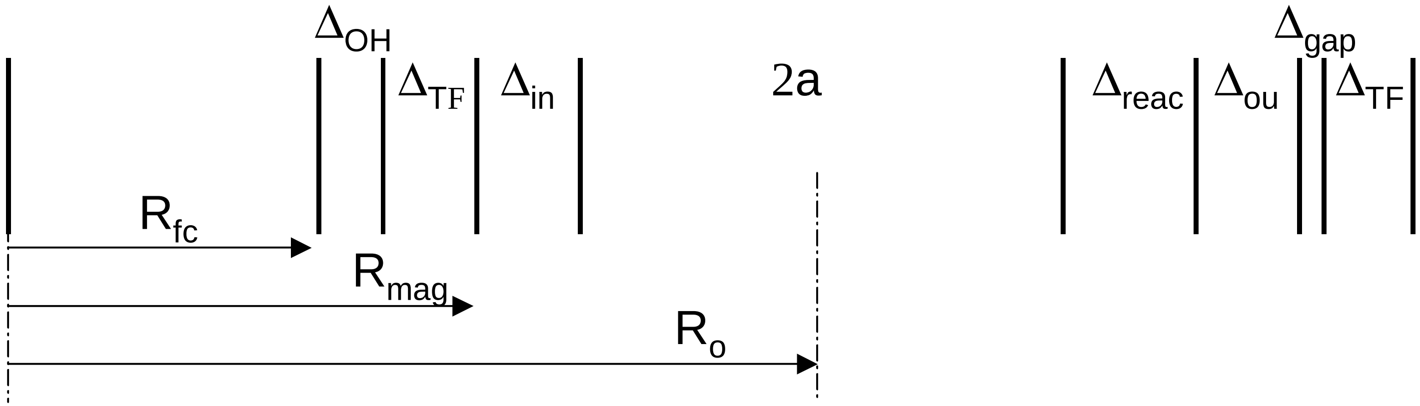
Adaptation of ATW Nuclear Technology to a Fusion Driven Reactor

- Tritium Production
  - Addition of lithium for tritium self-sufficiency
- Tokamak Geometry

Tokamak Design



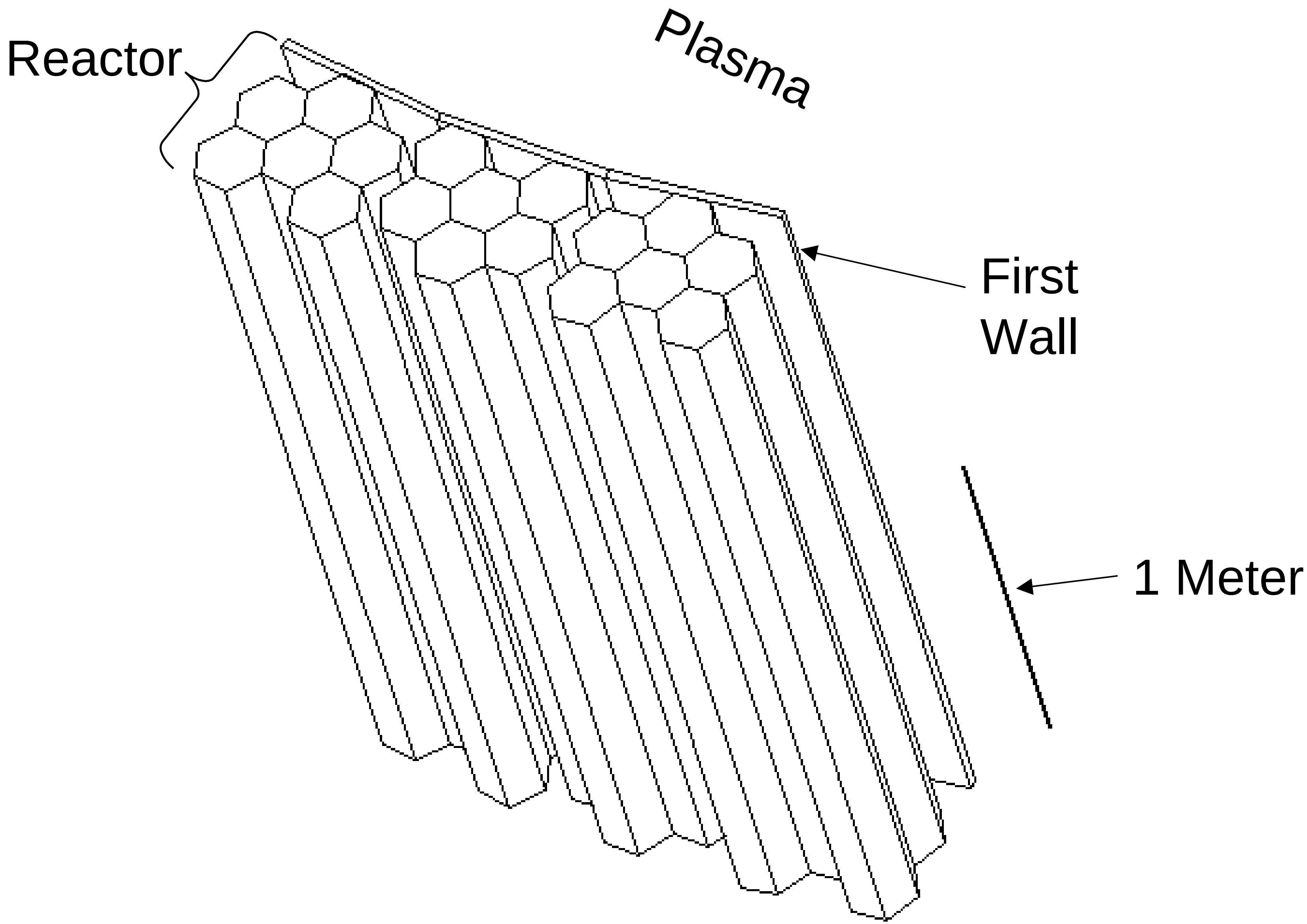
Midplane Radial Build



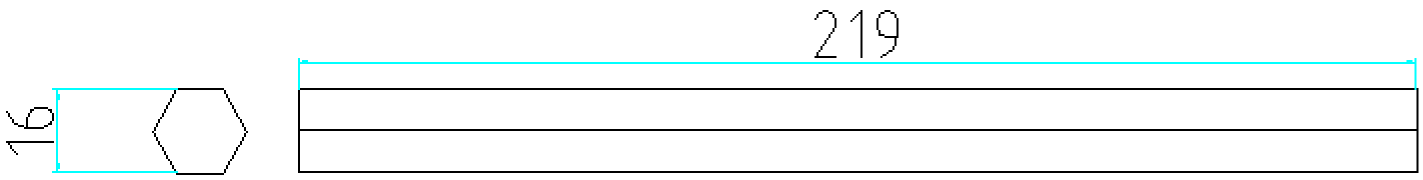
R_{fc}	=	flux core radius	=	1.20 m
Δ_{OH}	=	OH solenoid Δ	=	0.25
Δ_{TF}	=	TF coil Δ	=	0.35
Δ_{in}	=	inner refl/shld	=	0.40
a	=	minor radius	=	0.90
Δ_{reac}	=	reactor	=	0.40
Δ_{ou}	=	outer refl/shld	=	0.30
Δ_{gap}	=	outer gap	=	tbd
R_o	=	major radius	=	3.10
R_{mag}	=	magnet radius	=	1.80

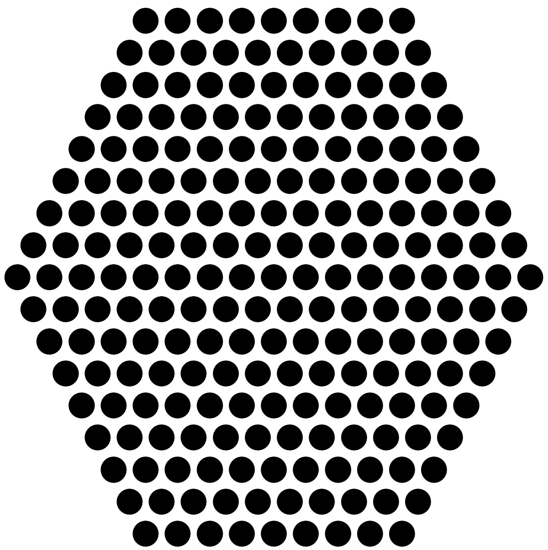
Note: refl/shld includes first wall, reflector, shield, and vacuum vessel

Tokamak Subcritical Reactor



Hexagonal Fuel Assembly





- Fuel Cell
  - Pin Diameter – 0.635 cm
  - Cladding Thickness – 0.056 cm
  - Pitch-to-Diameter – 1.727
- Fuel Assembly
  - 210 Fuel Pins, 7 Structural Pins
- Volume Fractions
  - Fuel – 0.14, Structure – 0.103, Coolant – 0.695
- Materials
  - Dispersion Fuel – TRU-10Zr/Zr
  - Structure/Clad – HT-9

System Design Constraints

- Plasma Physics Constraints
  - Tokamak Geometry
- Thermal Constraints
  - Power Density
- Radiation Damage Constraints
  - Shield Thickness
  - Fuel residence time
- Engineering Constraints
  - Lithium Concentration
  - Magnet Sizing
- Self Imposed
  - Total Power
  - Maximum Neutron Multiplication (k)

Magnet Radiation Damage Limits

Reflector / Shield Thickness Driver

- Designed as Lifetime Component
  - 40 Full Power Years
- Used Radiation Damage Limits
  - Ceramic Insulators
  - Fast fluence limit = 4E+22 n/cm^2
- Optimize Shield to Dose Limits
  - Organic Insulators
  - Dose limit = 1E11 Rads

Tritium Balance

$$\frac{dT(t)}{dt} = (1-\alpha) * \dot{T}(t) - \dot{F}(t) - \lambda_T T(t)$$

$T(t) = \text{Tritium inventory}$

$\alpha = \text{fractional loss of tritium}$

$\dot{T}(t) = \text{Tritium production rate}$

$\dot{F}(t) = \text{Fusion rate}$

$\lambda_T = \text{Tritium decay constant}$

Limit

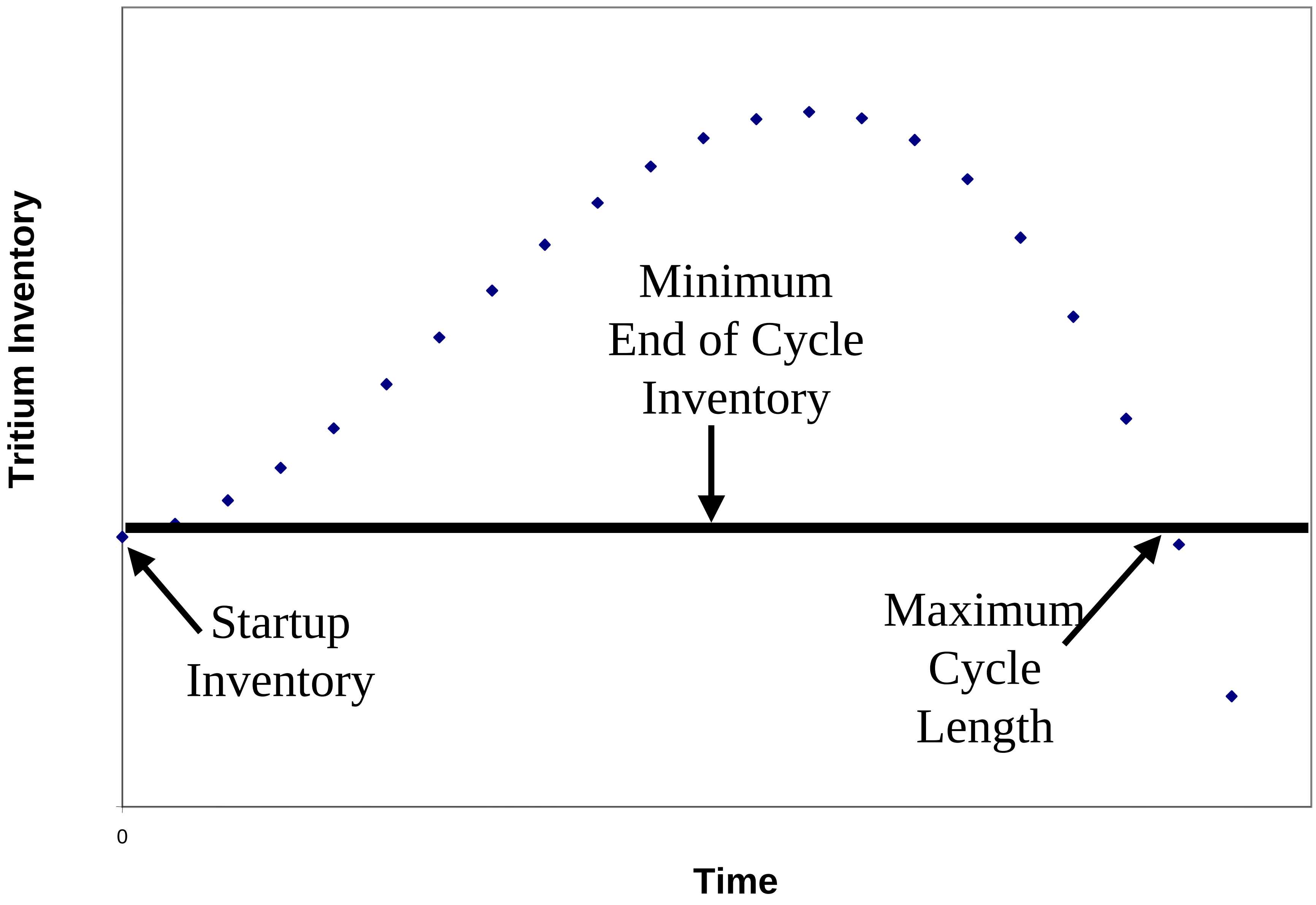
$$T_{EOC} \geq T_{BOC} e^{\lambda_T t_{down}}$$

$T_{BOC} = \text{Startup tritium inventory at the beginning of cycle}$

$T_{EOC} = \text{Tritium inventory at the end of cycle}$

$t_{down} = \text{Down time between cycles}$

Time Behavior of Tritium Inventory



Lithium Concentrations

- Tritium Production Cross Sections

		14 MeV	Fission Spectrum
Li6	7.5%	28.0 mb	330.7 mb
Li7	92.5%	302.9 mb	20.0 mb
Nat Li		282.3 mb	43.3 mb

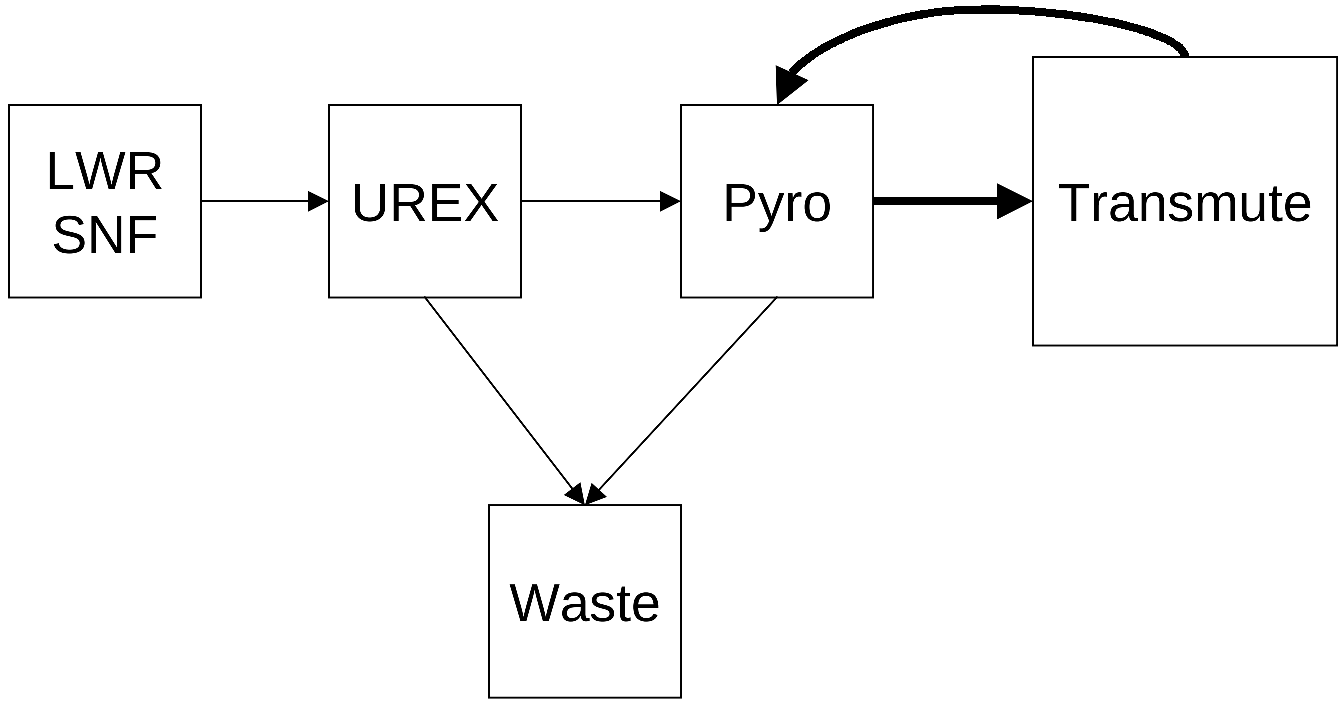
- Lithium Lead ($Li_{17}Pb_{83}$)
  - Enrichment ~20a/o Li-6

- Lithium in Lead BismuthEutectic ($Pb_{45}Bi_{55}$)
  - ($Li_xPb_yBi_z$)
  - Range of enrichments depending on x
  - Assuming 5% by volume Li – enrichment to ~40 a/o Li-6

Other Design Limits

Parameter	**Limit**
$P_{Blanket}$	3000 MWt (~1 GWe)
k	0.95
Power Density	175 kW/l
Cladding Lifetime	25% BU - go to DPA limit
First Wall Lifetime	DPA Limit
P_{fus}	~ 200 MW

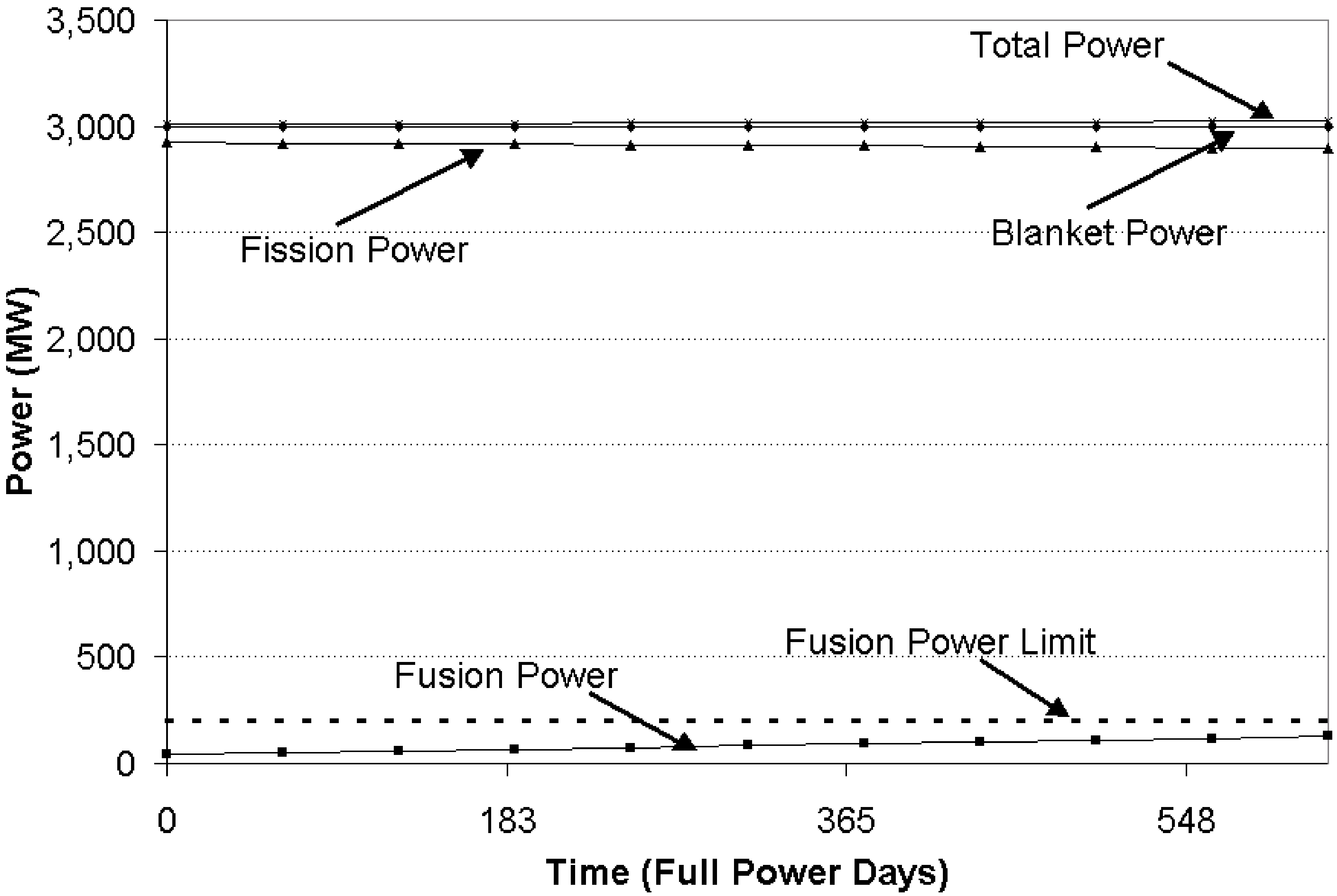
Equilibrium Fuel Cycle



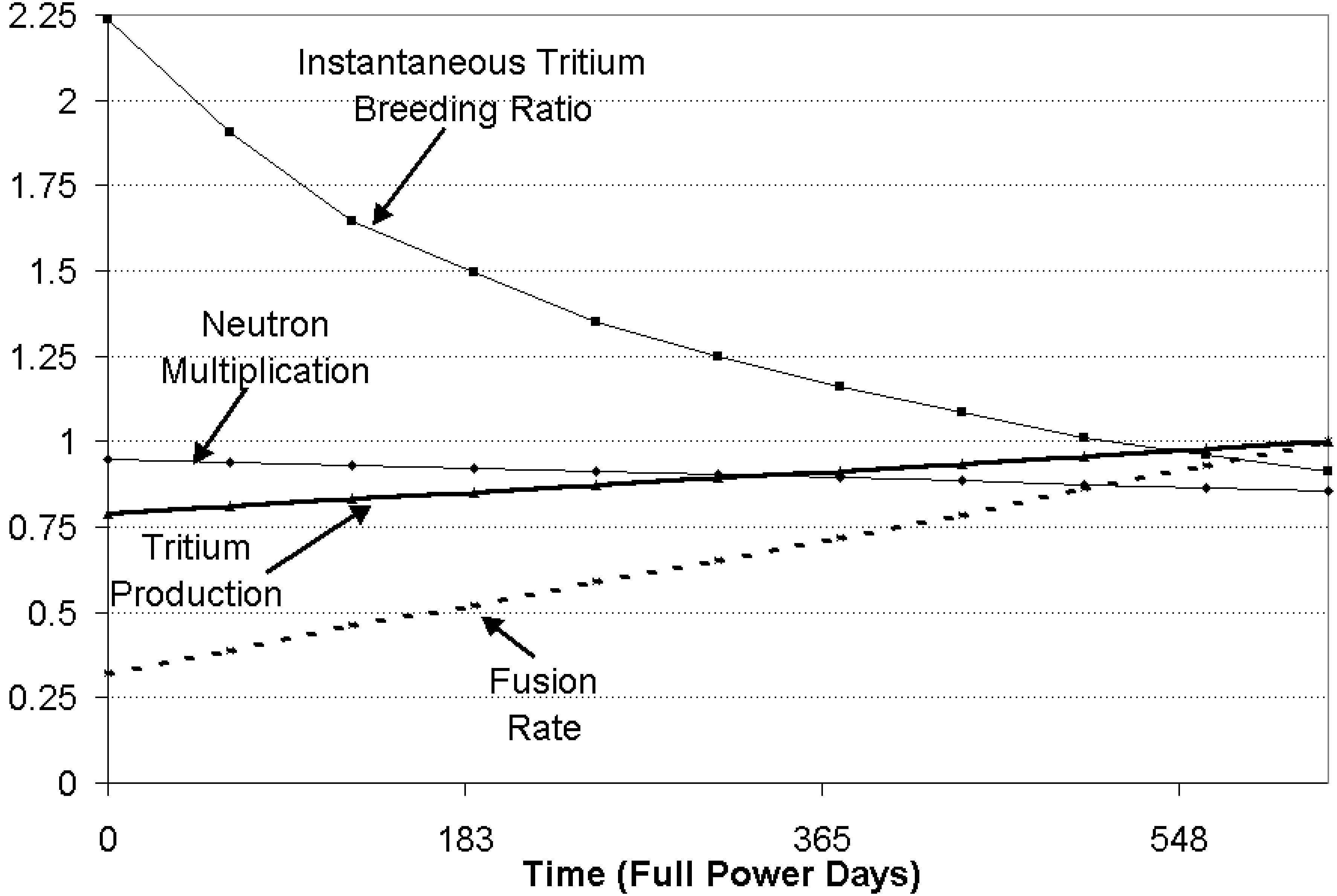
REBUS Fuel Cycle Code

- ANL Fast Reactor Fuel Cycle Code
- Same Code used by ANL for ATW Calculations
- Equilibrium Cycle Calculations
  - Input Target Beginning of Cycle K-eff
  - Input Irradiation Cycle Parameters
  - Input External Cycle Parameters
  - Iterates on Fuel “Enrichment”
    Volume HM/(Volume Zr + Volume HM)
- Calculates Fuel Cycle Parameters
  - Enrichment, Isotopic Composition
  - Power Density, Burnup, Source Strength
  - Mass Flow, Feed, Recycle, Waste

Power Production



Cycle Variation of Key Parameters



Preliminary Result

Case Name	LBE-5-40	LiPb-20
Coolant	Lead-Bismuth w/ Lithium	Lithium Lead
Li-6 Enrichment	40 a/o Li-6	20 a/o Li-6
Li Volume Fraction	5 v/o	n/a
Fuel Batches	3	3
Cycle Length (FPD)	624	624
Enrichment	43%	45%
BOC k	0.95	0.95
EOC k	0.86	0.86
BOC Fusion Power	41 MW	41 MW
EOC Fusion Power	127 MW	125 MW
Discharge Burnup	21%	20%
Cladding Damage	112 dpa	107 dpa
FW Damage	22 dpa/cycle	21 dpa/cycle
Tritium EOC / BOC	16	30
Reactor Power Density	118 kW/l	118 kW/l

Preliminary Transmutation Results

- Cycle Length = 624 FPD
  = 1.7 FPY

- Fuel Residence Time = 3 cycles

- Transmutation Rate ~2 MTHM/cycle
  ~ 1.1 MT/FPY

Fuel Composition

		LBE-5-40		LiPb-20	
	SNF Feed	Fresh Fuel	Discharged	Fresh Fuel	Discharged
Loading (MTHM)		10.2	8.2	10.5	8.6
Inventory* (MTHM)		27.5	25.6	28.5	26.6
U	0.4%	4.4%	5.2%	4.5%	5.3%
Np	4.2%	3.6%	3.4%	3.5%	3.3%
Pu	83.2%	77.9%	76.6%	77.9%	76.6%
Pu-239	52.8%	30.2%	24.4%	29.7%	24.1%
Am	10.0%	13.2%	13.6%	13.2%	13.5%
Cm	0.1%	0.9%	1.3%	0.9%	1.4%

* Inventory is the beginning of cycle & end of cycle actinide mass

Preliminary Conclusions

- Nuclear design feasible
  - Two Pb cooled options
    - 5% Li enriched to 40% Li-6 in LBE
    - Li-17Pb-83 enriched to 20% Li-6
  - Metal Fuel
    - TRU-10Zr dispersed in Zr
    - 30 - 45 v/o TRU

- Transmutation fuel cycle
  - 3 batch, 1.5 - 2 FPY cycle
  - ~2 MTHM fissioned per cycle

Future Work

- Optimized Fusion Cycle
  - Batches, Cycle Lengths, Shielding, Lithium, Reactivity Compensation, ...
- Waste Management Performance
  - Repository Requirements, Toxicity, Proliferation, Decay Heat, ...
- Examine Criticality Safety Margin
  - High Leakage Configuration
- Benchmarking