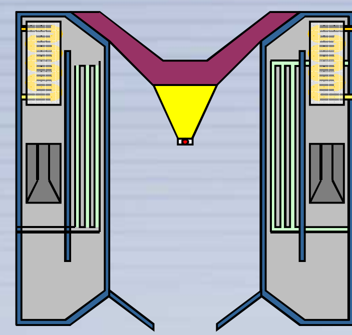
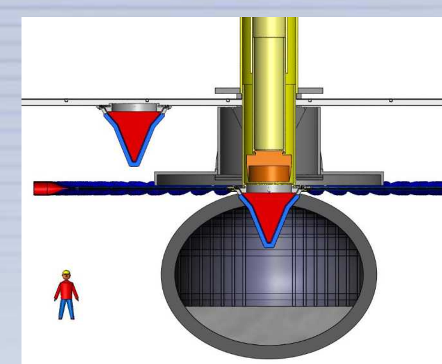
SAND2008-0449C

Fusion-Fission Hybrids for Nuclear Waste Transmutation: A Synergistic Step Between Gen-IV and Fusion Reactors





ISFNT-8 2007

Heidelberg, Germany - October 3, 2007

Tom Mehlhorn, Ben Cipiti, Craig Olson, Gary Rochau

Sandia National Laboratories, Albuquerque, NM

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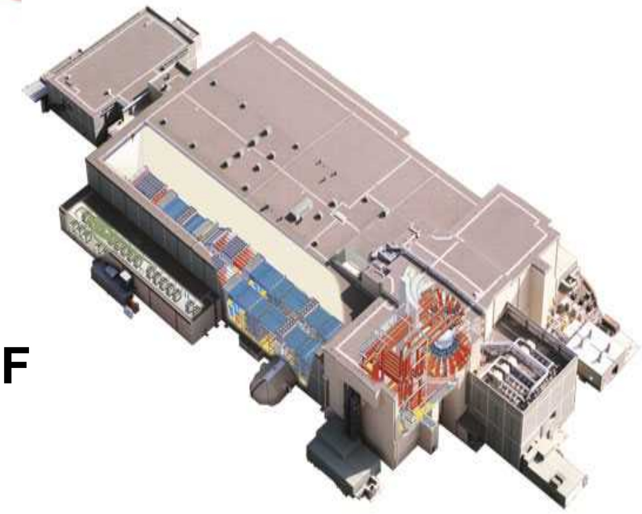
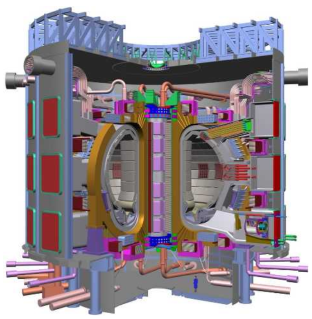
Z is focused on single-shot ICF & stewardship research – but fusion energy is the "dream"

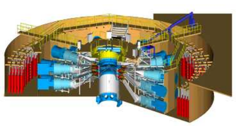
NIF



ITER



Z



Driver technology

Containment

Tritium

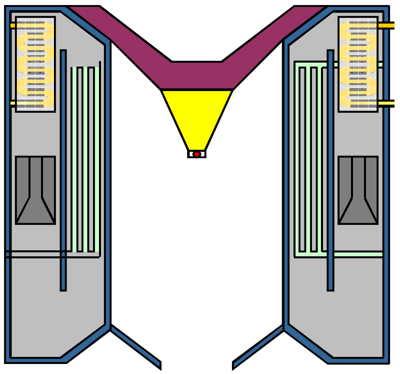
High temperature materials

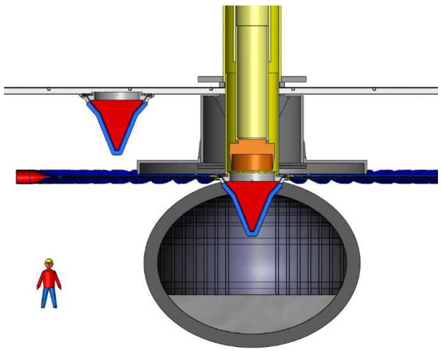
Conversion technology

Surety

System integration

…





"Burning plasmas" ⟶ Fusion energy

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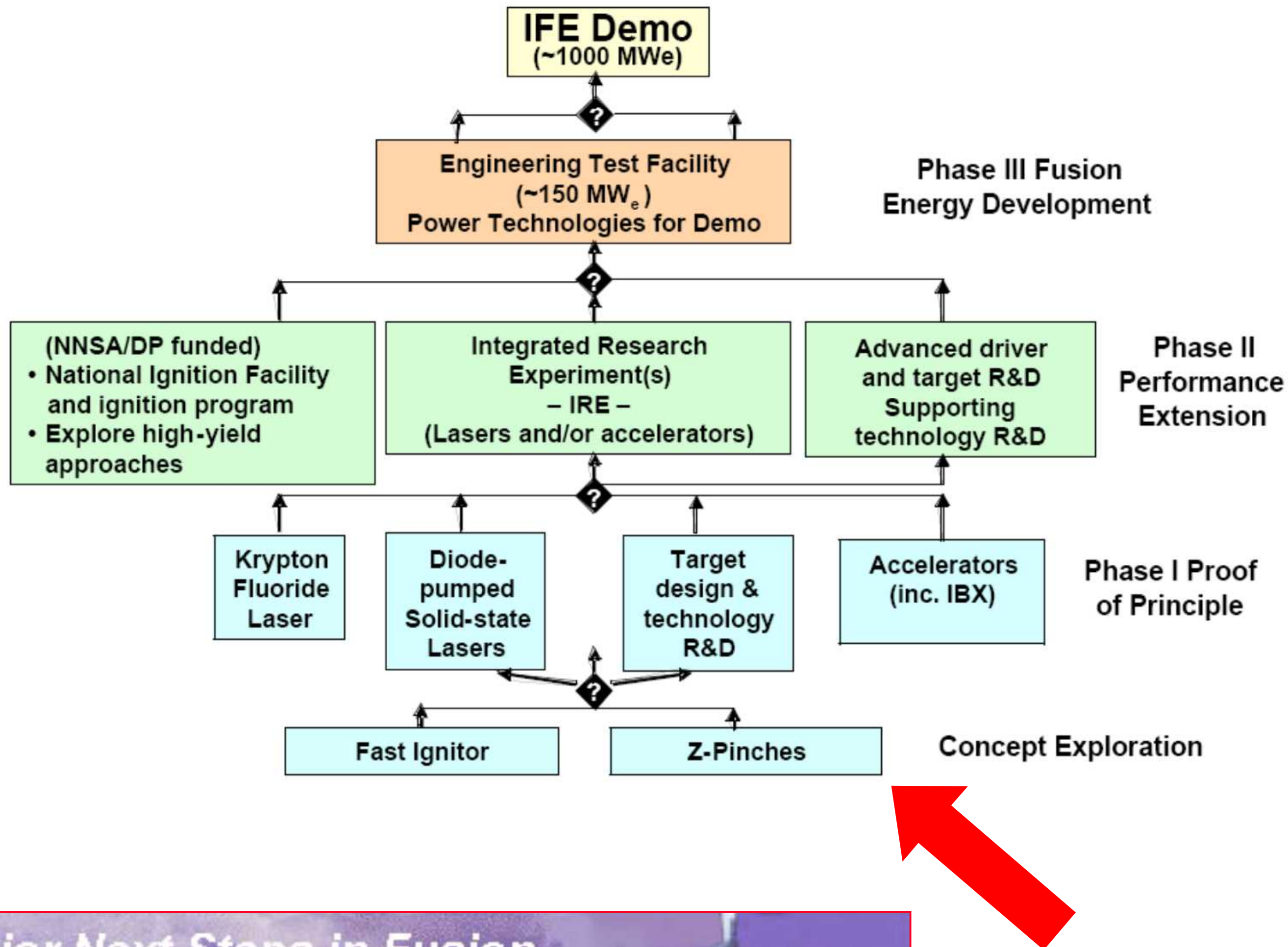
Z-pinches for Inertial Fusion Energy (IFE) were favorably received at Snowmass 2002

"There has been impressive progress in z-pinch targets and good progress in conceptual power plant designs. Producing economical recyclable transmission lines at low cost remains the most important issue."

- Press Release – 2002 Fusion Summer Study Group, Snowmass



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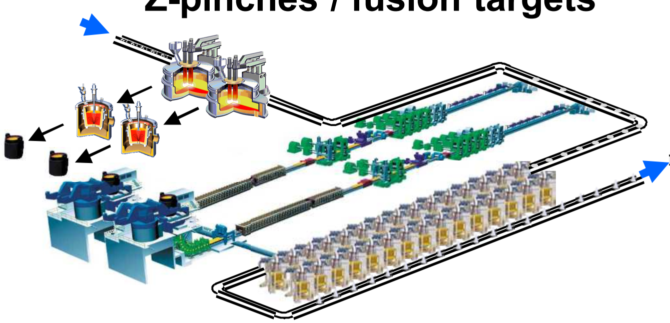
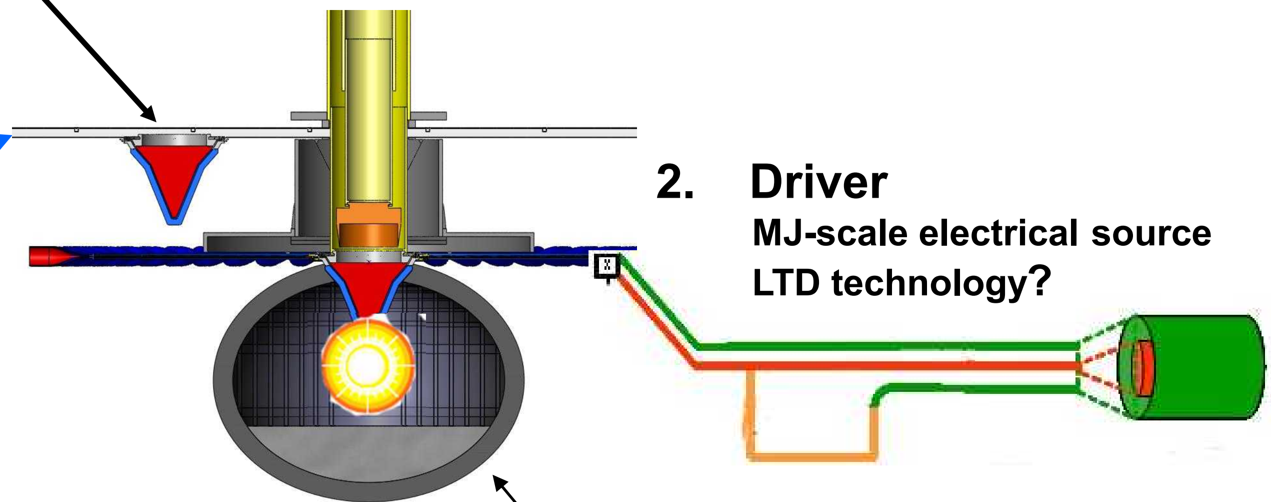
The conceptual Z-pinch IFE powerplant design has four major systems

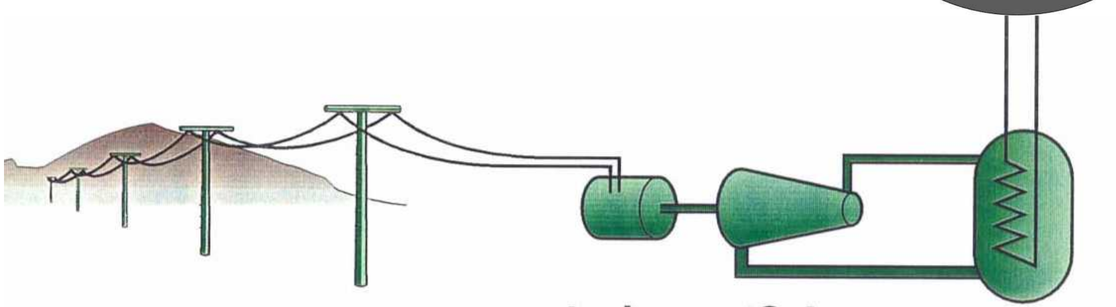
1. **Factory**
   Recyclable Transmission Lines (RTLs)
   Z-pinches / fusion targets





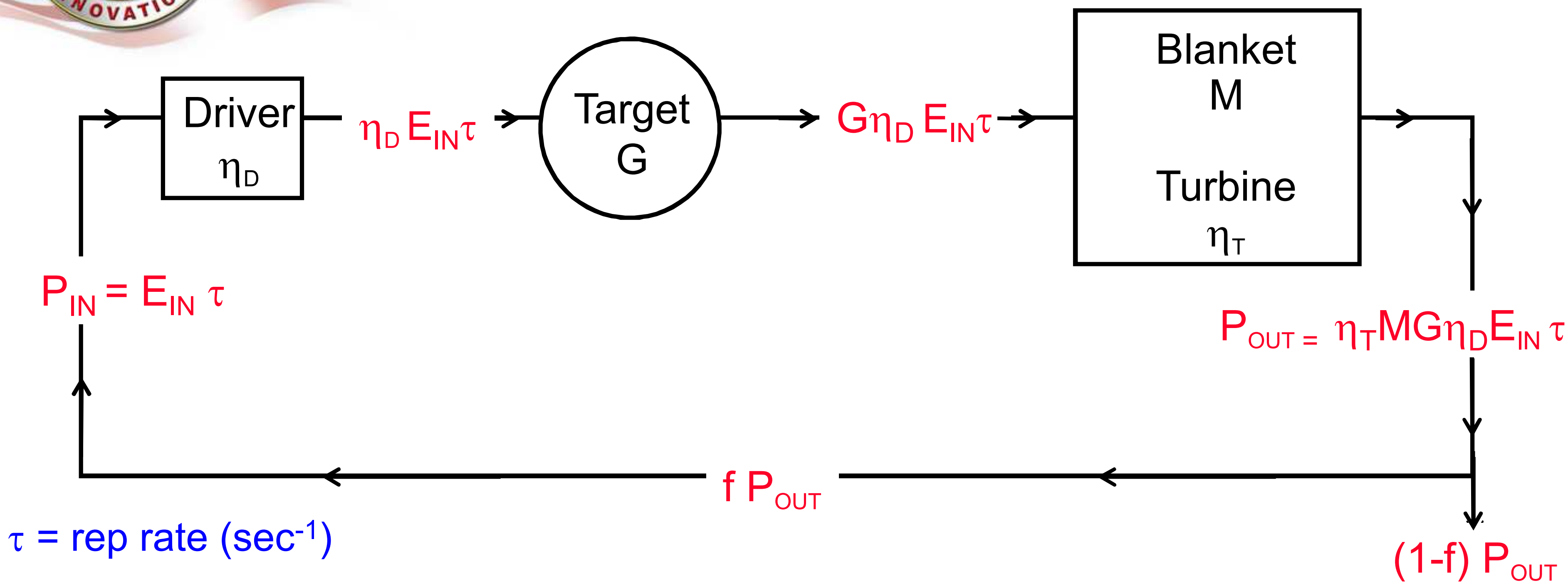
2. **Driver**
   MJ-scale electrical source
   LTD technology?

3. **Fusion Chamber/Blanket**
   Contain blast
   Recover fusion energy from targets
   Multiply energy in blanket



4. **Power conversion system**
   Convert thermal power to electricity

The power cycle of an IFE reactor is described by six parameters: E_{IN}, η_D, τ, G, M, η_T



$$P_{IN} = f\,P_{out} = f\,\eta_T M G \eta_D P_{IN}$$

$$\Rightarrow f\,\eta_T M G \eta_D = 1$$

We want $f << \frac{1}{4}$. With $\eta_T \approx 0.4 \Rightarrow$ $\eta_D MG >> 10$

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A pre-conceptual Z-pinch power plant design has established baseline parameters

Target Yield	3 GJ
Rep. Rate (per chamber)	0.1 Hz
Fusion Power per chamber	300 MWth
Number of Chambers	10

Chamber

Shape	Spherical or Ellipsoidal
Dimension	4 m internal radius
Material	F82H Steel
Wall Thickness	15-30 cm

Coolant

Coolant Choice	Flibe
Jet Design	Circular Array
Standoff (Target to First Jet)	0-2 m
Void Fraction	0.05 – 0.67
Curtain Operating Temperature	950 K
Average Curtain Coolant Flow	12 m^3/s
Heat Exchanger Coolant Flow	0.47 m^3/s
Heat Exchanger Temp. Drop	133 K
Pumping Power	1.3 MW/chamber
Heat Cycle	Rankine
Heat Exchanger Type	Shell and Tube

Tritium Recovery

Breeding Ratio	1.1
Tritium Recovered per Shot	0.017 g
Extraction Type	Countercurrent

RTL

RTL Material	1004 Carbon Steel
Cone Dimensions	1 m Ø x 0.1 m Ø x 2 m h
Outer Cone Thickness	0.9 mm → 0.52 mm
Inner Cone Thickness	0.52 mm
Mass per RTL (2 cones)	50 kg → 34 kg

RTL Manufacturing

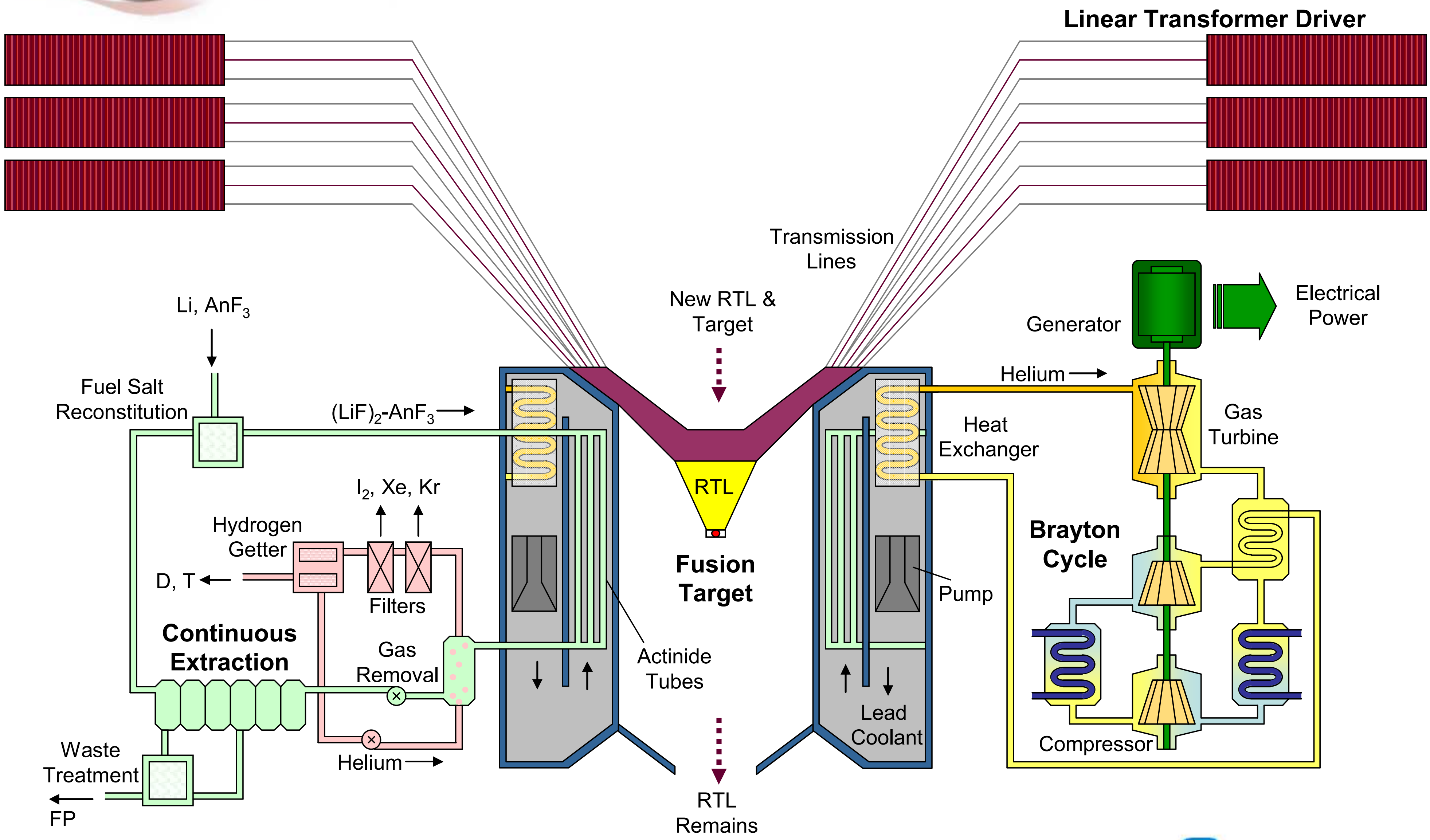
Furnace	Electric Arc
Production	Sheet Metal to Deep Draw
Energy Demand	184 MW for ten chambers

G. Rochau, J. Cook, B. Cipiti, et al. (SNL)

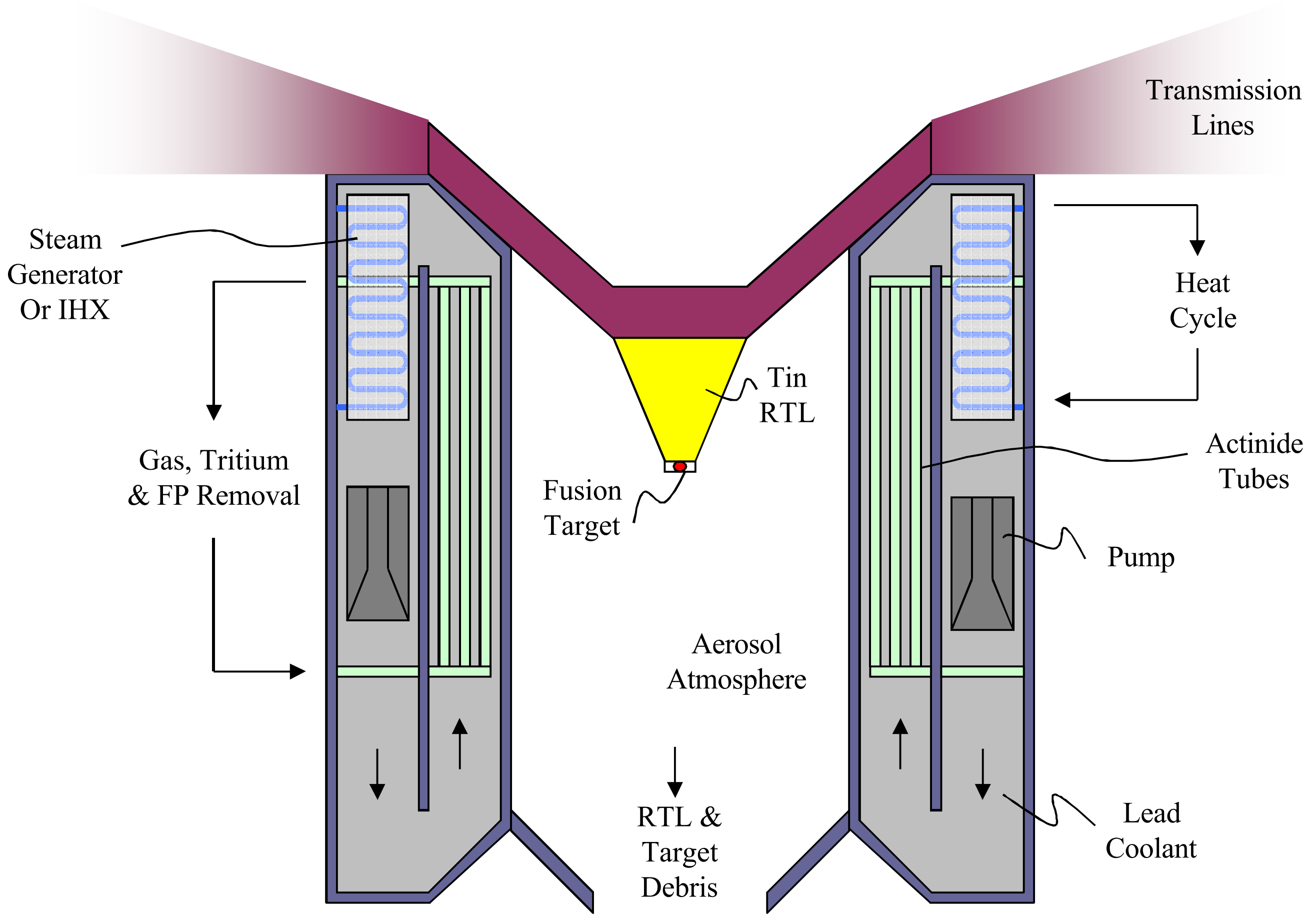
A fission-fusion hybrid increases the blanket multiplication (M) and can transmute nuclear waste

- **Fusion neutrons can be used for burning actinides in a sub-critical blanket**
  - This configuration minimizes the risk of a criticality excursion, and lessens the control requirements
  - No fertile material (like ^{238}U) is required that would otherwise breed additional actinides, so it can be designed with maximum burn efficiency
  - There is a great deal of flexibility in the fueling, which allows for the design of any type of actinide burner. As an example an Am/Cm fast reactor cannot be safely controlled, but an Am/Cm sub-critical fusion burner can be safely operated.
- **The fusion yield requirements are much lower than those required for fusion energy (<30 MW as opposed to 3000 MW)**
  - This helps to ease the engineering problems of fusion
  - For Z-Pinches: target yield is smaller, shock mitigation is easier, rep rate is lower, achieving Q>>1 is not as important
  - It provides a useful application on the path towards pure fusion power plants

Conceptual InZinerator Power Plant burns nuclear waste and has an energy multiplication (M) of 150



The Sub-Critical Transmutation Blanket is based on nuclear reactor technologies



- Actinide blanket captures fusion neutrons
- Actinides are dissolved into molten salt (proliferation resistant)
- Fusion neutrons initiate actinide fission – spent fuel is burned and power is produced:
  - 20 MW fusion required
  - Actinide blanket produces 3000 MWth
- Molten lead coolant removes heat and drives power plant

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The In-Zinerator requires a modest fusion power (20 MW) & extracts energy from LWR spent fuel

Overall Parameters	
Fusion Target Yield	200 MJ
Repetition Rate	0.1 Hz
K_{eff}	0.97
Power per Chamber	3,000 MWth
Transmutation Rate	1,280 kg/yr
Number of Chambers	1

RTL & Target	
RTL Material	Tin (or Steel)
RTL Cone Dimensions	1m Ø x 0.1m Ø x 1m H
Mass per RTL	93 kg (Tin)
Tritium per Target	1.35 mg

Chamber Design	
Shape	Cylindrical
Dimension	3.2 m outer radius
Chamber Material	Hastelloy-N
Wall Thickness	5 cm

Blanket	
Actinide Mixture	$(LiF)_2$-AnF_3
Coolant	Lead
Coolant Configuration	Shell & Tube
First Wall Configuration	Structural Wall
Shock Mitigation	Argon gas & aerosol
Coolant Temperature	950 K
Heat Cycle	Rankine or Brayton

Extraction Systems	
Tritium Breeding Ratio	1.1
Tritium production	3.8 g/day
Fission Product Removal	On-Line Removal

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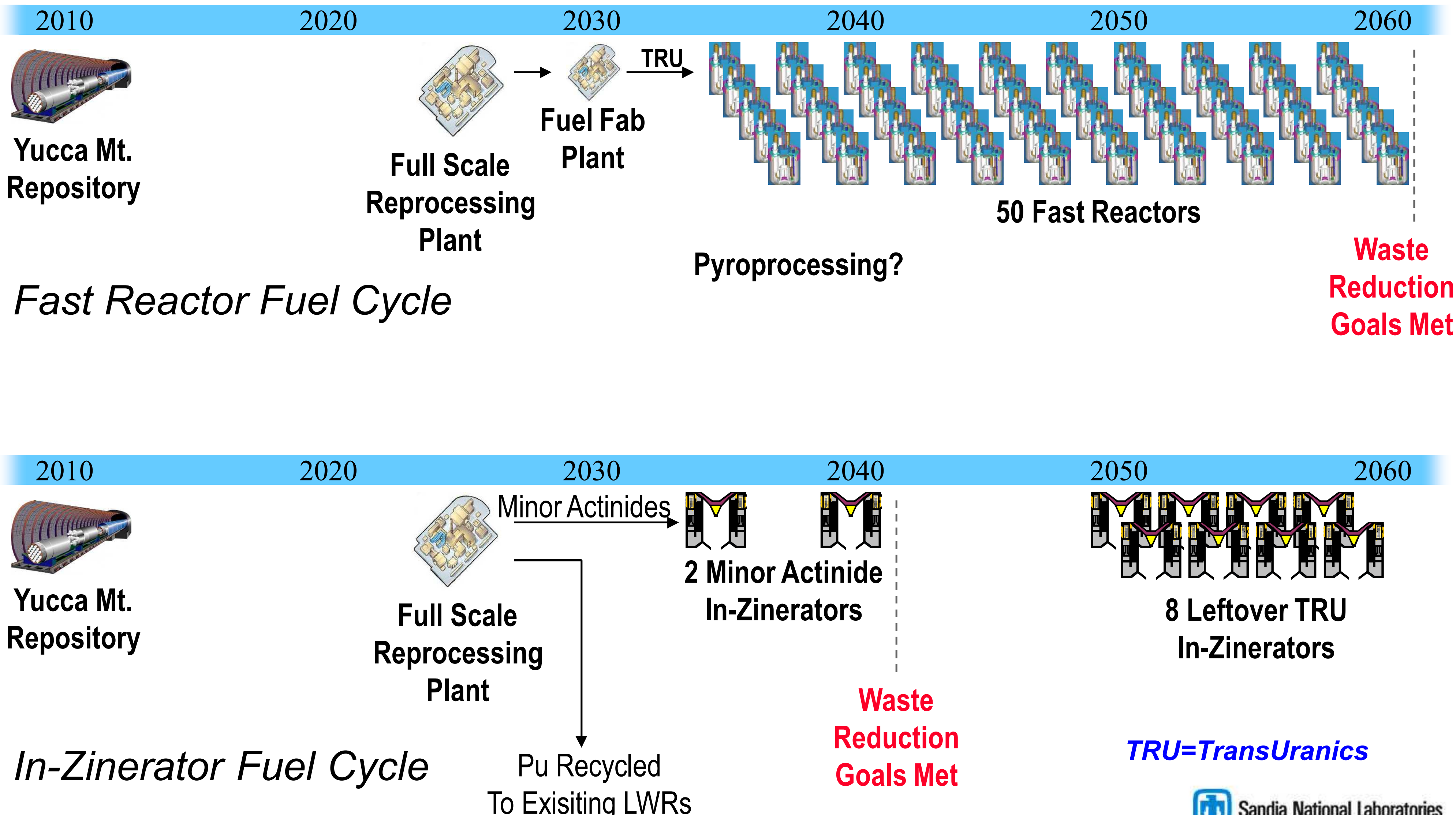
Transmutation by 14 MeV fusion neutrons meets waste reduction goals faster than fast reactors



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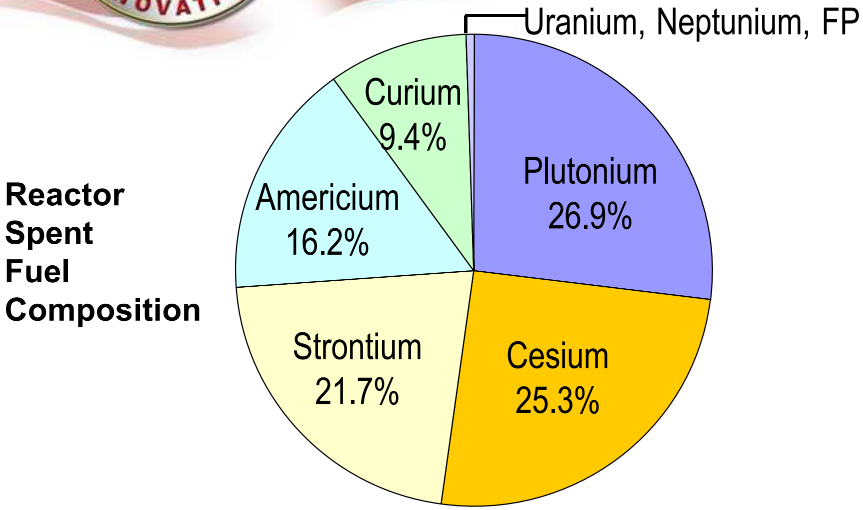
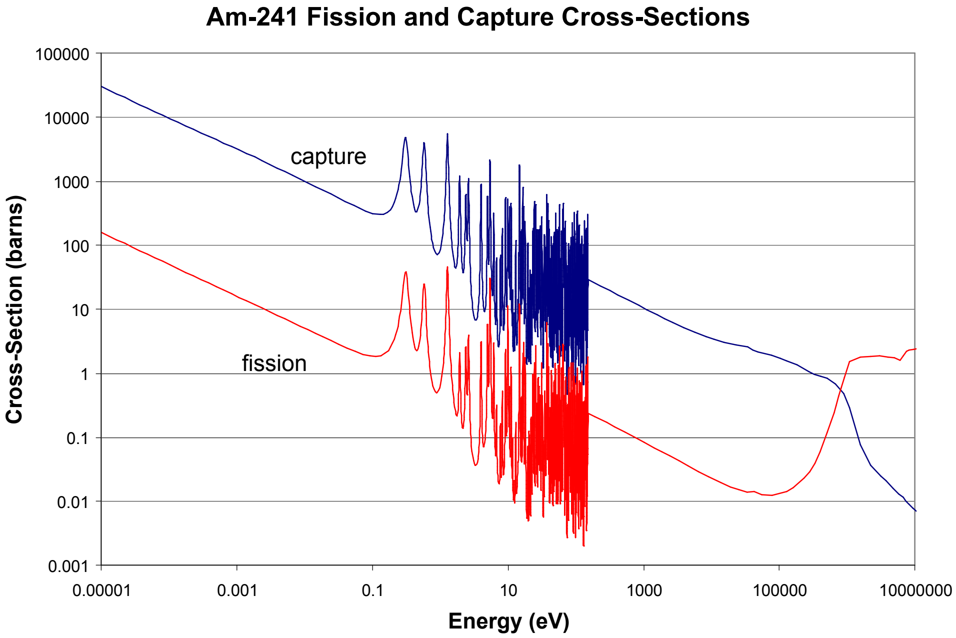
14 MeV neutrons from fusion are valuable for transmutation (both burning & breeding)





- Yucca Mountain repository has heat load limit
- Am, Cm, Pu, Cs & Sr dominate the heat production of spent fuel
- Fissioning actinides produces fission products with much shorter half-lives
- Transmutation can reduce heat load and radiotoxicity by factor of 50-100
- Fission cross section greater than capture cross section only above 1 MeV, so 14 MeV neutrons are valuable
- Subcritical blanket is safe and doesn't require fertile materials (e.g. U^{238})

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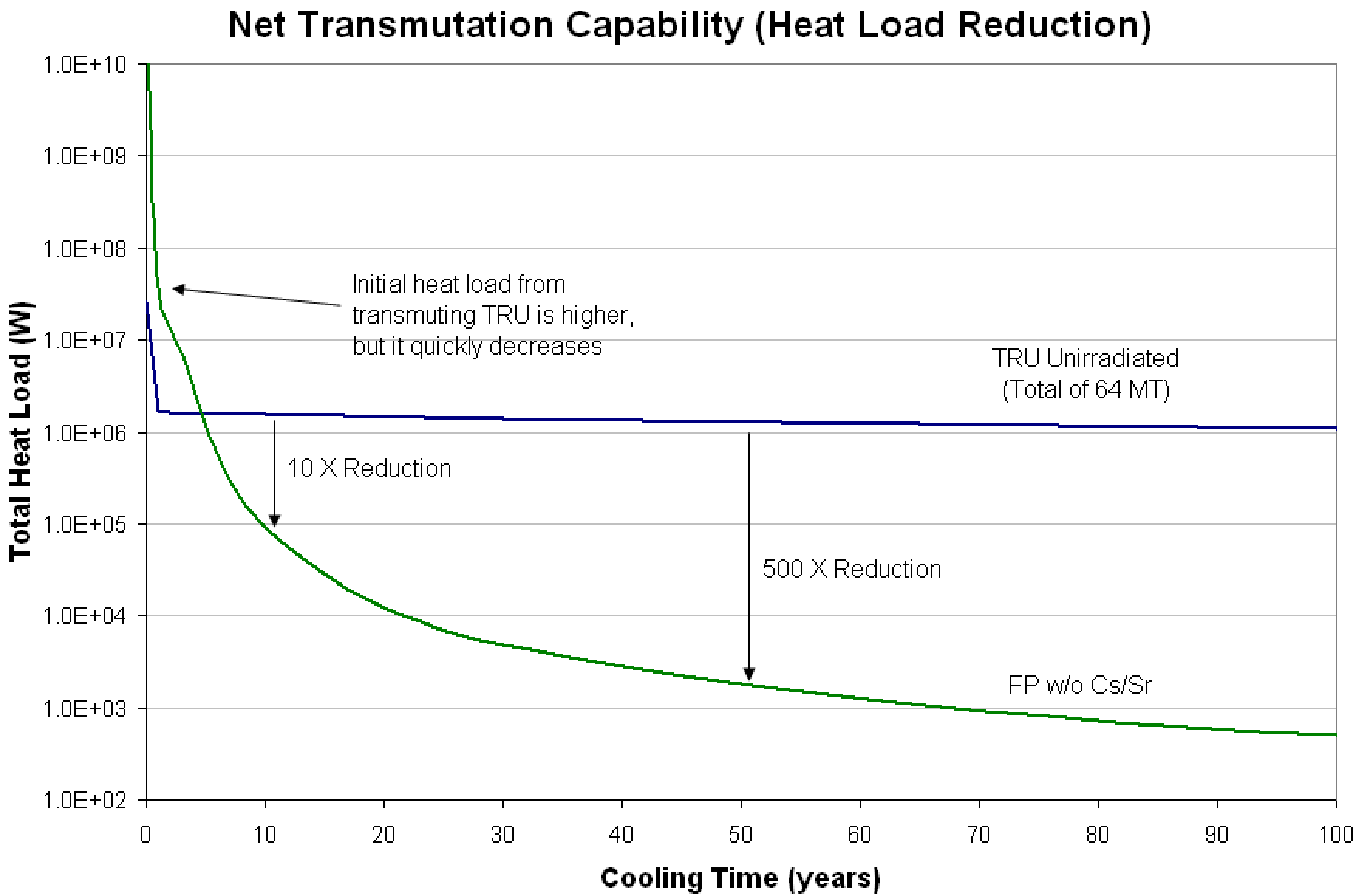
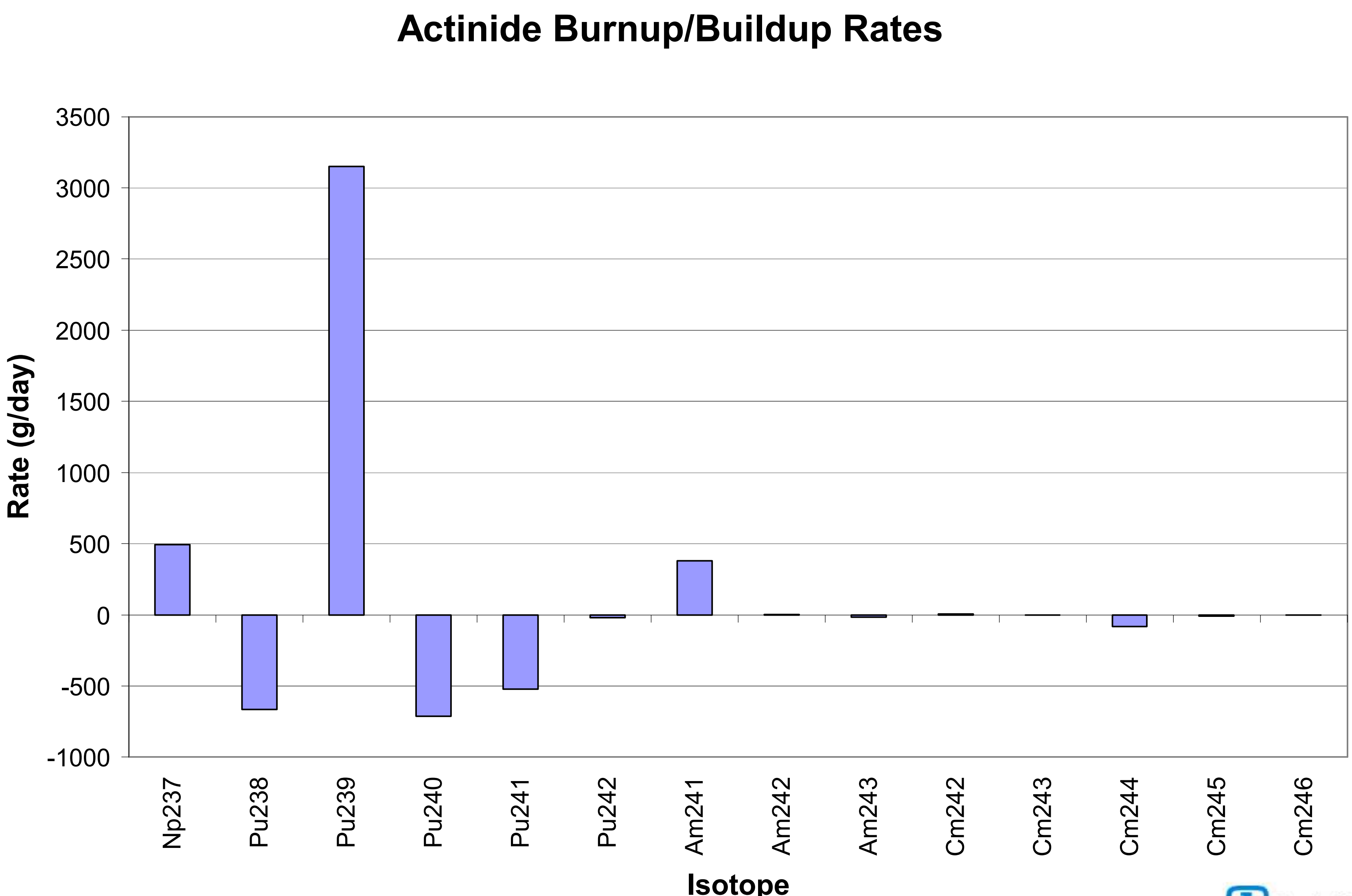
A Heat Load Reduction by a Factor of 500 is Seen after 50 Years



730 kg/yr TRU Burned with 20 MW Fusion Driver and 3000 MW Total Power



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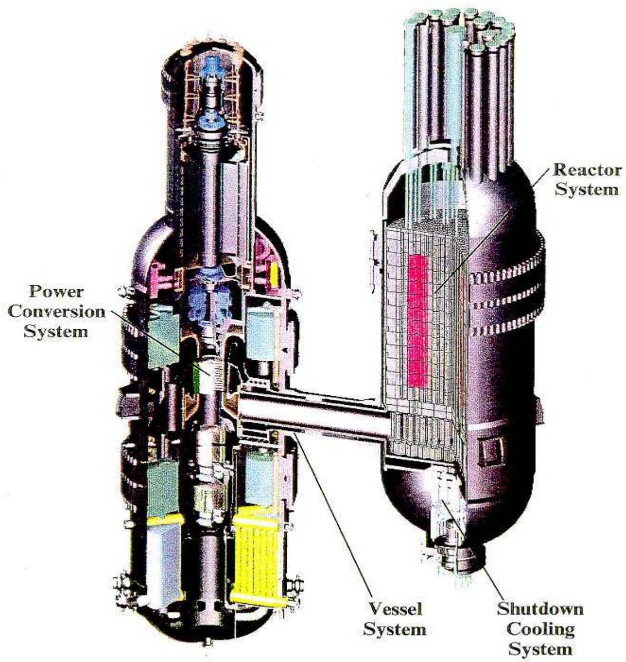
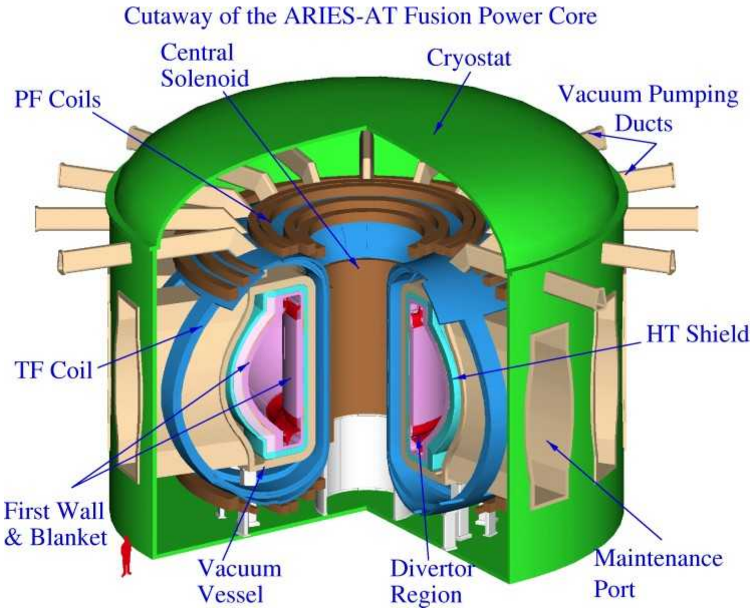
Fusion will share many advanced technologies that are used in fission powerplants

Gen-IV



Prismatic Very High Temperature Reactor: Brayton Cycle for Power Conversion

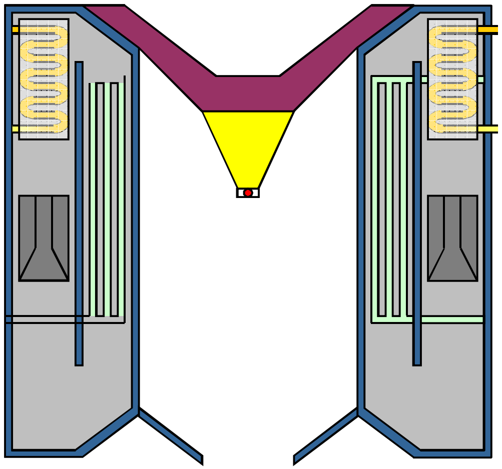
MFE



ARIES-AT: Brayton Cycle for Power Conversion

Power Conversion Technology

IFE



InZinerator: Z-pinch nuclear waste transmuter using Brayton Cycle for Power Conversion

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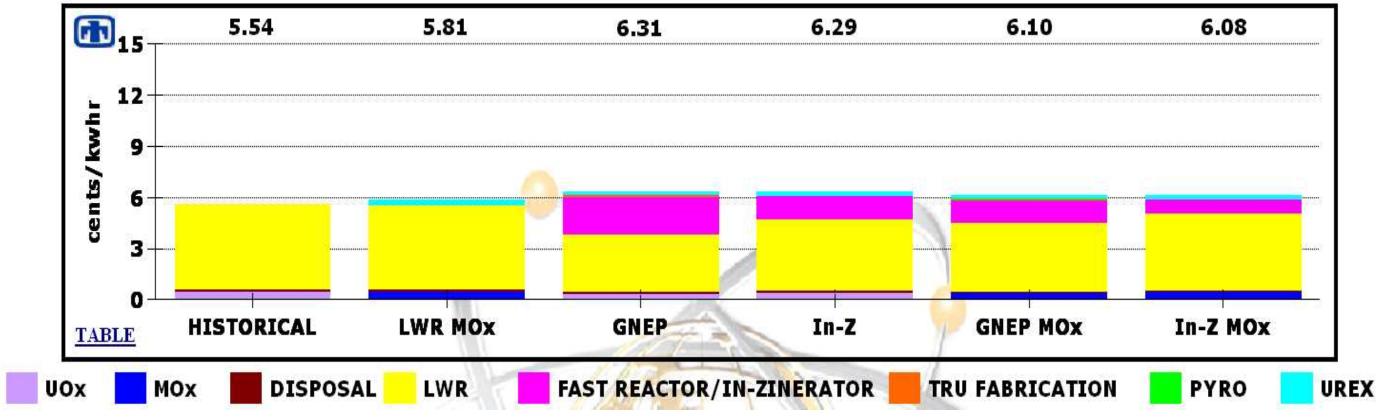
Even Assuming a Higher Capital Cost, a Fusion Transmuter Competes with Fast Reactors

FLEET AVERAGE LCOE



REACTOR COST ASSUMPTIONS

URANIUM COST ($/kg U)	100.00
LWR CAPITAL COST ($/kW)	1,800.00
FAST REACTOR CAPITAL COST ($/kW)	2,500.00
In-Zinerator CAPITAL COST ($/kW)	3,000.00

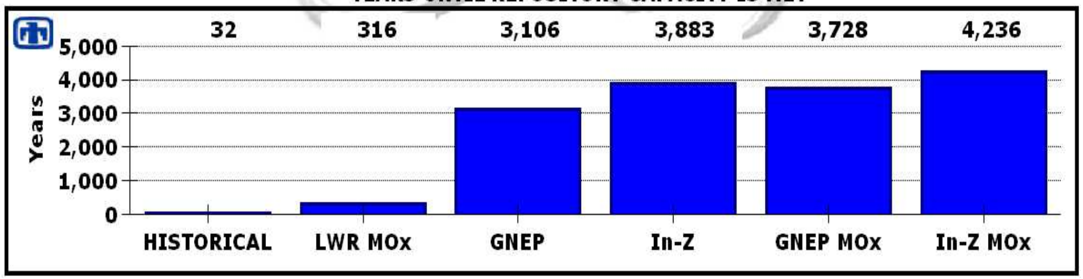
LWR TO FR/IN-Z SUPPORT RATIO

GNEP	2
IN-Z	5
GNEP - MOx	4
IN-Z - MOx	10

FUEL CYCLE COST ASSUMPTIONS ($/kgHM)

DISPOSAL COST (mill/kWh	1.00	
MOx FUEL FAB COST	1,500.00	
UREX REPROCESSING COST	1,000.00	
	FR	IN-Z
TRU FUEL FAB COST	2,600.00	0.00
PYRO REPROCESSING COST	2,000.00	2,000.00

YEARS UNTIL REPOSITORY CAPACITY IS MET



- Reprocessing and transmutation will cost more than the once-through fuel cycle, but the repository capacity is extended greatly
- Due to the higher costs of fast reactors and fusion transmuters, it makes more sense to use thermal recycle as long as possible followed by fast recycle to take care of the left over actinides.

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There are many technology issues that are common to advanced fission and fusion

- Power conversion technology
  - Brayton cycle for power conversion
- Coolant/structure material corrosion
  - He impurities effects on high temperature structural materials (Superalloy systems)
- Welding/joining technology
  - For both ferritic steels and high temperature Ni superalloys
- Material response under irradiation
  - Advanced ferritic steels (improved creep resistance)
  - SiC composites
  - Resistance to neutron damage
- High temperature materials design rules
  - Materials that can accommodate high temperature operation (700-1000°C) – need ASME design rules for nuclear environments

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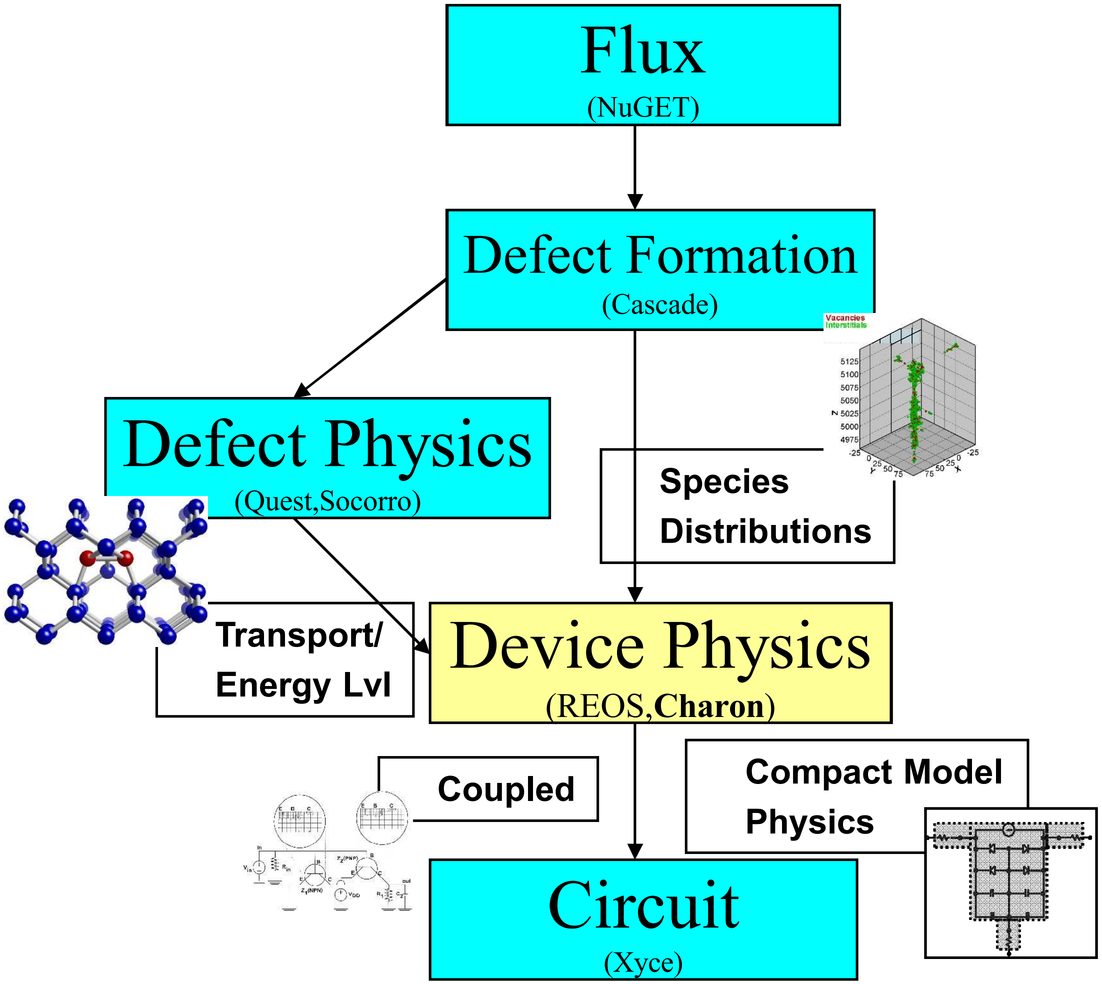
QASPR: Modeling Radiation Effects on Micro-Electronics Devices

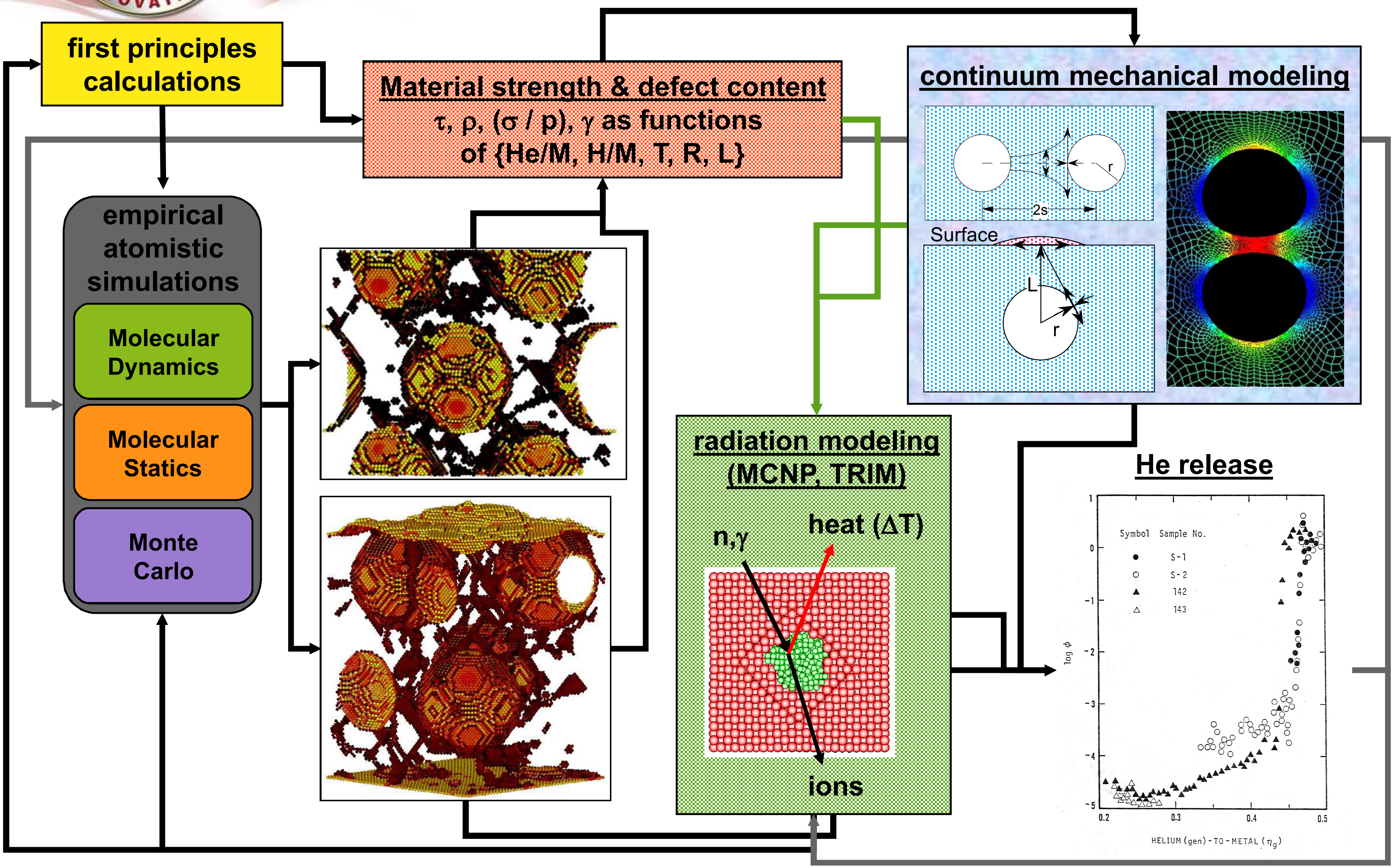
- **High Fidelity Modeling of Semiconductor Devices under Irradiation.**
  - **Bulk Defect Physics (REOS)**
  - **Oxide Defect Physics (REOS)**

- **Large Scale, HPC Simulations - Charon**
- Input
  - **Density Functional Theory (DFT)**
    - » **Transport Coefficients**
    - » **Energy Levels**
  - **Cascade**
    - » **Defect Species Distributions**

- Output → **XYCE**
  - **Direct Circuit/Device Coupling**
  - **Compact Model**
    - » **Physics**
    - » **Parameters**



Aging Effects Roadmap: Fission Product Gas Bubbles in Metal



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IFE strategy: ICF for targets; Pulsed Power for drivers, and LDRD for reactor technology issues

Pulsed power technology

Increase pulsed power efficiency (presently 10-15% on Z) e.g. LTD technology

Fusion technology

Increase blanket multiplication (baseline value = 1) e.g. fission/fusion hybrids

$$f_d = \frac{1}{\eta_d G M \eta_T}$$

ICF target physics

Increase target gain (baseline value ~500) e.g. direct implosions

Power plant technology

Increase conversion efficiency (baseline value = 0.35) e.g. Brayton vs Carnot cycle

Slide 20

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t1 tamehlh, 9/4/2007