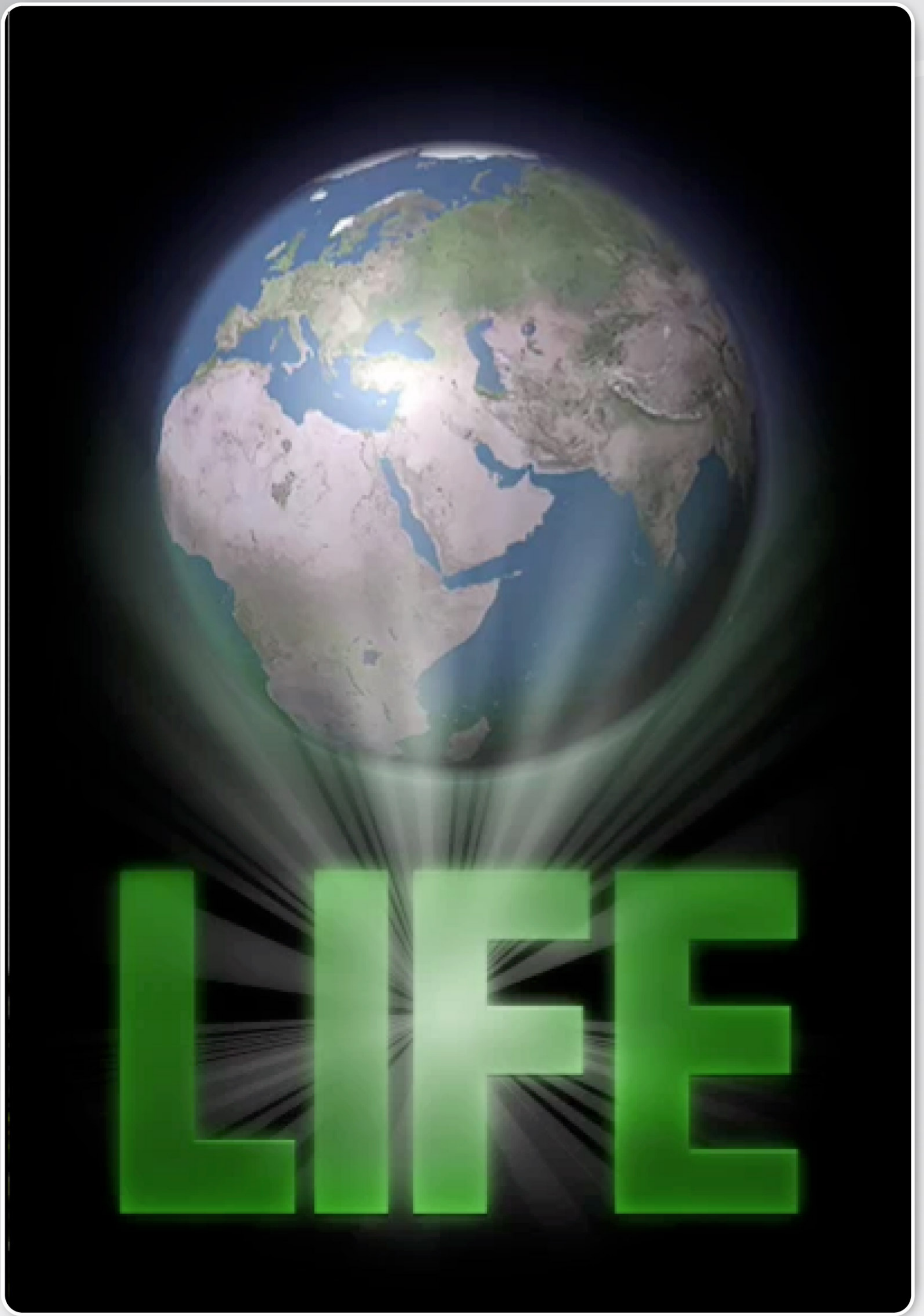


# System Integration Issues for the Laser Inertial Confinement Fusion Fission Energy (LIFE) Engine

Presented by

**Jeffery F. Latkowski**

**February 10, 2009**

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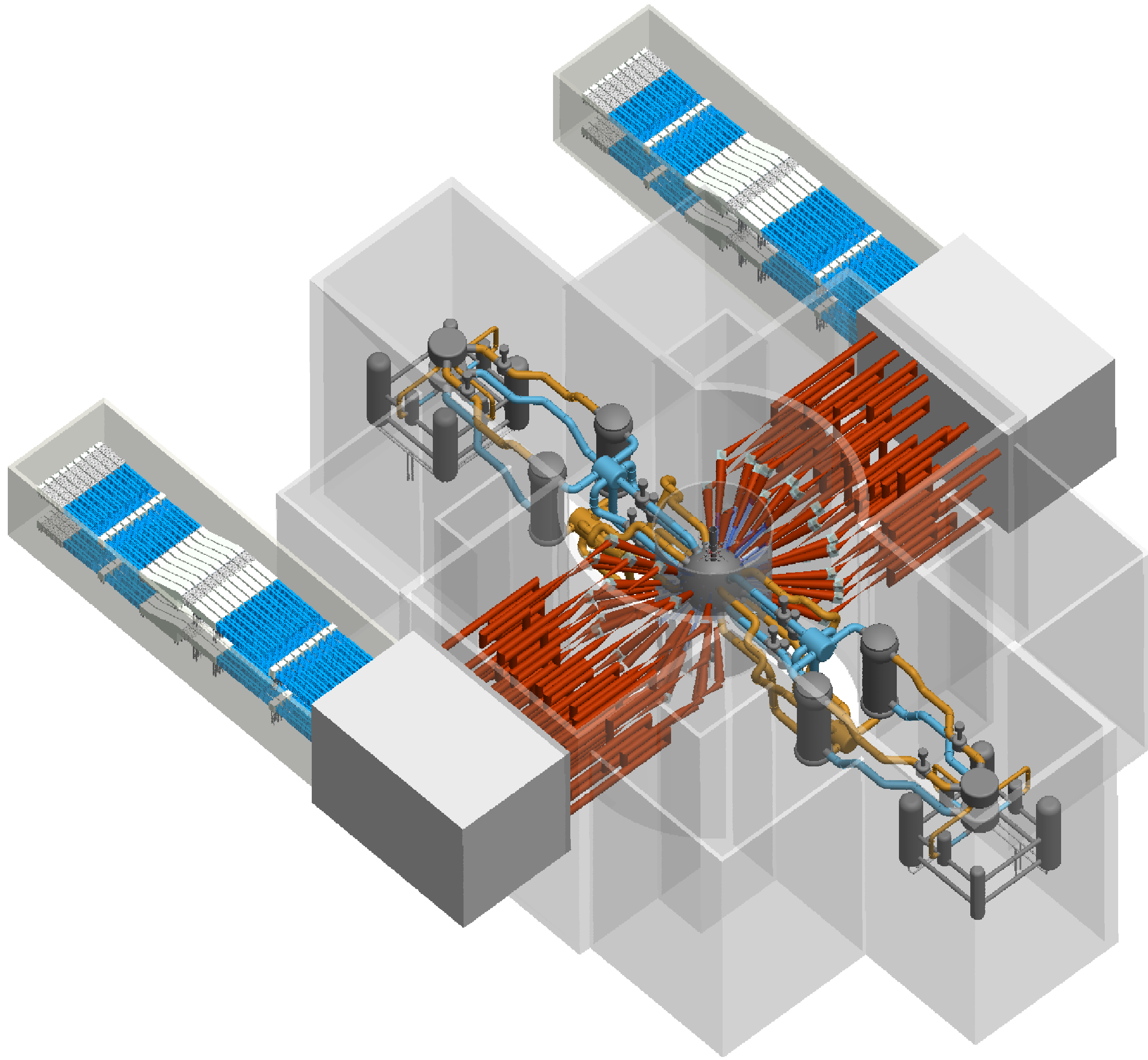
# There is significant overlap in the technologies required for LIFE, traditional IFE, and MFE

- **Design – radiation transport and activation codes and data libraries; thermal and stress modeling codes**
- **First wall / plasma facing components – high heat flux materials, high radiation damage rates, tungsten, ODS ferritic steel**
- **Neutron multipliers – beryllium**
- **Tritium breeding, separation/handling and storage**
- **Molten salt behavior – corrosion, erosion, etc.**
- **Power conversion systems – heat exchangers, secondary coolants, Brayton cycles**

# A suite of LIFE engines are under consideration

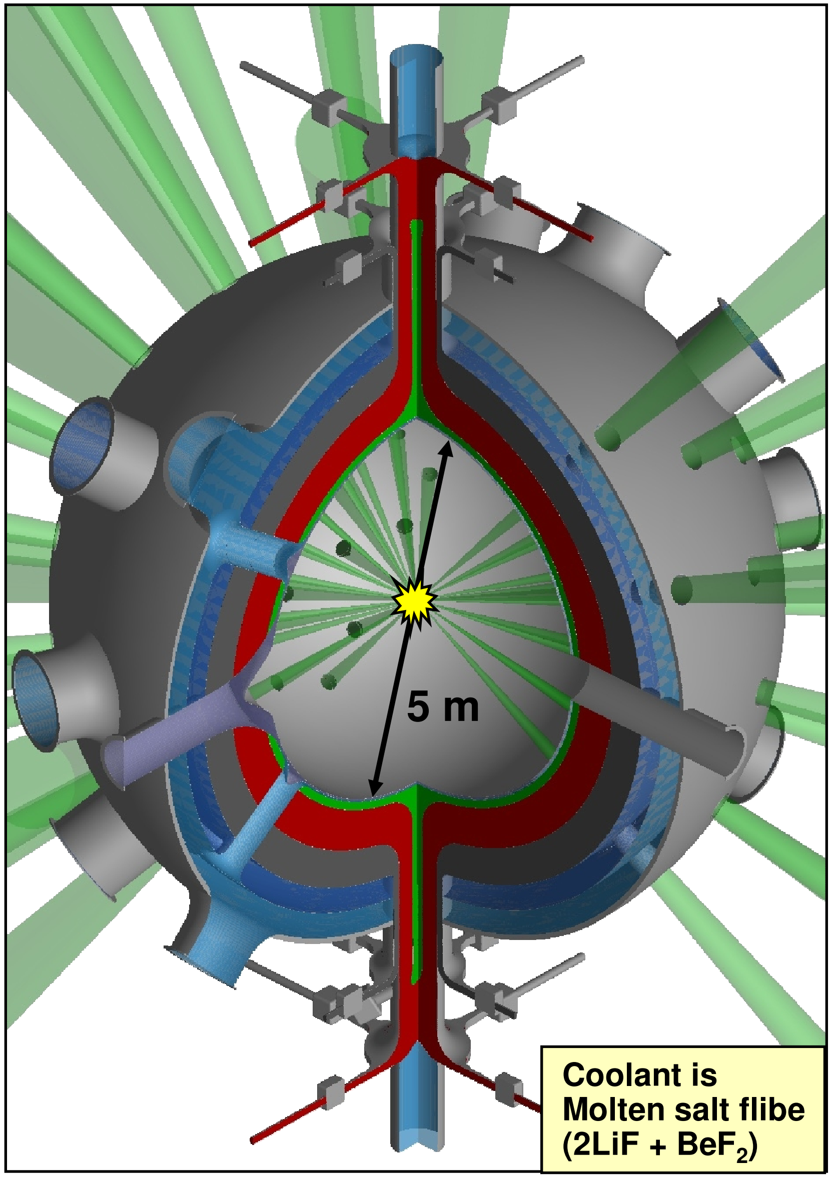
- All systems share a common set of goals:
  - No enrichment
  - No reprocessing
  - Minimize proliferation concerns
  - Sub-critical at all times
  - Commercial
- Different fuels can be used in the LIFE engine:
  - Depleted or natural uranium
  - Spent nuclear fuel
  - Excess weapons material
  - Thorium
- Simple technological solutions
  - Low-yield
  - Dry wall
  - Fast development path
  - Makes its own fuel (fusion & fission)
  - Eats waste

# LIFE Features and System Description

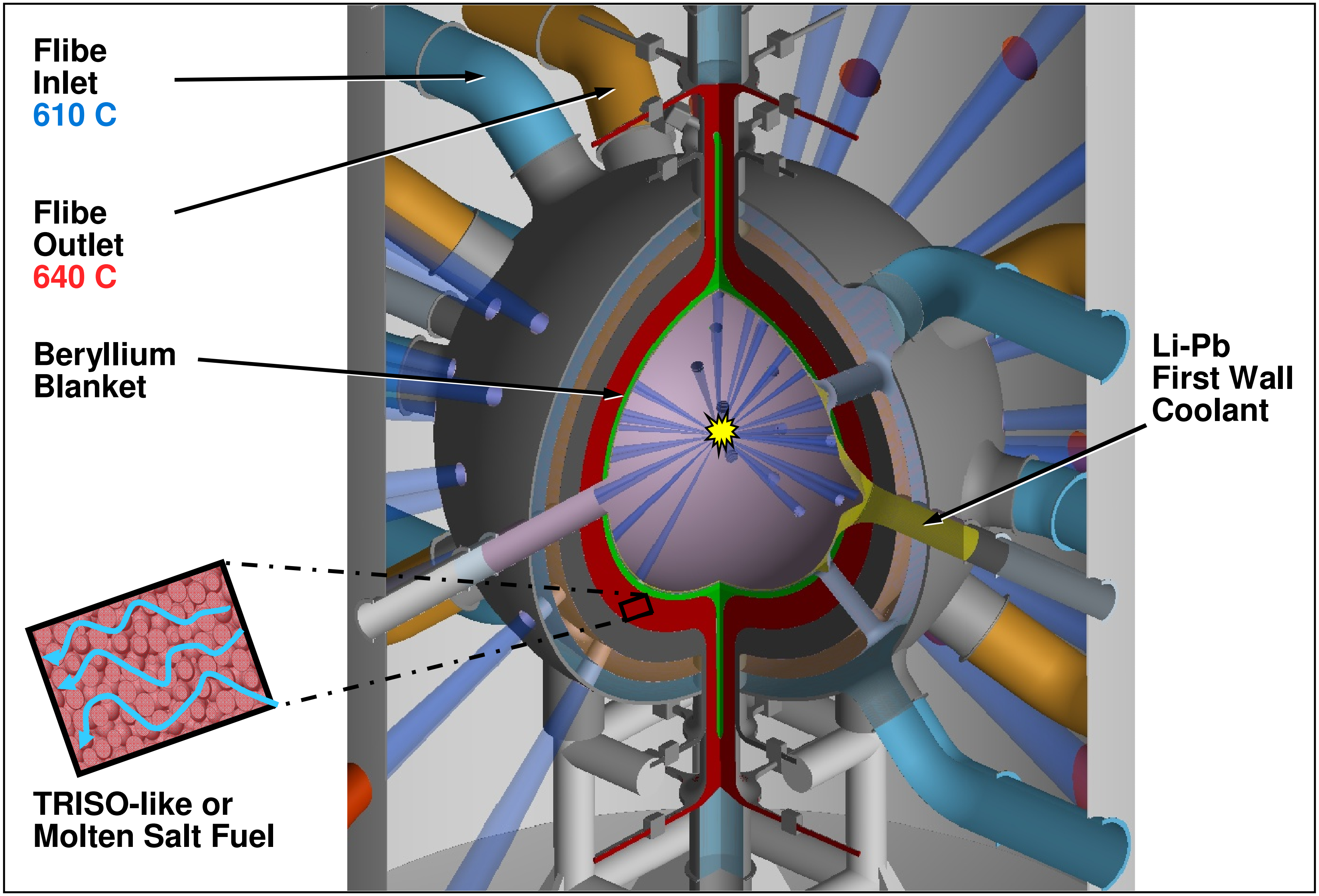


# LIFE uses hotspot ignition (HSI) targets and a fissionable blanket for energy multiplication

- Laser drive with 2ω or 3ω
- 37.5 MJ at 13.3 Hz = 500 $MW_f$
- Compact target chamber (5-m-diameter)
  - Thermally robust target enables gas-protected, dry wall
- 40 tons of depleted uranium in solid or liquid fuel
- Blanket gains of 4-8 → 2000-4000 $MW_{th}$
- $P_{e,net}$ → 750-1500 $MW_e$

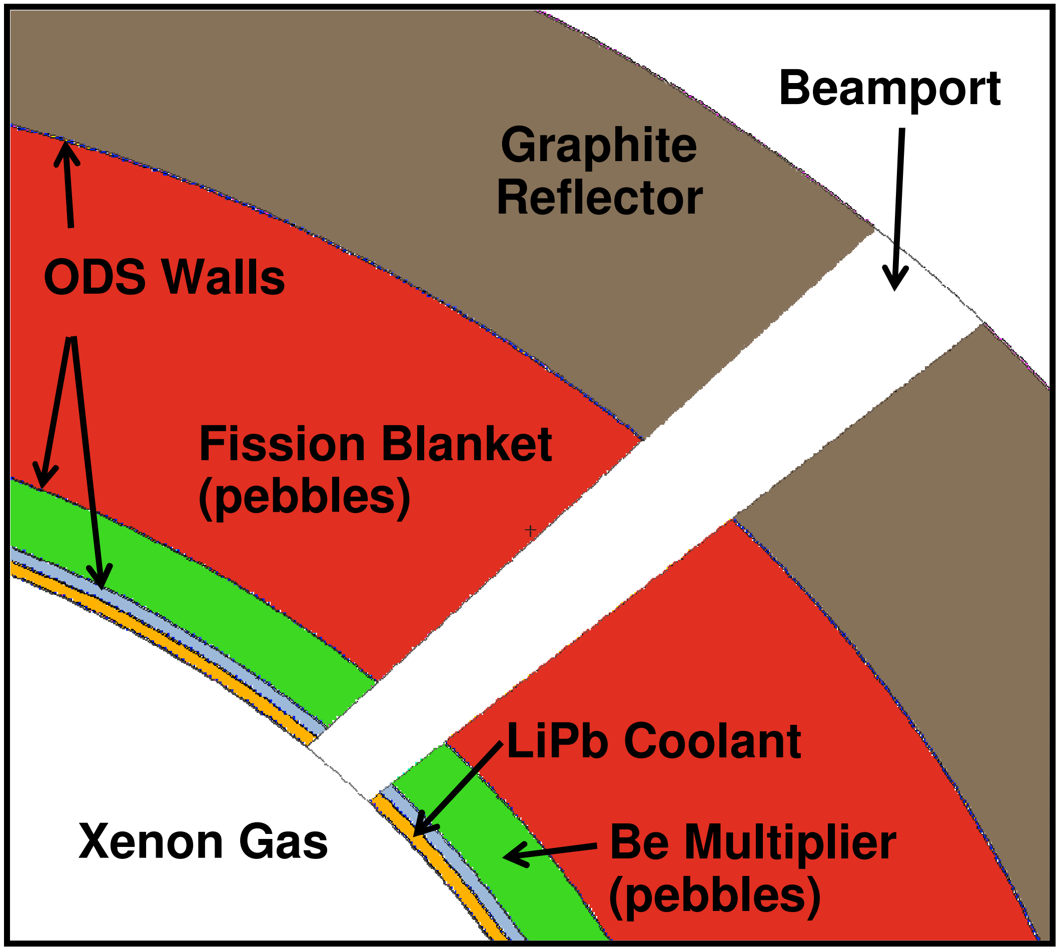


# LIFE features a dedicated first wall coolant with a pebble-based multiplier and fuel



# LIFE consists of concentric shells of coolant, multiplier, fuel, and reflector

- Xenon protects first wall
- First wall has dedicated coolant
- Flibe coolant plenum feeds multiplier, fuel and reflector regions





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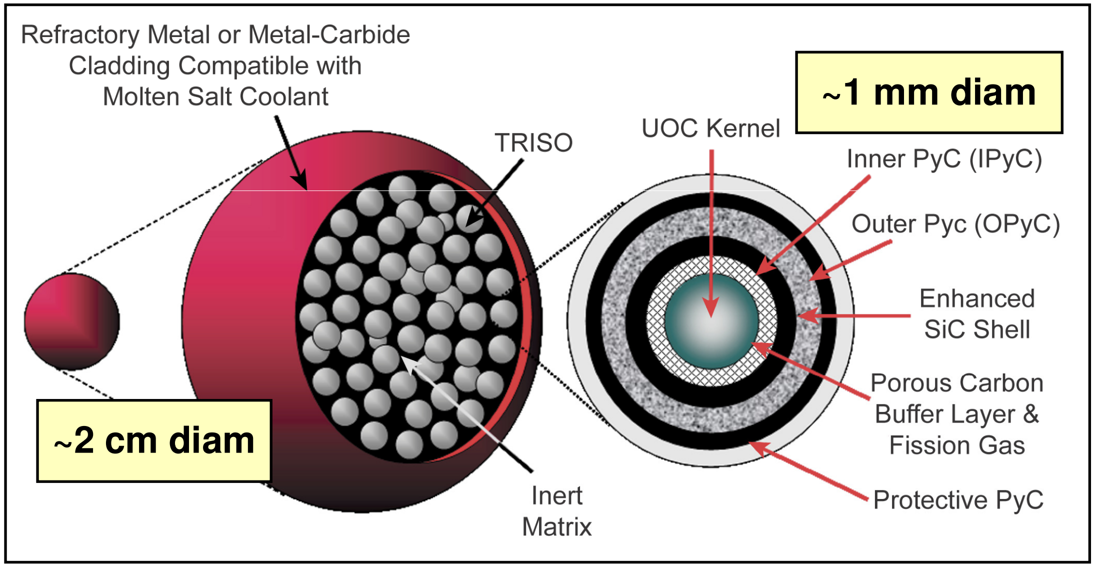
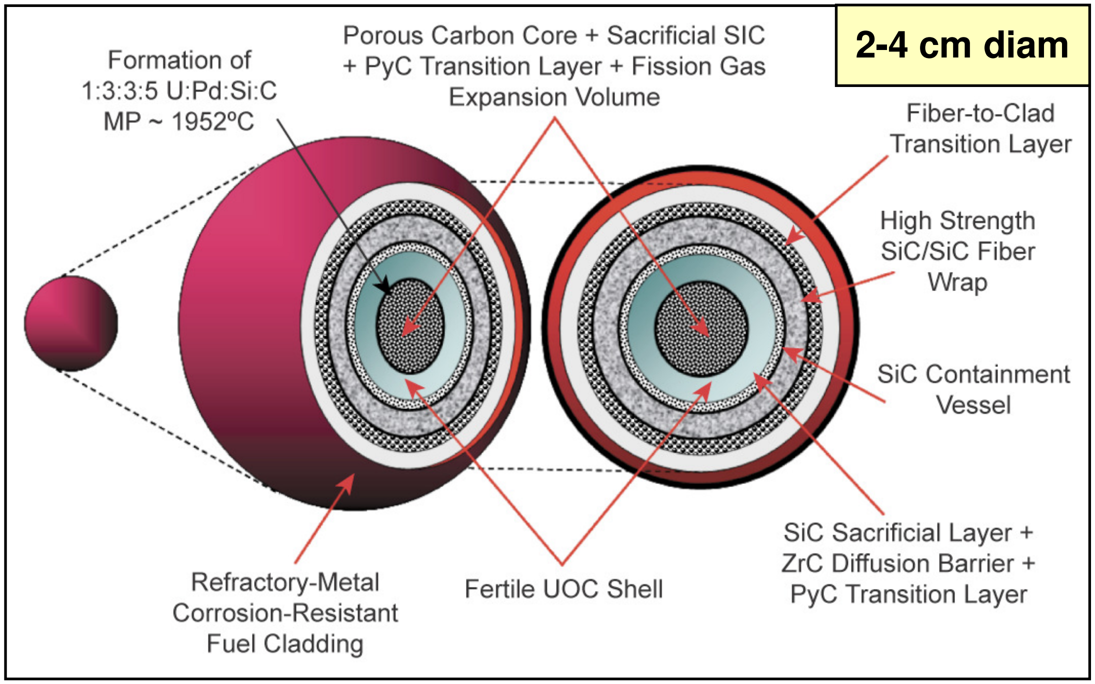
# LIFE could potentially use a variety of fuels

- **Solid fuel forms:**
  - Enhanced TRISO
  - Solid hollow core
  - Encapsulated powder

- **Fuel materials:**
  - Depleted uranium
  - Natural uranium
  - Thorium
  - Spent nuclear fuel
  - Excess weapons-grade materials



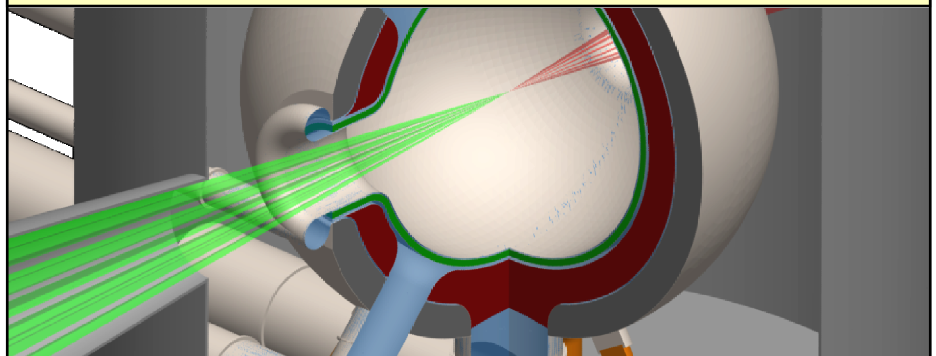



# It is important to note that the LIFE engine is *not* a critical reactor

## LWR

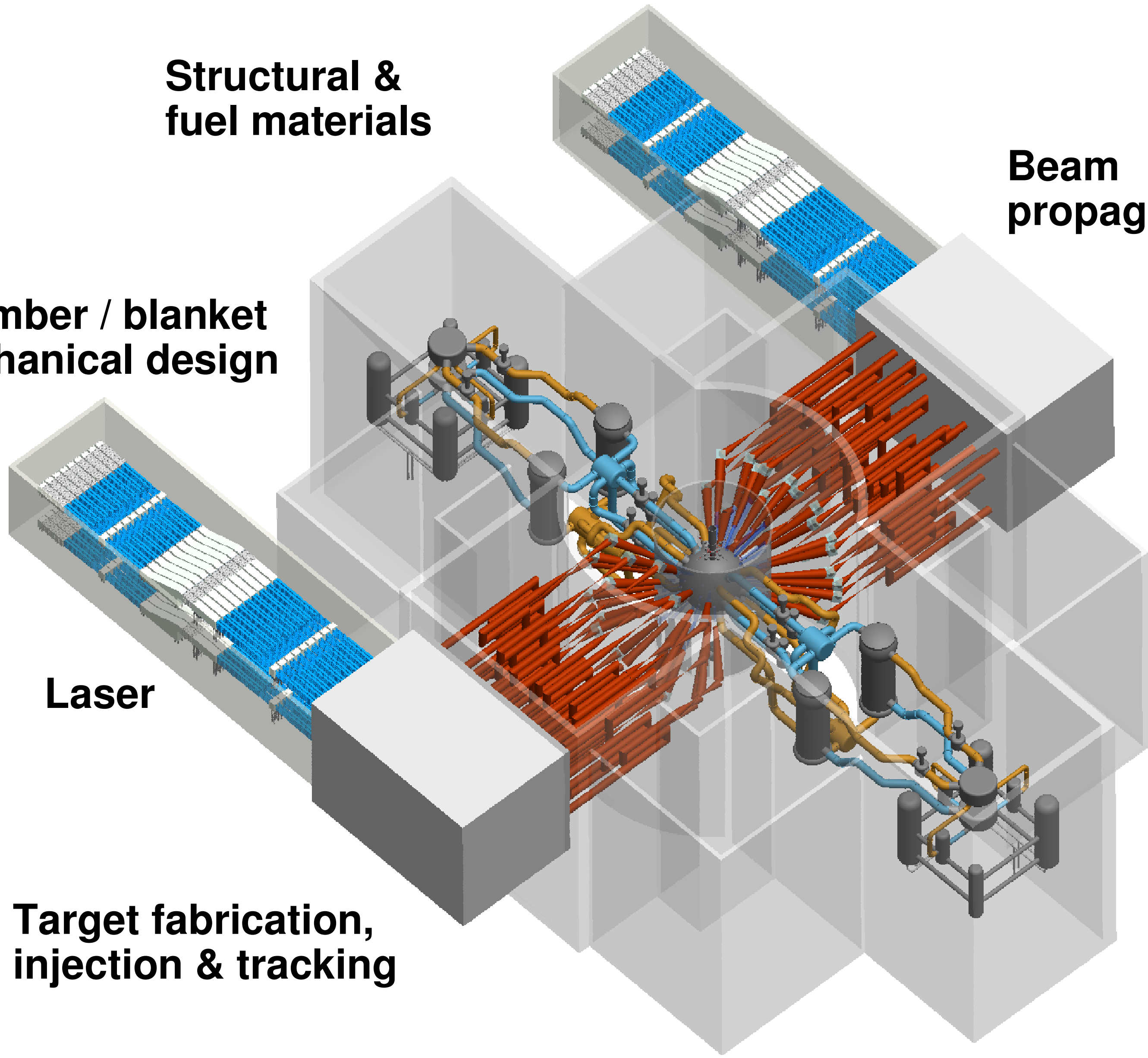
- Must maintain $k_{eff}$ = 1 to operate
- Neutron source is fission only
- Control based on delayed neutrons
- System sensitive to reactor dynamics
- Reactor shutdown by control rod insertion (SCRAM)
- Need to stay critical to produce power

## LIFE Engine



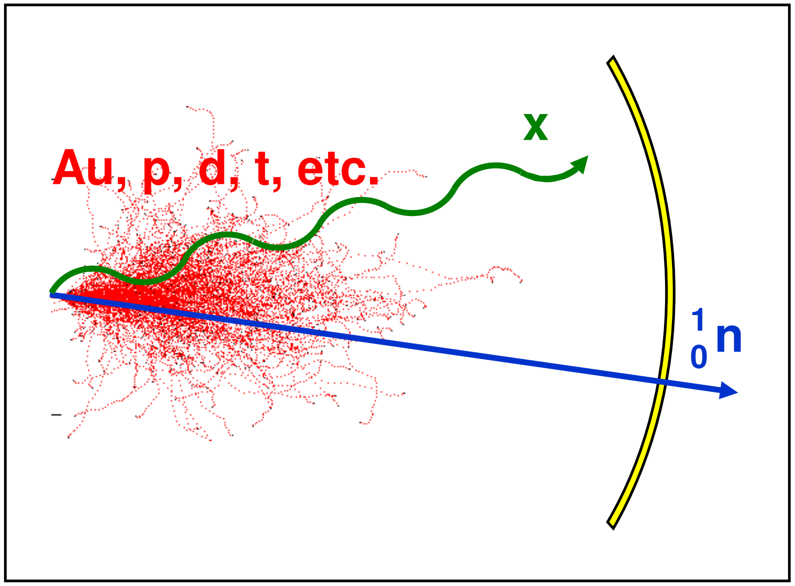
- Always subcritical / cannot go critical
- Neutron sources are fusion targets, Be(n,2n) and fission blanket
- Control systems based on fusion target output
- System insensitive to reactor dynamics
- Shutdown by turning the laser off and removing decay heat
- Burn-up not limited by need to stay critical

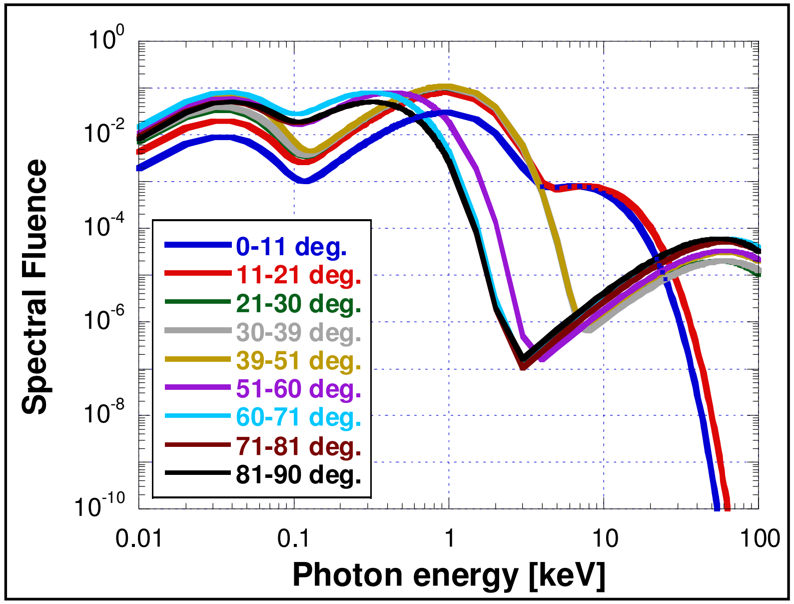
# A detailed system layout has been completed for LIFE



# X-rays and ion fluxes are simply mitigated

| Parameter | Value |
|---|---|
| Target yield | 37.5 MJ |
| Repetition rate | 13.3 Hz |
| Fusion power | 500 MW |
| Chamber radius | 2.5 m |
| X-rays | 4.5 MJ (12%) |
| Ions | 3.8 MJ (10%) |



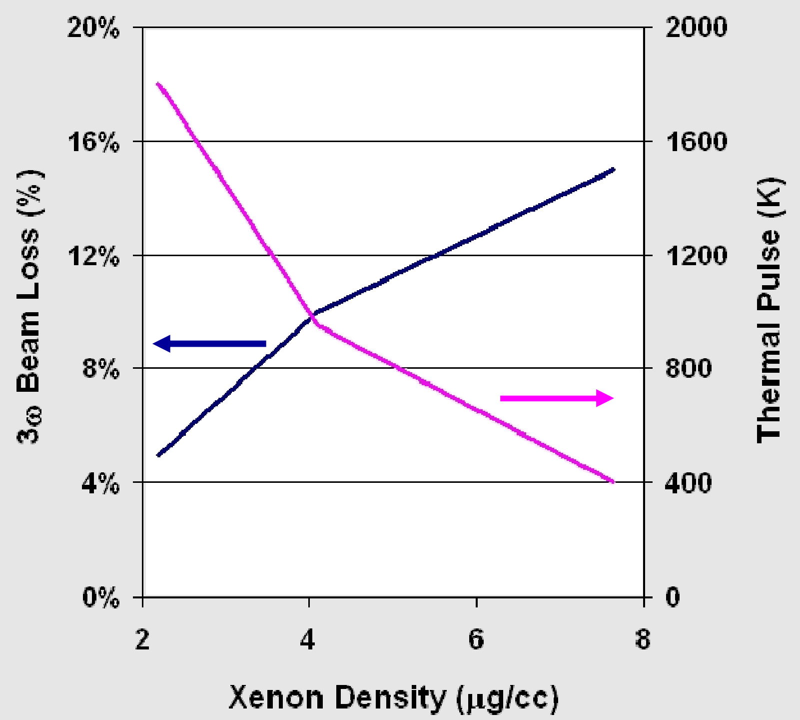




**Chamber fill gas can attenuate x-rays and ions to protect the first wall**

# The LIFE first wall builds upon MFE and IFE technologies

- **First wall is oxide dispersion strengthened ferritic steel**
- **Leaking hohlraum x-rays pre-ionize gas near the target**
- **Inverse Bremsstrahlung causes partial laser absorption**
- **Experiments and modeling have been conducted at LLNL, UCSD, and UW for ~1800 K pulses:**
  - — **Tungsten wall cracks, which relieves stress**
  - — **Cracks do not propagate**

**Xenon densities of ~4 µg/cc reduce the thermal pulse to <1000 K**




**Thermal robustness of indirect-drive targets enable use of chamber fill gases and more compact chambers**

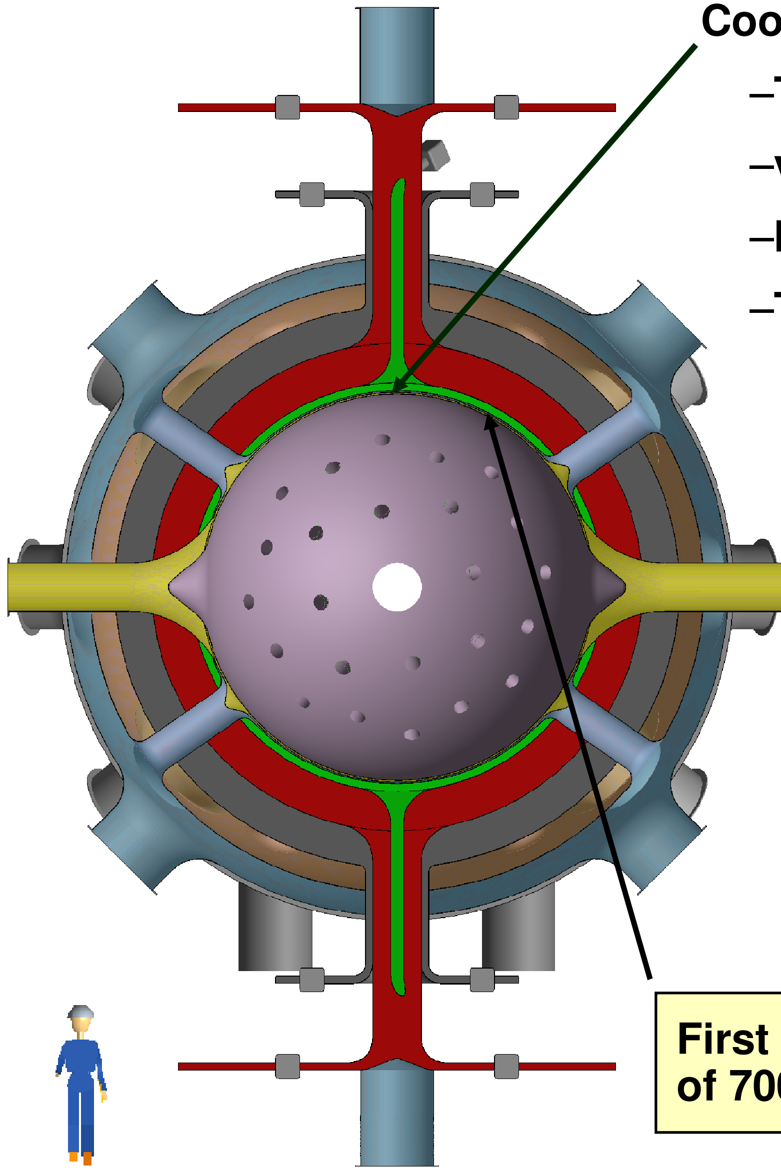
# Dedicated Pb-17Li first wall cooling removes 1.5 MW/m² of re-radiated ion and x-ray energy

**Coolant reaches midpoint**

- $T_c$ = 352 °C
- v = 1 m/s
- h = 8 kW/m²/K
- $T_w$ = 672 °C

**Pb-17Li enters**

- $T_c$ = 260 °C
- $\dot{m}$ = 4.5 MT/s
- v = 5.5 m/s
- h = 35 kW/m²/K
- $T_w$ = 450 °C



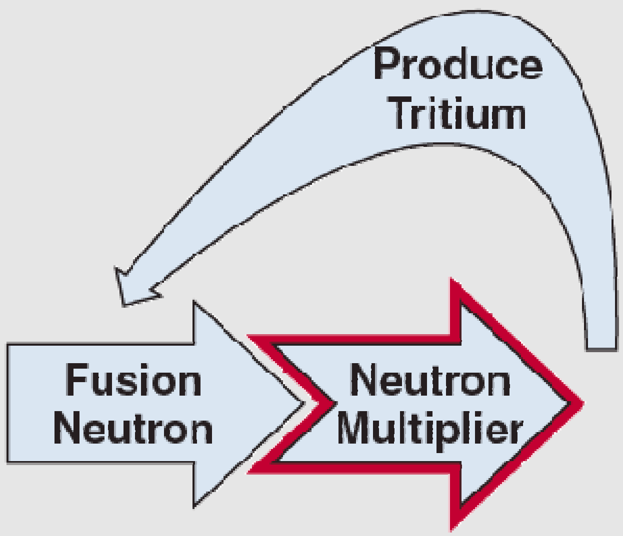
**Coolant reaches exit**

- $T_c$ = 445 °C
- v = 5.5 m/s
- h = 35 kW/m²/K
- $T_w$ = 632 °C

**First wall reaches highest temperature of 700 °C just beyond the midpoint**

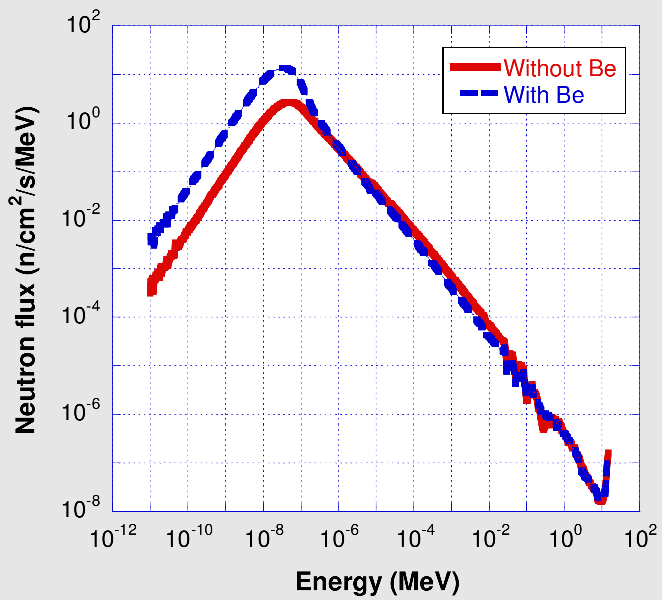
# Beryllium multiplication and moderation enables rapid production of fissile material

**Neutrons are multiplied via $^{9}Be(n,2n)$ reactions**




**Beryllium produces ~1.8 neutrons for every fusion neutron**

**Be region considerably softens the neutron spectrum**

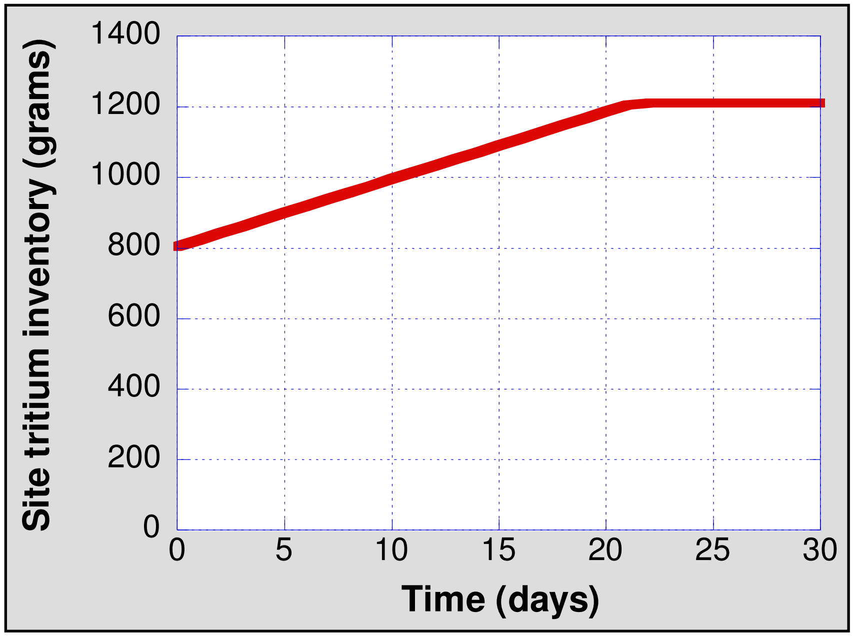



**More thermal neutrons are available to produce tritium and fissile material**

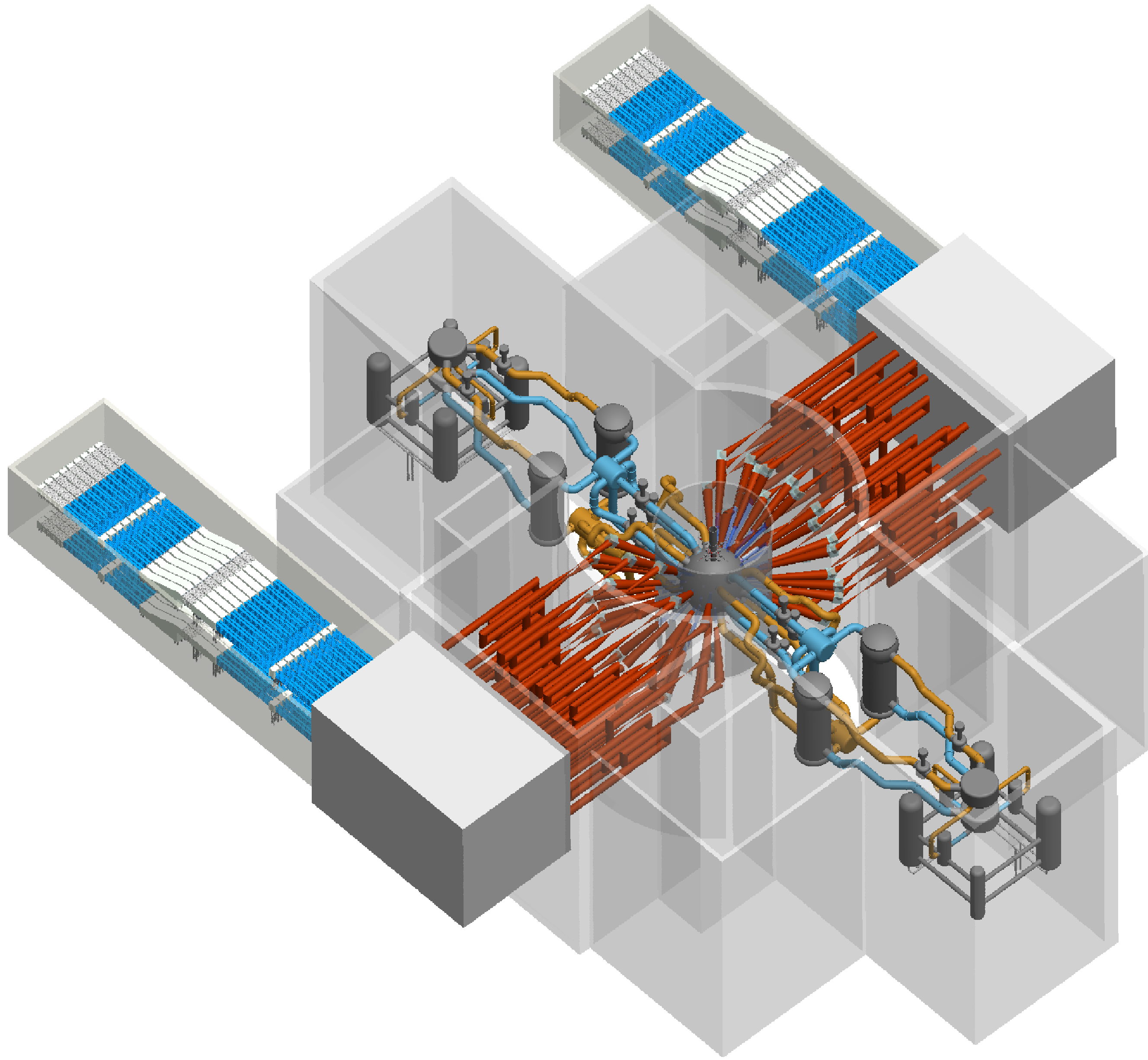
# LIFE plants will require ~800 grams of tritium for system start up

- Plant operations begin with ~800 grams of tritium:
  - Inventory starts in the target factory
  - Migrates into the structural materials
- Operations with increased tritium breeding ratio (1.25) allows additional 400 grams to be bred in ~3 weeks
- Excess tritium provides supply for intermediate storage and 1-day supply of extra targets

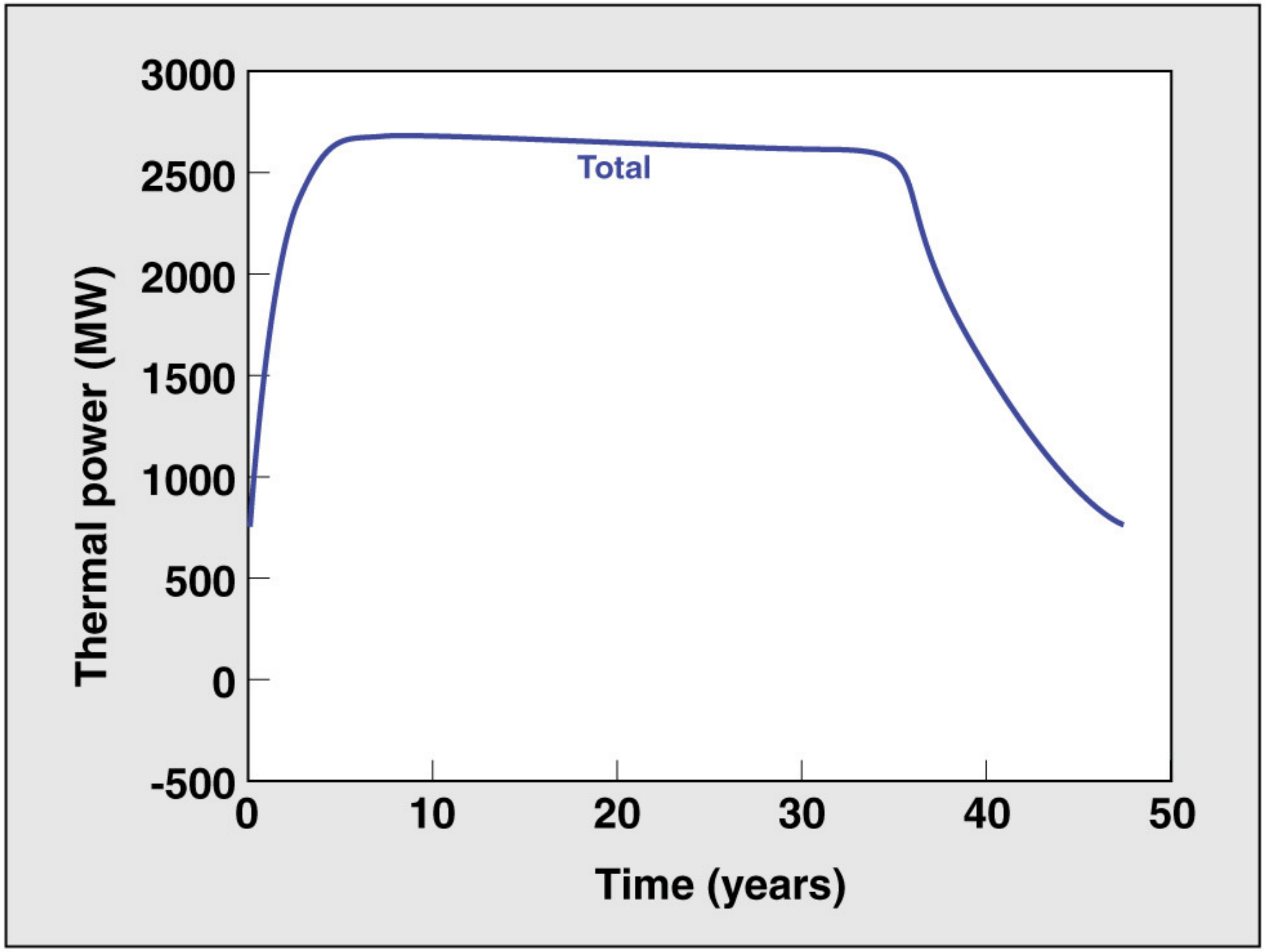
| Area | Inventory (g) |
|---|---|
| Target factory | 310 |
| Flibe coolant | 23 |
| Isotope separation sys. | 180 |
| Structural materials | 600 |
| Intermediate storage | 100 |
| Total inventory | 1210 |



# System Modeling & Performance with Depleted Uranium

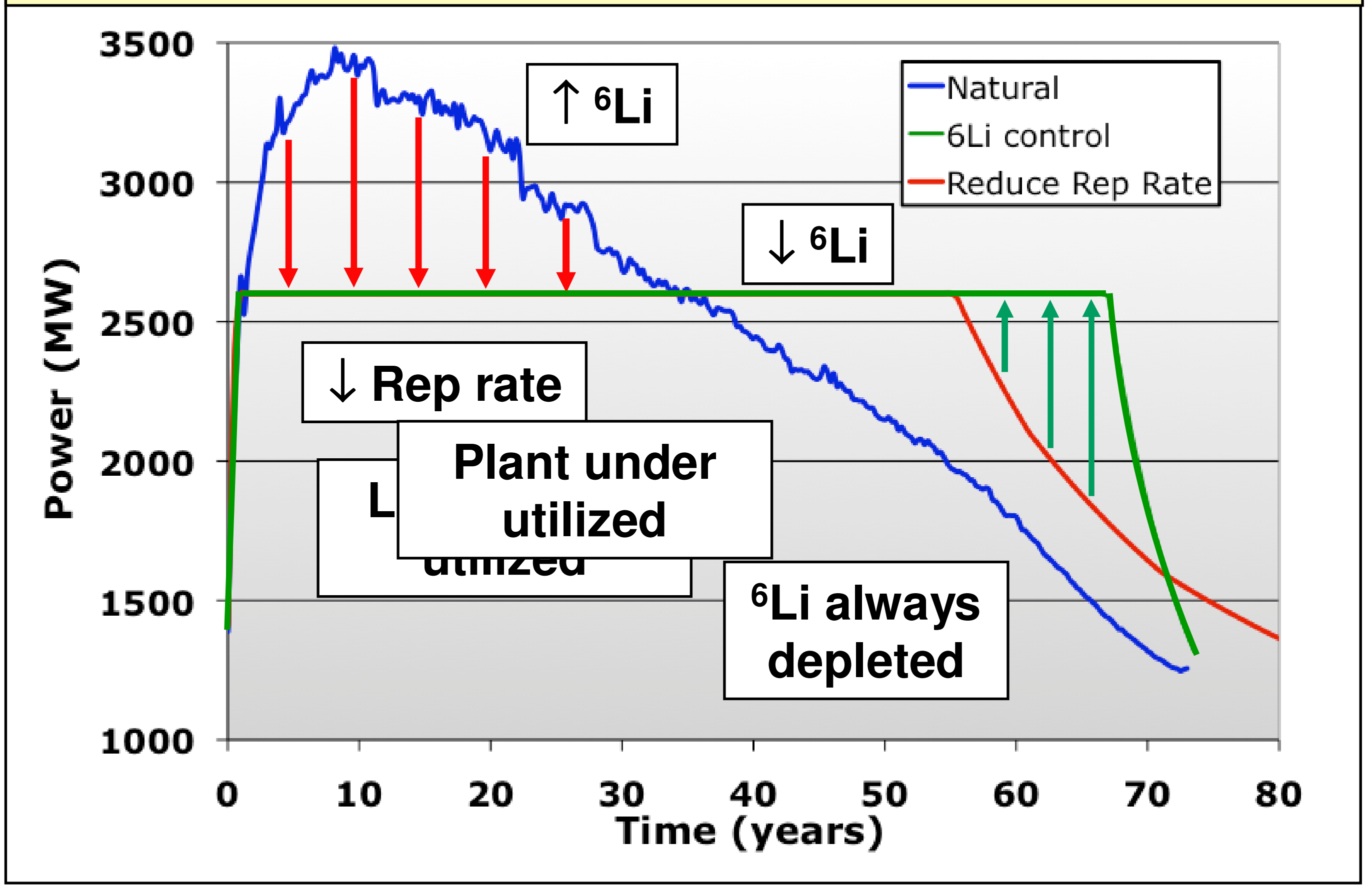


# LIFE provides decades of steady-power from a depleted uranium fuel loading



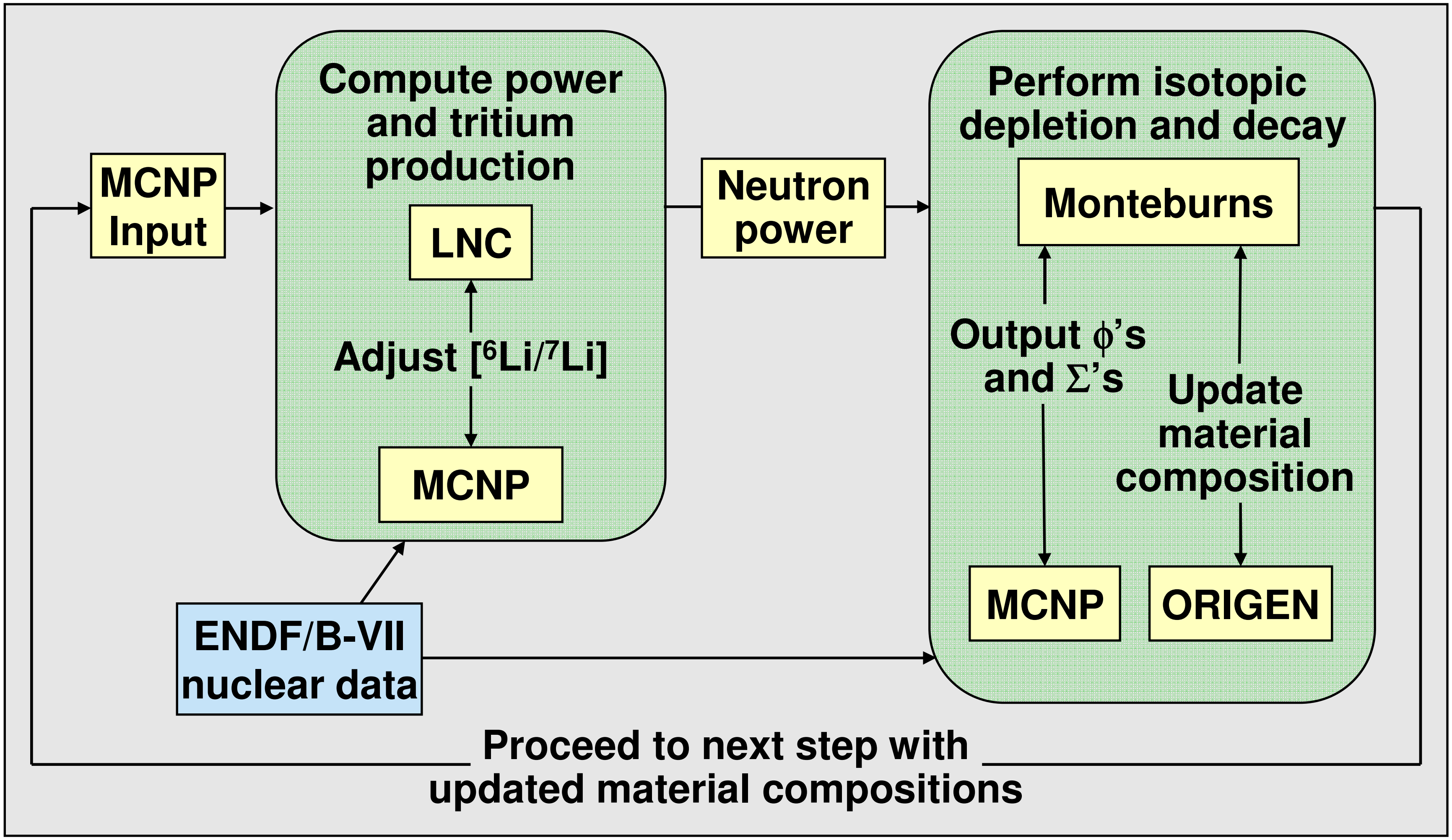
# LIFE uses $^6$Li as a burnable poison to control the thermal power and produce tritium

**A flat power curve is desirable**




**Systems achieving 90%+ balance of plant utilization may be possible through tritium management**

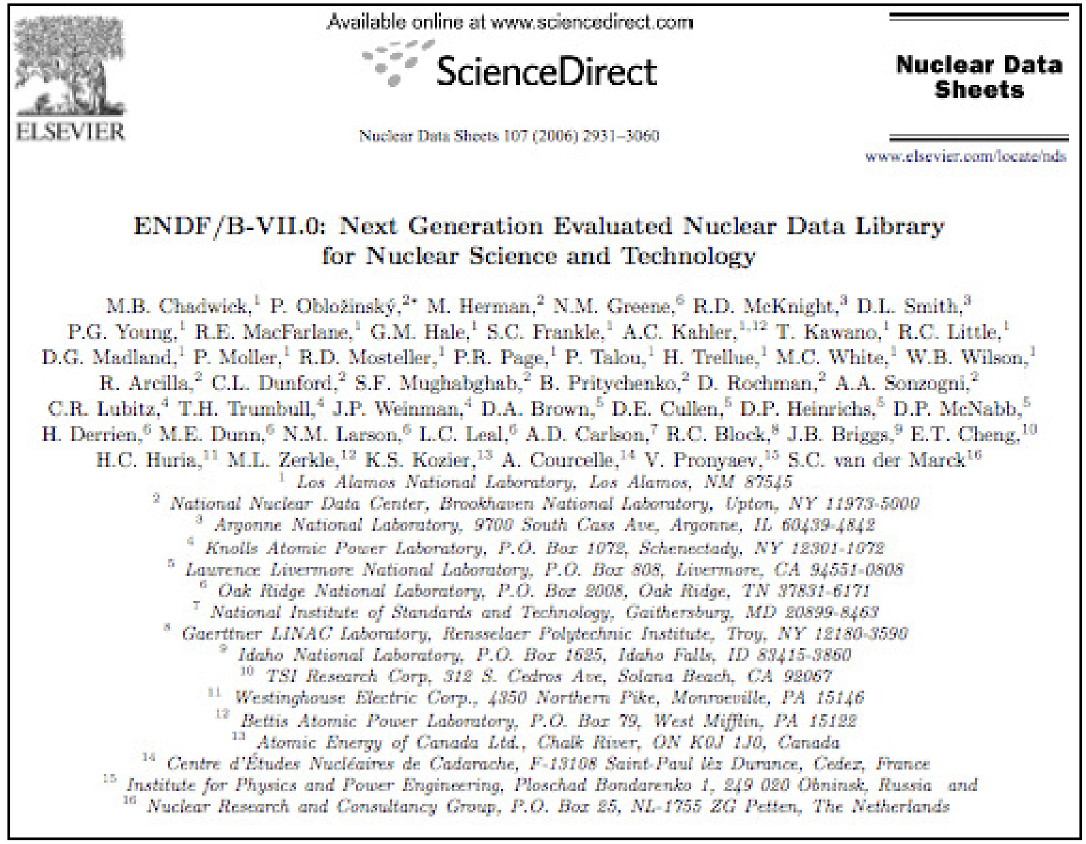
# LIFE neutronics analyses are built upon accepted codes with community-standard data




- MCNP5 → radiation transport
- ORIGEN → radionuclide generation & depletion
- LNC → control code

# Improvements in nuclear data are crucial for LIFE calculations

- **ENDF/B-VII expands upon ENDF/B-VI.8 to include data for 393 isotopes**
- **Monteburns discards mass if σ does not exist**
  - **Missing mass reduced from ~30% to < 1%**
- **Not as important in low burnup systems but very important for high burnup**
- **Future - add additional σ data for missing isotopes**



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ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology


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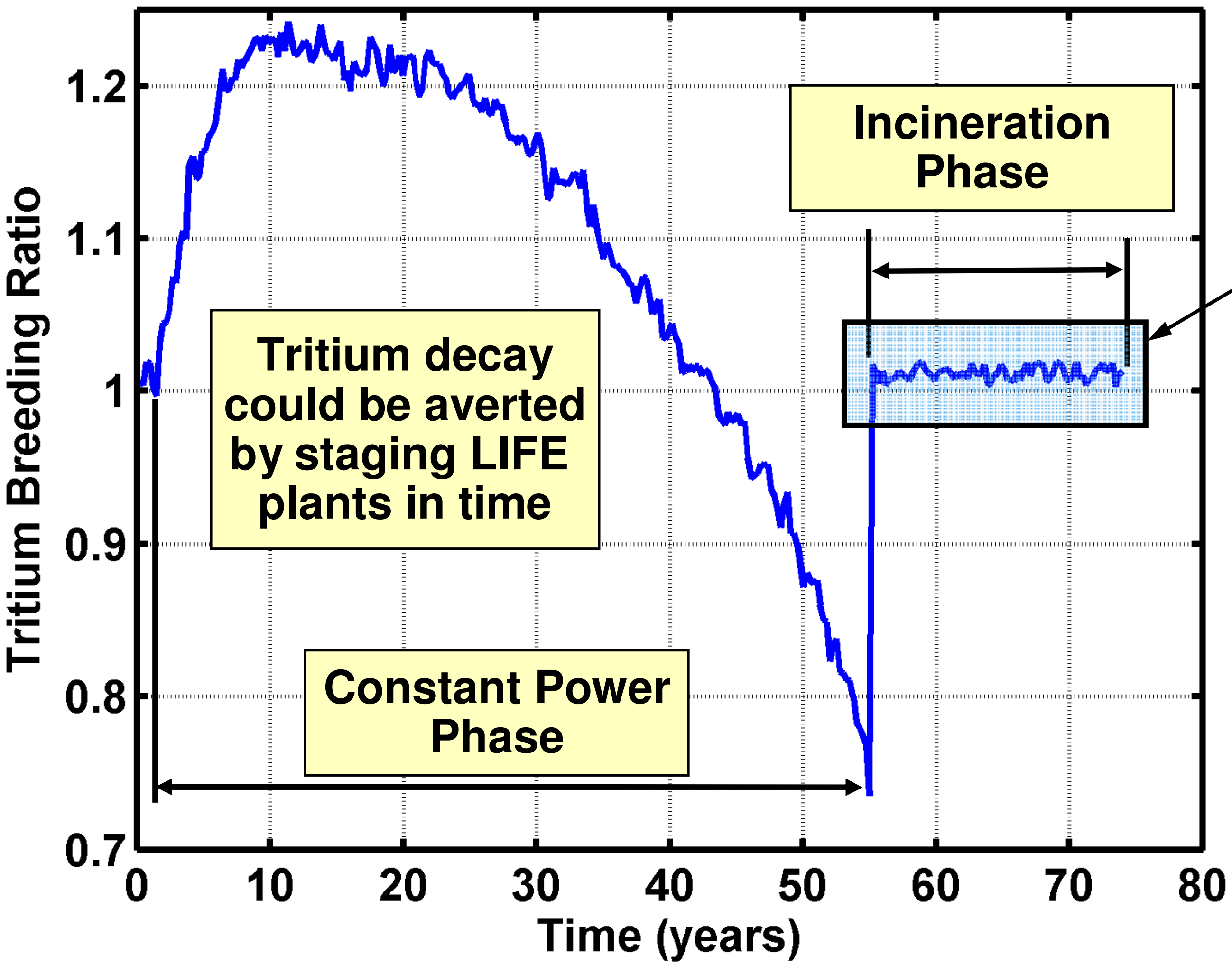
**Improvement in nuclear data is needed to improve accuracy of isotope inventories at high burnup**

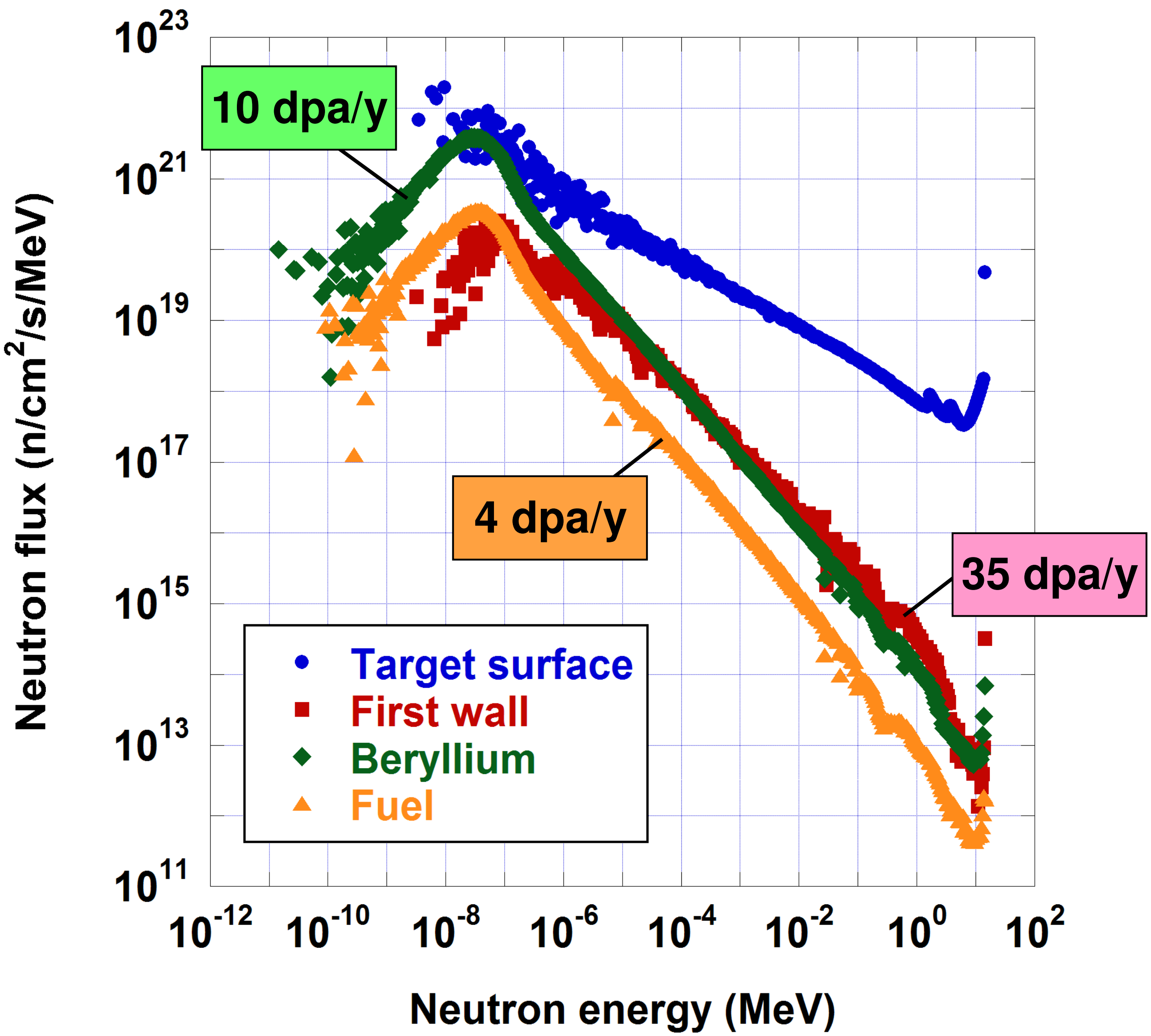
# Thermal power is controlled by adjusting the tritium breeding ratio (TBR) via $^6$Li enrichment




TBR is restored to unity once the tritium supply is exhausted

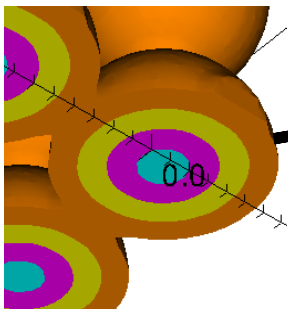
A LIFE engine produces excess tritium early in its life cycle and consumes this tritium later in time

# The neutron spectrum varies considerably in the different regions of a LIFE engine

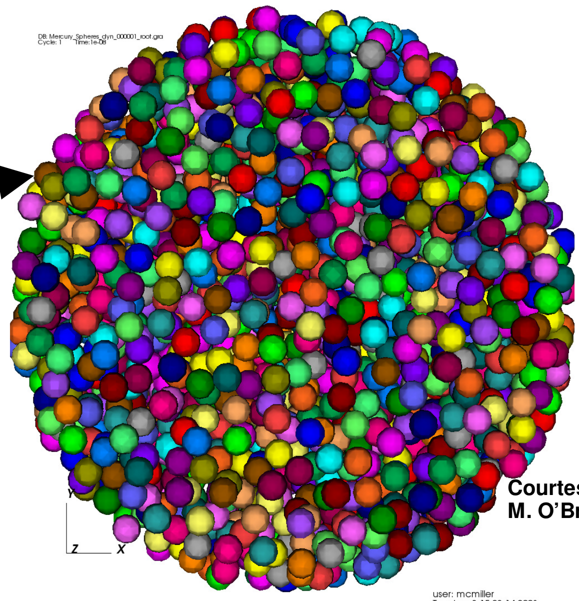


# We are determining the appropriate level of fidelity for LIFE simulations

- **Can homogeneous approximations be used to speed LIFE design?**
- **If fully heterogeneous calculations are required = billions of cells**

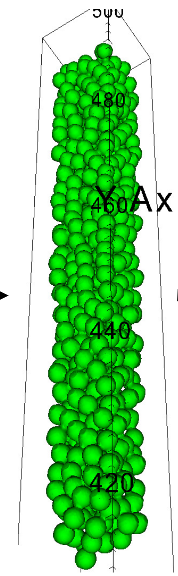



**4 Layers per TRISO**

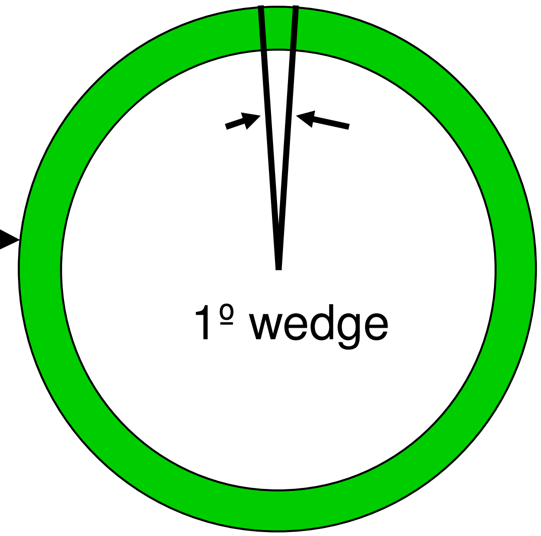


Courtesy
M. O'Brien

**2445 TRISOs per Pebble**



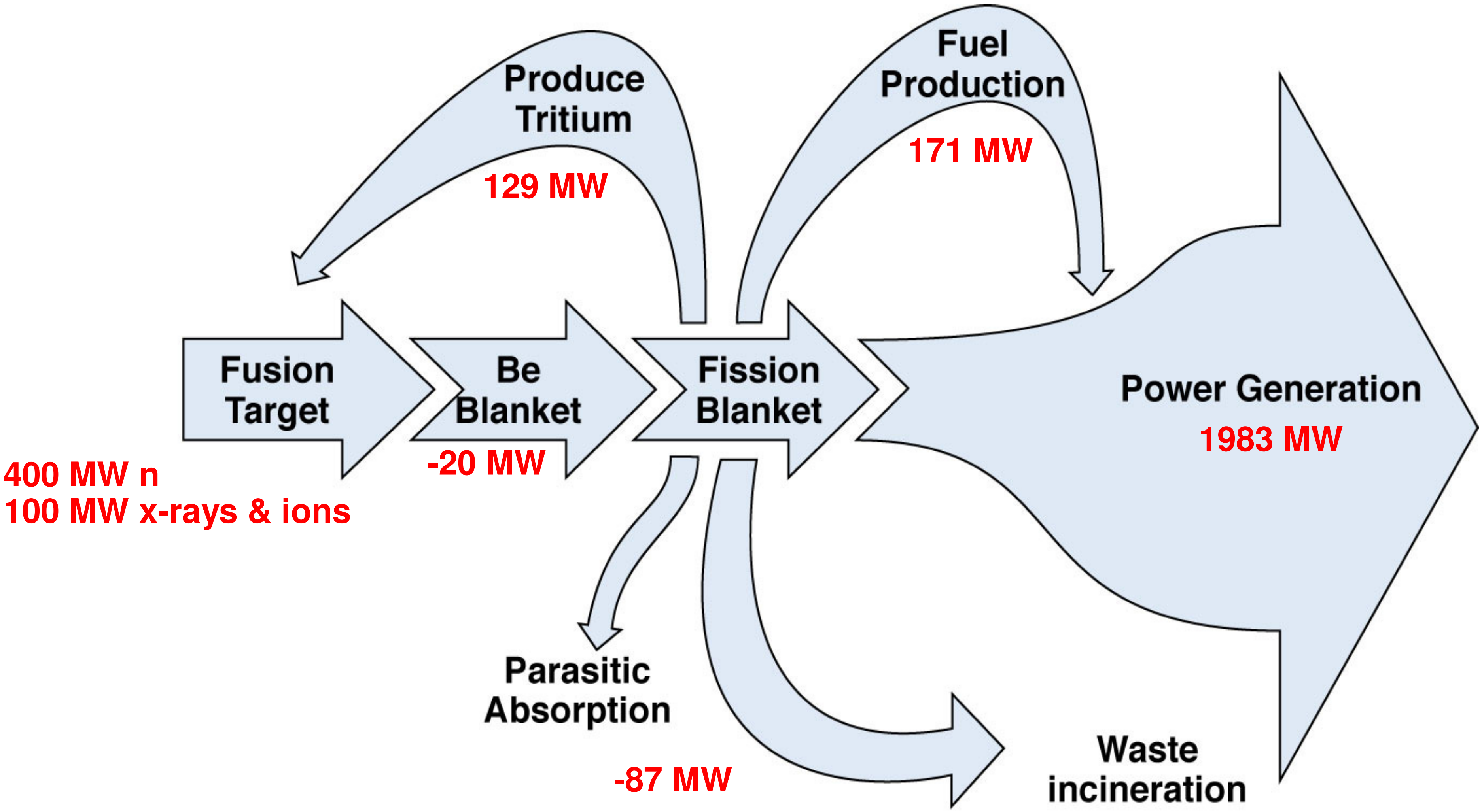

**569 pebbles**



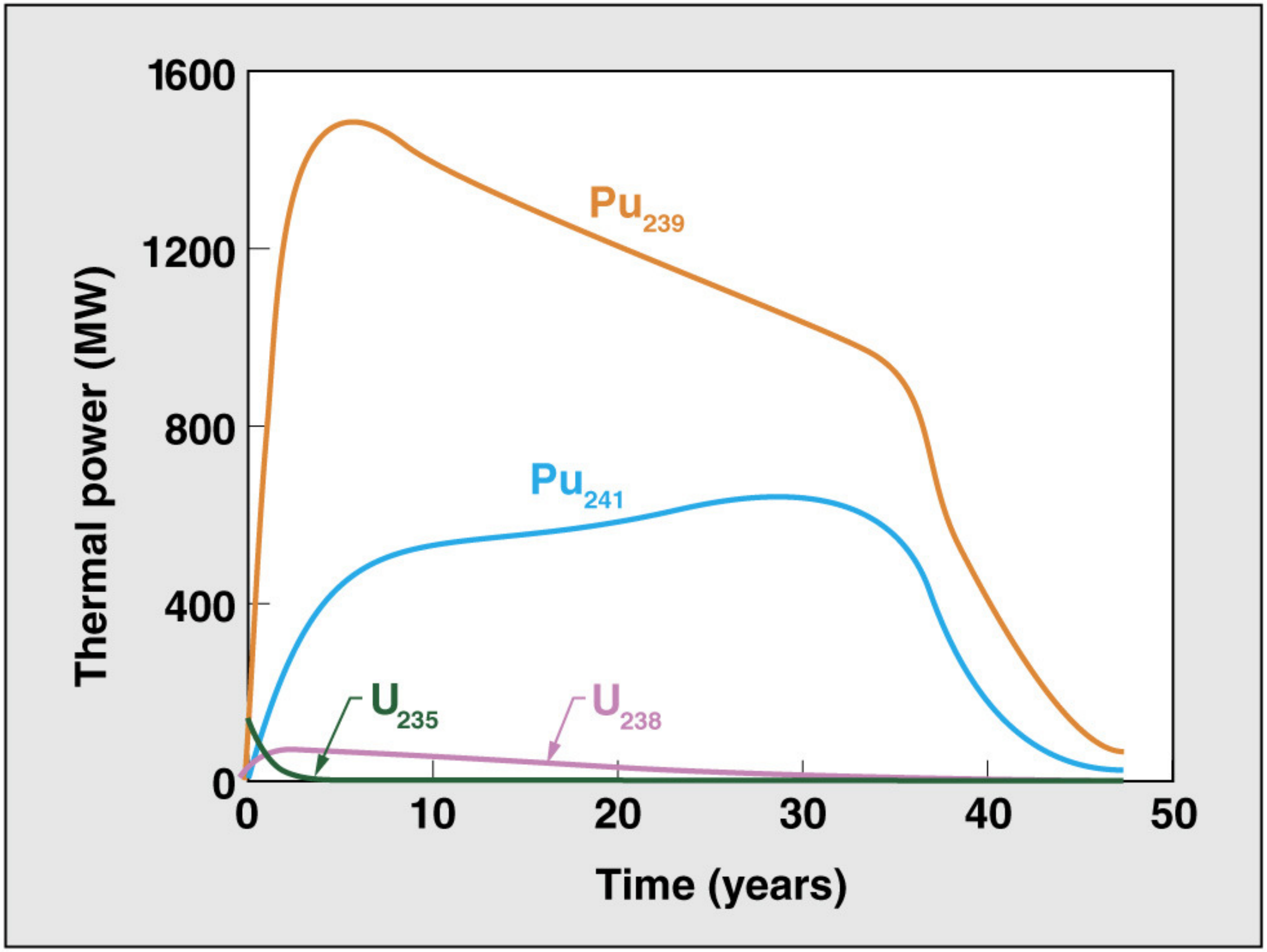

**5.6 Million cells**
**36 Gb memory**

**Detailed analyses are being performed as part of a supercomputing grand challenge**

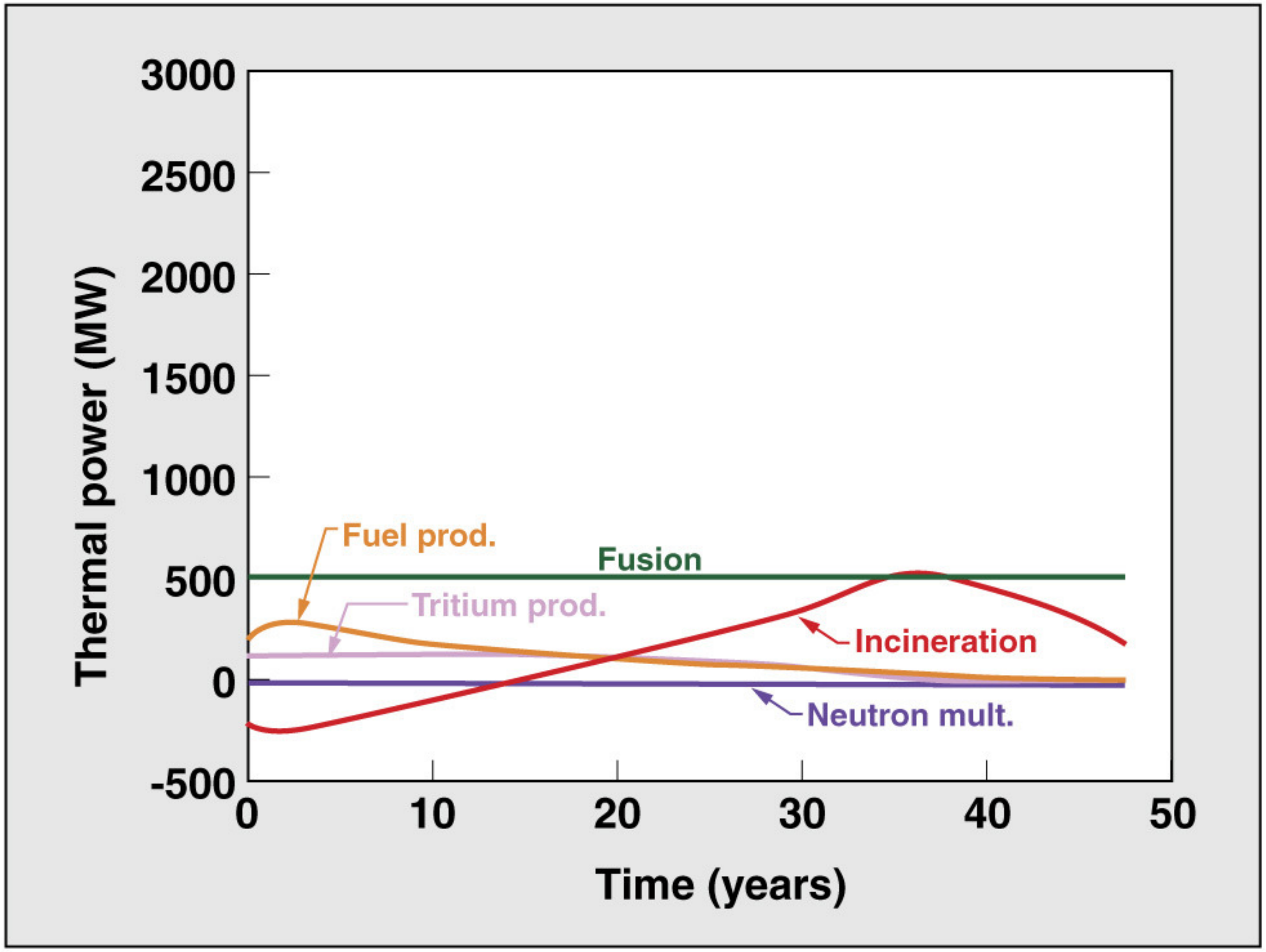
# Neutron power flow for DU case at time of peak $^{239}Pu$ (~17 years); TBR = 1.25



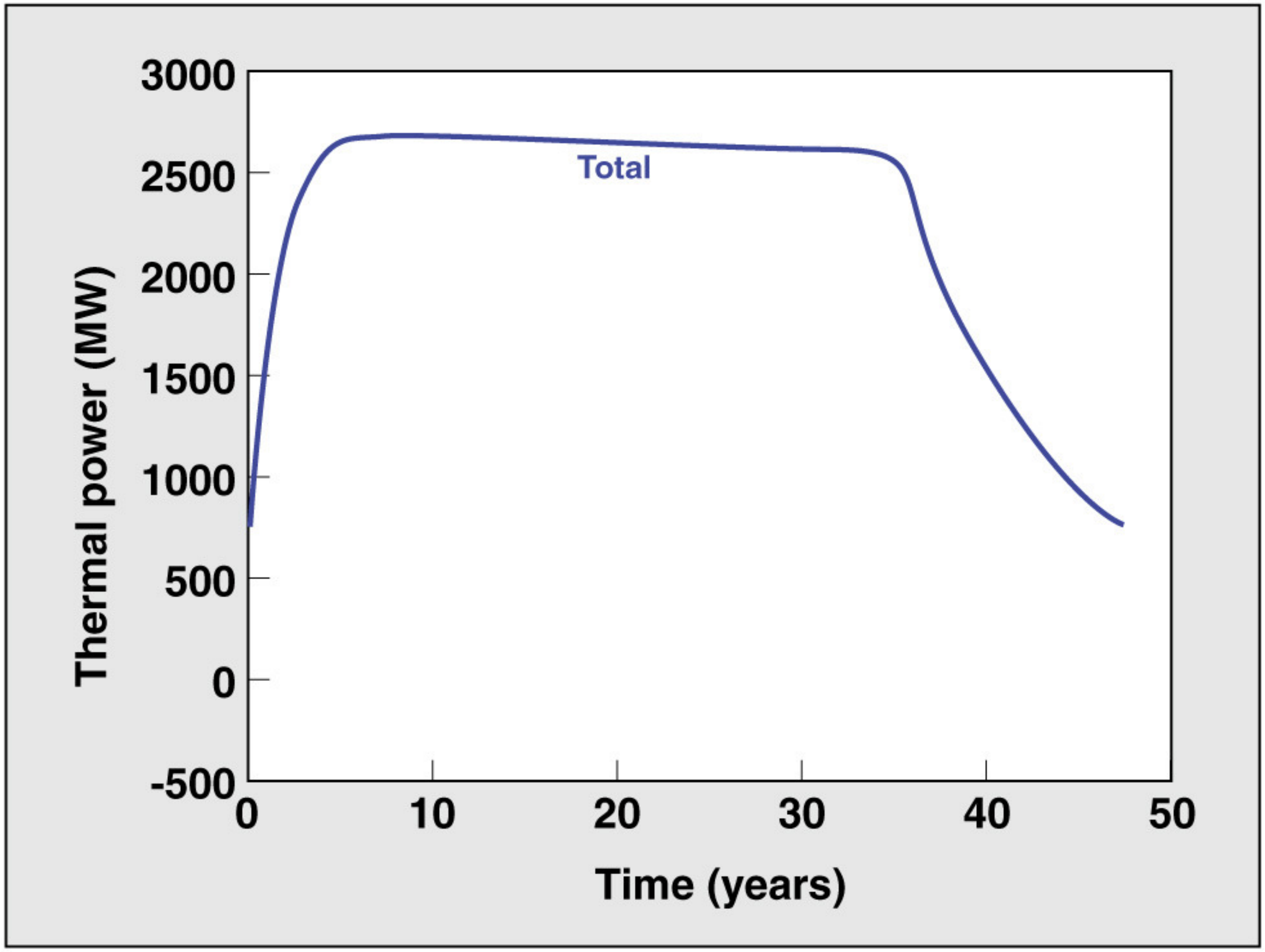
# Several isotopes are fissioning in the LIFE engine



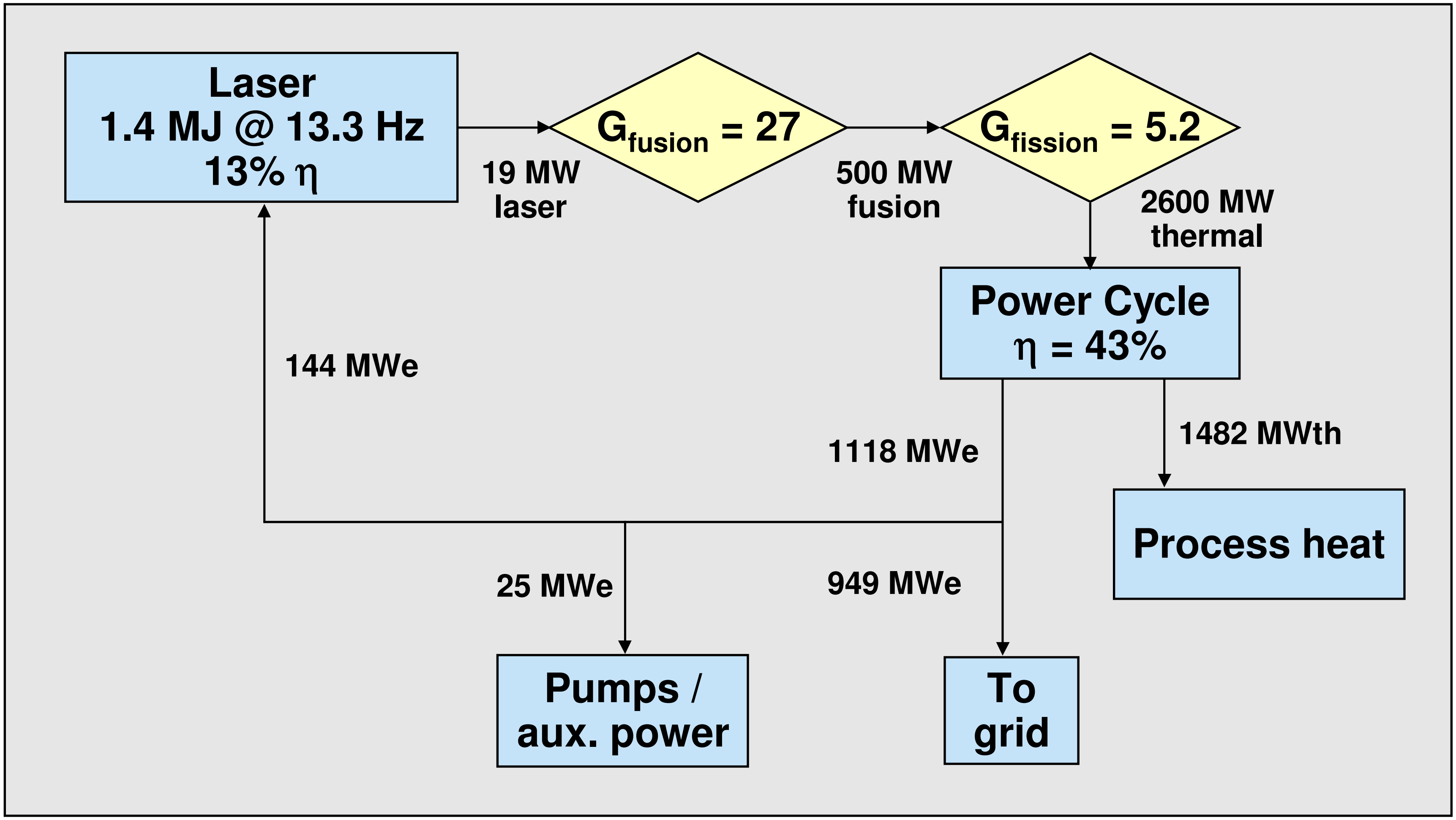
# Non-fission reactions make a significant contribution to the thermal power



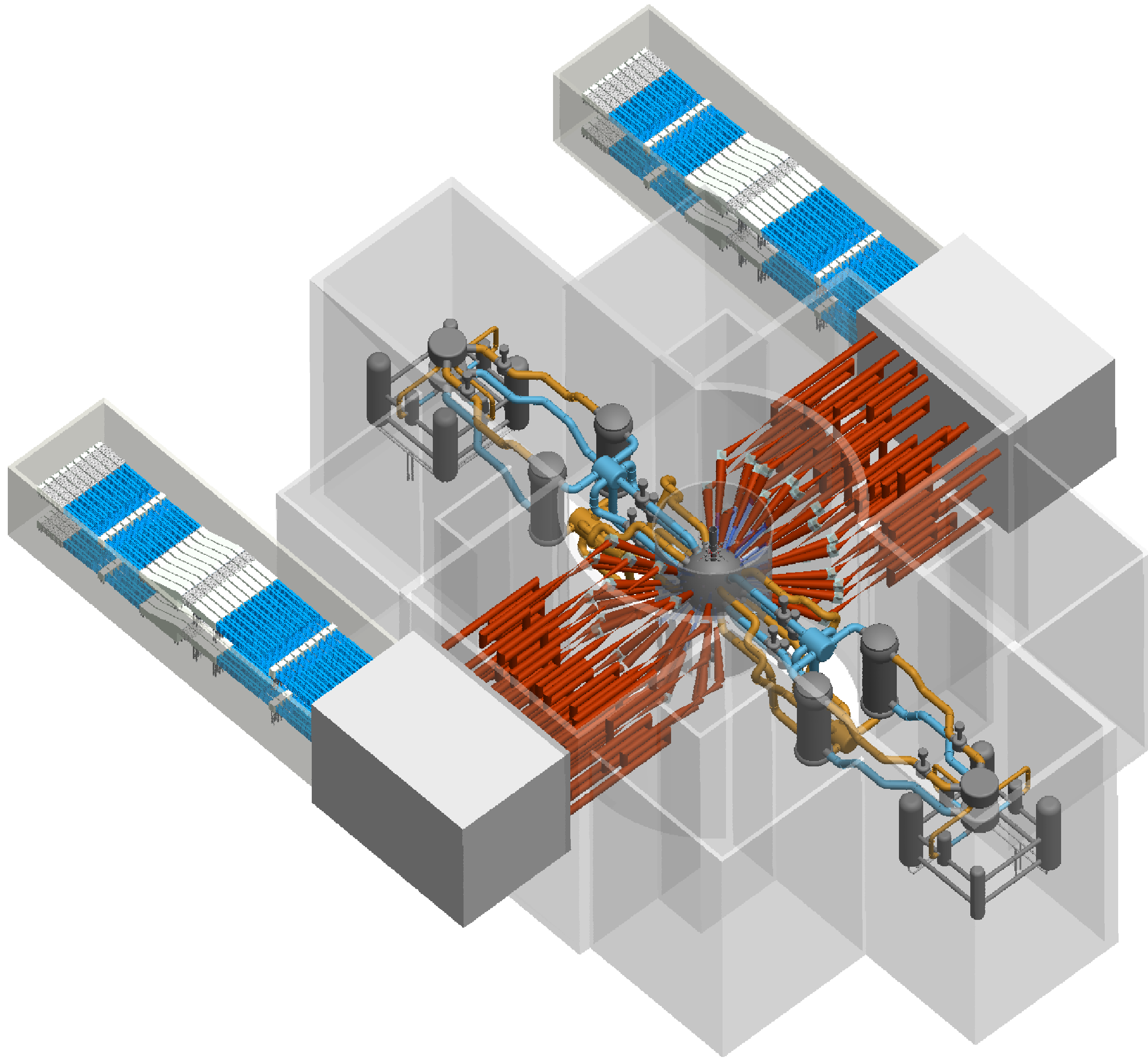
# LIFE provides decades of steady-power from a depleted uranium fuel loading



# LIFE power flow for DU blanket



# Advanced Options

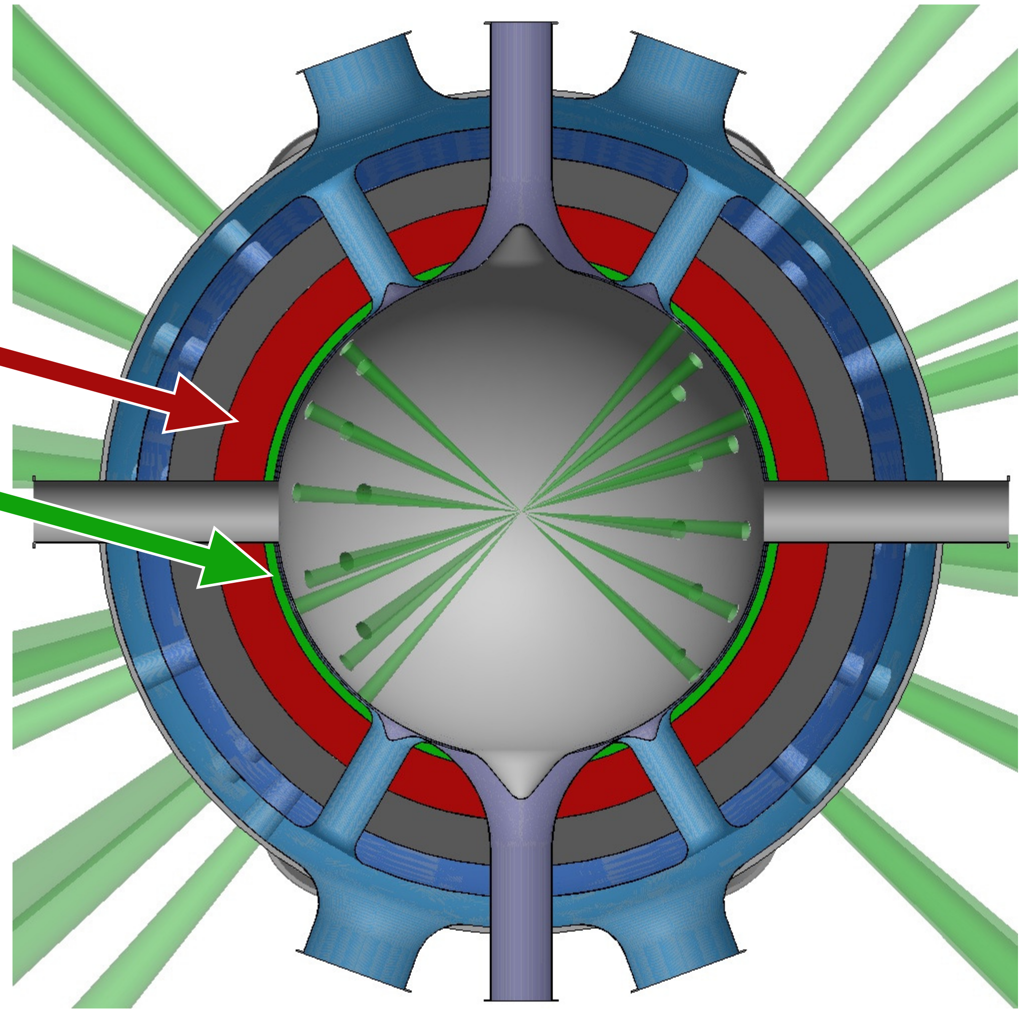


# LIFE designs can be modified for enhanced performance

- Molten salt fuels → no fuel radiation damage concerns
- Segmented blankets → continue flat-top power production indefinitely
- Variable moderator to provide improved fuel-to-moderator control → operate close to ideal moderator
- Tritium sharing between plants → defeat tritium decay during storage
- Fast ignition → high-gain fusion targets with reduced laser energy
- Two-sided laser illumination → improved chamber / facility geometry

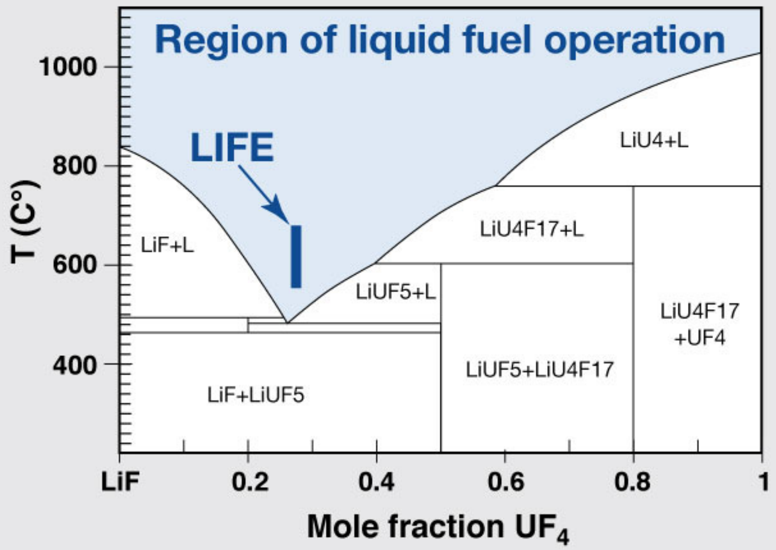
# The solid fuel pebbles would be replaced with molten salt containing $UF_4$ and/or $ThF_4$

- Replacement solid-fuel pebbles, with molten salt composed of $LiF + UF_4 + ThF_4$
- Neutron multiplier



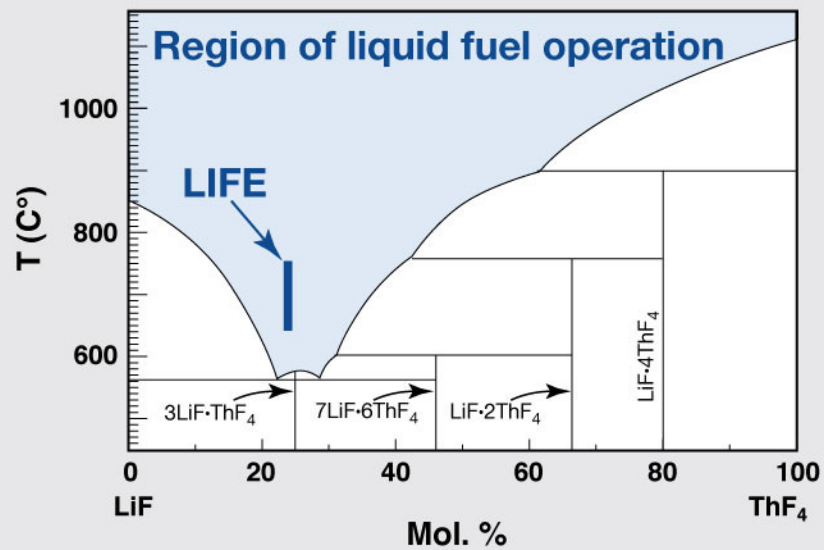
# Liquid fission fuel options for LIFE

## $LiF + UF_4$




- 73 mol% LiF + 27% $UF_4$
- $UF_4$ $T_{melt}$ = 960 °C
- $PuF_3$ $T_{melt}$ = 1425 °C

## $LiF + ThF_4$

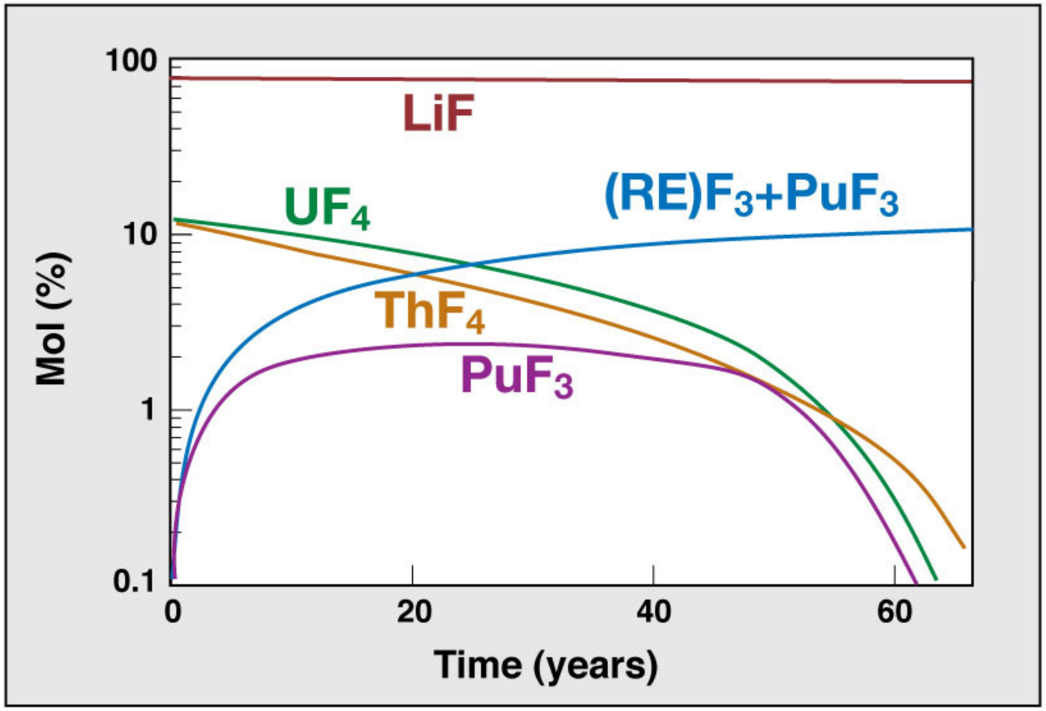



- LiF 75 mol% + $ThF_4$ 25%
- $ThF_4$ $T_{melt}$ = 1111 °C

NIF-0908-15385
29RWM/cld

# As uranium and thorium burn down, plutonium and rare-earths build up

- Rare-earth fluorides $(RE)F_3$ behave like Pu and will limit solubility of $PuF_3$
- We must remove the $(RE)F_3$

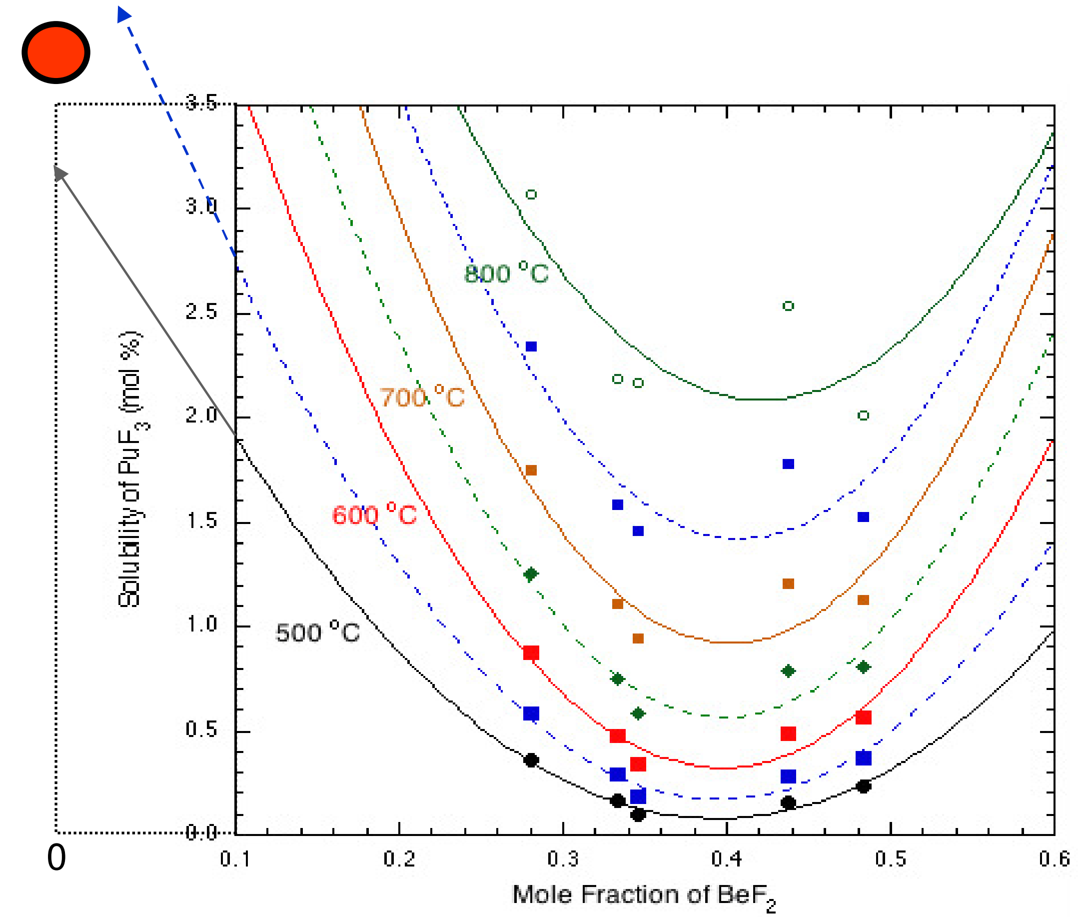



**Is 2 mol% $PuF_3$ soluble at >550°C?**

NIF-0908-15386
29RWM/cld

# Data suggest 2 mol% $PuF_3$ is soluble above 550°C

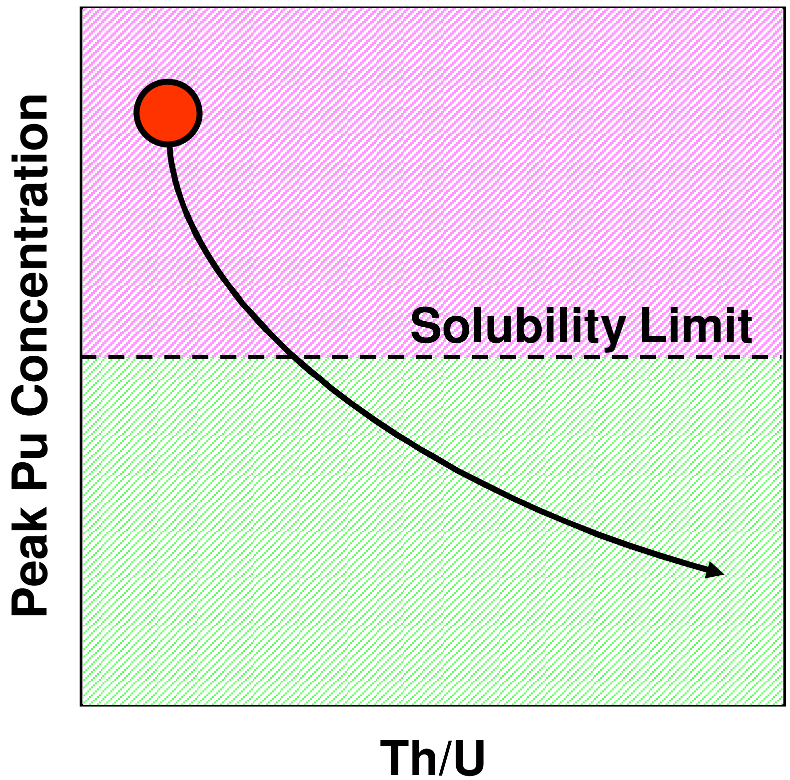
- **Available Pu solubility data is for $BeF_2$ salts**
- **Extrapolation suggests Be-free salts may have solubility >3.5% at 550°C**




**Planning experimental campaign to determine solubility**

# Plutonium concentration is easily controlled through addition of thorium

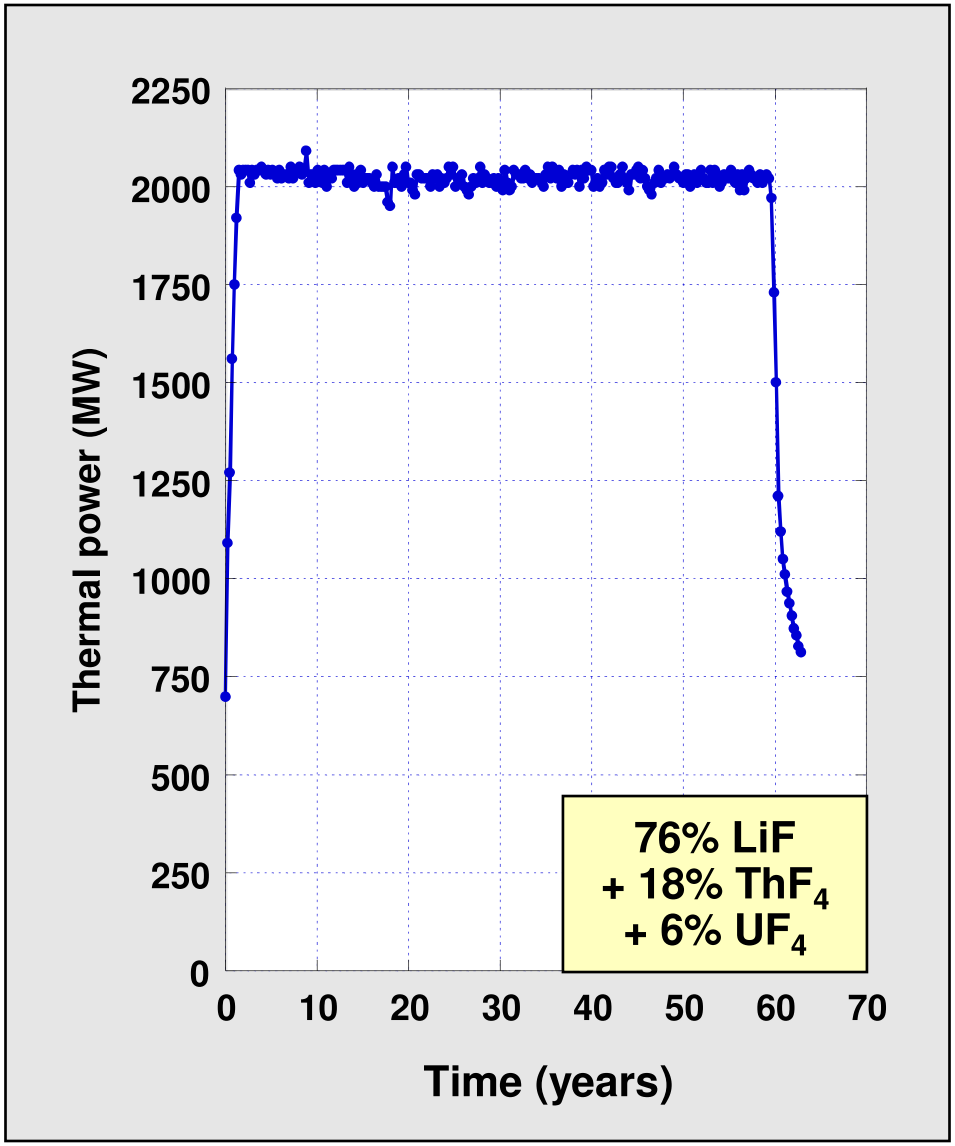
- Thorium and produced $^{233}U$ compete for thermal neutrons
- This reduces plutonium production




| Composition | Peak Pu (%) |
| --- | --- |
| $76LiF + 24UF_4$ | 4.3 |
| $76LiF + 12UF_4 + 12ThF_4$ | 2.0 |
| $76LiF + 6UF_4 + 18ThF_4$ | 1.2 |

# Molten salt fuel is an attractive choice for burning SNF

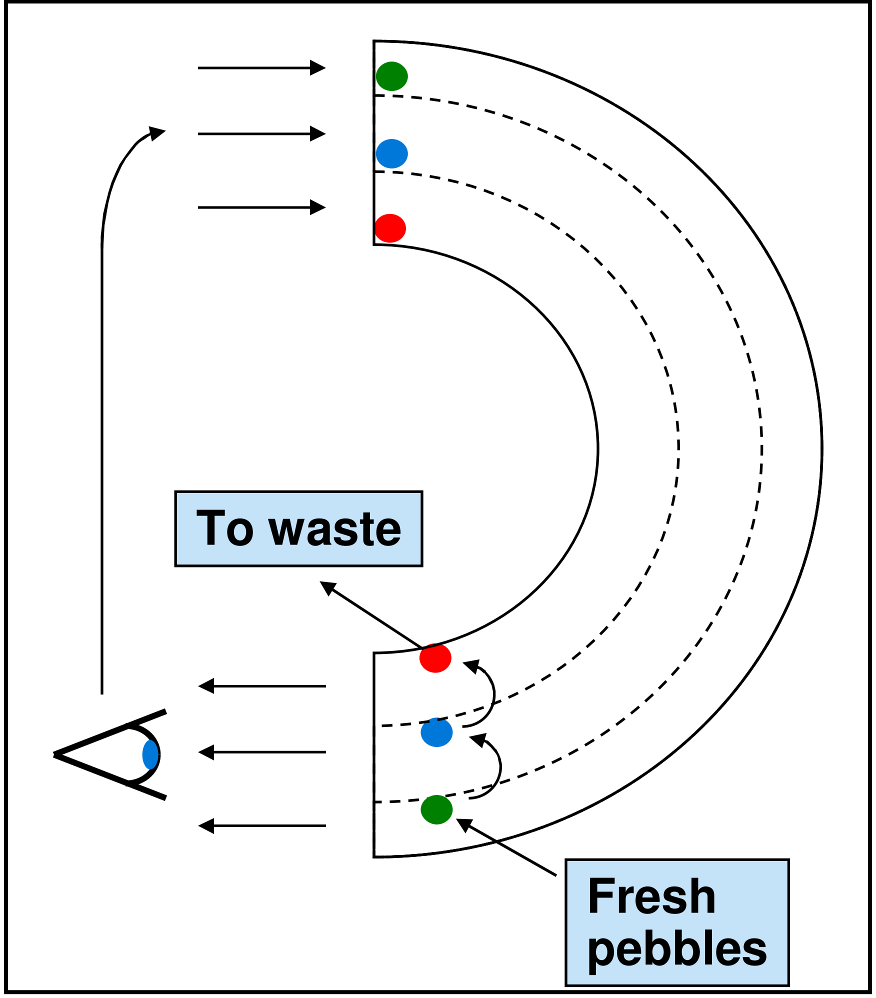
- Radiation damage to fuel is a non-issue
- Rare earth elements removed to avoid precipitation (on-line processing)
- Plutonium maintained below solubility limit → can adjust Th/U ratio to control $[Pu]_{max}$
- Blanket gain of 6-10× possible:
  - Fuel-to-moderator control
  - U/Th replacement
  - Tritium sharing between LIFE engines



# Improved performance is realized by segmenting the blanket and extending the lifetime

- Different blanket regions (e.g., front, middle, back) experience different neutron fluxes
- When the front region is fully burned, successive layers are promoted, and new fuel is added to the back

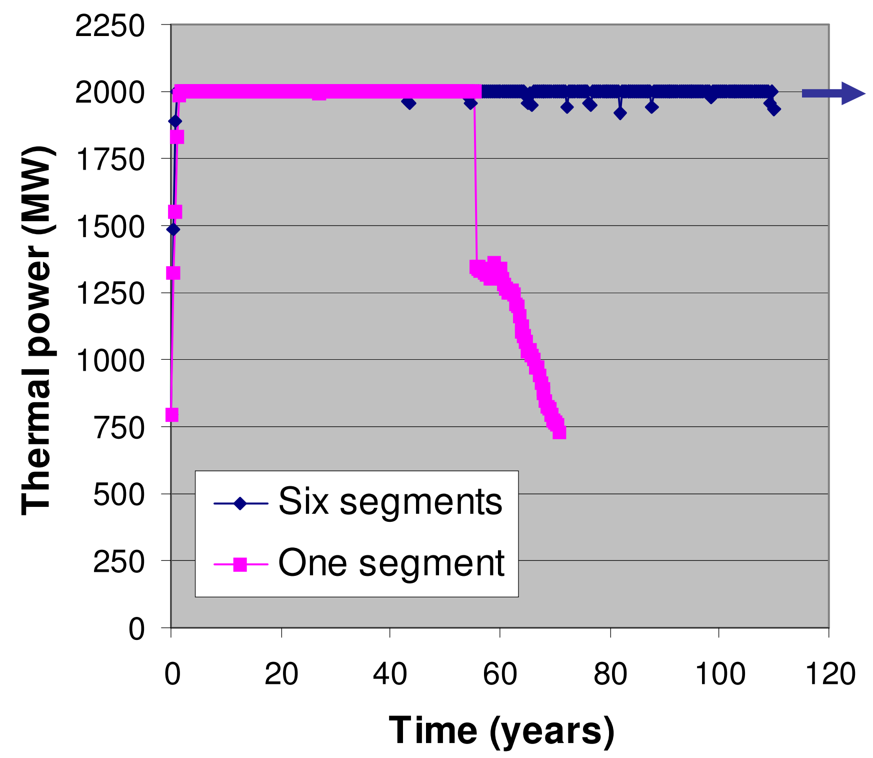
**Segmented blankets would enable fuel burn-up to be tuned as desired**



# Improved performance is realized by segmenting the blanket and extending the lifetime

- **Different blanket regions (e.g., front, middle, back) experience different neutron fluxes**
- **When the front region is fully burned, successive layers are promoted, and new fuel is added to the back**
- **Full power mode can be extended indefinitely**

**Segmented blankets can be operated as long as desired**

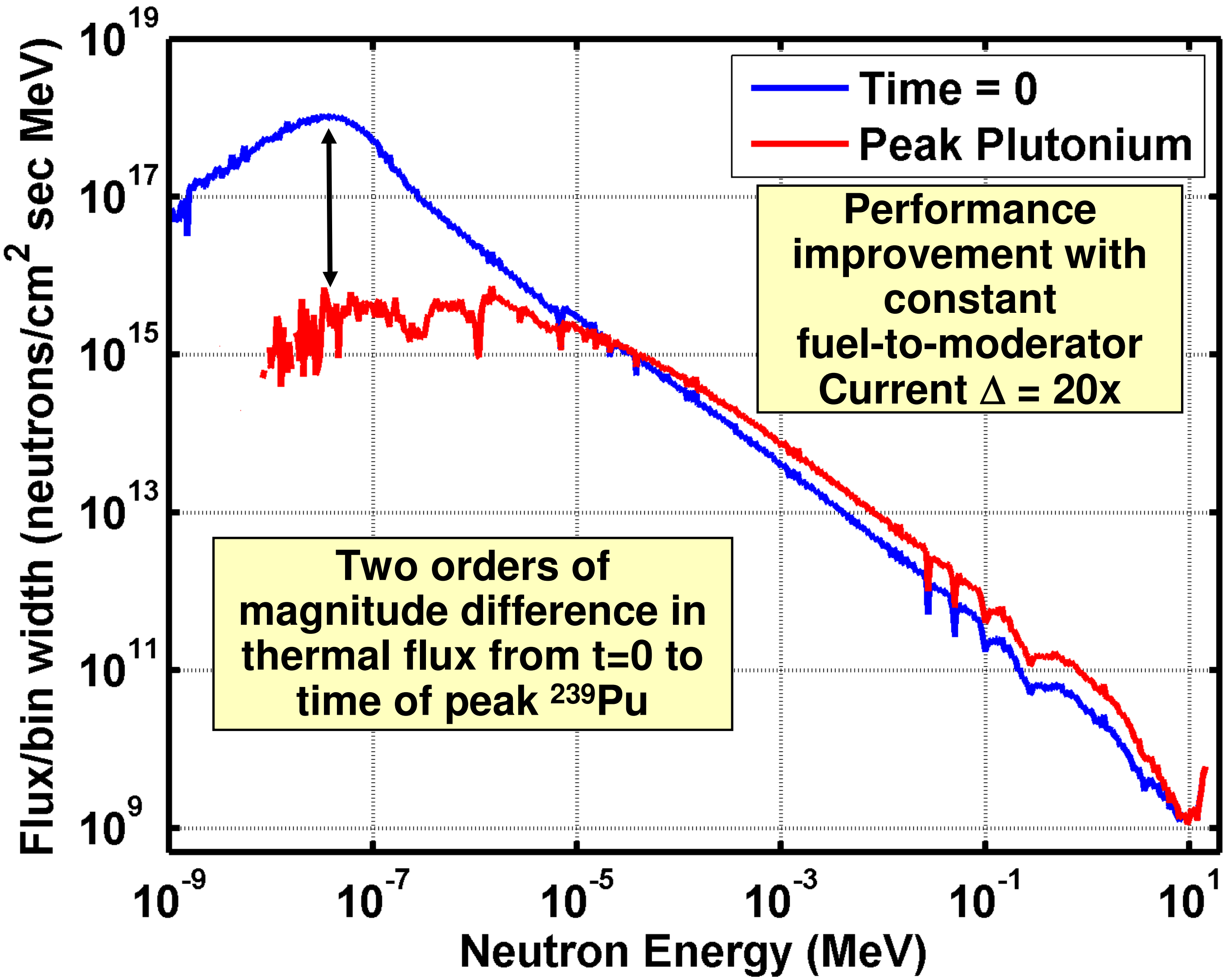


# Improved performance is realized by segmenting the blanket and extending the lifetime

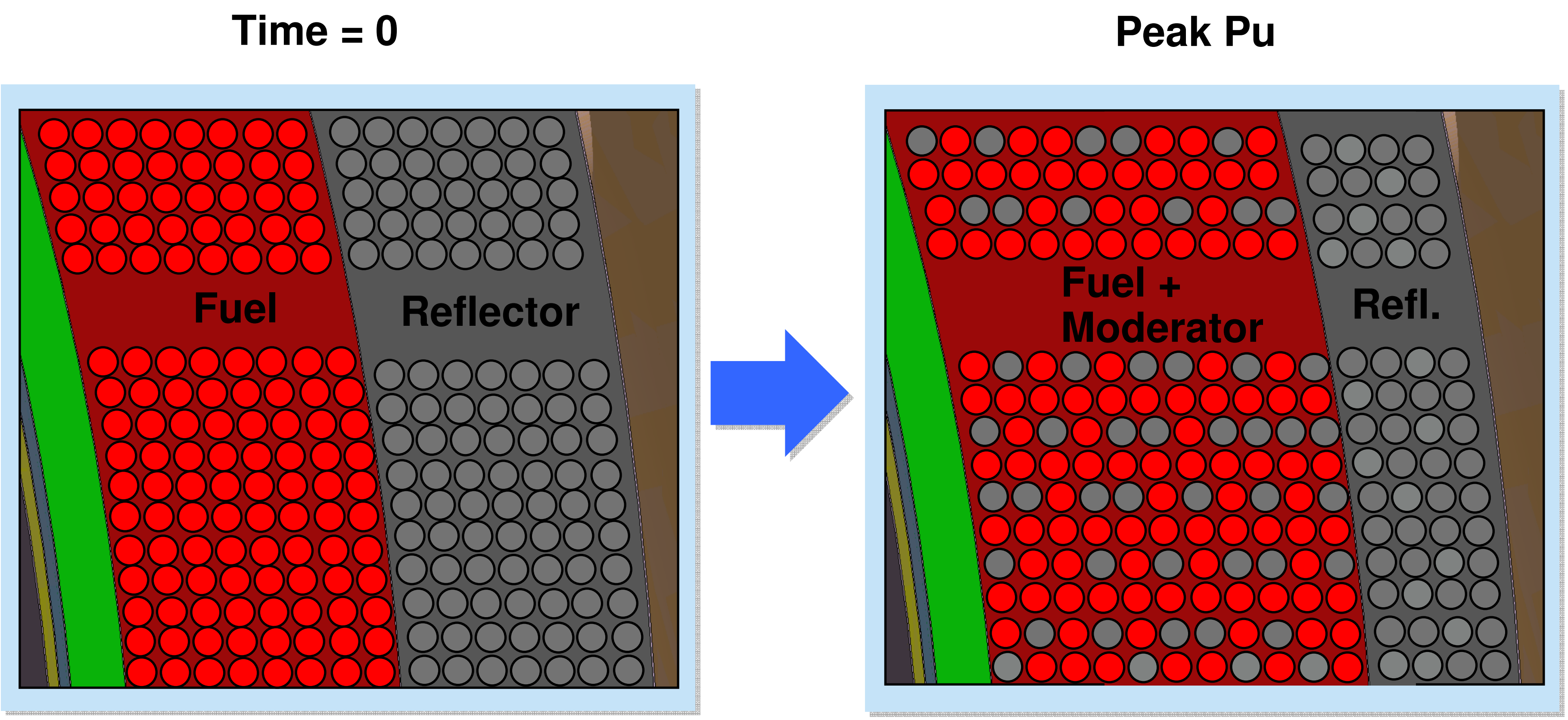
- Different blanket regions (e.g., front, middle, back) experience different neutron fluxes
- When the front region is fully burned, successive layers are promoted, and new fuel is added to the back
- Full power mode can be extended indefinitely
- UC-Berkeley PREX experiment shows that flow stays stratified in cylindrical geometry
- Needs to be tested for spherical chamber

PREX experiment at UC-Berkeley

# Neutron spectrum in fission blanket shows a significant change due to varying fuel-to-moderator ratio

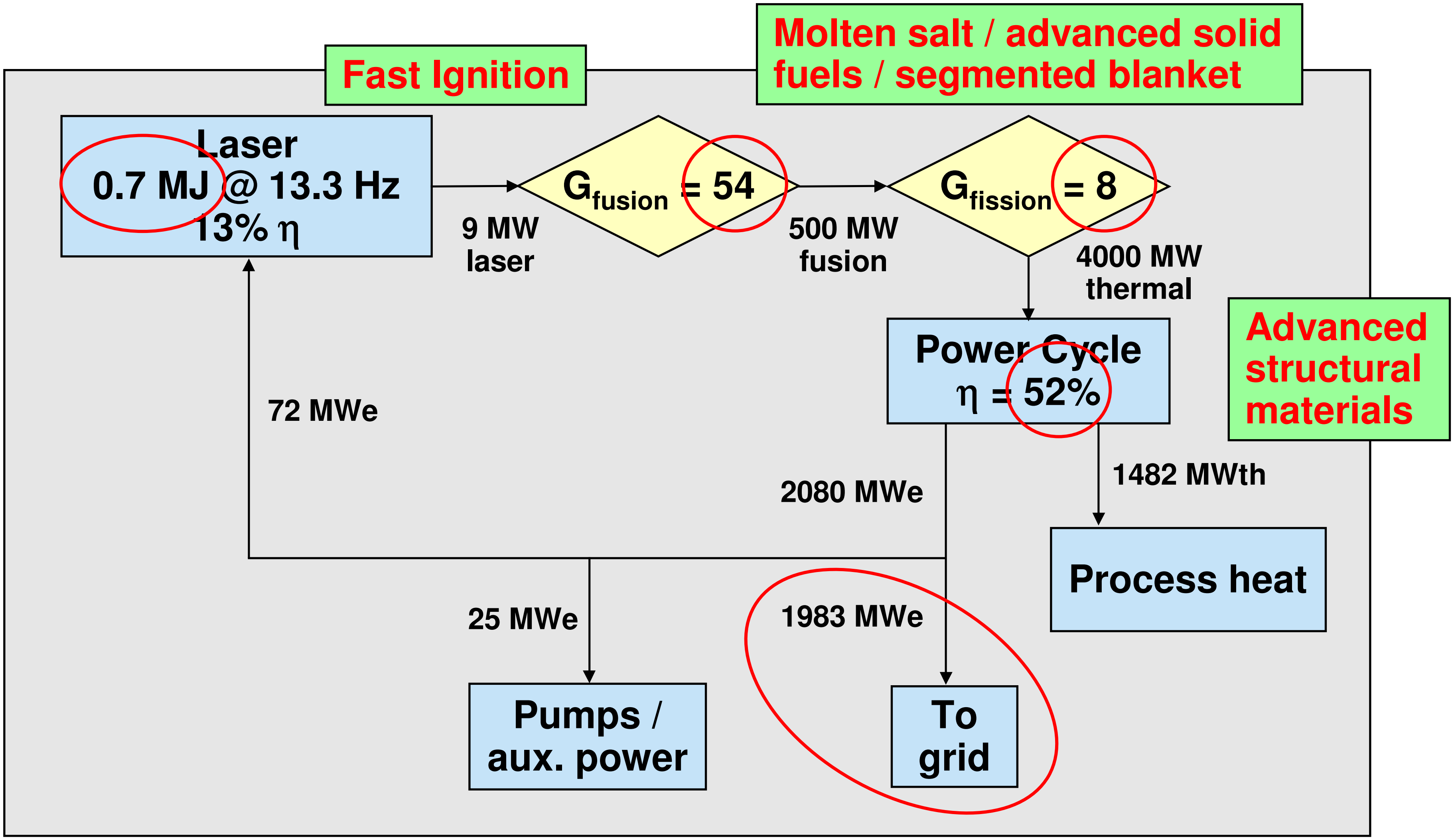


# Pebble based fuel and reflector design allows for continual adjustment of fuel-to-moderator ratio




**Optimizing fuel-to-moderator ratio throughout burnup could significantly improve performance**

# LIFE power flow for an advanced DU system



# We are working with a number of outside teams

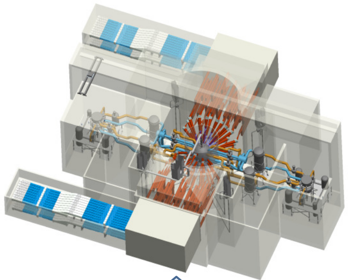
- University of California-Berkeley: neutronics, pebble management, structural materials, safety
- General Atomics: target fabrication
- BWXT: fuel materials
- University of Wisconsin-Madison: first wall response, chamber clearing
- California Institute of Technology: structural materials
- Los Alamos Nat'l Lab: neutronics, fuel materials
- University of Nevada-Las Vegas: neutronics, fuel materials
- University of California-San Diego: target injection, chamber dynamics, final optics
- Idaho Nat'l Lab: aerosol formation, molten salts, fuel materials, cross section measurements, safety
- Oak Ridge Nat'l Lab: structural and fuel materials
- Savannah River Nat'l Lab: tritium handling and storage

# LIFE is a flexible system that can support a variety of missions

- A variety of fusion targets and illumination geometries can be used
- LIFE fuels do not require enrichment – DU/NatU/SNF/Th can be used
- Solid and liquid fuels are under consideration
- Low fusion yields & thermally robust targets result in compact target chambers
- LIFE development path mapped to likely missions: destruction of excess weapons materials, burning of SNF, and the ultimate energy solution

**The LIFE team has been assembled – a collection of point designs will be delivered during FY2009**

# There are three phases that lead to commercial power in the NIF-based LIFE



2030 Commercial power on the grid

**The separability of ICF and LIFE makes such a rapid demonstration path possible**

**2022**

**LIFE Prototype Power Plant**

Full scale 500 MW fusion facility with partial fission blanket operating at plant performance specifications for a total of 350 MW of electric power
Full life test of structural and fuel materials for licensing of commercial plant

**2018**

**LIFE Integrated Technology Demonstration Facility (ITDF)**

Full Scale Laser Plant, with subscale, Integrated Technology Demonstration of LIFE's fusion facilities operated in burst mode (15 Hz for minutes)
Demonstrate molten salt system and tritium recovery
Fuel blanket pebble injection (without fissile fuel), flow and extraction
Materials test facility at full neutron, ion and x-ray fluences

**2014**

**LIFE Technology Development Program (TDP)**

Demonstrate LIFE fusion performance on the National Ignition Facility (NIF)
Establish and validate LIFE-ITDF technologies
(Ignition will be demonstrated by the separately NNSA funded National Ignition Campaign)

**2010**

# There is significant overlap in the technologies required for LIFE, traditional IFE, and MFE

- Design – radiation transport and activation codes and data libraries; thermal and stress modeling codes
- First wall / plasma facing components – high heat flux materials, high radiation damage rates, tungsten, ODS ferritic steel
- Neutron multipliers – beryllium
- Tritium breeding, separation/handling and storage
- Molten salt behavior – corrosion, erosion, etc.
- Power conversion systems – heat exchangers, secondary coolants, Brayton cycles

**We are interested in figuring out where it is appropriate to collaborate and partner in these common efforts**