GEM*STAR

Green Energy-Multiplier
Sub-critical, Thermal-spectrum, Accelerator-driven, Recycling Reactor

R. Bruce Vogelaar
Virginia Tech

Recent Developments

"At least 40 developing countries have recently approached the U.N. to signal interest in starting nuclear power programs"

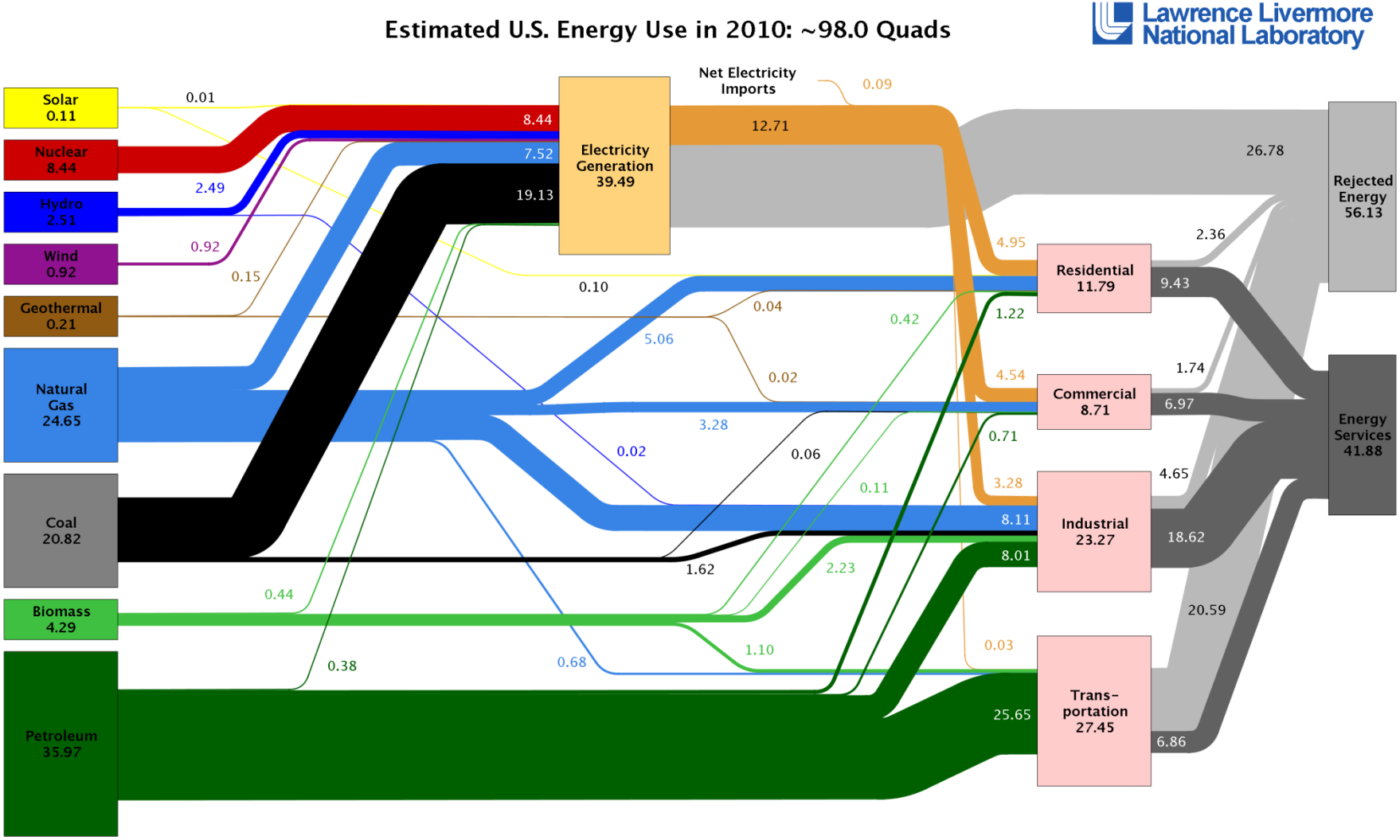
Joby Warrick, **Washington Post**, May 12, 2008

meanwhile…

- **Fukushima accident**
- **Germany shuts down its nuclear plants**
- **Japan shuts down most of its nuclear plants**
- **US shuts down San Onofre…**

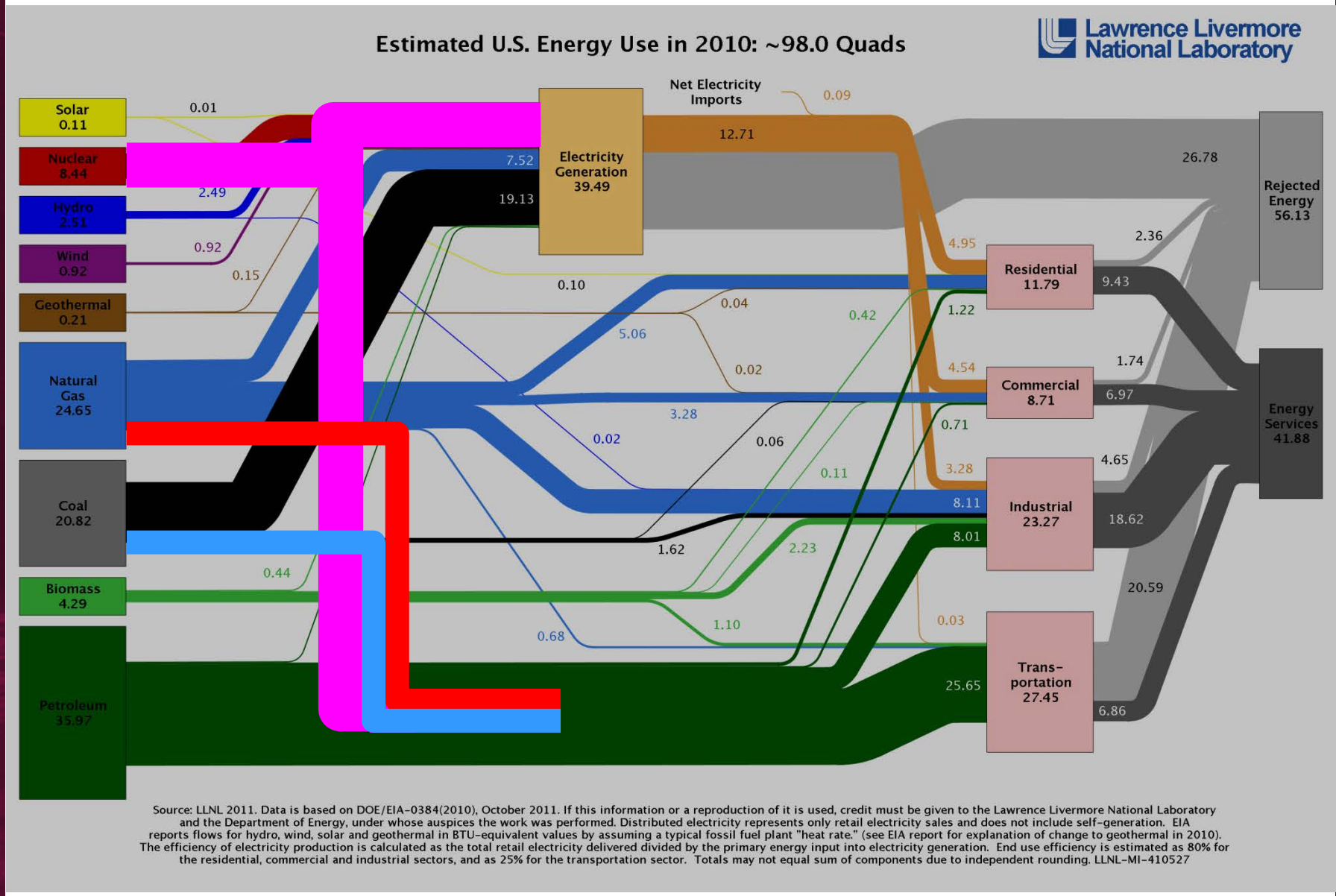
US Energy Flow

Lawrence Livermore National Laboratory

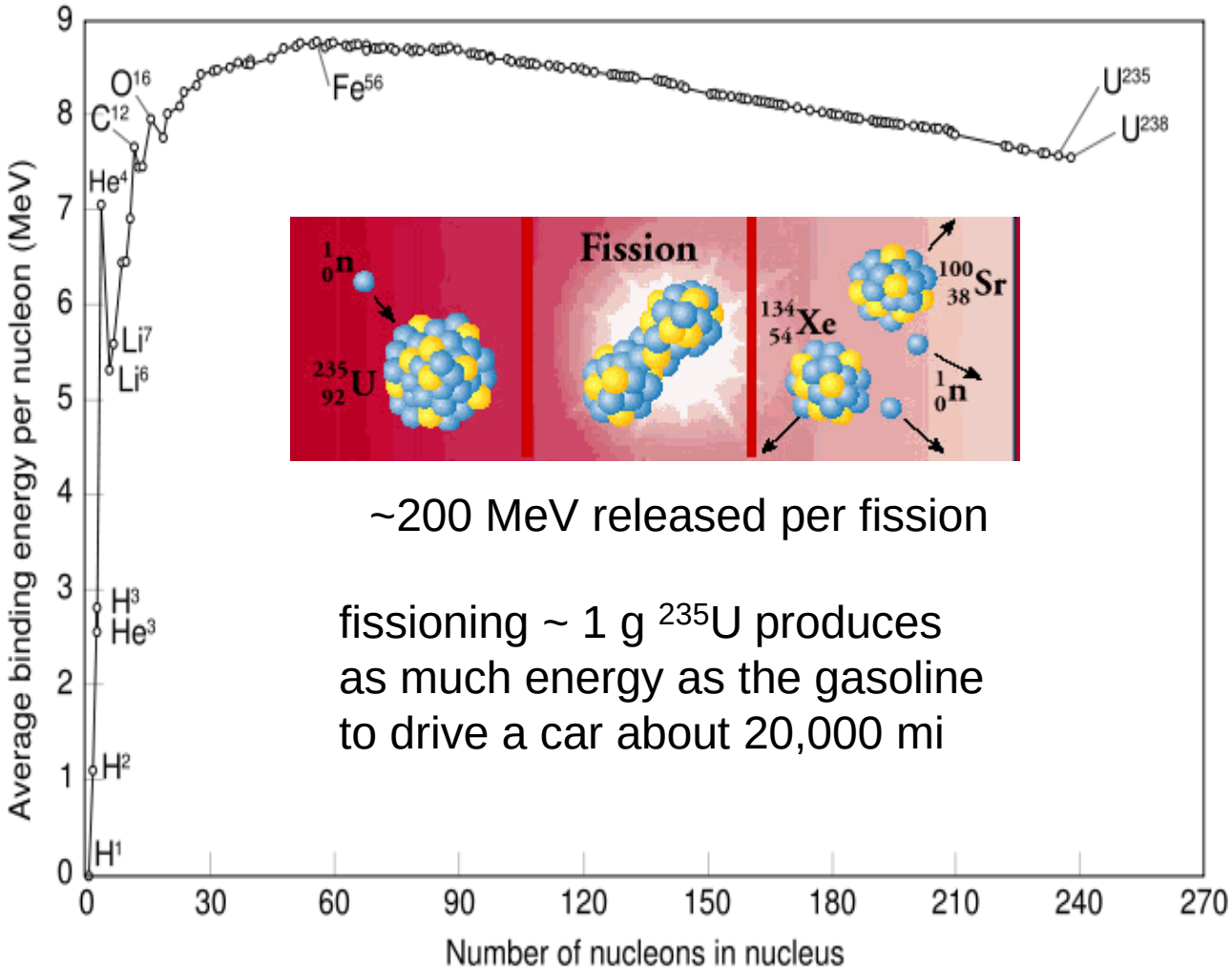


Source: LLNL 2011. Data is based on DOE/EIA-0384(2010), October 2011. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for hydro, wind, solar and geothermal in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." (see EIA report for explanation of change to geothermal in 2010). The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

the classic 'nuclear' option



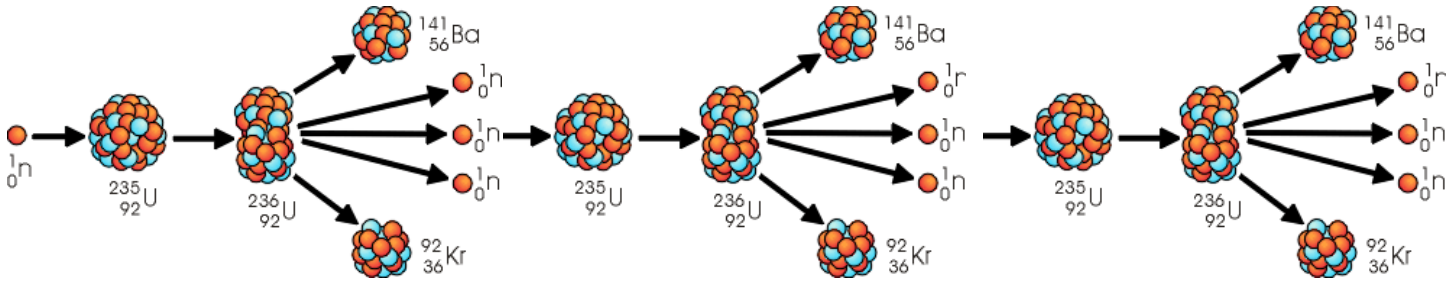
Fission



~200 MeV released per fission

fissioning ~ 1 g ^{235}U produces as much energy as the gasoline to drive a car about 20,000 mi

Chain Reaction

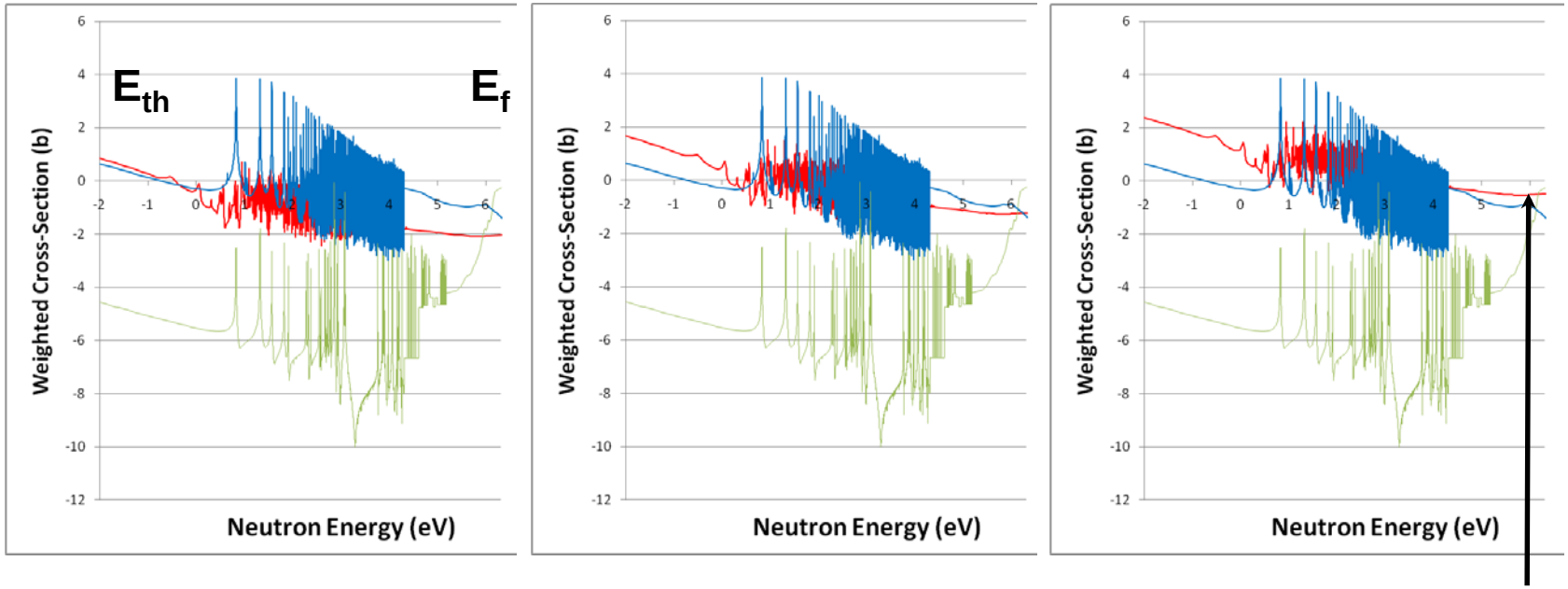


On Average: 1 fission → 1 fission → 1 fission "$k_{eff} = 1$"

$k_{eff} > 1$ → runaway reaction

$k_{eff} < 1$ → chain has finite length

Sustaining a chain reaction



0.72 % Natural **4.5 % "Low" Enriched** **> 20 % Weapons Usable**

^{235}U fission

^{238}U capture

^{238}U fission

Need to thermalize fission neutrons in U-free region to avoid capture before fission

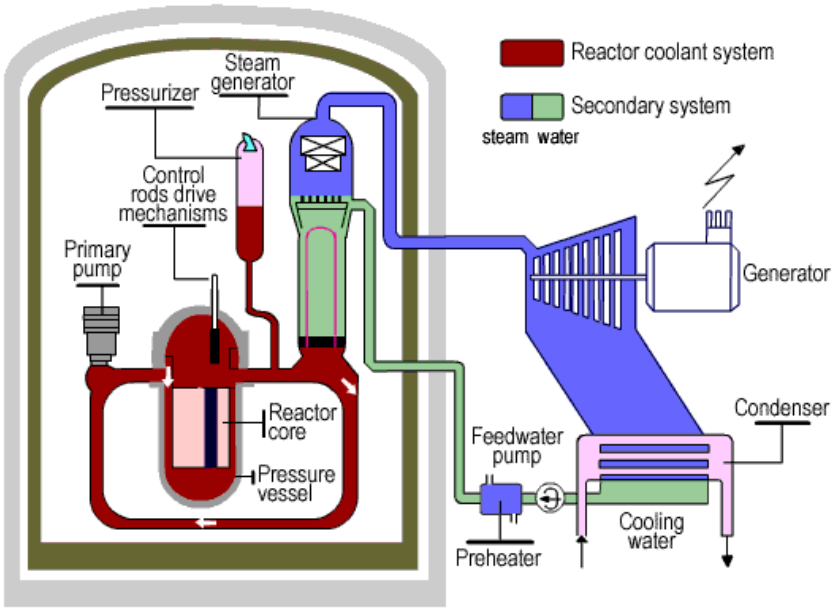
Possible Fuels

99	Es237 0.121s	Es238 0.97s	Es239 0.196s	Es240 5.34s	Es241 8s	Es242 11s	Es243 21s	Es244 37s	Es245 1.1m	Es246 7.7m	Es247 4.55m	Es248 27m	Es249 1.7h	Es250 8.6h	Es251 1.375d
98	Cf236 0.136s	Cf237 2.1s	Cf238 0.021s	Cf239 39s	Cf240 1.06m	Cf241 3.78m	Cf242 3.49m	Cf243 10.7m	Cf244 19.4m	Cf245 46.3m	Cf246 1.49d	Cf247 3.11h	Cf248 333.5d	Cf249 350.6y	Cf250 13.08y
97	Bk235 10.6s	Bk236 22.1s	Bk237 30.4s	Bk238 2.4m	Bk239 1.63m	Bk240 4.8m	Bk241 4.6m	Bk242 7m	Bk243 4.5h	Bk244 4.35h	Bk245 4.94d	Bk246 1.8d	Bk247 1380y	Bk248 9y	Bk249 320d
96	Cm234 51s	Cm235 1.27m	Cm236 2.02m	Cm237 3.98m	Cm238 2.4h	Cm239 2.9h	Cm240 27d	Cm241 32.8d	Cm242 162.8d	Cm243 29.1y	Cm244 18.1y	Cm245 8500y	Cm246 4730y	Cm247 1.56e+07y	Cm248 3.4e+05y
95	Am233 3.2m	Am234 2.32m	Am235 10.3m	Am236 3.6m	Am237 1.22h	Am238 1.63h	Am239 11.9h	Am240 2.12d	Am241 432.2y	Am242 141y	Am243 7370y	Am244 10.1h	Am245 2.05h	Am246 39m	Am247 23m
94	Pu232 33.1m	Pu233 20.9m	Pu234 8.8h	Pu235 25.3m	Pu236 2.858y	Pu237 45.2d	Pu238 87.74y	Pu239 2.41e+05y	Pu240 6564y	Pu241 14.35y	Pu242 3.73e+05y	Pu243 4.956h	Pu244 8.08e+07y	Pu245 10.5h	Pu246 10.84d
93	Np231 48.8m	Np232 14.7m	Np233 36.2m	Np234 4.4d	Np235 1.084y	Np236 1.54e+05y	Np237 2.14e+06y	Np238 2.117d	Np239 2.356d	Np240 1.032h	Np241 13.9m	Np242 5.5m	Np243 1.85m	Np244 2.29m	Np245 50.3s
92	U 230 20.8d	U 231 4.2d	U 232 68.9y	U 233 1.59e+05y	U 234 0.0055	U 235 0.72	U 236 2.34e+07y	U 237 6.75d	U 238 99.2745	U 239 23.45m	U 240 14.1h	U 241 18.5m	U 242 16.8m	U 243 3.18m	U 244 25.8s
91	Pa229 1.5d	Pa230 17.4d	Pa231 3.28e+04y	Pa232 1.31d	Pa233 26.97d	Pa234 6.7h	Pa235 24.5m	Pa236 9.1m	Pa237 8.7m	Pa238 2.3m	Pa239 1.77h	Pa240 26.6s	Pa241 17.3s	Pa242 11.4s	Pa243 4.22s
90	Th228 1.913y	Th229 7880y	Th230 7.54e+04y	Th231 1.063d	Th232 100	Th233 21.83m	Th234 24.1d	Th235 7.1m	Th236 37.5m	Th237 4.7m	Th238 9.4m	Th239 33.1s	Th240 11.2s	Th241 8.17s	Th242 2.32s
89	Ac227 21.77y	Ac228 6.15h	Ac229 1.05h	Ac230 2.03m	Ac231 7.5m	Ac232 1.98m	Ac233 2.42m	Ac234 44s	Ac235 18.1s	Ac236 5.55s	Ac237 7.57s	Ac238 3.03s	Ac239 1.6s	Ac240 1.44s	
88	Ra226 1600y	Ra227 42.2m	Ra228 5.75y	Ra229 4m	Ra230 1.55h	Ra231 1.72m	Ra232 4.2m	Ra233 30s	Ra234 30s	Ra235 9.65s	Ra236 7.18s	Ra237 4.17s			
87	Fr225 4m	Fr226 49s	Fr227 2.47m	Fr228 39s	Fr229 50.2s	Fr230 19.1s	Fr231 17.5s	Fr232 5.5s	Fr233 3.92s	Fr234 2.01s	Fr235 1.88s				
86	Rn224 1.78h	Rn225 4.5m	Rn226 7.4m	Rn227 22.5s	Rn228 1.08m	Rn229 14.3s	Rn230 6.66s	Rn231 5.41s	Rn232 3.43s						
85	At223 50s	At224 10.7s	At225 16.2s	At226 6.42s	At227 7.15s	At228 5.56s	At229 2.63s								
84	Po222 9.3m	Po223 2.87m	Po224 1.56m	Po225 20.4s	Po226 10.2s										
83	Bi221 5.42s	Bi222 2.09s	Bi223 2.24s	Bi224 0.993s											

"Breeder" reactions

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**

What are the obstacles?

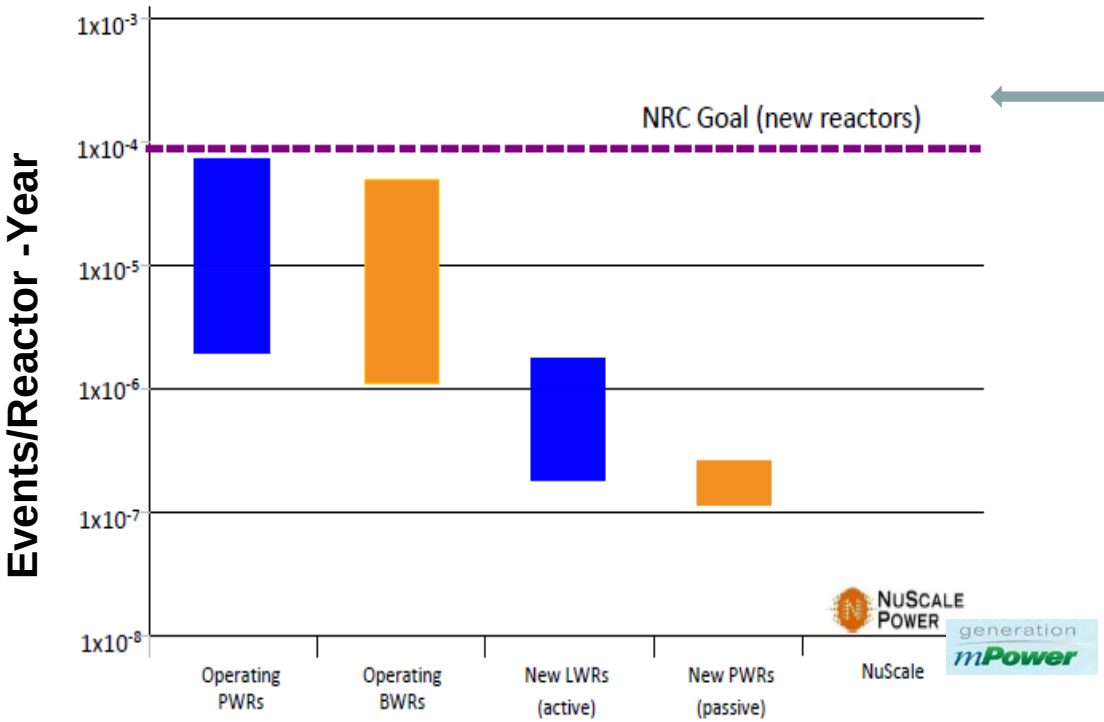
in the US:

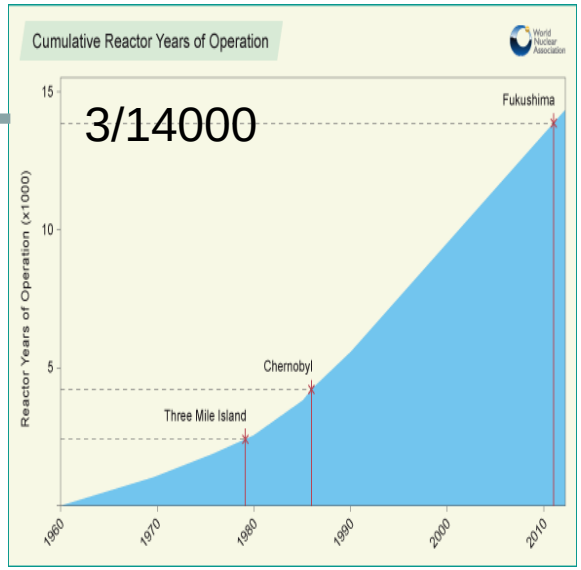
- safety
- waste
- weapons proliferation
- cost

in other countries?

➢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?…

- **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**

➢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
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

GEM*STAR: 4.5 ¢ per kWh with natural uranium fuel

What is being done…

DOE-NE

'small modular reactors'

- safety ←
- waste
- weapons proliferation
- cost ←

DOE-Science

'high intensity frontier'

- safety
- waste ←
- weapons proliferation
- cost

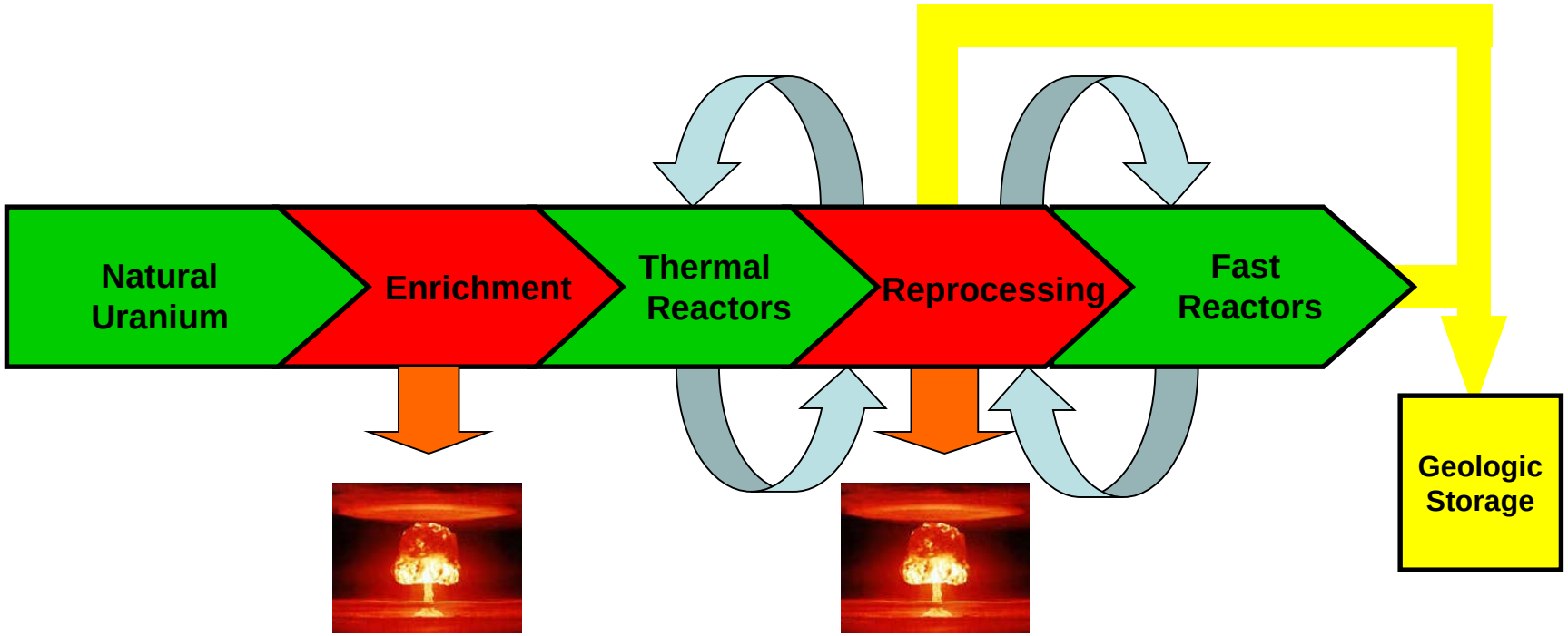
India

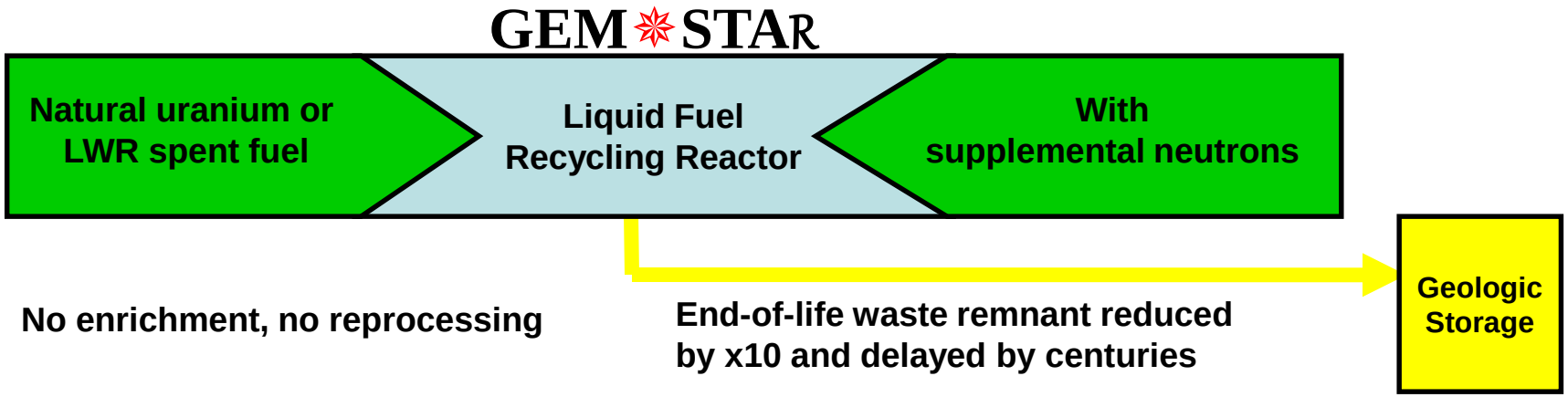
- PHWR (nat U) →
- FBR (^{239}Pu & Th) →
- AHWR (^{233}U & Th)

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

Different Paradigm





No enrichment, no reprocessing

End-of-life waste remnant reduced by x10 and delayed by centuries

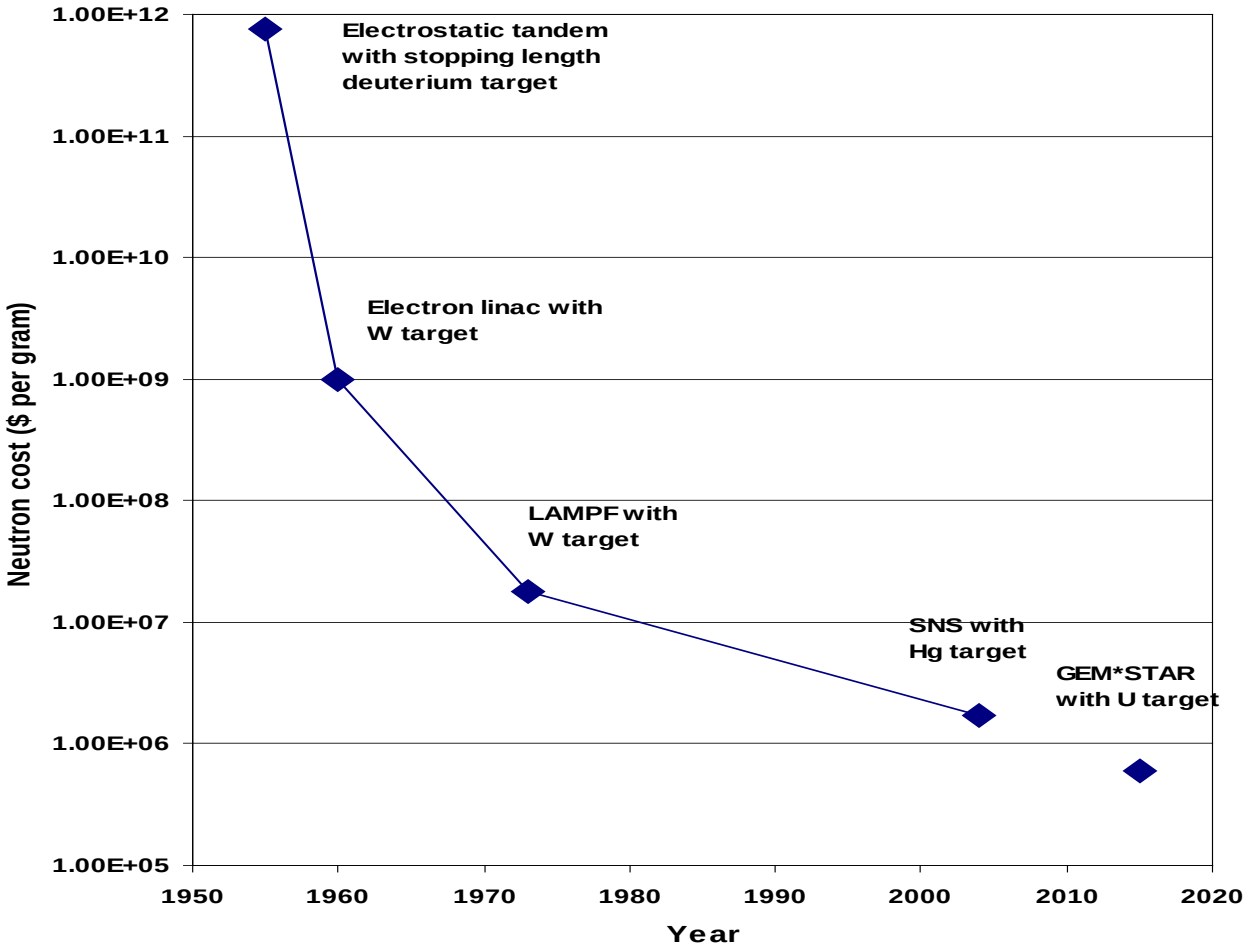
Existing Enabling Technologies

- 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*

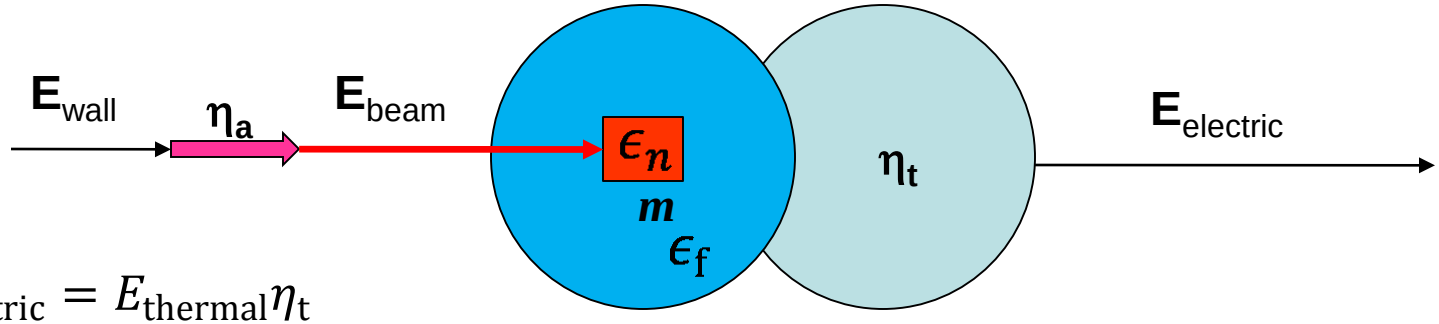
The cost of neutrons has dropped dramatically



~40 grams of neutrons will produce 1GWe for one year

($432M @ 5 ¢/kWh)

Proton Driven Sub-Critical System



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

$\eta_a \equiv$ 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

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

$$G = \frac{\text{net electric power out}}{\text{power on target}} = \left(1 + \frac{\epsilon_f}{\epsilon_n} m\right)\eta_t - \frac{1}{\eta_a}$$

Reference parameters:

- ϵ_f 200 MeV / fission
- ϵ_n 19 MeV / neutron (for 1 GeV protons on Uranium)
- m 15 fissions / neutron
- η_t 44% thermal to electric conversion
- η_a 20% accelerator efficiency

G = 65 (ie: $1MW_{target} \rightarrow 65\ MW_e$ net output)

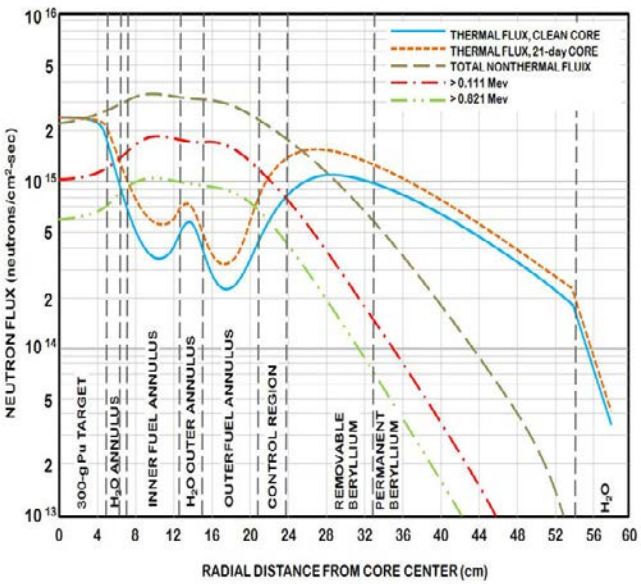
$$G = \frac{\text{net electric power out}}{\text{power on target}} \approx 4.6m - \frac{1}{\eta_a}$$

Design criteria: large m (fissions per neutron), reduces need to maximize η_a (accelerator efficiency)

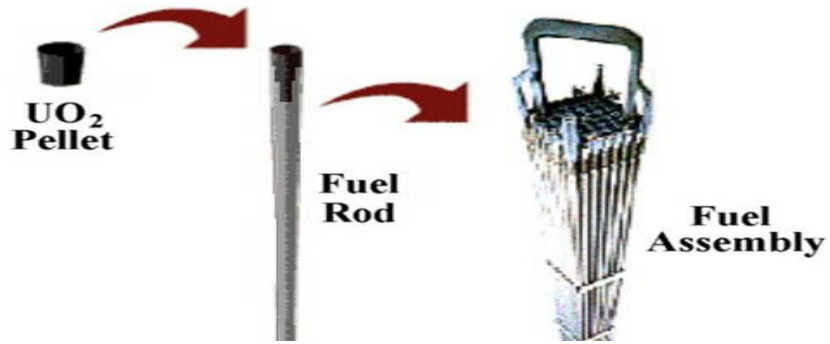
eg: changing accelerator efficiency from 20% to 10% only lowers G from 65 to 60

Today's accelerators are already efficient enough.

Solid Fuel Issues



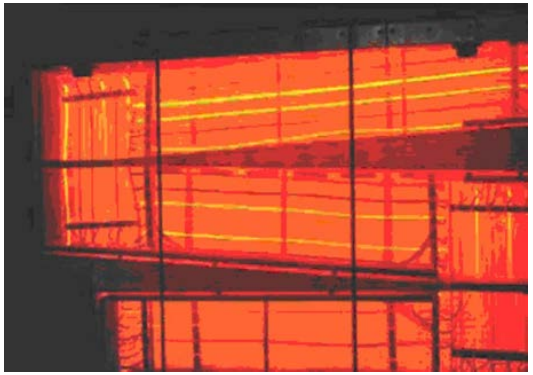
non-uniform fuel consumption requires fuel repositioning



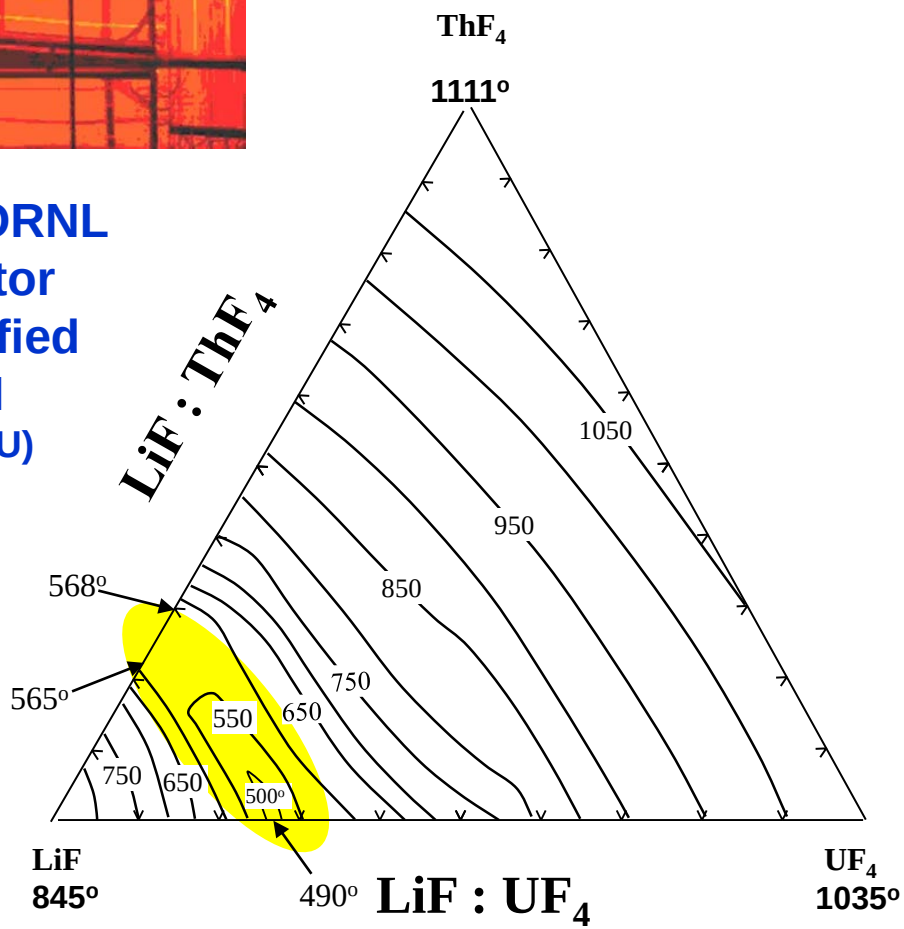
volatile fission-product build-up within cladding

thermal shock due to beam trips (~800↔320)

Molten Salt Eutectic Fuel



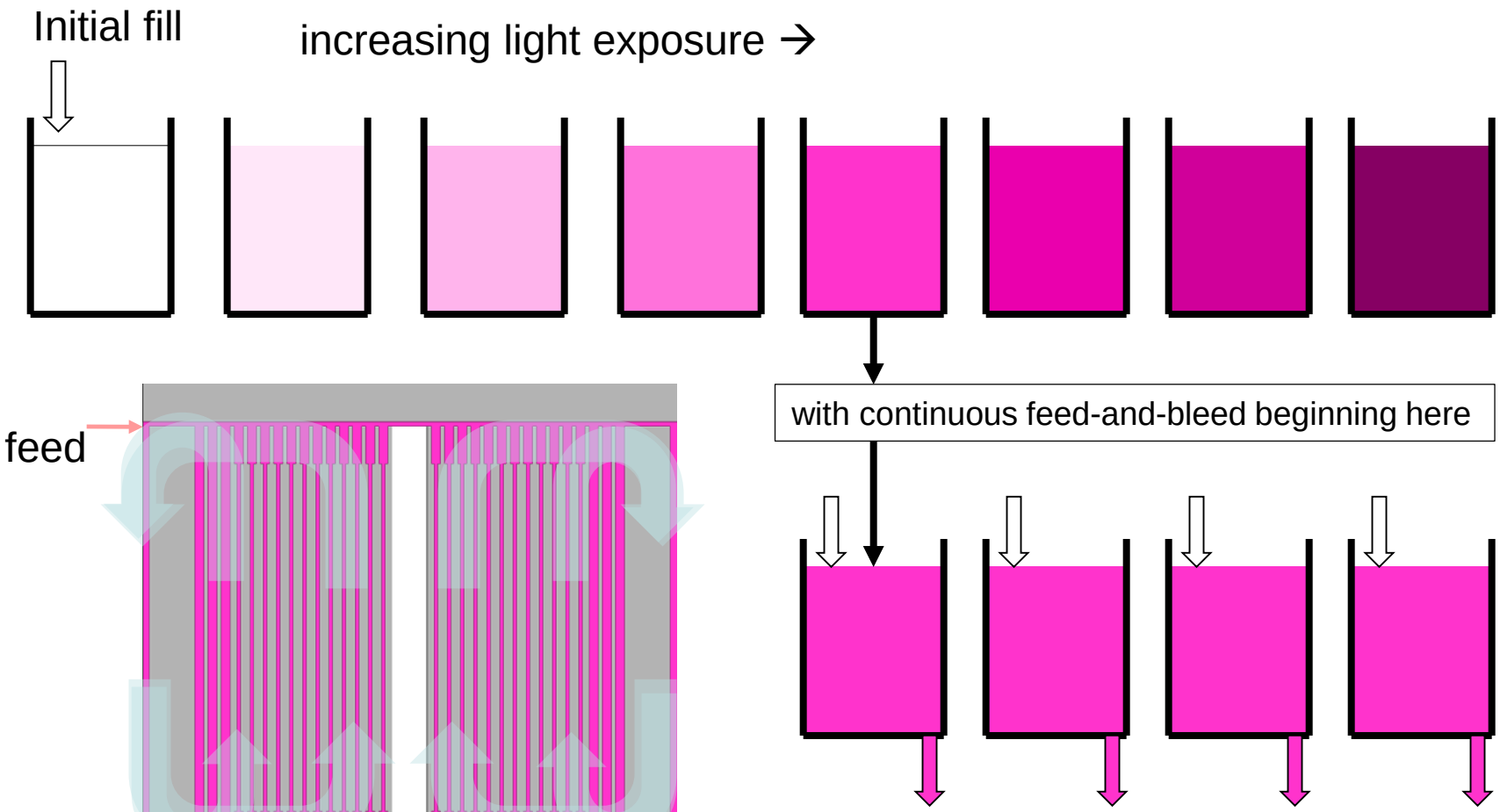
Proven in ORNL MSRE reactor using Modified Hastelloy-N
(^{235}U, ^{239}Pu, ^{233}U)

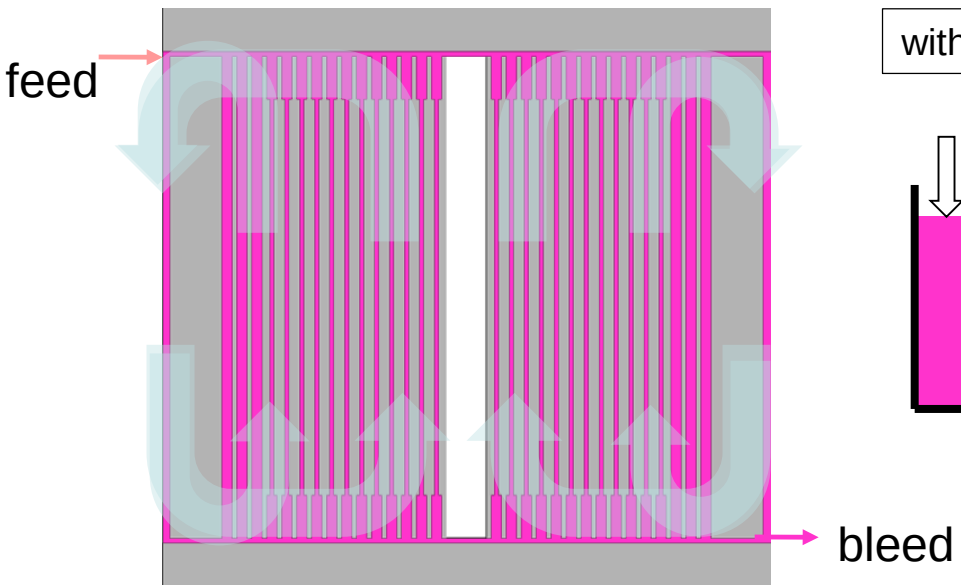


Uranium or Thorium fluorides form eutectic mixture with ^{7}LiF salt.

High boiling point → low vapor pressure

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





fast internal mixing

color and heat output remains constant indefinitely

→ equilibrated isotope fractions throughout core and throughout time

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

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

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

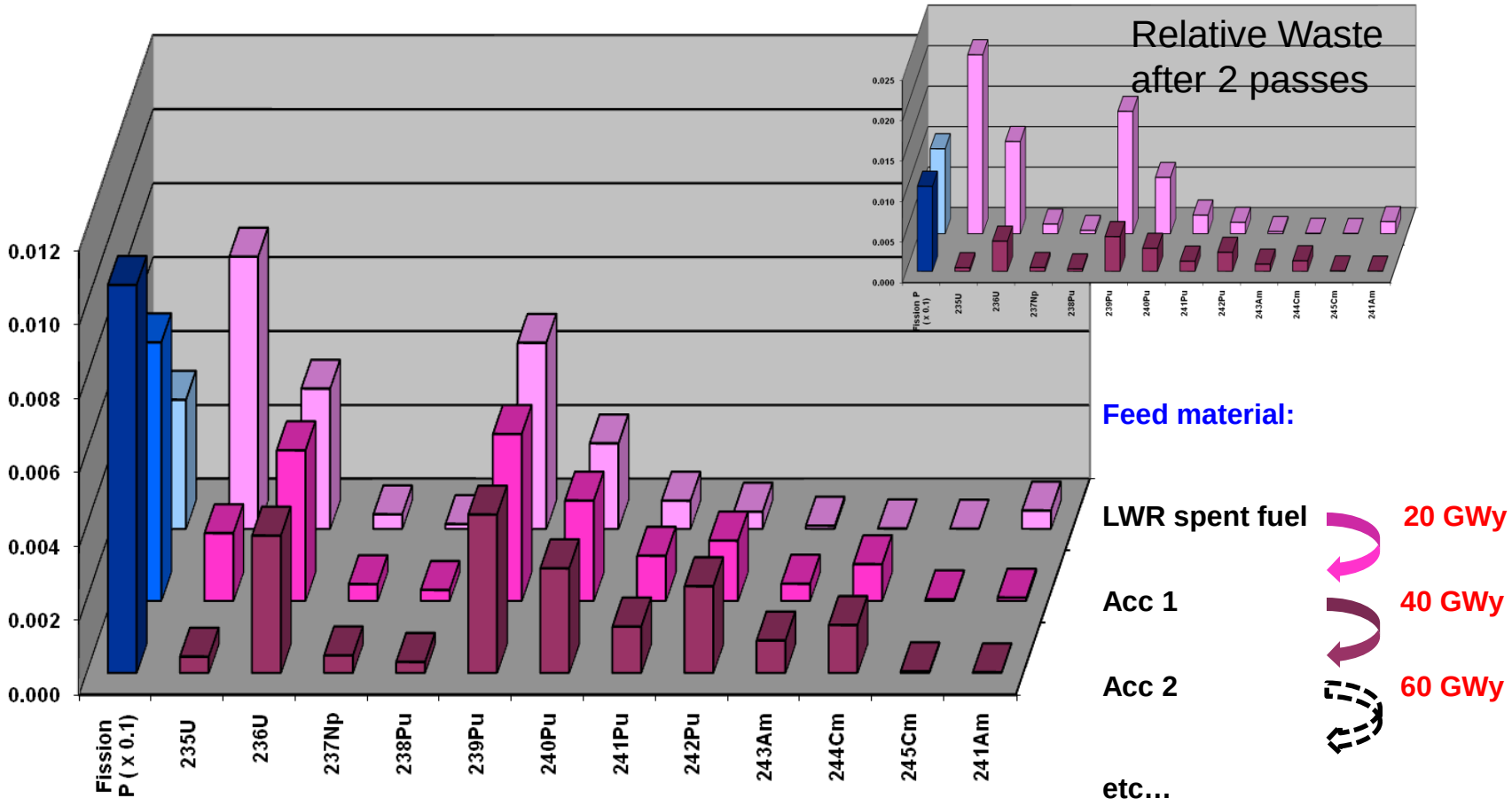
and its $n_{capture}$ and β_{decay} daughters are given by

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

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

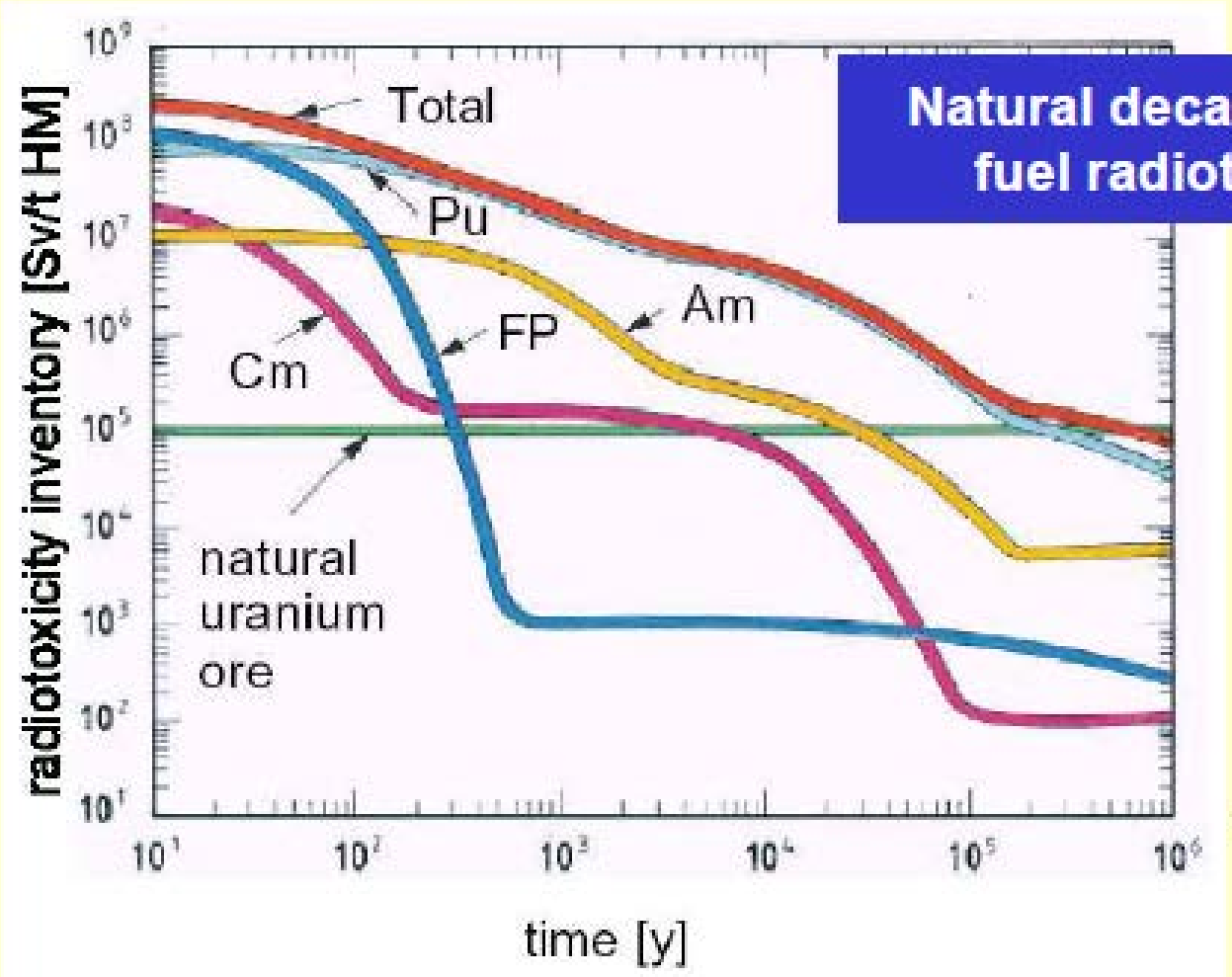
note: feed rate is determined by power extracted

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



major reduction and deferral of waste

Natural decay of spent fuel radiotoxicity



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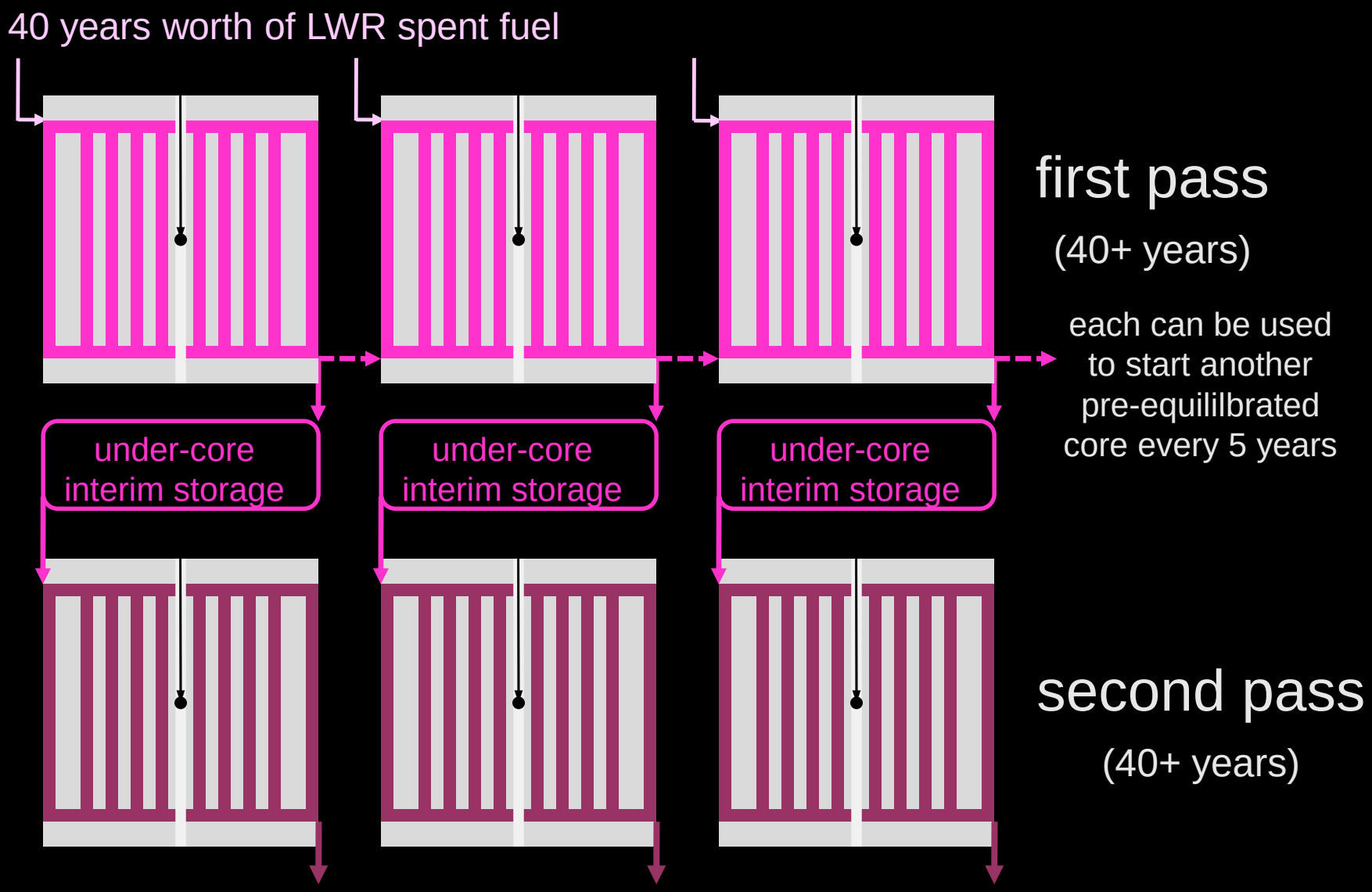
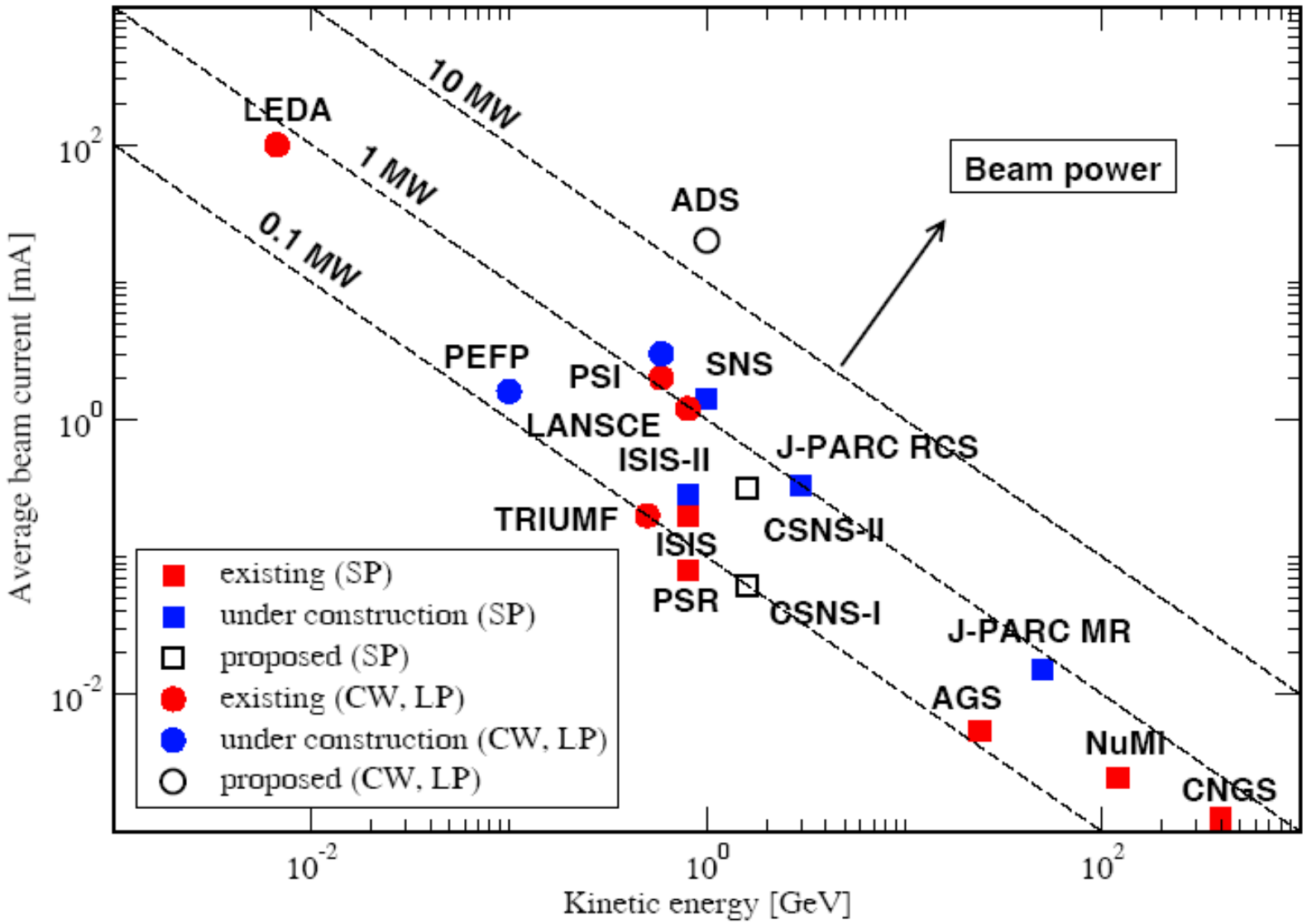
Recycling

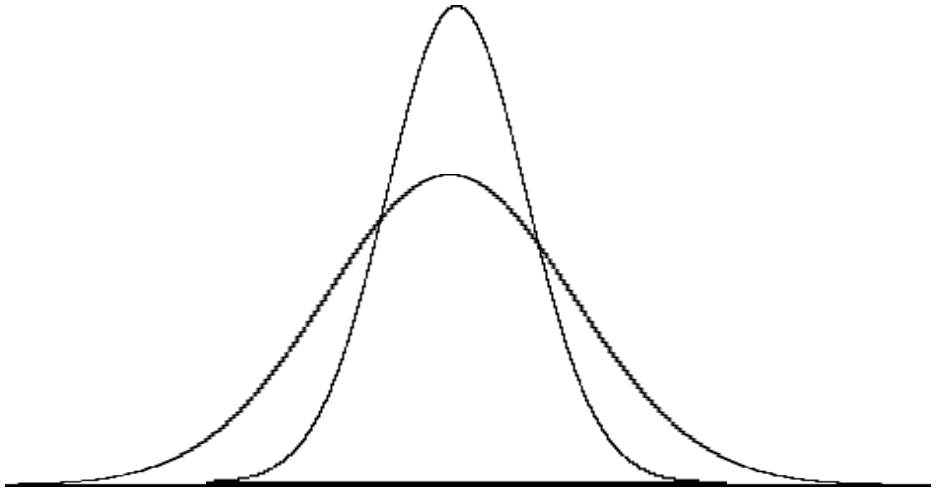


subsequent passes… (fusion n source?)

Existing Proton Beam Power



Target Considerations

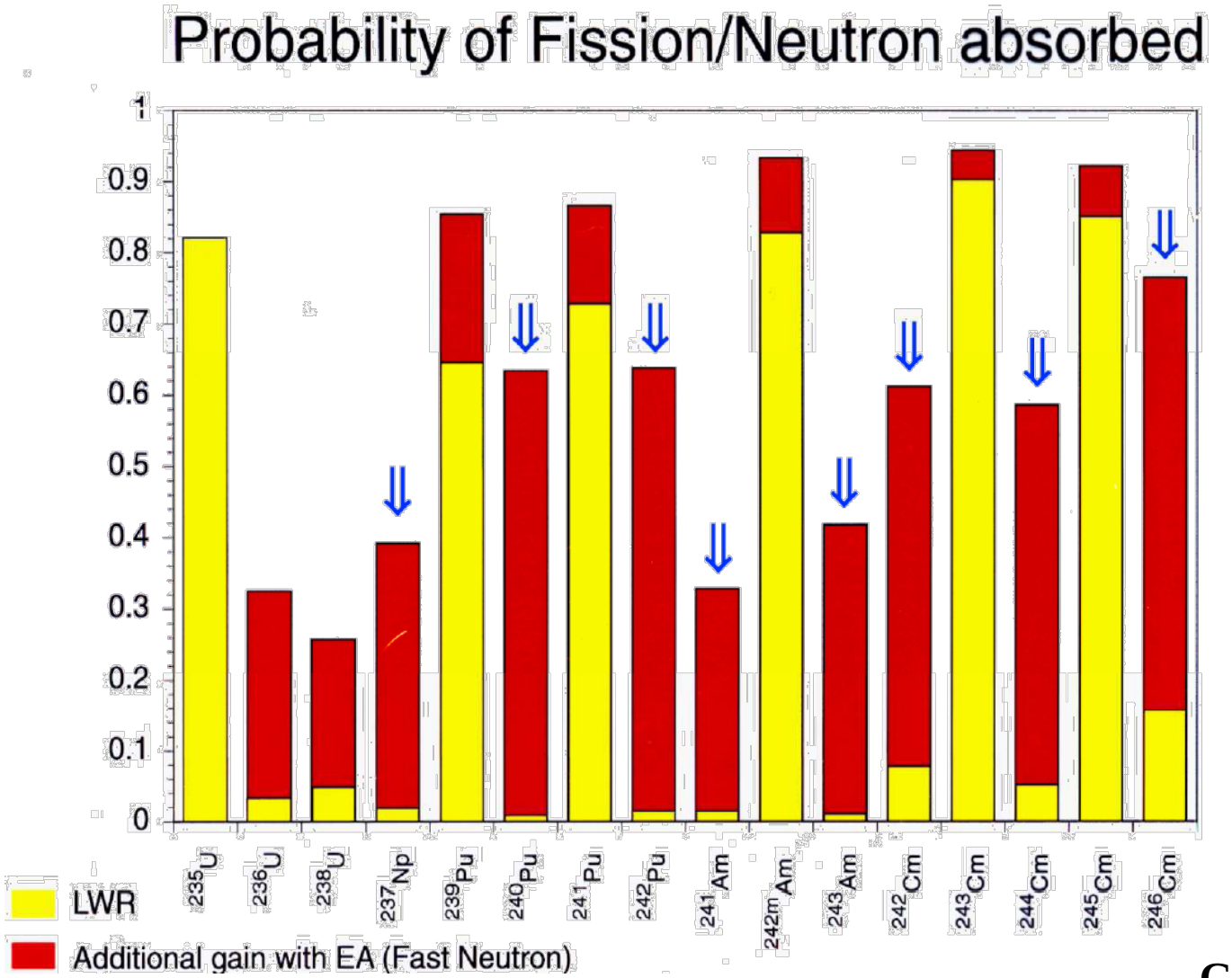


- **using "k_{eff}" is really *very* misleading for a driven system**
- **a driven system should not have the standard neutron reflector around the core**

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:

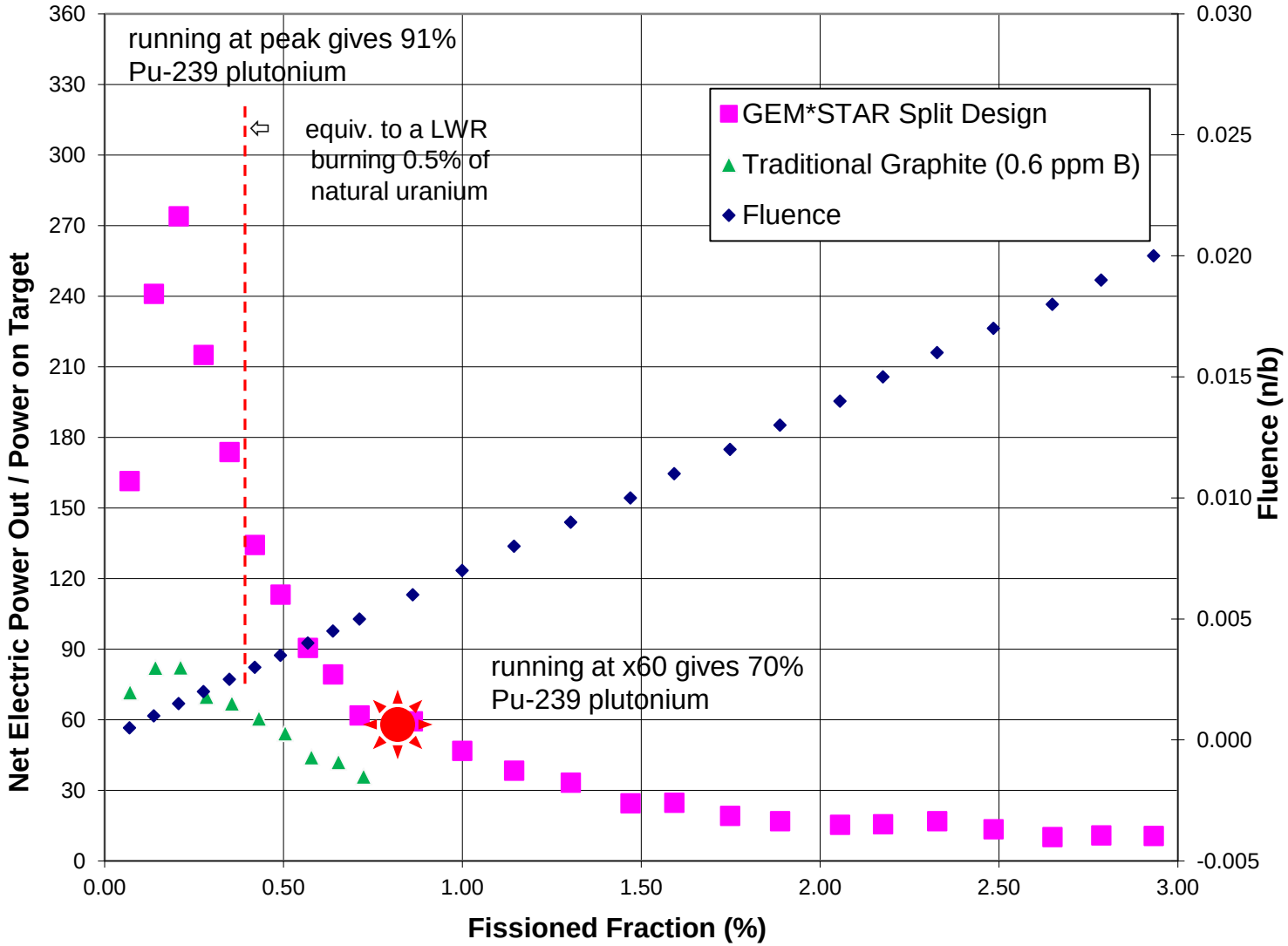
- spin structure and resonance spacing reduces capture cross-section at thermal energies:

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

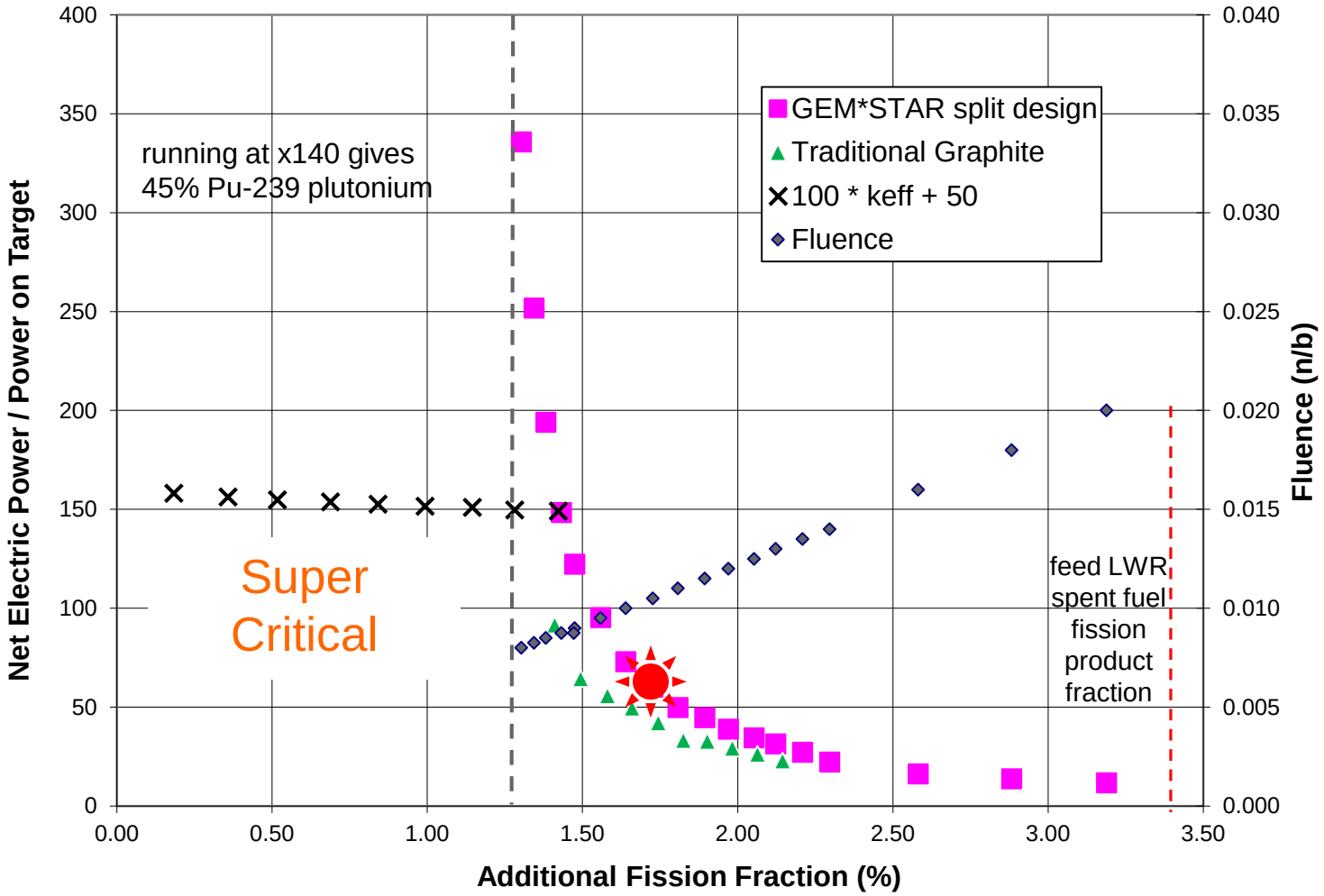
- ^{151}Sm (transmuted rapidly to low σ_c nuclei)
- ^{135}Xe (continuously removed as a gas)

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

Fuel: Natural Uranium (MCNPX)



Fuel: un-reprocessed Light-Water-Reactor spent fuel



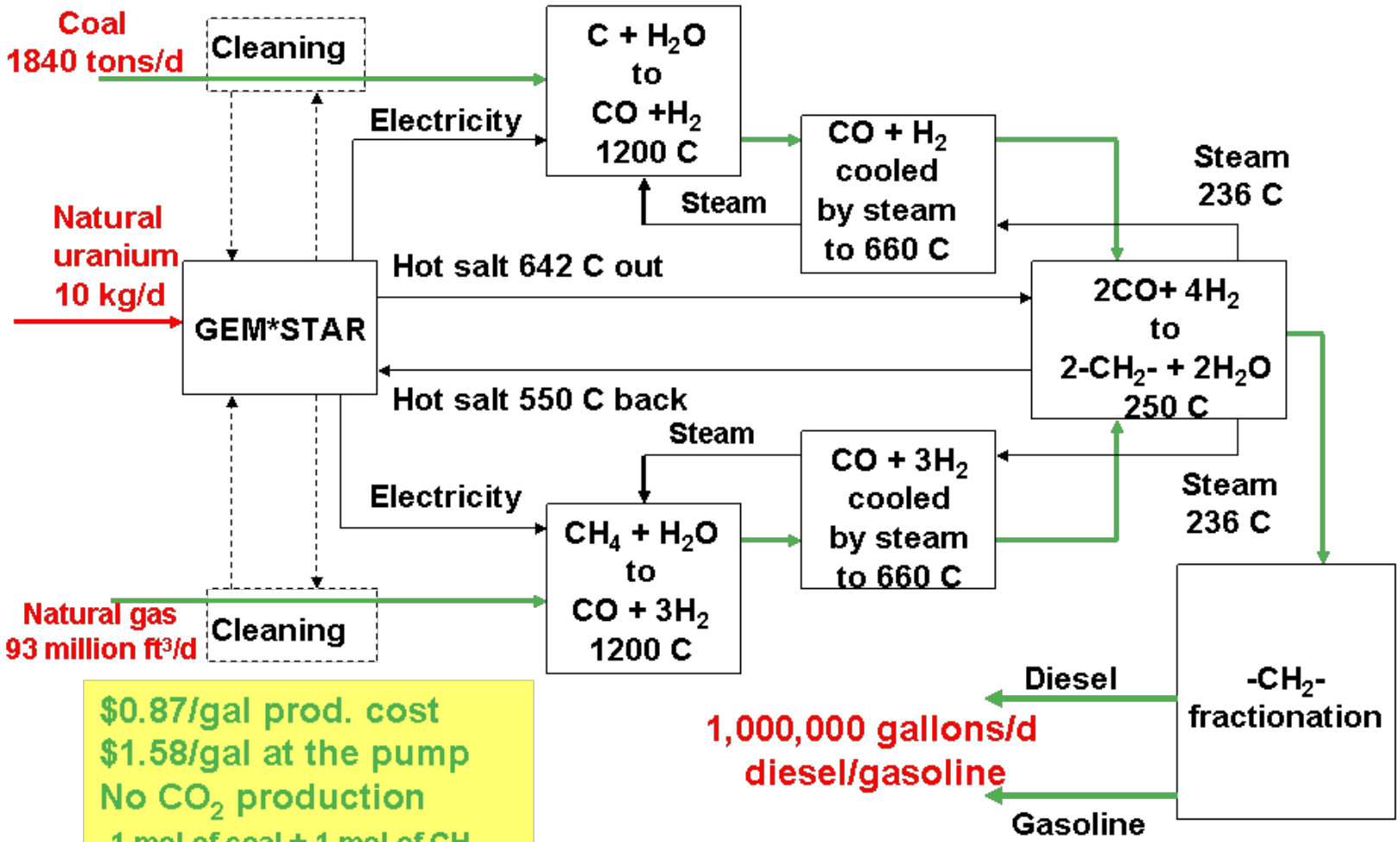
GEM*STAR System

no enrichment; no reprocessing; can burn MANY fuels (pure, mixed, *including* LWR spent fuel) with no redesign required

High Temperature MS Advantages over LWRs

- no high-pressure containment vessel
- 34% → 44% efficiency for thermal to electric conversion (low-pressure operation)
- match to existing coal-fired turbines, enables staged transition for coal plants, addressing potential "cap-and-trade" issues
- synthetic fuels via modified Fischer-Tropsch methods – very attractive (much more realistic than hydrogen economy)

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

GEM*STAR

What are the obstacles?

- GEM*STAR uses liquid fuel – but NRC is only "comfortable" with solid fuel, despite MSRE success
- Existing commercial deployed fleet of LWRs
- Engineers in nuclear industry have little experience with accelerators; physicists using accelerators have little experience with nuclear power plants ⇒ little cooperation in base programs (vague talk about a distant ATW application)
- current focus (in US) only on existing and new "modular" reactors (scaled down versions of existing deployed technology)

resulting in policies such as

- **DOE NE Report to Congress, April 2010, "Nuclear Energy Research and Development Roadmap" does not include the word 'accelerator' even once.**
- **DOE Science (HEP & NP) ADS Report (September 17, 2010)**
  - **Finding #2: Accelerator-driven sub-critical systems offer the potential for safely burning fuels which are difficult to incorporate in critical systems, for example fuel without uranium or thorium. [WHY not U ???]**
  - **Finding #3: Accelerator driven subcritical systems can be utilized to efficiently burn minor actinide waste.**
  - **Finding #4: Accelerator driven subcritical systems can be utilized to generate power from thorium-based fuels**
- **MIT Energy Initiative; Obama's Blue Ribbon Panel**
  - **100 year horizon, no new direction, yet continue DOE-NE funding at current level**
- **DOE NE "thinking about an ADS demonstration in 2050" (ie, when I'm 90 ☹)**

ADS Technology Readiness Assessment

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance			
	Reliability			
Accelerating System	RF Structure Development and Performance			
	Linac Cost Optimization			
	Reliability			
RF Plant	Performance			
	Cost Optimization			
	Reliability			
Beam Delivery	Performance			
Target Systems	Performance			
	Reliability			
Instrumentation and Control	Performance			
Beam Dynamics	Emittance/halo growth/beamloss			
	Lattice design			
Reliability	Rapid SCL Fault Recovery			
	System Reliability Engineering Analysis			

Green: “ready”, Yellow: “may be ready, but demonstration or further analysis is required”, Red: “more development is required”.

how is this rationalized?

Table 1: Range of Parameters for Accelerator Driven Systems for four missions described in this whitepaper

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

…helps motivate "Intensity Frontier" (ie: **Project X** at **Fermilab)**;
but higher efficiency via higher-power beams is not a requirement;
$100's of millions are going into solar and wind which have ***far*** greater outages.

DOE-NE: "It takes about 20 years to validate any new fuel system, so 2050 is the earliest one might imagine for ADS."

…based on input from solid-fuel manufacturers;
but consider how this might change if a new system ***actually*** addressed waste, proliferation, LWR spent fuel usage, and safety (thus becoming politically, publicly, and financially desirable).

People (and agencies), in the US and India, and pretty much everywhere, are legitimately afraid that if they 'blink' they might lose what they already have.

Or that if they don't first obtain consensus opinion they won't get new funding.

How can one then even try GEM*STAR in this environment?