Reducing Global Warming

unblocking a nuclear energy solution

R. Bruce Vogelaar, Virginia Tech Physics

VT Nuclear Engineering Seminar
September 30, 2022 10:10 am and via Zoom

GEM STAR

Green Energy-Multiplier
Safe-Technology for Alternative Reactors

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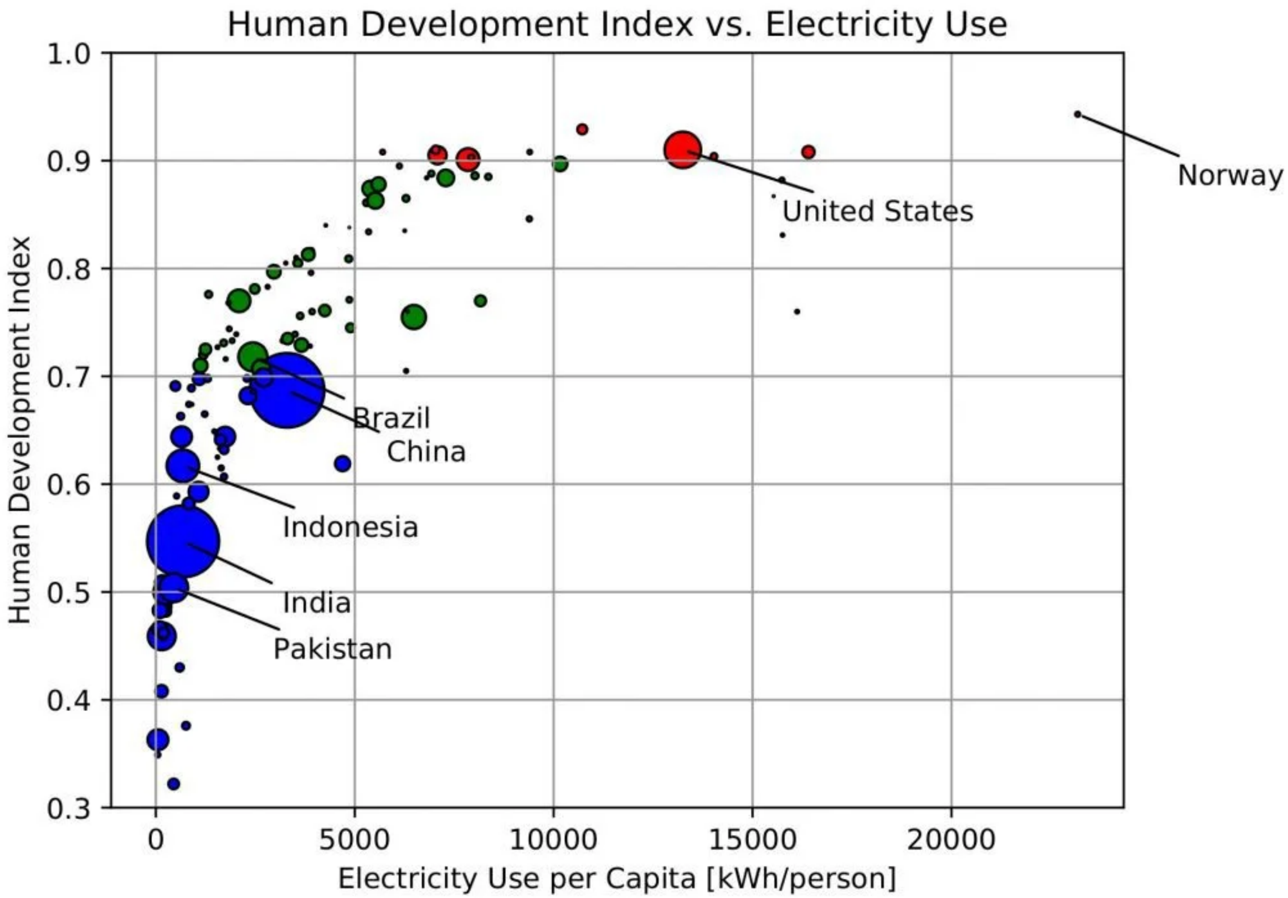
Human development has grown hand-in-hand with energy development:

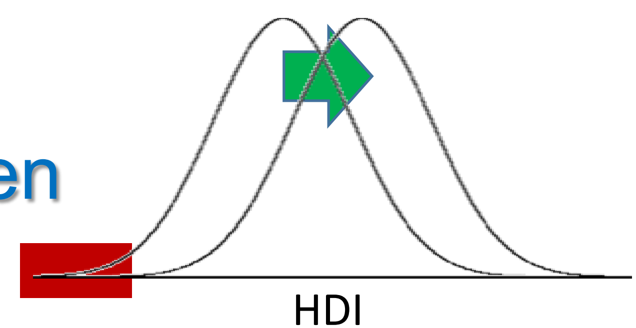
- free sunlight - which provides rain via wind from ocean evaporation, and photosynthesis for food crops.
  - advances in engineering and chemistry - which allowed us to convert energy into many different forms, and made possible portable fuels.
    - harnessing electricity, enabling most modern technologies (including alternate ways of getting energy from sunlight – such as solar, wind, and hydro).
      - more recently fission – which allows us to harness stellar energy locked in heavy nuclei on Earth
        - in the future we may also master fusion, which would let us harness energy from light nuclei like the stars do).

Access to power improves Human Development Index



correlated benefit:

far fewer extremists to handle when more of society is empowered



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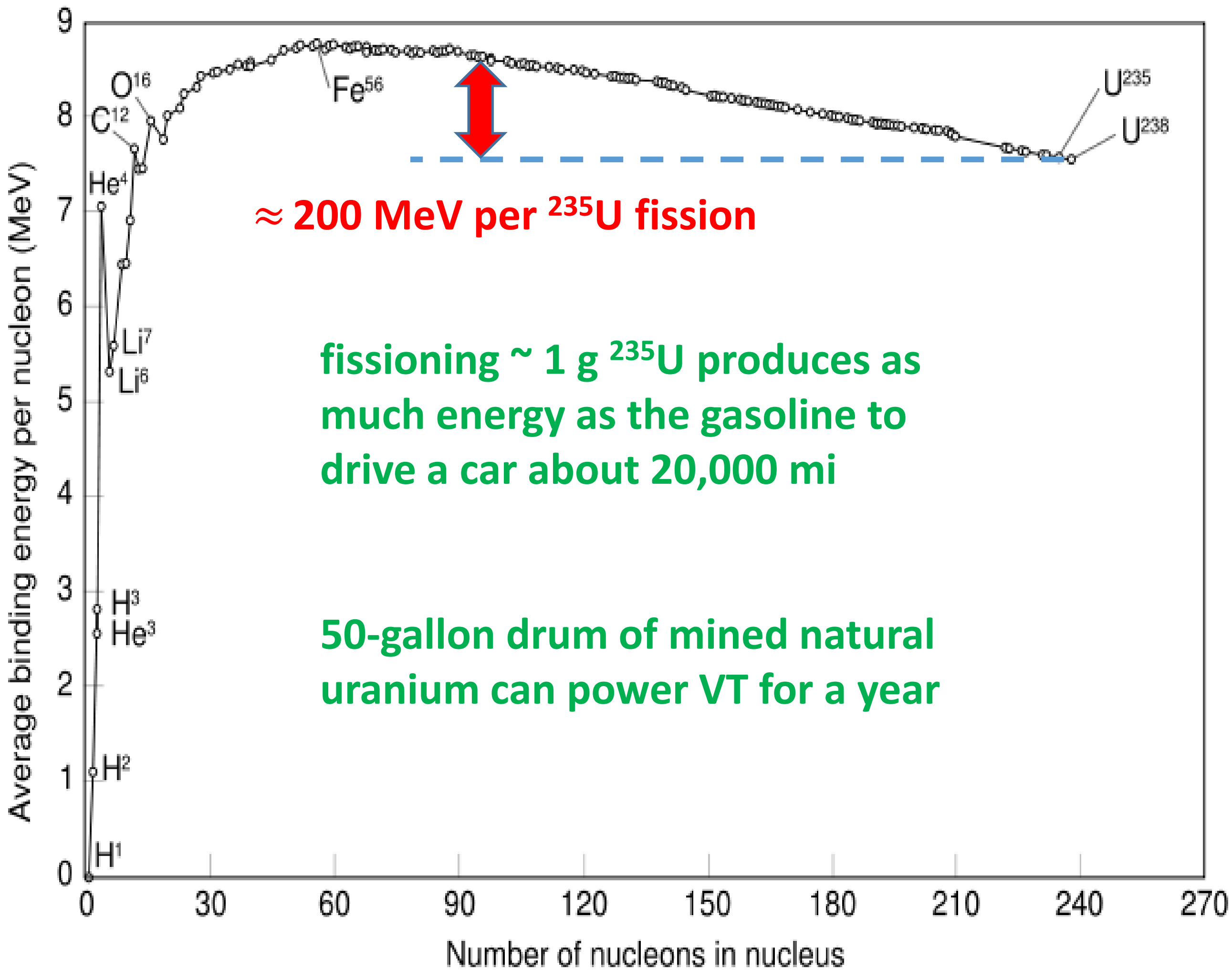
Consider the recent "fission step" which uses 'star' energy already stored in nuclei



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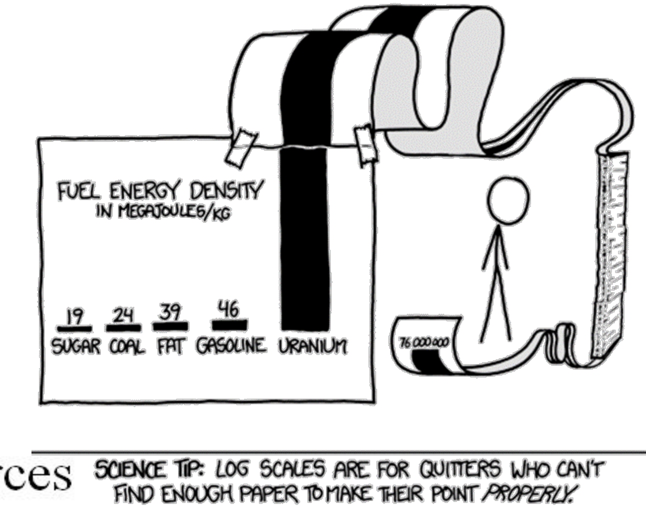
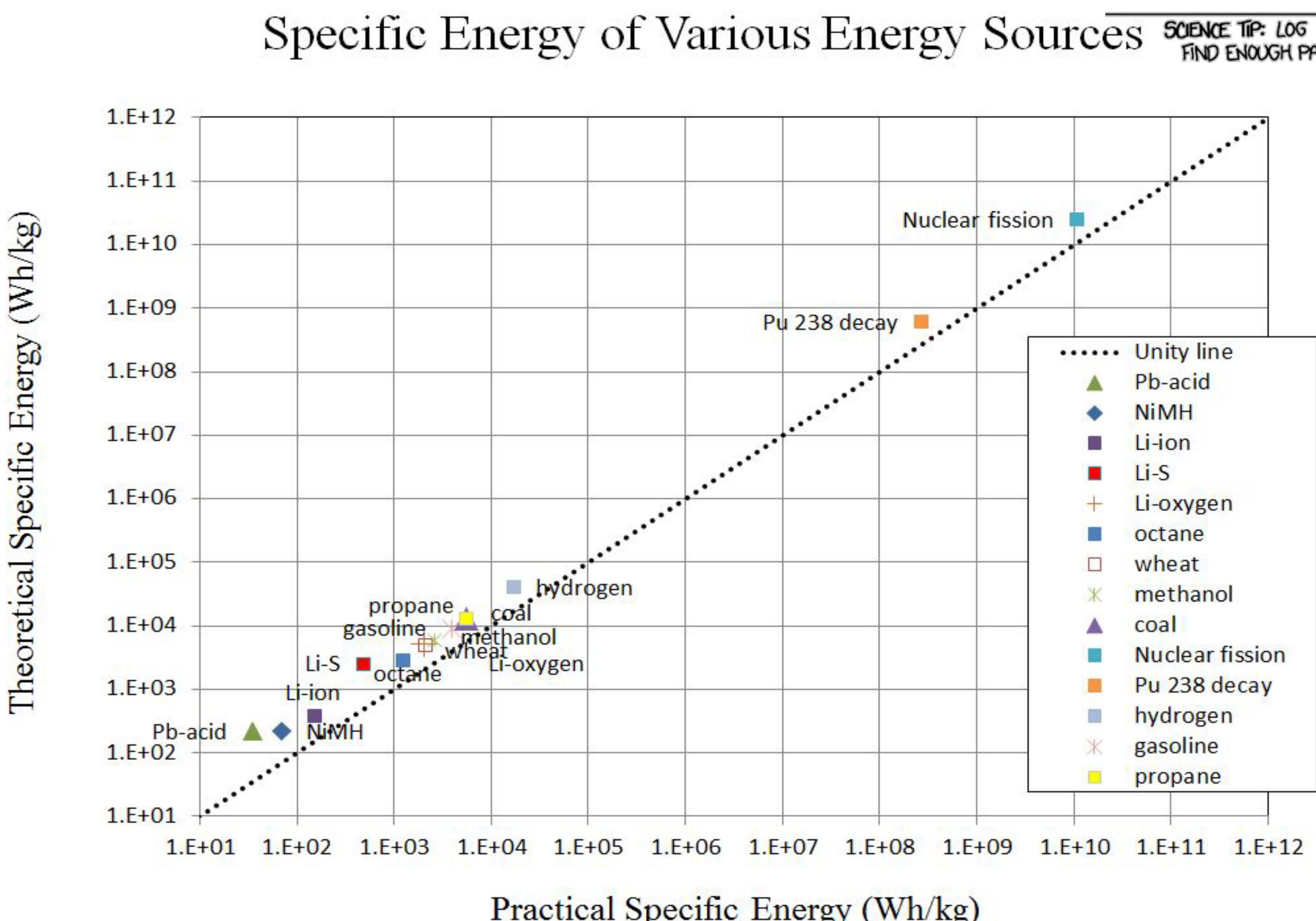
with six orders-of-magnitude higher energy density than prior energy sources.





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One might reasonably ***expect*** some new challenges i.e. “teething pains”.

the mass of waste is indeed dramatically lower than other energy sources

but potential hazard per unit mass – in the form of intrinsic radiation and toxicity - is significantly higher.

There are additional new challenges:

the higher energy-density also means proportionately more powerful weapons are possible;

operational safety is trickier;

cost - must compete well with other energy sources (if you want adoption).

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What makes it especially urgent

today

is we face global warming
-
an existential and immediate threat which portents whole new levels of 'pain'

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Our world is changing *significantly*

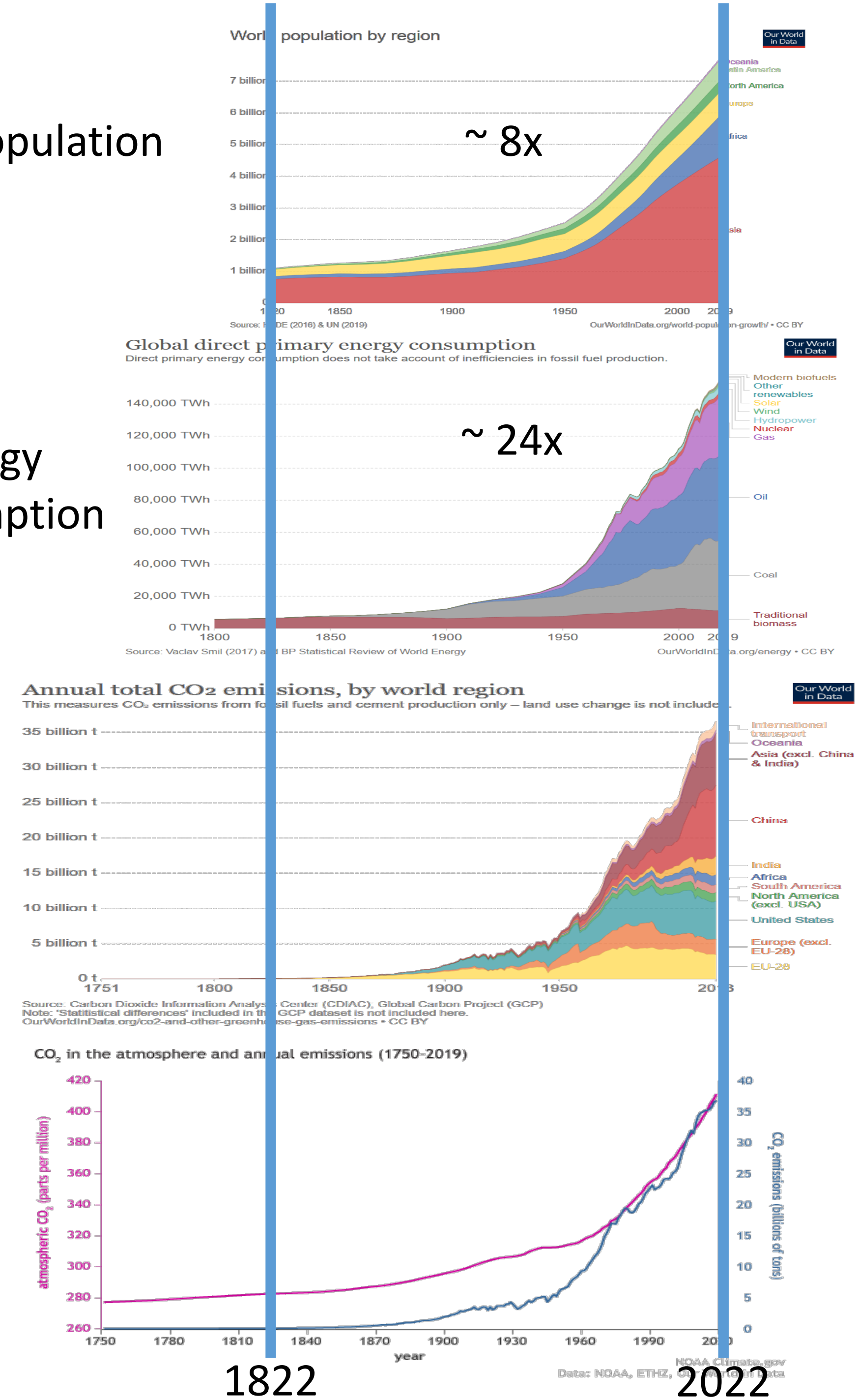
Causes
&
Effects

Population

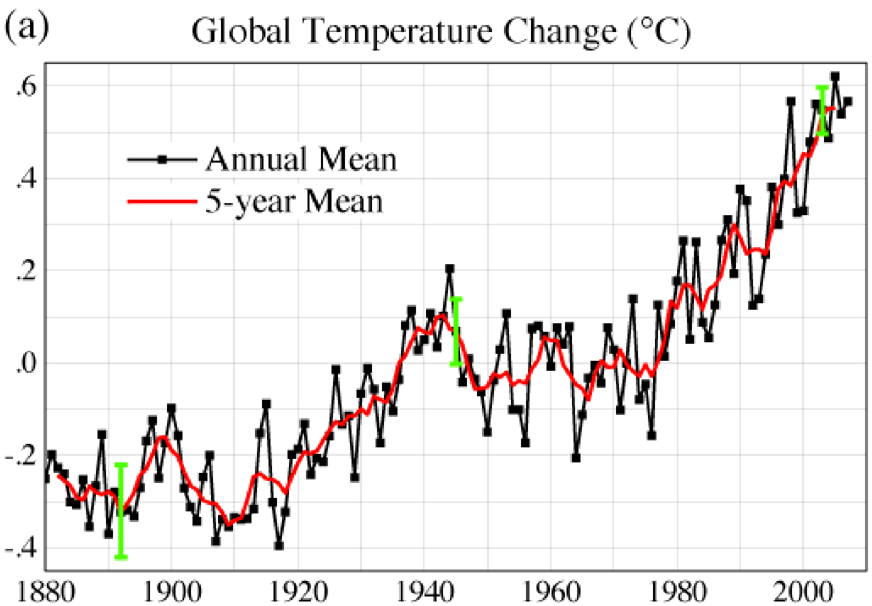
Energy Consumption

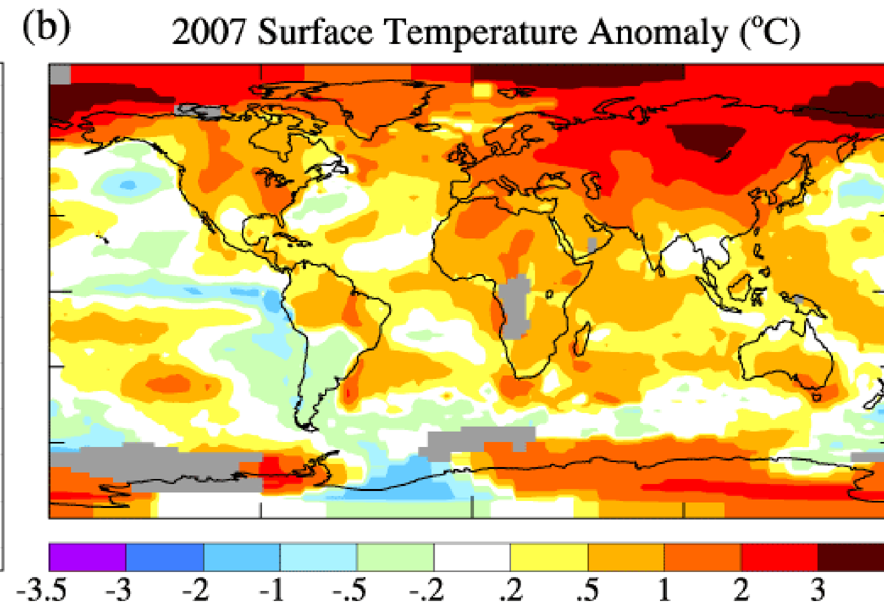
CO_2 emission

Atmospheric CO_2

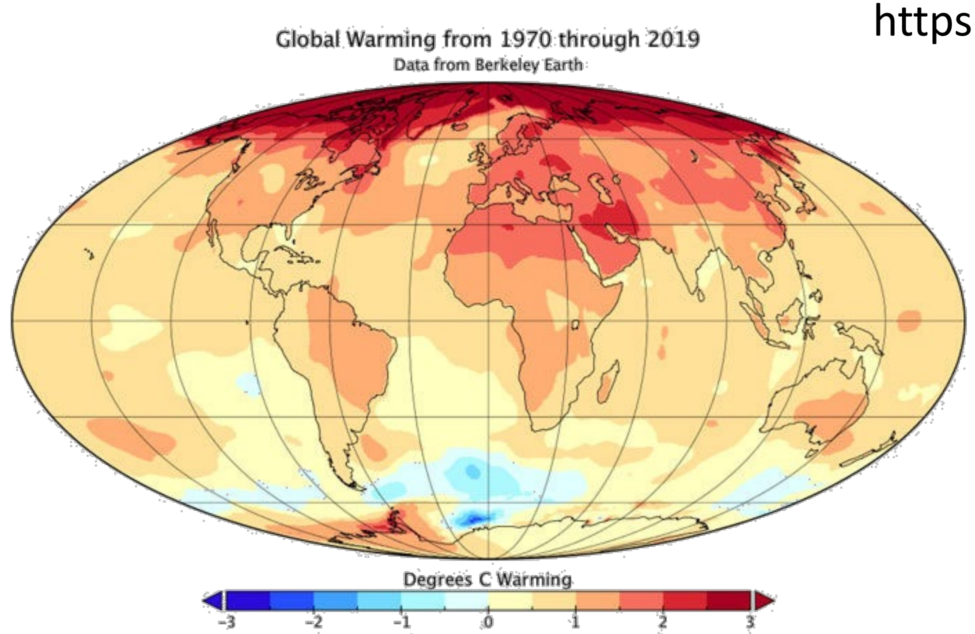


Earth is warming…





https://data.giss.nasa.gov/



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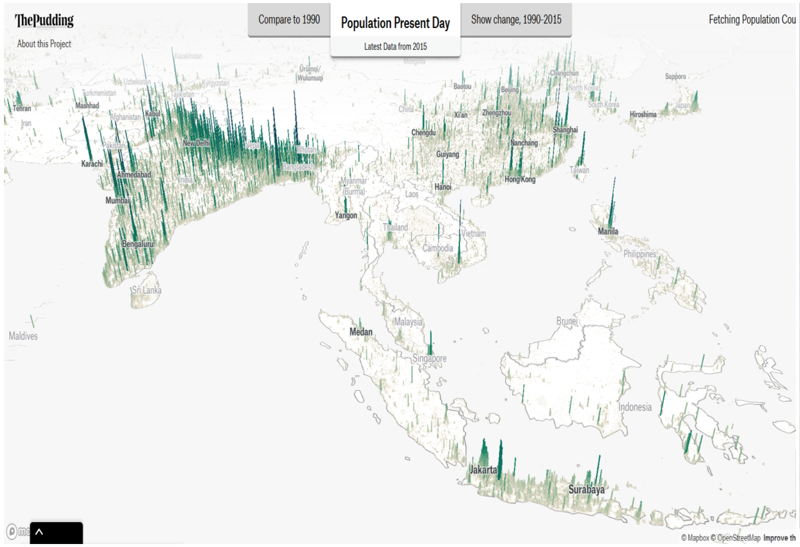
…with more storms for populations near coasts



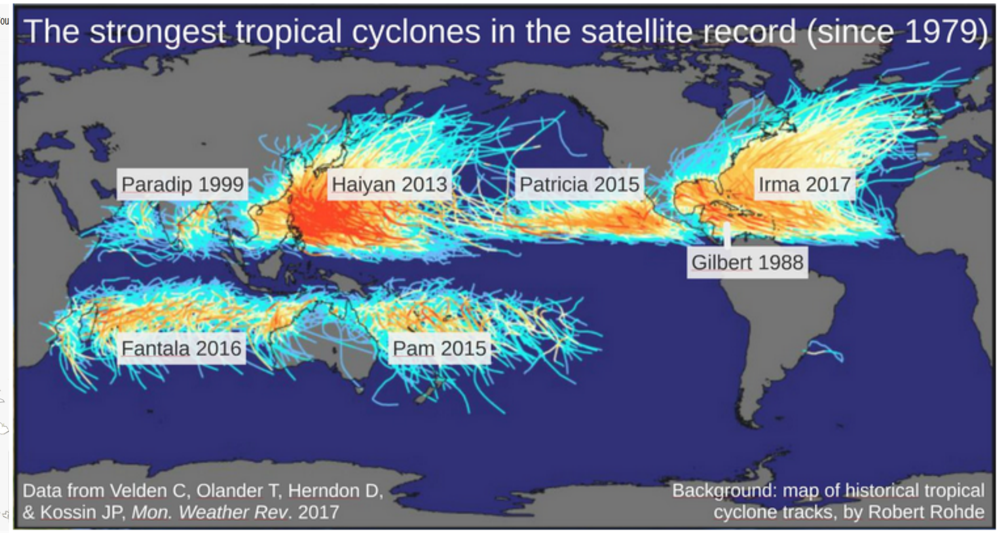
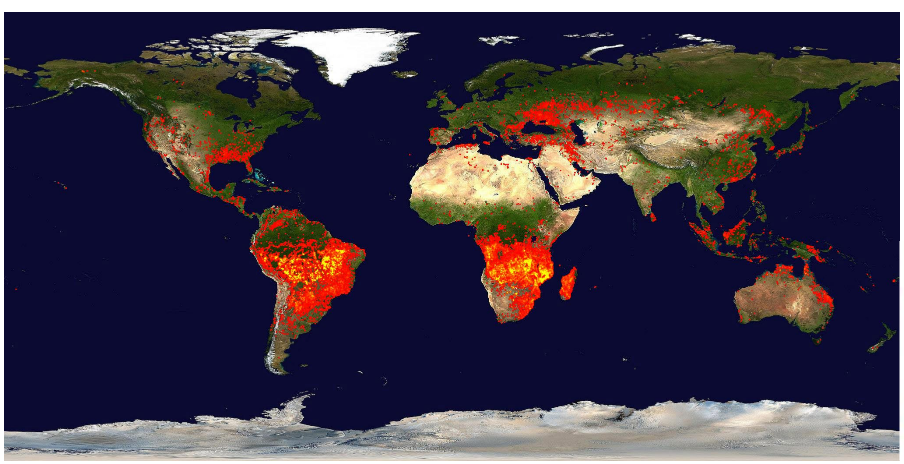


Fig. 1 *The strongest storms for the major storm regions Western and Eastern North Pacific, North Indian, South Indian and South Pacific, Caribbean/Gulf of Mexico and open North Atlantic. Of these seven regions, five had the strongest storm on record in the past five years, which would be extremely unlikely just by chance. Irma was added by personal communication from Chris Velden, and a tie of two storms with equally strong winds in the South Indian was resolved by selecting the storm with the lower central pressure (Fantala). (Graph by Stefan Rahmstorf, background image from Robert Rohde, Creative Commons License CC BY-SA 3.0.)*



…and more droughts and fires globally

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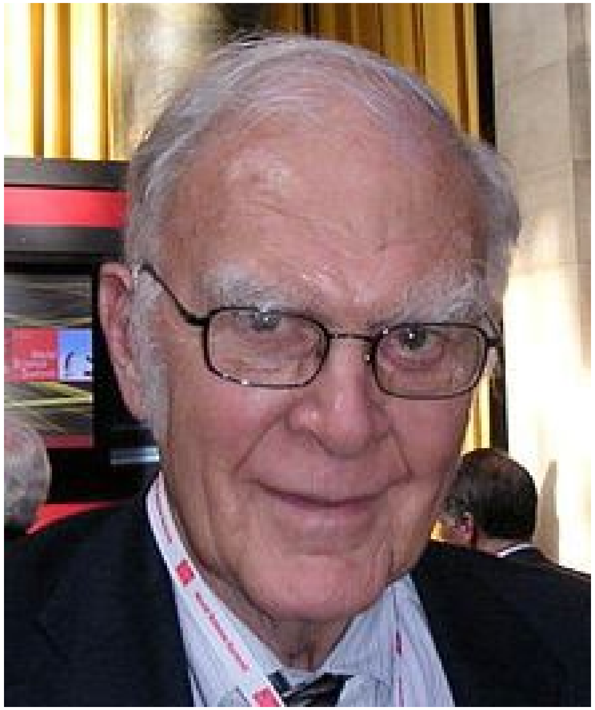
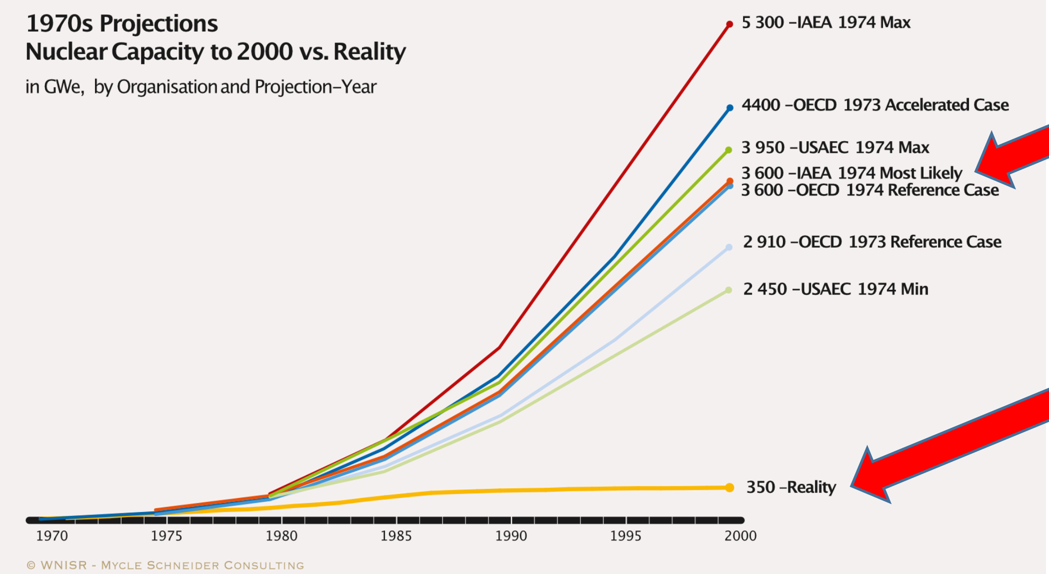
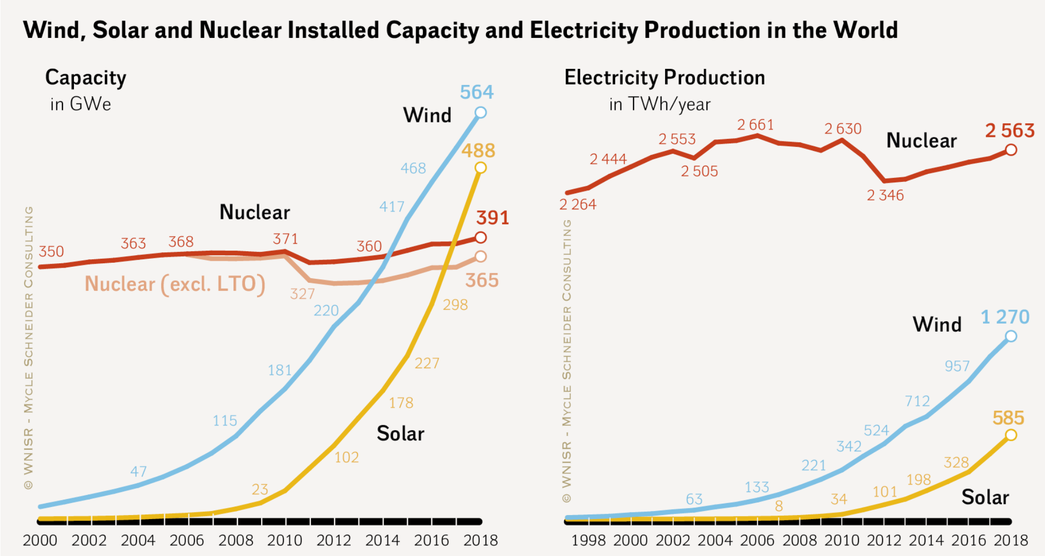


Dr. F. Sherwood "Sherry" Rowland - Nobel Prize in Chemistry 1995
White House Roundtable on Climate Change 1997

"Is it enough for a scientist simply to publish a paper?
Isn't it a responsibility of scientists,
if you believe that you have found something that can affect the environment,
isn't it your responsibility to actually do something about it?
enough so that action actually takes place?
If not us, who? If not now, when?*"*

How has it gone so far?



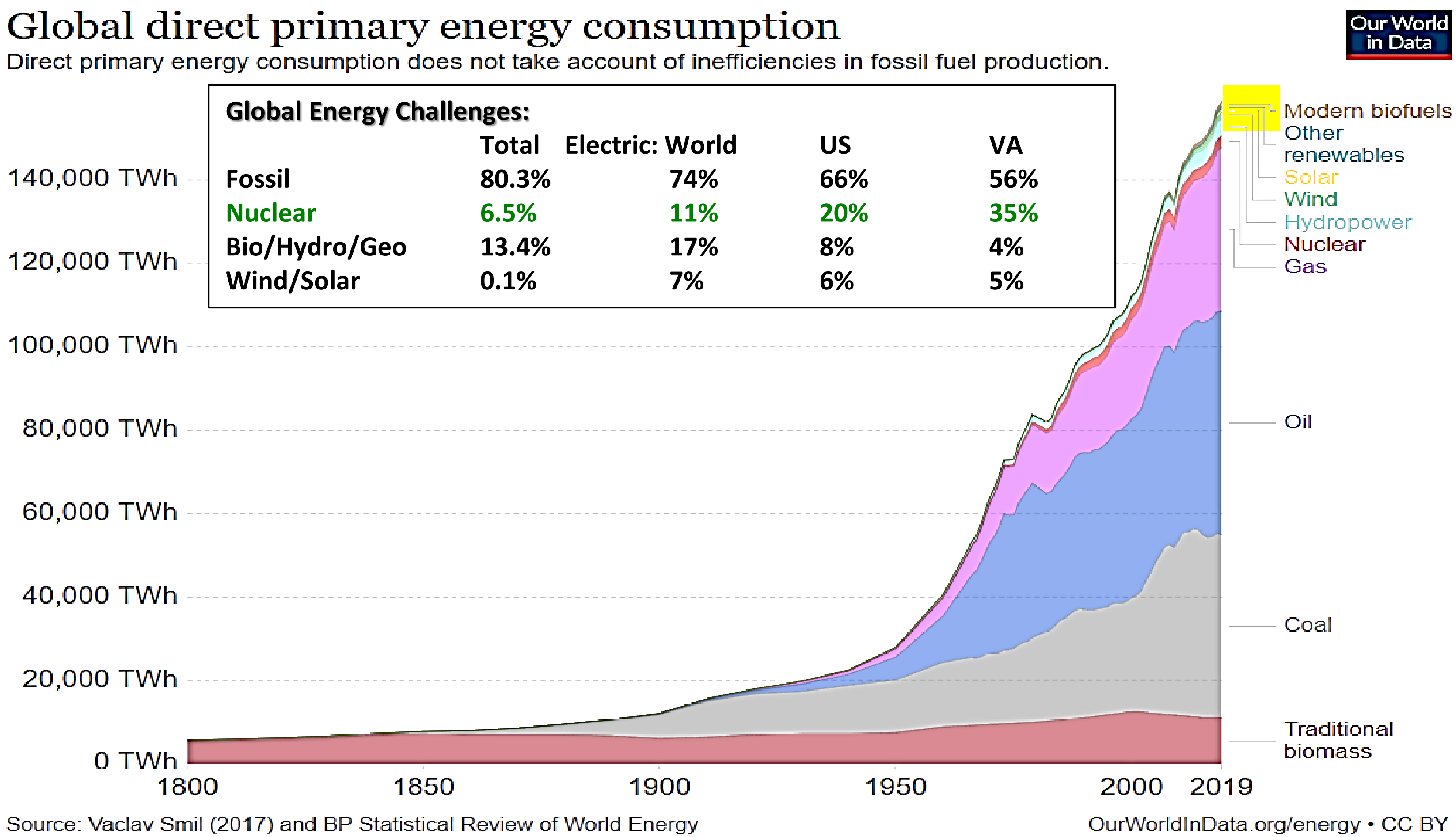


75% duty

26% duty

14% duty

Push for (green) renewable energy



Global Energy Challenges:

	Total	Electric: World	US	VA
Fossil	80.3%	74%	66%	56%
Nuclear	6.5%	11%	20%	35%
Bio/Hydro/Geo	13.4%	17%	8%	4%
Wind/Solar	0.1%	7%	6%	5%

challenge seems to remains finding a (non-nuclear) ideal battery:

- large energy density
- long safe storage
- controlled release on demand
- rechargeable

What has “blocked” nuclear energy?

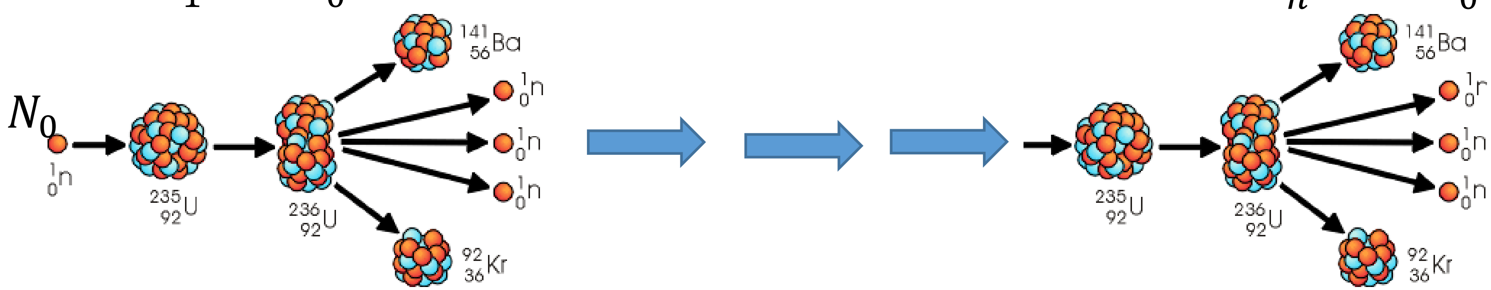
Basic Fission Chain Reaction

1st generation

$$N_1 = kN_0$$

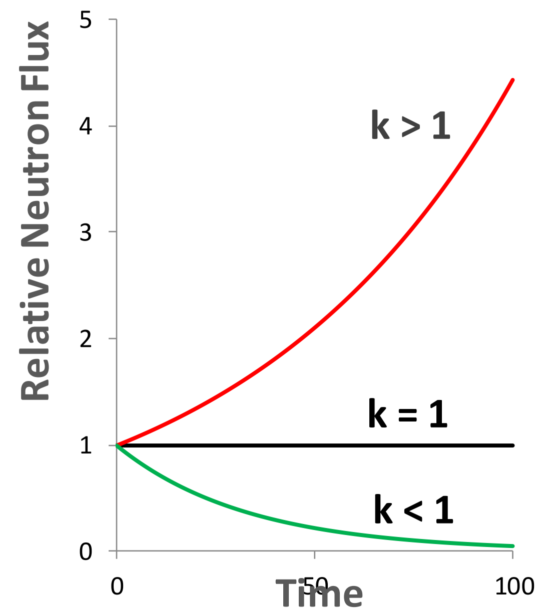
n'th generation

$$N_n = k^n N_0$$

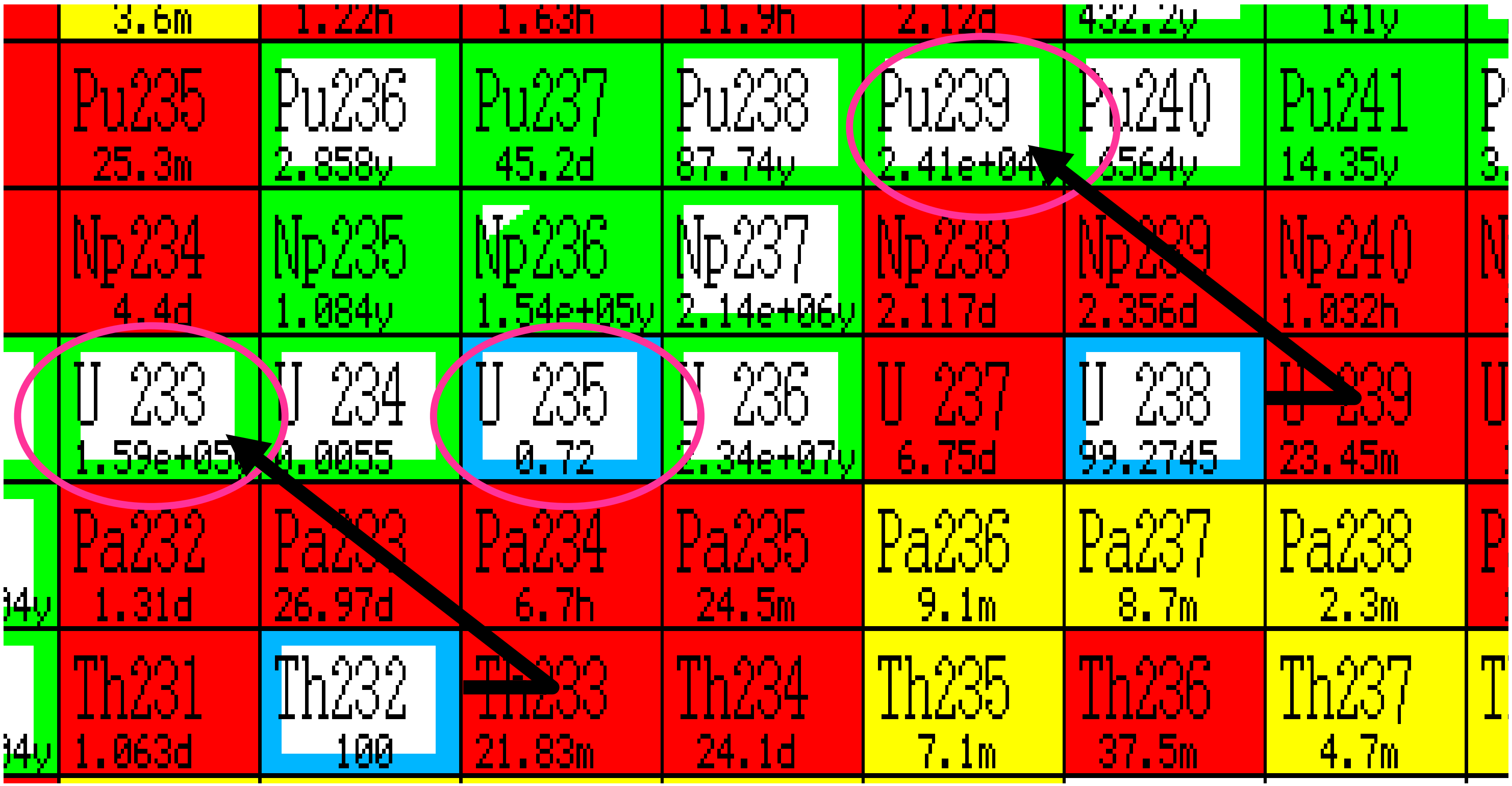


$$k = \frac{\#\,fission\ neutrons\ in\ one\ generation}{\#\ of\ fission\ neutrons\ in\ the\ preceding\ generation}$$

Reactor Physics Condition	k
Critical	1
Super-Critical	> 1
Sub-Critical	< 1



Possible Fuels



“Breeder” reactions can make new fissionable nuclei

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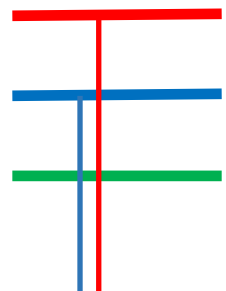
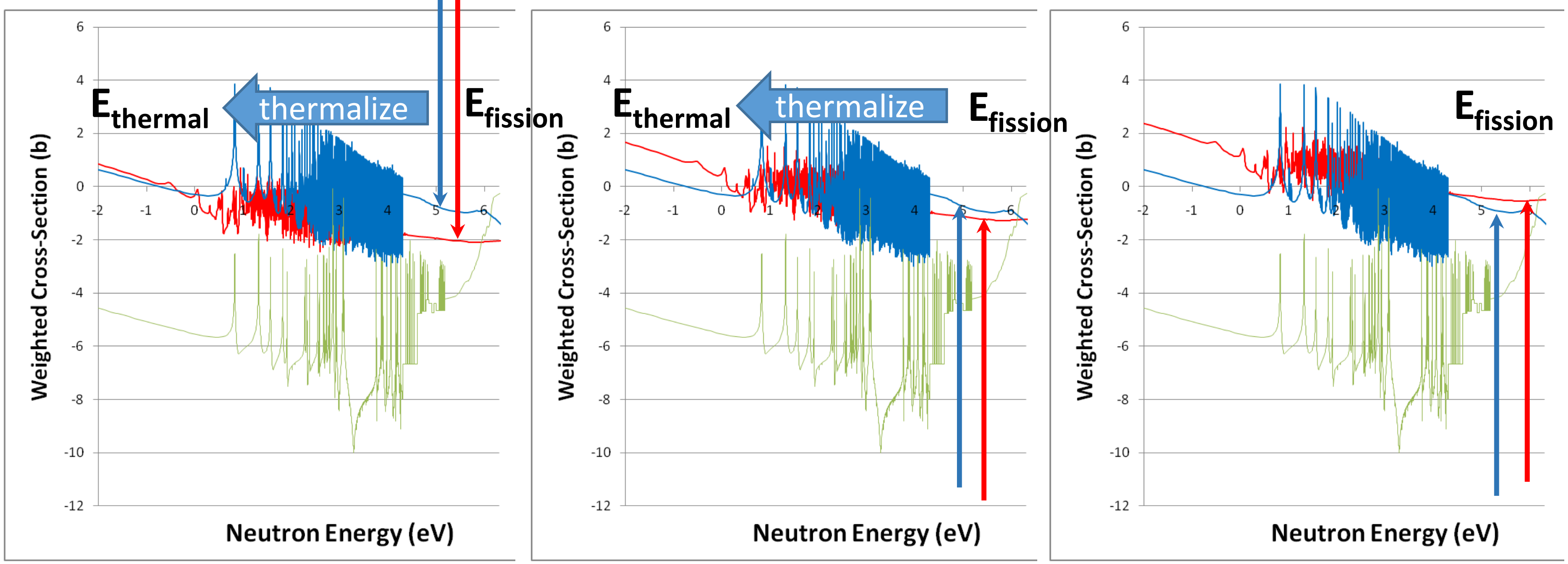
Sustaining a chain reaction

^{235}U fission
^{238}U capture
^{238}U fission



Need to thermalize fission neutrons in Uranium-free region to avoid capture



0.72 % Natural U

4.5 % "Low" Enriched U

> 20 % Weapons Usable
< 20 % new HALEU fuel

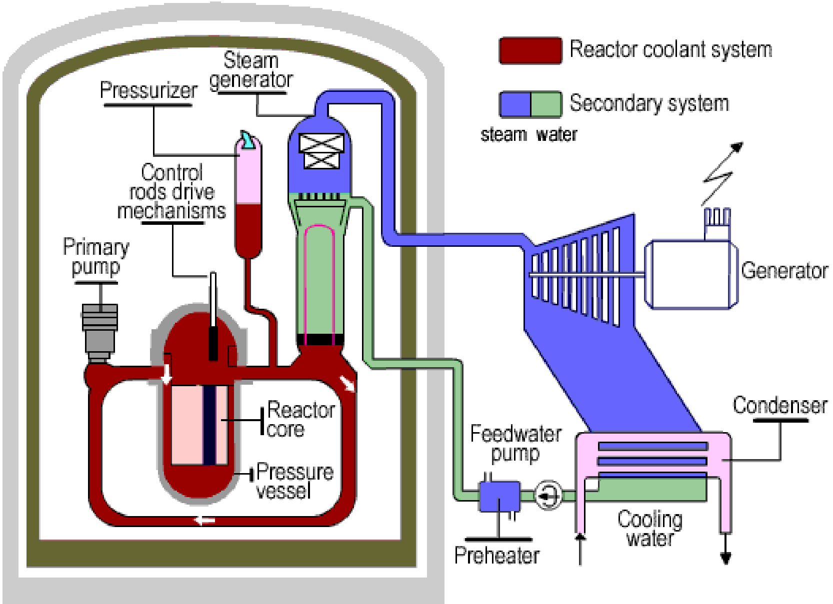
Classic "Critical" Reactor (eg LWR)

Typical 1 GW_e

Water Moderation

Enriched ^{235}U fuel

Solid fuel in cladding



Pressurized Water Reactor (AREVA)

Uses negative feedback to avoid runaway

- Prompt –vs– delayed critical
- Doppler broadening
- Thermal expansion

Eventual Build up of Fission Products poisons chain reaction, so use:

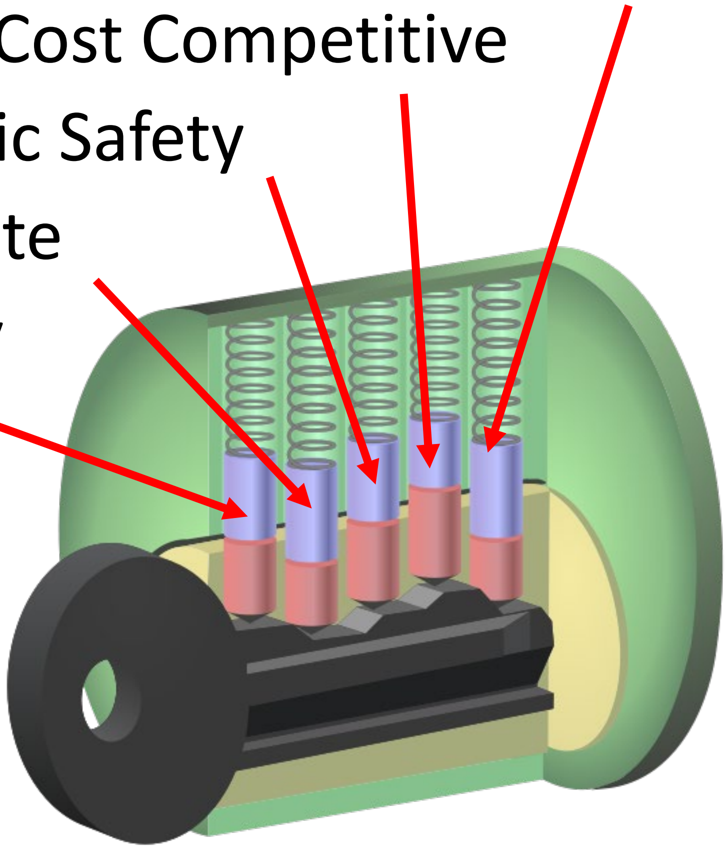
- Several critical mass initial loading
- add 'burnable/removable' neutron poisons to reduce reactivity back to k_{eff}=1

burns only 0.5% of available (fertile + fissile) energy in mined uranium

Nuclear Energy Conundrum

(solving *'one issue at a time'* is simply *not enough*)

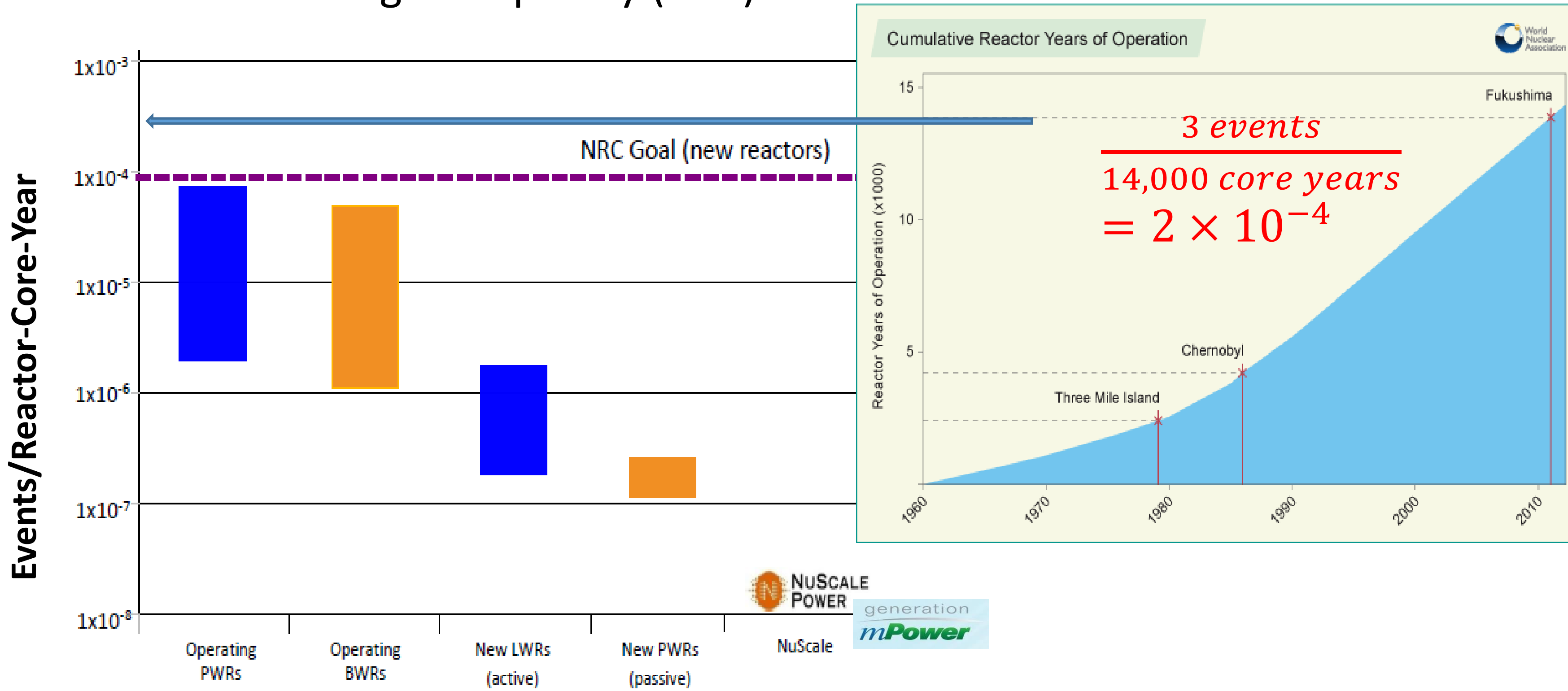
Any 'tumbler' out of alignment ***will*** stymie progress.



consider each in turn…

Safety

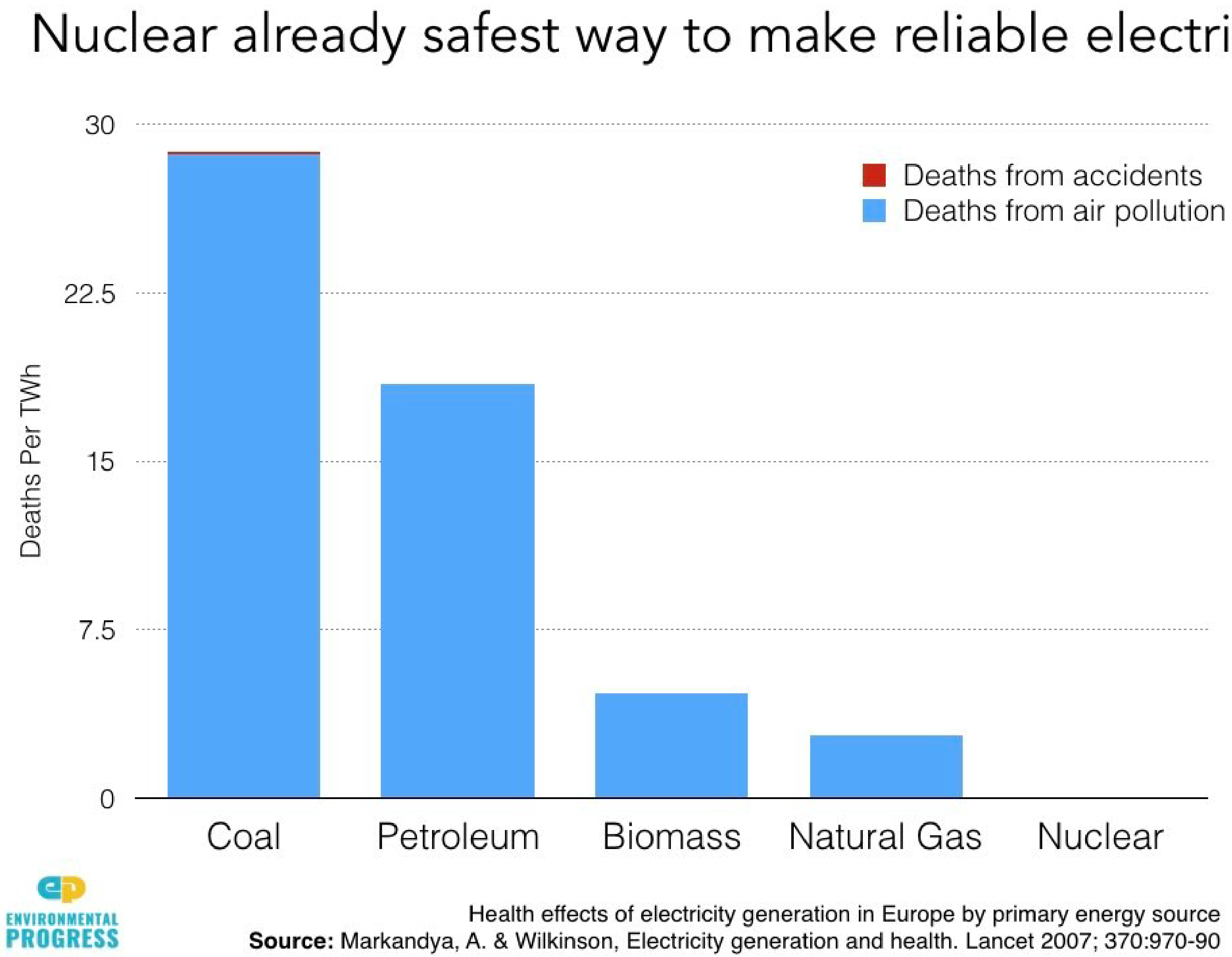
Probabilistic Risk Assessment (PRA)
of Core Damage Frequency (CDF)



SMR claim 10^{-8} events per reactor-core-year
…that's 1 core-damage event in 1,000,000 reactors over 100 years!!!

so, the problem is not just technology – but also public perception (and maybe a little lost credibility)

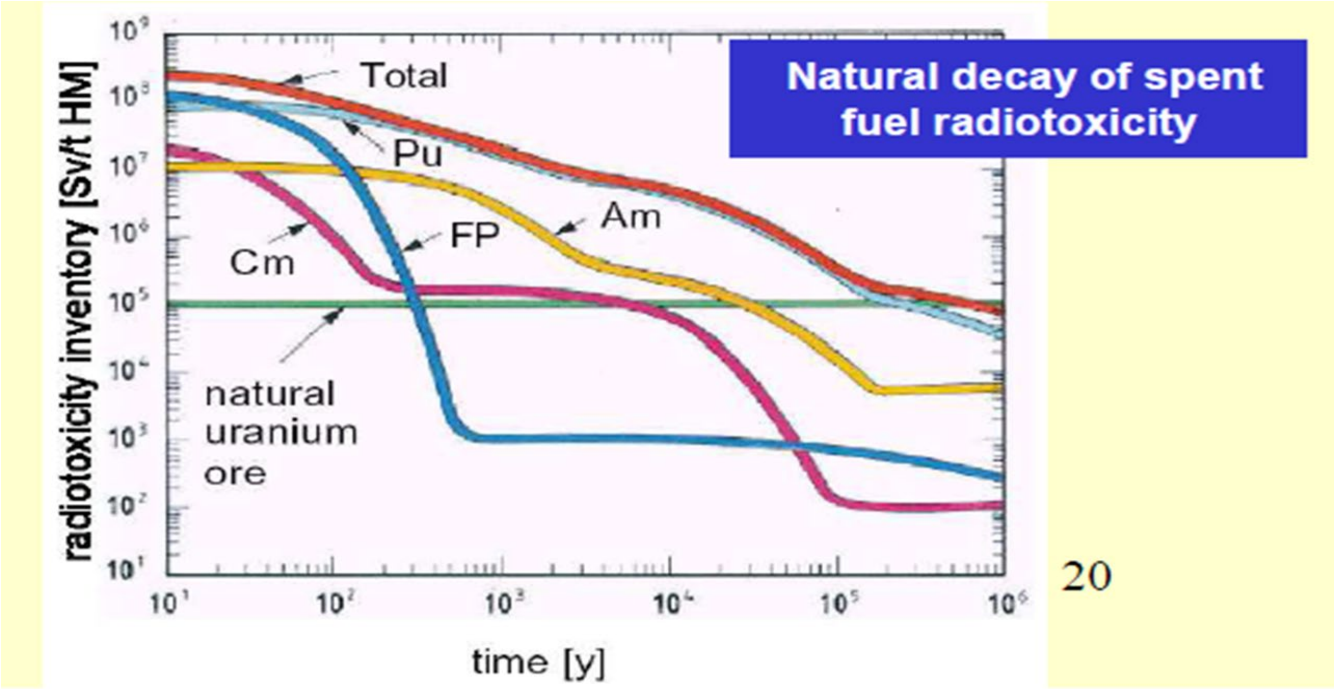
Safety



Deaths per TWh from nuclear energy is a factor of 1100 less than coal (mostly due to air pollution).

Waste

- long-lived fission products and actinides
  - bury in Yucca Mountain? (uncertain future)
  - burn with accelerators?
  - burn in next generation reactors?
  - **store on site…the current practice**



- FP (fission products) activity approaches original uranium ore after about 300 years

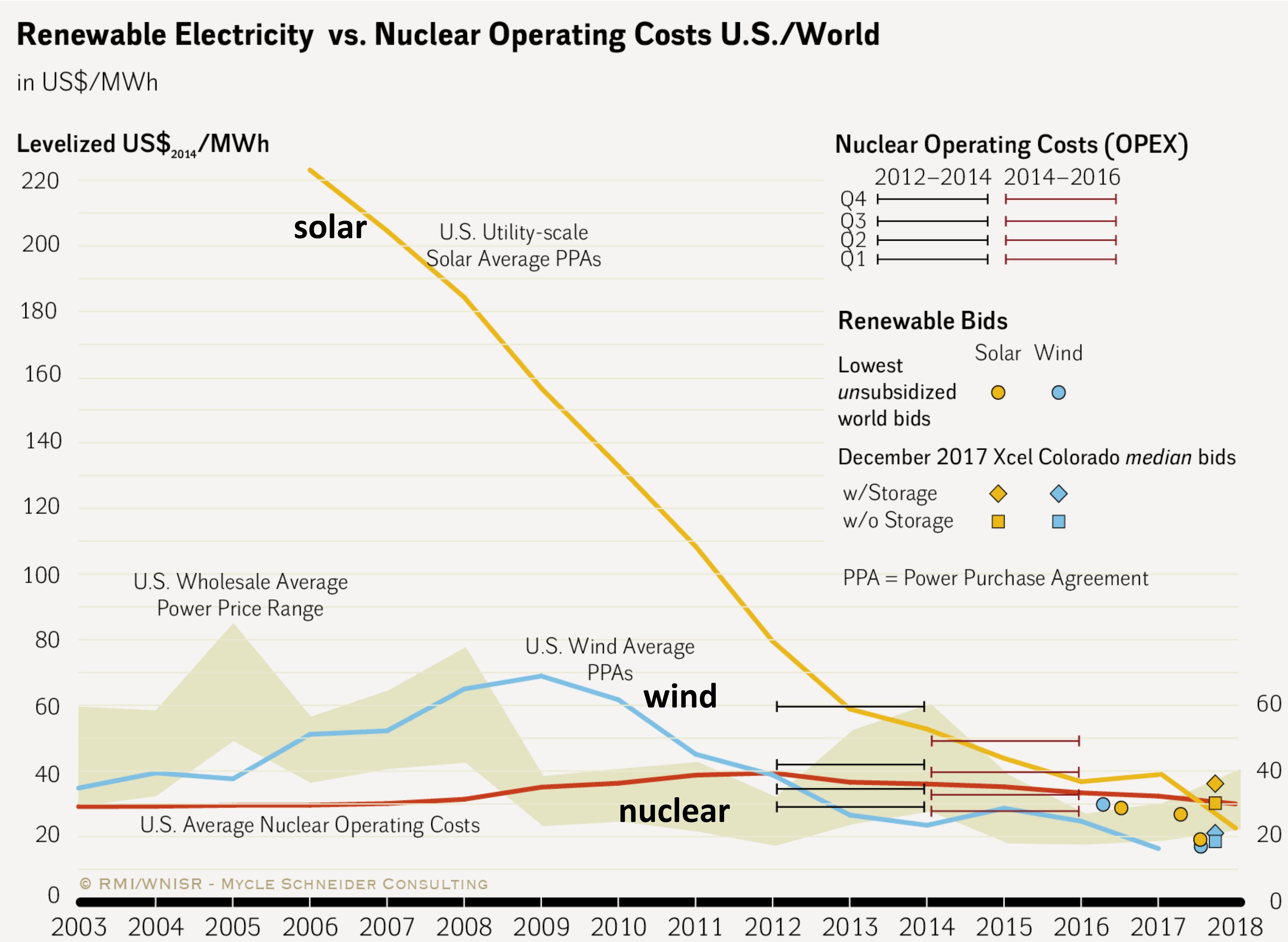
(although this graph is perhaps misleading…)

Weapons Proliferation

can the "battery" be discharged "all at once" !?

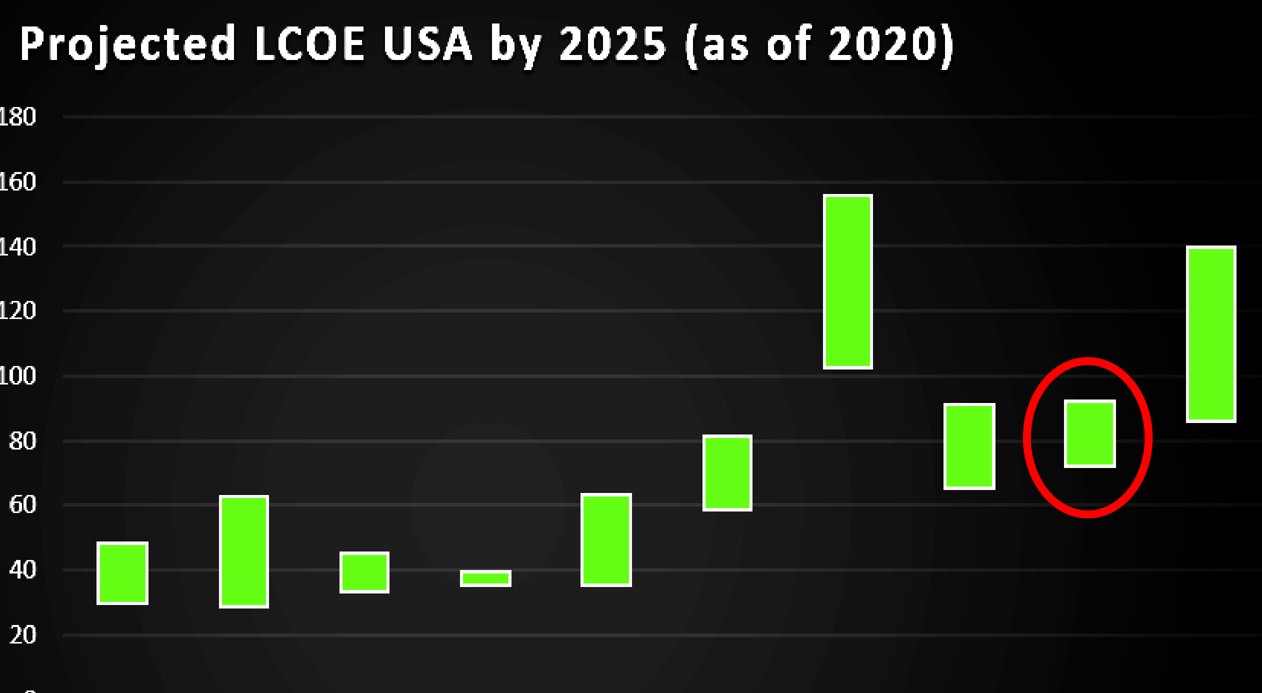
- enrichment (hard to enforce stopping at a fixed percentage; people want HALEU now…)
- reprocessing (chemical separation of Pu is easier than isotope enrichment of U)
- disposition of WGPu…
- GNEP concept rejected
- US (has recently been) leaving non-proliferation treaties…

Cost



Renewable Electricity vs. Nuclear Operating Costs U.S./World
in US$/MWh
Levelized US$2014/MWh
220
200
180
160
140
120
100
80
60
40
20
0
solar
U.S. Utility-scale Solar Average PPAs
U.S. Wholesale Average Power Price Range
U.S. Wind Average PPAs
wind
nuclear
U.S. Average Nuclear Operating Costs
Nuclear Operating Costs (OPEX)
2012–2014 2014–2016
Q4
Q3
Q2
Q1
Renewable Bids
Solar Wind
Lowest unsubsidized world bids
December 2017 Xcel Colorado median bids
w/Storage
w/o Storage
PPA = Power Purchase Agreement
© RMI/WNISR - Mycle Schneider Consulting
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

Cost



	Solar photovoltaic (PV)	Wind, onshore	Combined cycle	Geothermal	Hydroelectric	Combustion Turbine	Wind, offshore	Ultra-supercritical coal	Advanced Nuclear	Biomass
Min	29.75	28.72	33.35	35.13	35.37	58.48	102.68	65.1	71.9	86.19
Simple Average	35.74	39.95	38.07	37.47	52.79	66.62	122.25	76.44	81.65	94.83
Capacity weighted average	32.8	34.1	36.61	37.47	39.54	68.71	115.04			
Max	48.09	62.72	45.31	39.6	63.24	81.37	155.55	91.27	92.04	139.96

GEM*STAR: estimated at $45 per MWh with natural uranium fuel

TRUE cost of nuclear must include its current impact on our foreign policy and military with regards to Iran, North Korea, India, and pretty much every country.

What's new on the horizon…

DOE-NE

'small modular reactors'

- safety ←
- waste
- weapons proliferation
- cost ←

pyroprocessing

molten-salt / Na cooling

DOE-Science

'high-intensity frontier'

- safety
- accelerator transmutation of waste (demo in 2050?) ←
- weapons proliferation (maybe monitoring?) ←
- cost

in fact, growing desire for HALEU fuels for longer operation

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US Nuclear Energy Generation - R&D & Construction

US Energy Context:

- coal/natural gas: not 'green'
- solar/wind: baseload challenges

US Nuclear Energy Context: (list is a few years dated already…)

- 3 reactors were under construction (GEN 3+ LWRs):
  - 2 in Georgia & 1 in Tennessee (completed)
- New government and industry activities – Advanced Reactor Design
  - Whitehouse Nuclear Energy Summit (Nov '15)
  - COP-21 climate talks (Dec '15, Paris, France)
  - DOE new opportunities for advanced reactor research (public-private partnership), $80 M (Funded, Jan 2016);
    Southern Co. to develop Molten Chloride Fast Reactor;
    X-energy to develop Xe-100 pebble bed HTGR
  - Breakthrough Energy (investment group led by Bill Gates)
  - DOE, Advanced Reactor Technologies, industry-driven projects, $30 M (Nov 2017)
  - DOE, U.S. Industry Awards in Support of Advanced Nuclear Technology Development, $60 M (April 2018)
  - DOE, in the next 6 months, ANT Development, $40 M (pending)

Startups (about 50), for example:

TerraPower (Traveling Wave (now Natrium) - Bill Gates) ; Terrestrial Energy (MSR in Canada); Flibe Energy (MSR LFTR – Sorensen); ThorCon Power (MSR [uranium fuel]); Moltex Energy (MSR – British); *Transatomic Power (MSR – MIT); NuScale Power (SMR-LWR – DOE & industry supported); mPower (SMR-LWR– B&W); Kairospower (MSR Berkeley)*

ALL are CRITICAL reactors

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my view: current plans will not enable nuclear energy to seriously address global warming

– at least today within the developed world

"In the United States, the government concluded that neither breeder reactors nor spent fuel reprocessing could compete economically with water-cooled reactors fueled by once-through low-enriched uranium fuel."

"Some fuels never learn. US Energy Department returns to costly and risky plutonium separation technologies"

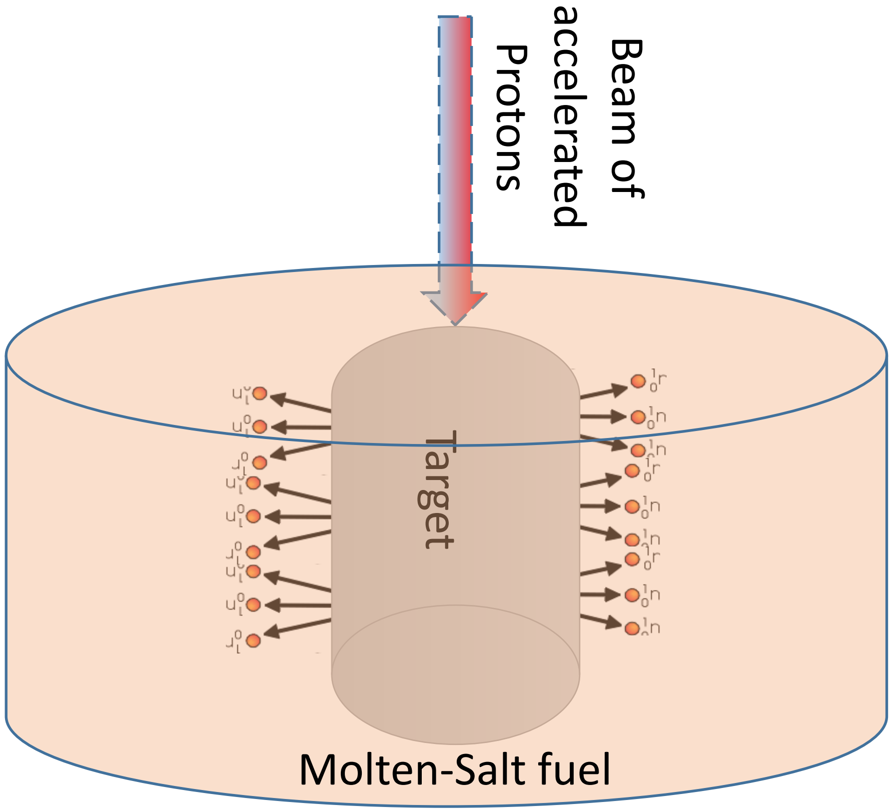
By Jungmin Kang, Masafumi Takubo, Frank von Hippel | September 14, 2022 (Bulletin of the Atomic Scientists)

– are there other options?

what about an

Accelerator-Driven (Subcritical) Molten-Salt Fueled Reactor

An accelerator generates the needed neutrons



Sub-Critical - ***incapable*** of power production (only decay heat) - unless 'driven' by supplemental neutrons
using enriched fuel — Micro Reactor Short-term
using spent nuclear fuel — SNF Mid-term
using natural uranium — Global Use

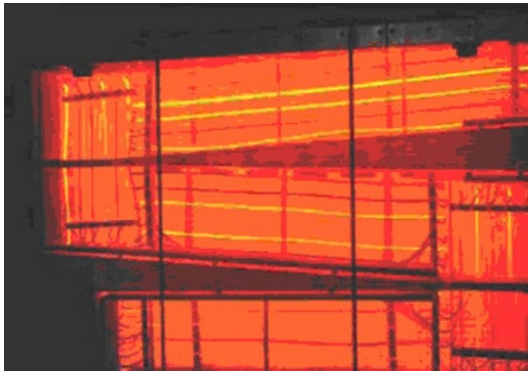
Existing Enabling Technologies

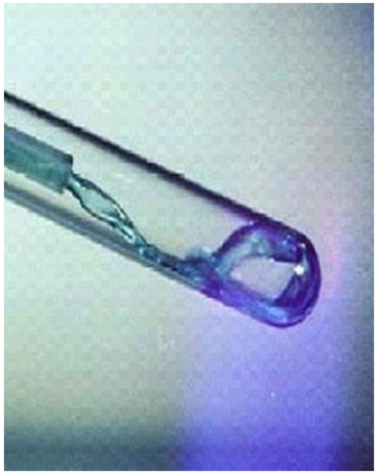
- efficient & proven LINAC accelerators
- proven molten salt eutectic fuels
- running MW class beam targets
- measured modern graphite purity & properties

Hasn't this been tried before?

Molten-Salt Fueled Reactor

Proven in 1960's ORNL MSRE reactor using Modified Hastelloy-N
Ran on fission of ^{235}U, ^{239}Pu, ^{233}U





Uranium or Thorium fluorides form eutectic mixture with LiF salt.

The MSRE and all current startups are focused on *critical* reactors.

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Accelerator Transmutation of *Waste* (ATW)

1991-2007 DOE development program at LANL (~$280M/yr)

"Energy Amplifier"

Carlo Rubbia (Nobel Laureate) Science 1993
(using Bowman ideas at LANL)

cited concerns

- accelerators add complexity & cost
- accelerator performance (e.g., thermal shock rate)
- unpredictable licensing path

let's look beyond corporate and DOE traditional concepts and comfort zones…

The new approach

integration - *from the beginning*

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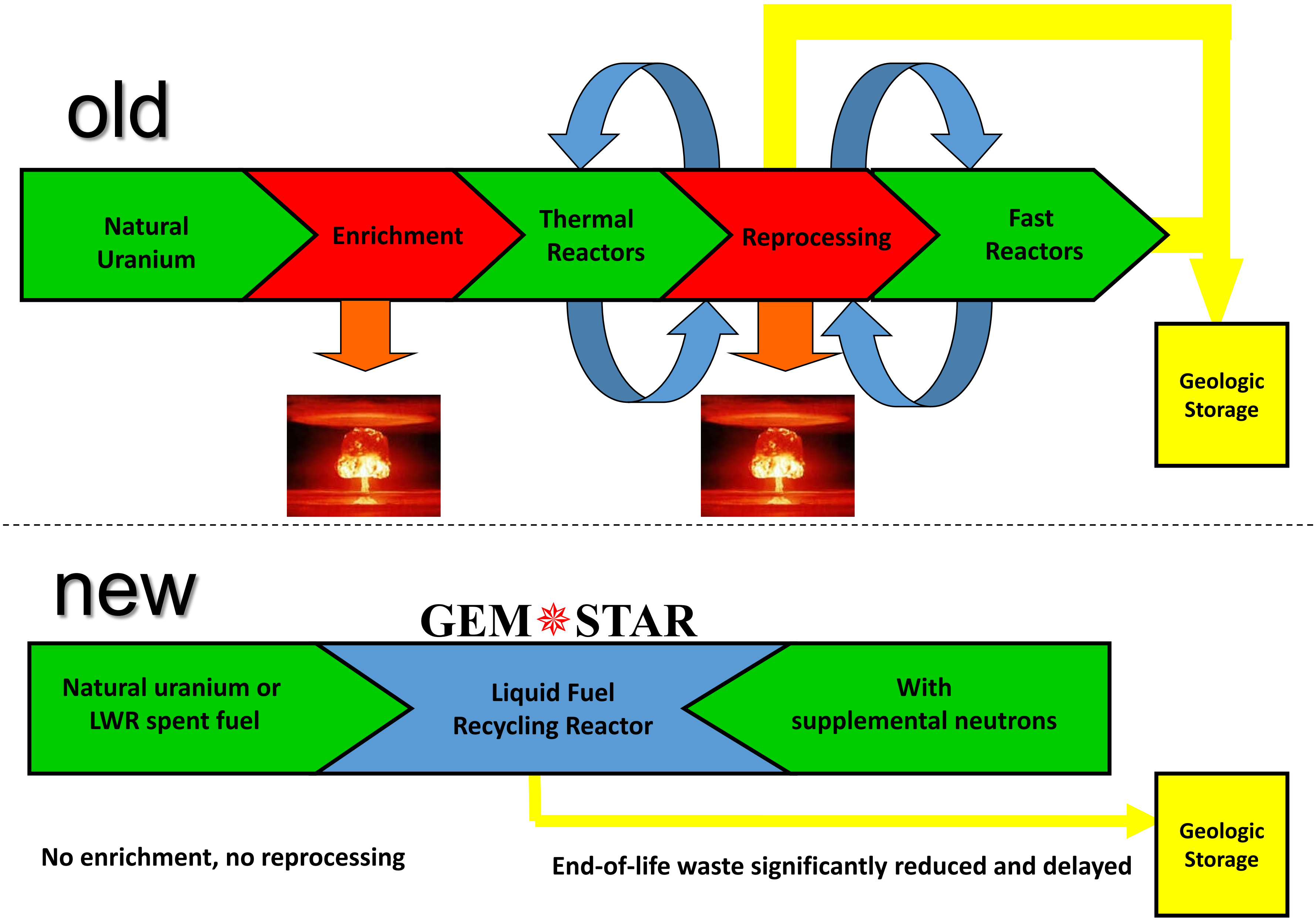
(original concept by Dr. Charles Bowman)

Two unique insights

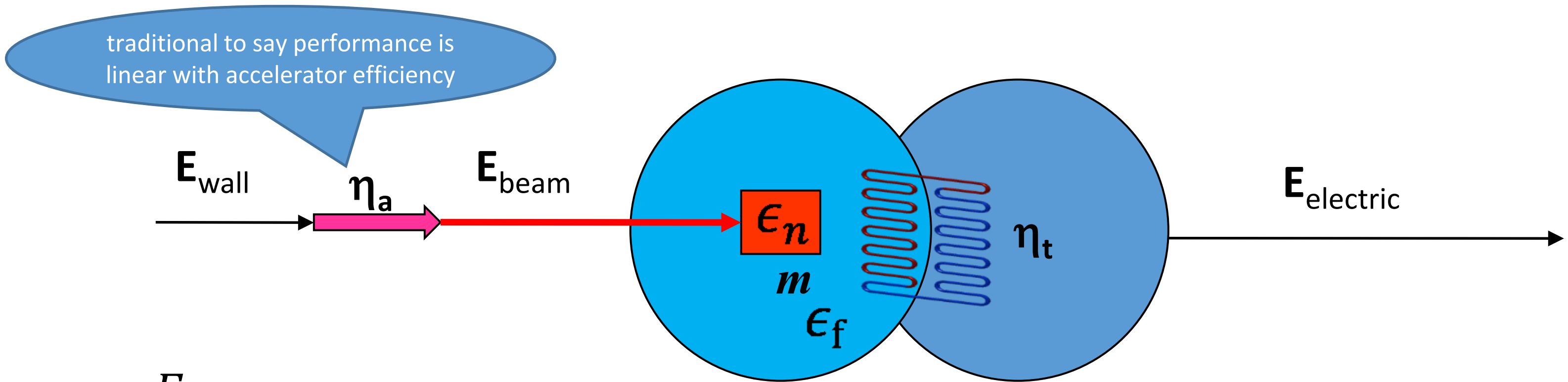
- **first: an accelerator-driven molten-salt reactor**
  - *when designed to optimize this coupling from the start* - can address *all five* challenges ("tumblers") at once
  (the accelerator is *needed* for non-proliferation aspects)

- **second: high-temperature continuous fission product removal may essentially avoid refueling for the lifetime of the reactor (does not necessarily require accelerator)**

Change Paradigm for Nuclear Energy



Accelerator Driven Figure-of-Merit



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

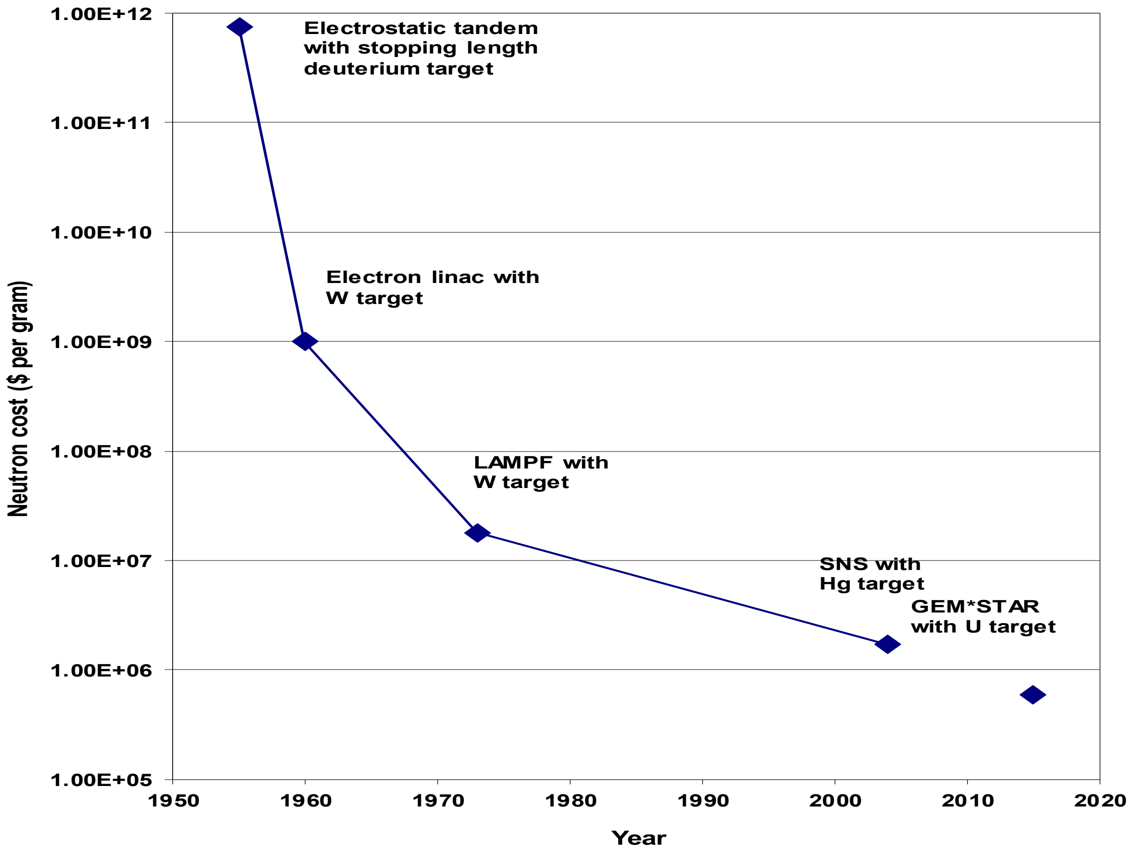
$\eta_a \equiv efficiency\ of\ accelerator$ (typ 20%)
$\epsilon_n \equiv energy\ to\ liberate\ neutron$ (typ 20 MeV for 1 GeV protons)
$m \equiv number\ of\ fissions\ per\ neutron$ (typ 15)
$\epsilon_f \equiv energy\ per\ fission$ (typ 210 MeV)
$\eta_t \equiv efficiency\ converting\ thermal\ to\ electrical\ energy$ (typ 44%)

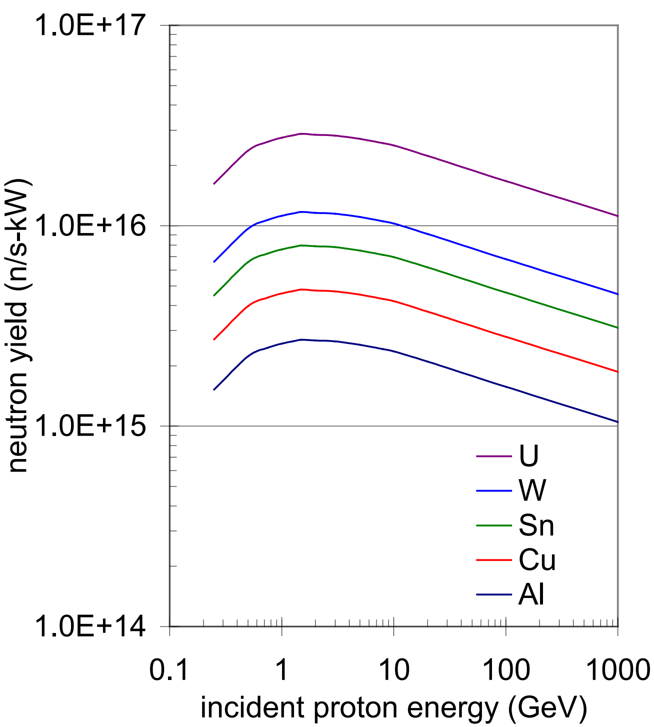
$$
G = \frac{\text{net electric power out}}{\text{power on target}} = \frac{E_{\text{electric}} - E_{\text{wall}}}{E_{\text{wall}}\eta_{\text{a}}} = \left(1 + \frac{\epsilon_{\text{f}}}{\epsilon_{\text{n}}} m\right)\eta_{\text{t}} - \frac{1}{\eta_{\text{a}}} \approx 4.6m - \frac{1}{\eta_{\text{a}}}
$$

Existing accelerators and G*S design give G ≈ 70 – 5

(note: increasing accelerator efficiency from 20% to 50% only increases G from 65 to 68)

What is needed by way of accelerators?



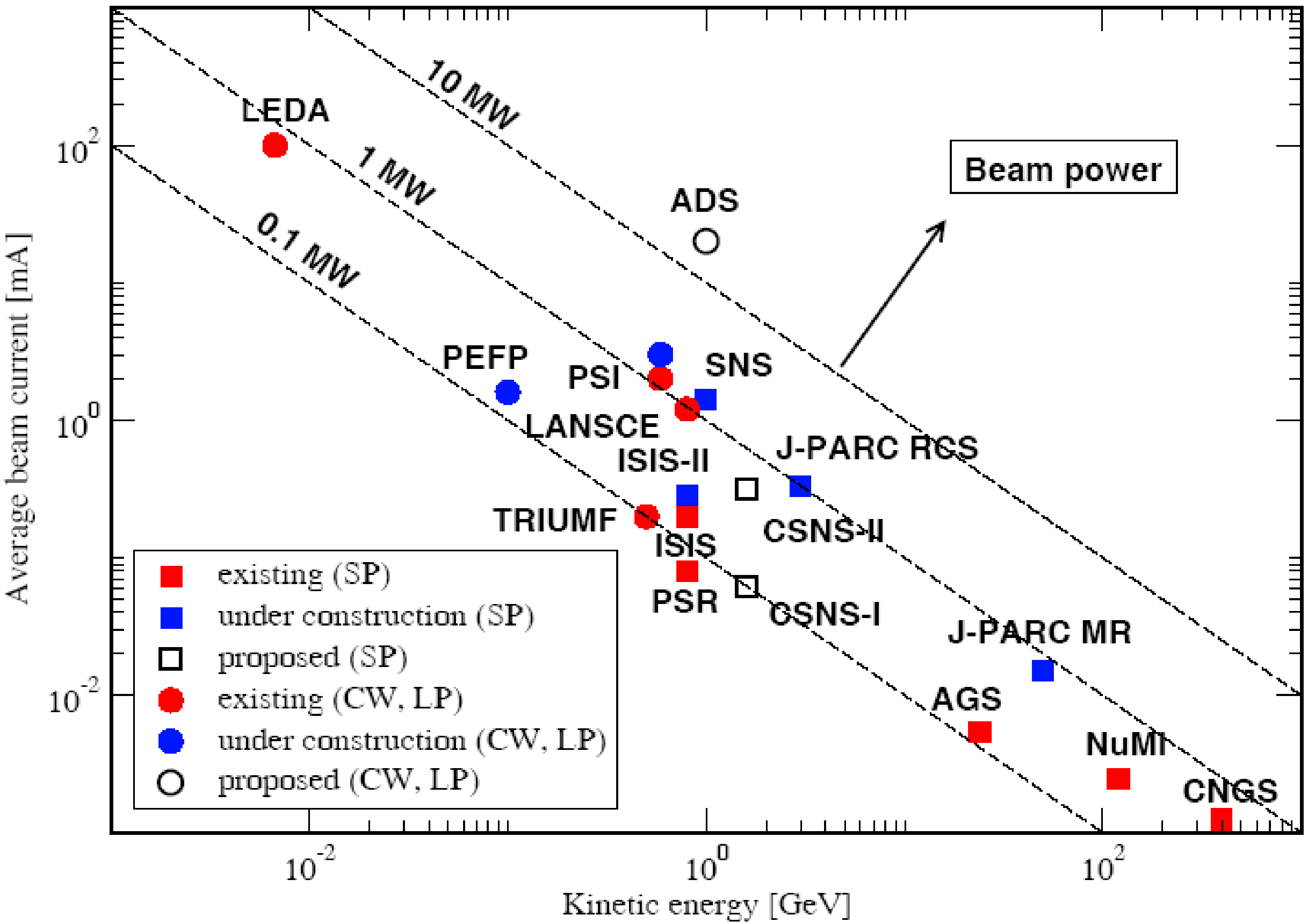


~40 grams of neutrons will produce 1GWe for one year

($432M/yr revenue @ 5 ¢/kWh)

(much better margin for synthetic transport fuels)

Existing Proton Beam Power



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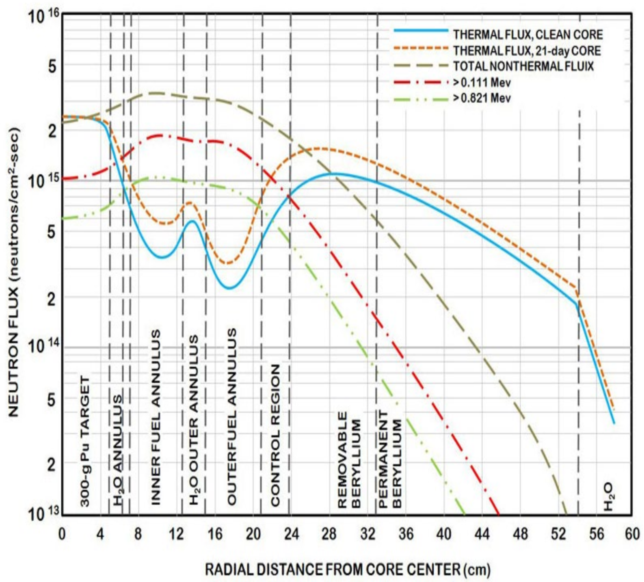
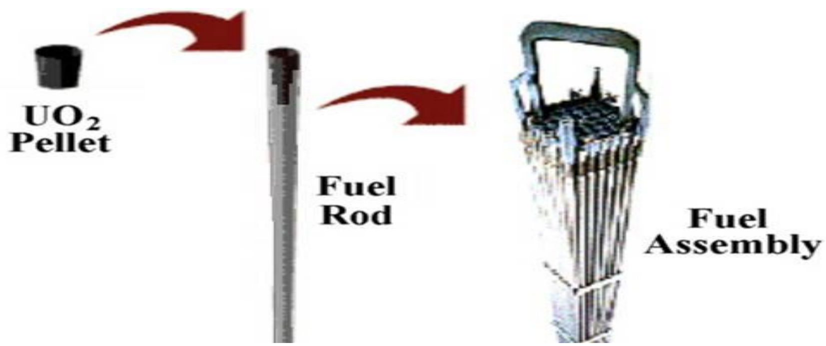
Solid Fuel Issues



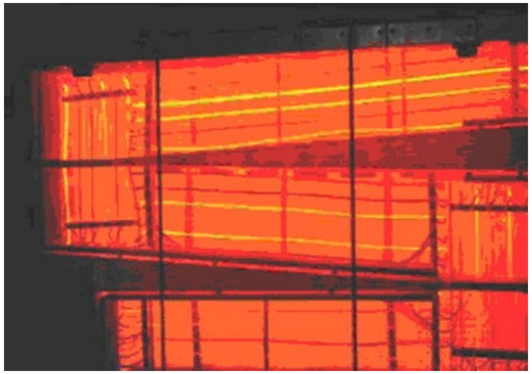


non-uniform fuel consumption requires fuel repositioning

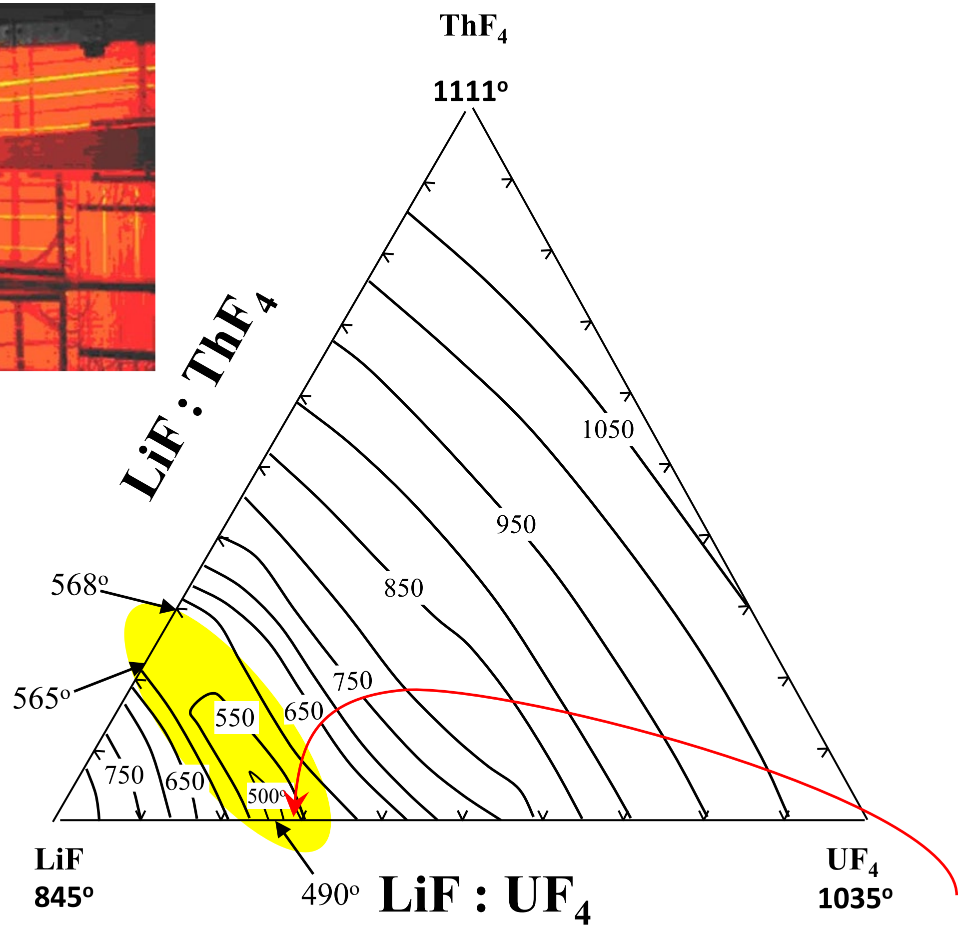
volatile fission-product build-up within cladding (Fukushima, 3-Mile Island)

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

Molten Salt Eutectic Fuel



Similar **to 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

LiF : UF_4 set to 2:1

Eutectic ratio NOT ARBITRARY!

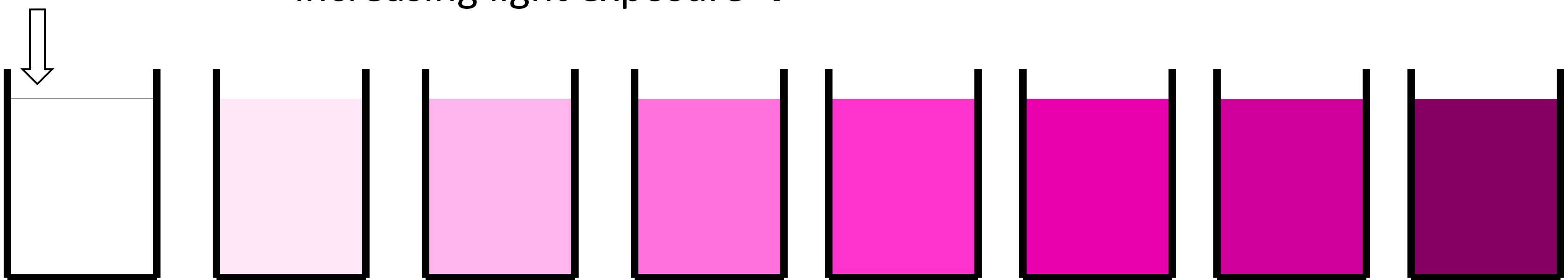
you might not be able to add a little LWR spent fuel to LiF, or remove all the uranium, and remain molten

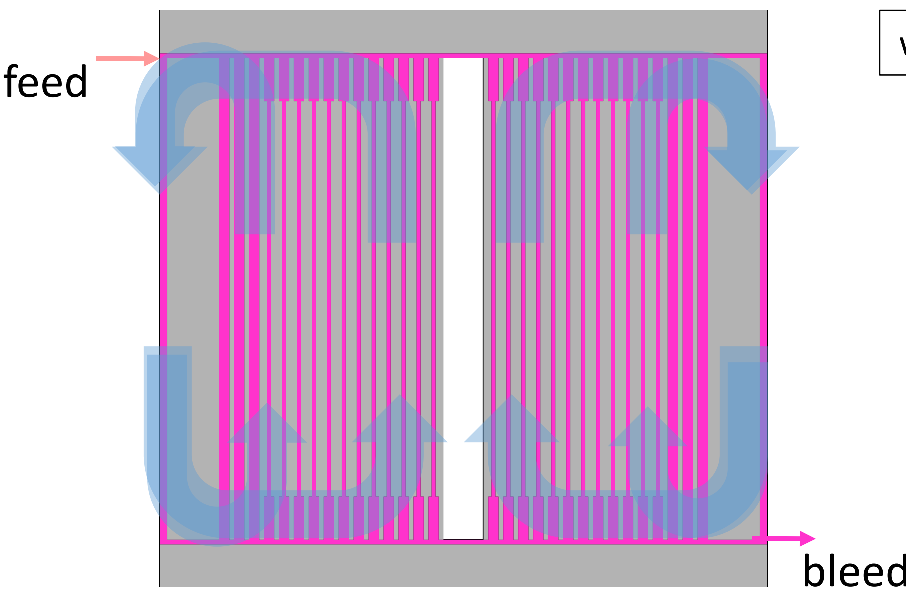
FLiBe can help with this, but at a cost to neutronics and viscosity, among other issues

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

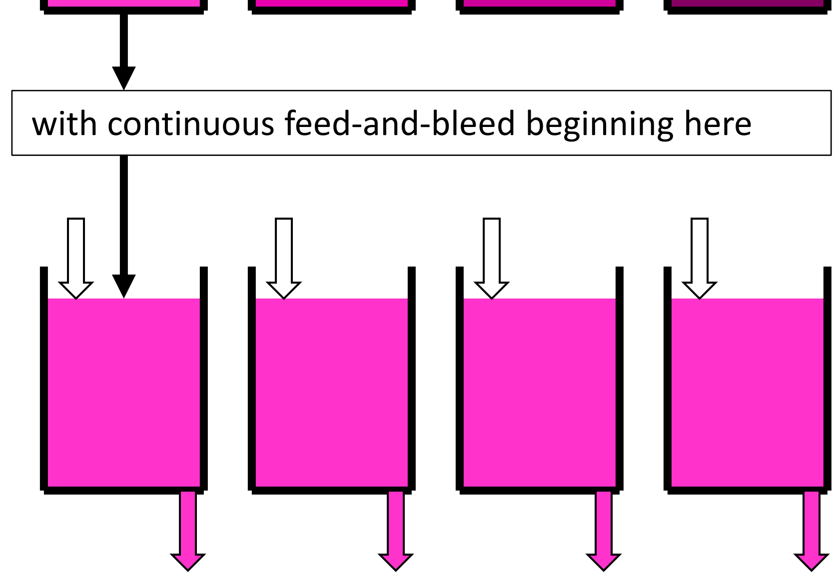
Initial fill

increasing light exposure →





fast internal mixing



color and heat output remains constant indefinitely

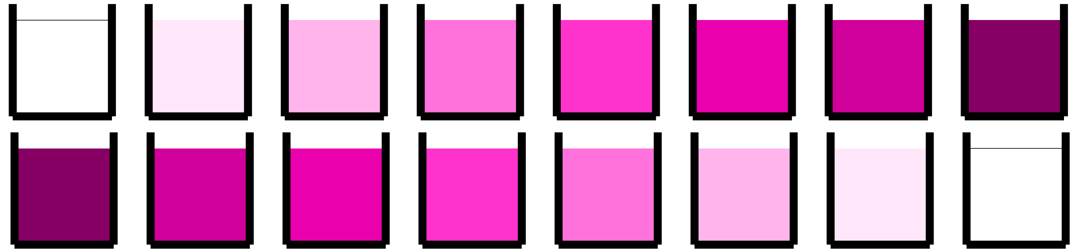
→ equilibrated isotope fractions throughout core and throughout time

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

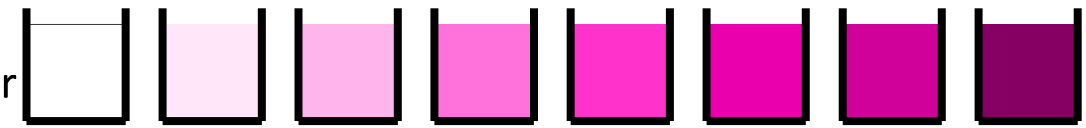
Critical Reactor

Fuel

+ poisons

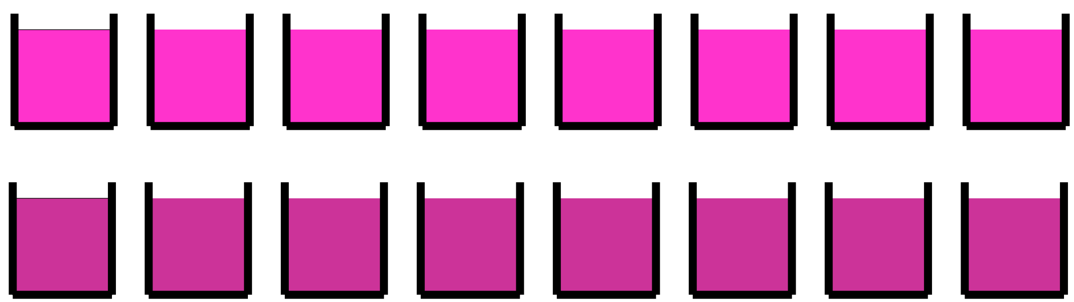


Once through concept
(burn as deep as your accelerator power will let you go)



GEM*STAR concept (1st pass)

GEM*STAR concept (2nd pass)



how we simulated this…
Liquid fuel enables operation with constant and uniform isotope fractions

including fission products

V salt volume in the tank and internal heat exchanger
v volume flow rate into the tank in cm^3/s
N_i concentration of the nuclide i per cm^3
$\sigma_{ai} = \sigma_{ci} + \sigma_{fi}$ absorption, capture and fission cross section of nuclide i
ϕ neutron flux ($ns^{-1}cm^{-2}$) averaged over the tank
F atom density of feed nuclide N_1 in atoms per cm^3

The rate of change in the tank of the total amount of the starting nuclide N_1 is

feed absorption overflow

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

Neutron absorption by nuclide N_1 can lead to fission, or by neutron capture (and any rapid beta decay) to nuclide N_2. The total amount N_2 in the volume is then given by

production absorption overflow

$$dN_2/dt = + \phi N_1 \sigma_{c1} - \phi N_2 \sigma_{a2} - N_2(v/V)$$

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$$0 = F(v/V) - N_1\phi\,\sigma_{a1} - N_1(v/V)$$ since in equilibrium $dN_1/dt = 0$

$$N_1 = F/[1 + \phi\sigma_{a1}(V/v)]$$

$$N_2 = N_1\,\phi\sigma_{c1}(V/v)\,/[1 + \phi\sigma_{a2}(V/v)]$$

$$N_2 = N_1(N_2/N_1)$$

$$N_3 = N_1(N_2/N_1)(N_3/N_2)$$

...

define neutron fluence: $\mathcal{F} = \phi(V/v)$; then $N_1 = F / [1 + \mathcal{F}\,\sigma_{a1}]$

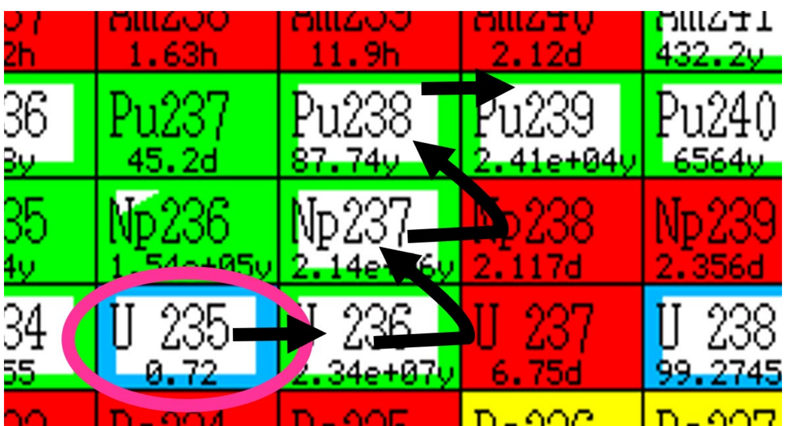
$$N_i = N_1 \prod_{j=2,i}\{\mathcal{F}\,\sigma_{c(j-1)}\,/[1 + \mathcal{F}\,\sigma_{aj}]\} \qquad i \geq 2$$

This sequence must be done for all feed actinides (j) in the input fuel (giving N_{ij}).

Typical ‘feed’ input for LWR spent fuel:

```
c START FEED DATA into material: 2
c 92235 .00737    92236      93237    94238     94239
c 92236 .00380               93237    94238     94239     94240     94241
c 93237 .00040                        94238     94239     94240     94241     94242
c 94238 .000137                                 94239     94240     94241
c 94239 .00504                                            94240     94241     94242     95243     96244     9624
c 94240 .00232                                                      94241     94242     95243     96244     96245
c 94241 .000769                                                               94242     95243     96244     96245
c 94242 .000471                                                                         95243     96244     96245
c 95243 .000091                                                                                   96244     96245
c 96244 .000018                                                                                             96245
c 95241 .000503                        94238     94239     94240     94241     94242     95243
c 92238 .9451                          94239     94240     94241     94242     95243     96244     96245
c END OF FEED DATA
```

This says there is 0.737% of ^{235}U coming in, and it can capture to ^{236}U, to ^{237}Np (assuming ^{237}U beta decays first due to 6.75d half-life), to ^{238}Pu (assuming ^{238}Np decays first due to 2.35d half-life) to ^{239}Pu.



this is NOT a complete picture!

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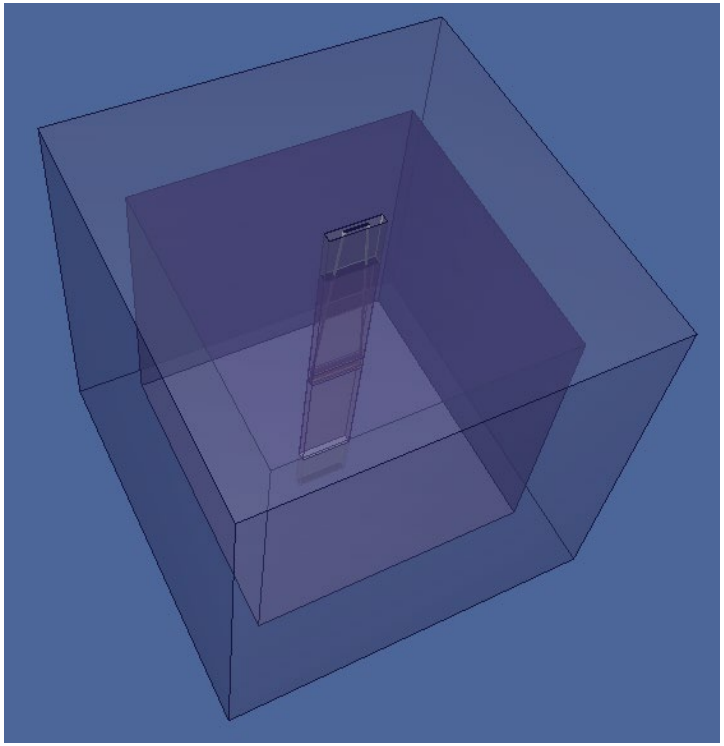
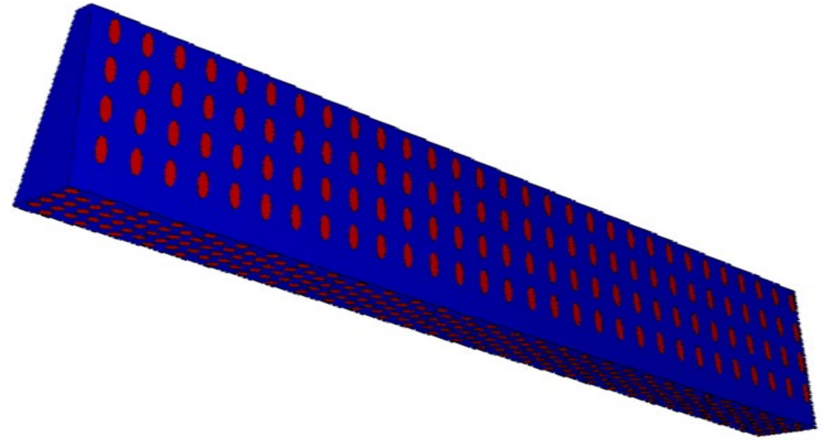
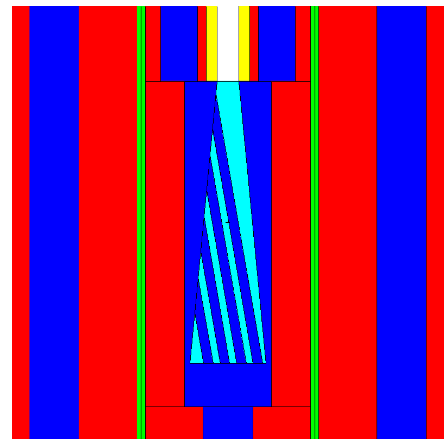
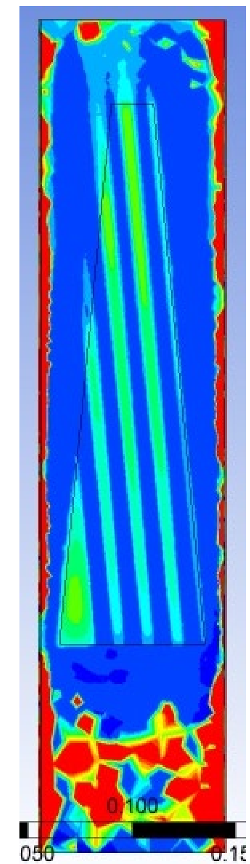
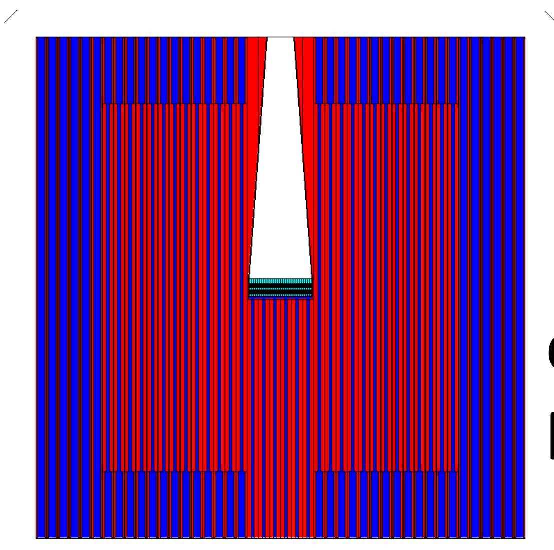






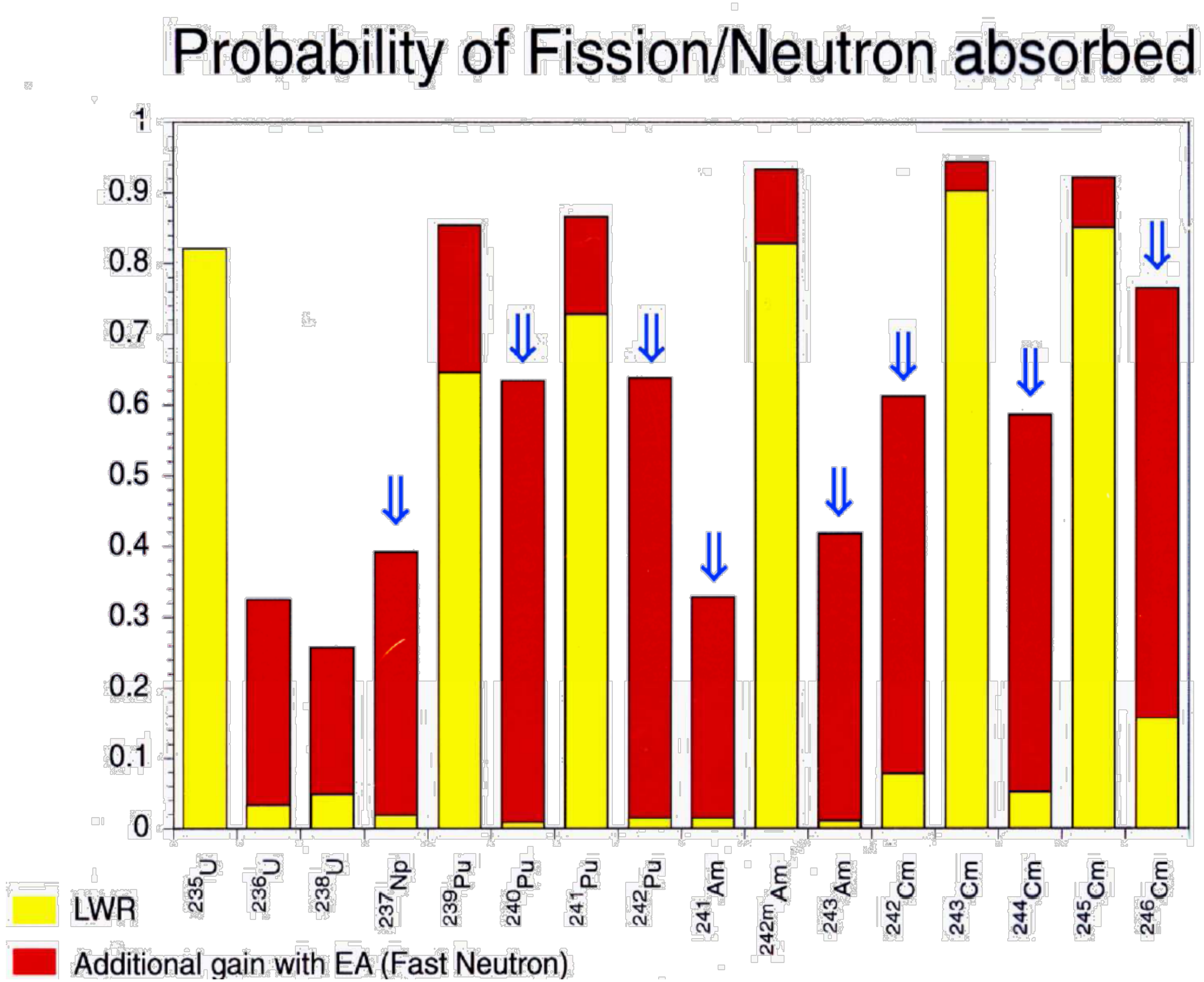




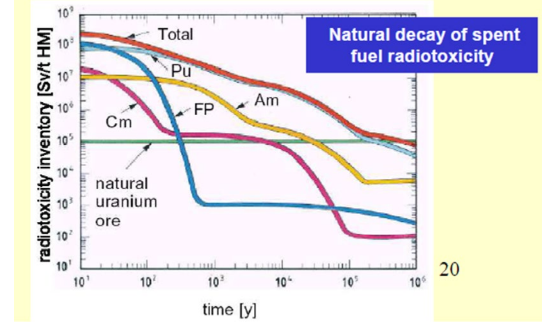
Core and Target Design are critical for commercial viability
MCNPX & FLUENT Calculations

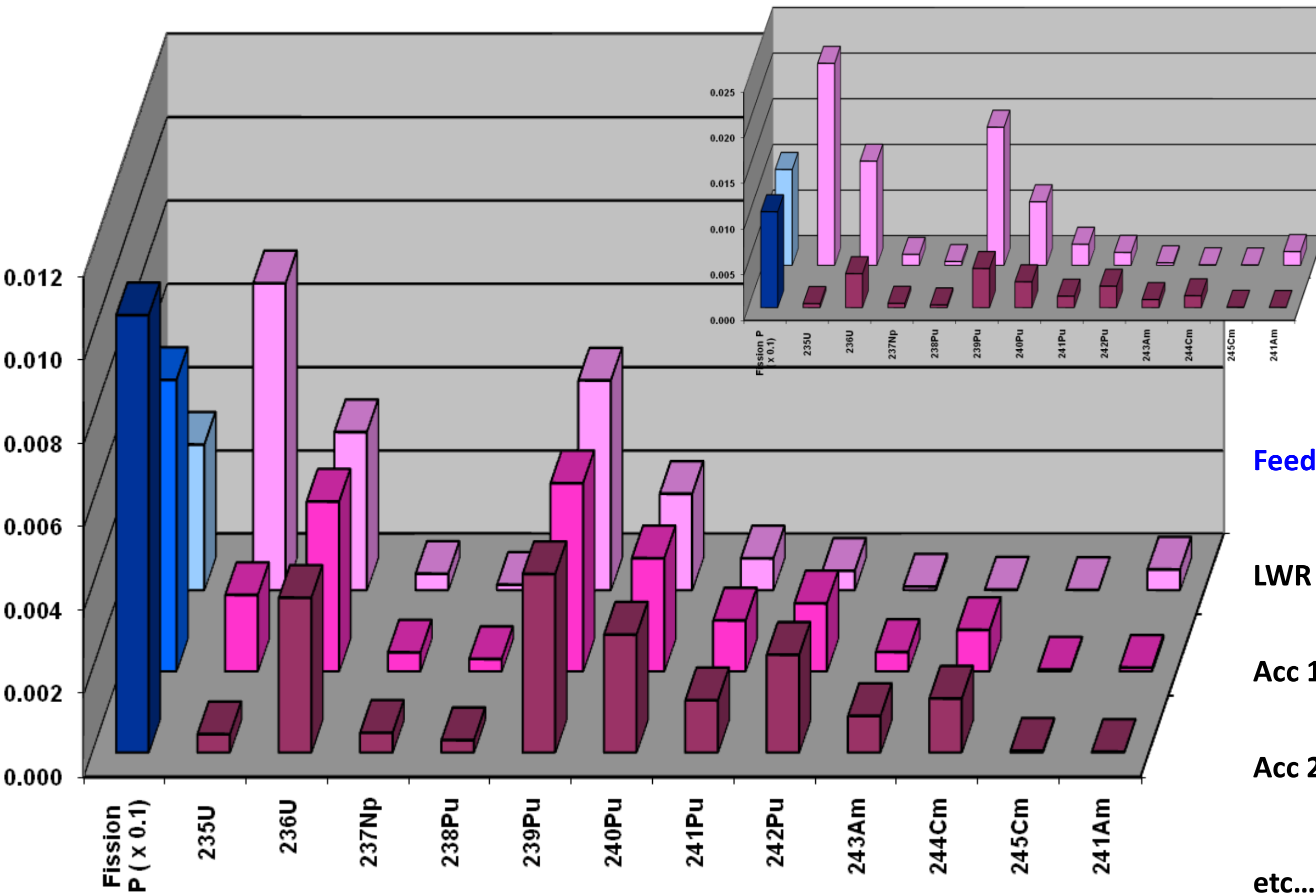
MS Thesis VT NE

Overcomes traditional concerns of thermal versus fast-spectrum reactors.



Note how the fission product goes up with each pass, ^{235}U continues to decline, Pu isotopes gets bred and burned, and Am and Cm are mixed.





Relative Waste after 2 passes

Feed material:

LWR spent fuel **20 GWy**

Acc 1 **40 GWy**

Acc 2 **60 GWy**

etc…

(similar to an endless breeder reactor, but one that doesn't choke on its own fission products)

Performance:

"Energy" multiplication:

- Net electrical energy produced per MW beam on target
- use simulation to predict number of fissions per proton

Fission fraction:

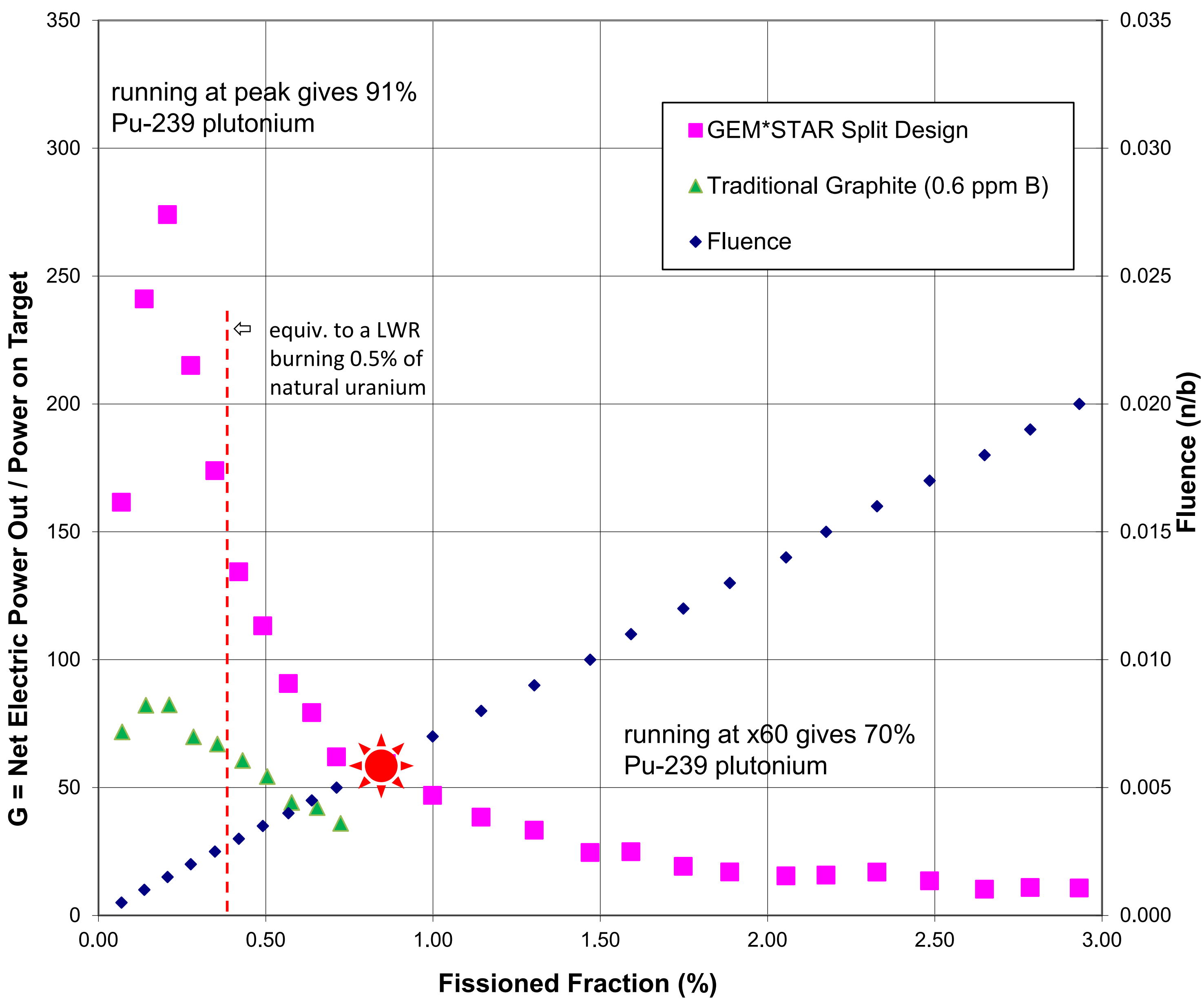
- what percentage of feed actinide was actually fissioned

(this is directly related to GWd/tHM often quoted for critical reactors)

Fluence:

- determined by residence time in core and core neutron flux when operating at reference power

Fuel: Natural Uranium



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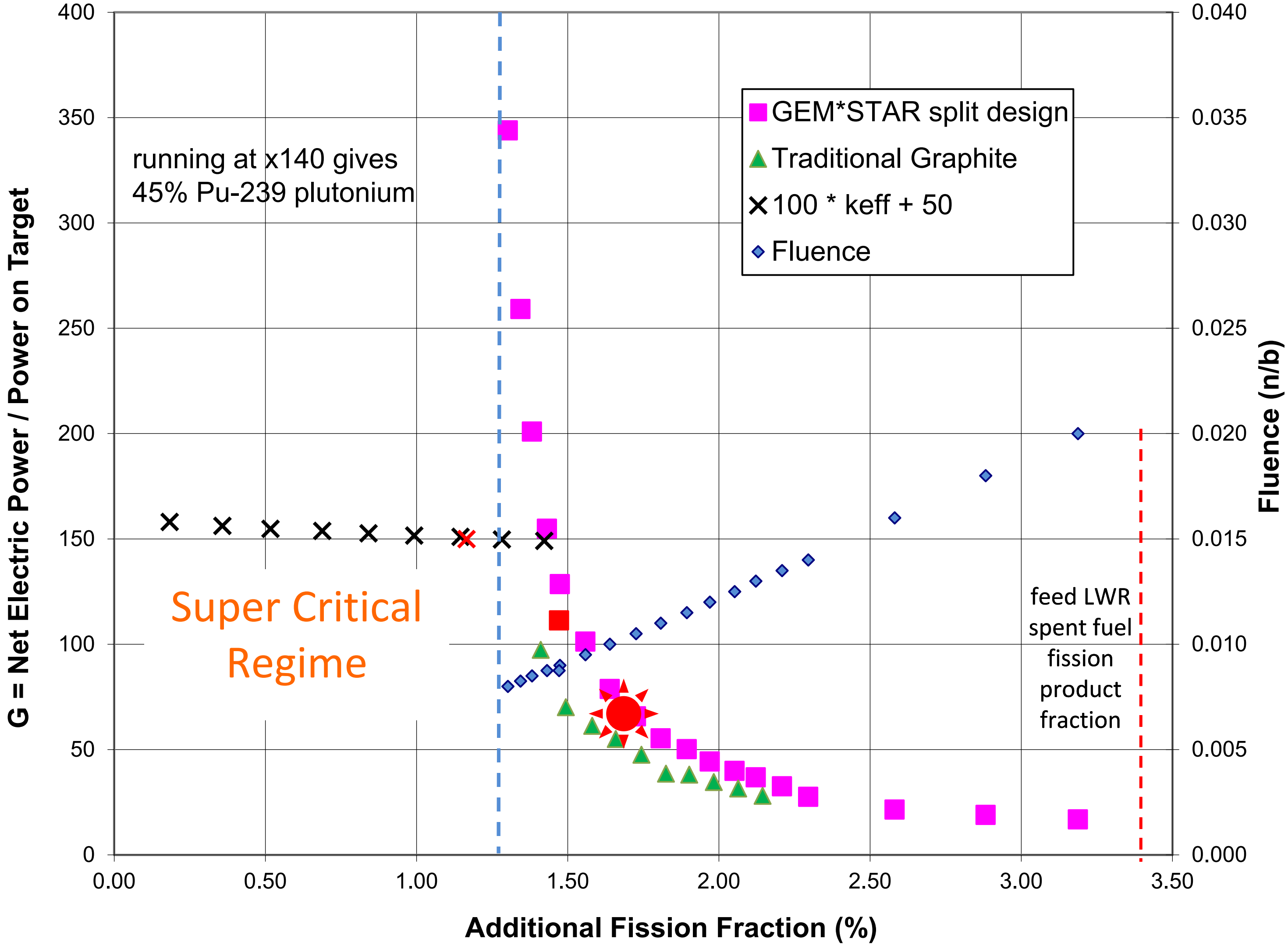
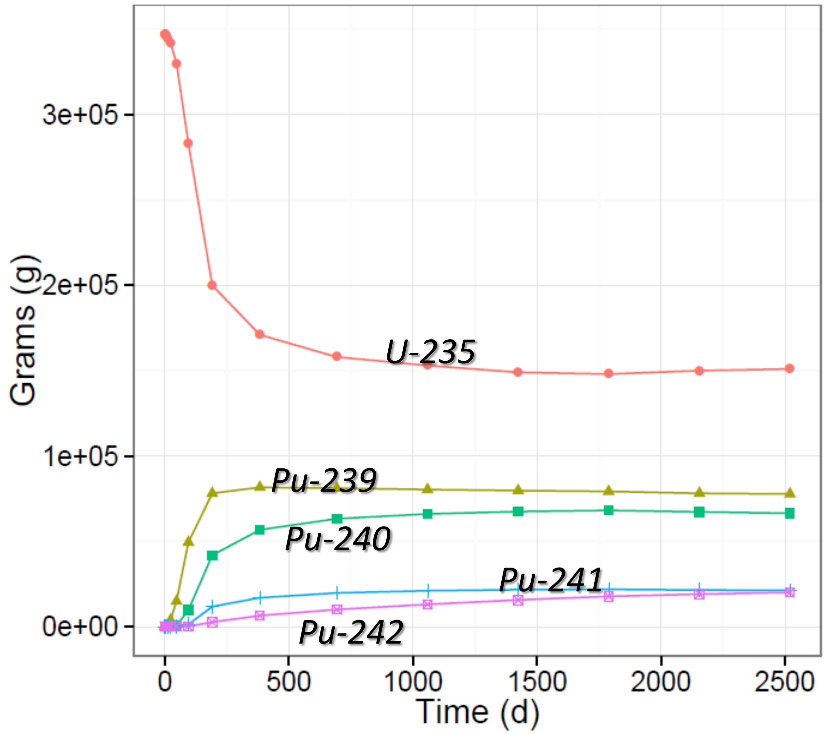
Fuel: un-reprocessed Light-Water-Reactor spent fuel



LWRs enriched to about 3.5% ^{235}U, and burned down to 0.7%, have fissioned 3.4% of their actinides (incl. some ^{238}U); **at 60x multiplication, an additional 1.7% burn-up is obtained.**

Haghighat et al. studied a much more complete model (and published) various approaches to equilibrium in 2015:

Typically, equilibrium is achieved after only 2 years



Remark: for natural uranium fuel and feed

Current design and simulations projections:

Cost

- mostly proven, known costs
- very competitive with fossil fuel
- simplified safety system
- reduced nuclear security cost

Nonproliferation

- no enrichment required
- no reprocessing (just fluorination)

Waste

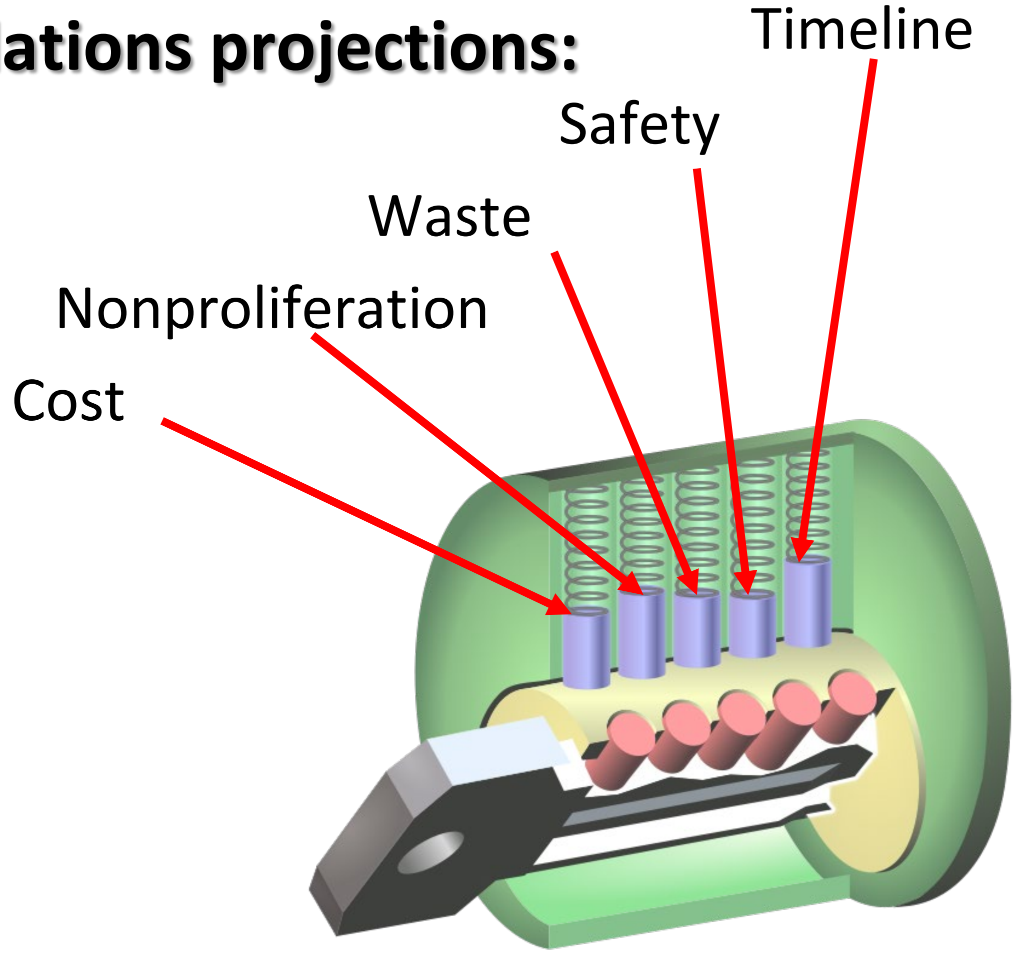
- reduced by order of magnitude
- can run on LWR spent fuel
  (with bulk fluorination)

Safety

- no concern for fuel melting (Accident Tolerant Fuel)
- subcritical - no criticality accidents
- reduced volatile radioactive inventory
- low-pressure system

Timeline

- no missing technology
- reduced licensing time (system and public acceptance)



This is very unique to the GEM*STAR approach – addressing all at the same time.

now for the second 'insight'

- first: an accelerator-driven molten-salt reactor
  - ***when designed to optimize that coupling from the start*** -
  can address all five challenges ("tumblers") at once
  (accelerator is needed for non-proliferation aspects)

Using above results, we then noted:

✓ **feed-and-bleed for continuous operation requires only 1 liter/hr for a 500 MWt reactor**

✓ **can replace this with a contained 'polishing loop' where U235 'feed' is replaced with 'bred' Pu239** ***minus fission products***

✓ **do this in containment, never removing the actinides**

Thus giving:

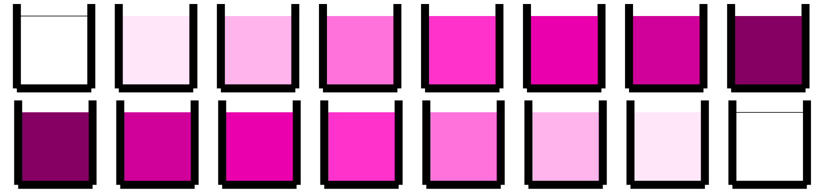
- **second: high-temperature continuous fission product removal may essentially avoid refueling for the lifetime of the reactor**

Our Revised Fueling Concept

Traditional Critical Reactor (solid or liquid fuel):

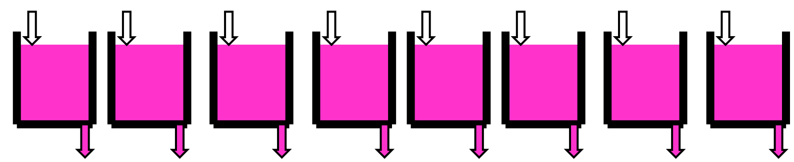
(start with N critical masses)

+ (burnable/removable) neutron poisons



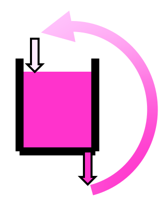
(when poisons are exhausted, need to refuel)

Feed/Bleed System:



("continuous" refuel)

Feed/Bleed System (with closed 'polishing' loop):



(fission product removal loop)

- works for all molten-salt reactors
- 'driven' reactors are easier to manage since criticality and fuel chemistry not as tightly coupled
- new realm: ***in-containment*** separation via high-temp(I^2R)

Can we make this new version work?

which f.p. are most important to remove?

(e.g. repeat "Demand driven salt clean-up in a molten salt fast reactor - Defining a priority list" by B. Merk, D. Litskevich, R. Gregg, A. R. Mount, (2018) but for thermal spectrum)

how do eutectic salt components separate at high temperatures?

Boiling points of some expected elements in irradiated fluoride and chloride fuel salts

	X=F	X=Cl		X=F	X=Cl	metals	
HX	19.5	-85.05	RhX_3	600	717	Se	685
IX_3	98	97.4	SnX_4	705	623	Te	988
NbX_4	decomp	275	ZrX_4	918	331	Pd	2963
SbX_3	376	223.5	AgX	1159	1547	Mo	4639
			CsX	1251	1297	Rh	3697
			CoF_2	1400	1049	Ru	4150
			Rb_X	1408	1393	Tc	4265
			UF_4	1417	791		
			LiF	1680	1382		
			CdX_3	1748	964		
			ThX_4	1680	921		
			PuX_4	1277	unknown		
				X=F	X=Cl		
			UX_4	1417	791		
			PuX_3	1975	1767		
			AmX_3	850	1253		
			PmX_3	unknown	1670		
				X=F	X=Cl		
			ErX_3	2200	1500		
			NpX_3	2223	800		
			YX_3	2230	1900		
			BaX_2	2260	1560		
			EuX_3	2280	decomp		
			GdX_3	2280	1580		
			NdX_3	2300	1600		
			LaX_3	2327	1000		
			SmX_3	2427	decomp		
			PrX_3	2300	1710		
			CeX_3	2300	1727		
			SrX_2	2460	1250		
			UX_3	2300	1657		

can one maybe use mass distributions of fission products as a separation factor in the vapor phase?

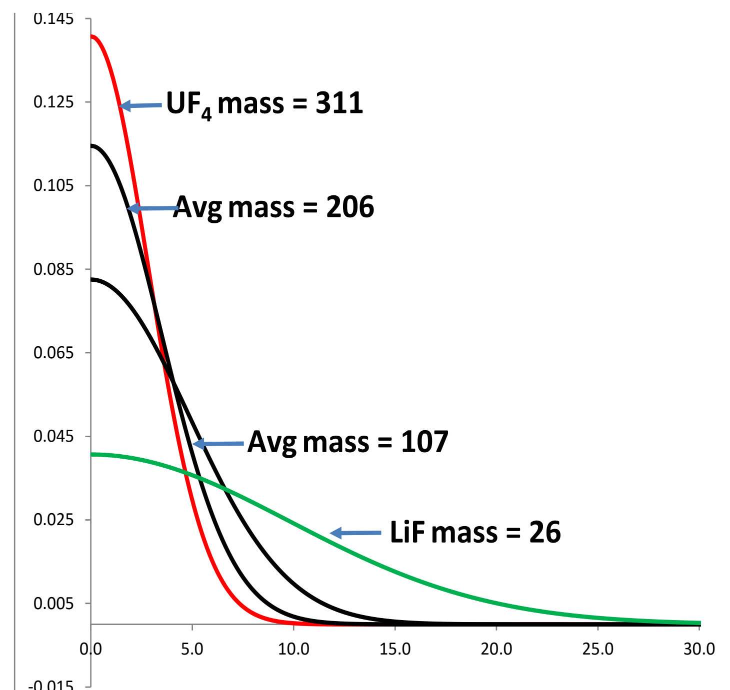


Fig.2.1. Normal distribution of gas diffusion as ($mass^{-1/2}$) on an arbitrary time axis.

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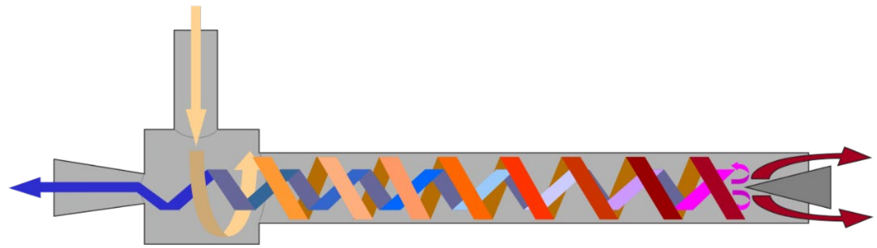
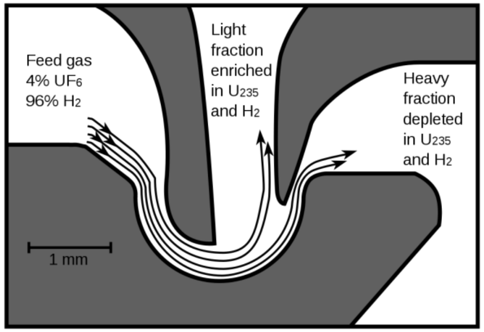
vortex tube: https://en.wikipedia.org/wiki/Vortex_tube "The vortex tube was used to separate gas mixtures: oxygen and nitrogen, carbon dioxide and helium, carbon dioxide and air, in 1967 by Linderstrom-Lang."

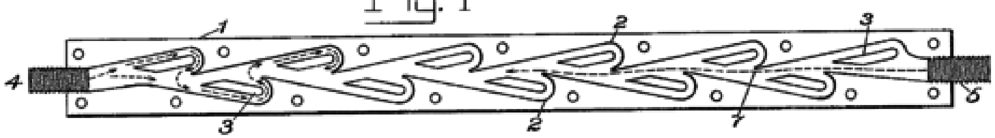


Helikon vortex separation cascade for enrichment: https://en.wikipedia.org/wiki/Enriched_uranium "The Uranium Enrichment Corporation of South Africa (UCOR) developed and deployed the continuous Helikon vortex separation cascade for high-production rate low-enrichment, and the substantially different semi-batch Pelsakon low-production rate high-enrichment cascade both using a particular vortex tube separator design, and both embodied in industrial plants" This mass separation is clearly far in excess anything needed for the separations envisioned here, but does demonstrate the idea that helium as a carrier can improve efficiency.



Tesla Valve: https://en.wikipedia.org/wiki/Tesla_valve "valvular conduit, is a fixed-geometry passive check valve. It allows a fluid to flow preferentially in one direction, without moving parts" A similar concept might work in the gas phase to separate by molecular weight – an application perhaps never previously envisioned? (something like a higher-throughput gas diffusion column)

Fig. 1



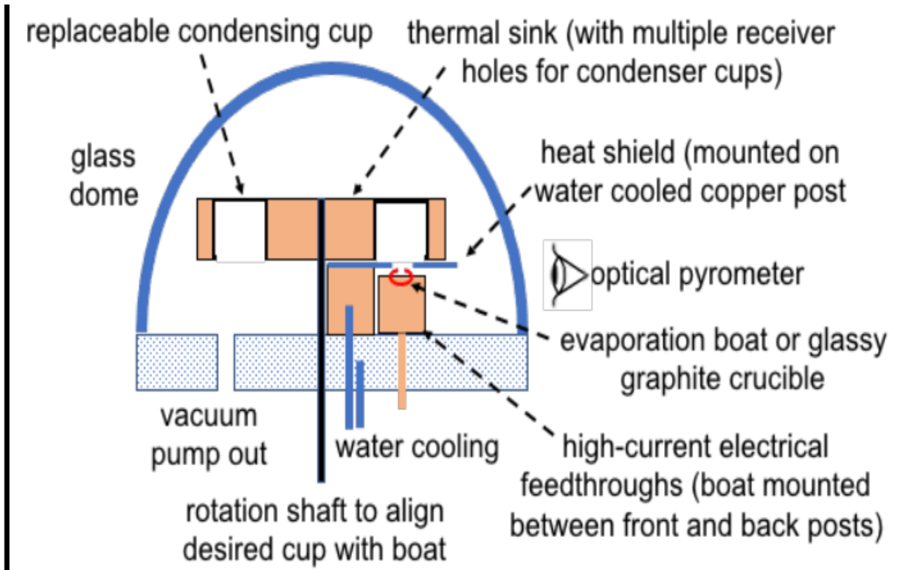
e.g. Gain Voucher proposal:

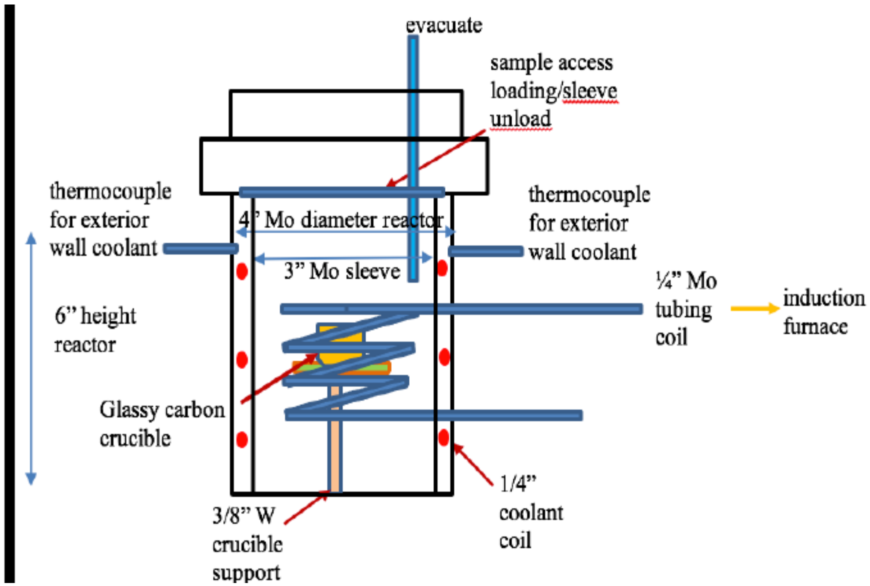
Continuous Fission Product Removal
from Molten Salt Fueled Reactors

Muons, Inc.
Dr. Thomas J. Roberts, PI
(630) 677-4321, tjrob@muonsinc.com

with Virginia Tech
and PNNL (Dr. Bruce McNamara)

While many boiling points are known, how these salts behave in a molten-salt eutectic is not known, which is the subject of this project.





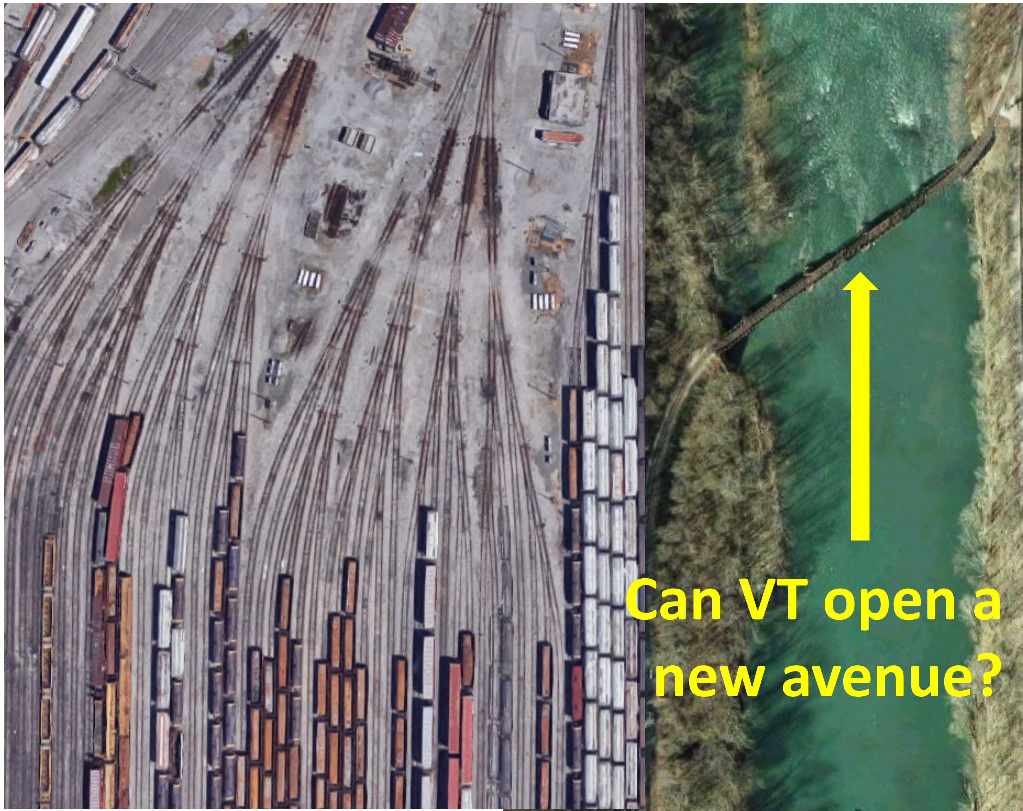
How to move forward?

- for fifty years new tracks have been laid mostly parallel to the old ones
- but maybe we really need to be on the other side of the river!
- definitely not ‘group-think’ or ‘consensus funding’ (at least to get going)

When using wind to cross the Atlantic
- new sail configurations were great

- **until** someone developed propeller propulsion.

for nuclear energy ARPA-E and DOE have so far followed classic approaches fairly exclusively.



This is a Multi (trans?) Disciplinary Project

College of Science (COS)
- Physics
- Chemistry
- Geosciences

College of Engineering (COE)
- Nuclear Engineering
- Mechanical Engineering
- Chemical Engineering
- Materials Science and Engineering
- Civil and Environmental Engineering

College of Natural Resources and Environment
- Sustainable Biomaterials

College of Liberal Arts and Human Science (COLAHS)
- Public & International Affairs

also: ICTAS Energy and Materials Initiative (EMI):

Safe, Secure, and Sustainable Nuclear Power (S^3NPower) cluster funded

Potential collaborators
(although a single capable partner might be best)

Corporate Collaborators:
- Virginia Tech Foundation
- General Atomic
- Newport News Shipbuilding
- Nuclear Innovation Alliance
- Flibe Energy
- ADNA, BCLF, MuStar
- Southern Nuclear

University & Nonprofits:
- George Washington University
- Georgia Tech
- NCSU
- Penn State
- Paul Scherrer Institute, Switzerland
- Turin Polytechnic University, Italy
- University of Lausanne, Switzerland
- Virginia Nuclear Energy Consortium (VNEC)

National Laboratories:
- Oak Ridge National Laboratory (met with key leaders and technical staff in Sept. 2015)
- J-Lab, LANL, INL, ANL, and PNNL

Public Policy Groups
- Nuclear Energy Institute
- Virginia Nuclear Energy Consortium
- VA Chamber of Commerce
- ADMIRE (accelerator-driven micro-reactors)

Advisory/Legal:
- Center for Strategic and International Studies (CSIS)
- Federal Government Affairs Group LLC
- James Decker, Sandy Rupprecht

Success at offering civilian nuclear energy ***decoupled from its historically fatal flaws*** is demonstrably of Nobel Peace Prize significance:

- 1962 Linus Carl Pauling “for his campaign against nuclear weapons testing”
- 1985 International Physicians for the Prevention of Nuclear War "for authoritative information and by creating an awareness of the catastrophic consequences of atomic warfare”
- 1995 Joseph Rotblat and Pugwash Conferences “for their efforts to diminish the part played by nuclear arms in international politics and, in the longer run, to eliminate such arms"
- 2005 IAEA and El Baradei “for their efforts to prevent nuclear energy from being used for military purposes and to ensure that nuclear energy for peaceful purposes is used in the safest possible way"
- 2007 IPCC and Gore “for their efforts to build up and disseminate greater knowledge about man-made climate change”

References:

Chapter on G*S in NE handbook: https://link.springer.com/content/pdf/10.1007/978-0-387-98149-9_24.pdf

Multiple references here:
User: gem
Password: (ask vogelaar@vt.edu)
http://www.phys.vt.edu/~kimballton/gem-star/prot/reference/blank.shtml

A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology
http://sciencepolicy.colorado.edu/about_us/archives/projects/gccs/2002/jvc/pdf-docs/doe_rw-0519.pdf

Report of Advanced Nuclear Transformation Technology Subcommittee of the Nuclear Energy Research Advisory Committee
http://energy.gov/sites/prod/files/antt14Jan_03.pdf

Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production
http://lss.fnal.gov/archive/test-fn/0000/fermilab-fn-0907-di.pdf

Reliability of accelerator driven systems (letter to editor and reply)
http://www.symmetrymagazine.org/article/march-2012/reliability-of-accelerator-driven-systems

International Workshops on Accelerator-Driven Sub-Critical Systems & Th Utilization:
- 2010 (Virginia Tech): http://www.phys.vt.edu/~kimballton/gem-star/workshop/schedule.shtml
- 2011 (BARC, India): http://www.ivsnet.org/ADS/ADS2011/
- 2014 (VCU, Virginia): http://adsthu.org/
- 2016 (England): http://www.hud.ac.uk/research/researchcentres/iiaa/meetingsandworkshops/ads2016/

Multiple proposals over the years (upon request)

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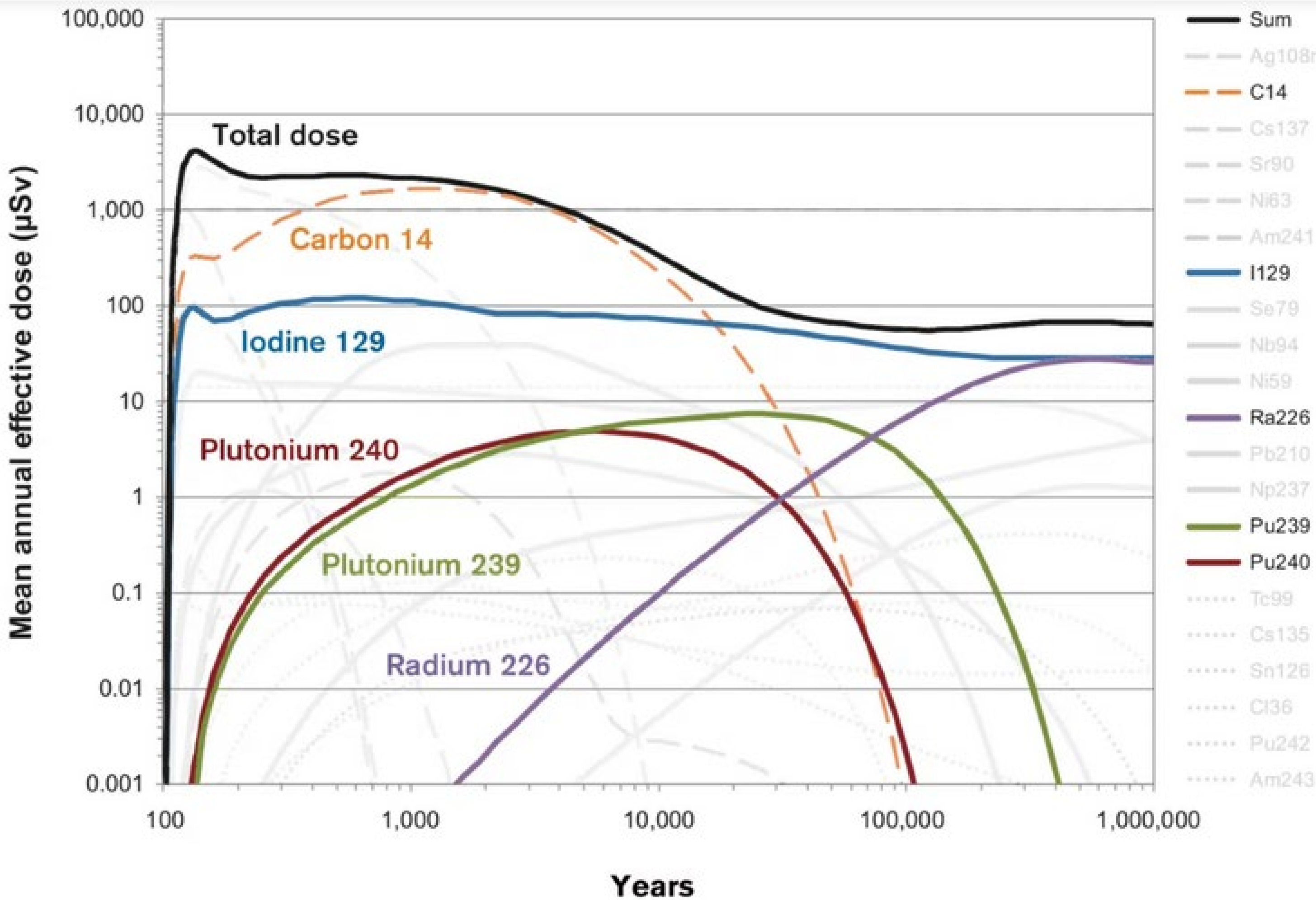
VIRGINIA TECH.

GEM STAR



SKB, the company responsible for designing and building Sweden's spent fuel repository, calculated the dose to a subsistence farmer on the surface from various radioisotopes if the spent fuel were not contained in a copper cask surrounded by a layer of clay. In this adaptation, showing the contributions from a few of the radioisotopes, the doses from plutonium never dominate. Note the logarithmic scale used. (Source: SKB, modified by Thomas Gaulkin.)

from 1991-2007 there was a DOE Accelerator Transmutation of *Waste* (ATW) development program at LANL (~$280M/yr)

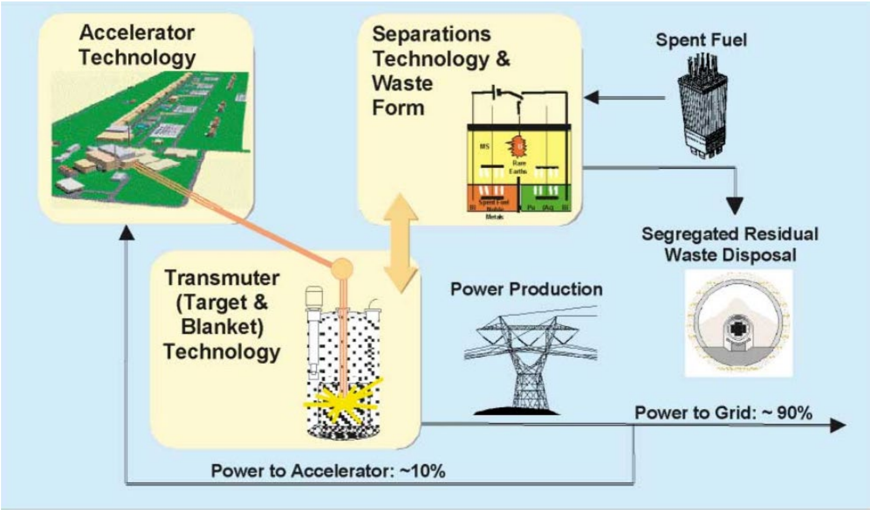


Figure E.1. Components of an ATW System

break even performance on *waste*

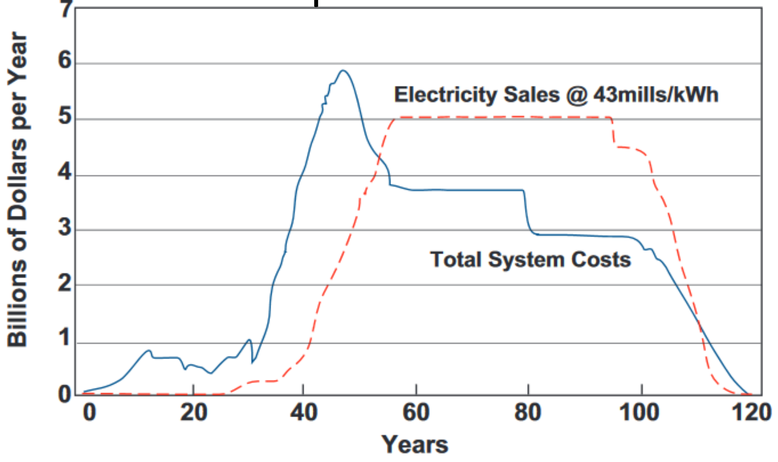


Figure 7.2. Annual Undiscounted (1999 Dollars), Total System Costs and Electricity Credit as a Function of Time

above: from DOE Report to Congress 1999

Burton Richter (SLAC – Nobel Laurette) Chair of 2003 committee leading to the end of DOE's ATW program. "That meant that such systems were going to put gigawatts of electricity on the grid. At that level, frequent power trips would be too disruptive to tolerate…Frequent starting and stopping of a reactor, even a subcritical facility driven by an accelerator, stress the reactor.

…they were finding the right answers, but to the wrong questions...

Simulation Steps:

1. specify fluence, estimate <spectrum-averaged> cross-sections (or extract from previous run) and calculate N_{ij} for all actinides present in molten-salt feed and their defined progeny
2. Calculate the fraction of feed which has been fissioned – use this to calculate fission product amount (then mimicked by ^{10}B, with remainder made up by helium)
3. tweak LiF amount to obtain desired eutectic mixture
4. run MCNP(X) to simulate reactor with these parameters
5. use the newly found cross-sections to recalculate initial isotope amounts [more details later on]
6. iterate until initial and final isotope amounts do not change significantly (typically just a few runs)

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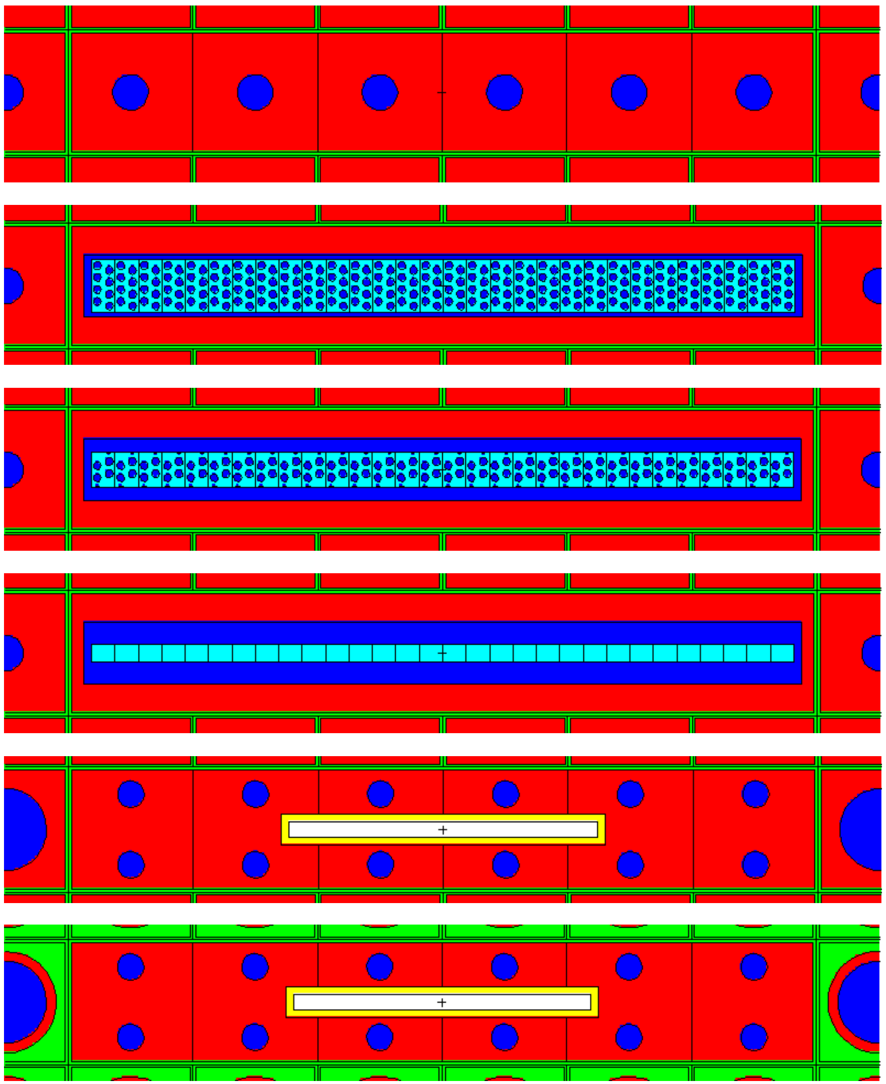
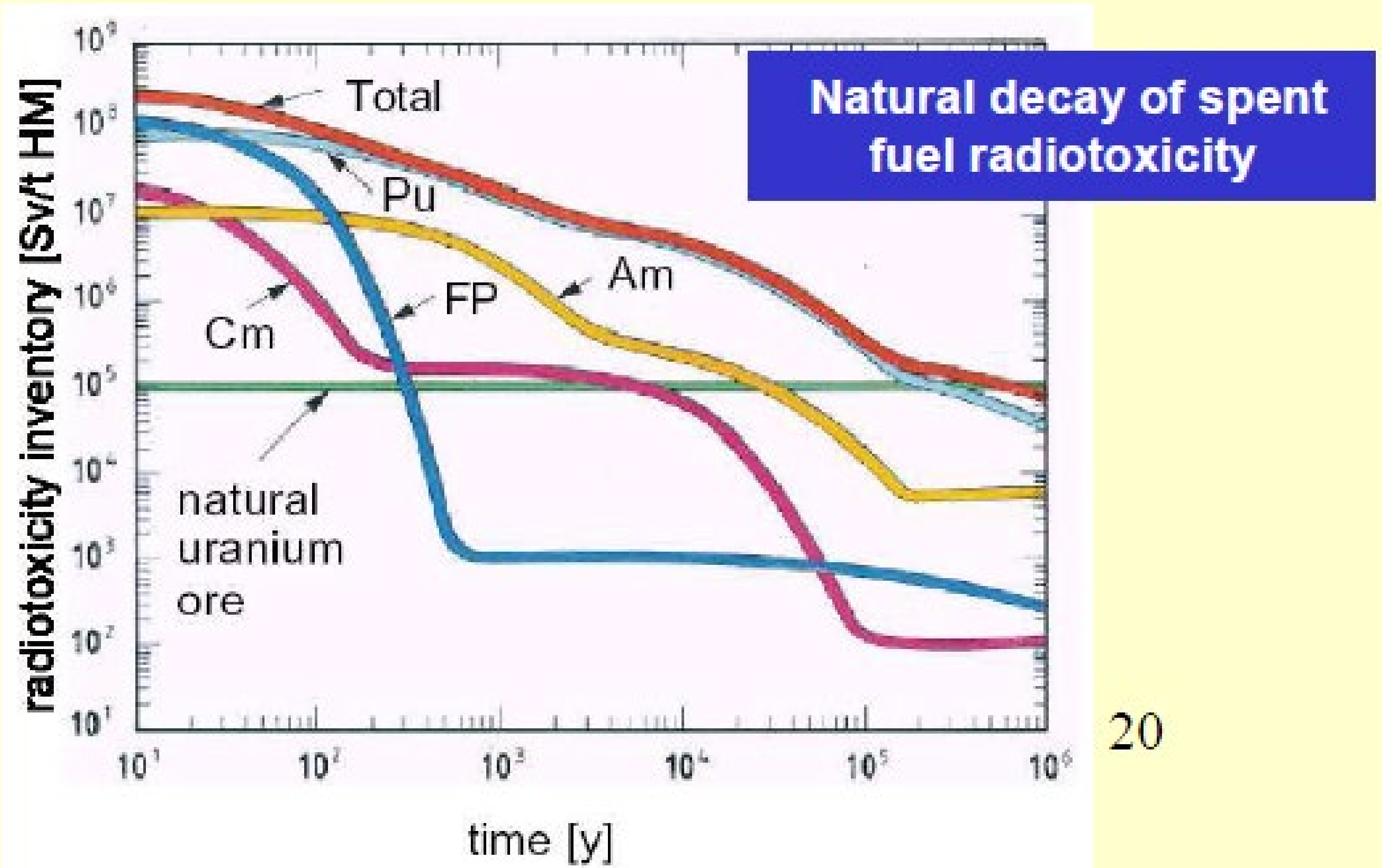
Core Design Features



- 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

Fission Products do increase, but decay to lower activity than the original mined uranium in about 300 years.



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But Using Thermal Spectrum
0.01 – 0.2 eV

high tolerance for fission products:

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

$$\frac{\left(\sigma_{^{239}Pu\ fission}/\sigma_{fp\ capture}\right)_{thermal}}{\left(\sigma_{^{239}Pu\ fission}/\sigma_{fp\ capture}\right)_{50\ keV}} \approx 10$$

^{151}Sm (transmuted rapidly to low σ_c nuclei)

- ^{135}Xe (continuously removed as a gas)

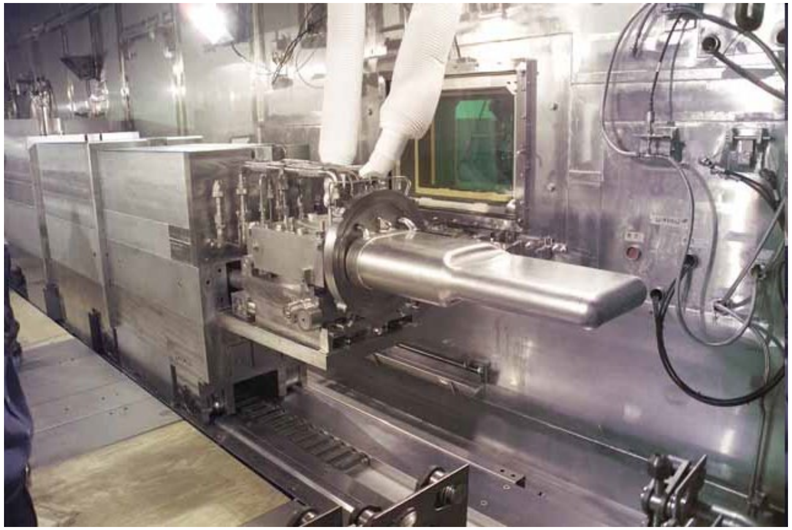
⇒ more than compensates for slower fission of heavy actinides (which are burned anyway)

MW Targets: Proven & Studied – but not the right ones…

… these are compact

… have external cooling

… have cladding or 'container'



Existing Oak Ridge SNS Molten Hg target (1 MW)

(Existing LANL MW target is tungsten.)

IPNS Target Design and Function

- IPNS neutron production target is made of eight depleted uranium disks, each 1 inch thick and 4 inches in diameter

Argonne NATIONAL LABORATORY 11

Dr. Bradley J. Micklich
Intense Pulsed Neutron Source
7 November 2007

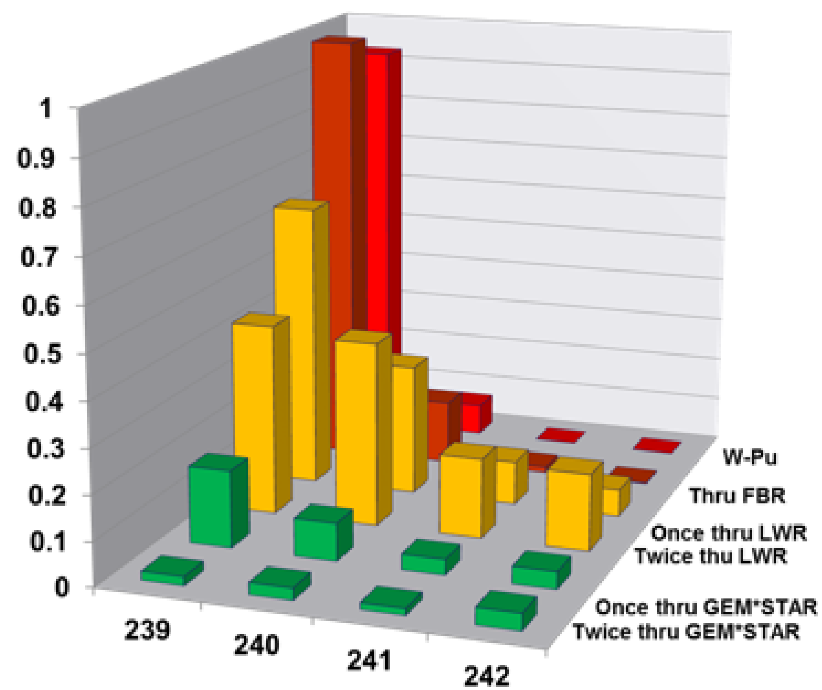
Advantages Over Direct Burial and MOX burning in LWRs

- ✓ **Permanent** disposition of WGPu (unlike 'down-blend' and burial)
- ✓ Cheaper option than either MOX or 'down-blend'; in fact, profitable.
- ✓ MOX does not have any customers; utilities are not interested!
- ✓ Burning technology for LWR waste
- ✓ Reprocessing is never required for either WGPu or waste

Pu Isotope Distribution

^{239}Pu	α	24,110 years
^{240}Pu	α,sf	6,561 years
^{241}Pu	β	14 years
^{242}Pu	α,sf	373,300 years

note that ^{240}Pu decays much faster than ^{239}Pu



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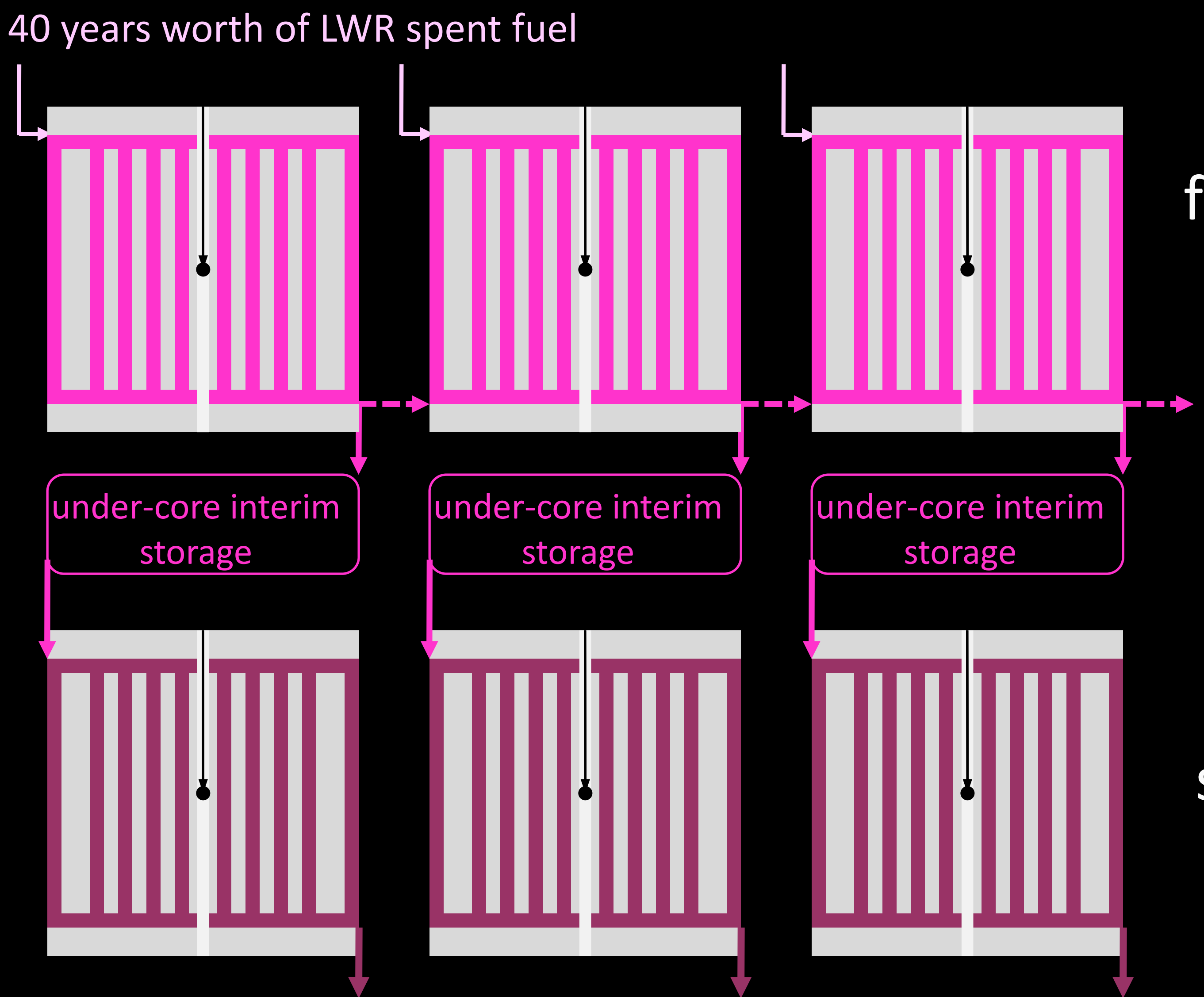
Deployed Civilian Reactor Types

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% are LWRs

Recycling



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?)

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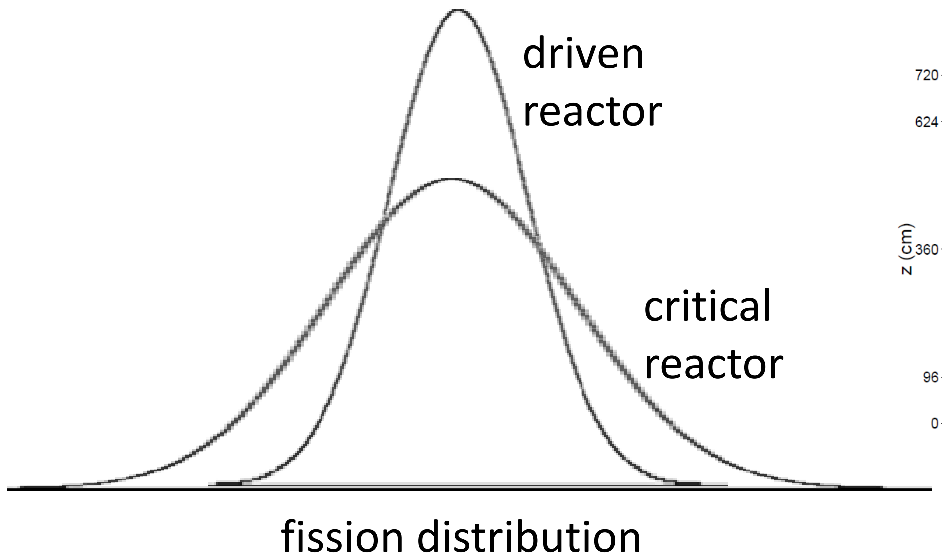
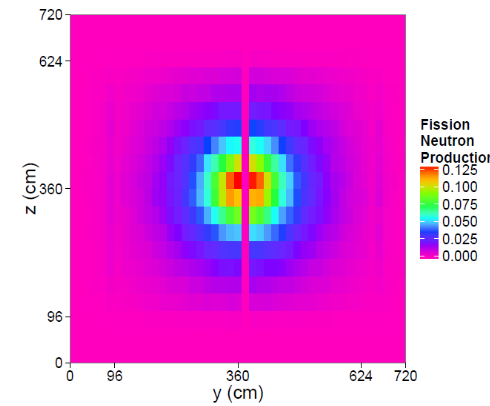
Target Considerations

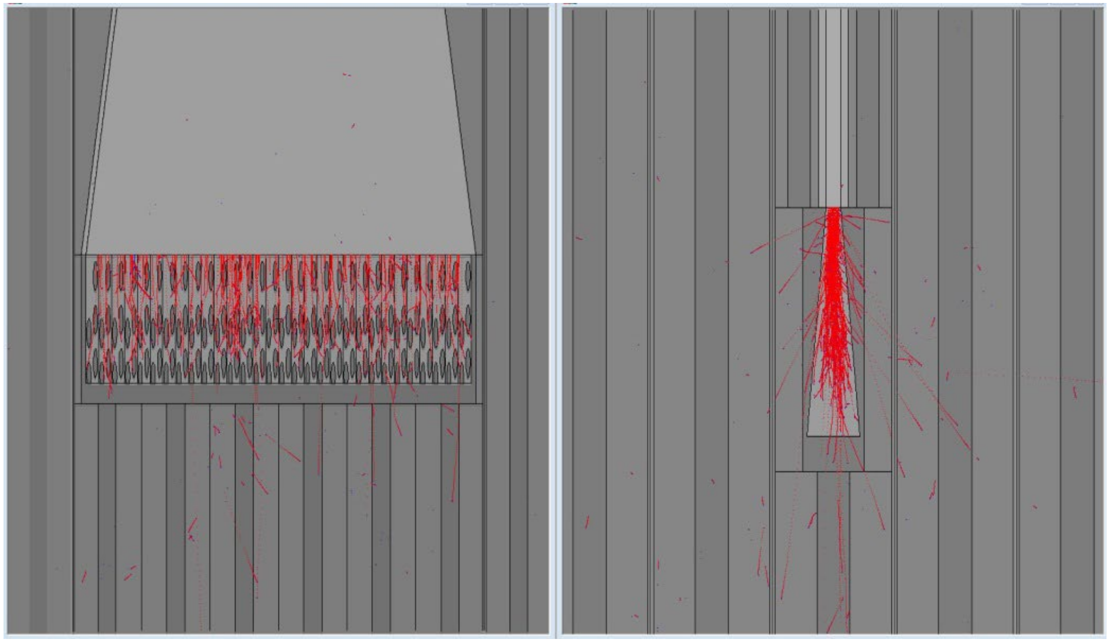




- **"k_{eff}" should *only* be used to evaluate 'safety factor'**
- **ADS "multiplication" is *very* target dependent**

(separating these two concepts also reveals that ADS should not have the traditional neutron reflector around the core)

Target Considerations



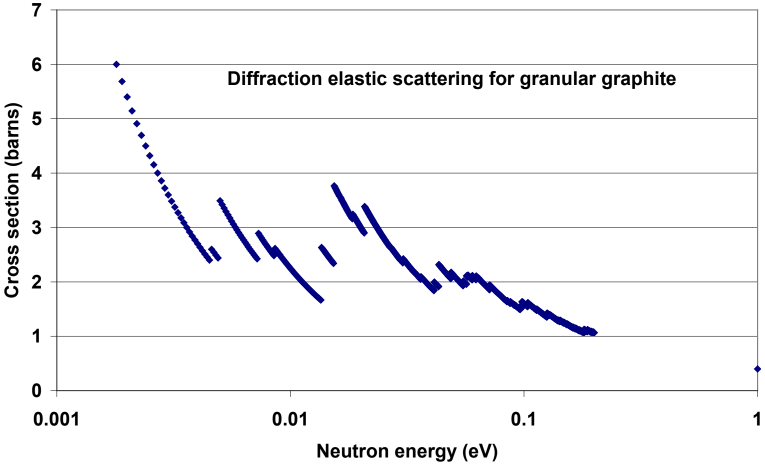
GEM*STAR Internal Target

- 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

3. new graphite results

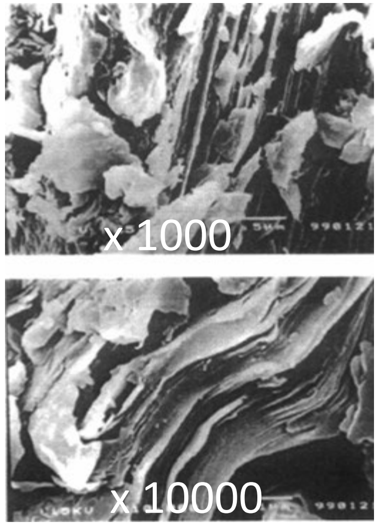
Diffusion/Absorption @ Duke

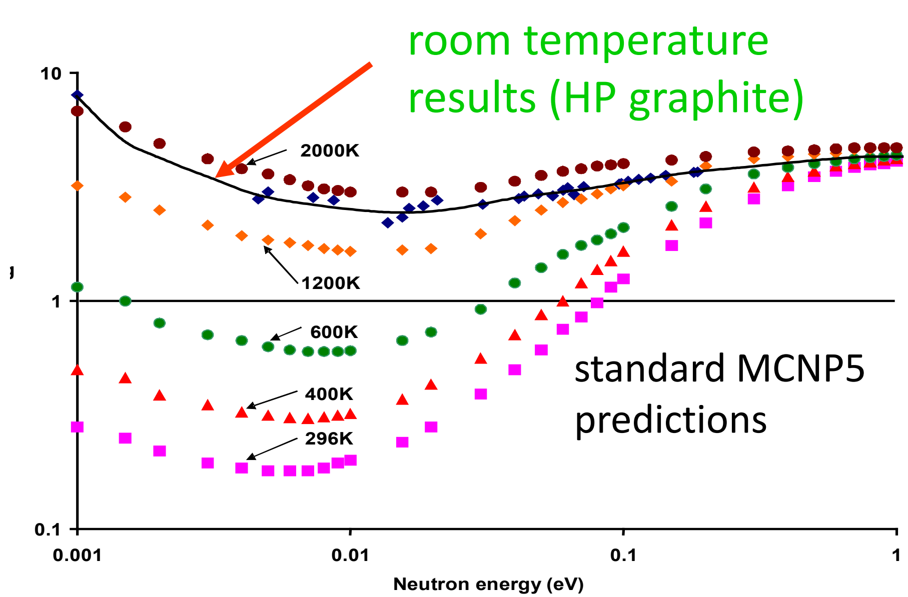


Diffraction @ LANL

"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





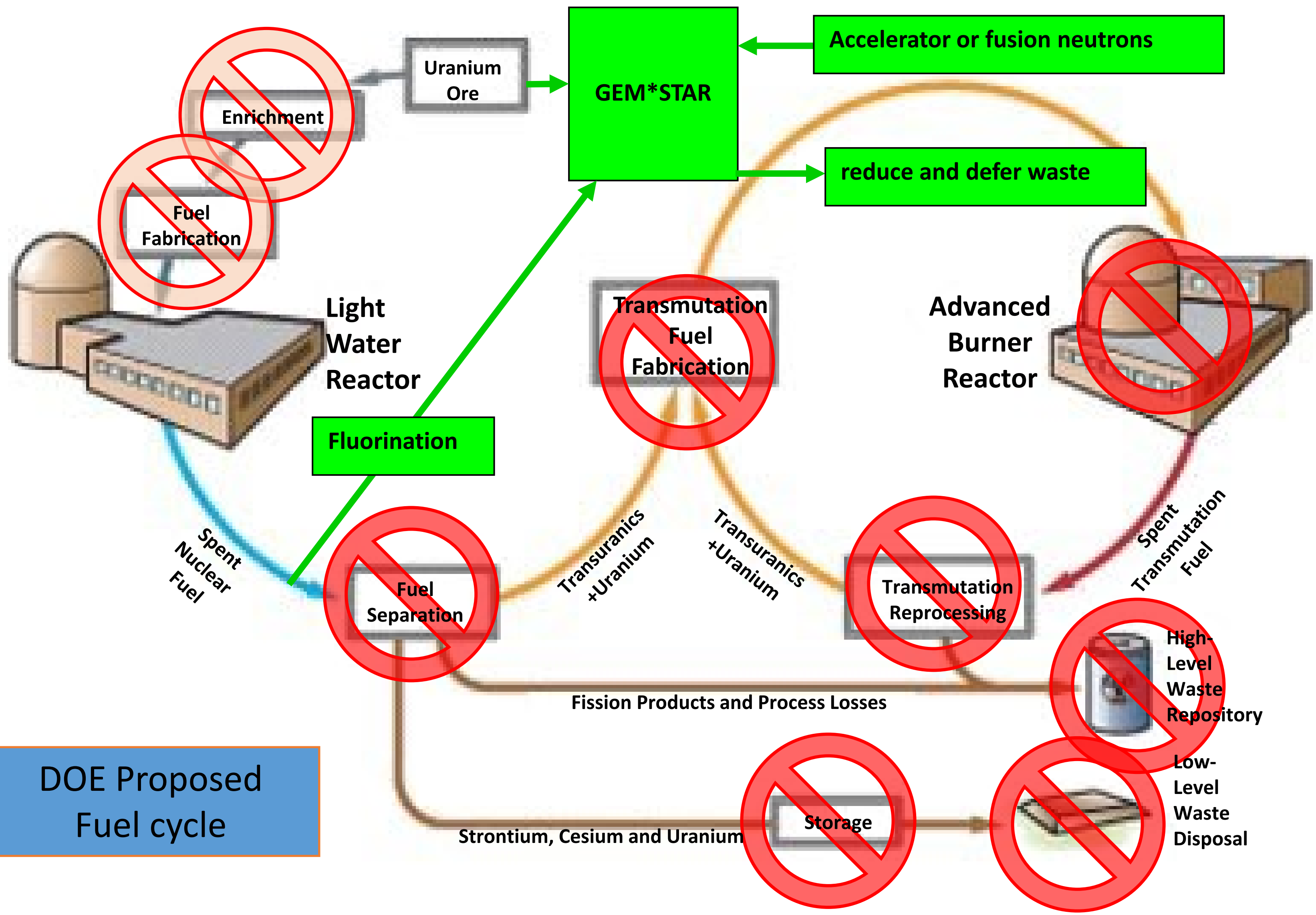
Discovered ***and measured*** a commercial graphite source with:

- 24% increase in thermal diffusion length
  ('HP' manufacturing process creates distorted crystals reducing coherent scattering)
- boron contamination down by factor of 3
  (less than 2 parts in 10,000,000)

$\Rightarrow$ 30% reduction in parasitic neutron absorption

Vogelaar implemented in MCNP via **modified** graphite ZAID ENDF file, with manually reduced absorption cross-section [easier than delving into s(α, β)]!

(full proposal exists to try and confirm this with assembled blocks of graphite)



DOE Proposed Fuel cycle

List of nuclear accidents (INES level 4 -7)

Name	Location	Year	Reactor	FOAK	Accident Description	INES
St. Laurent	France	1969	GCR	FOAK	Scrap piece of graphite moderator blocked coolant channel, and a few fuel elements melted.	4
Lucens	Switzerland	1969	GCHWR	FOAK	Scrap of graphite moderator blocked coolant channel and led to fire that destroyed the reactor and irradiated the cavern within which it operated.	5
Jaslovské Bohunice	Czechoslovakia	1976	GCHWR	FOAK	Experimental power plant suffered carbon dioxide gas leak during re-fueling that suffocated two workers.	4*
Jaslovské Bohunice	Czechoslovakia	1977	GCHWR	FOAK	Failure to remove silica gel packs from nuclear fuel after shipped to site. Silica gel packs blocked coolant flow leading to over-heating and heavy corrosion of fuel cladding. Some radioactive particles leaked out.	4
Three Mile Island	USA	1979	PWR		Inexperienced operator incorrectly responded to confusing instrument display leading to cascading problems and eventual meltdown of reactor core.	5
Saint Laurent des Eaux	France	1980	GCR	FOAK	A coolant channel led to melting of fuel elements. Some leakage but not enough to pose serious radiation exposure.	4
Chernobyl	Ukraine (USSR)	1986	LWGR		Inexperienced operator conducted experiement & suffered runaway reaction followed by explosion, fire and then, finally, meltdown.	7
Fukushima	Japan	2011	BWR		Plant lost power after tsunami, emergency cooling failed & operator failed to keep reactors cool.	7

ENVIRONMENTAL PROGRESS

Reactors: Gas-Cooled Reactor (GCR); Gas Cooled Heavy Water Moderated Reactor (GCHWR); Pressurized Water Reactor (PWR); Light water graphite moderated reactor (LWGR); Boiling Water Reactor (BWR)

Sources: IAEA; accident reports; summarized at Environmental Progress, "History of Nuclear," 2017.

*EP-rated — accident was never given an official INES rating.

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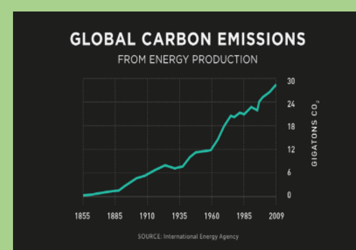
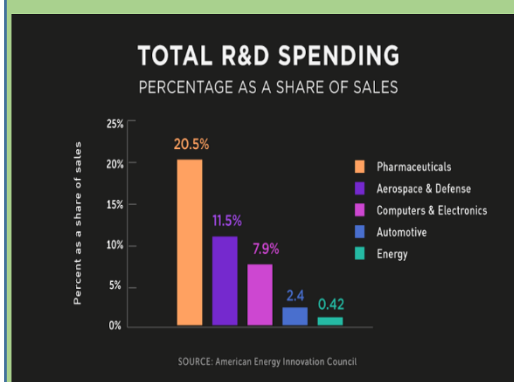
BILL GATES' Challenge → VT opportunity

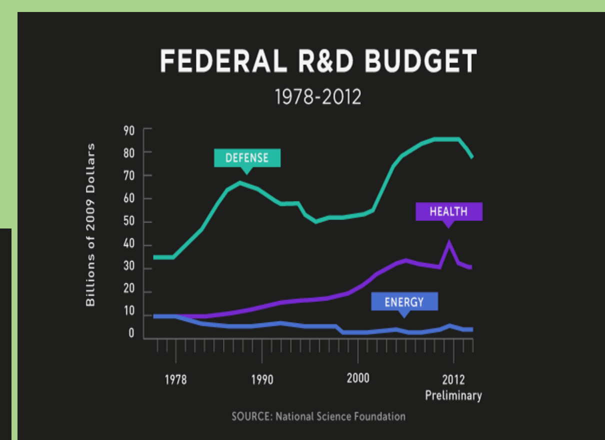
From Tech Insider Interview: Monday (Feb 22, 2016)
Bill Gates talks about bringing electricity to the billion people .
He states
"Within the next 15 years, I expect the world will discover a clean energy breakthrough...."
Bill Gates is has a new initiative, 'Miracle Energy,' that seeks world's billionaires."

He's been ramping up his own commitments since then, and pledged last year to double his investments (to $2 billion) on a host of energy frontiers in the next five years – from new battery and solar technologies to a safer nuclear plant design to tethered, high-flying wind turbines that might harness the power of the jet stream.

A few supporting data







Boiling points of some expected elements in irradiated fluoride and chloride fuel salts

	X=F	X=Cl
HX	19.5	-85.05
IX_3	98	97.4
NbX_4	decomp	275
SbX_3	376	223.5

	X=F	X=Cl
RhX_3	600	717
SnX_4	705	623
ZrX_4	918	331
AgX	1159	1547
CsX	1251	1297
CoF_2	1400	1049
Rb_X	1408	1393
UF_4	1417	791
LiF	1680	1382
CdX_3	1748	964
ThX_4	1680	921
PuX_4	1277	unknown

	X=F	X=Cl
UX_4	1417	791
PuX_3	1975	1767
AmX_3	850	1253
PmX_3	unknown	1670

	X=F	X=Cl
ErX_3	2200	1500
NpX_3	2223	800
YX_3	2230	1900
BaX_2	2260	1560
EuX_3	2280	decomp
GdX_3	2280	1580
NdX_3	2300	1600
LaX_3	2327	1000
SmX_3	2427	decomp
PrX_3	2300	1710
CeX_3	2300	1727
SrX_2	2460	1250
UX_3	2300	1657

metals	
Se	685
Te	988
Pd	2963
Mo	4639
Rh	3697
Ru	4150
Tc	4265

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NEW: merge accelerator and molten-salt fuel, not as add-ons to existing systems, but in the *original design (not like ATW)*:

Sub-critical buys us:

- Highly flexible fuel cycle
  - removes challenges of maintaining ‘criticality’
  - no enrichment required; no reprocessing
  - deeper burning of multiple fuels (e.g., LWR spent fuel or WGPu), reducing waste
- intrinsically a safer regime of operation
- economically viable today (10^6 reduction of cost to produce neutrons)

Molten salt fuel buys us:

- Higher temperatures at lower pressures
- No concern about fuel melting
- proven operation with multiple fuels
- feed-and-bleed fueling
- relieves accelerator ‘trip’ issues (no solid-fuel thermal shock)
- direct cooling of beam target
- continuous removal of volatile fission products

Homologous target/core design buys us:

commercially viable performance

Thermal neutron spectrum:

- High tolerance for fission products (eliminates need for their removal.)