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GEM✱STAR

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

R. Bruce Vogelaar
Virginia Tech

November 5, 2010
4:00 PM, Room 204 Physics Building
University of Virginia Physics Colloquium

Recent Developments

1st International Workshop on Accelerator Driven Subcritical Systems and Th Utilization

(Virginia Tech and Jefferson Laboratory, Sept 27-29, 2010)

- **DOE Report**
  - **Finding #14: Technology is sufficiently well developed to meet the requirements of an ADS demonstration facility; some development is required for demonstrating and increasing overall system reliability.**
- **GEM*STAR Consortium formed (VT, UVa, VCU, JLab, others?)**
  - **ADNA's reactor design is well matched to existing accelerator technology. A demonstration facility is being pursued in the near term. GEM*STAR portents significant new research avenues.**
- **India's Nuclear Energy Program**
  - **The use of Thorium in their program would be significantly enhanced by utilization of accelerators.**

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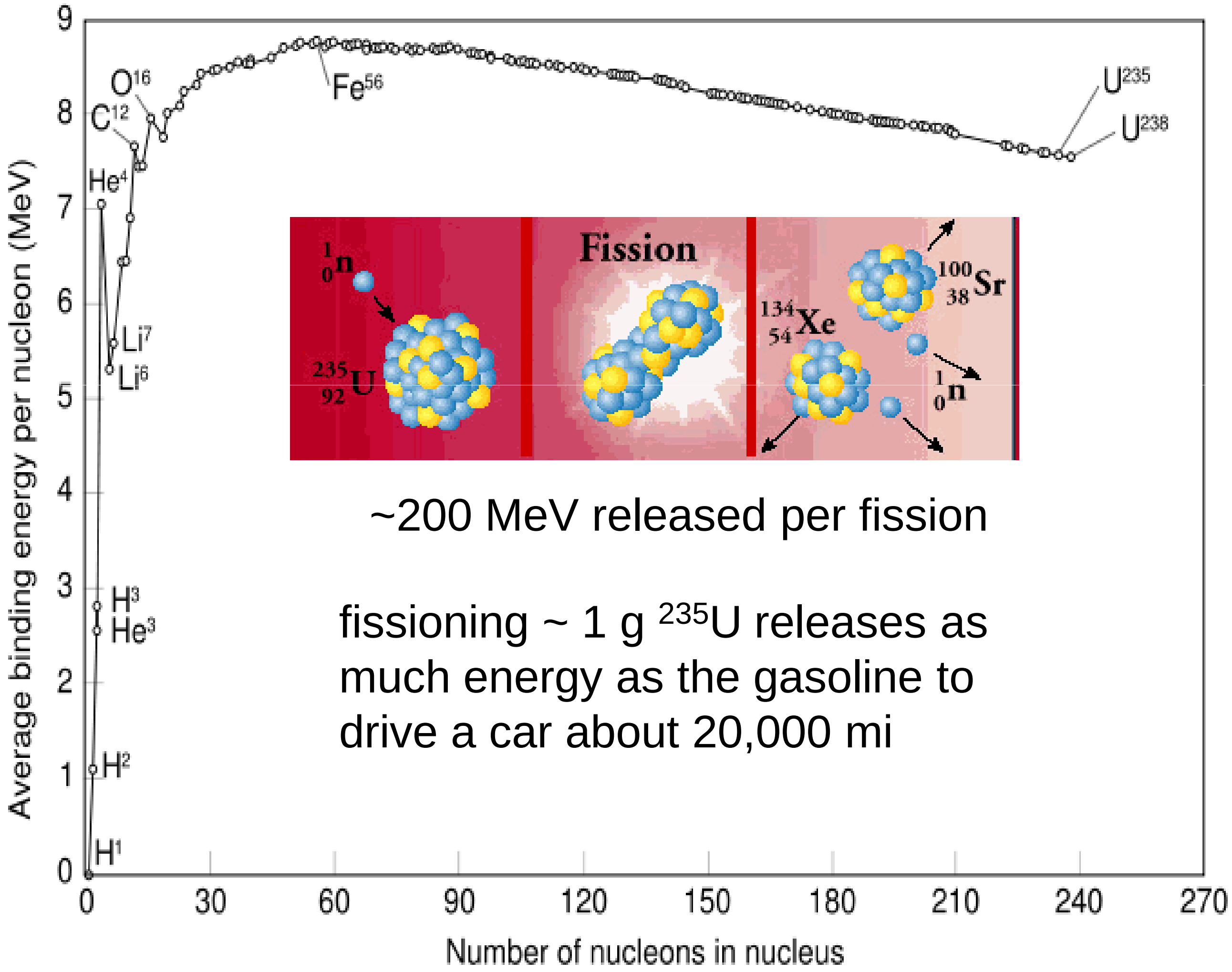
Fission



~200 MeV released per fission

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

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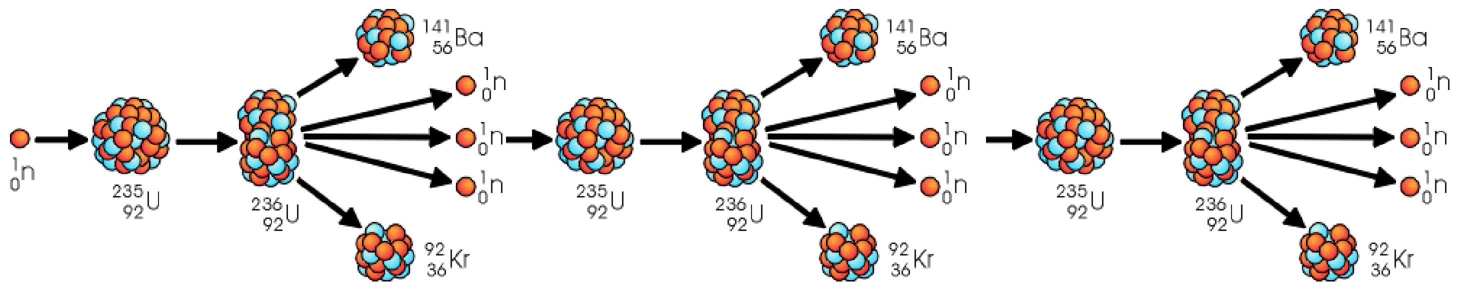
Chain Reaction



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

$k_{eff} > 1$ → runaway reaction

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

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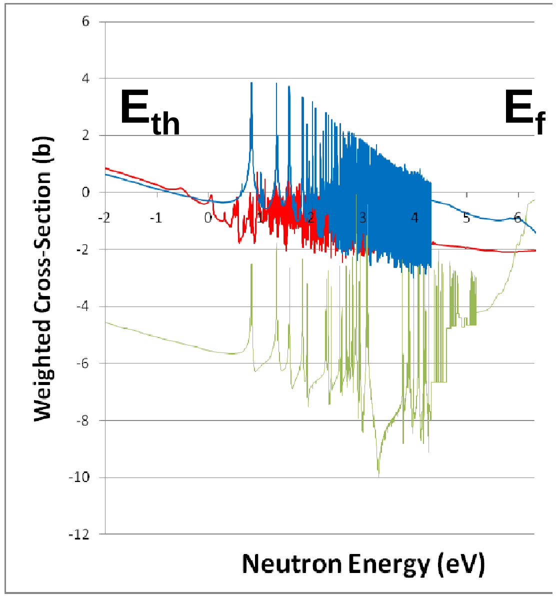
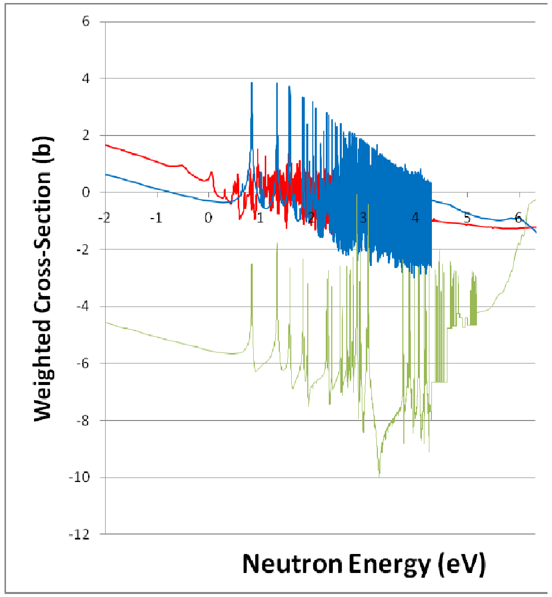
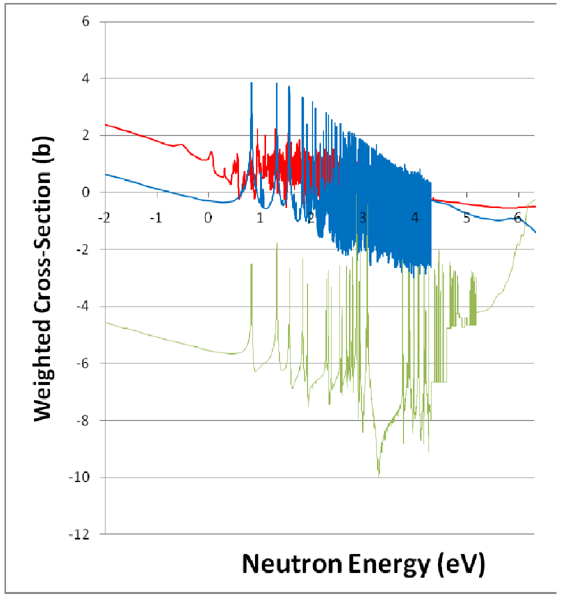
Sustaining a chain reaction



0.72 % Natural



4.5 % "Low" Enriched



> 20 % Weapons Usable

^{235}U fission (red)

^{238}U (n,g) (blue)

^{238}U fission (green)

Need to thermalize fission neutrons in U-free region to avoid capture, rather than fission

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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+04	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+05	U 234 .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

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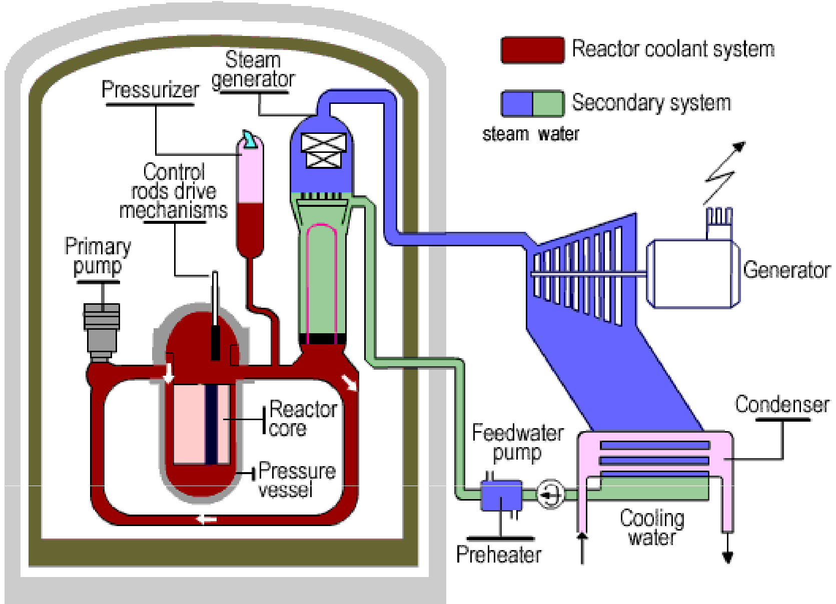
Classic (LWR) Operation

- Water Moderation:
  enriched ^{235}U fuel
- Solid fuel assembly in cladding
- During operation K_{eff} is kept at 1.0
- 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:
  - Excess fuel loaded per fueling
  - 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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Principle Concerns

- **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 default
- **Weapons Proliferation**
  - **enrichment:**
    - enrich ^{235}U to ~5%

      (note: >20% enrichment can be used for weapons)
  - **reprocessing:**
    - remove minor actinides and fission products (neutron poisons)
    - proliferation resistance primarily administrative
    - halted by Carter due to proliferation concerns; forcing one-pass fuel use + Yucca Mountain Repository

      (note: ~300,000 kg of weapons grade Pu had been produced by earlier 'Purex' reprocessing, but only ~5 kg is needed for a bomb)
- **Safety**
  - positive void coefficient: Chernobyl (not possible most places)
  - decay heat: Three Mile Island
  - core inventory of volatile radioactivity

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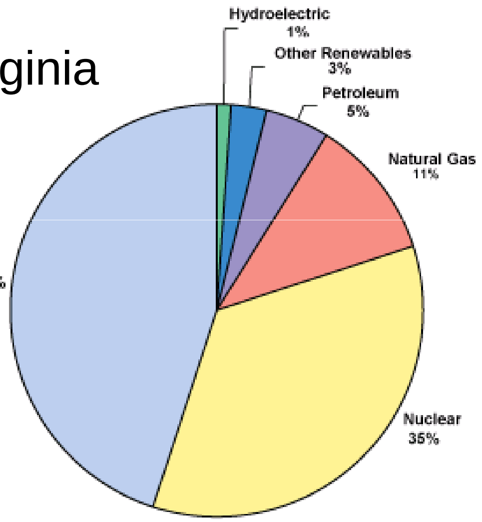
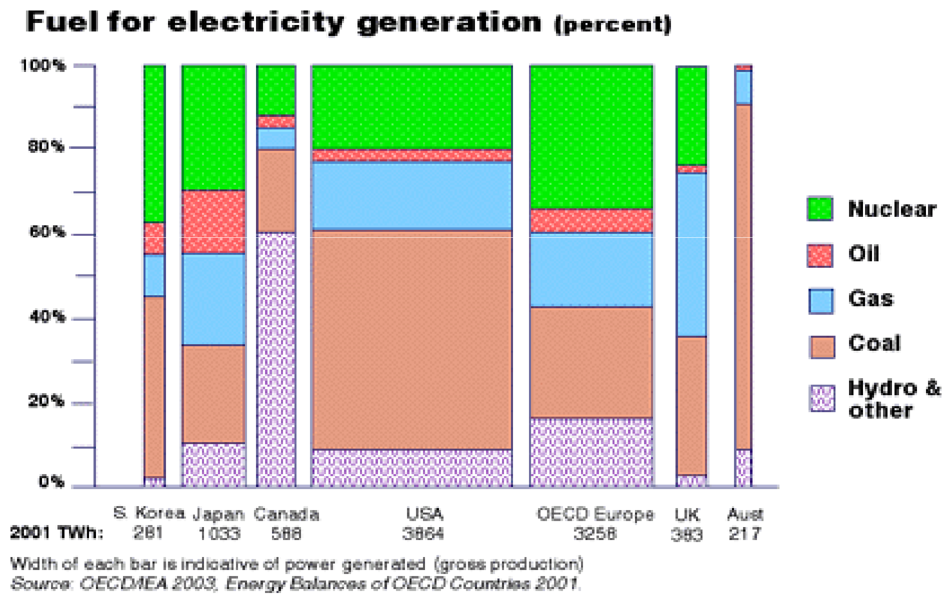
Trends in Global Energy Sources

nuclear energy accounts for 17% of global electricity production

in Virginia





"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

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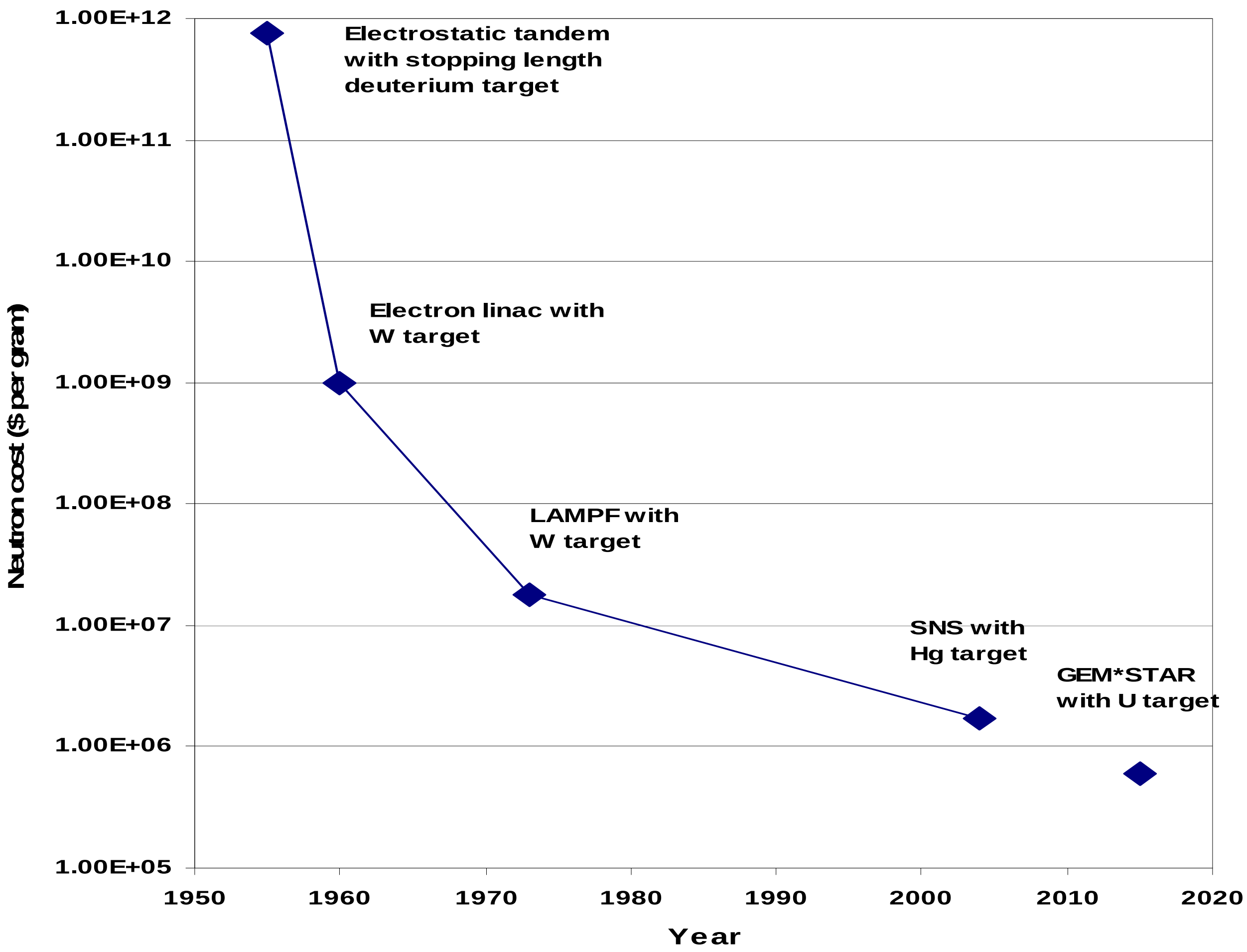
However, the cost of neutrons has dropped dramatically, enabling another approach…



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

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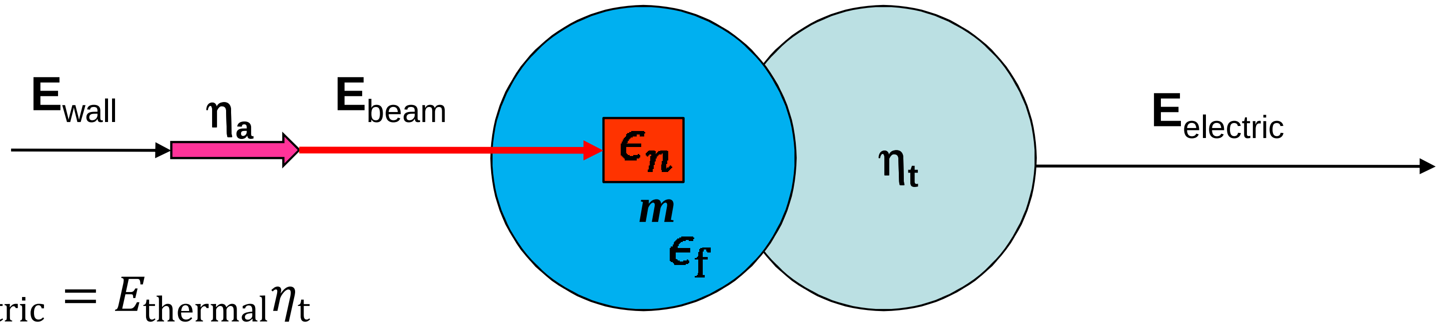
Proton Driven Sub-Critical System



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

$\eta_a \equiv$ 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

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

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

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)

note: a 10% accelerator efficiency only lowers this to 60

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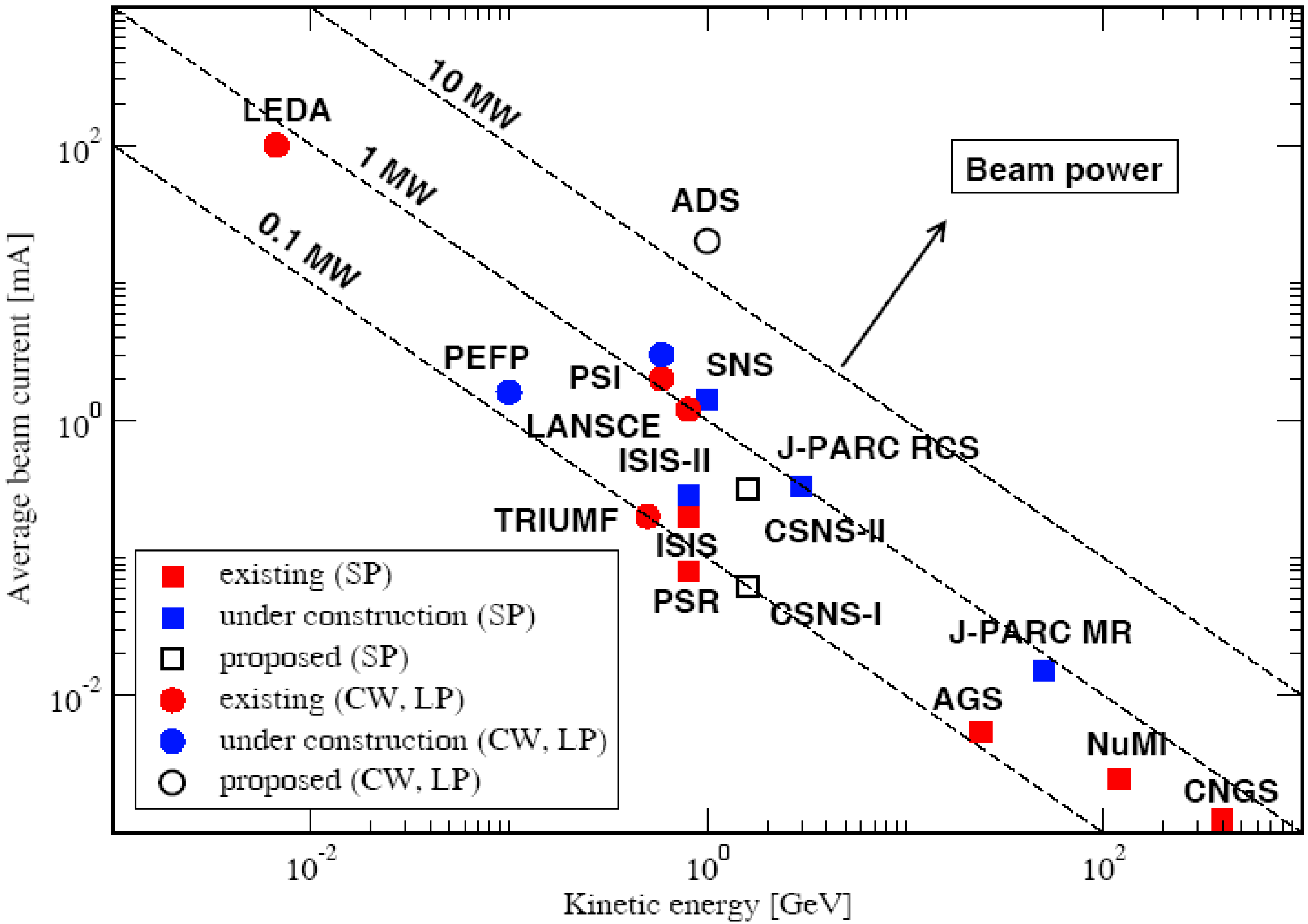
Existing Proton Beam Power



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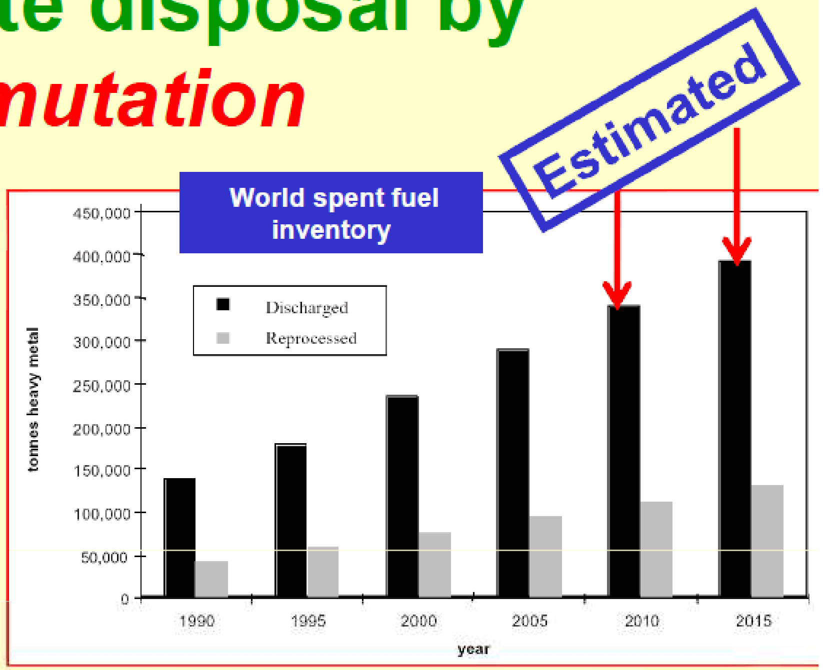
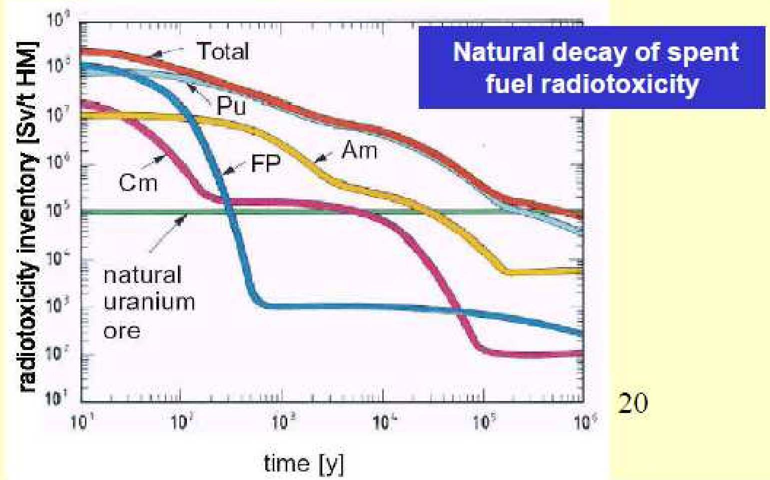
Nuclear waste disposal by *Transmutation*

- **Accumulation of spent fuel: a global issue.**
- **Spent fuel requires > 100,000 years to decay.**
- **Transuranic elements (<u>TRUs</u>: Np, Pu, Am & Cm) + a few long-lived fission products (FPs): decay very slowly.**
- **Bulk of FPs decay to safe disposal levels in 3-5 centuries.**
- **If all TRUs transmuted into FPs by fission: bulk of FPs decay very fast, & it generates electricity too…!**





Typical arguments given for accelerators.

ADS Technology Readiness Assessment

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

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

Fermilab

Path (and funding) thus seems clear…however:

- 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, 3 year study (presented by Ernest Moniz at CSIS, September 16, 2010)
  - 100 year horizon, no new direction, yet continue DOE-NE funding at $1B/yr
- DOE NE representative at workshop, said DOE NE was thinking about an ADS demonstration in 2050. (ie, when I'm 90 ☹)

Statements (or lack thereof) based on outdated criteria, permitting modest R&D but deferring ADS for power to distant future.

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, and $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).

Capitalize on these first opportunities, but need to go much further.

create true energy solutions for the needs of today

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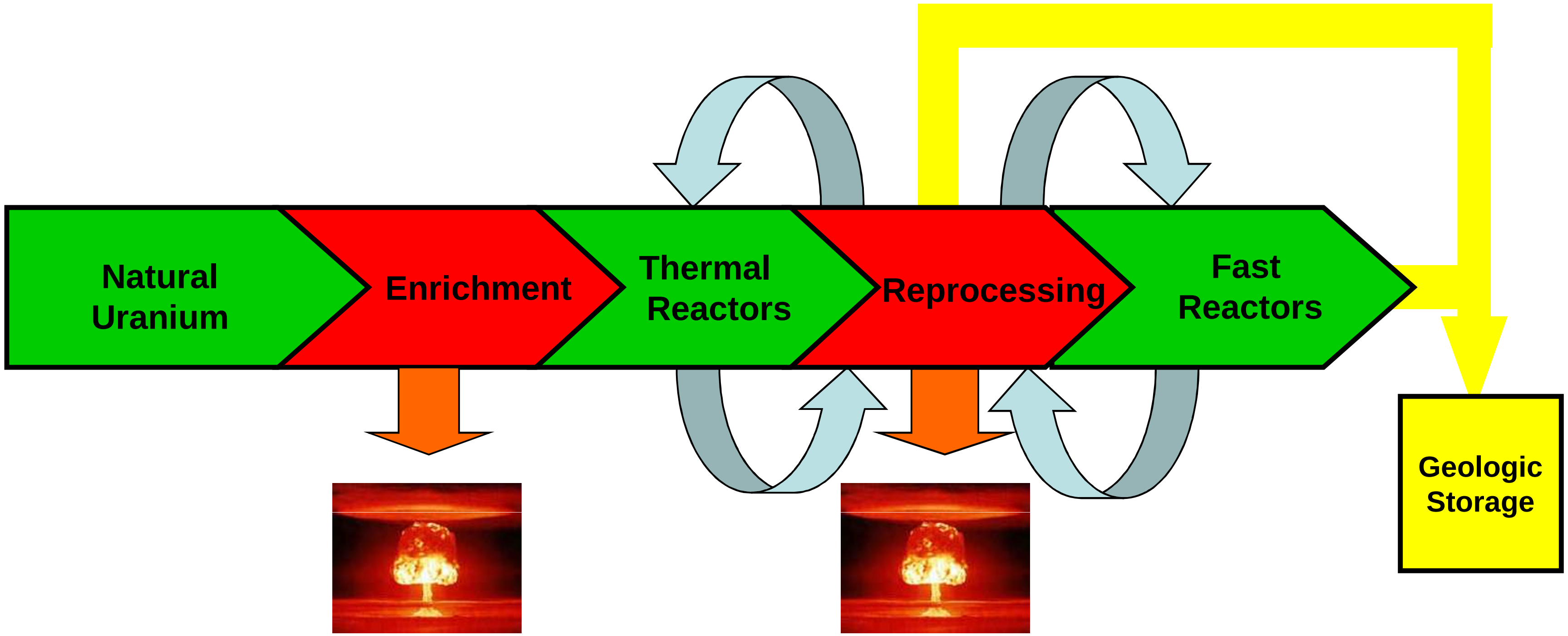
Paradigm Shift



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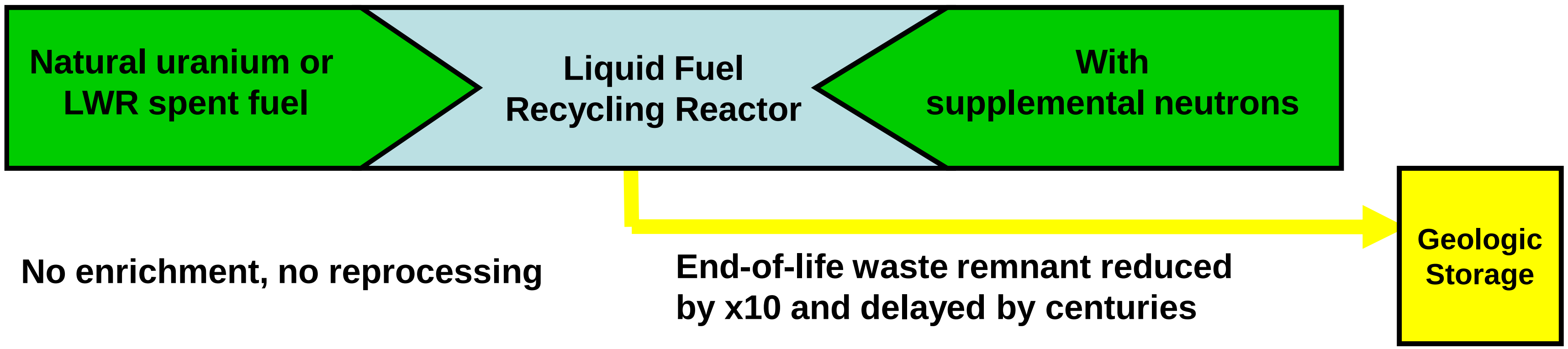

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Recall that for a spallation target:

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

Design system to sustain large m (fissions per neutron), limiting the need to maximize η_a (accelerator efficiency)

- uranium fuel (*un-reprocessed* LWR spent fuel is actually better)
- molten salt eutectic
- improved neutron utilization

This is what the GEM*STAR project achieves, resulting in multiple advantages over existing (or planned) nuclear energy systems.

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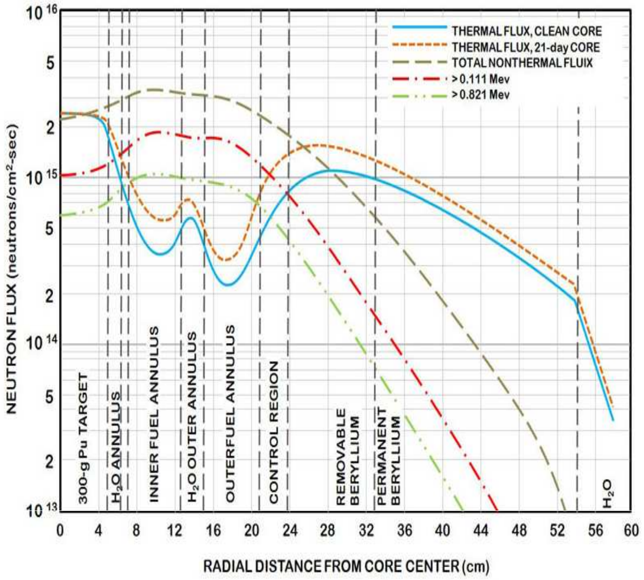
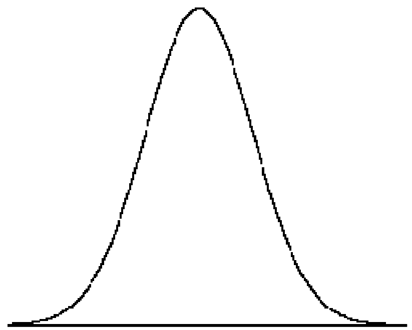
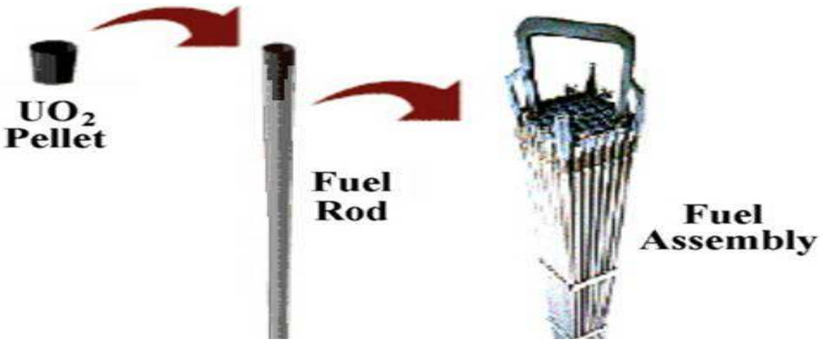
Solid Fuel Issues





much more centrally peaked for driven systems

non-uniform fuel consumption



volatile fission-product build-up within cladding

thermal shock due to beam trips

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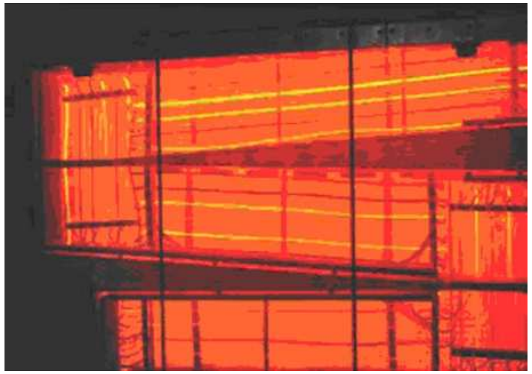
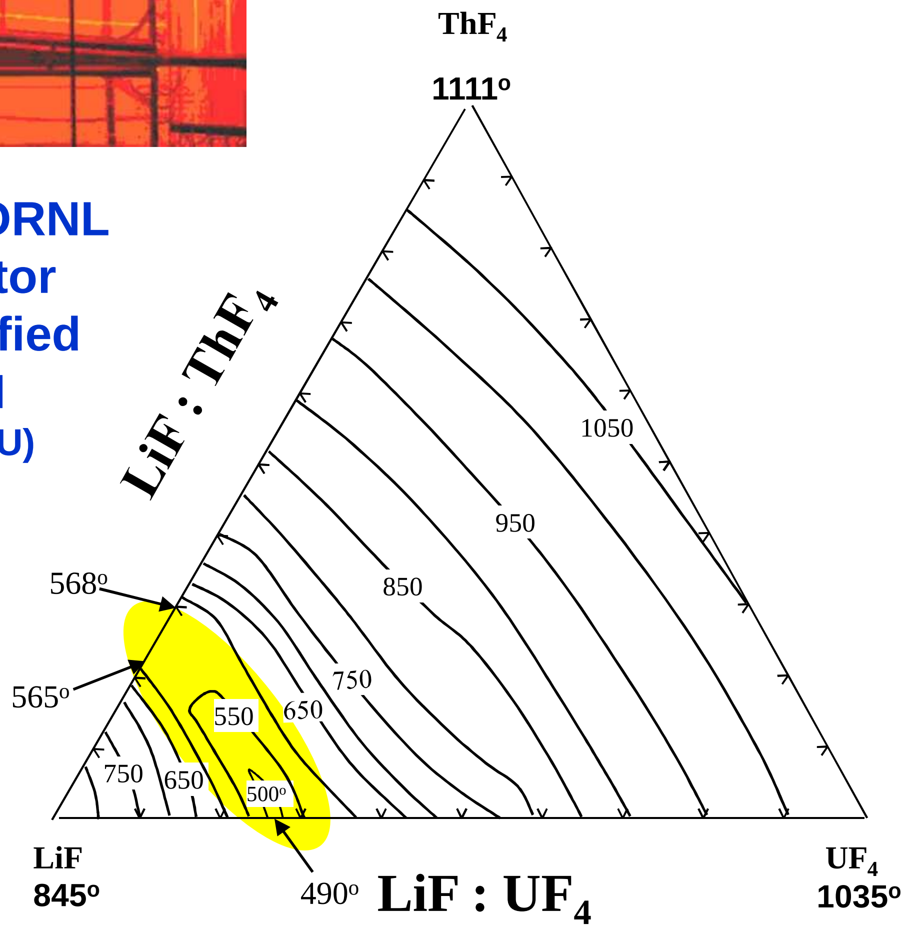
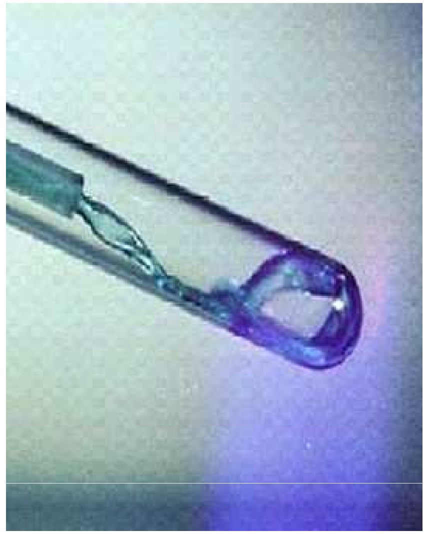
Molten Salt Eutectic Fuel



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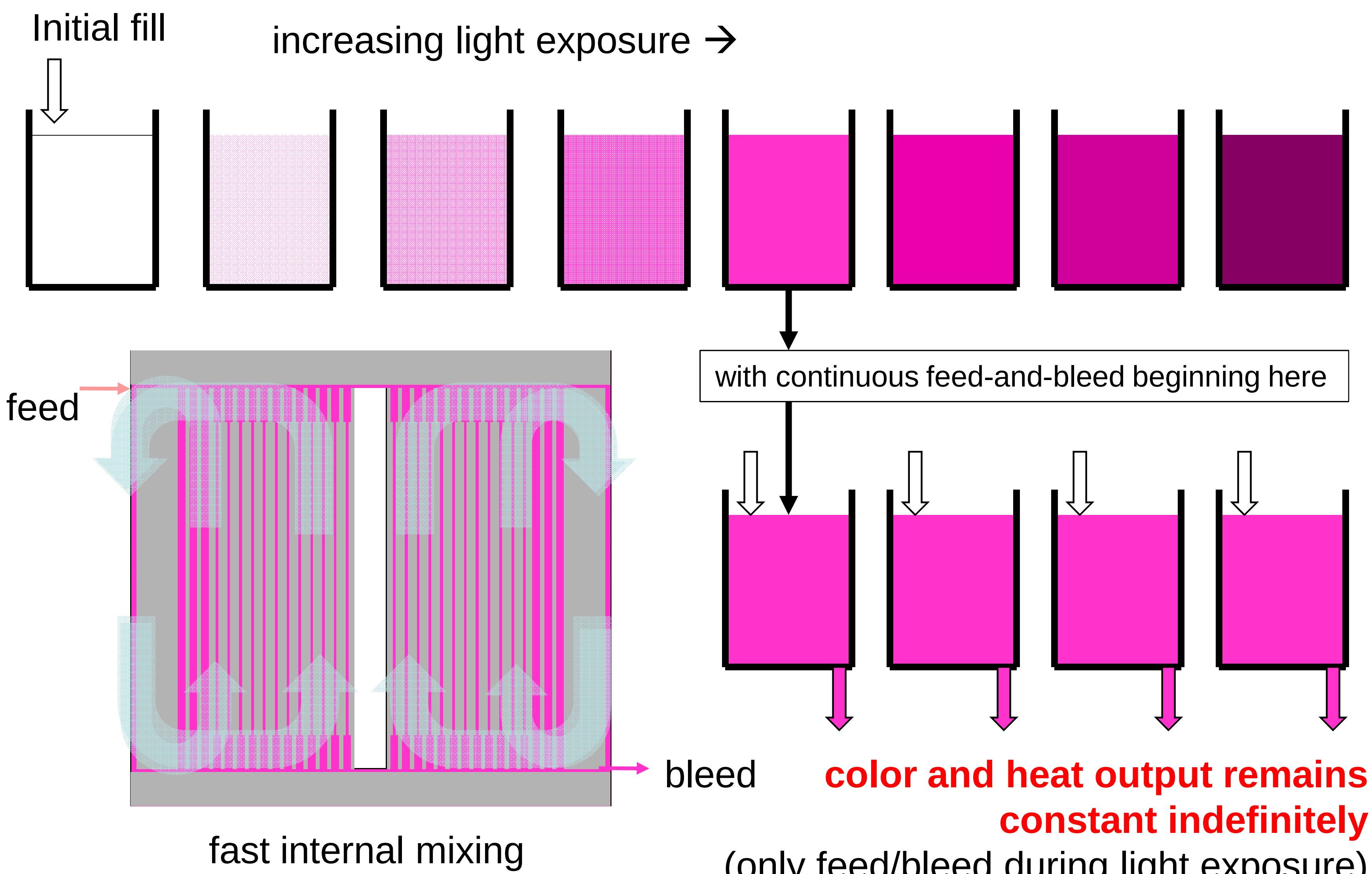
consider a clear liquid which releases heat when exposed to light, eventually turning a dark purple



color and heat output remains constant indefinitely
(only feed/bleed during light exposure)

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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

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

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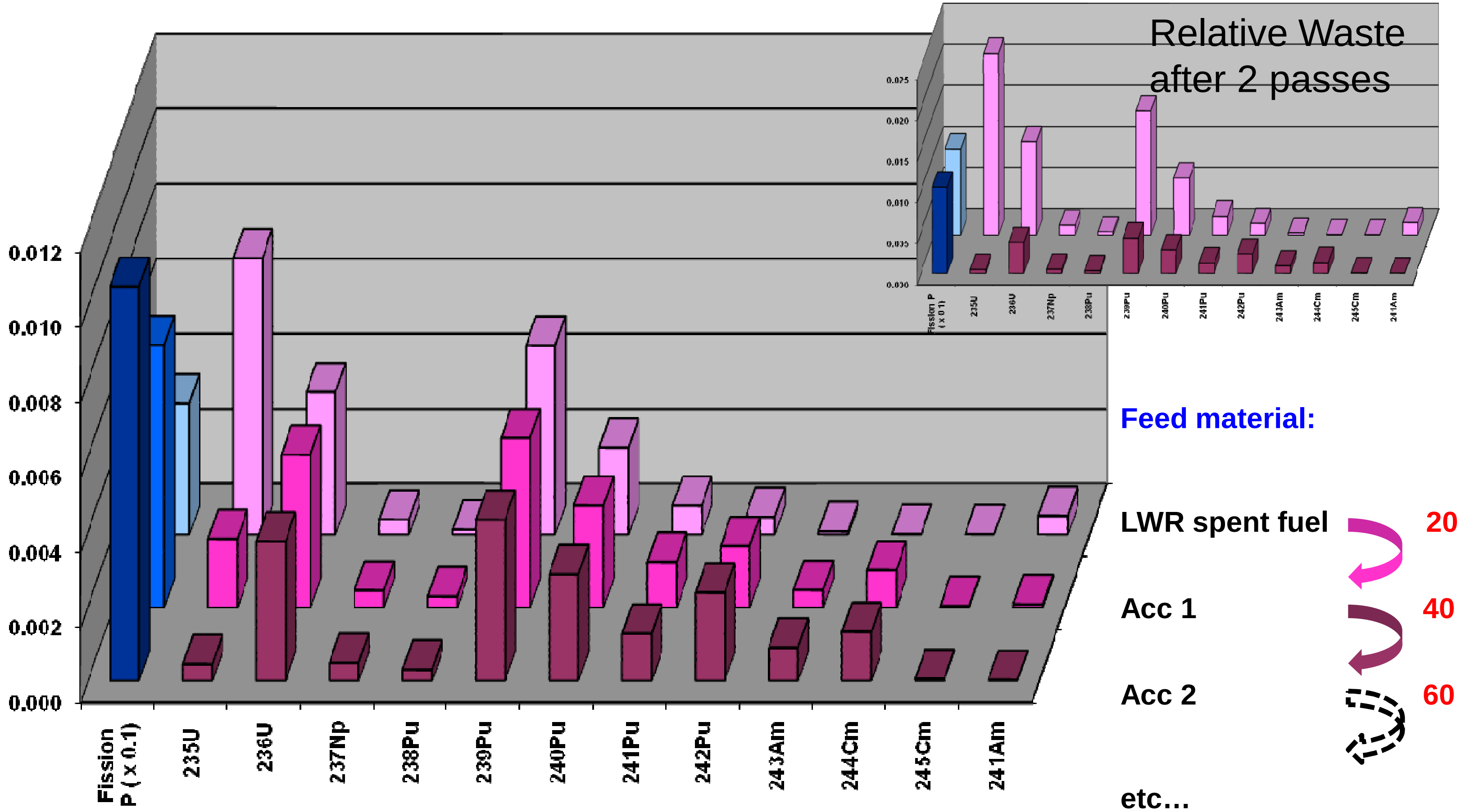
extracts many times more fission energy, without additional long-lived actinides



Feed material:

LWR spent fuel	**20 GWy**
Acc 1	**40 GWy**
Acc 2	**60 GWy**
etc…	

major reduction and deferral of waste

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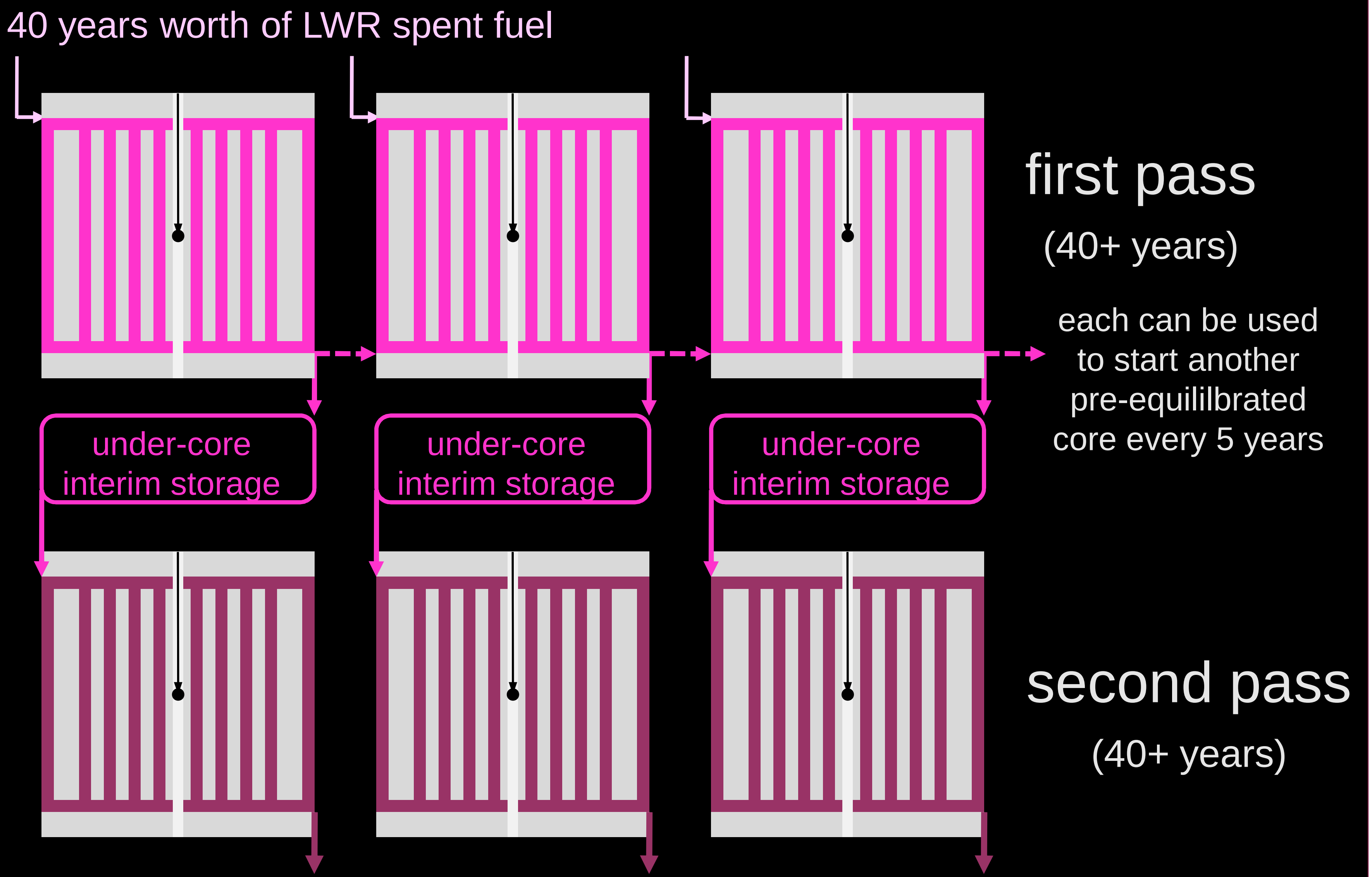
Recycling



subsequent passes… (fusion n source?)

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

Why?

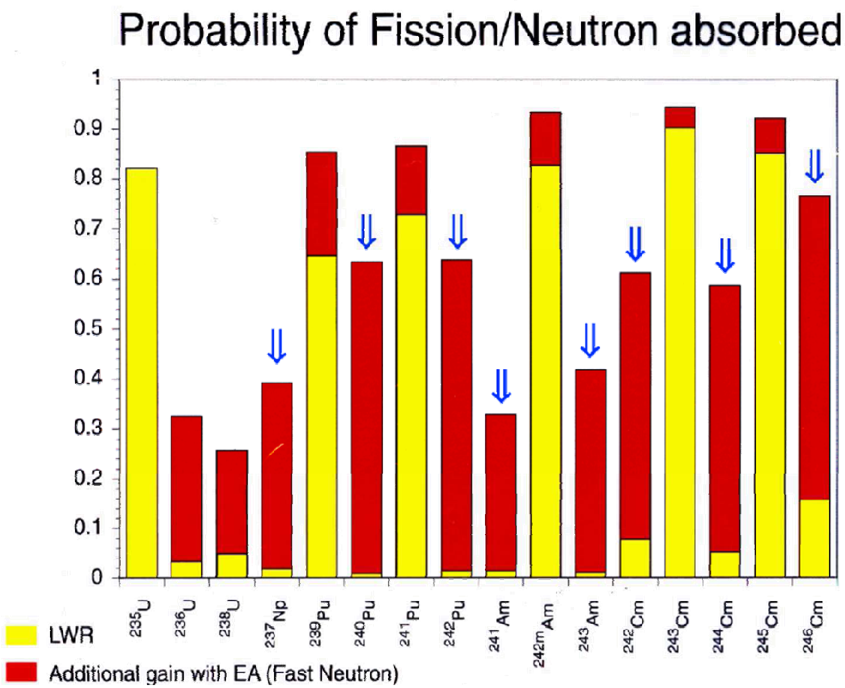
Faster burn-up of heavy actinides.

BUT:

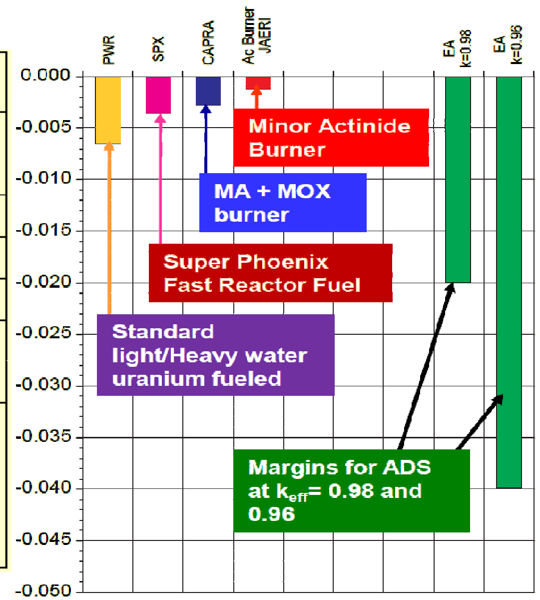
- smaller difference between delayed and prompt criticality.
- higher energy-density cores (to keep neutrons 'fast')

(meaning LOCA accidents much more difficult; translate → higher cost)

•already an argument for sub-critical system, but if you don't want reprocessing, fission products will quickly create problems.



Isotope	$\beta = \nu_d / \nu_{total}$
^{238}U	0.0151
^{232}Th	0.0209
^{235}U	0.00673
^{239}Pu	0.00187
^{233}U	~0.0030
^{241}Pu	0.00462
^{242}Pu	0.00573
^{237}Np	0.00334
^{241}Am	0.00114
^{243}Am	0.00198
^{242}Cm	0.00033



GEM*STAR

Thermal Spectrum

0.01 – 0.2 eV

highest tolerance for fission products:

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

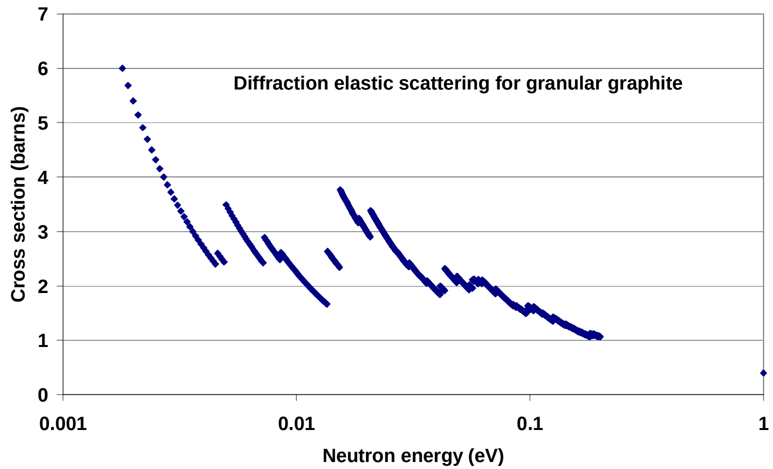
$$\frac{\sigma\text{-fission } (^{239}\text{Pu})}{\sigma\text{-capture (f.p.)}} \sim 100 \quad (\text{vs} \sim 10 \text{ @ } 50 \text{ keV})$$

- ^{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)

New Graphite Results
(ADNA)

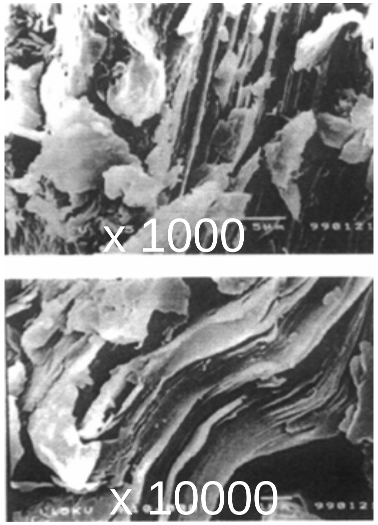
Diffusion/Absorption @ Duke

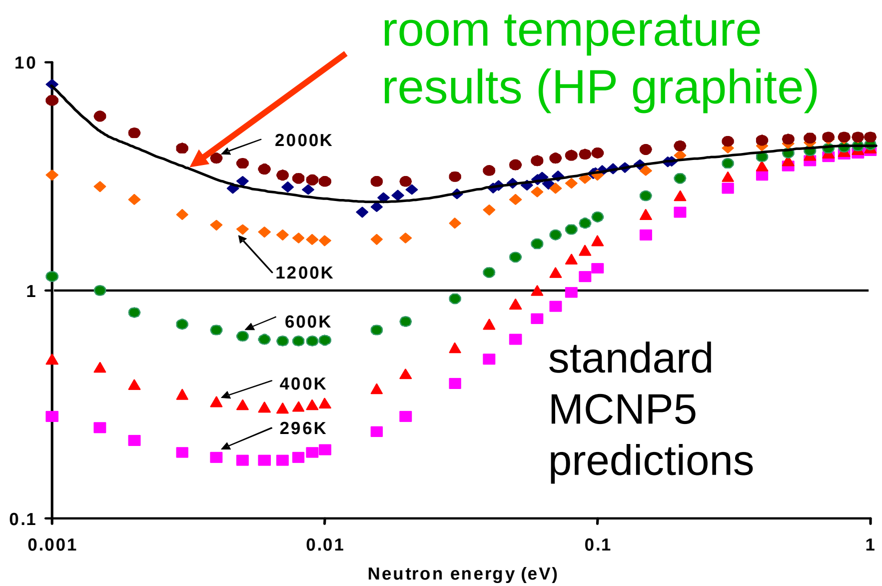


Diffraction @ LANL

"Measurements of Thermal Neutron Diffraction and Inelastic Scattering in Reactor-Grade Graphite"
Nuclear Science and Engineering Vol. 159 · No. 2 · June 2008

"Reducing Parasitic Thermal Neutron Absorption in Graphite Reactors by 30%"
Nuclear Science and Engineering Vol. 161, No. 1, January 2009

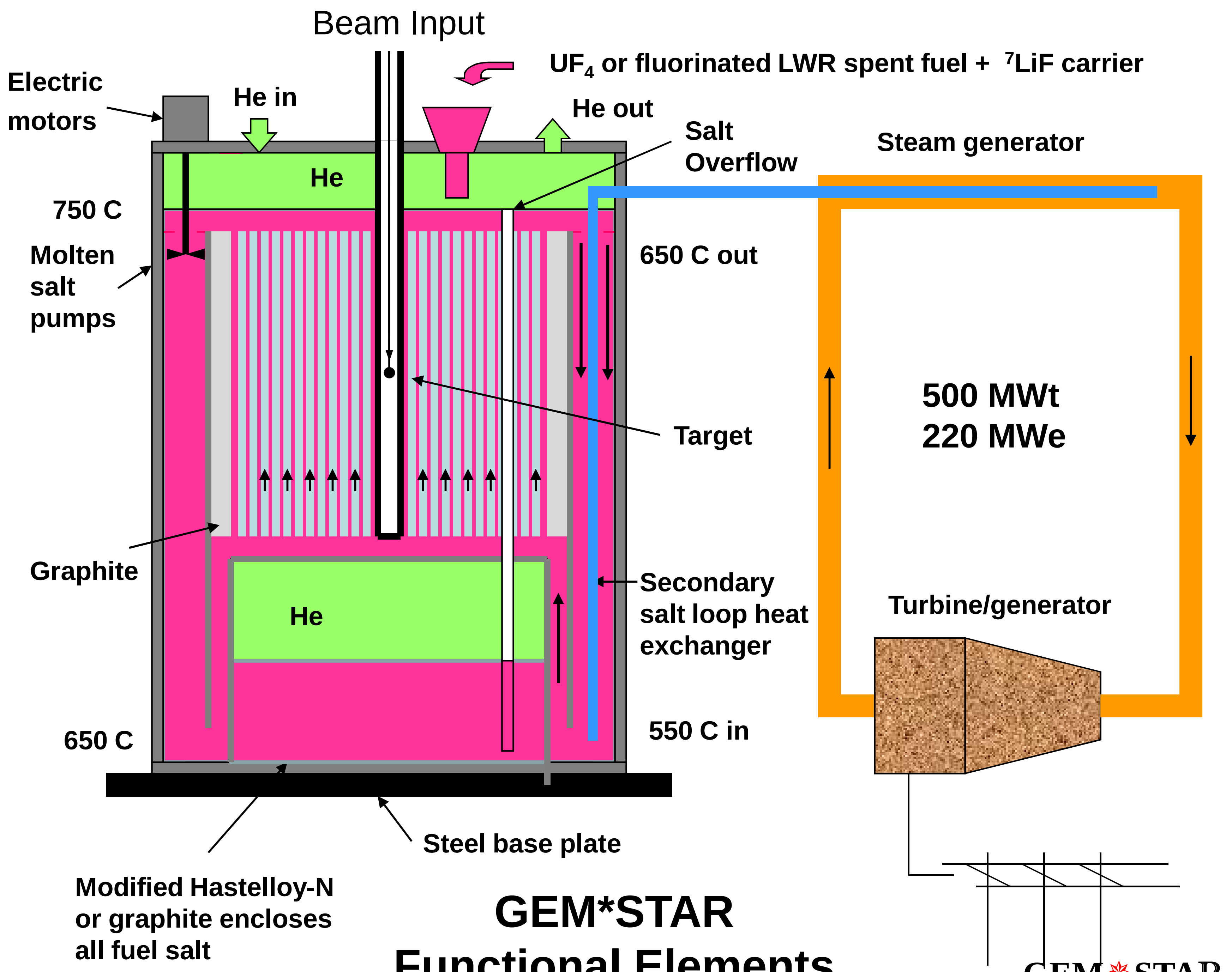




Discovered ***and measured*** a commercial graphite source with:

- 24% increase in room temperature thermal diffusion length *('HP' manufacturing process creates distorted crystals reducing coherent scattering)*
- boron contamination less than 2 parts in 10^7

$\Rightarrow$ significant reduction in parasitic neutron absorption



GEM*STAR Functional Elements

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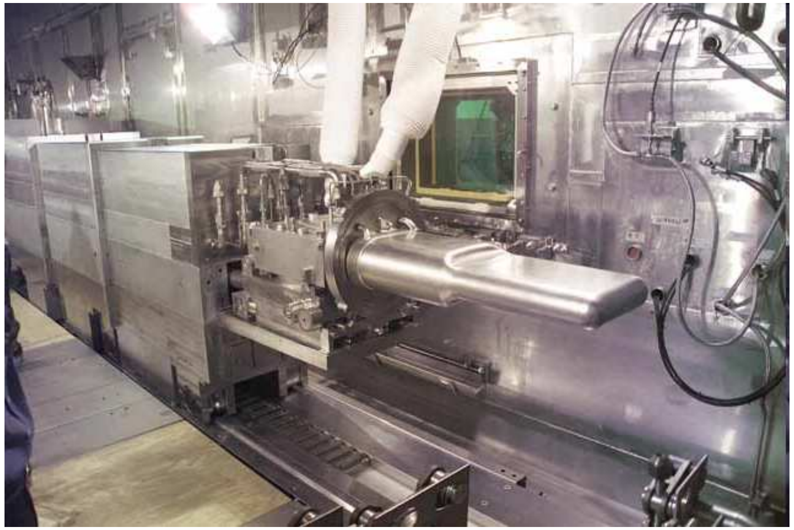
Target Considerations



Existing Oak Ridge SNS Molten Hg target (1 MW)

- ~ 4 MW to produce 220 MW_e net output
- diffuse (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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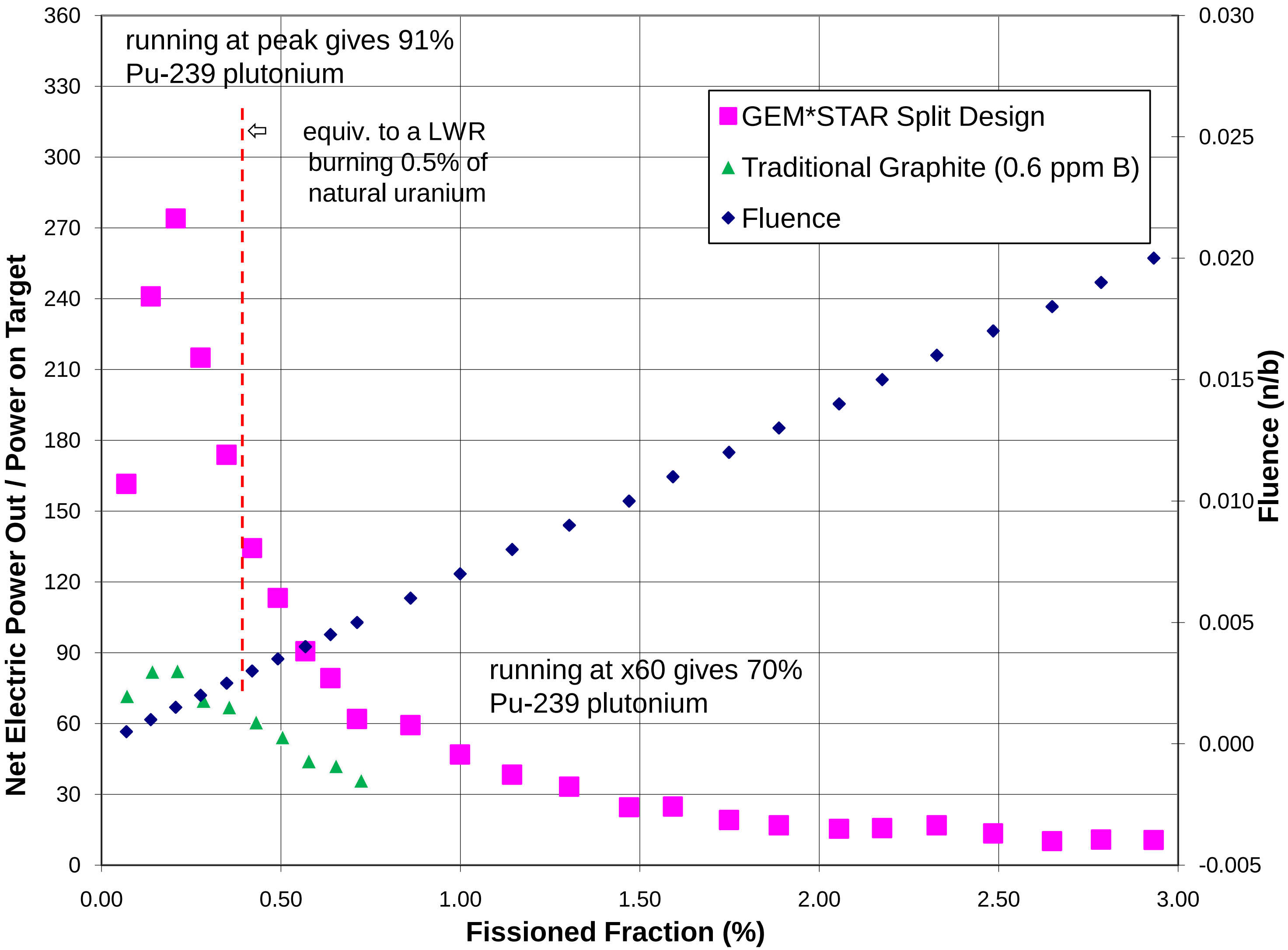
Fuel: Natural Uranium (MCNPX)



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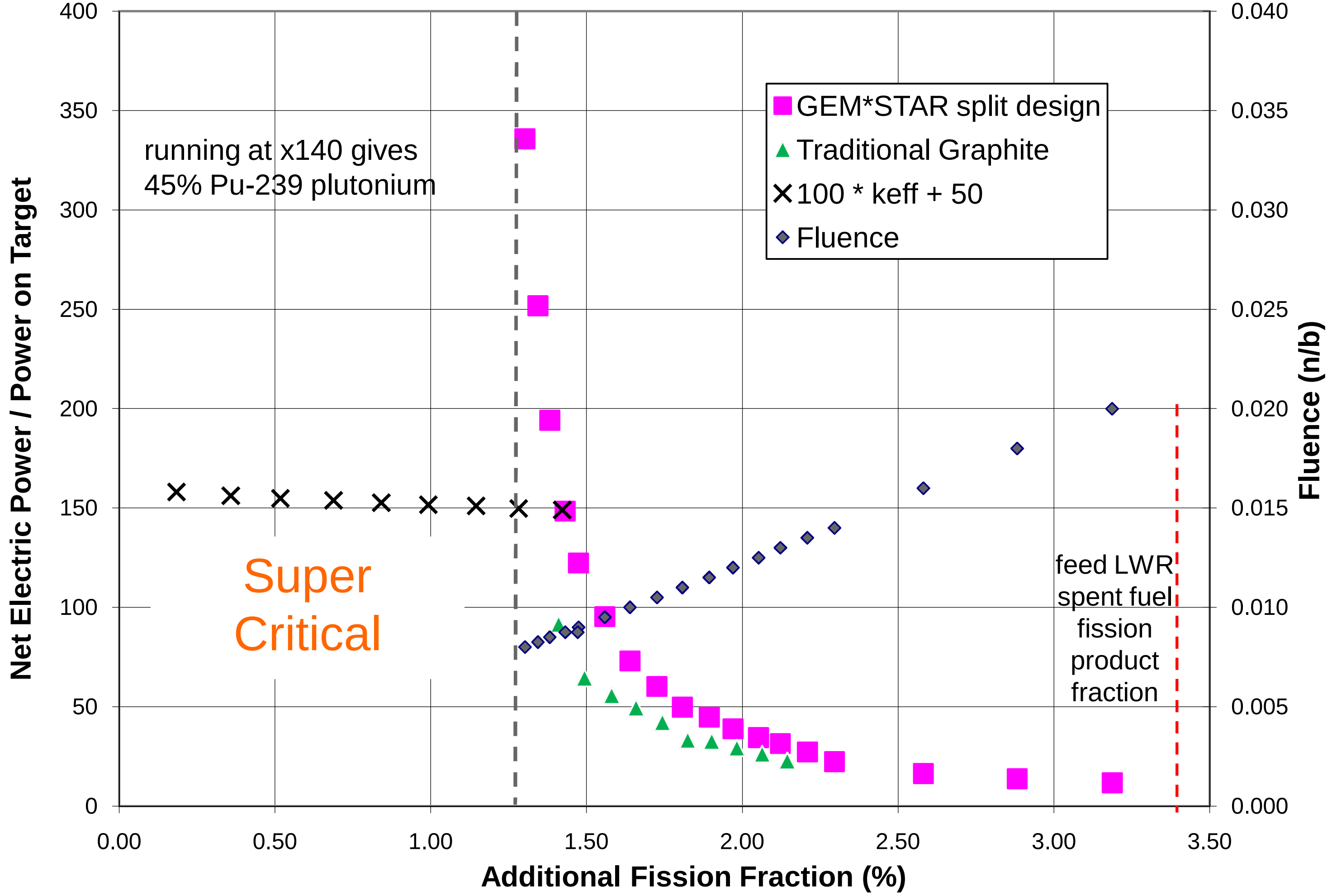
Fuel: un-reprocessed Light-Water-Reactor spent fuel



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GEM*STAR System

- intrinsic safety: no critical mass ever present; far less volatile reactivity in core
- no high-pressure containment vessel
- thermal neutrons: high tolerance to fission products; allows deeper burning
- higher thermal to electric conversion efficiency

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

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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

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High Temperature MS Advantages over LWRs

- 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 (including new insights to coal & methane utilization) – very attractive (much more realistic than hydrogen economy)

$3C + 6H_2O$ + heat input → $3CO_2 + 6H_2$ → $2CH_2 + 4H_2O + CO_2$

$C + O$ → CO; $CO + 2C + CH_4 + 3H_2O$ + heat → $4CO + 5H_2$ → $3CH_2 + 2H_2O + CO_2$

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potential to transform the nuclear policy landscape:

- not a 'niche', but rather **base-line capable** (green) energy source
- reduce US dependence on imported oil via cost-competitive synthetic fuel production
- exportable technology (non-proliferating)
- current "once-through-U", "supplier–user" US policy towards developing countries not viable for many; **GEM*STAR** provides a real alternative

(especially towards India, whose Th program is based on a proliferation prone technology)

What are the obstacles?

- GEM*STAR uses liquid fuel – but NRC is only "comfortable" with solid fuel, despite MSRE success
- Commercial nuclear power is an outgrowth of Naval Nuclear Propulsion program using pressurized water reactors
- 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 "modular" reactors (scaled down versions of existing deployed technology)

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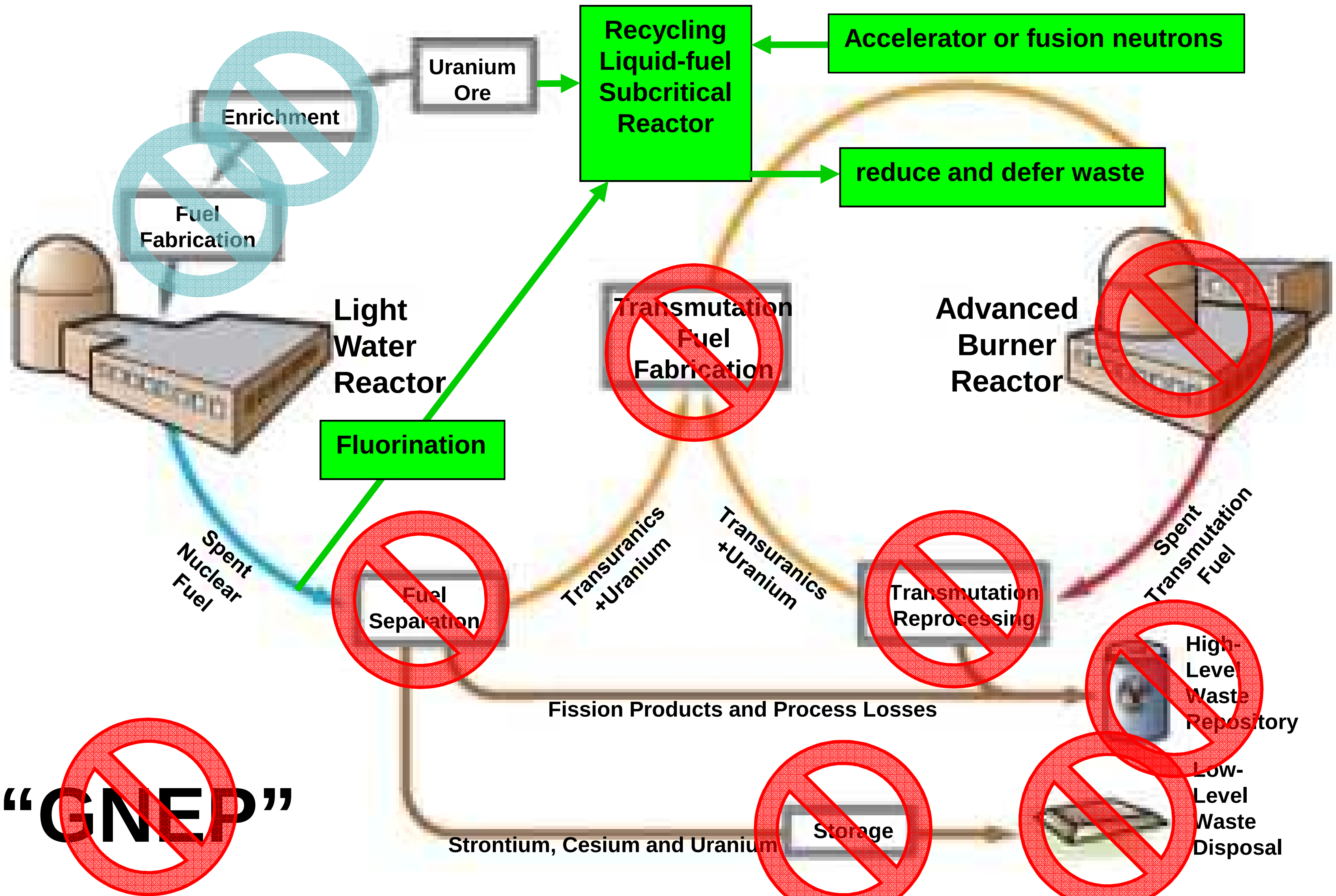
from an establishment perspective…



ADNA (Accelerator Driven Neutron Applications, Inc)

- venture capital for demonstration facility
- commercial project for liquid transportation fuel

GEM*STAR Consortium (VT, UVa, VCU, JLab)

- continue to engage funding agencies and raise awareness (DOE, ARPA-E, DTRA, NSF, NNSA, Foundations, Federal and State governments, etc)
  - already prompted DOE to re-visit ADS less than a year after its “Accelerators for America’s Future” study, resulting in a positive first step
- Virginia research facility
  - SC LINAC (protons or electrons) driving a sub-critical system for study and training; potential India partner
- Powerful motivation for existing and **NEW** multi-disciplinary research avenues…

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Research Avenues for GEM*STAR Consortium Members

Engineering:

- Spallation Target Designs
- RF Power Systems
- MS Heat Exchanger
- Systems and Failure Mode Analysis
- ^{7}Li Isotopic Enrichment
- Reactor Design
- Fusion Neutron Sources
- Brayton Cycle Systems

Science:

- Neutronics of New Graphite Forms
- Synthetic Liquid Transportation Fuel
- Alloys for MS Containment
- Fission Product and Actinide Solubilities in MS
- Fluorination Techniques
- SC Spoke and Elliptical Cavities
- Simulations (MCNPX, GEANT4, etc)
- Improved & New Cross-Sections

Humanities:

- Energy Policy
- Regulatory Environment
- Work-Force Development
- Business Models for Trans. Tech.
- National Security
- Foreign Policy & IAEA
- Virginia Industrial Development
- Coal Industry and CO_2 Issues
- Environmental Implications

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Return on Investment

1) Waiting for solicitations means that ***someone else*** wrote them, and is in the best position to answer them.
2) Chance to lead in a solution to one of the world's most challenging problems.
3) No science reason this will not work – just a question of final cost (projected to be very economical). Solves so many problems so well, that even a partial success is significant (no way to completely "guarantee" the technology can not be misused).
4) Ideal role for Universities: "This offers the scope, impact, and long-range research funding potential we've been looking for." VT President Steger

Join, and become part of the solution!

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Deployed Civilian Reactor Types

Reactor Type	Main Countries	GWe	Fuel	Coolant	Moderator
Light Water Reactors	US, France, Japan, Russia	337	enriched UO_2	water	water
Heavy Water Reactors	Canada	43	natural UO_2	heavy water	heavy water
Gas-cooled Reactors	UK	18	natural U (metal), enriched UO_2	CO_2	graphite
Light Water/ Graphite Reactors	Russia	12	enriched UO_2	water	graphite

82% produced by LWR