Invent
the
Future

ADNA & GEM*STAR Consortium

GEM*STAR

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

R. Bruce Vogelaar
Virginia Tech
December 12, 2011

ADS & TU Mumbai, India

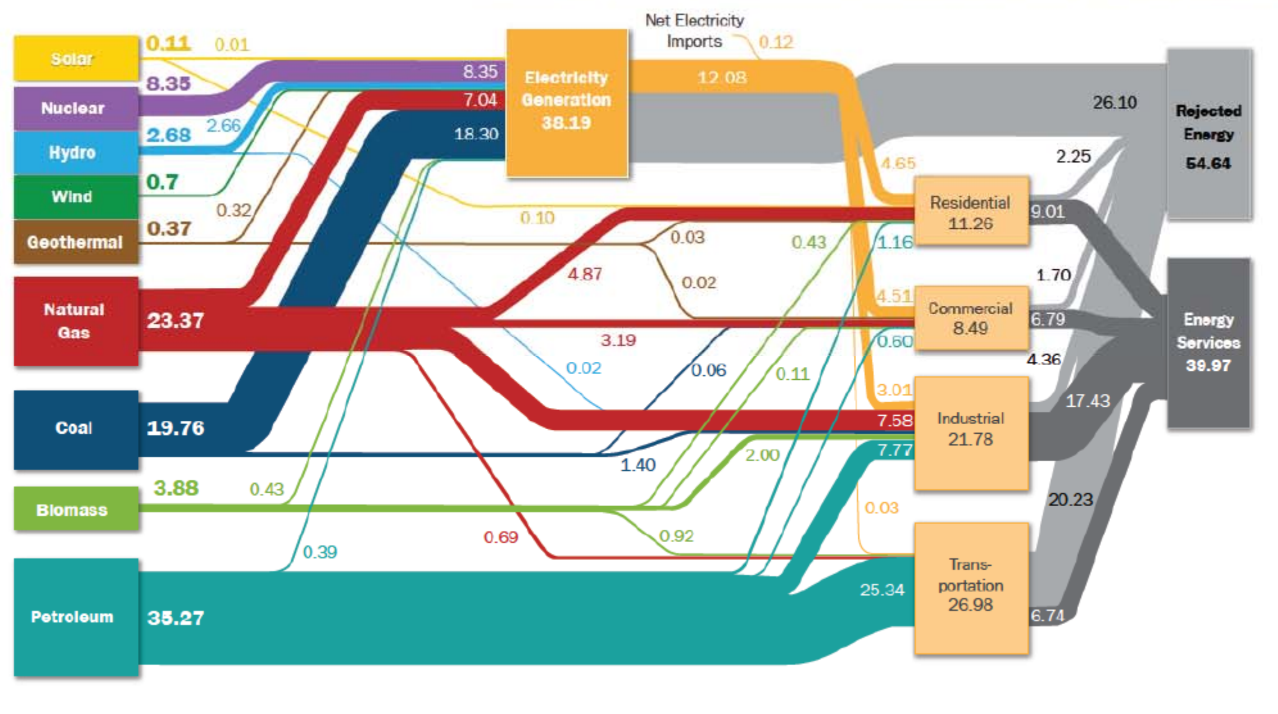
view from a newcomer

(who asks and perhaps answers questions in a slightly different way)

U.S. energy flow in 2009 and our goals

"By 2035, 80 percent of America's electricity wil come from clean energy sources"-- change the mix.

Reduce per capita consumptio



Values are in quadrillion british thermal units. Total energy input is approximately 95 Quads. EIA data as portrayed by Lawrence Livermore National Laboratory.[17]

Reduce the ratio (rejected/ used)– increase energy efficiency.

Address the consequences of GHG emission -- goal for 2050 emissions is 50% of 2000 emissions, i.e., 12.8 Gt/yr*.

Mitigation

Adaptation

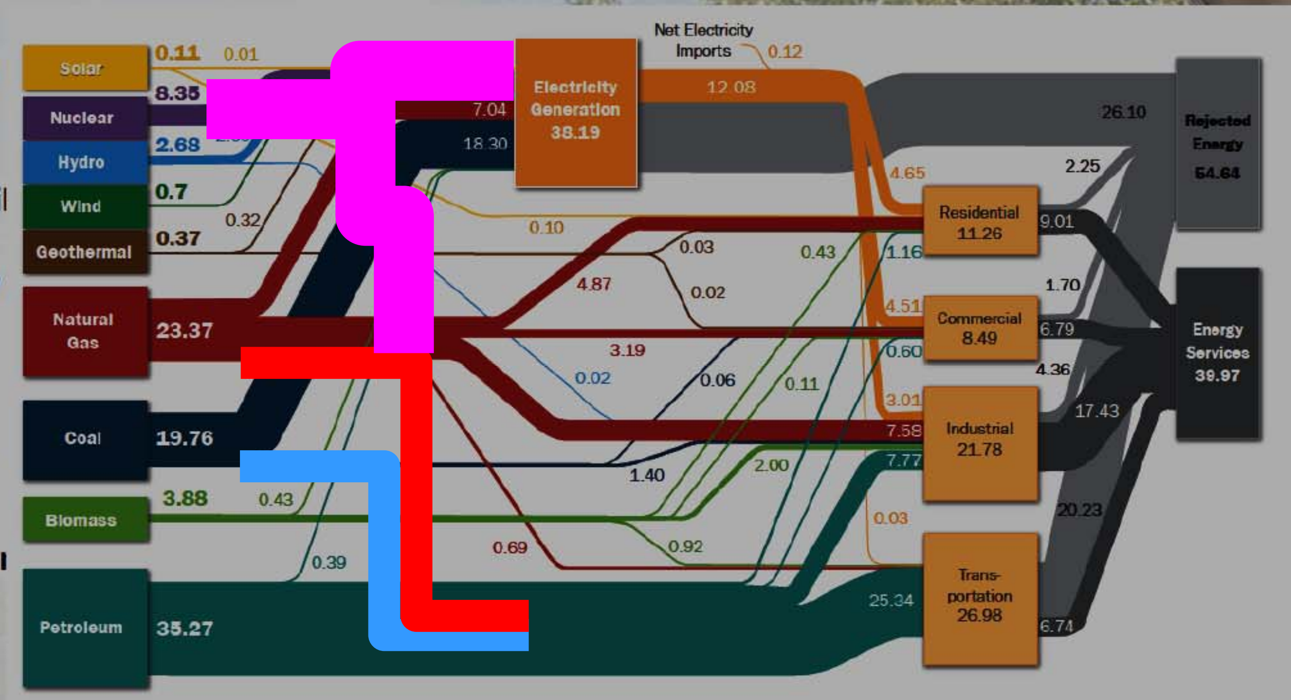
* e.g., 1 Gt (Gigaton) of GHG is equivalent to building 273 'zero emission' 500MW coal-fired plants

the classic ‘nuclear’ option

U.S. energy flow in 2009 and our goals

“By 2035, 80 percent of America’s electricity wil[l] come from clean energy sources”-- change the mix.

Reduce per capita consumptio[n]



Values are in quadrillion british thermal units. Total energy input is approximately 95 Quads. EIA data as portrayed by Lawrence Livermore National Laboratory.[17]

Reduce the ratio (rejected/used)– increase energy efficiency.

Address the consequences of GHG emission -- goal for 2050 emissions is 50% of 2000 emissions, i.e., 12.8 Gt/yr*.

Mitigation

Adaptation

* e.g., 1 Gt (Gigaton) of GHG is equivalent to building 273 ‘zero emission’ 500MW coal-fired plants

Invent the Future

ADNA & GEM*STAR Consortium

What are the obstacles?

in the US:

- safety
- waste
- weapons proliferation
- cost

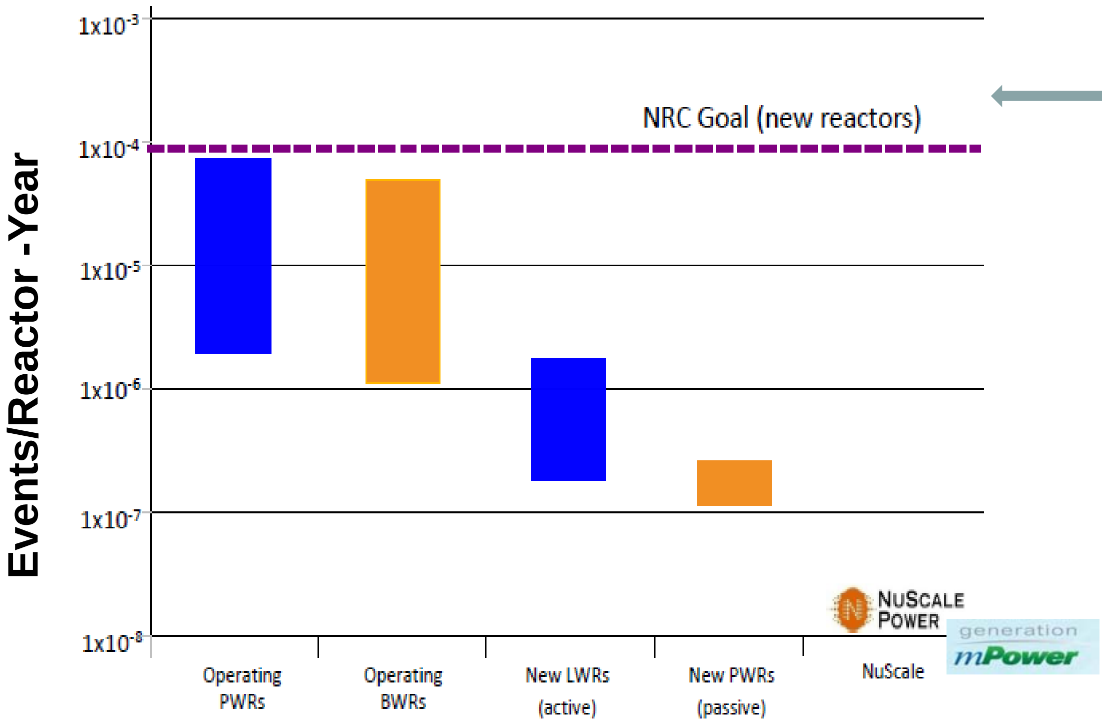
in India?

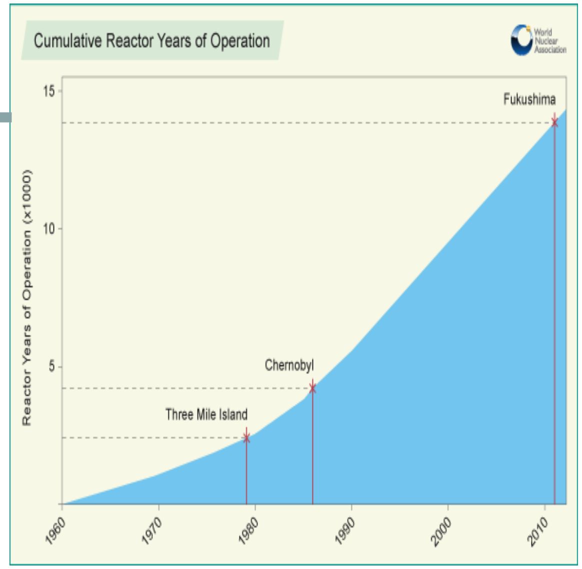
Invent the Future

ADNA & GEM*STAR Consortium

➢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?…

GEM*STAR

- **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**

Invent the Future

ADNA & GEM*STAR Consortium

➢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

GEM*STAR

Invent the Future

ADNA & GEM*STAR Consortium

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)

GEM*STAR

Invent
the
Future

ADNA & GEM*STAR Consortium

Are there other avenues to explore?

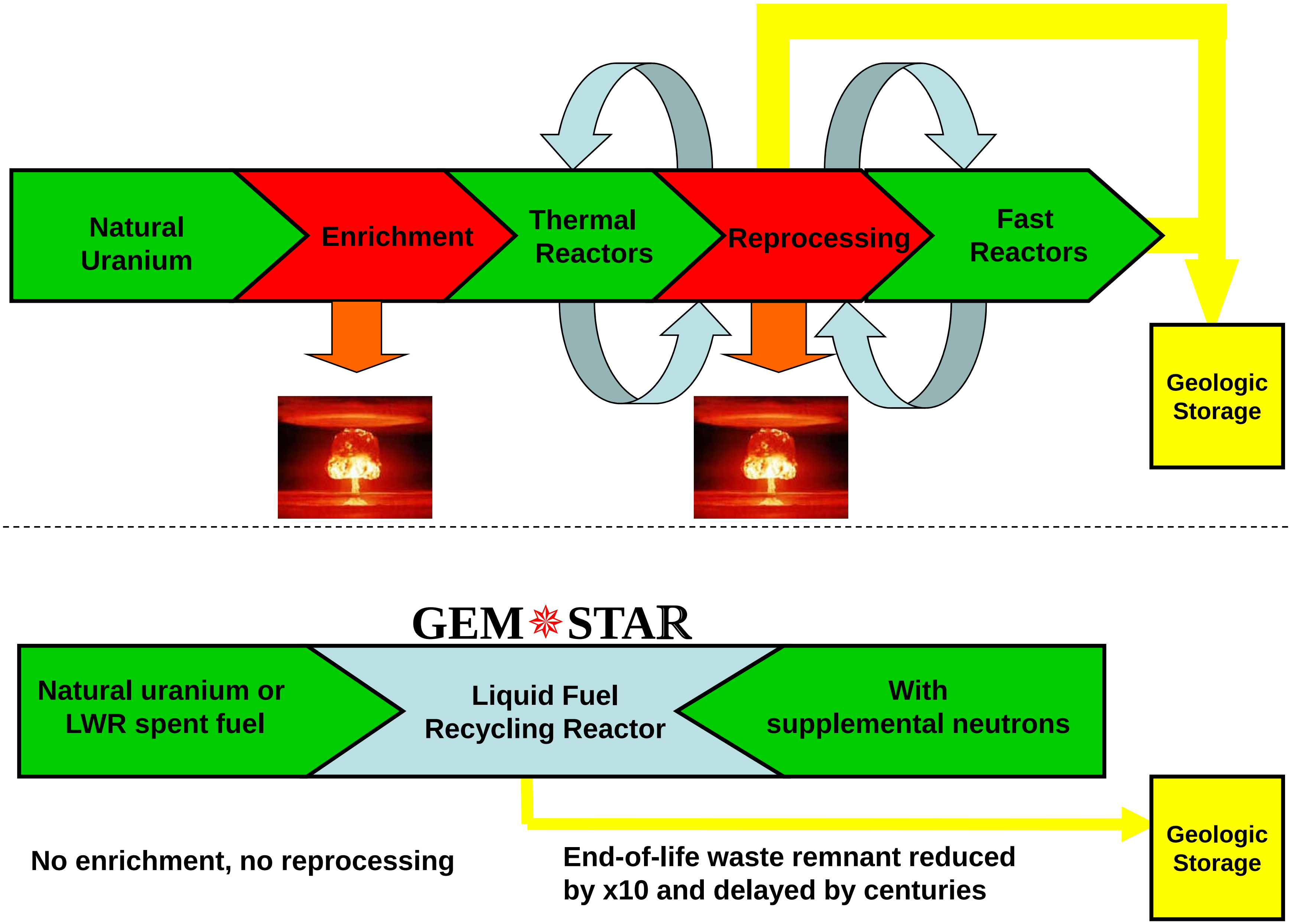
- to address ‘clean energy’ ‘now’
- that would compete today with coal costs
- not being ‘captured’ by the previous slide
- low enough cost to try without requiring broad ‘consensus’ first

GEM*STAR

Invent the Future

ADNA & GEM*STAR Consortium

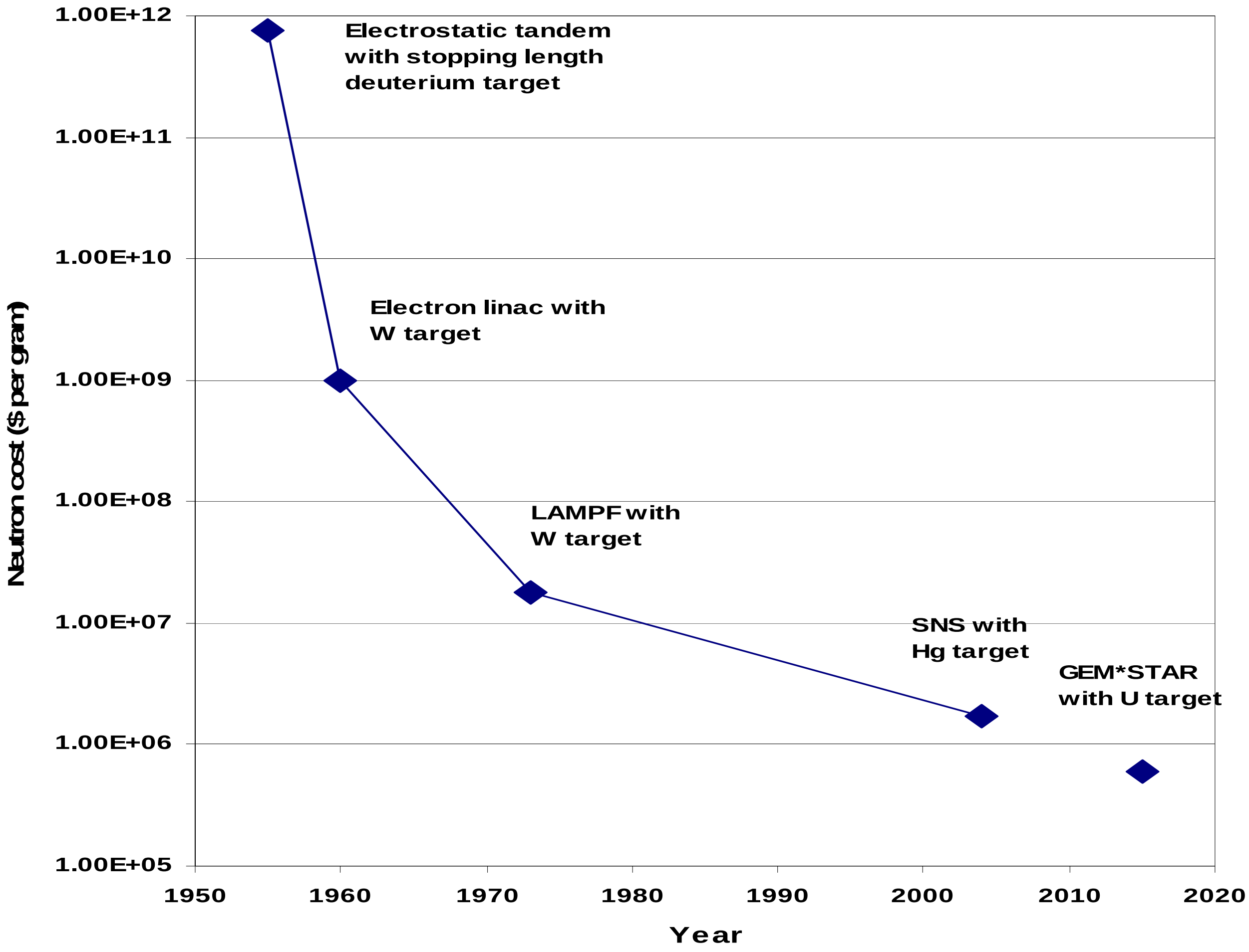
Base Energy Paradigm Shift



Invent
the
Future

ADNA & GEM*STAR Consortium

The cost of neutrons has dropped dramatically

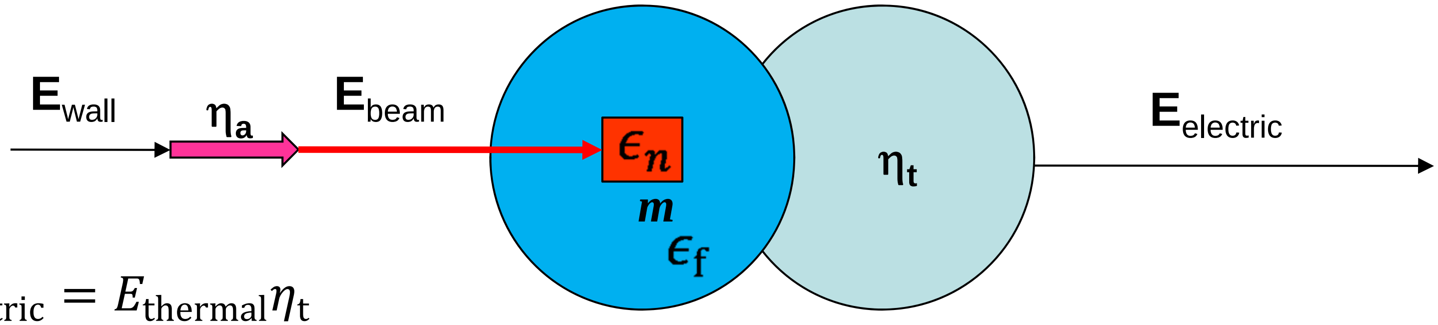


~40 grams of neutrons will produce 1GWe for one year

($432M @ 5 ¢/kWh)

GEM*STAR

Proton Driven Sub-Critical System



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

$\eta_a \equiv$ **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: $1MW_{target}$ → 65 MW_e net output)

Invent the Future

ADNA & GEM*STAR Consortium

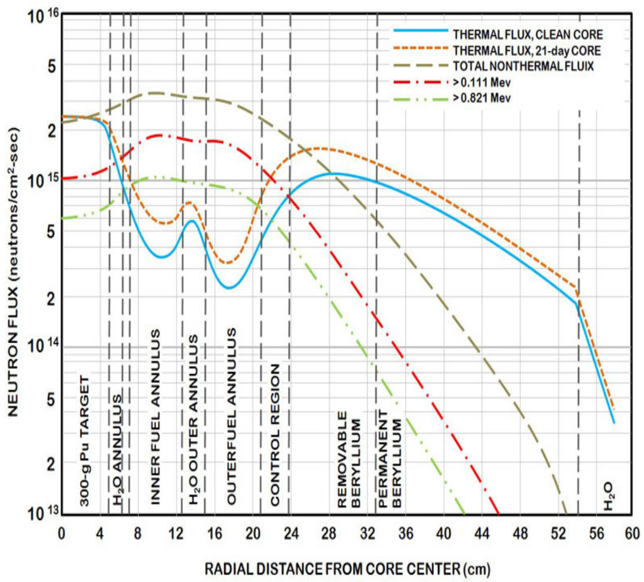
$$G = \frac{\text{net electric power out}}{\text{power on target}} \approx 4.6m - \frac{1}{\eta_a}$$

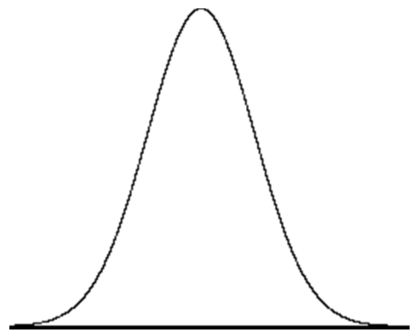
Design criteria: large m (fissions per neutron), reduces need to maximize η_a (accelerator efficiency)

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

note: using "k_{eff}" is really *very* misleading for a driven system

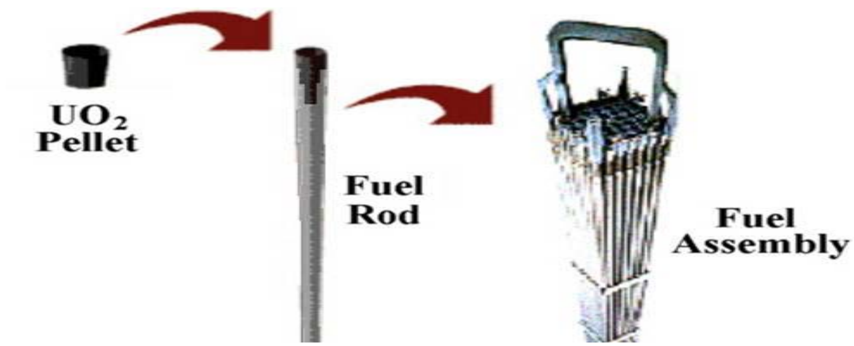
Solid Fuel Issues





much more centrally peaked for driven systems

non-uniform fuel consumption



volatile fission-product build-up within cladding

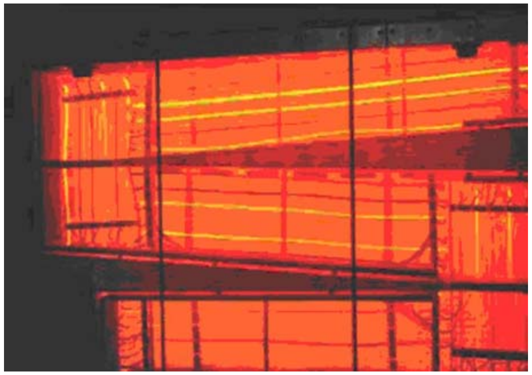
thermal shock due to beam trips (~800↔320)

GEM*STAR

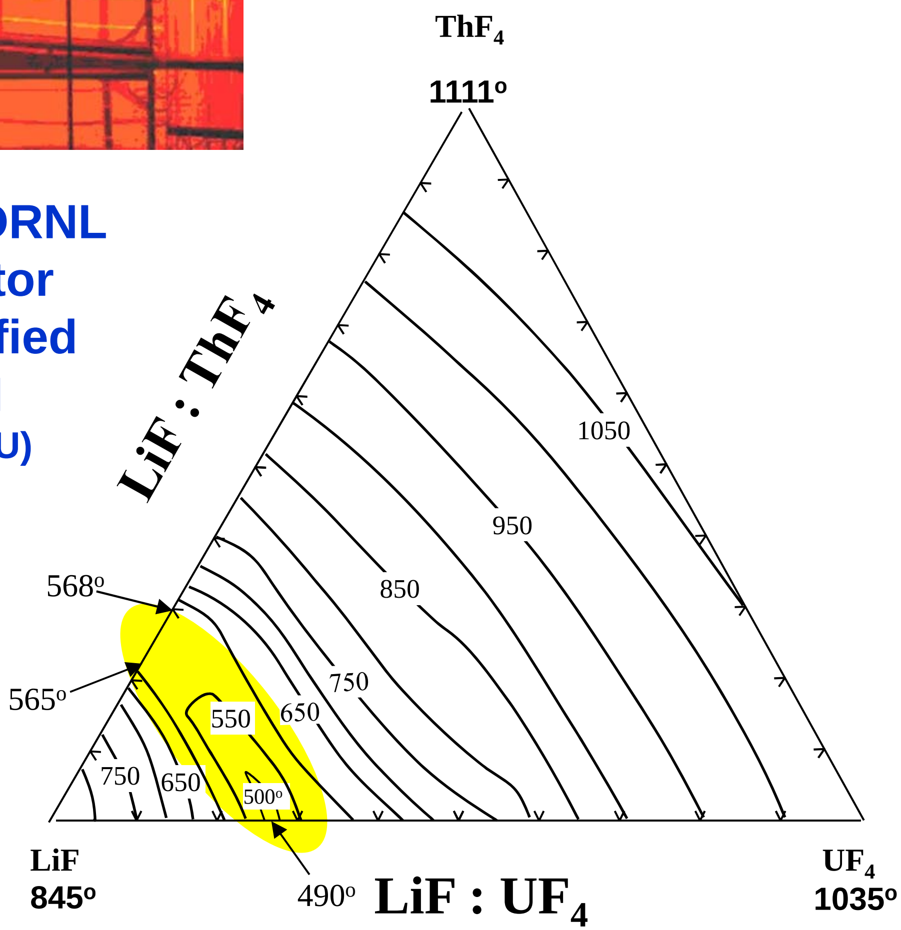
Invent the Future

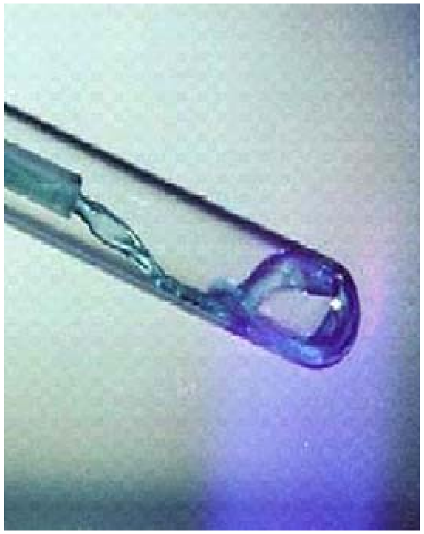
ADNA & GEM*STAR Consortium

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.

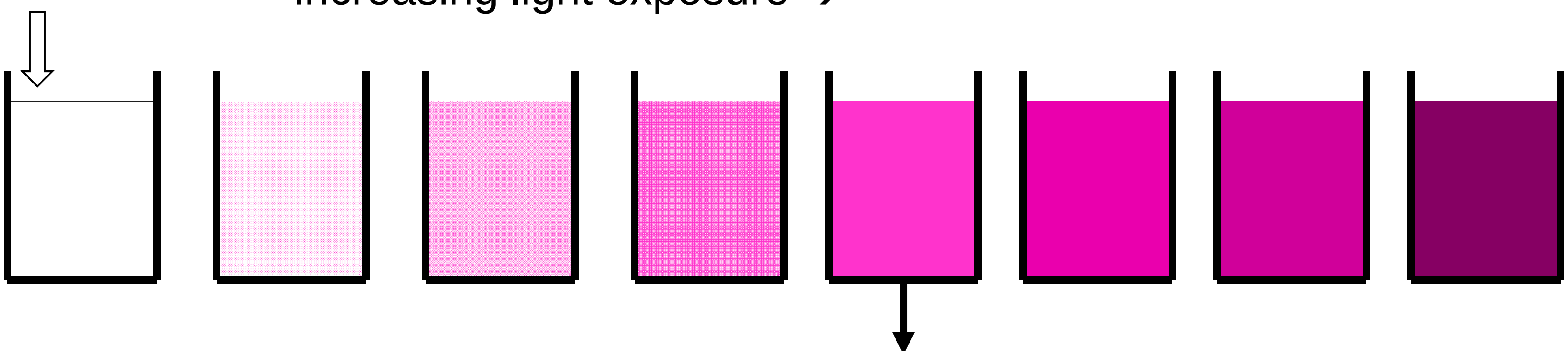
High boiling point → low vapor pressure

GEM*STAR

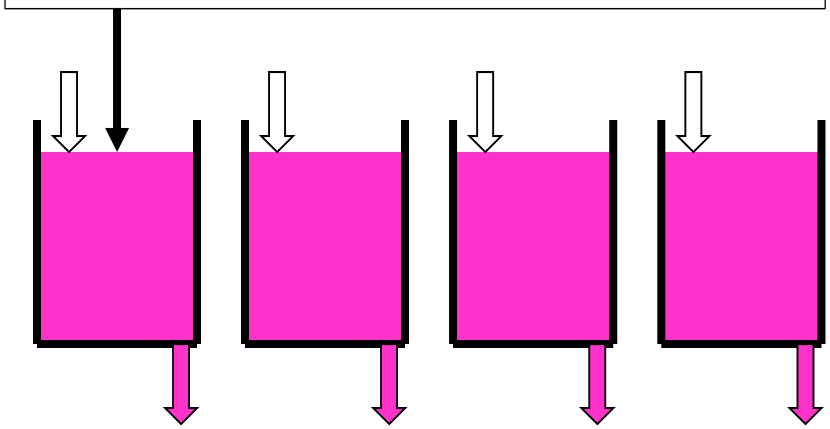
consider a clear liquid which releases heat when exposed to light, eventually turning a dark purple

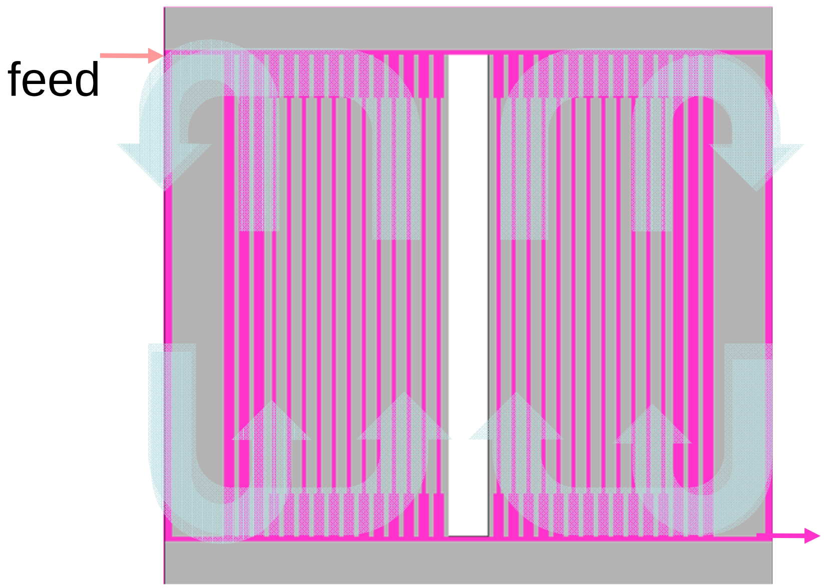
Initial fill

increasing light exposure →



with continuous feed-and-bleed beginning here





fast internal mixing

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

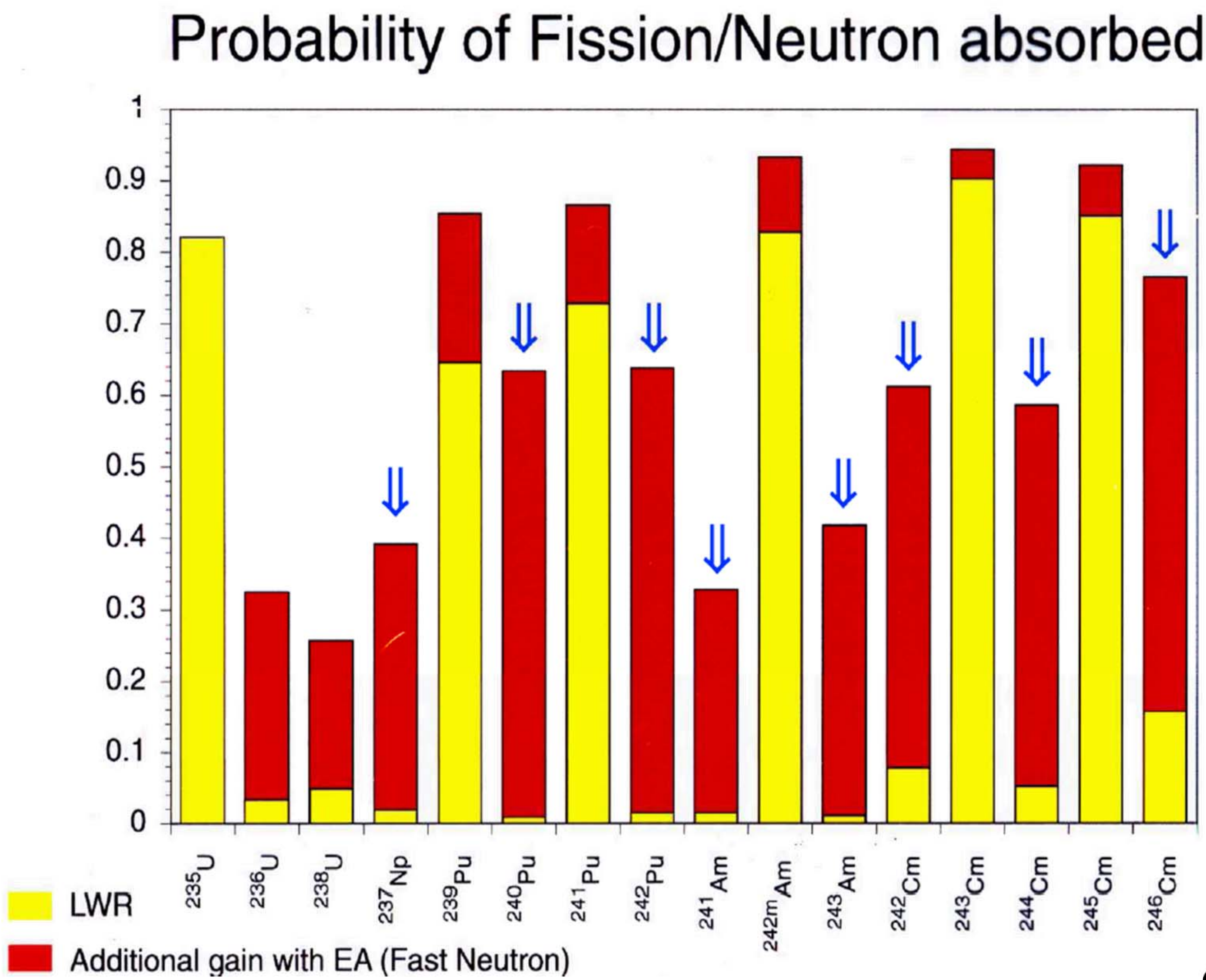
Invent the Future

ADNA & GEM*STAR Consortium

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

Why?

Faster burn-up of heavy actinides.



GEM*STAR

Invent the Future

ADNA & GEM*STAR Consortium

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:

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

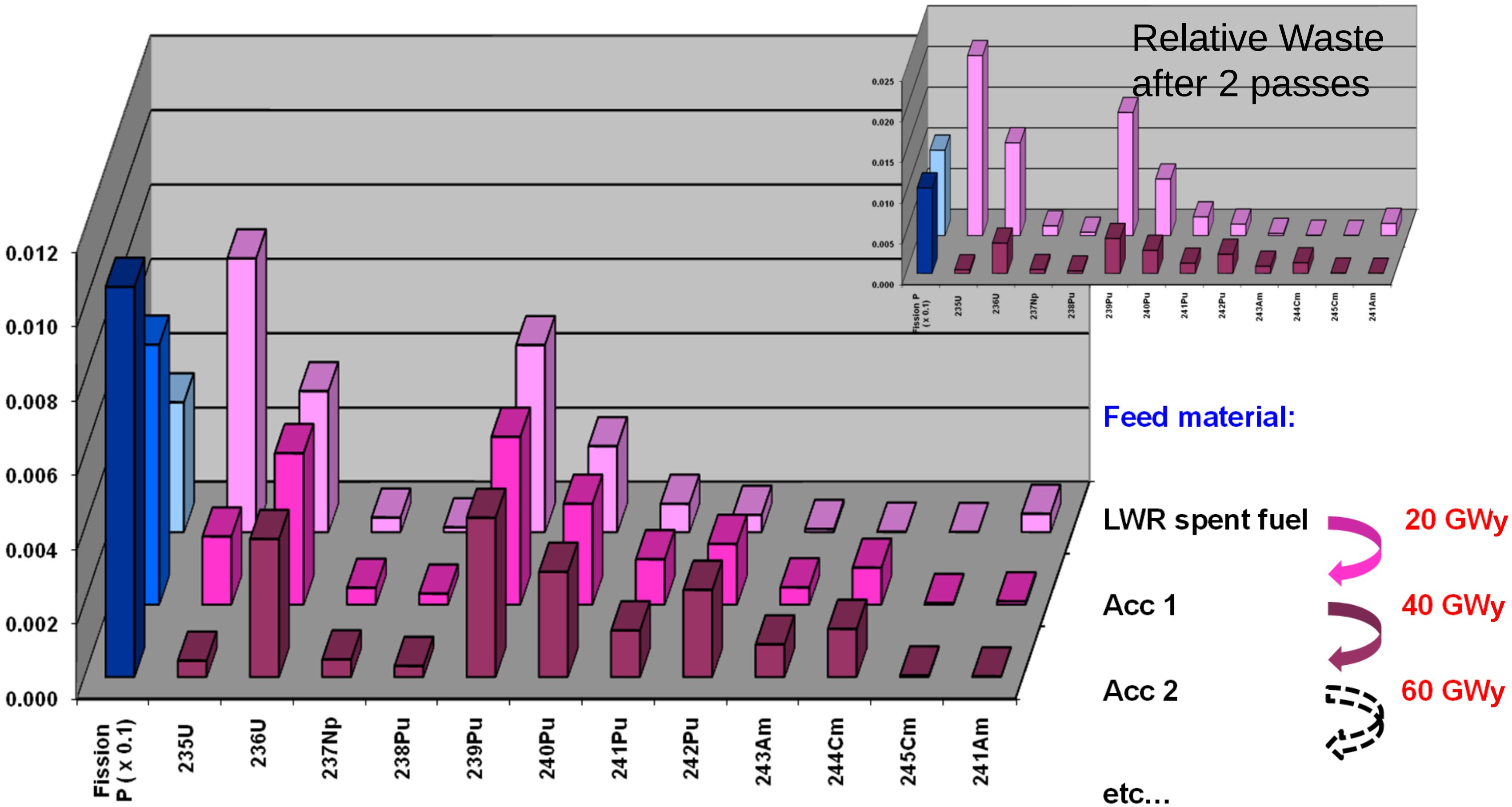
- ^{151}Sm (transmuted rapidly to low σ_c nuclei)
- ^{135}Xe (continuously removed as a gas)

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

Invent the Future

ADNA & GEM*STAR Consortium

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



major reduction and deferral of waste

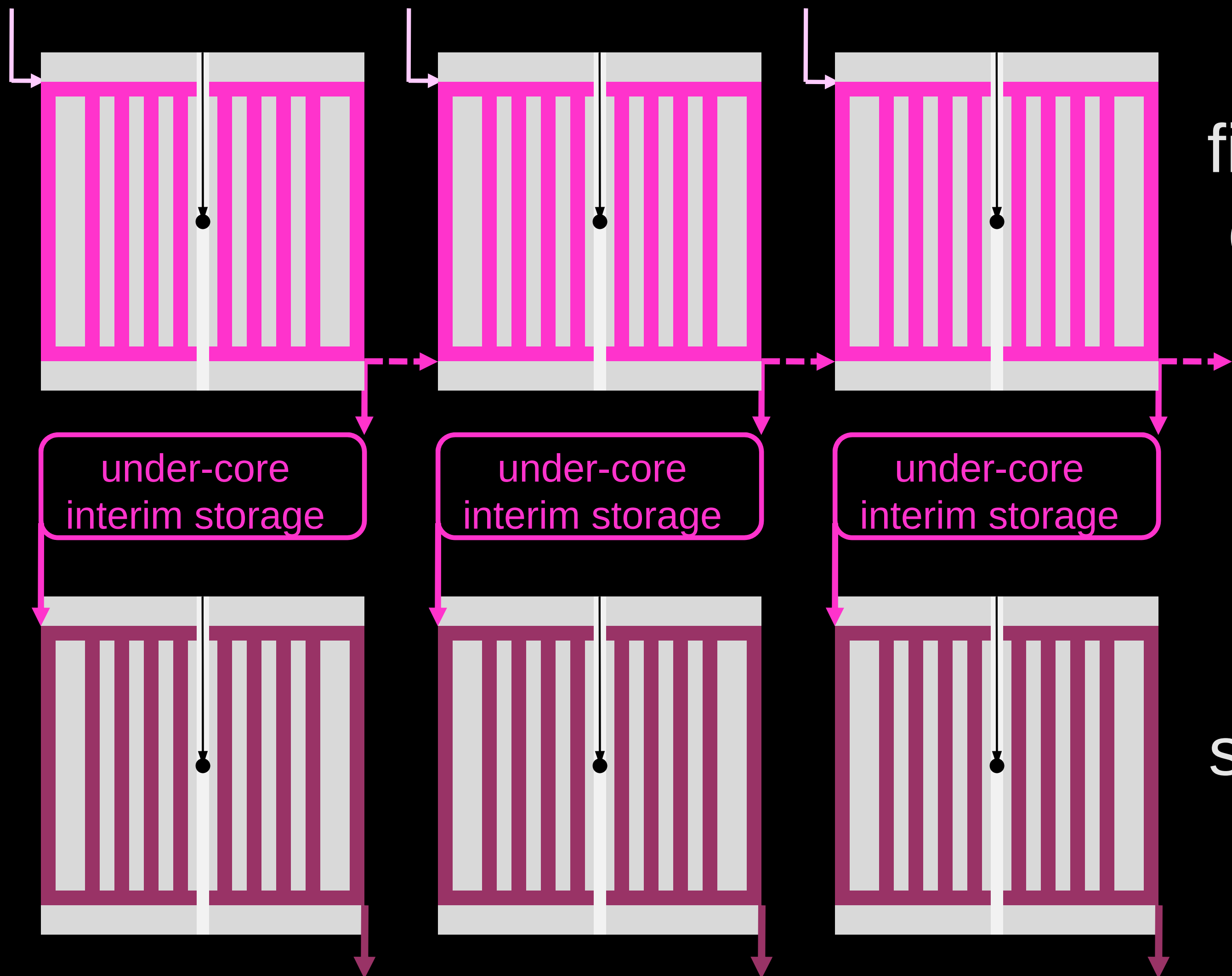
GEM*STAR

Invent the Future

ADNA & GEM*STAR Consortium

Recycling

40 years worth of LWR spent fuel



first pass

(40+ years)

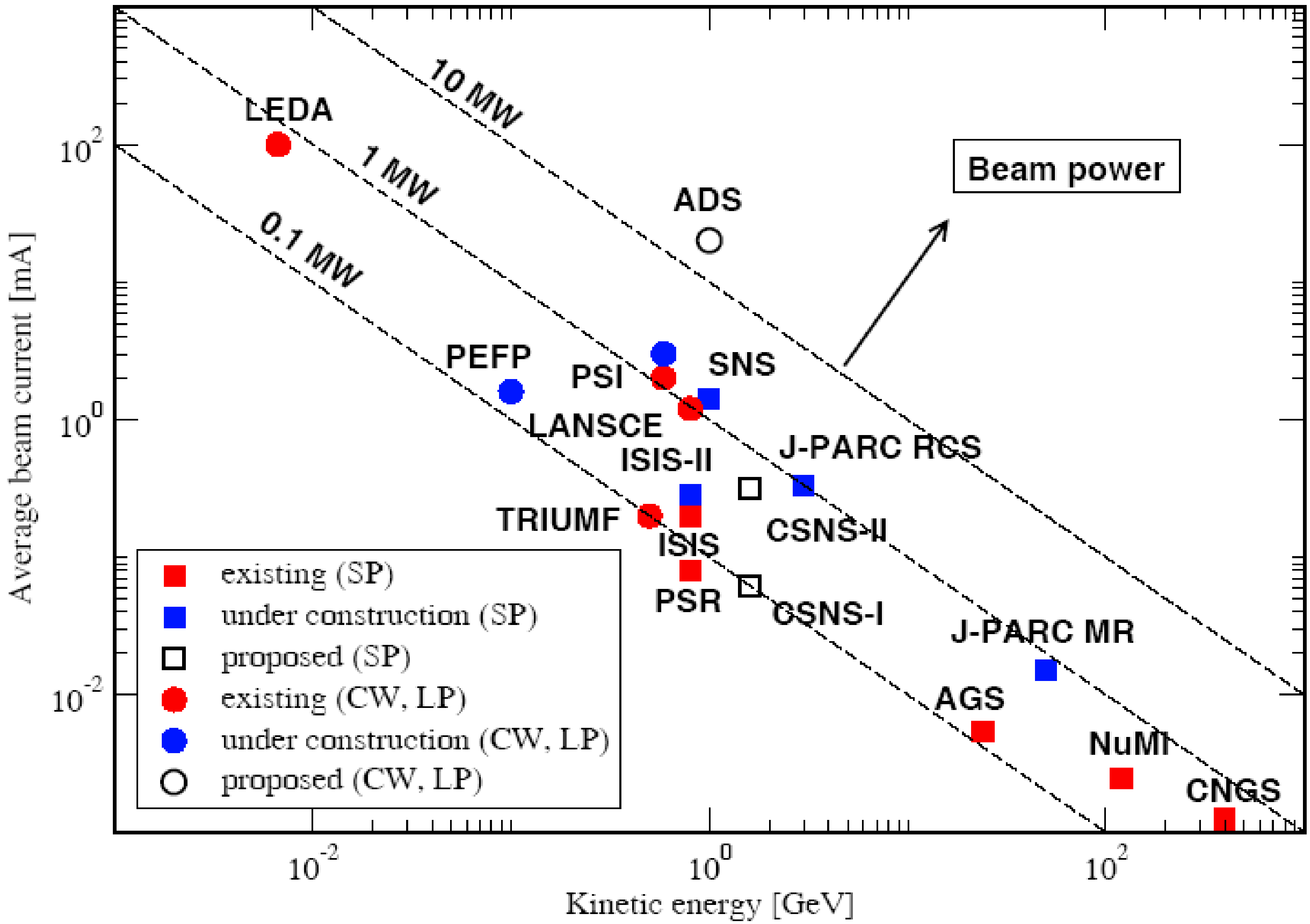
each can be used to start another pre-equilillbrated core every 5 years

second pass

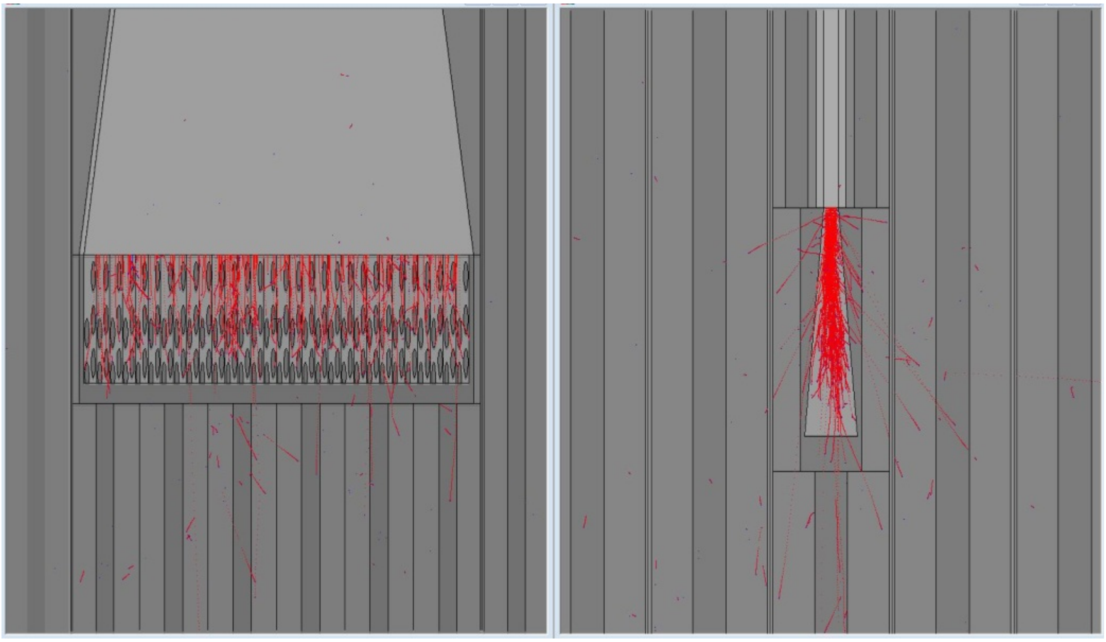
(40+ years)

subsequent passes… (fusion n source?)

Existing Proton Beam Power



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

Invent the Future

ADNA & GEM*STAR Consortium

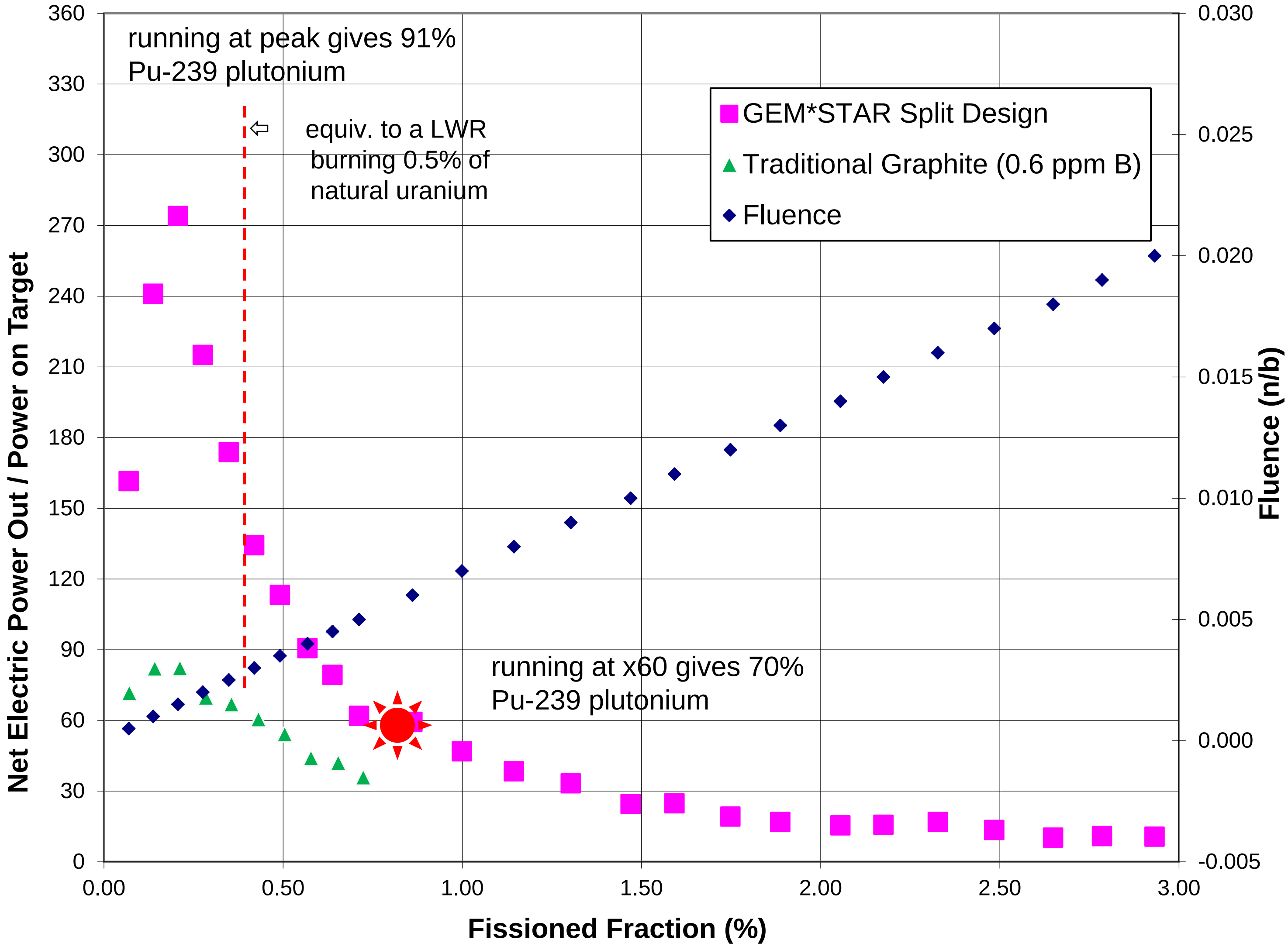
redacted

GEM STAR

Invent
the
Future

ADNA & GEM*STAR Consortium

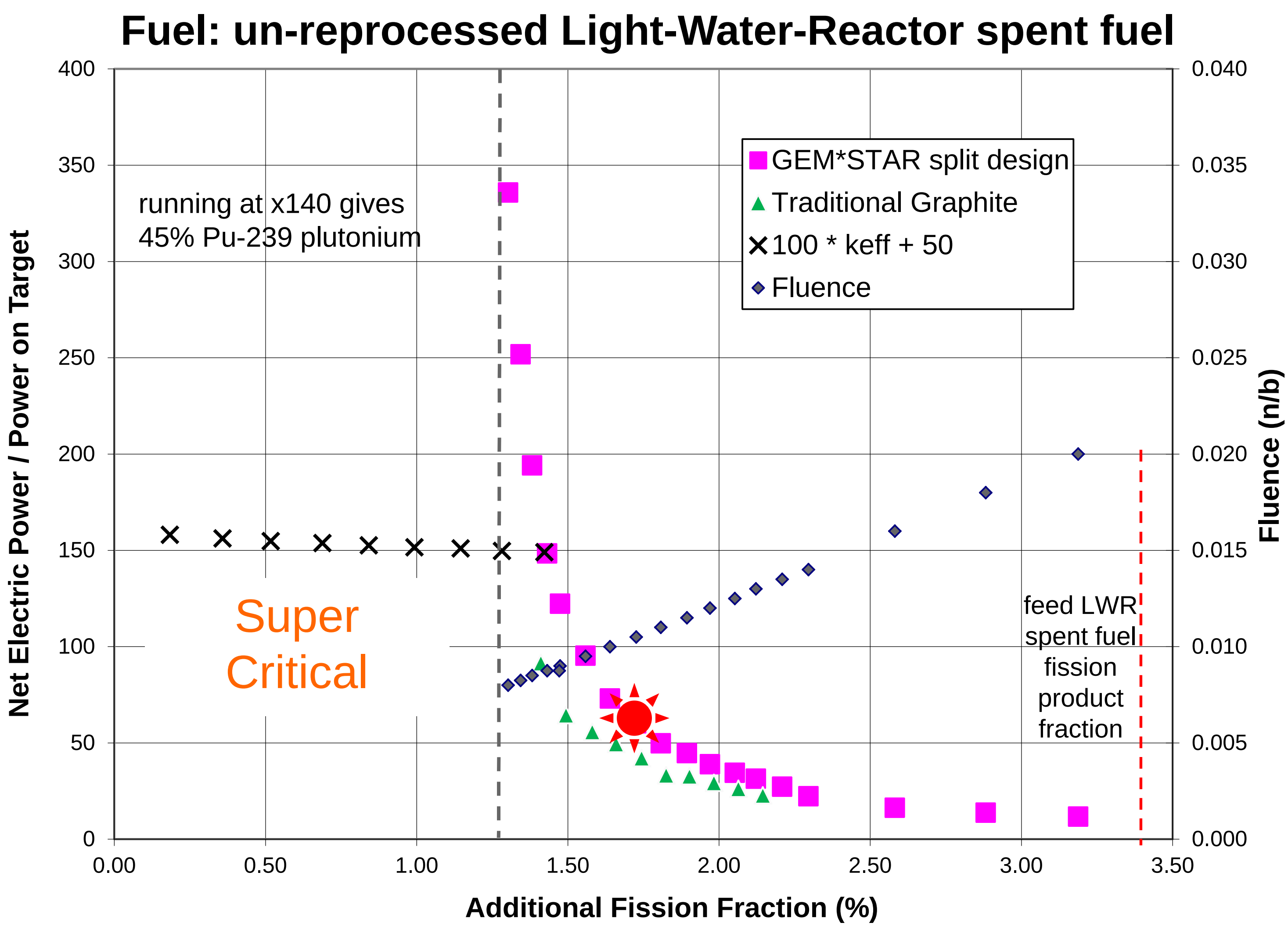
Fuel: Natural Uranium (MCNPX)



GEM*STAR

Invent the Future

ADNA & GEM*STAR Consortium



GEM*STAR

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)

redacted

Invent
the
Future

ADNA & GEM*STAR Consortium

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 $\Rightarrow$ 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)

GEM*STAR

advantages seem clear … so why does *this* happen…

- **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;O'Bama'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”.

what drives this?

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).

Invent the Future

ADNA & GEM*STAR Consortium

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?

Invent the Future

ADNA & GEM*STAR Consortium

Sequencing

CLF Corp.

Synthetic Liquid Fuel (driven with traditional 'green energy')

Interested parties in this room? (with ADNA)

GEM*STAR Design

first G*S demo

profits help fund nuclear effort

transition SLF production to G*S heat source

Full Scale GEM*STAR

Synthetic Liquid Fuel Production

Electricity Generation

Commercialization

(Long-Term 'Stretch' Research for all)

GEM*STAR