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Green Energy-Multiplier

Sub-critical,
Thermal-spectrum,
Accelerator-driven,
Recycling-reactor

for Utilization and Disposition of Weapons Grade Plutonium

Muons Inc
ADNA Corp.
Virginia Tech
The FGA Group

Nov 25, 2013 Moscow, Russia

U.S. President's Vision

"We must harness the power of nuclear energy on behalf of our efforts to combat climate change, and to advance peace opportunity for all people." President Obama

Challenges

- Safety
- Spent Fuel
- Weapons Proliferation
- Cost (compared to coal/gas)

DOE & Corporate U.S. Strategy

- LWR: sustain (and augment) current fleet
- Small Modular Reactors (addresses Safety, Up-Front cost)
- Gen IV Reactors
- Interim SNF storage until ultimate geologic storage (in 2048)

Accelerators were "Explored" and Deferred Indefinitely

"Nuclear Energy Research and Development Roadmap" (DOE-NE Apr 2010) – *"accelerator" never mentioned*

"Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste" (DOE Jan 2013) – *"accelerator" never mentioned*

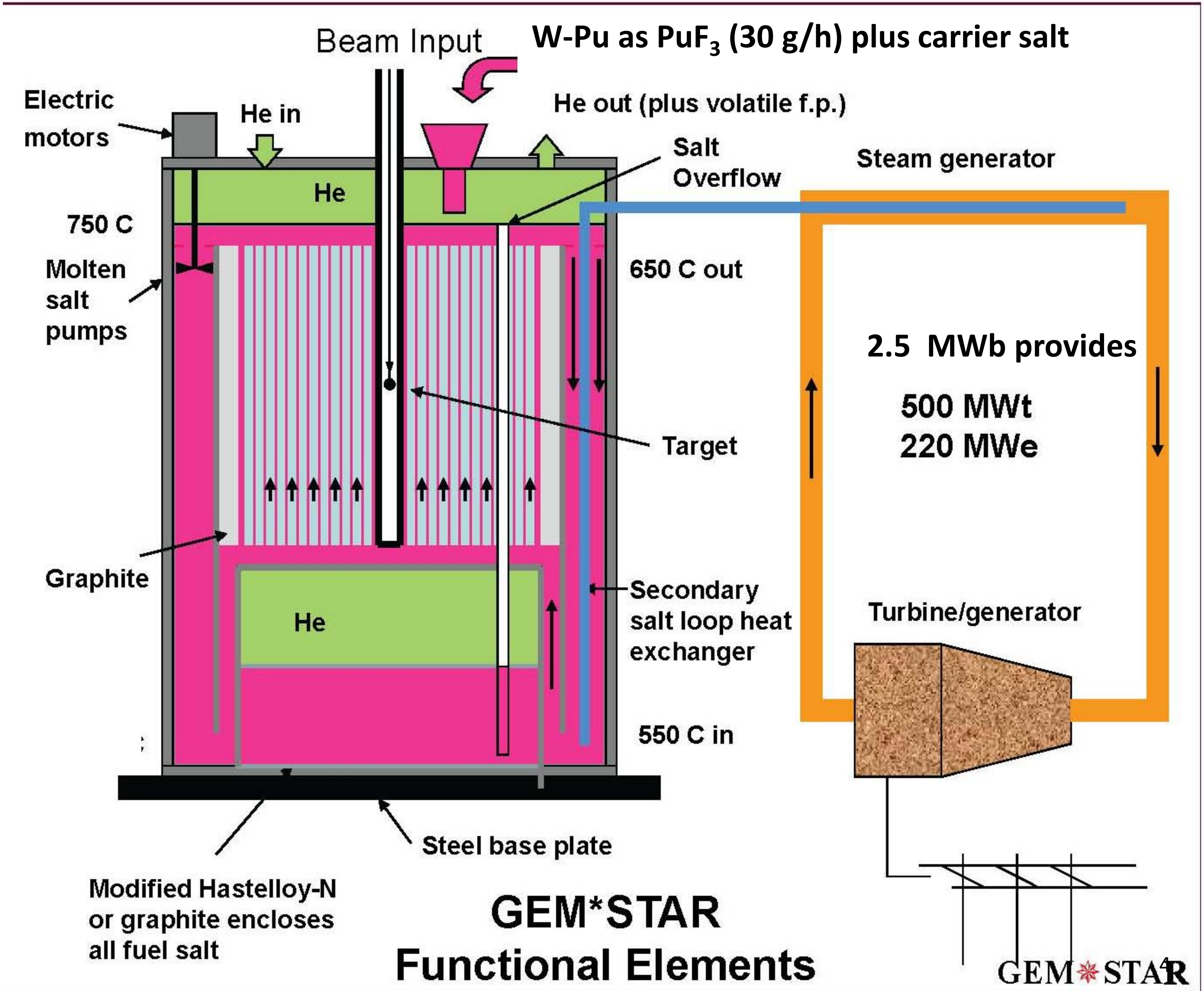
frequently cited concerns

- additional cost and complexity
- only for transmutation of waste (non U/Pu actinides)
- beam power requirements not met yet
- beam 'trip-rate' not satisfactory yet
- no commercial or governmental operational experience
- unpredictable licensing path and/or delay

Accelerators: discovery and creation of the missed solution

Critical insight was optimizing an ADS approach from first principles, not as an add-on.

- ***minimizes primary safety concerns***
- ***minimizes primary nuclear waste concerns***
- ***minimizes primary weapons proliferation concerns***
- ***expect lower cost electricity and/or synthetic transport fuel than currently available***
- ***makes nuclear energy technology exportable to all countries***
- ***can constructively utilize and destroy HEU and W-Pu stocks***


Beam Input
W-Pu as PuF_3 (30 g/h) plus carrier salt
Electric motors
He in
He out (plus volatile f.p.)
Salt Overflow
Steam generator
He
750 C
Molten salt pumps
650 C out
2.5 MWb provides
500 MWt
220 MWe
Target
Graphite
He
Secondary salt loop heat exchanger
Turbine/generator
550 C in
Steel base plate
Modified Hastelloy-N or graphite encloses all fuel salt
GEM*STAR Functional Elements
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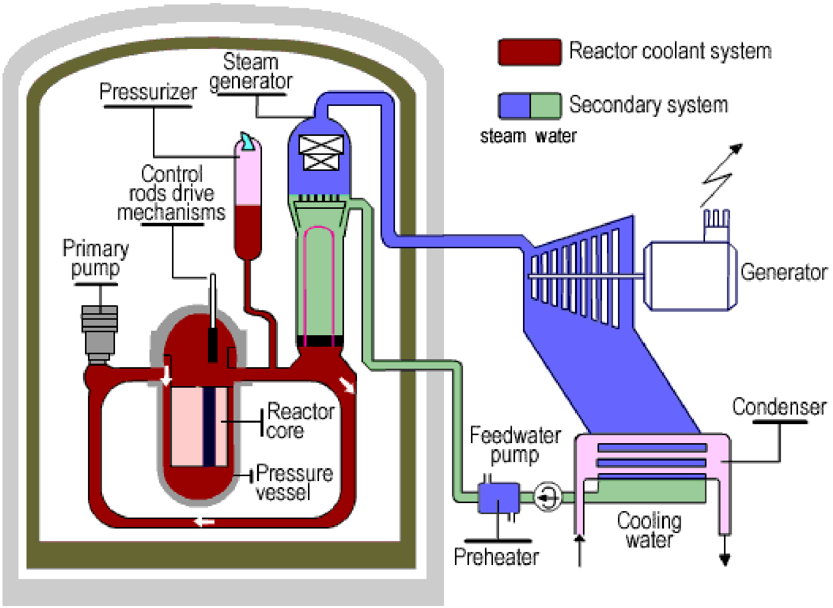
Classic (LWR) Operation

- Water Moderation: enriched ^{235}U fuel
- Solid fuel in cladding
- Uses negative feedback
  - Prompt –vs– delayed critical
  - Doppler broadening
  - Thermal expansion



Pressurized Water Reactor (AREVA)

- Build up of Fission Products poisons chain reaction, so use:
  - Several critical mass initial loading
  - add ‘burnable/removable’ neutron poisons to reduce reactivity back to $k_{eff}=1$
- **only 0.5% of energy in mined uranium gets used**

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What are the obstacles to broader adoption?

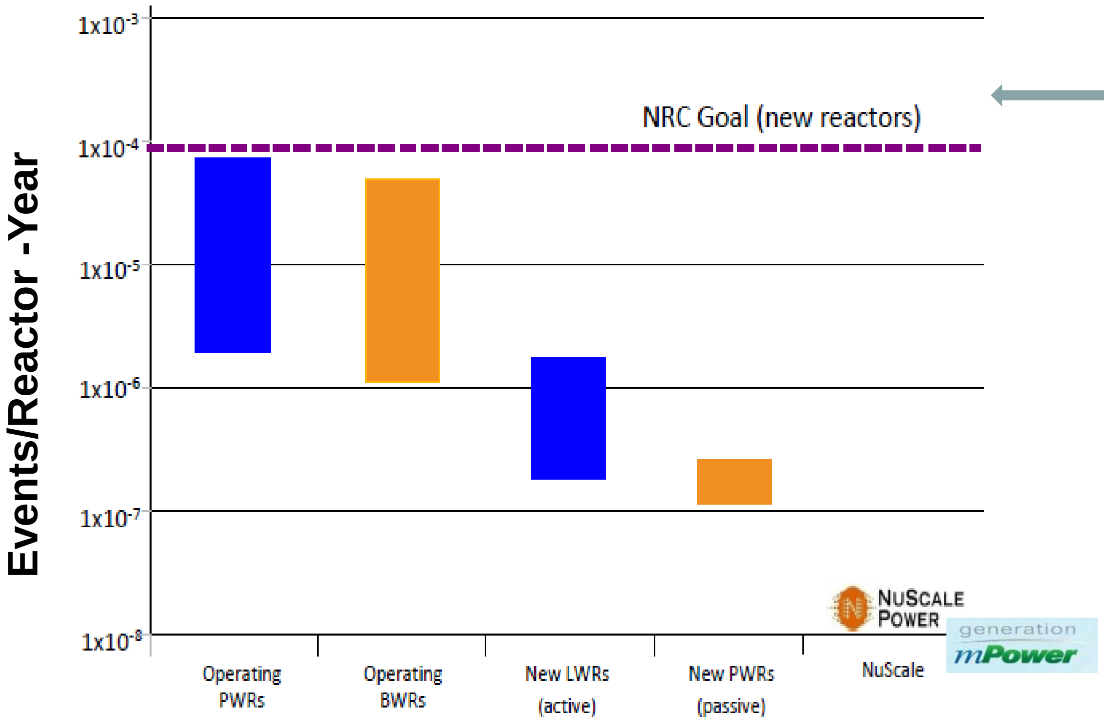
in the US:

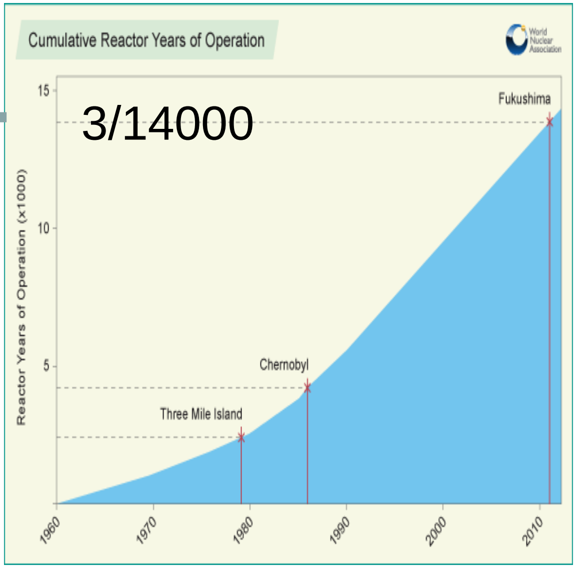
- safety
- waste
- weapons proliferation
- cost

in Russia?

➤Safety

Probabilistic Risk Assessment (PRA)
of Core Damage Frequency (CDF)





SMR claim 10^{-8} events per reactor-year
…that's 1 event in 1,000,000 reactors over 100 years
…is there a credibility issue?…

*(versus G*S: INHERENTLY safe sub-critical operation)*

- **Waste**
  - long-lived fission products and actinides
    - bury in Yucca Mountain? (now cancelled!)
    - burn with accelerators?
    - burn in next generation reactors?
    - **store on site…current practice**

- **Weapons Proliferation**
  - **enrichment**
  - **reprocessing**

*(versus G*S: waste becomes fuel; no enrichment and no reprocessing)*

➢Cost

current prices for electricity

(estimated by Black and Veatch, Overland Park, Kansas)

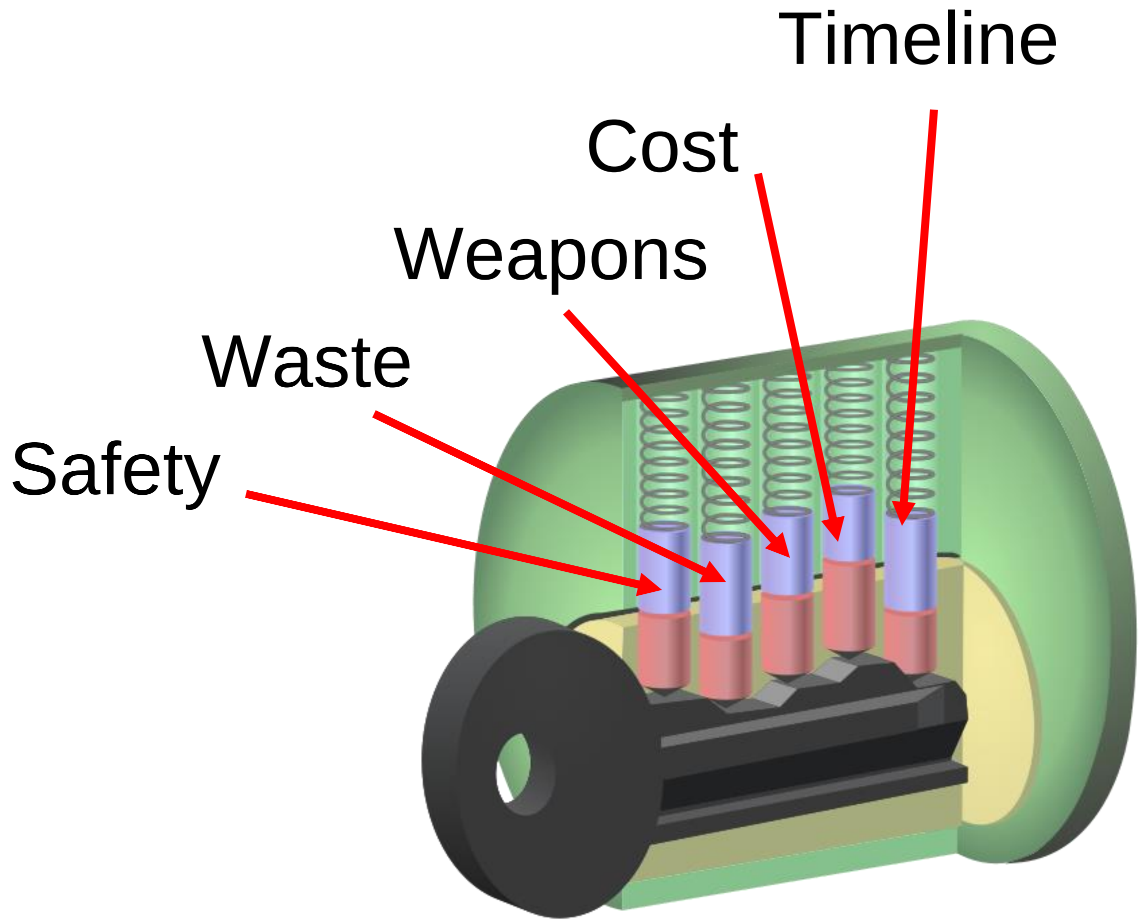
	cents/kwh
Coal without CO_2 capture	7.8
Natural gas at high efficiency	10.6 (4.5!)
Old nuclear	"3.5"
New nuclear	10.8
Wind in stand alone	9.9
Wind with the necessary base line back-up	12.1
Solar source for steam-driven electricity	21.0

Solar voltaic cells; higher than solar steam electricity

*NYT, Sunday (3/29/09) by Matthew Wald

versus G*S: 4.5 ¢ per kWh with natural uranium fuel

Any 'tumbler' out of alignment is problematic.



Don't let solutions in one area preclude solutions in others.

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What is being done…

DOE-NE

'small modular reactors'

- safety ←
- waste
- weapons proliferation
- cost ←

DOE-Science

'high intensity frontier'

- safety
- waste ←
- weapons proliferation
- cost

India

- PHWR (nat U) →
- FBR (^{239}Pu & Th) →
- AHWR (^{233}U & Th)

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Are there other avenues to explore?

- to address ‘clean energy’ ‘now’
- that would compete today with coal costs
- not being ‘captured’ by the previous slide
- low enough cost to try without requiring broad ‘consensus’ first
- a Russian proverb heard recently:
  Going **AROUND** the pillar, rather than **OVER** it.

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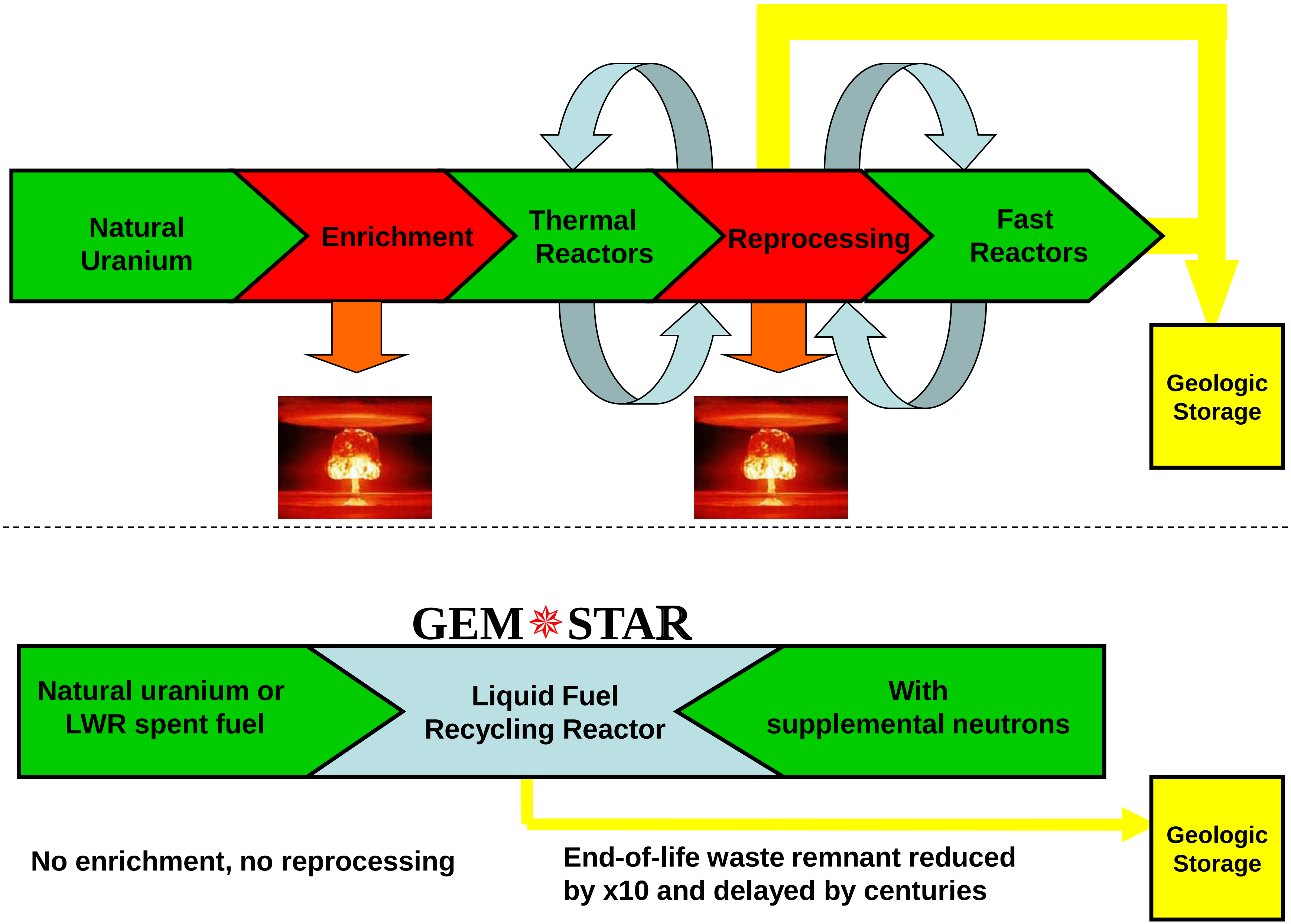
Different Paradigm



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Existing Enabling Technologies

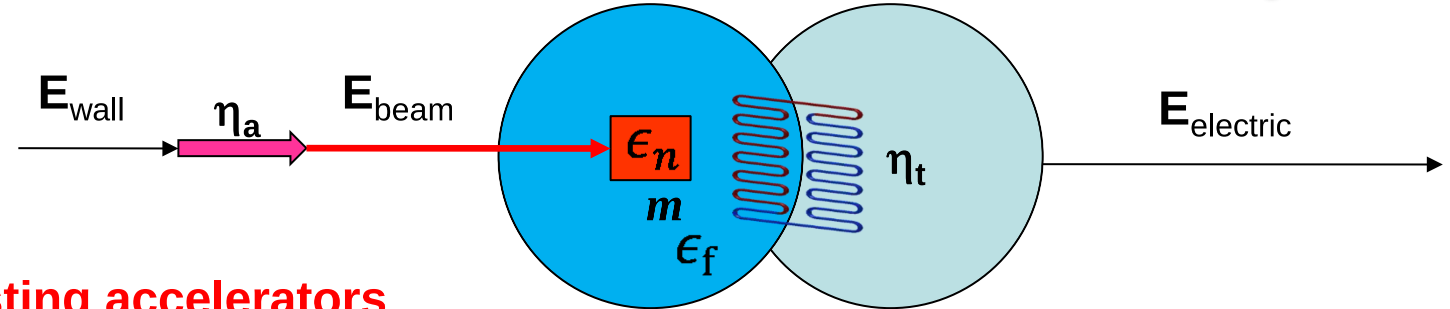
- efficient & proven LINAC accelerators
- proven molten salt eutectic fuels
- running MW class beam targets
- measured modern graphite purity & properties

the key:

proper integration

- from the beginning

Proton Driven Sub-Critical System



Existing accelerators

- **are efficient enough to not require more power**
- **are low-enough in cost**

(DOES NOT require 10's of MW to get started)

$$
\begin{aligned}
E_{\text{electric}} &= E_{\text{thermal}}\eta_{\text{t}} \\
&= (E_{\text{beam}} + E_{\text{fission}})\eta_{\text{t}} \\
&= \left(E_{\text{beam}} + \frac{E_{\text{beam}}}{\epsilon_{\text{n}}} m\epsilon_{\text{f}}\right)\eta_{\text{t}} \\
&= E_{\text{beam}}\left(1 + \frac{\epsilon_{\text{f}}}{\epsilon_{\text{n}}} m\right)\eta_{\text{t}} \\
&= E_{\text{wall}}\eta_{\text{a}}\left(1 + \frac{\epsilon_{\text{f}}}{\epsilon_{\text{n}}} m\right)\eta_{\text{t}}
\end{aligned}
$$

$\eta_a \equiv$ efficiency of accelerator

$\epsilon_n \equiv$ energy to create a neutron

$m \equiv$ number of fissions per neutron

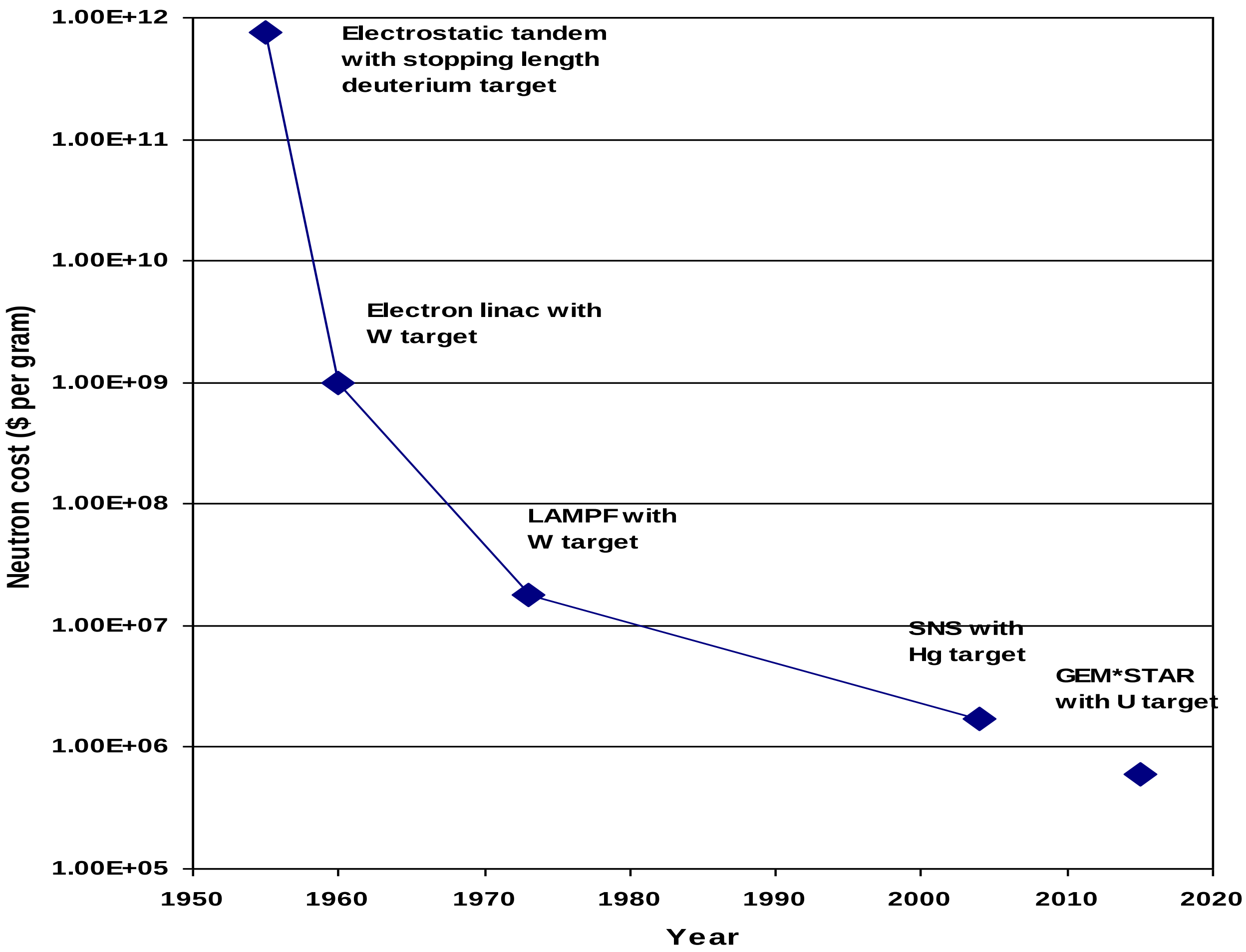
$\epsilon_f \equiv$ energy per fission

$\eta_t \equiv$ efficiency converting thermal to electrical energy

about: 70 - 5

$$
\frac{\text{net electric power out}}{\text{power on target}} = \frac{E_{\text{electric}} - E_{\text{wall}}}{E_{\text{wall}}\eta_{\text{a}}} = \left(1 + \frac{\epsilon_{\text{f}}}{\epsilon_{\text{n}}} m\right)\eta_{\text{t}} - \frac{1}{\eta_{\text{a}}} \approx 4.6m - \frac{1}{\eta_{\text{a}}}
$$

What is needed by way of accelerators?



~40 grams of neutrons ($40M) will produce 1GWe for one year

($432M/yr revenue @ 5 ¢/kWh)

(much better margin for synthetic transport fuels)

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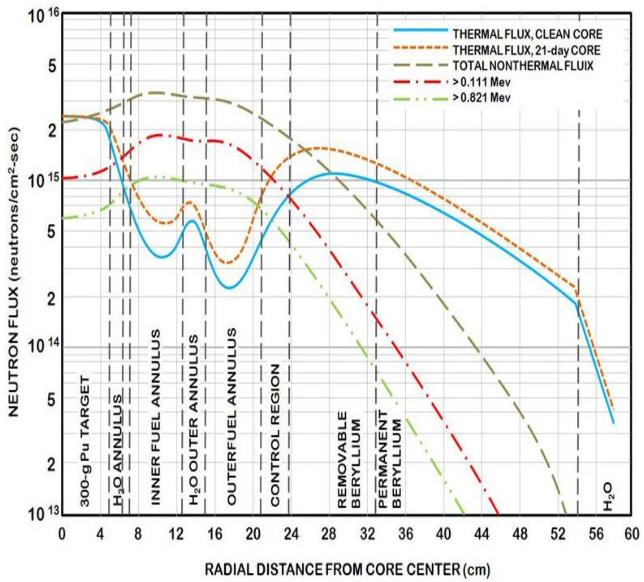
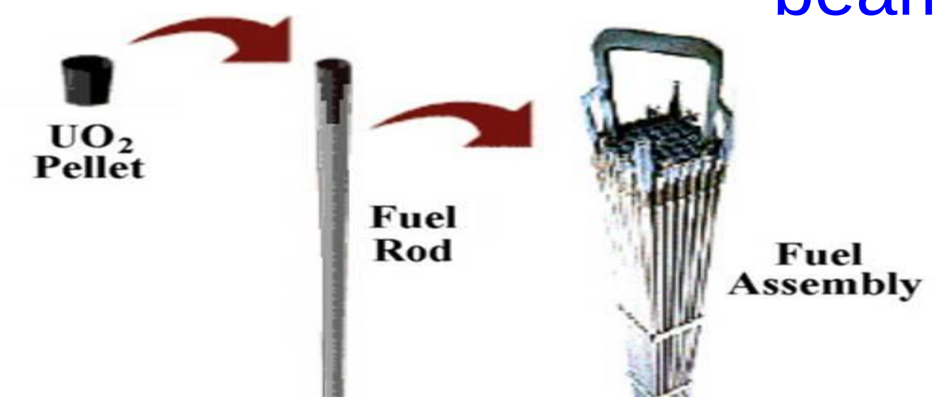
Solid Fuel Issues:



1- non-uniform fuel consumption requires fuel repositioning

2 - volatile fission-product build-up within cladding (Fukushima, 3-Mile Island)

3 - thermal shock due to beam trips



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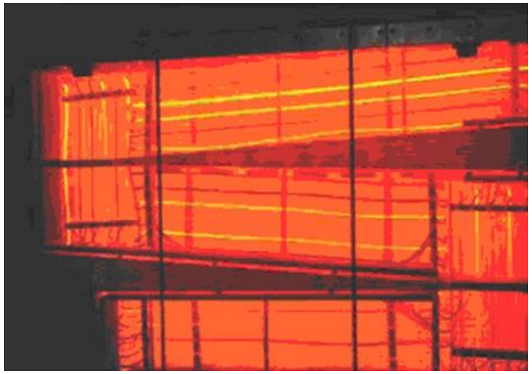
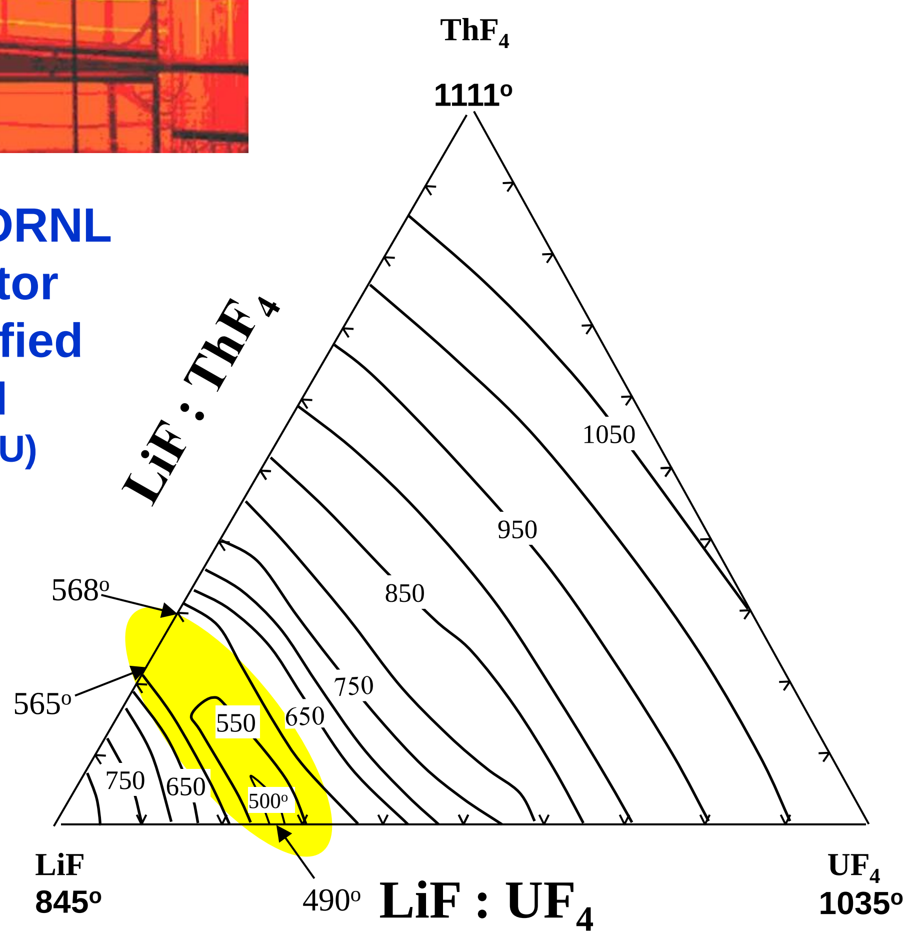
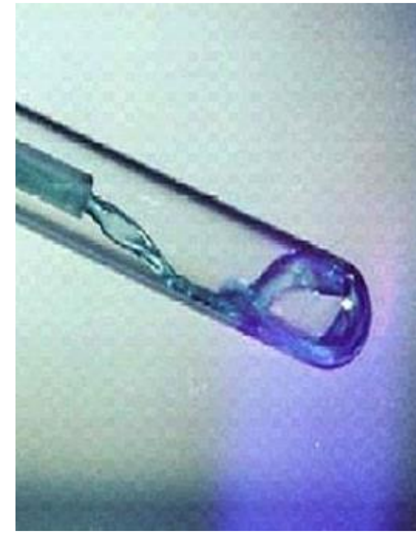
Solution: Molten Salt Eutectic Fuel



Proven in ORNL MSRE reactor using Modified Hastelloy-N
(^{235}U, ^{239}Pu, ^{233}U)





Uranium or Thorium fluorides form eutectic mixture with ^{7}LiF salt.

High boiling point → low vapor pressure

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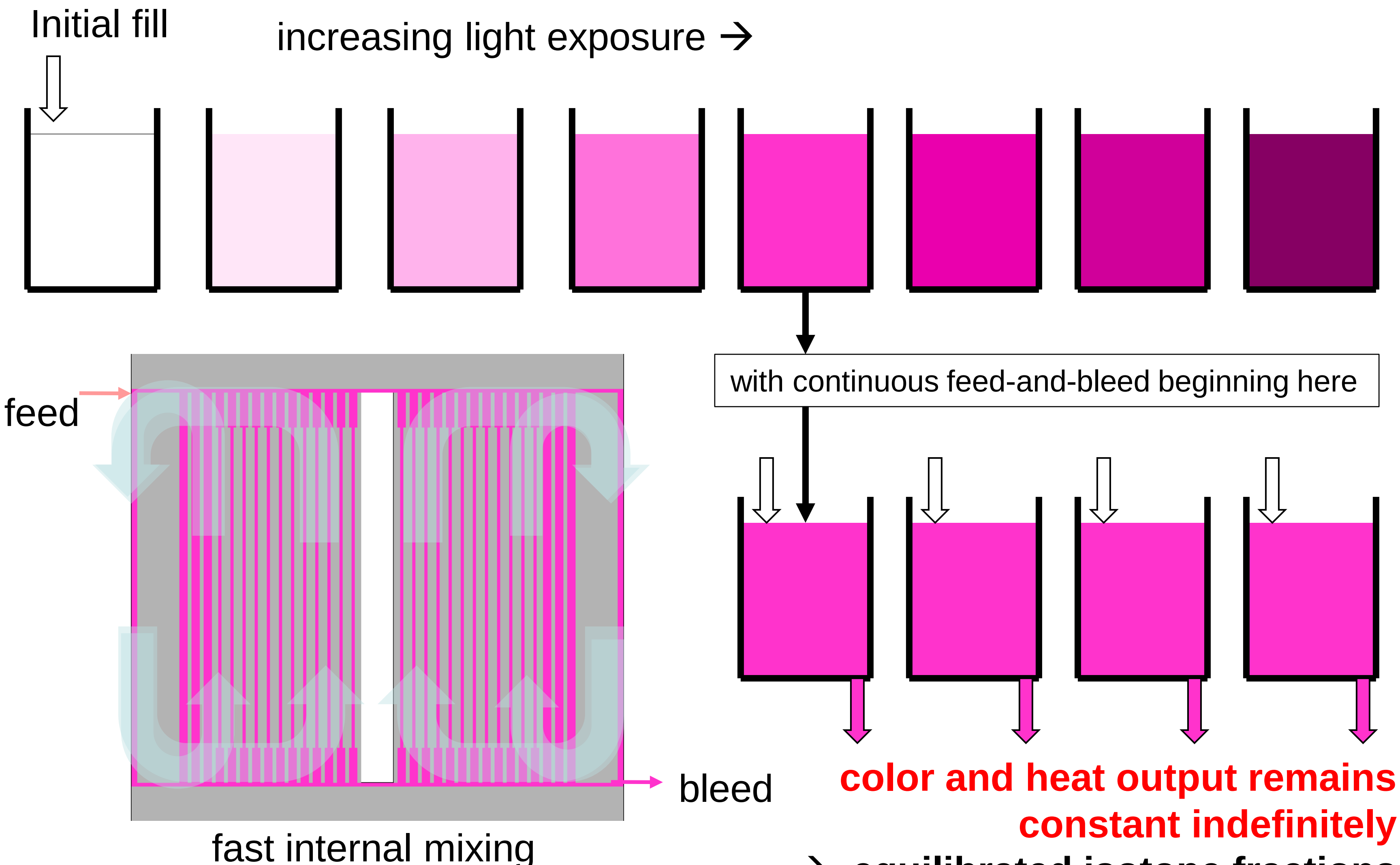
consider a clear liquid which releases heat when exposed to light, eventually turning a dark purple



10^{-6} less volatile fission-product build-up in core

color and heat output remains constant indefinitely

→ equilibrated isotope fractions throughout core and throughout time

Liquid fuel enables operation with constant and uniform isotope fractions

including fission products

consider isotope N_1 present in molten-salt feed:

feed *absorption* *overflow*

$$dN_1/dt = F(v/V) - N_1 \phi \, \sigma_{a1} - N_1(v/V)$$

define neutron fluence: $\mathcal{F} = \phi(V/v)$; then in equilibrium $dN_1/dt = 0$

$$N_1 = F / [1 + \mathcal{F} \, \sigma_{a1}]$$

and its $n_{capture}$ and β_{decay} daughters are given by

$$N_i = N_1 \, \Pi_{j=2,i} \{\mathcal{F} \, \sigma_{c(j-1)} / [1 + \mathcal{F} \, \sigma_{aj}]\} \qquad i \geq 2$$

do this for all actinides present in molten-salt feed and add together the results

note: feed rate is determined by power extracted

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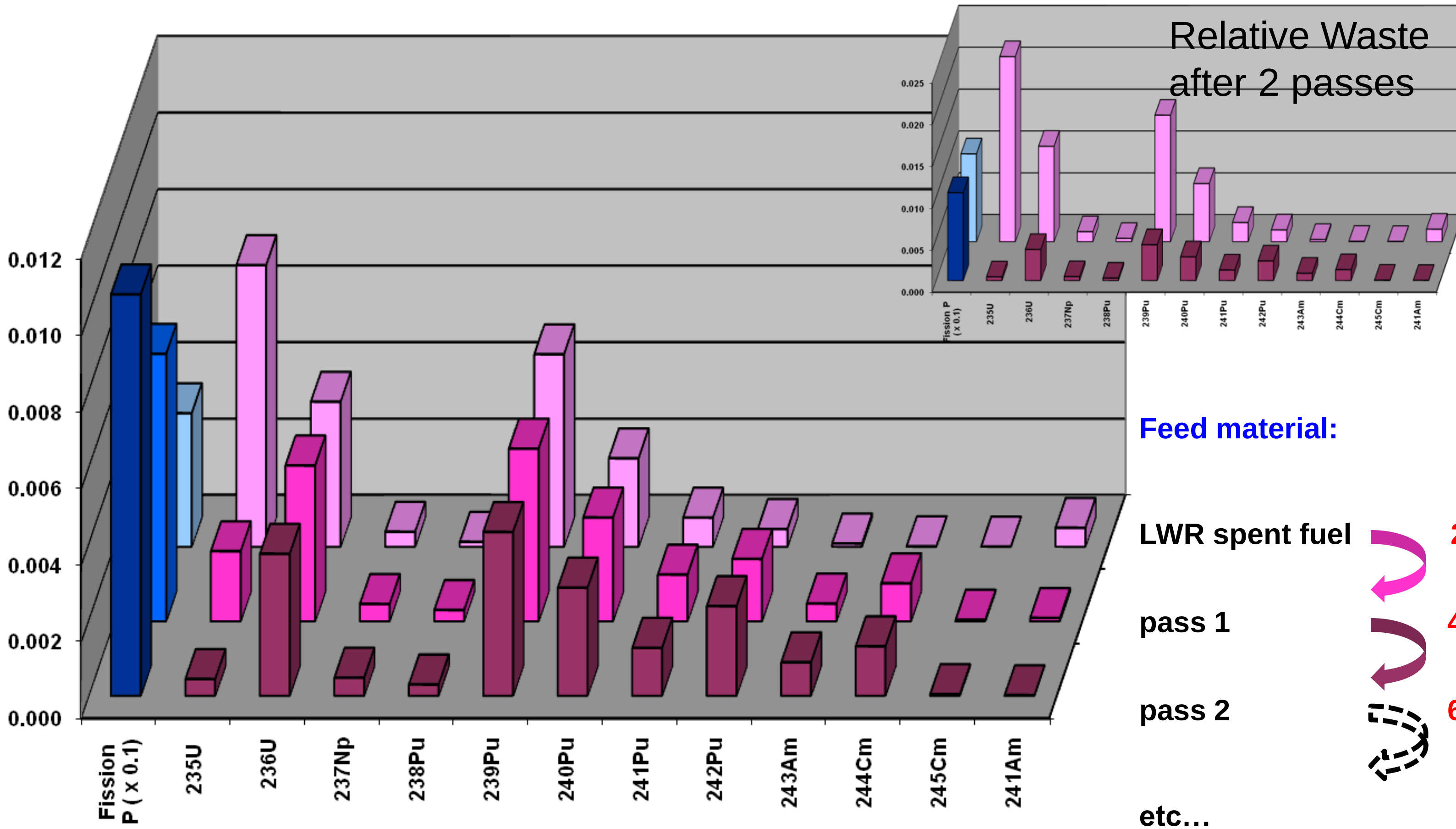
extracts many times more fission energy, without additional long-lived actinides



Feed material:

LWR spent fuel — 20 GWy

pass 1 — 40 GWy

pass 2 — 60 GWy

etc…

*

major reduction and deferral of waste

**presence requires thermal spectrum*

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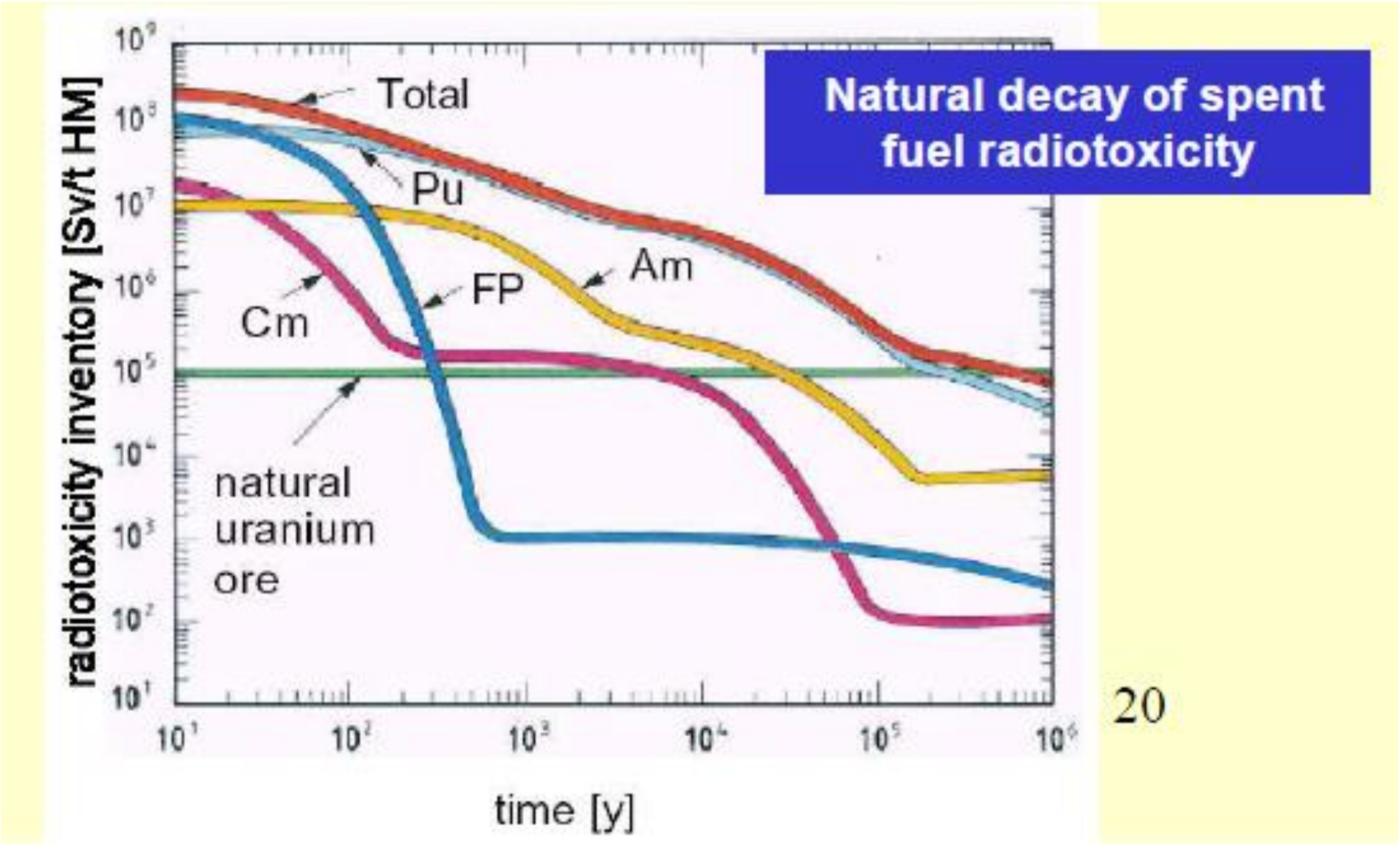
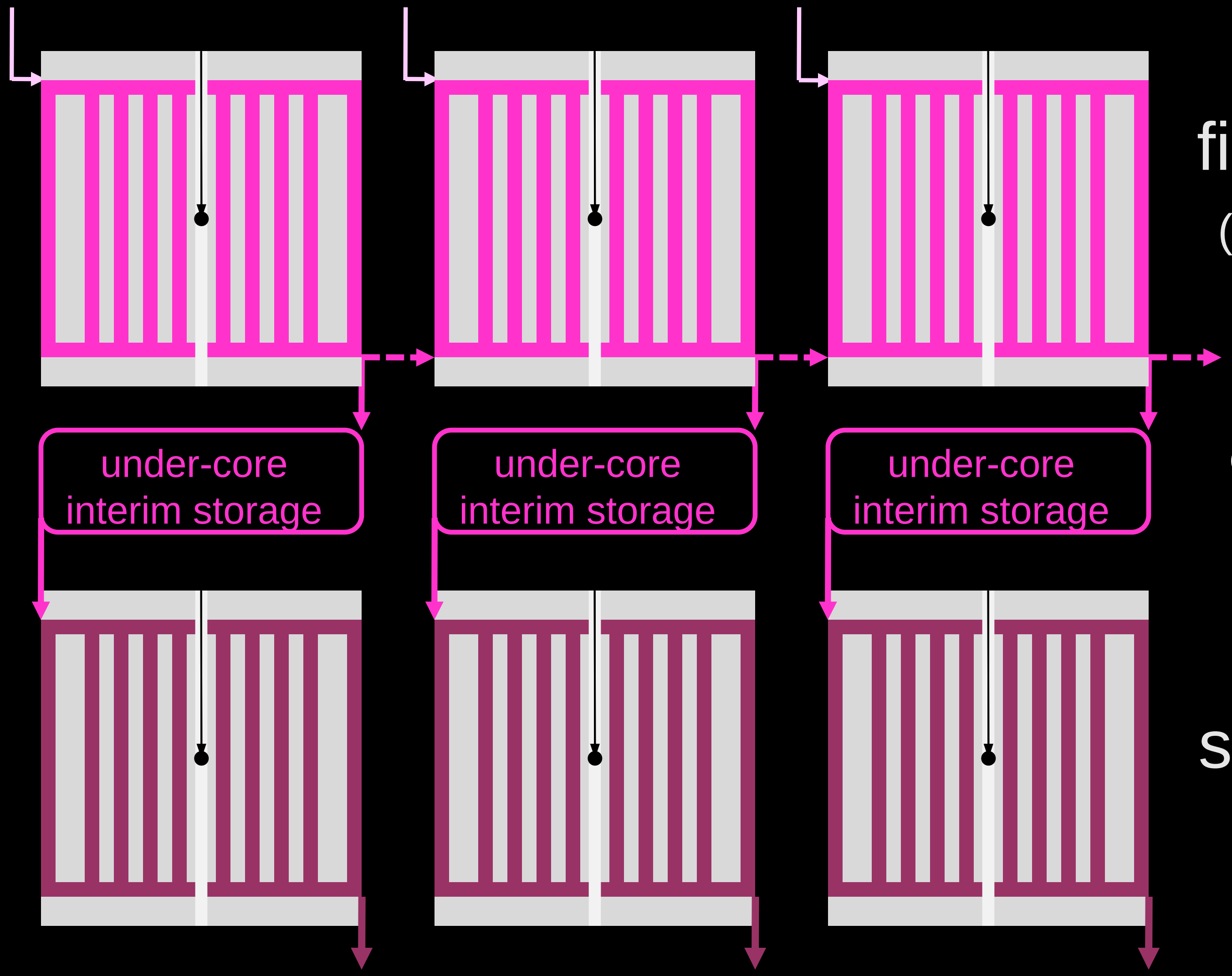

Natural decay of spent fuel radiotoxicity
radiotoxicity inventory [Sv/t HM]
time [y]
Total
Pu
Am
FP
Cm
natural
uranium
ore
20

Recycling

40 years worth of LWR spent fuel



first pass

(40+ years)

each can be used
to start another
pre-equililbrated
core every 5 years

second pass

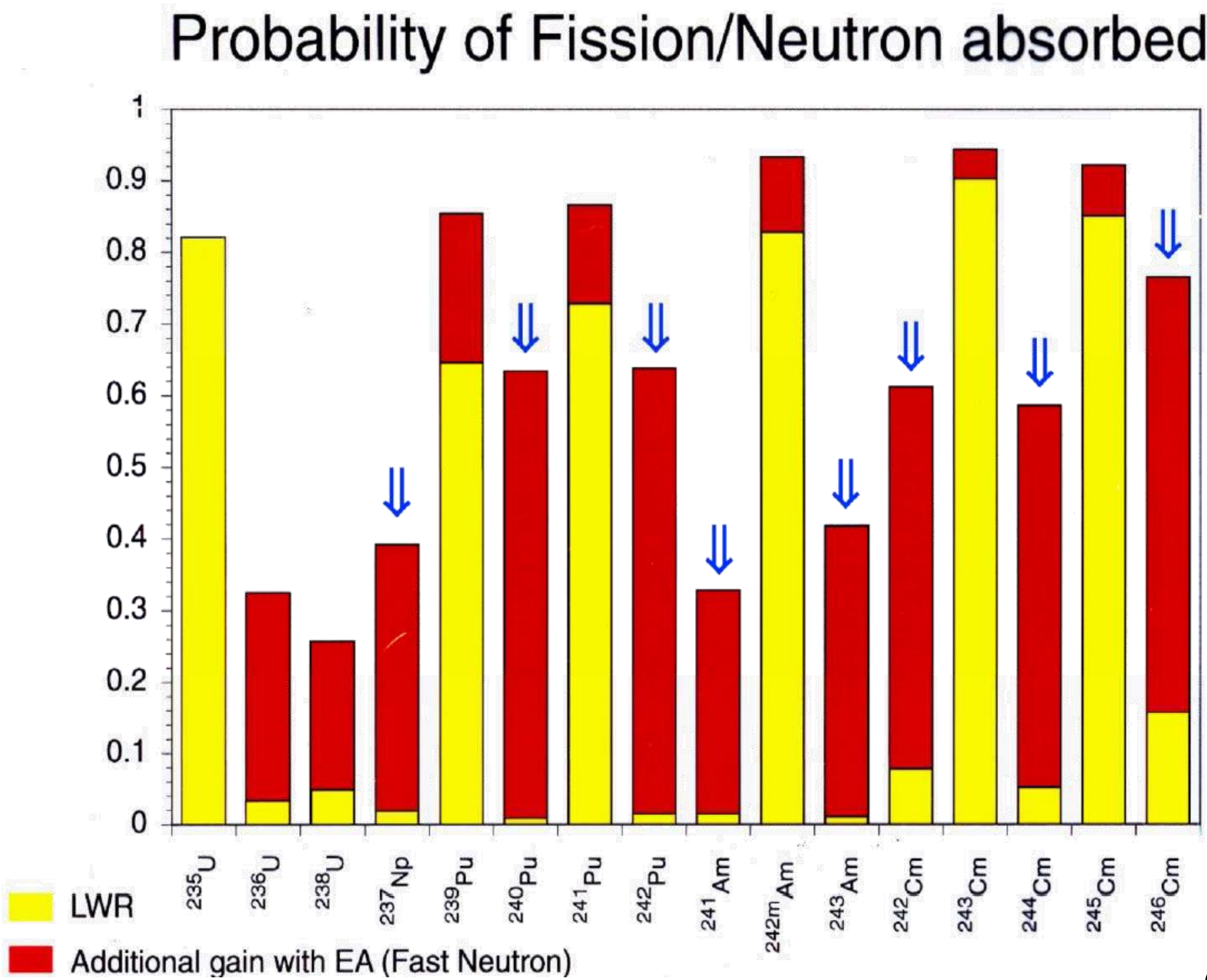
(40+ years)

subsequent passes… (fusion n source?)

For 50 years, and even today, people argue for fast-spectrum systems.

Why?

Faster burn-up of heavy actinides.



But Using Thermal Spectrum

0.01 – 0.2 eV

highest tolerance for fission products:

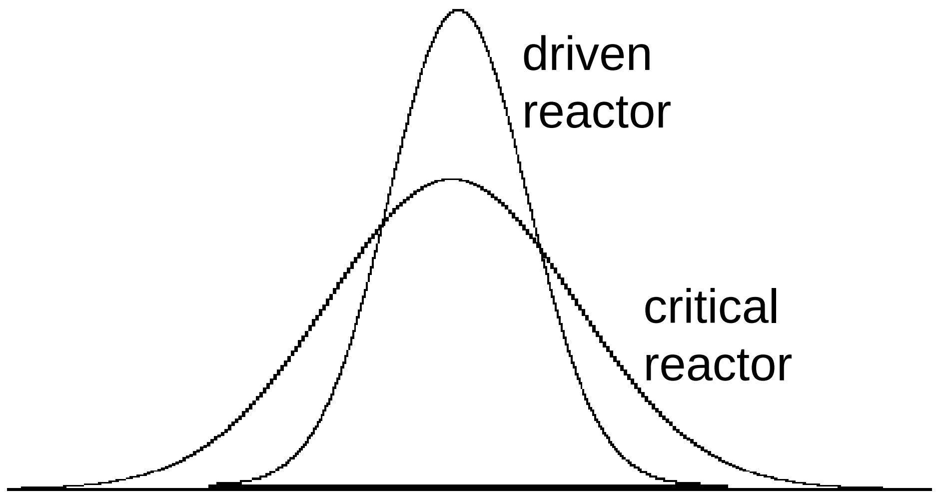
• spin structure and resonance spacing reduces capture cross-section at thermal energies:

$$\frac{\sigma\text{-fission } (^{239}\text{Pu})}{\sigma\text{-capture (f.p.)}} \sim 100 \quad \text{(vs} \sim 10 \text{ @ 50 keV)}$$

- ^{151}Sm (transmuted rapidly to low σ_c nuclei)
- ^{135}Xe (continuously removed as a gas)

⇒ more than compensates for slower fission of heavy actinides (which are burned anyway)

Target Considerations



“k_{eff}” *only* be used to evaluate ‘safety factor’

ADS “multiplication” is *very* target dependent

separating these two concepts reveals ADS should not have the traditional neutron reflector around the core

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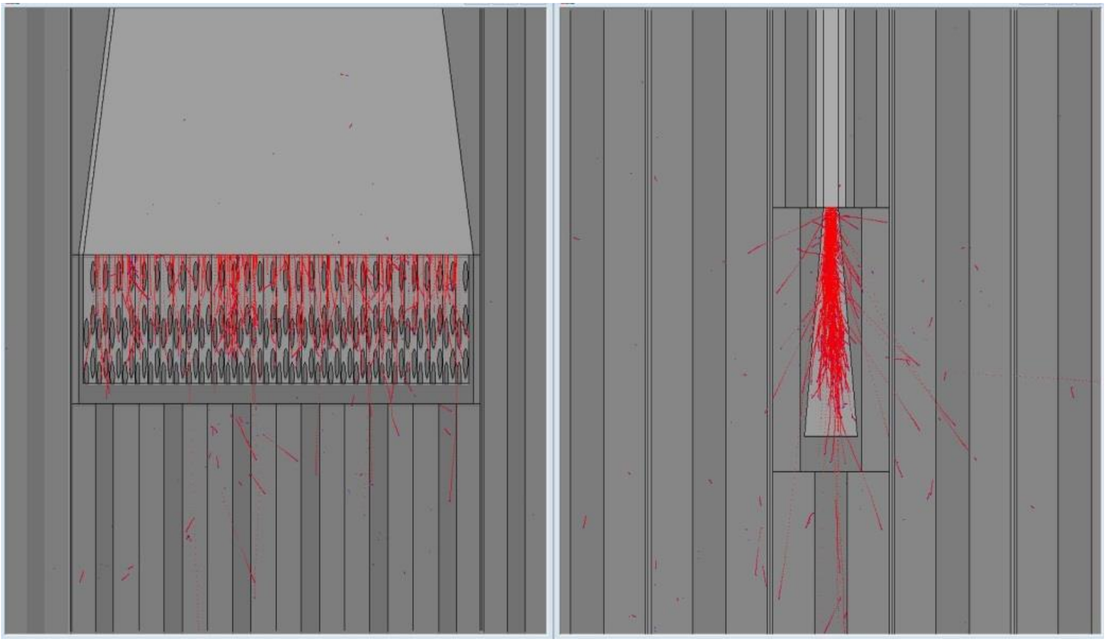
Target Considerations



GEM*STAR Internal Target

- diffuse (or multiple) beam spots
- molten salt used for heat removal
- high neutron yield from uranium

  (but minimize target fission)
- spent target fluorinated and used as fuel
- minimize impact on local reactivity

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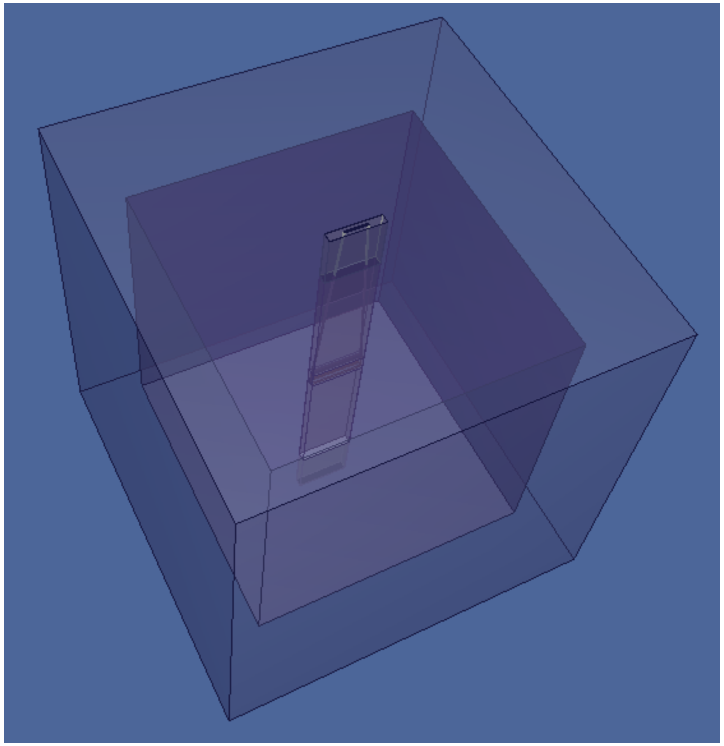

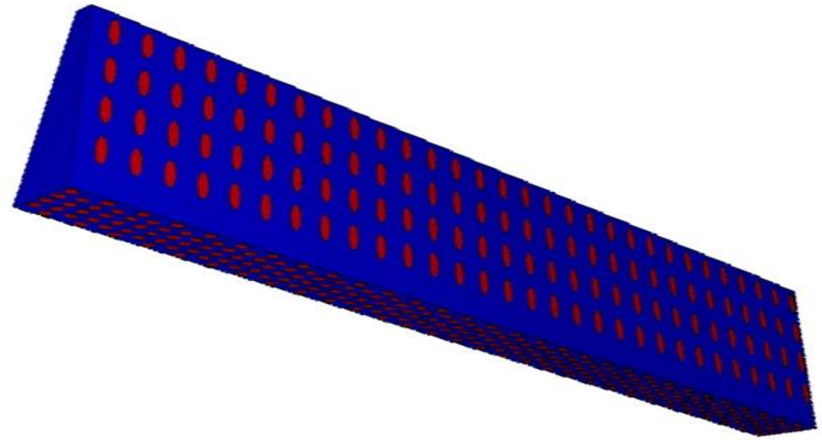

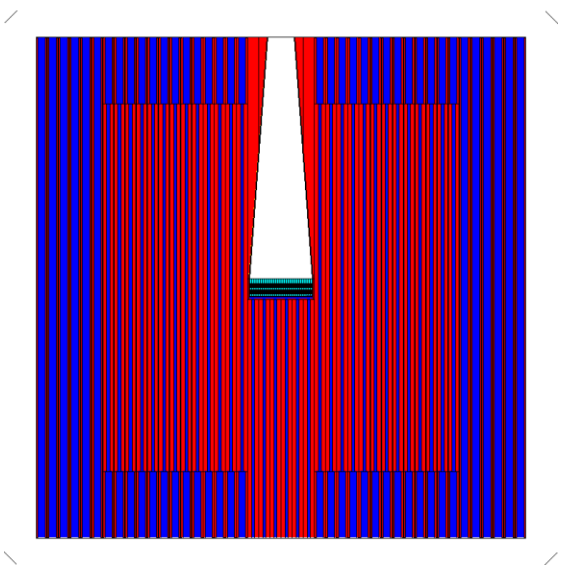

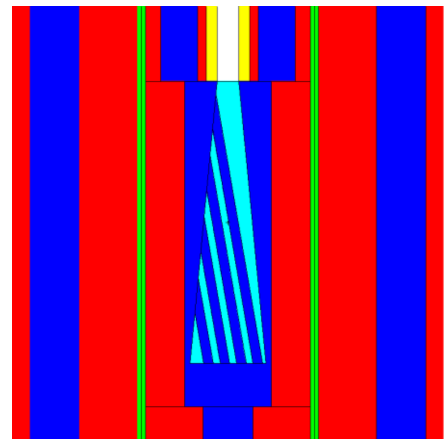

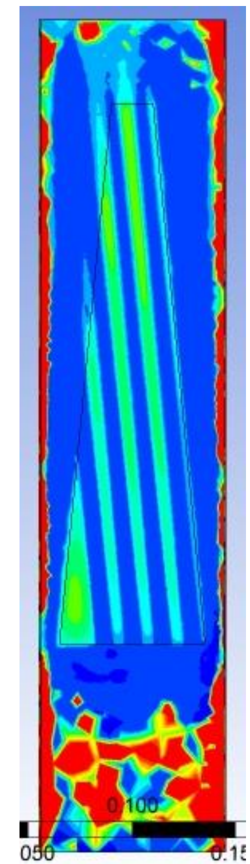

MCNPX & FLUENT Calculations

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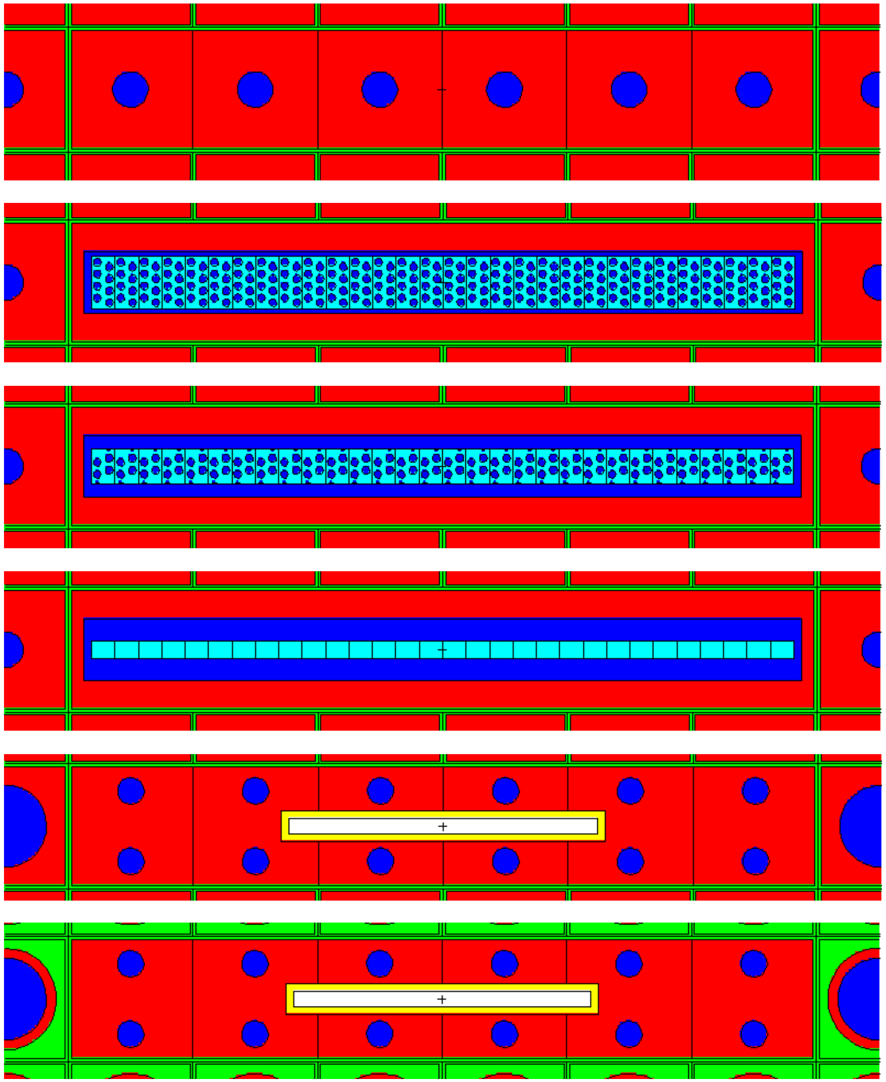
Core Design Features



- **extractable target region**
- **individual graphite square tubes separated by He blankets**
- **no 'reflector' around core**
- **under-core fuel storage**

graphite
MS eutectic
Helium
Uranium
Beryllium

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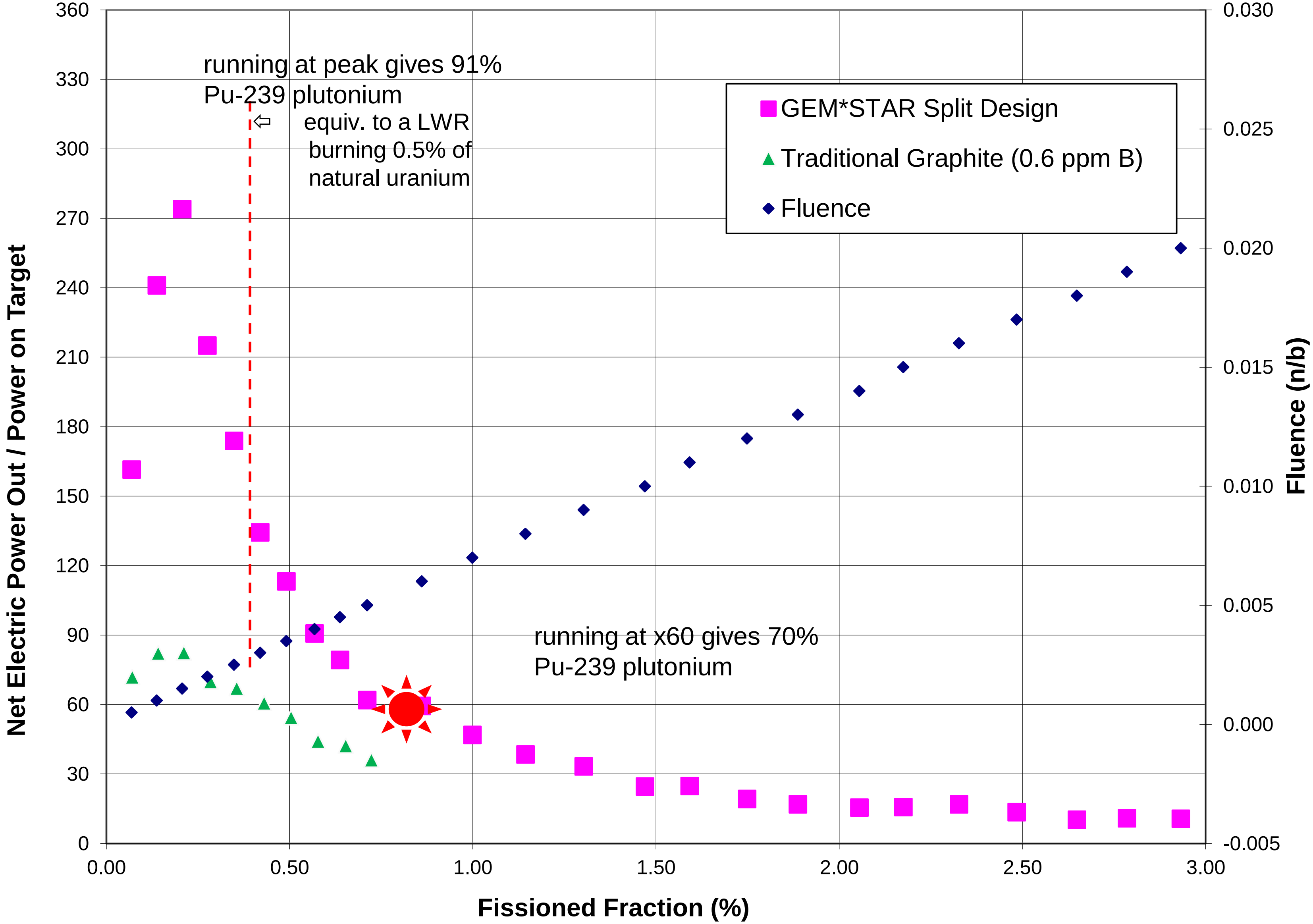
Fuel: Natural Uranium (MCNPX)



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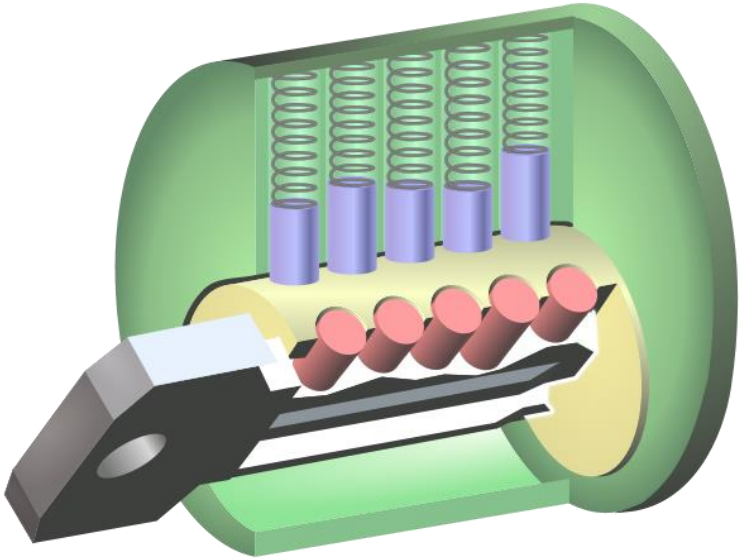
Cost

- mostly proven, known costs
- integration costs understood
- synthetic diesel best margins
- very competitive with fossil fuel



Weapons

- no enrichment required
- no reprocessing (just fluorination)

Waste

- reduce by factor of 10
- can productively use today's LWR spent fuel (bulk fluorination)

Safety

- never a critical mass
- vastly reduced volatile radioactive inventory
- low-pressure system

Timeline

- no missing technology
- actually directly addressing the above concerns motivates public and thus regulatory/political action

First Application:

render 34t of weapons-grade Pu unusable for nuclear weapons - as required by 2000 U.S.-Russian Plutonium Management and Disposition Agreement

while capitalizing on its full economic potential

Private

focus: Muons Inc
ADNA Corp

NNSA

National Nuclear Security Administration mission need

Laboratories

national
university
VNEC?

Pu Weapons

Small time window (during maximum compression) for full yield:

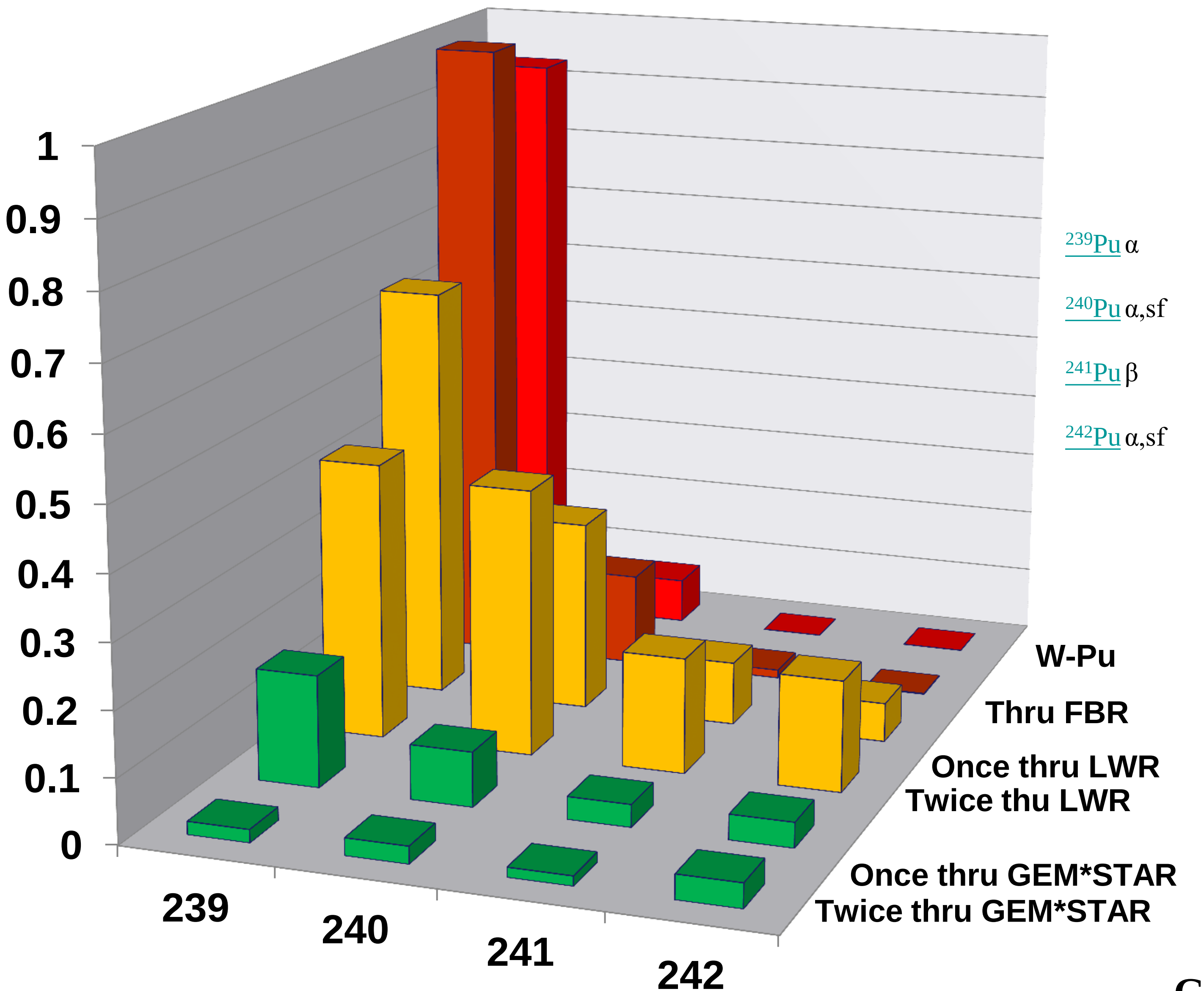
- no ignition ⇔ pre-ignition

  probability depends on rate of spontaneous fission
- timed ignition

  engineered pulse of neutrons

Pu amount *and* isotope distribution matters…

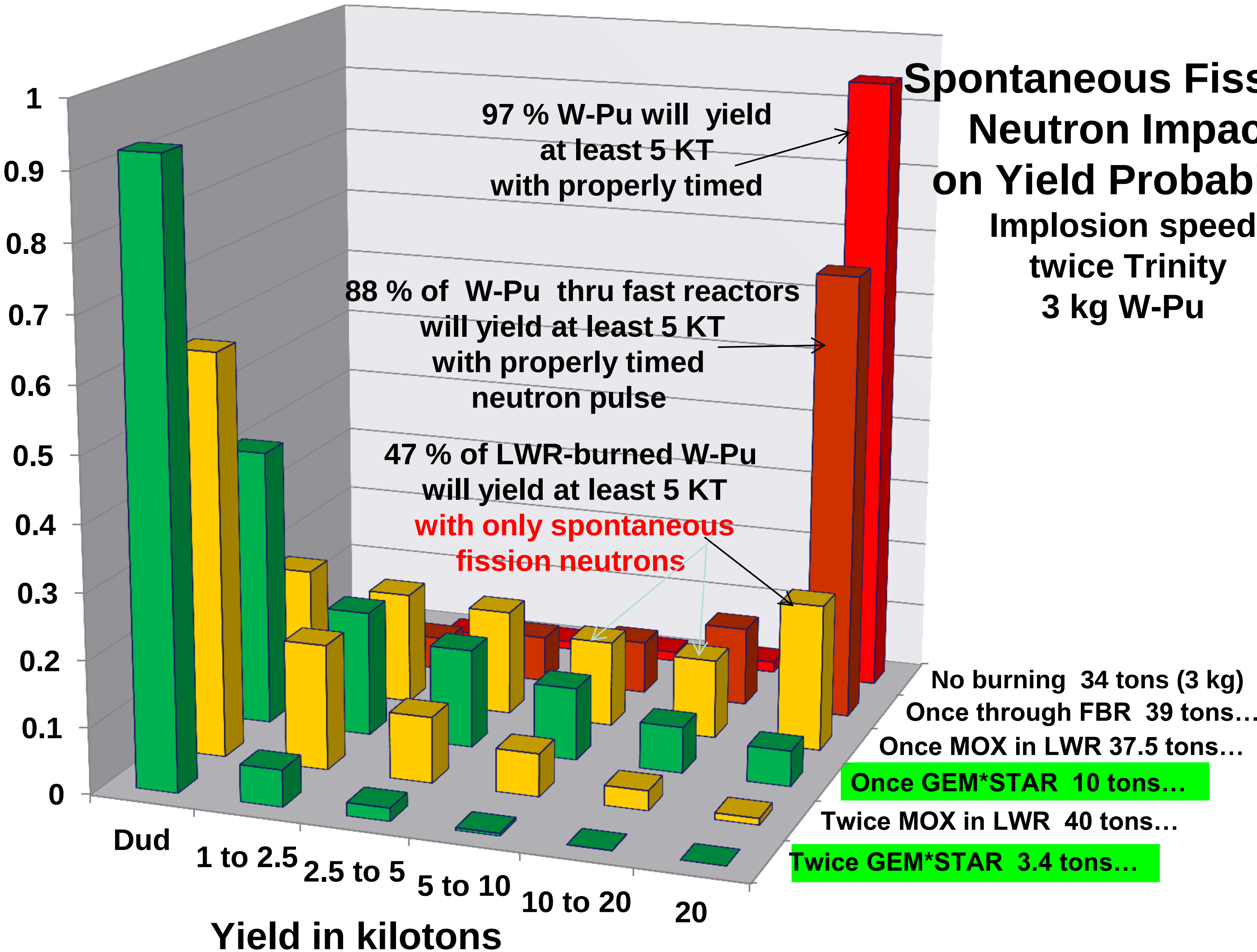
FB BN800 MOX-LWR GEM*STAR



^{239}Pu	α	24,110 years
^{240}Pu	α,sf	6,561 years
^{241}Pu	β	14.325 years
^{242}Pu	α,sf	373,300 years

Spontaneous Fission Neutron Impact on Yield Probability

Implosion speed twice Trinity 3 kg W-Pu



GEM*STAR Burns W-Pu Without U or Th
34 Tons in 30 Years

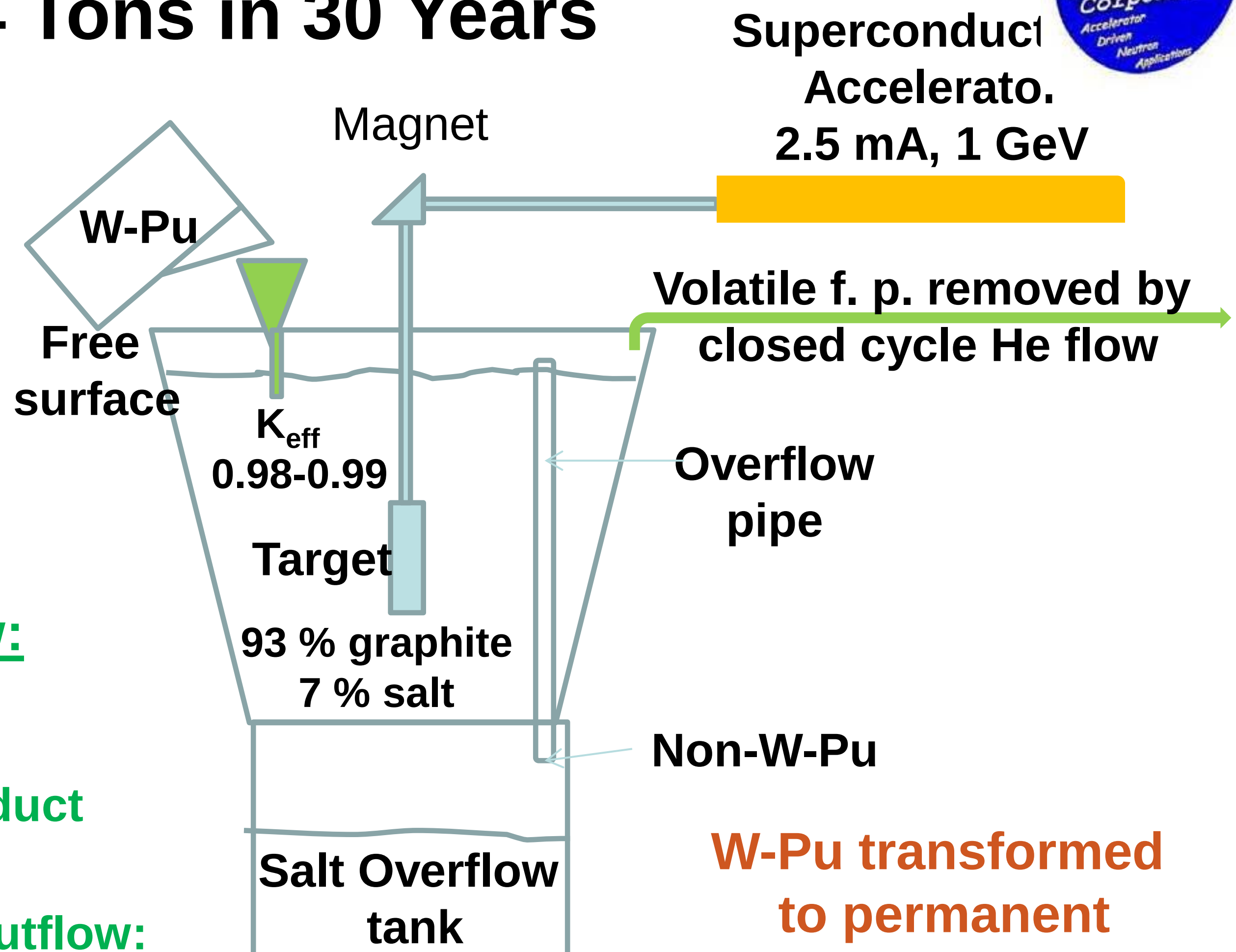
Hourly fill:

30 g W-Pu as
PuF_3:BeF_2:NaF
(1:45:54)
mp: 350 C

Inflow W-Pu:
93 % ^{239}Pu
7 % ^{240}Pu

Hourly overflow:
7.5 g as PuF_3 +
carrier salt +
22.5 g of fission product

Non-weapons Pu Outflow:
52.4 % ^{239}Pu
25.4 % ^{240}Pu
10.6 % ^{241}Pu
11.7 % ^{242}Pu



Fission power 500 MWt

W-Pu transformed to permanent non-weapons Pu immediately upon adding and mixing

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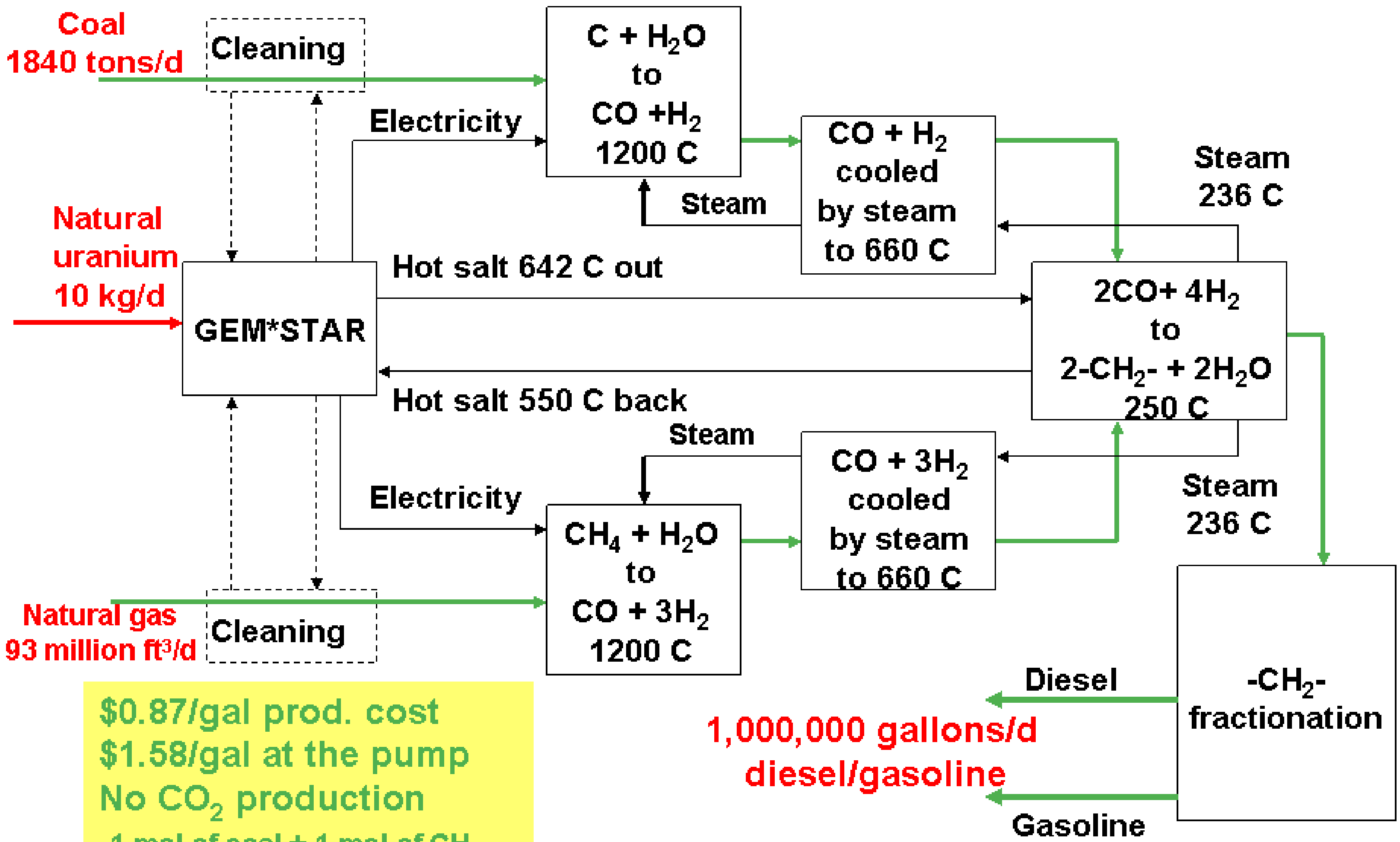
Coal and Natural Gas to Diesel/Gasoline with GEM*STAR at 500 MWt (~3.4MW on target)



$0.87/gal prod. cost

$1.58/gal at the pump

No CO_2 production

1 mol of coal + 1 mol of CH_4 yields 2 mols of diesel/gasoline

affordable diesel without CO_2 production

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Advantages Over Direct Burial and MOX burning in LWRs

1. **W-Pu conversion to PuF_3 simpler and cheaper than to PuO_2 or MOX fuels**
2. **Commercial profitability of diesel production reduces DOE cost of W-Pu disposition**
3. **W-Pu never recoverable as weapons useful material**
4. **NNSA can develop its own technology for disposition, moving beyond current reliance on other parts of the DOE for burning technology and remnant storage**
5. **NNSA burning technology may be broadly applied to LWR waste to prevent future recovery for weapons use**
6. **GEM*STAR's underlying technology we believe to be attractive to Russia and responds to Russia's concern for economic benefit from W-Pu**

GEM✵STAR System

- **no enrichment**
- **no reprocessing**
- **can burn MANY fuels**

(pure, mixed, *including* LWR spent fuel)

with no redesign required