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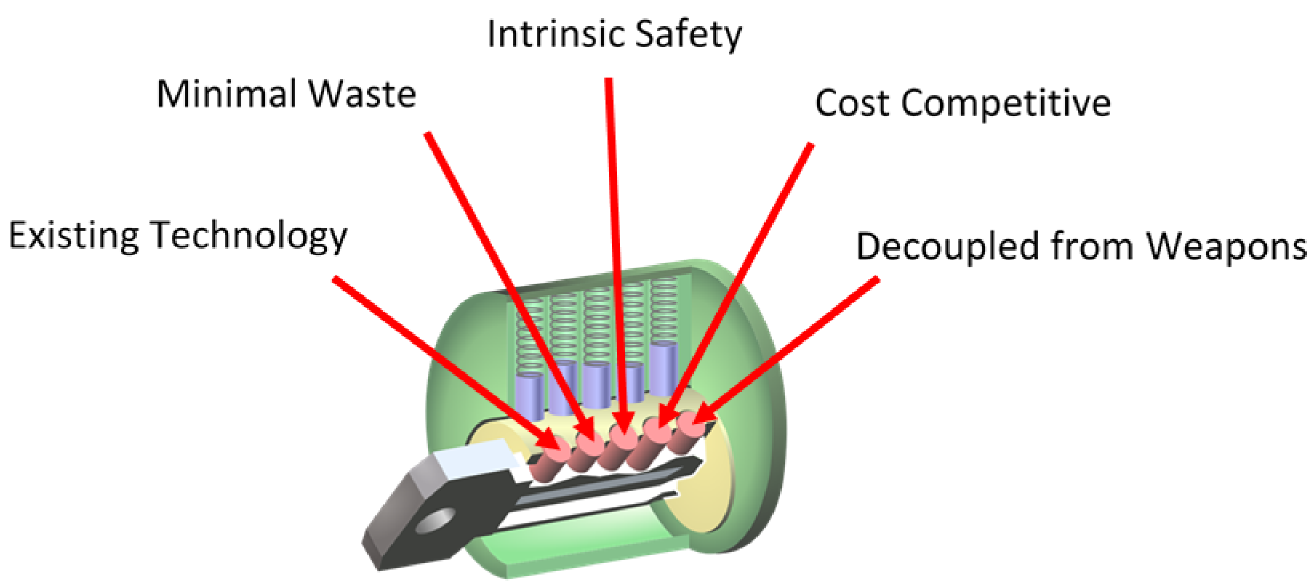
Reducing Global Warming

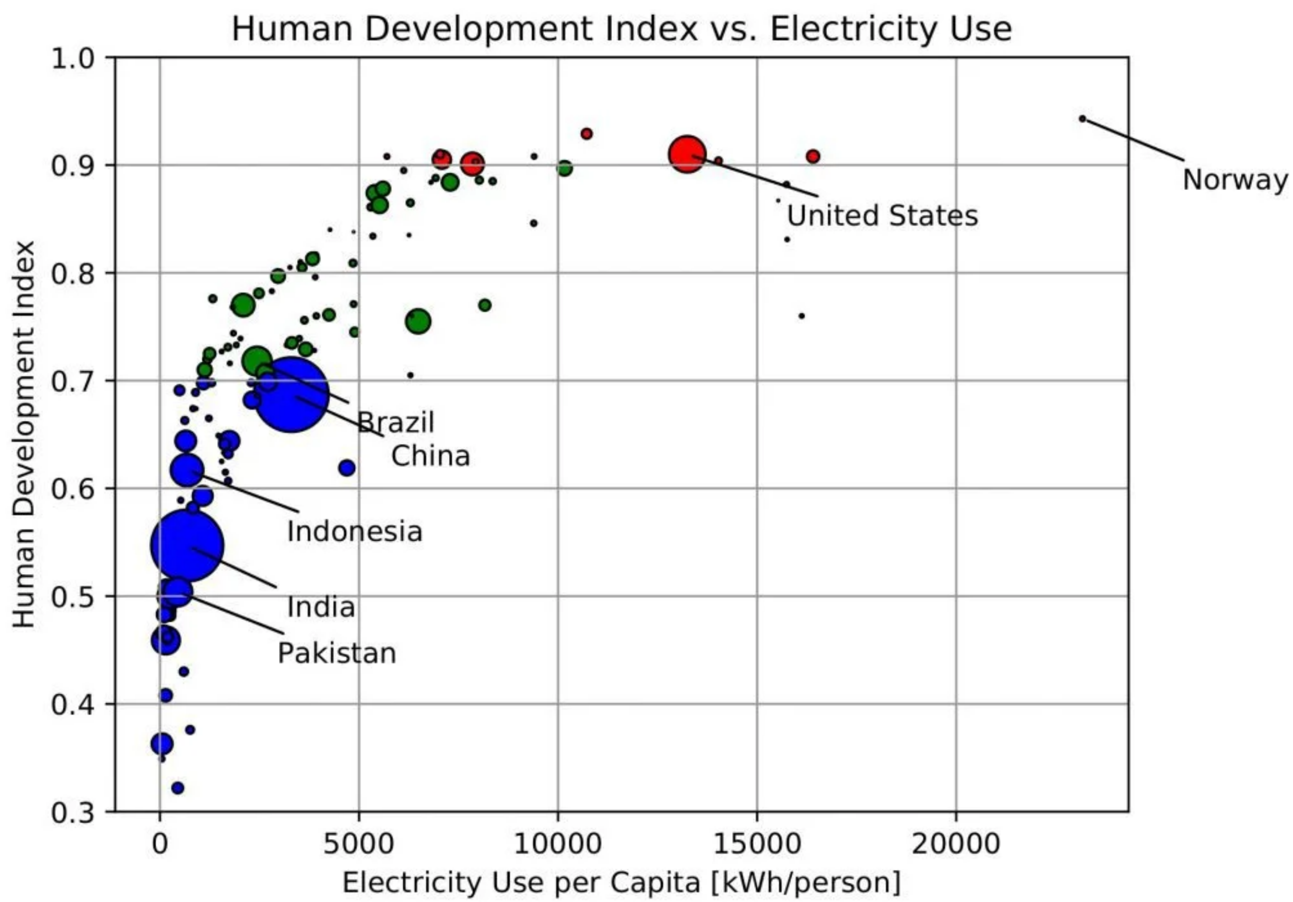
an urgent quest to find an acceptable avenue for nuclear energy

R. Bruce Vogelaar, Virginia Tech

NCSU Physics Colloquium, October 12, 2020 4-5 pm via Zoom

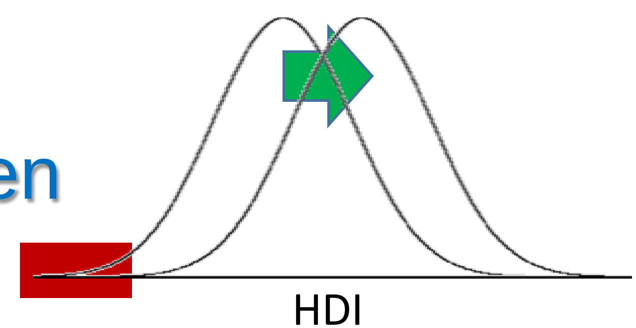


Access to power improves Human Development Index



correlated benefit:

far fewer extremists to handle when more of society is empowered



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Our world is changing *significantly*

Causes

&

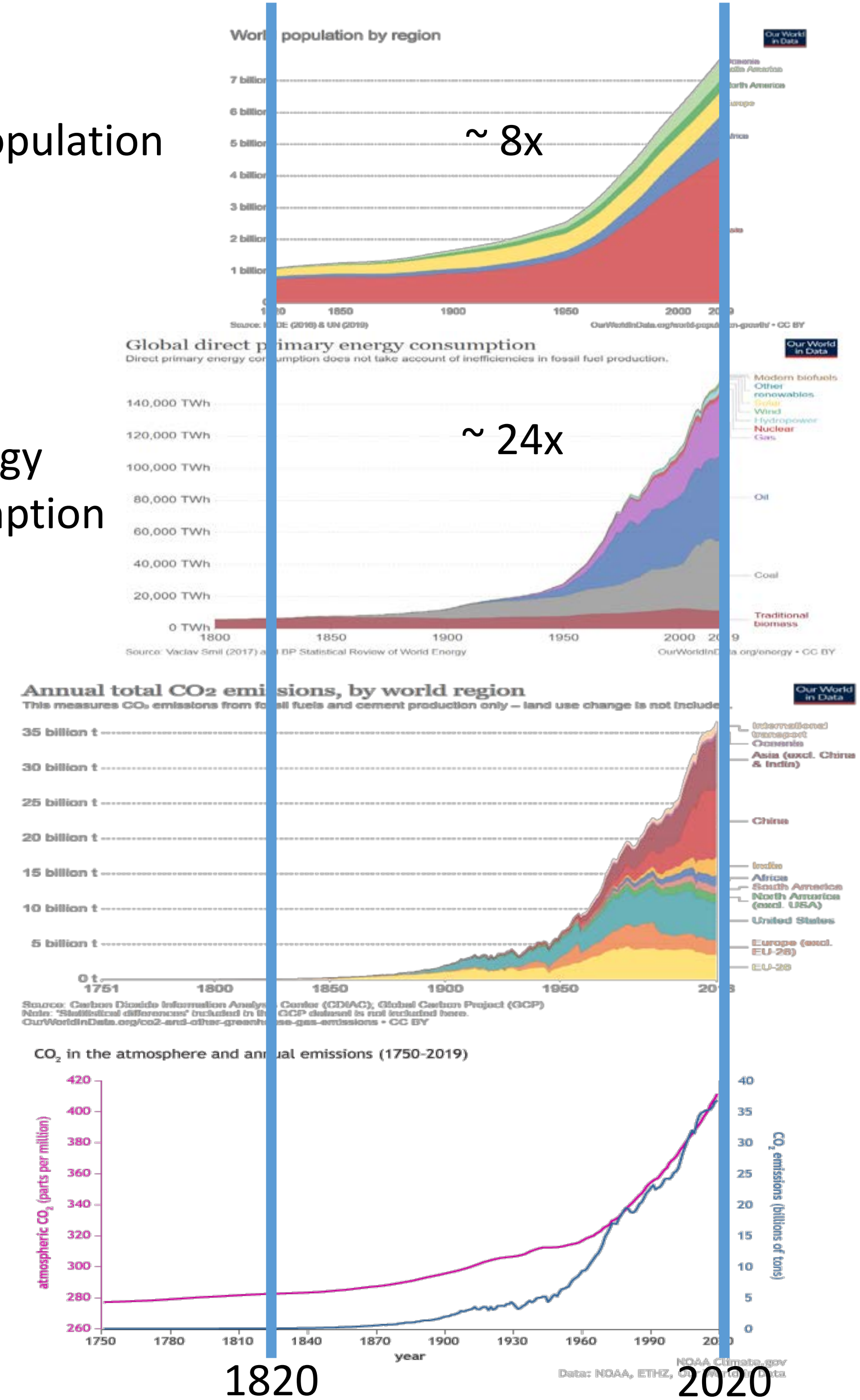
Effects

Population

Energy Consumption

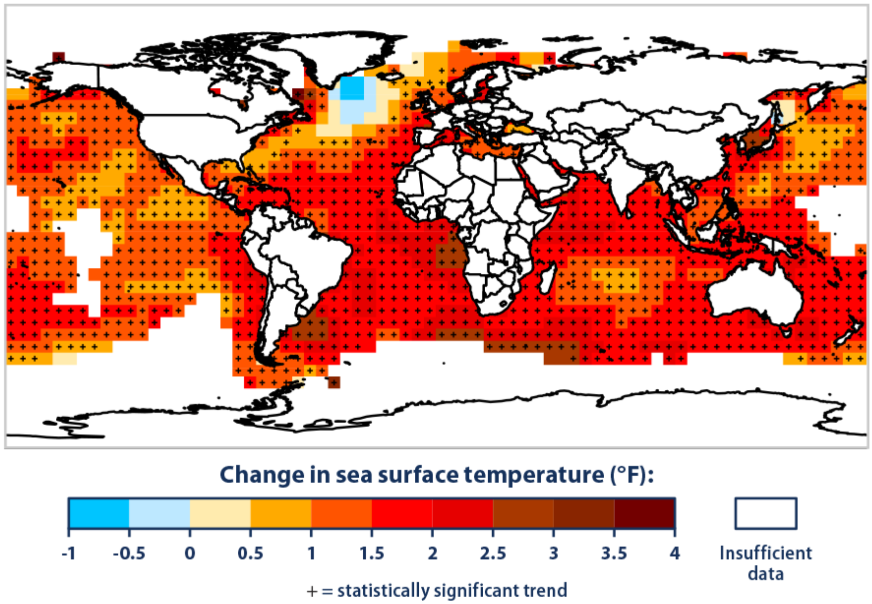
CO_2 emission

Atmospheric CO_2



Earth is warming…

Change in Sea Surface Temperature, 1901–2015



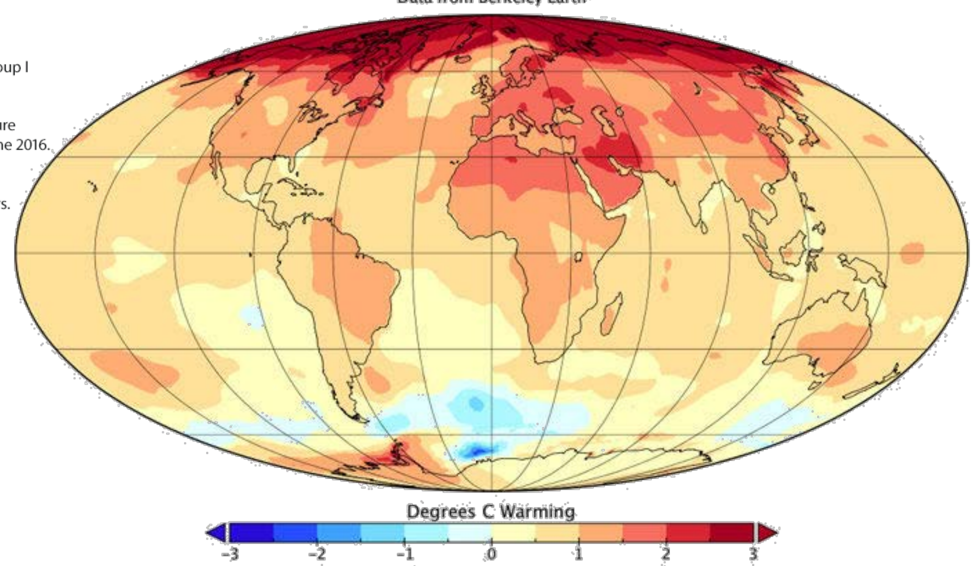
Data sources:

- IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Working Group I contribution to the IPCC Fifth Assessment Report. Cambridge, United Kingdom: Cambridge University Press. www.ipcc.ch/report/ar5/wg1.
- NOAA (National Oceanic and Atmospheric Administration). 2016. NOAA Merged Land Ocean Global Surface Temperature Analysis (NOAAGlobalTemp): Global gridded 5° x 5° data. National Centers for Environmental Information. Accessed June 2016. www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Global Warming from 1970 through 2019

Data from Berkeley Earth



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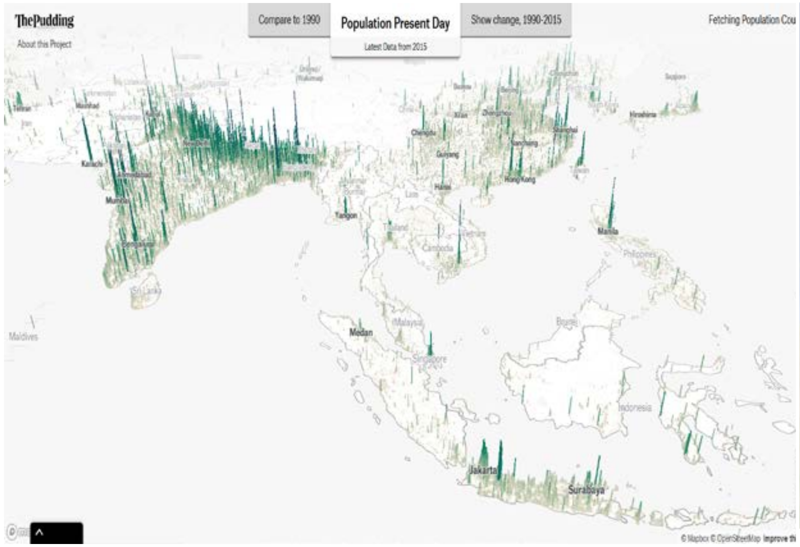
…with more storms for populations near coasts



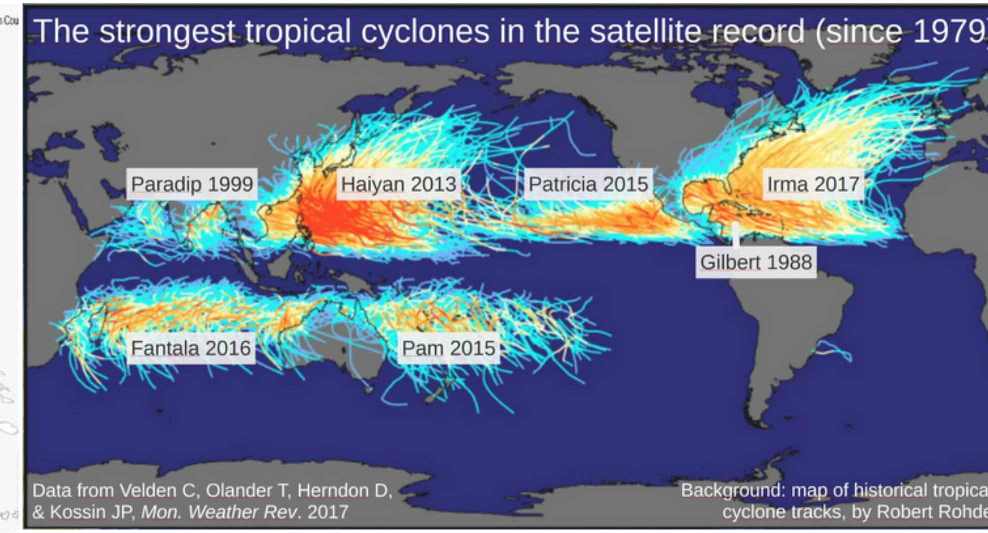
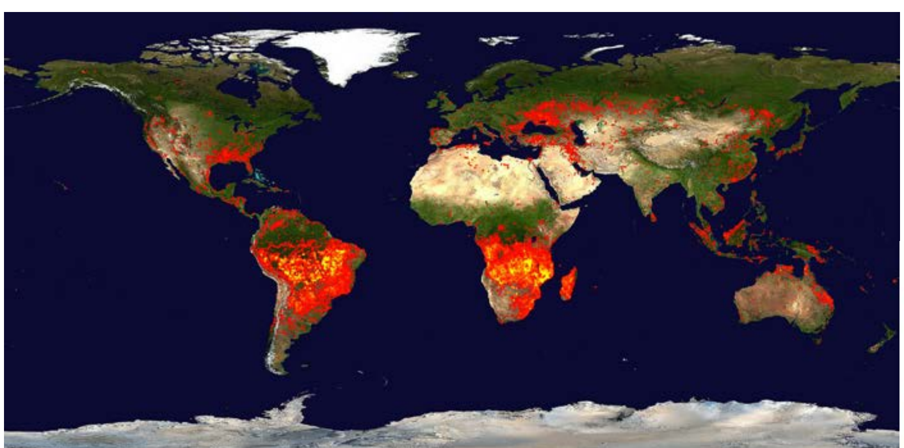
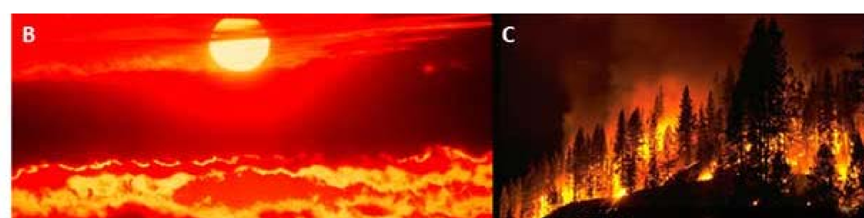


Fig. 1 *The strongest storms for the major storm regions Western and Eastern North Pacific, North Indian, South Indian and South Pacific, Caribbean/Gulf of Mexico and open North Atlantic. Of these seven regions, five had the strongest storm on record in the past five years, which would be extremely unlikely 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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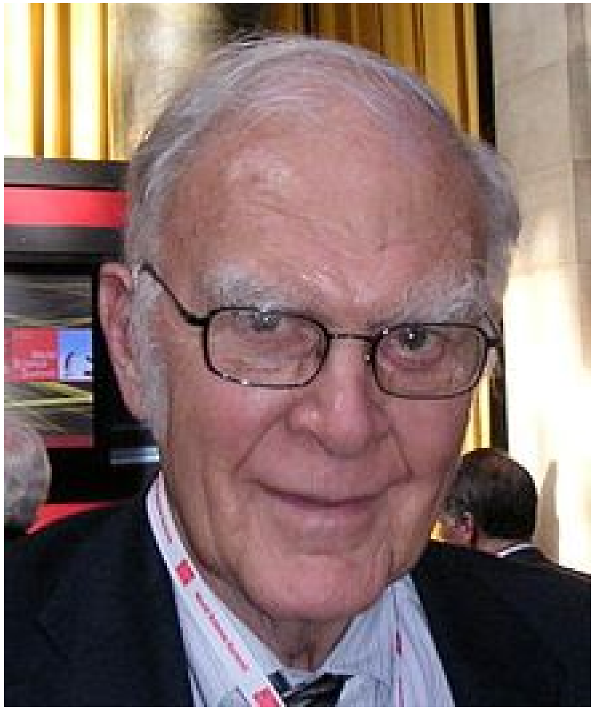

Dr. F. Sherwood “Sherry” Rowland - Nobel Prize in Chemistry 1995
White House Roundtable on Climate Change 1997

“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?**”*

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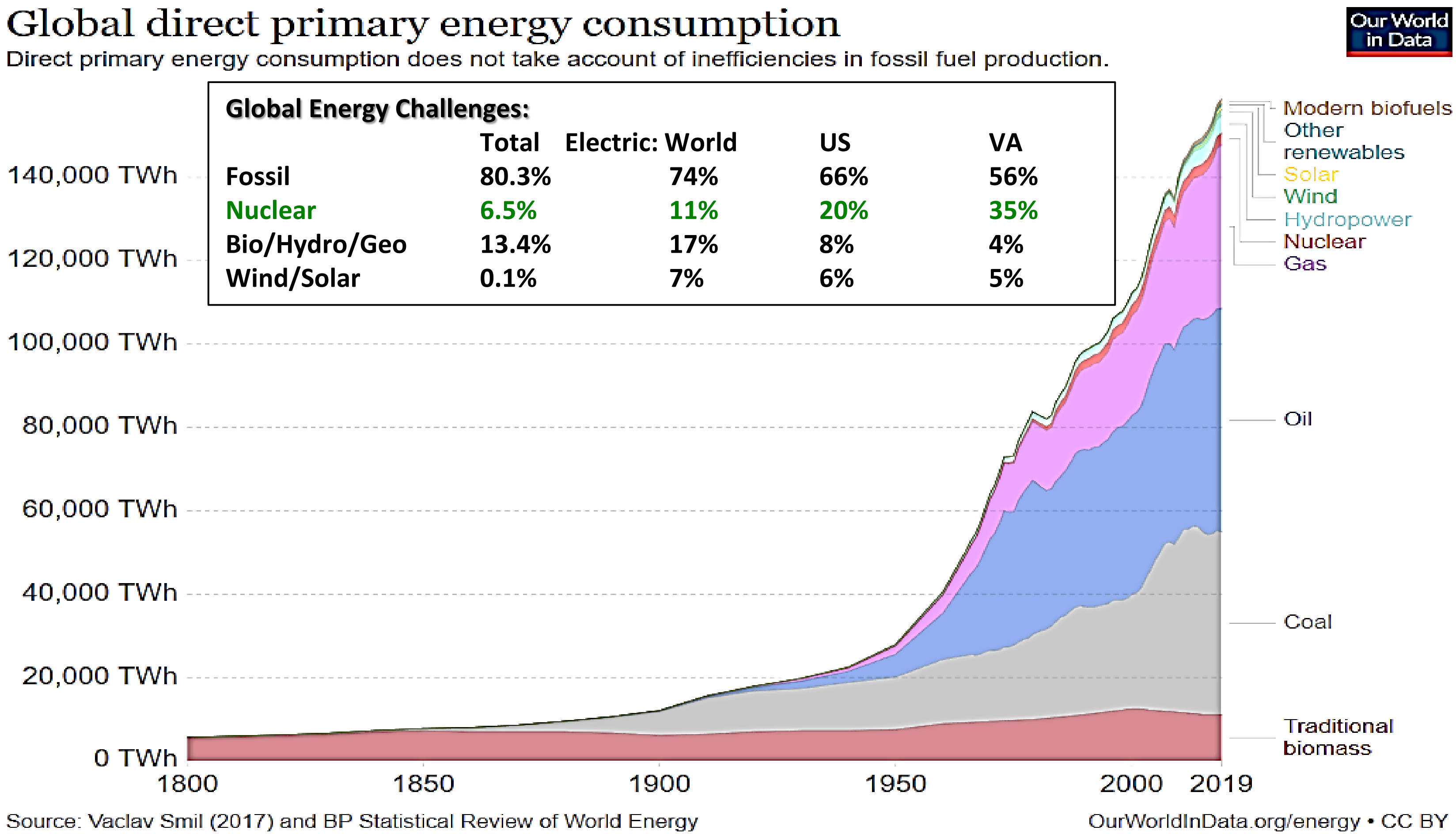
Push for (green) renewable energy

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 to find ideal battery:

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

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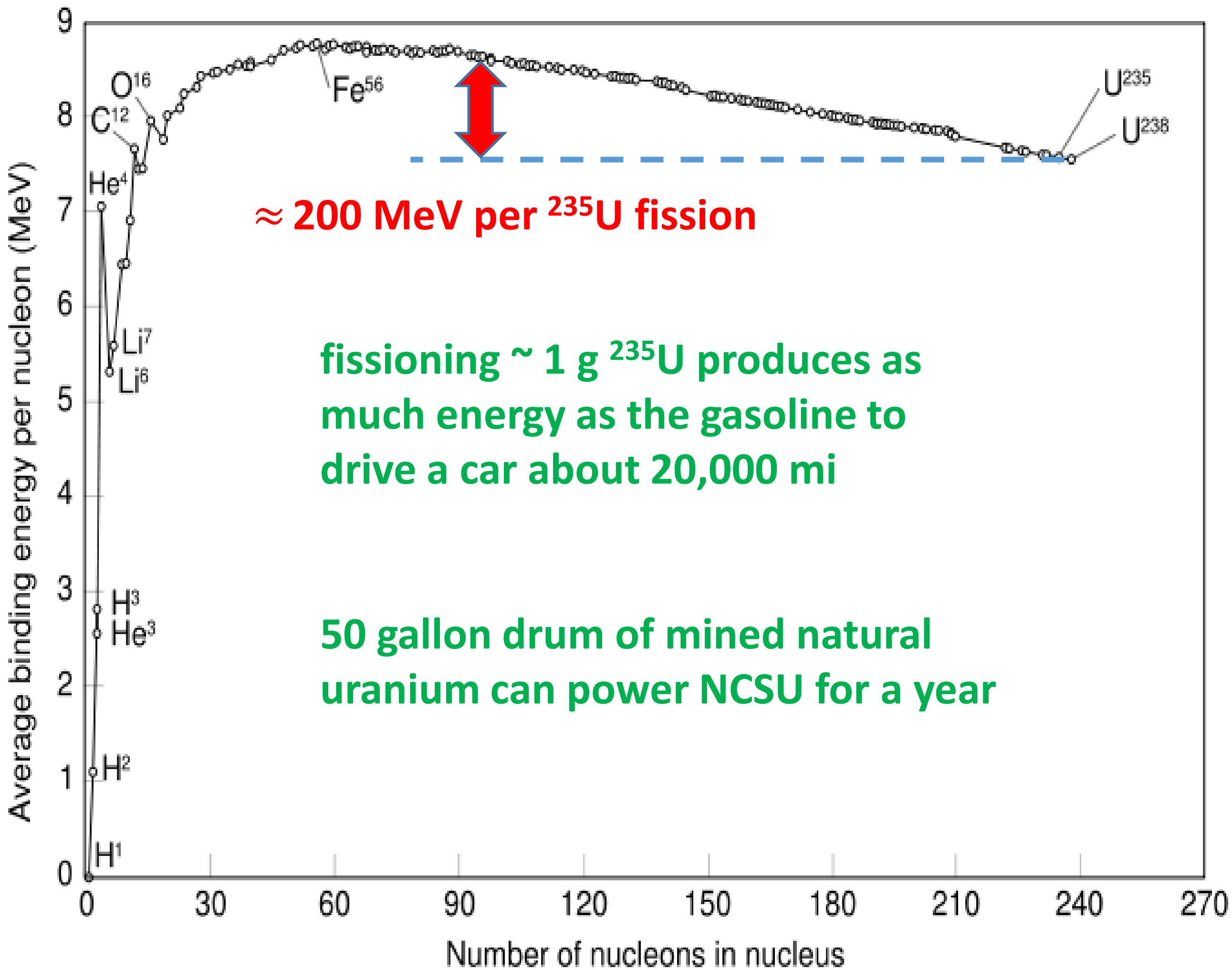
Nature tempts us with free ‘star’ energy already stored in nuclei



≈ 200 MeV per ^{235}U fission

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

50 gallon drum of mined natural uranium can power NCSU for a year

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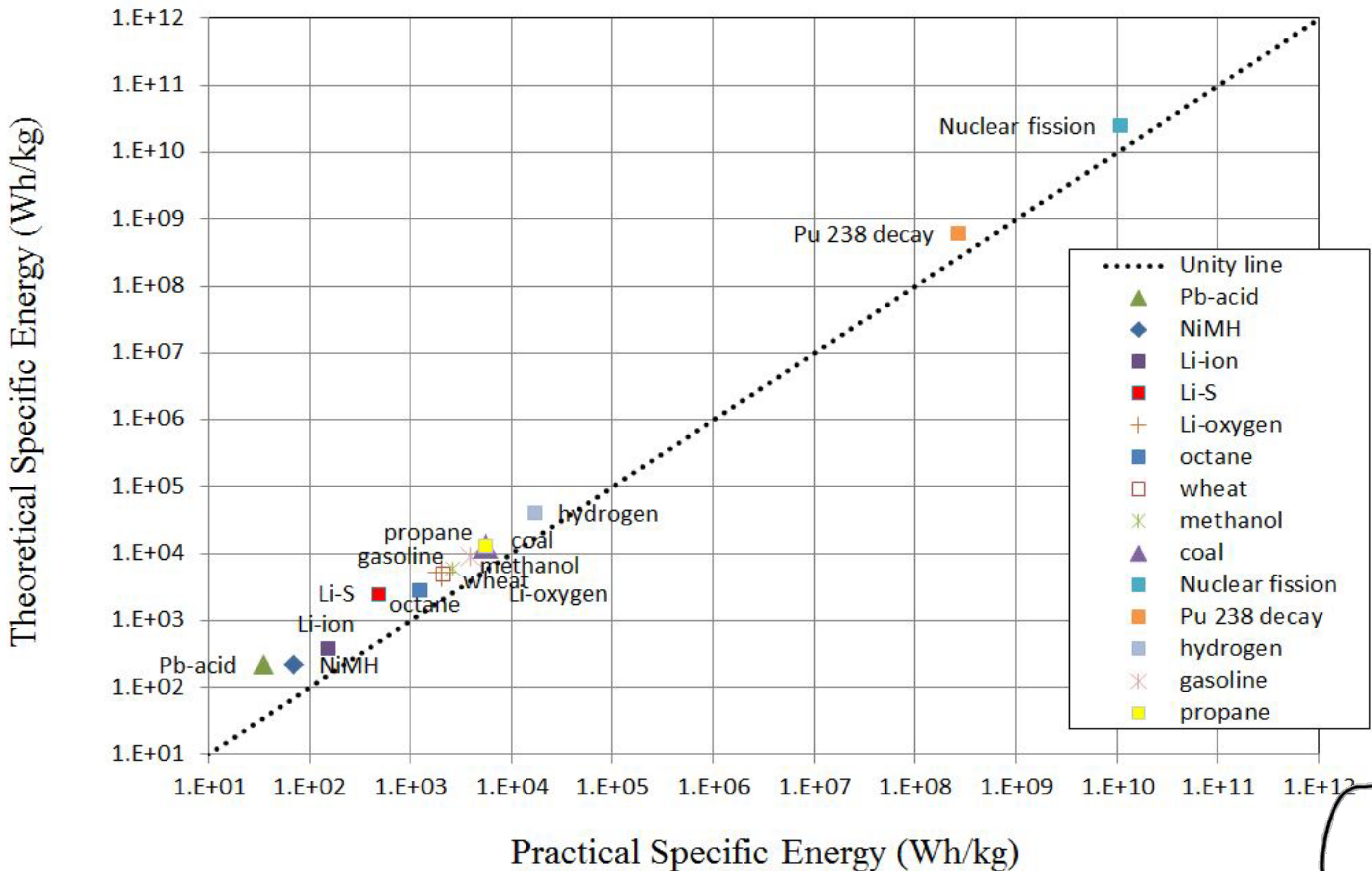
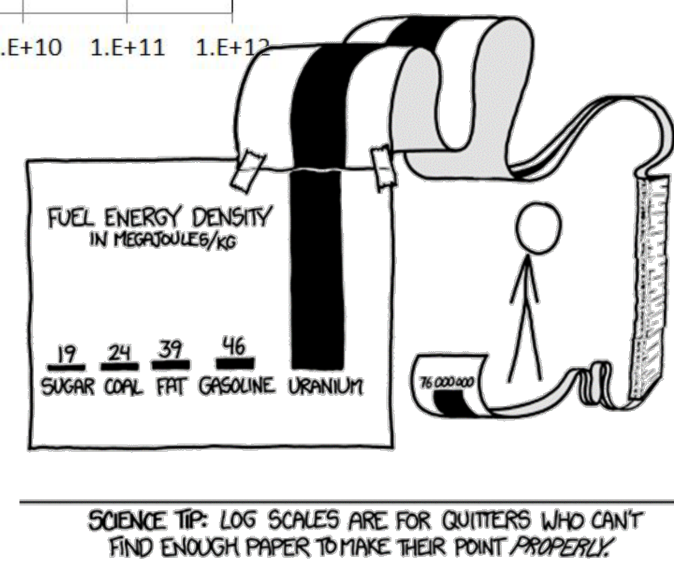
Specific Energy of Various Energy Sources



Note: these are log scales!



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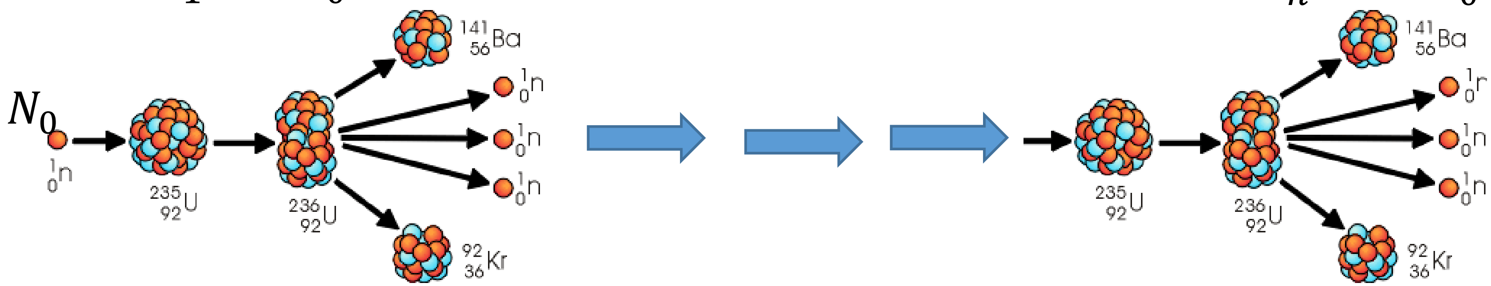
Basic Fission Chain Reaction

1st generation

$N_1 = kN_0$

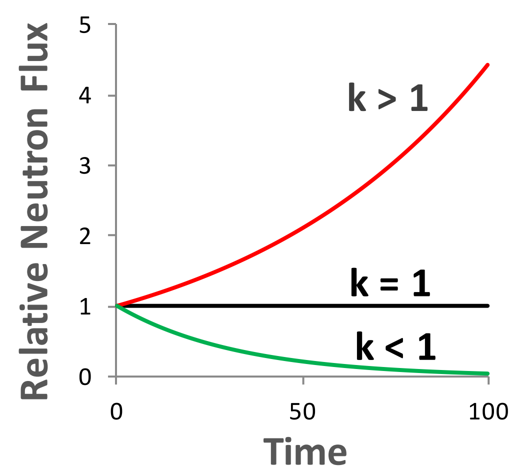
n'th generation

$N_n = k^n N_0$

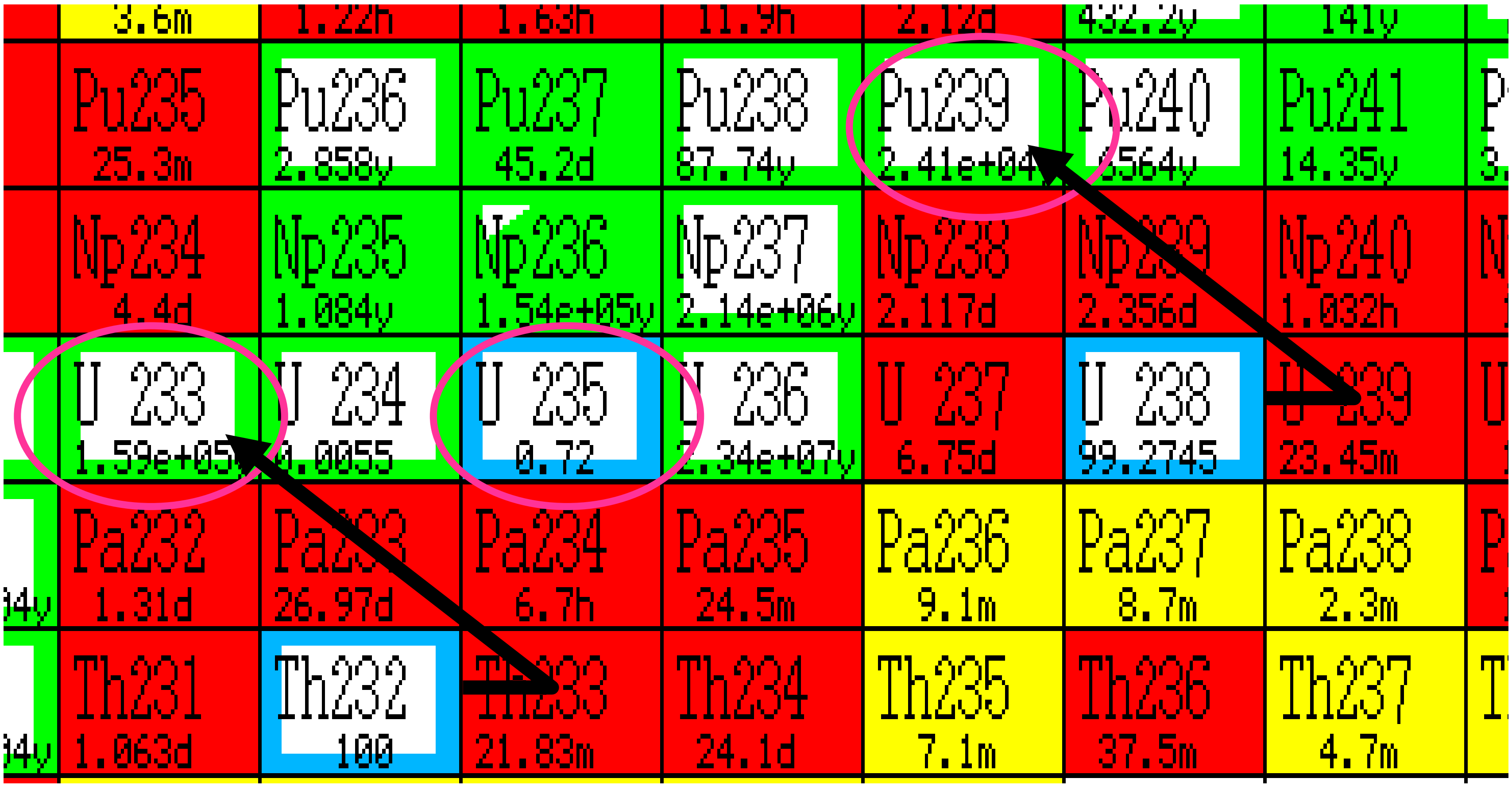


$$k = \frac{\#\, fission\ neutrons\ in\ one\ generation}{\#\ of\ \ fission\ neutrons\ in\ the\ preceeding\ generation}$$

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



Possible Fuels

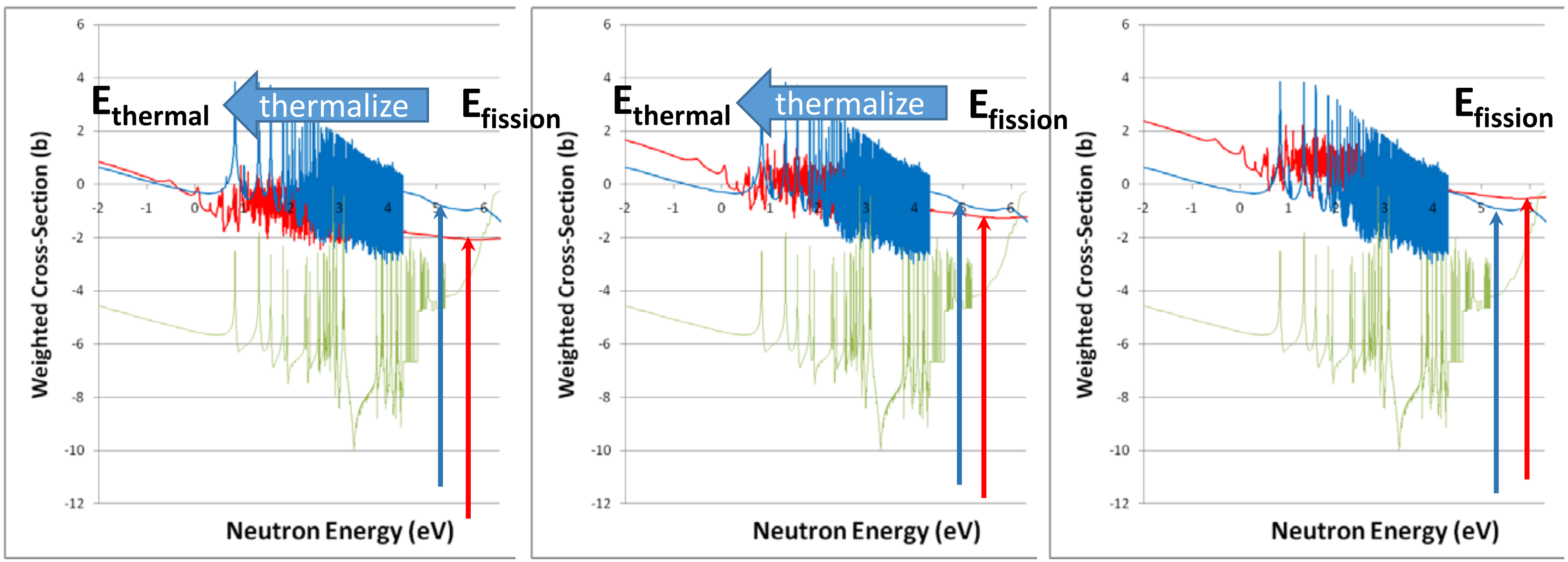


“Breeder” reactions can make new fissionable nuclei

Sustaining a chain reaction

^{235}U fission — red line
^{238}U capture — blue line
^{238}U fission — green line

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

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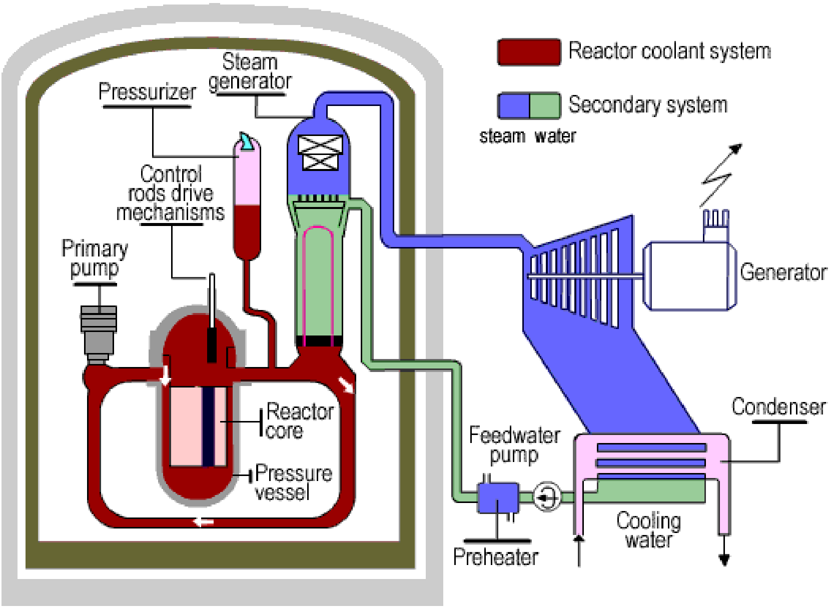
Classic "Critical" Reactor (eg LWR)

Typical 1 GW_e

Water Moderation

Enriched ^{235}U fuel

Solid fuel in cladding



Pressurized Water Reactor (AREVA)

Uses negative feedback to avoid runaway

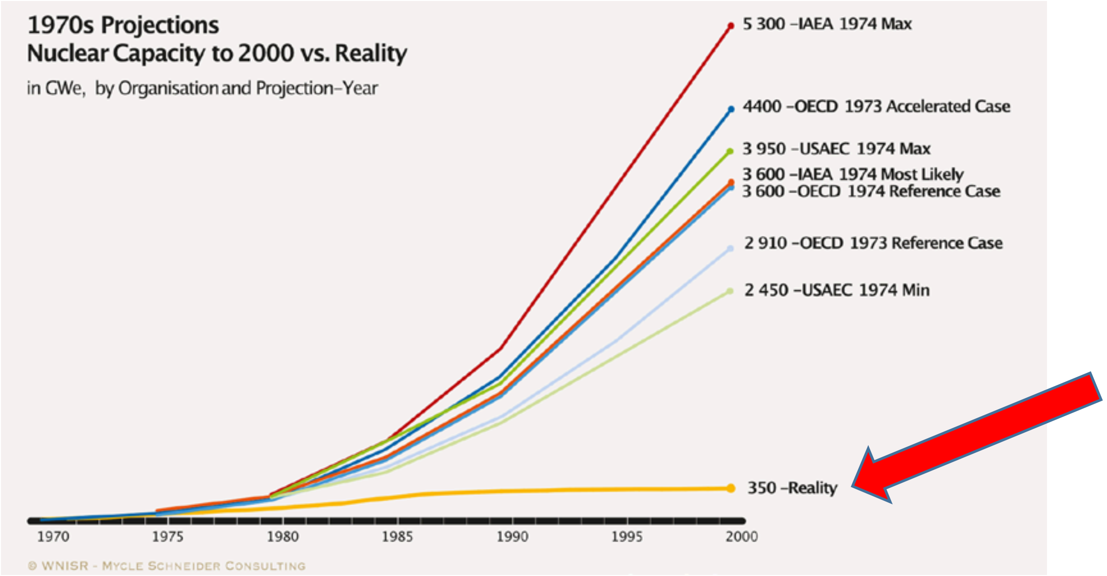
- Prompt –vs– delayed critical
- Doppler broadening
- Thermal expansion

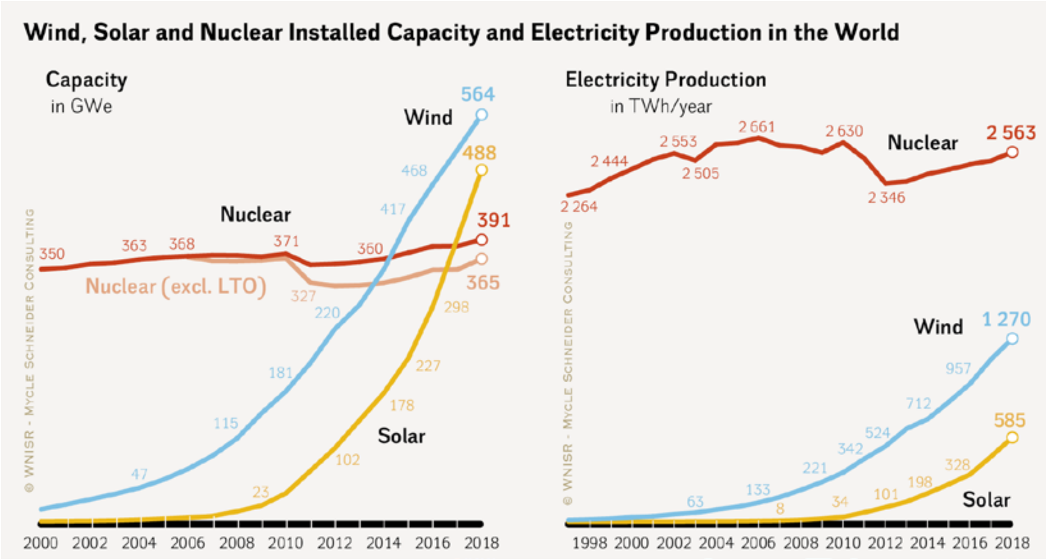
Build up of Fission Products poisons chain reaction, so use:

- 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

How has it gone so far?





75% duty

26% duty

14% duty

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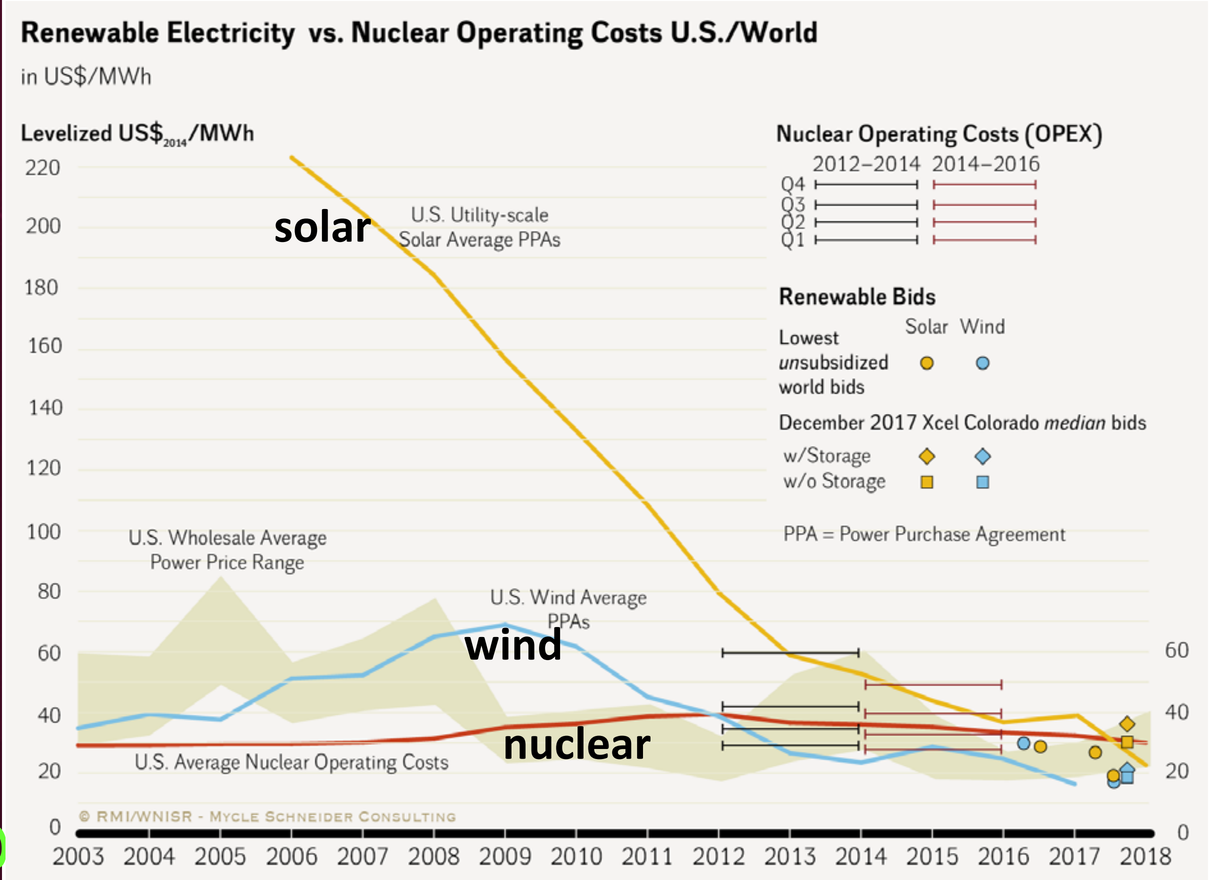
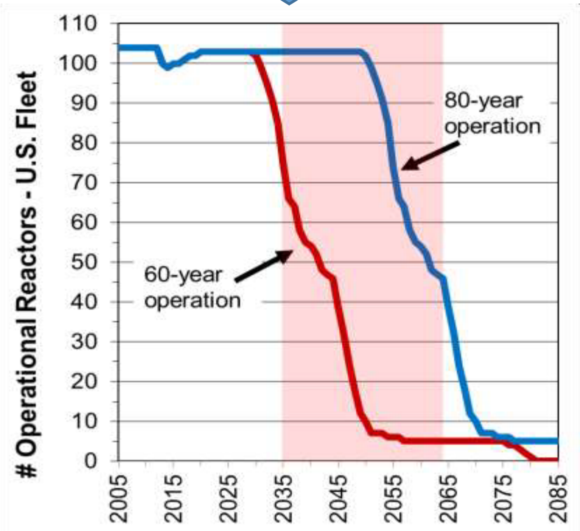


Domestic:

US Nuclear Reactors produce 20% of electricity.

US reactors are approaching their 40-year life; majority have permission for 20 years of plant life extension (PLE).

Even with 20-year PLE, we must START building NOW!



With so much global need, and so much potential, why are we turning away?

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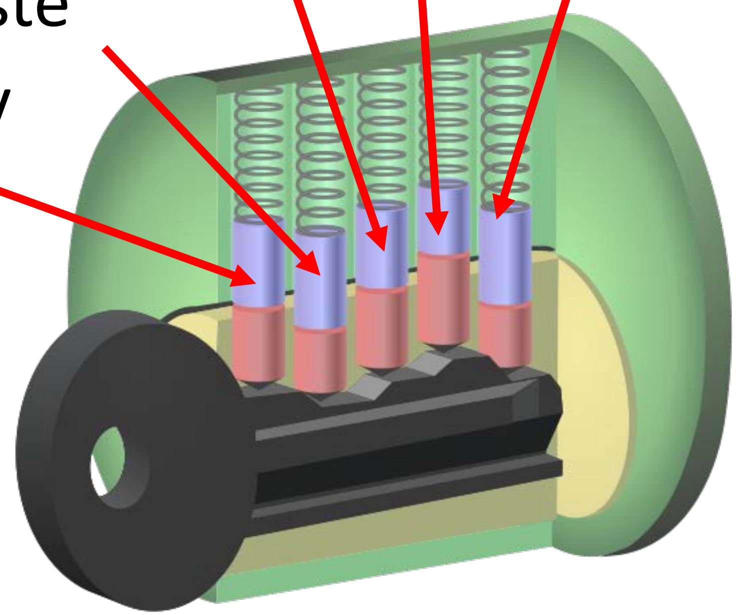
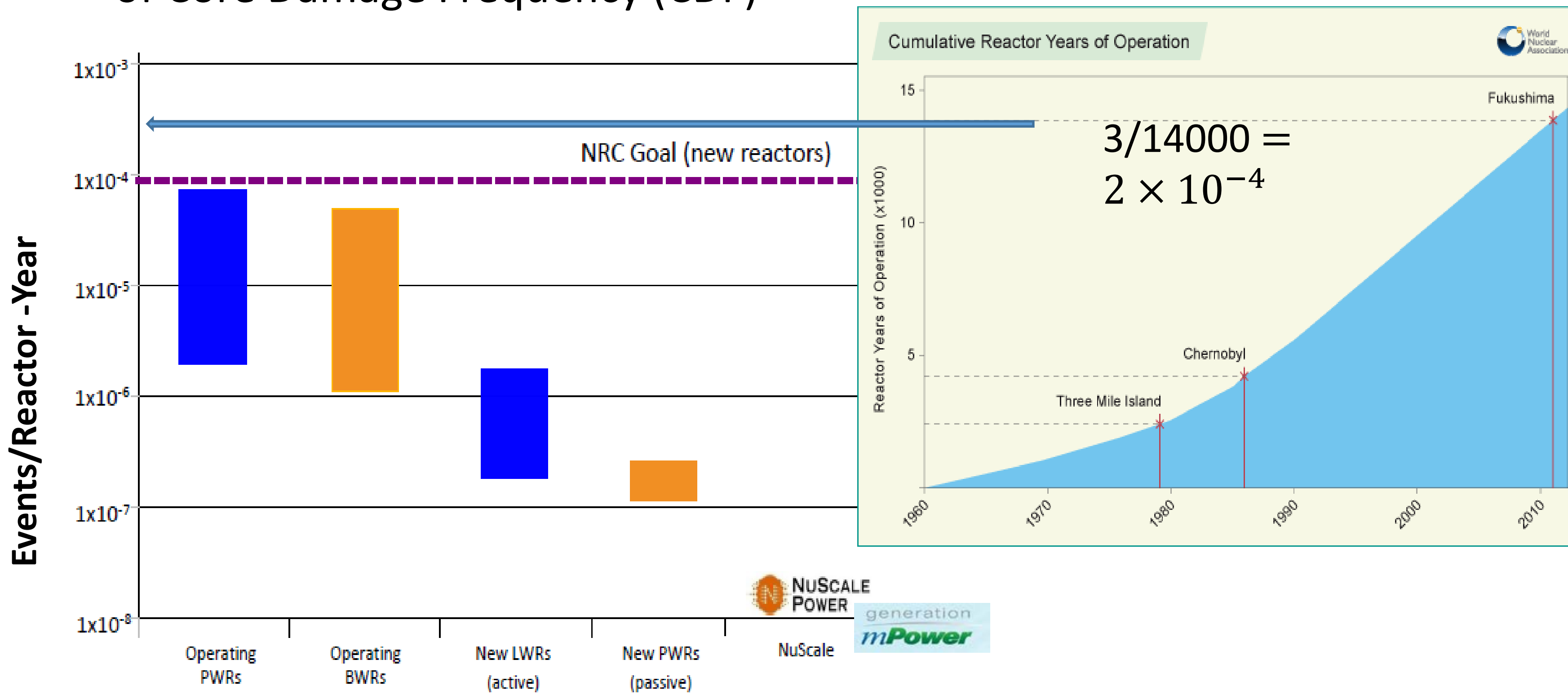
Nuclear Energy Conundrum
(solving a ‘*majority*’ is simply ***not enough***)

Any ‘tumbler’ out of alignment can halt progress.

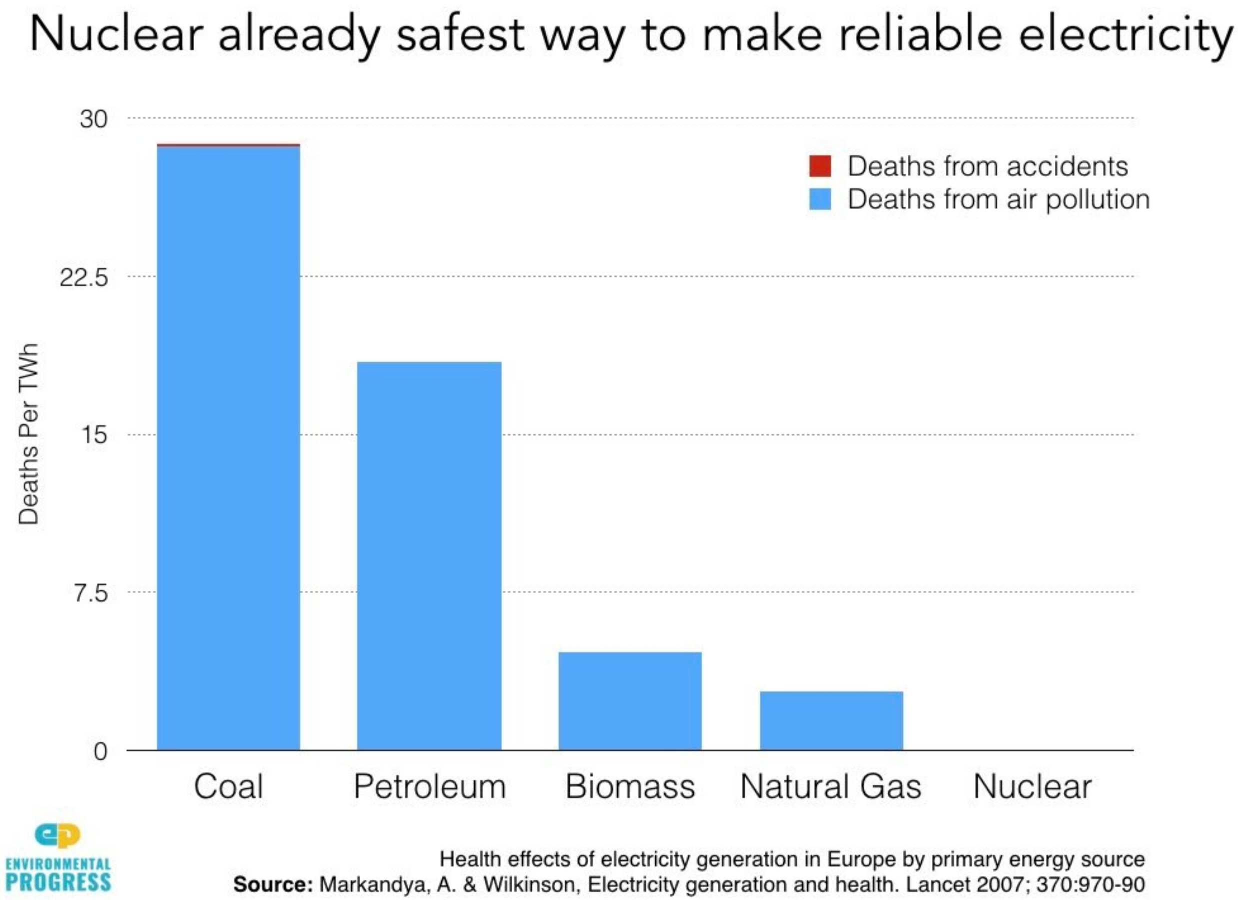


Safety

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



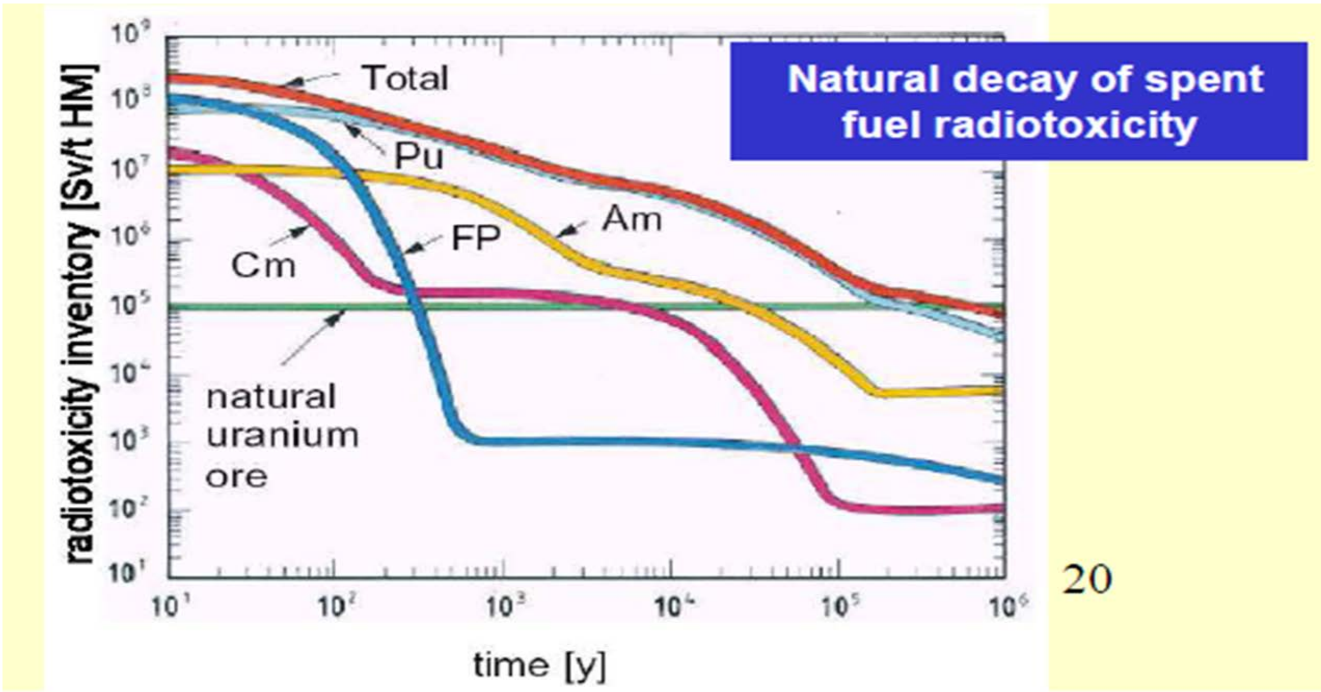
SMR claim 10^{-8} events per reactor-year
…that's 1 core-damage event in 1,000,000 reactors over 100 years; hmmm….



Deaths per kWh 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…current practice**



- FP (fission products) activity approaches what had been in its natural uranium ore after about 300 years

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Weapons Proliferation

can the 'battery' to be discharged all at once !?

- **enrichment** (hard to enforce stopping at a fixed percentage)
- **reprocessing** (chemical separation of Pu is easier than isotope enrichment of U)
- **disposition of 34t of WGPu…**
- **GNEP concept rejected**
- **US leaving non-proliferation treaties…**

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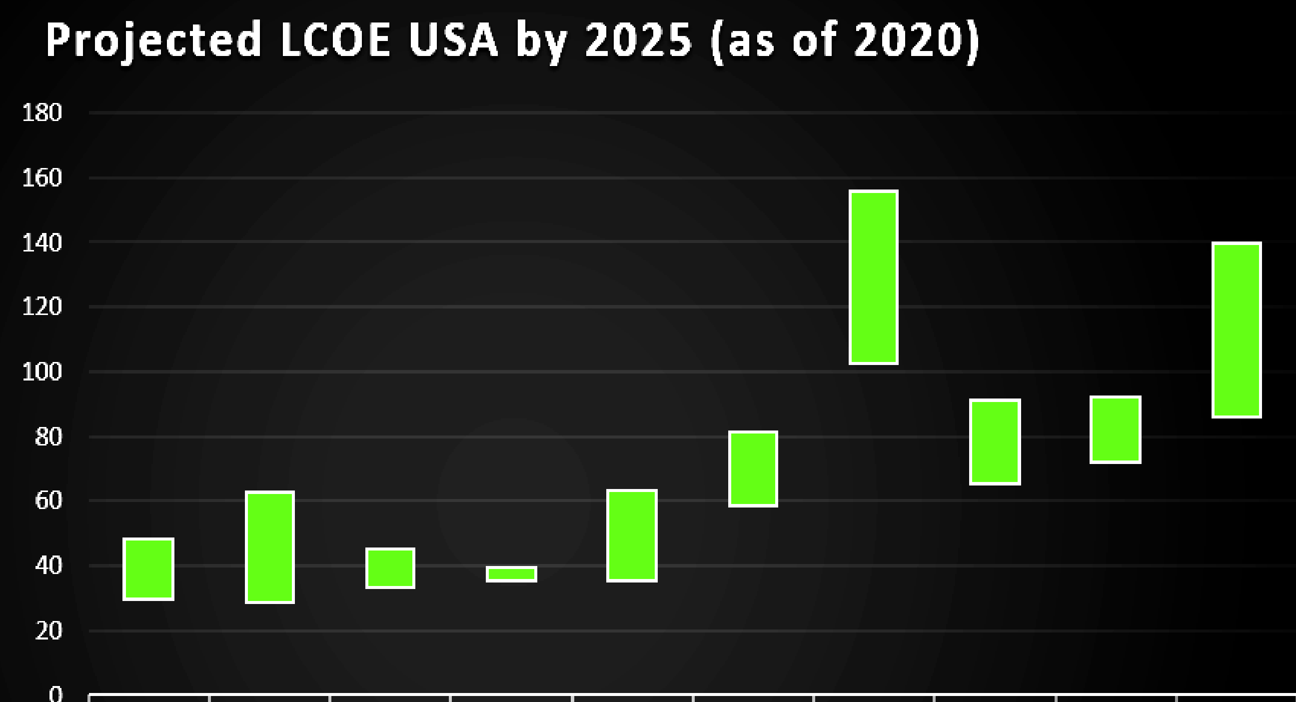
➢Cost



	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 is being done...

DOE-NE

'small modular reactors'

- safety
- waste
- weapons proliferation
- cost

DOE-Science

'high-intensity frontier'

- safety
- accelerator transmutation of waste
- weapons proliferation
- cost

development of HALEU fuels for long life

US Nuclear Energy Generation - R&D & Construction

US Energy Context:

- coal/natural gas: not 'green'
- solar/wind: not baseload-capable due to low density, intermittent, transmission loss, and cost

US Nuclear Energy Context:

- 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)
  - GAIN (Gateway for Accelerated Innovation in Nuclear)
  - 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
  - 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, ARDP Program

Startups (about 50), for example:

TerraPower (Traveling Wave - 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)*

ALL are CRITICAL reactors; NONE address all the requirements at once

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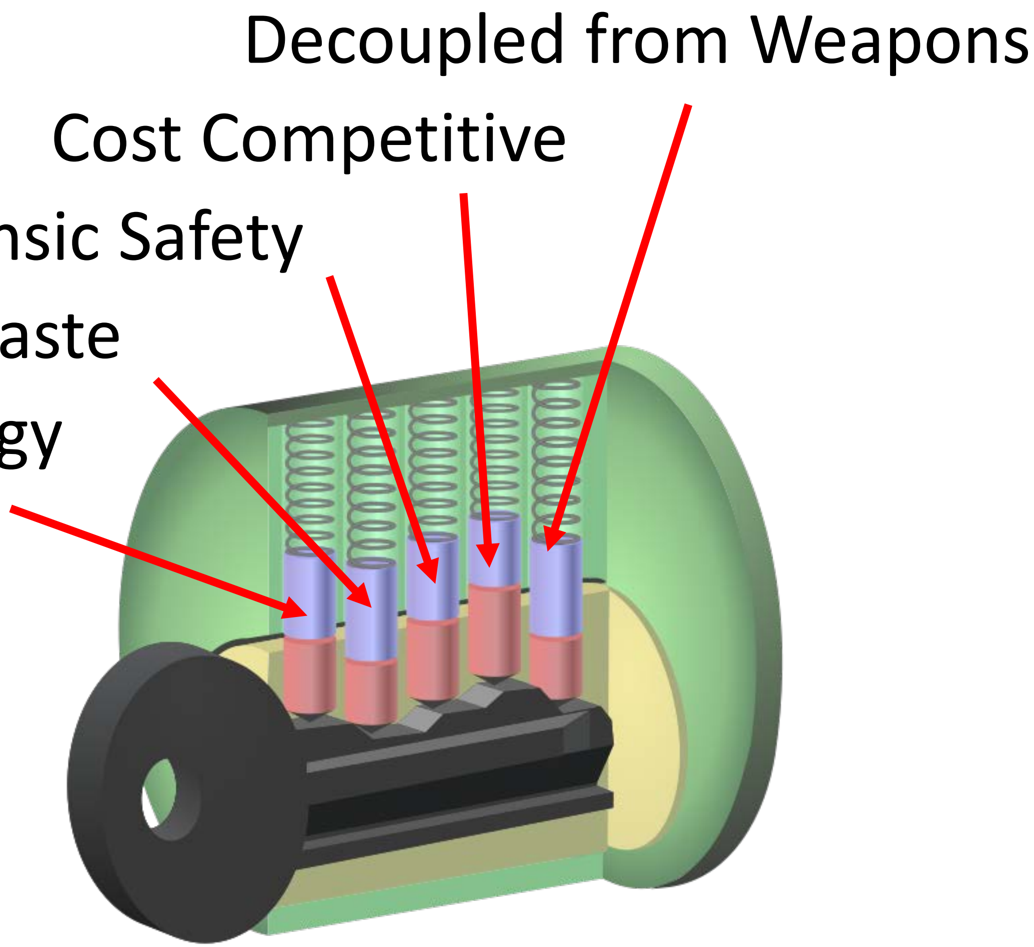
so we come back to the urgent quest !

can we do it all at once?



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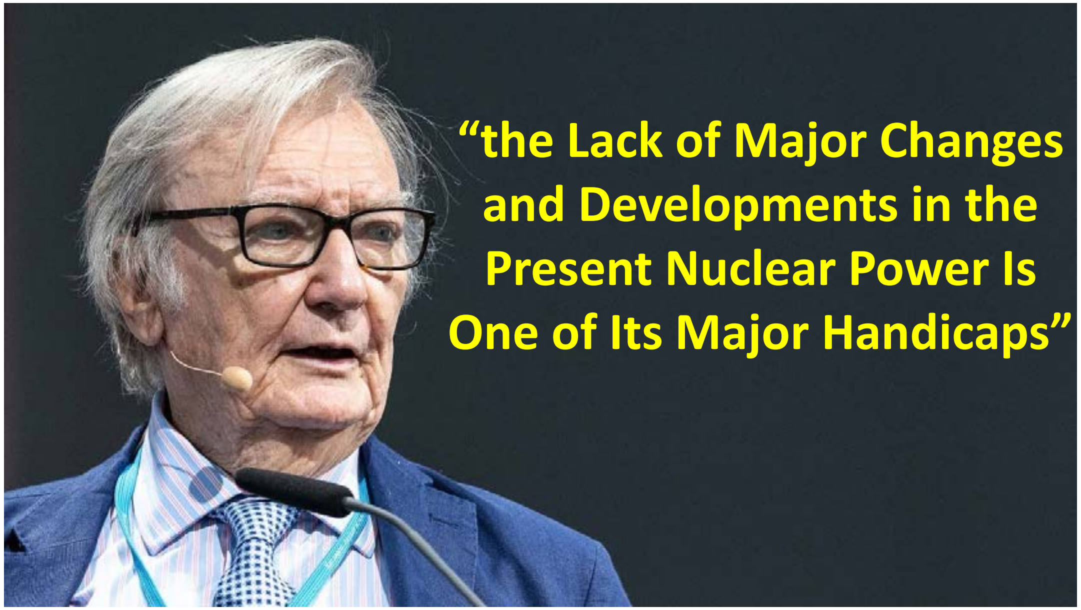

Carlo Rubbia (October, 2020)
Nobel Prize 1984
Global Energy Prize 2020
“Energy Amplifier”

Charles D. Bowman, Ph. D.
President ADNA Corporation
Accelerator-Driven Neutron Applications
“GEM*STAR”

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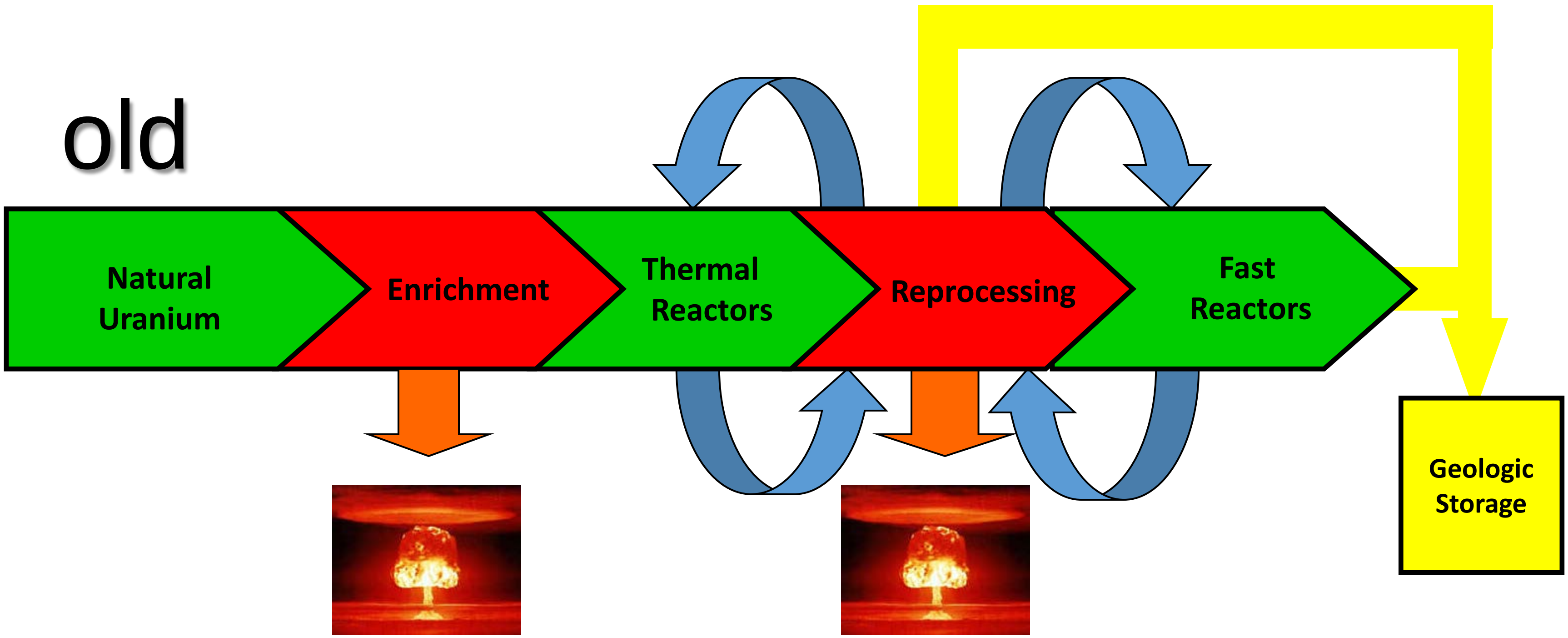
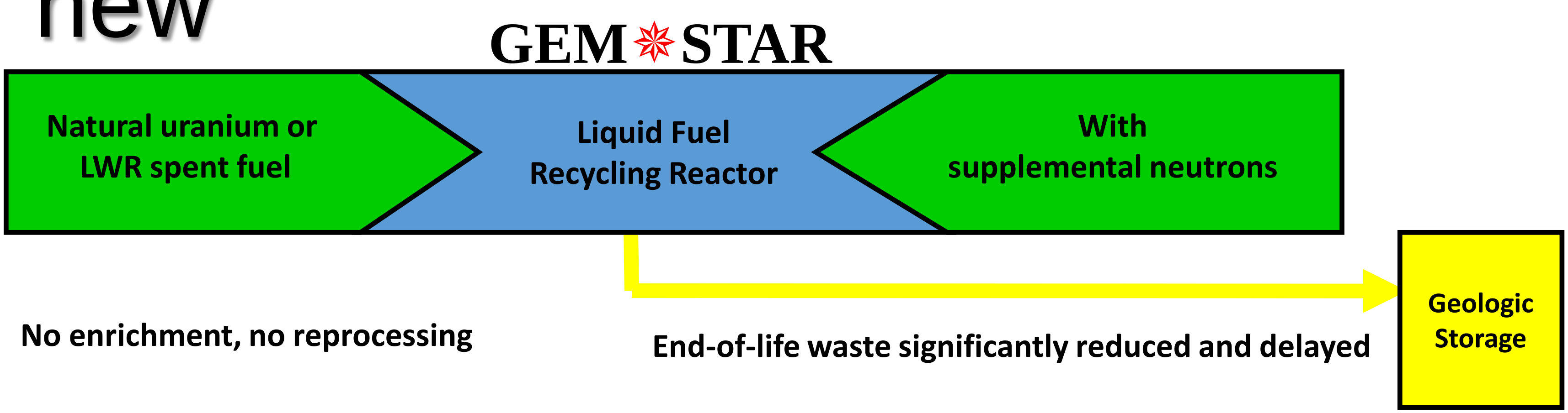
Change Paradigm for Nuclear Energy

old



new



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.)

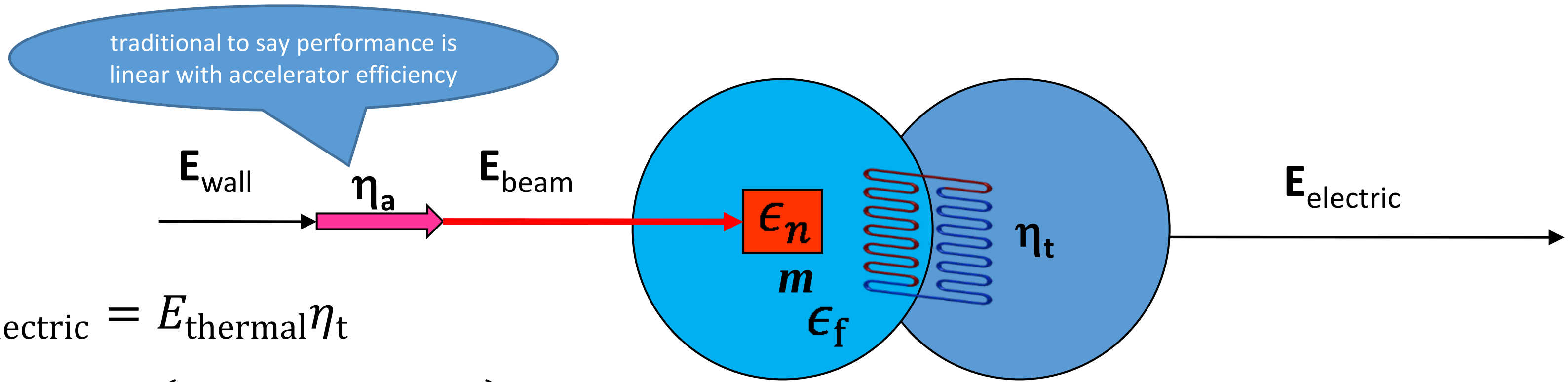
Existing Enabling Technologies

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

the key:

integration - *from the beginning*

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)

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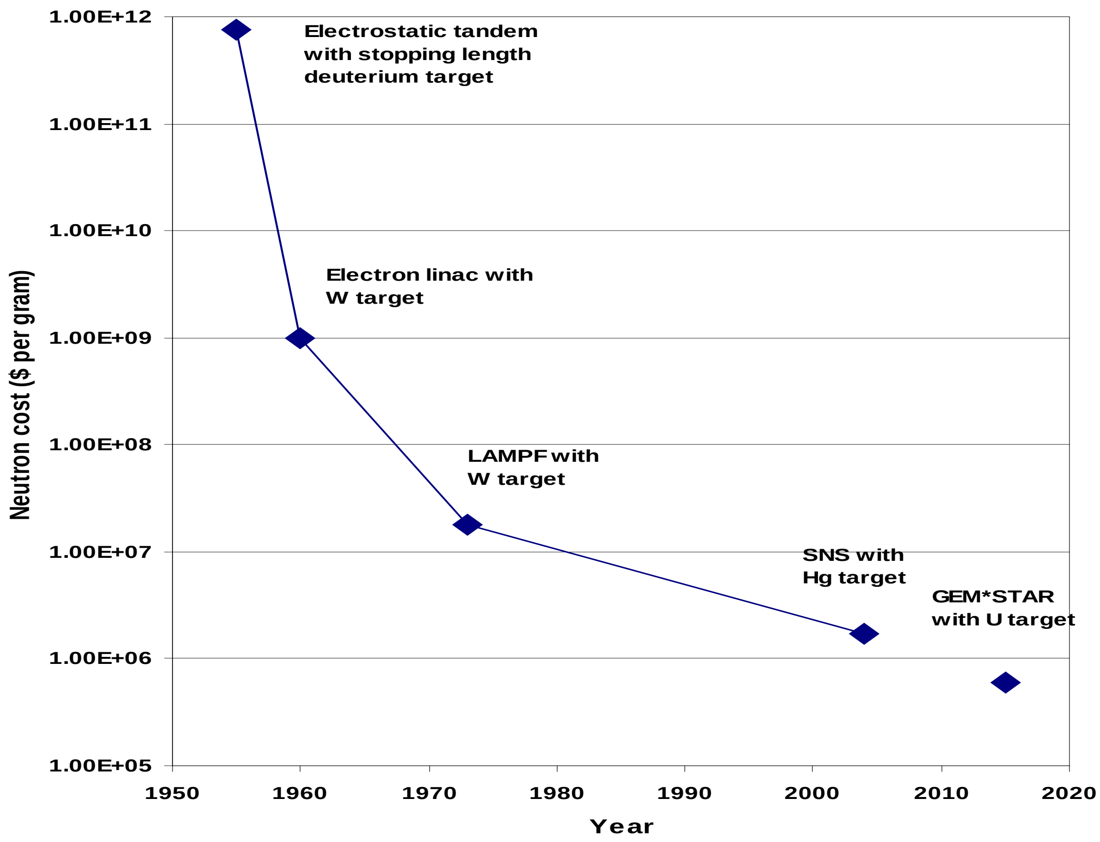
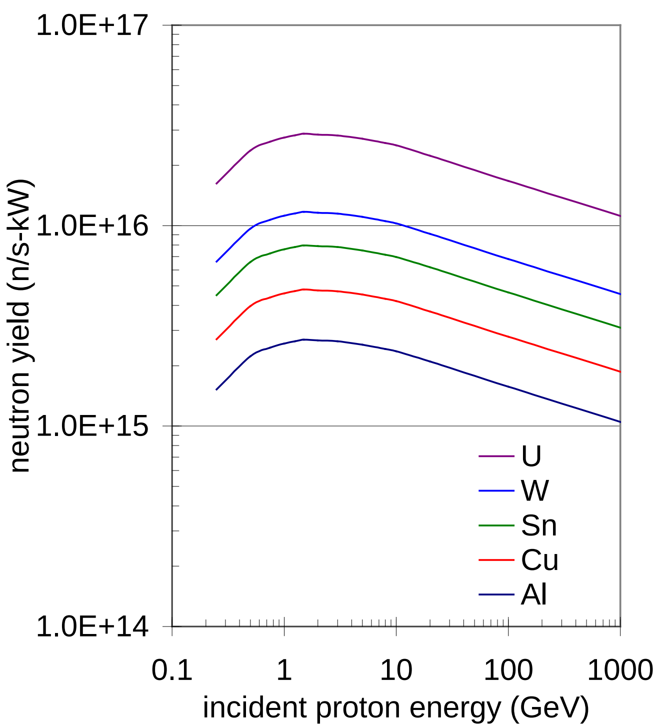
What is needed by way of accelerators?



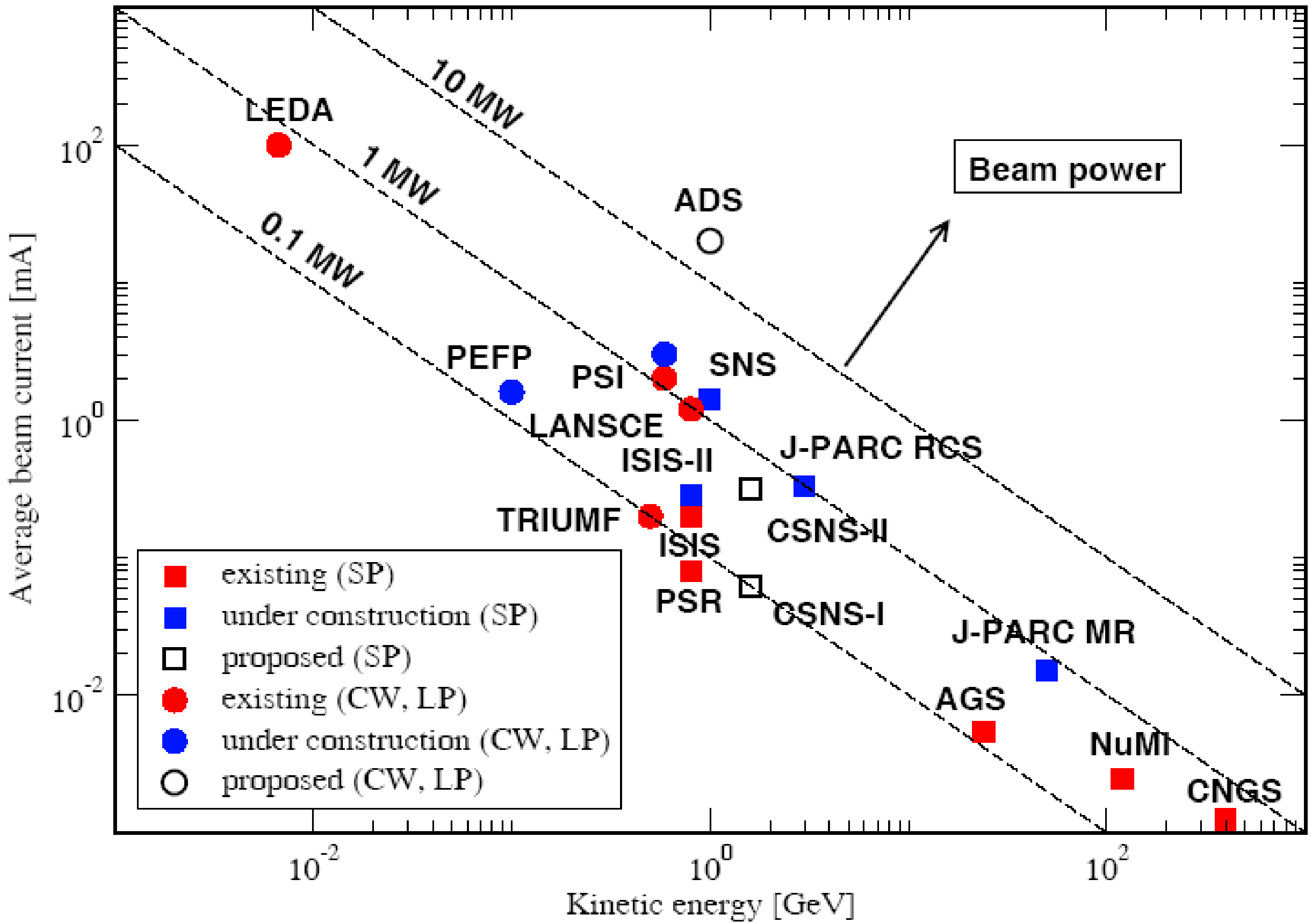


~40 grams of neutrons will produce 1GWe for one year

($432M/yr revenue @ 5 ¢/kWh)

(much better margin for synthetic transport fuels)

Existing Proton Beam Power



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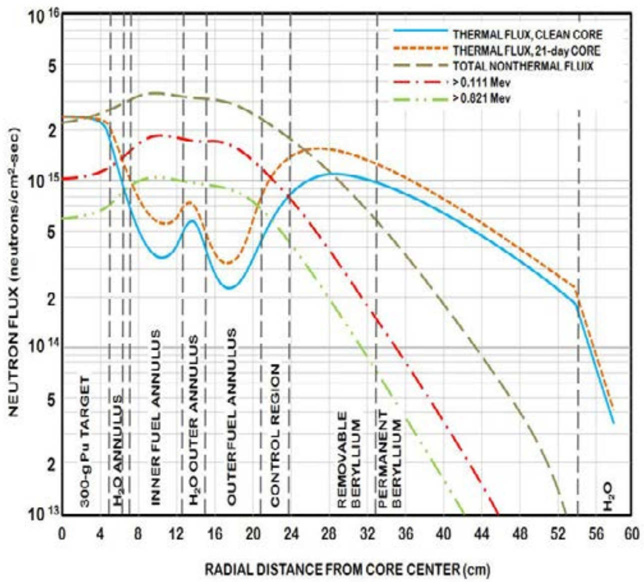
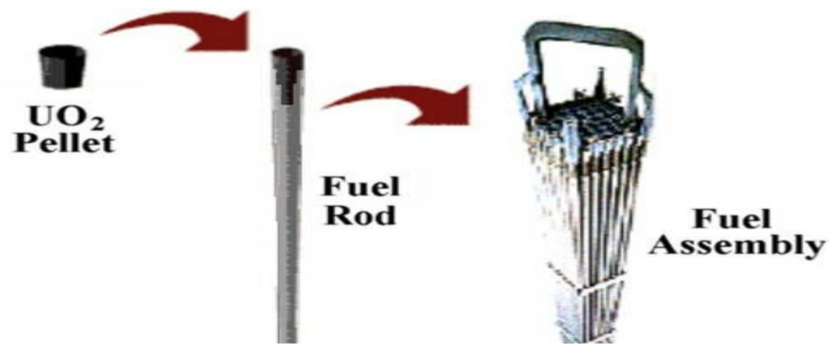
Solid Fuel Issues





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)

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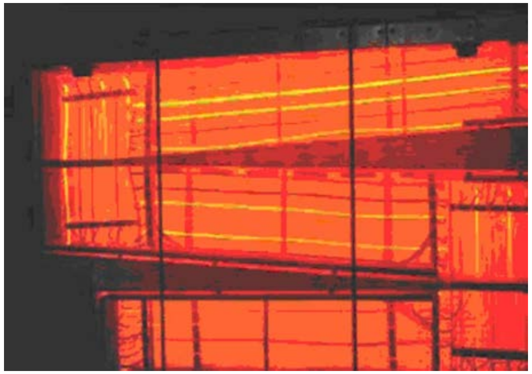
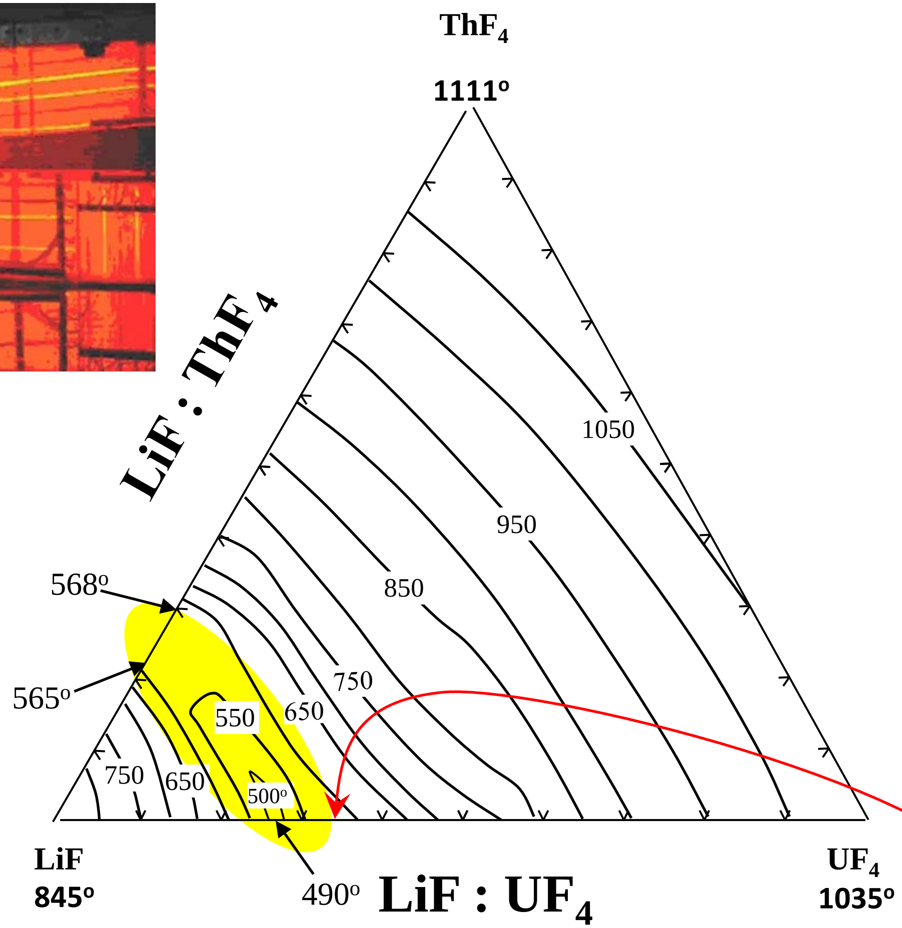
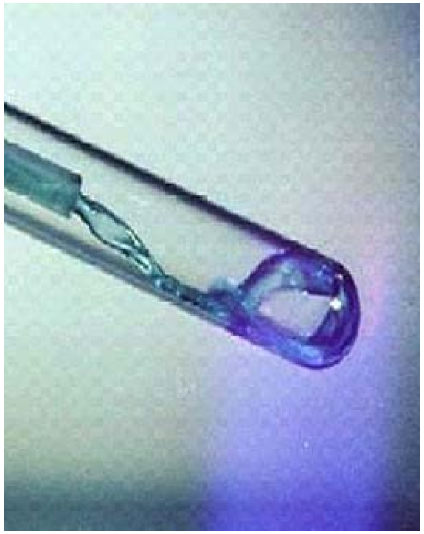
Molten Salt Eutectic Fuel



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

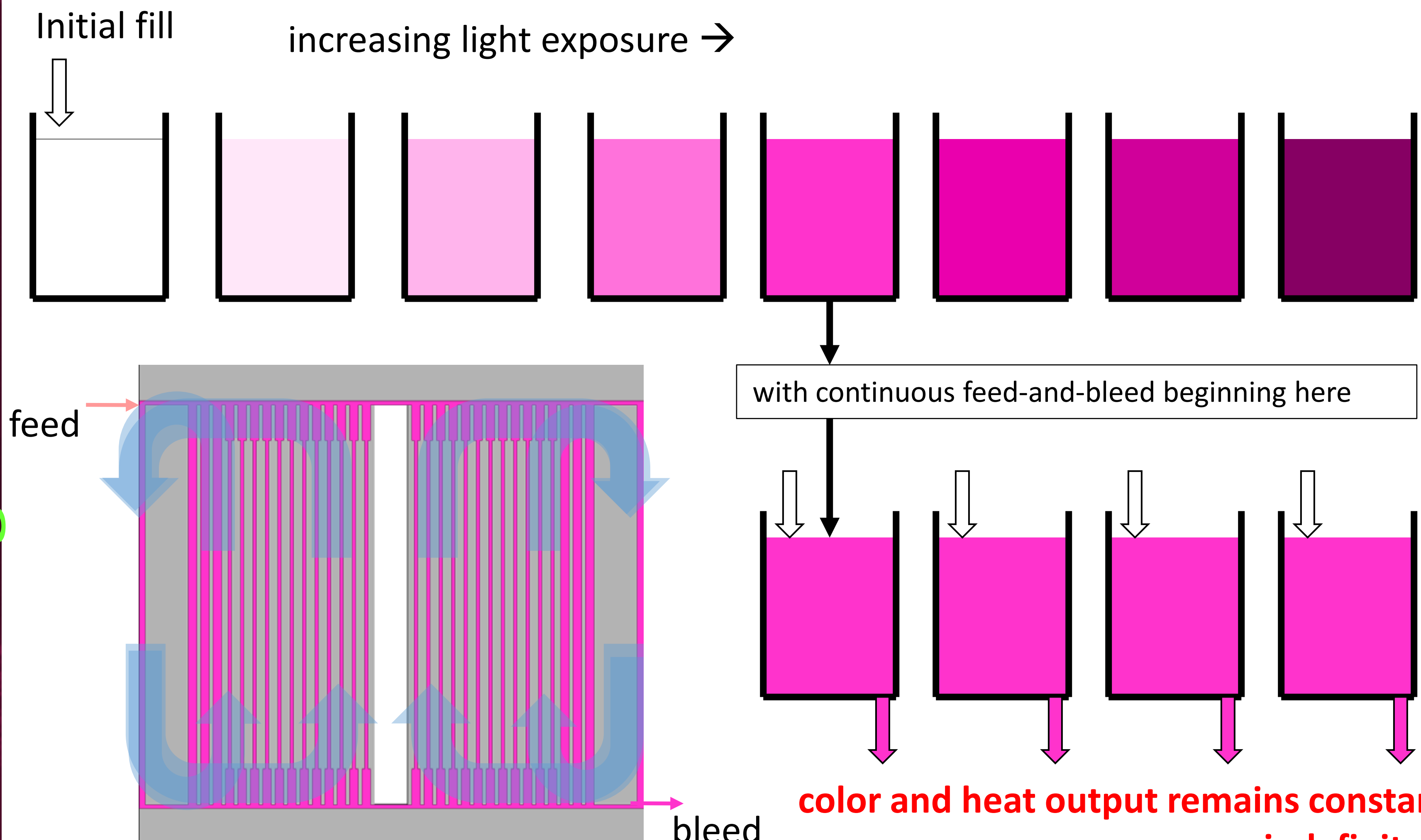
LiF : UF_4 set to 2:1

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



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

Critical Reactor

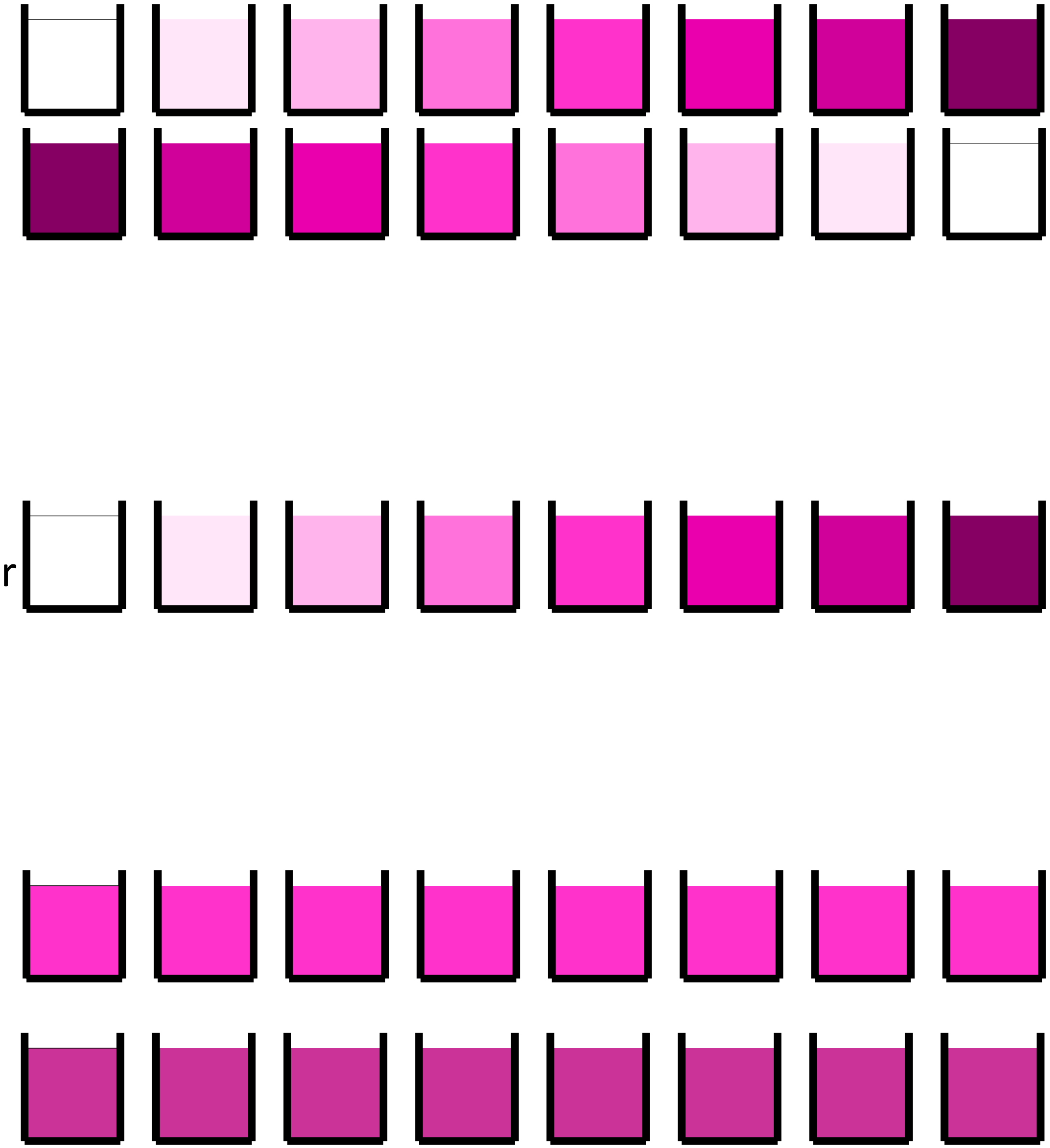
Fuel

+ 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)



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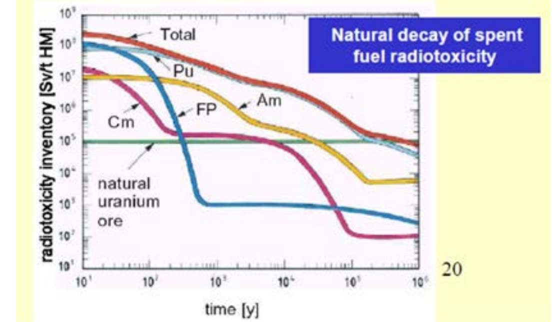
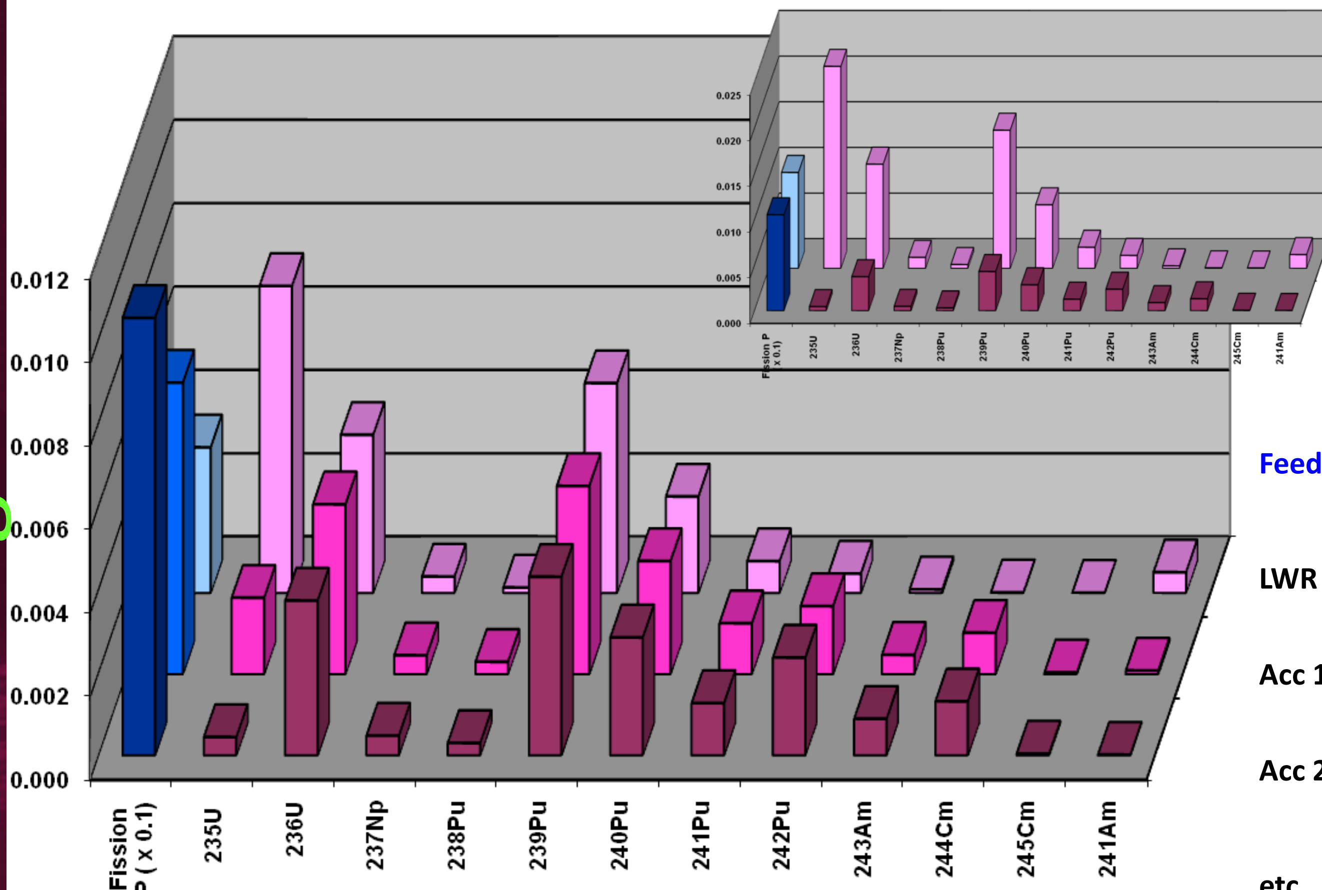
Note how the fission product goes up with each pass, ^{235}U continues to decline, Pu isotopes gets bred and burned, and Am and Cm are mixed.





Relative Waste after 2 passes

Feed material:

LWR spent fuel **20 GWy**

Acc 1 **40 GWy**

Acc 2 **60 GWy**

etc…

(calculated at a fluence to provide the displayed burn-up indicated by the extra fission products)

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

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Performance:

“Energy” multiplication:

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

Fission fraction:

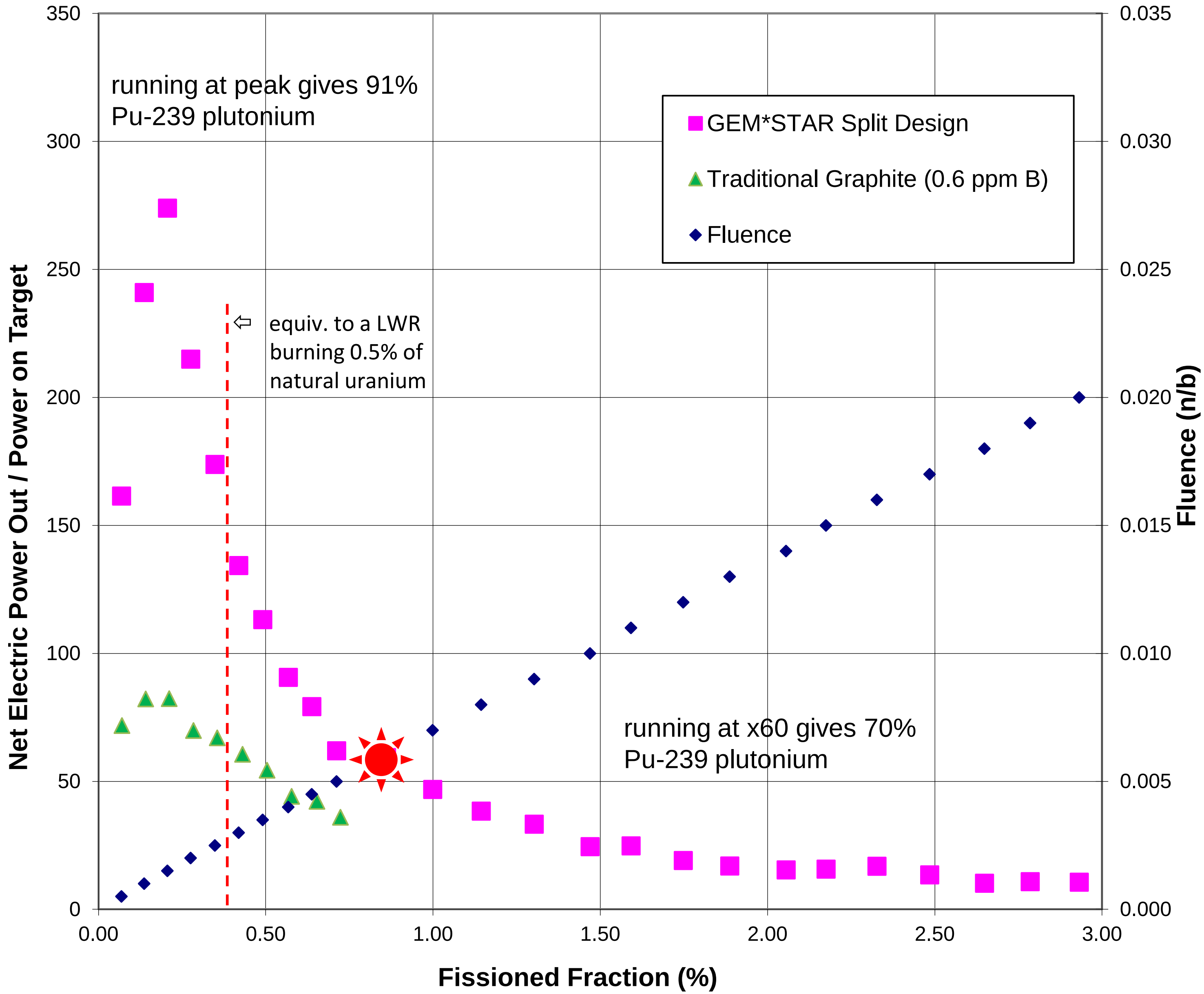
- what percentage of feed actinide was actually fissioned

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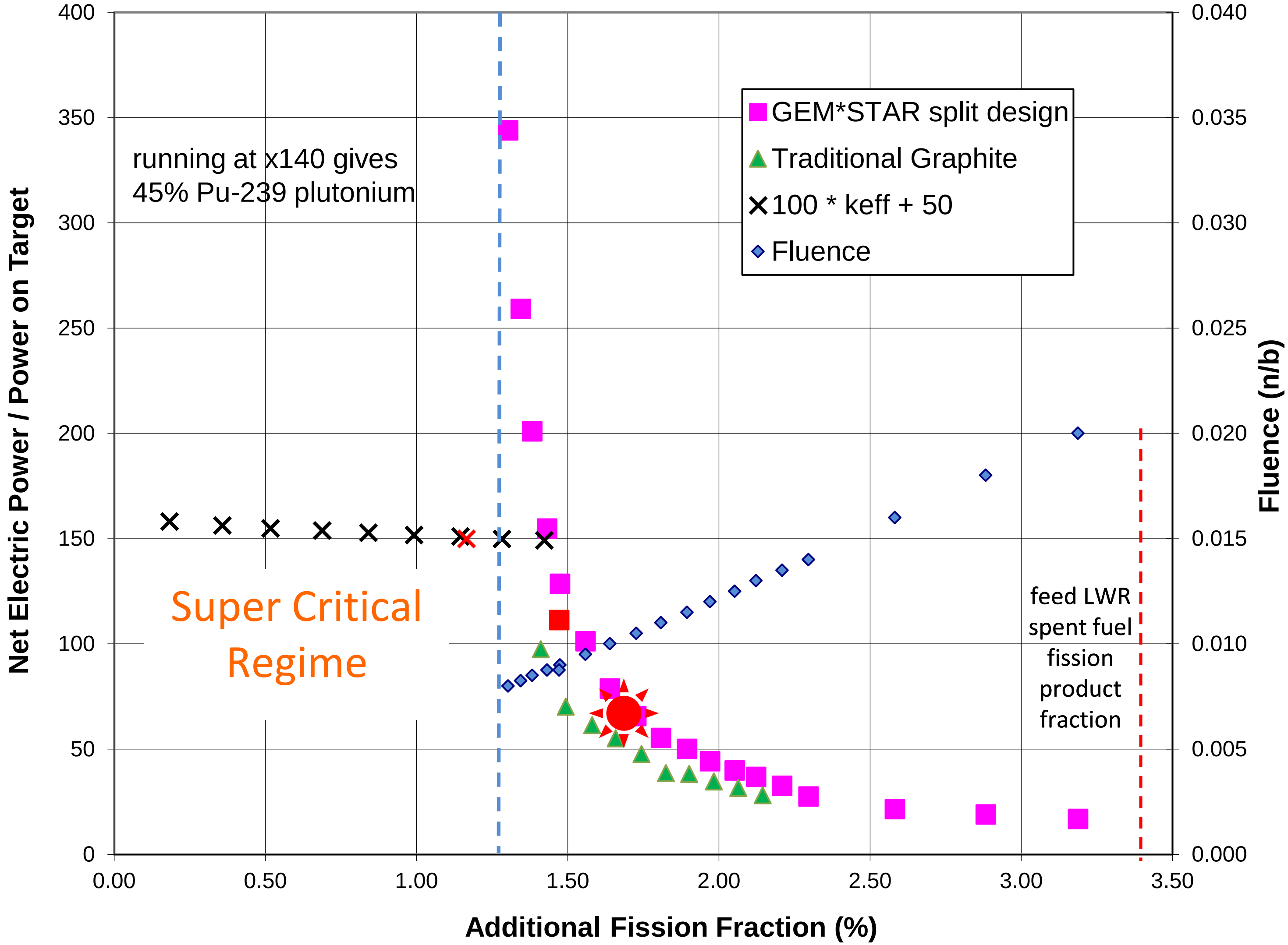
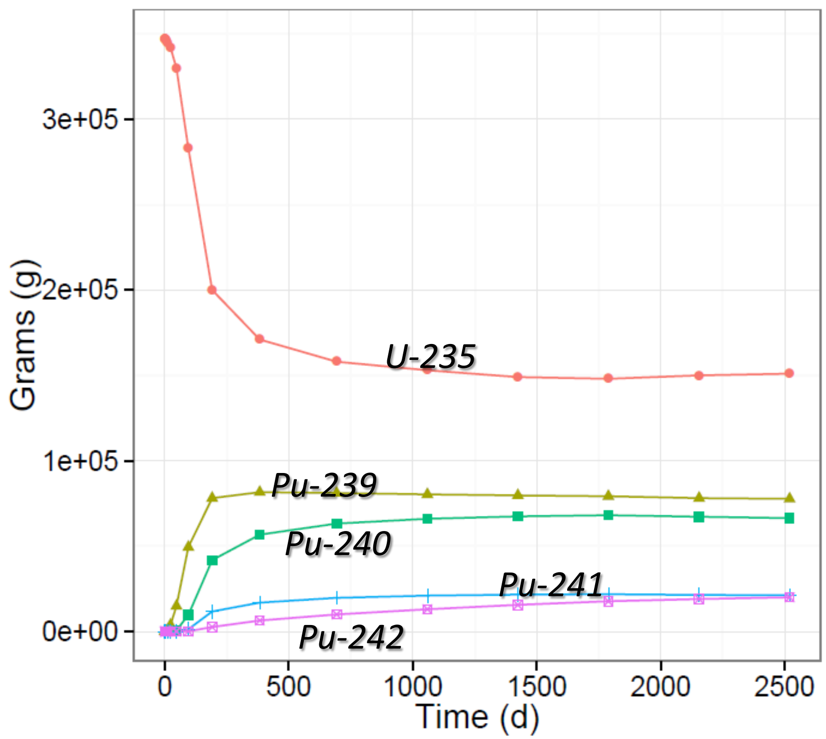
Fuel: un-reprocessed Light-Water-Reactor spent fuel



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.

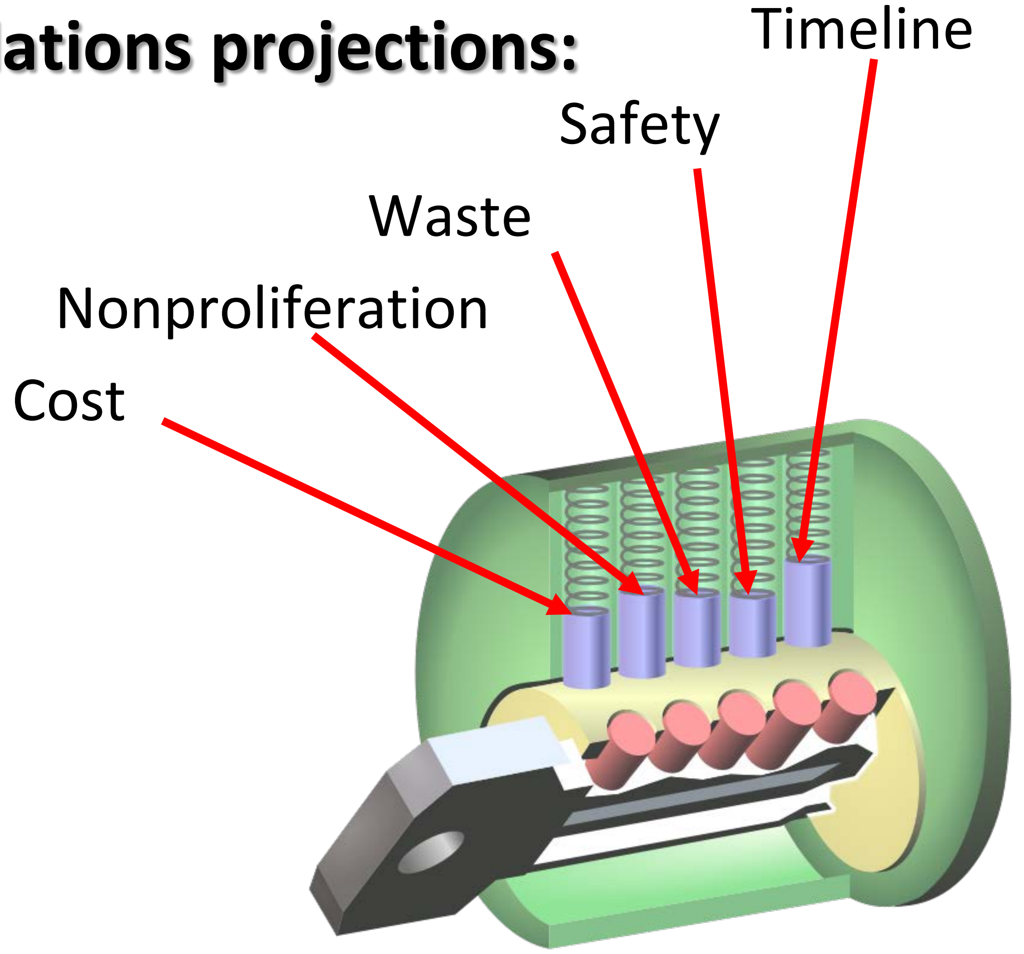
Haghighat et al. studied various approaches to equilibrium in 2015:

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.

GEM*STAR – A Transformative Player

- **Confident basic design can be made to work.**
  - **optimize design via full simulation and engineering**
  - **study operation and failure modes**
  - **confirm costing, performance, and commercial viability**
  - **study sub-systems as part of 'research stretch'**

- **Determine best path to demonstration and financial backing.**
  - **FUEL:** **Natural Uranium**
Weapons Grade Plutonium
Existing LWR spent fuel
  - **USE:** **Synthetic transport fuel**
Electricity
Tritium (for NNSA)
High-temp process heat

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Companies Pursuing Technique

Charles D. Bowman, Ph. D.
President ADNA Corporation
Accelerator-Driven Neutron Applications

Initial focus is on using natural uranium fuel and high-temperature molten-salt as the working fluid to produce synthetic transport fuel via the Fischer-Tropsch process.

Rolland P. Johnson, Ph. D.
President Mu*Star Inc.
www.muonsinc.com

Initial focus is on using SNF co-located at a nuclear plant to extract additional energy, then finally burn-down remaining actinides (after removing Uranium), and potentially have sufficiently reduced radiation remaining to allow local underground disposal – thus closing the fuel cycle.

major collaborative ARDP R&D proposal is under review

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The US is actually behind … global ADS research and development

Japan: ADS experiment Japan began in March 2009 at the Kyoto University Research Reactor Institute (KURRI), utilizing the Kyoto University Critical Assembly (KUCA). The experiment irradiates a high-energy proton beam (100 MeV) from the accelerator on to a heavy metal target set within the critical assembly, after which the neutrons produced by spallation are bombarded into a subcritical fuel core.

India: The Indian Atomic Energy Commission is designing a 200 MWe PHWR accelerator-driven system (ADS) fuelled by natural uranium and thorium. Ultimately there is a fully-thorium core with in situ breeding and burning of thorium. Achieves a high burnup of thorium – about 100 GWd/t. A 30 MW accelerator would be required to run it. India is also pursuing an electron neutron source for potential ADS applications.

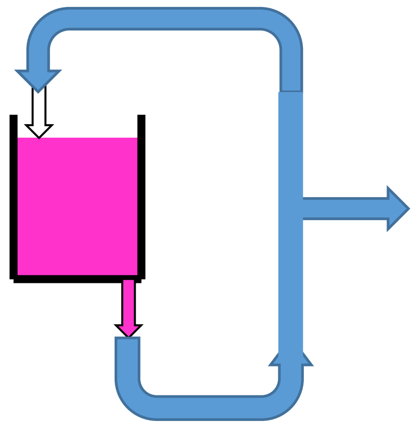
Belgium: The Belgian Nuclear Research Centre (SCK.CEN) is building MYRRHA (Multipurpose Hybrid Research Reactor for High-tech Applications) research reactor at Mol. It will be a 57 MWt ADS, consisting of a proton accelerator delivering a 600 MeV, 2.5 mA (or 350 MeV, 5 mA) proton beam to a liquid lead-bismuth (Pb-Bi) spallation target that in turn couples to a Pb-Bi cooled, subcritical fast nuclear core.

Sweden: The Swedish are constructing the European Spallation Source (ESS) facility in Lund. The research facility will feature the world's most powerful neutron source. The ESS will be used for material research and life sciences. The facility set to be fully operational by 2025.

China: In March 2016 a strategic cooperation agreement to develop accelerator-driven advanced nuclear energy systems was signed between China General Nuclear (CGN) and the Chinese Academy of Sciences (CAS). It will include a 2 MWe accelerator-driven sub-critical liquid fuel prototype designed to demonstrate the thorium cycle as well as its Venus II ADS for transforming long-lived radioactive waste into short-lived waste.

What it might finally take…

The best of both:



- this would be a single loading, run for life
- no enrichment, no separation of U from Pu possible within design
- G*S shows it can run with only 1 liter/hour filtering
- accelerator allows one to not maintain ‘criticality’ during loop

Former U.S. President's Vision

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

Virginia Tech Programmatic Interest to date:

College of Science (COS)

- Physics .... Mark Pitt (Chair), Patrick Huber, Bruce Vogelaar
- Chemistry .... James Tanko (Chair), Joe Merola
- Geosciences .... Bob Bodnar (UDP)

College of Engineering (COE)

- Nuclear Engineering .... Ali Haghighat (NE&NSEL Director), Jinsuo Zhang
- Mechanical Engineering .... Azim Eskandarian (Head)
- Chemical Engineering .... David Cox (Head)
- Materials Science and Engineering .... David Clark (Head), Bob Hendricks
- Civil and Environmental Engineering .... John Little

College of Natural Resources and Environment

- Sustainable Biomaterials .... Bob Smith (Head)

College of Liberal Arts and Human Science (COLAHS)

- Public & International Affairs .... Anne Khademian (Director)

also: ICTAS Energy and Materials Initiative (EMI):

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

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links from http://www.phys.vt.edu/~vogelaar

1st ADS Workshop '10 (VT)
2nd ADS Workshop '11
3rd ADS Workshop '14
4th ADS Workshop '16
5th ADS Workshop ‘19

R. Bruce Vogelaar
vogelaar@vt.edu
cell: (540) 239-5963

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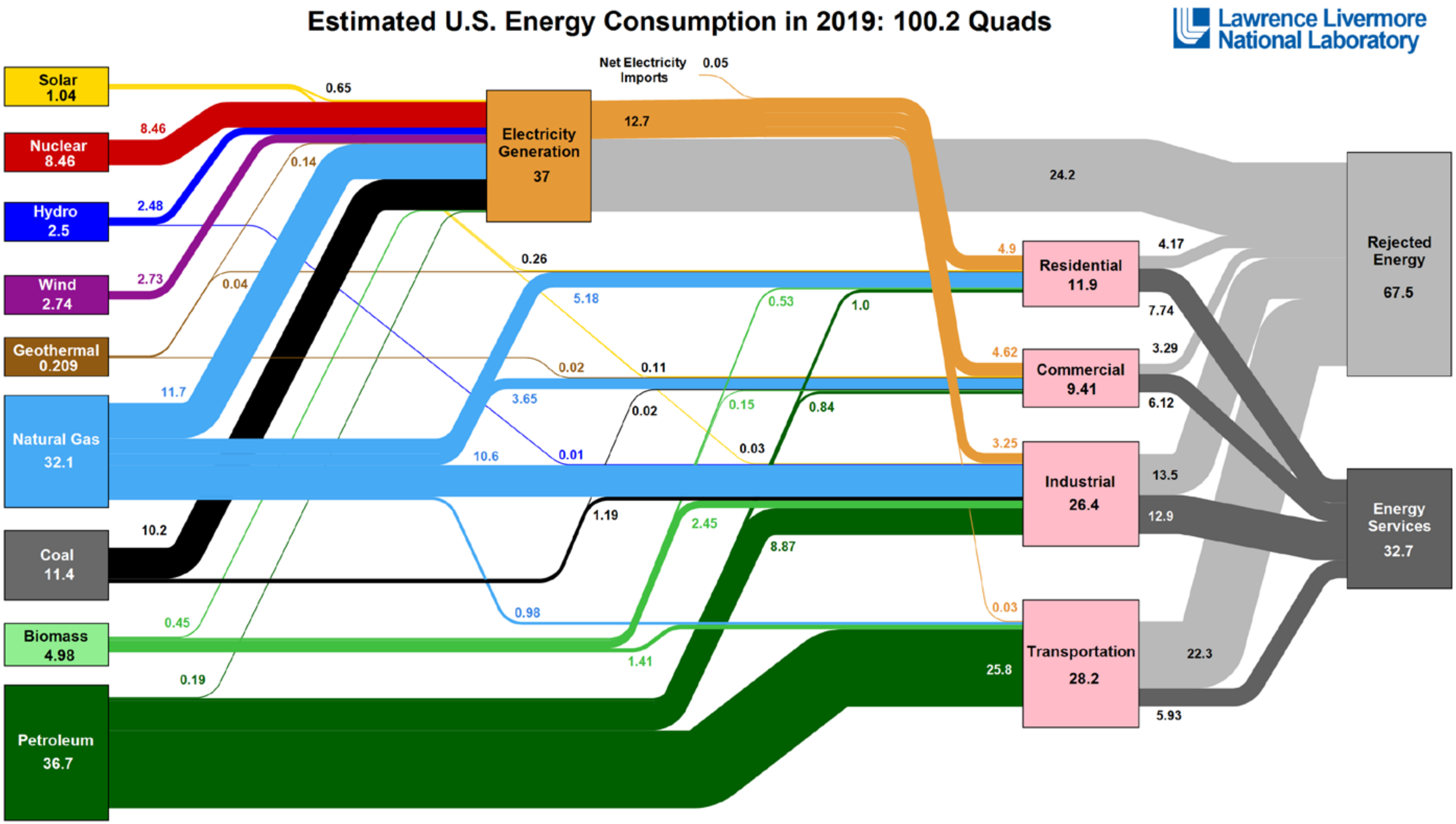
Estimated U.S. Energy Consumption in 2019: 100.2 Quads



Source: LLNL March, 2020. Data is based on DOE/EIA MER (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

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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%

Clear national and global need to break ties between:

Nuclear Energy

⇔ Nuclear Weapon Proliferation (Enrichment/Reprocessing)
⇔ Long-lived Waste (used nuclear fuel)
⇔ Radiation Release and Safety Concerns
⇔ High Investment Cost

Ties to break!

domestic note: US commercial reactor fleet also urgently needs alternatives, as reactors face end-of-life…

…in about 15 years with 60-year operation (35 years with 80-year operation)

Has this been tried?

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

which showed cost break-even performance on *waste*

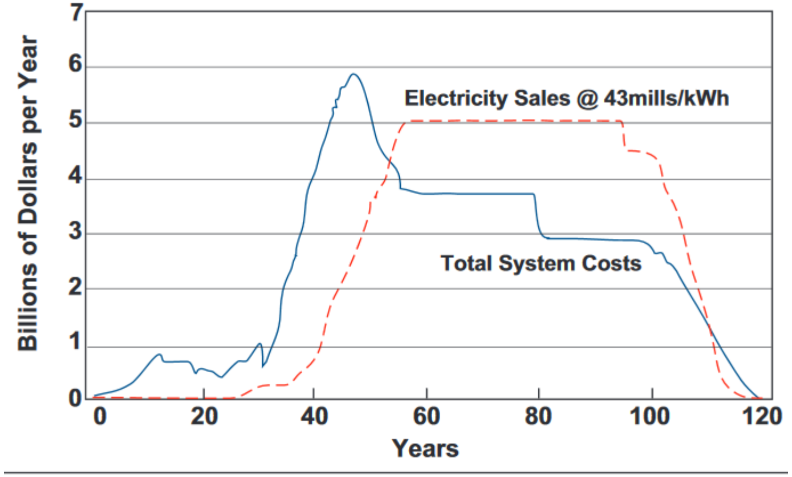

Figure 7.2. Annual Undiscounted (1999 Dollars),
Total System Costs and Electricity Credit as a Function of Time

cited concerns

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

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

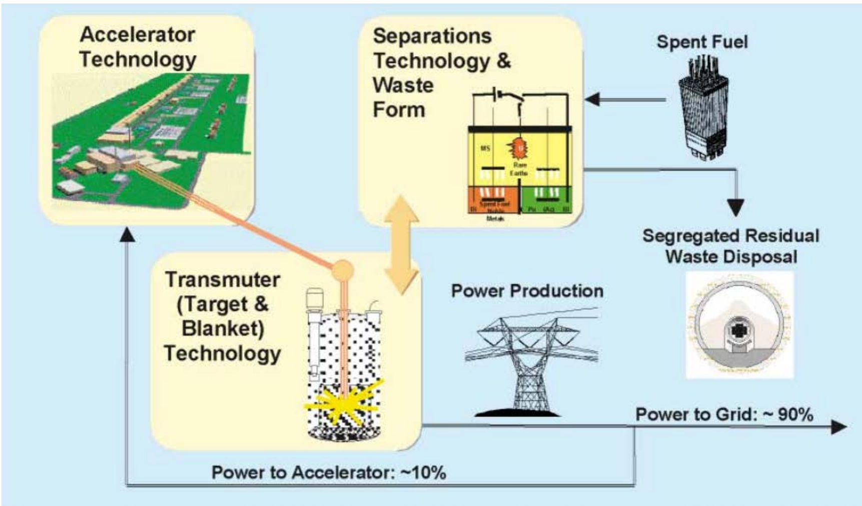

Figure E.1. Components of an ATW System

break even performance on *waste*

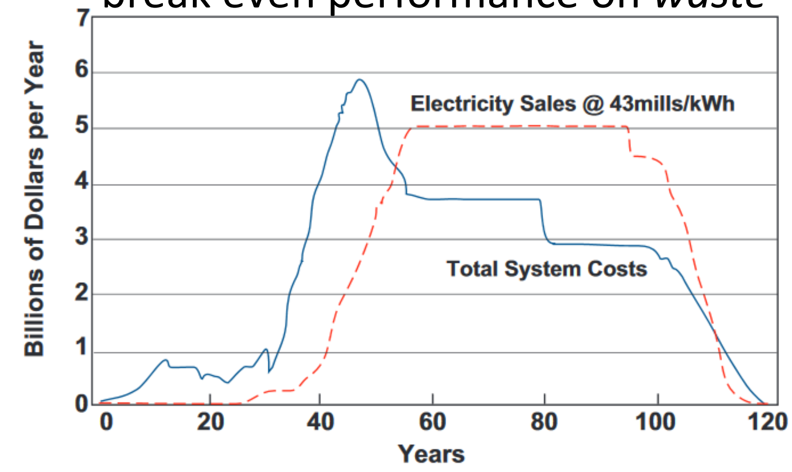

Figure 7.2. Annual Undiscounted (1999 Dollars), Total System Costs and Electricity Credit as a Function of Time

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...

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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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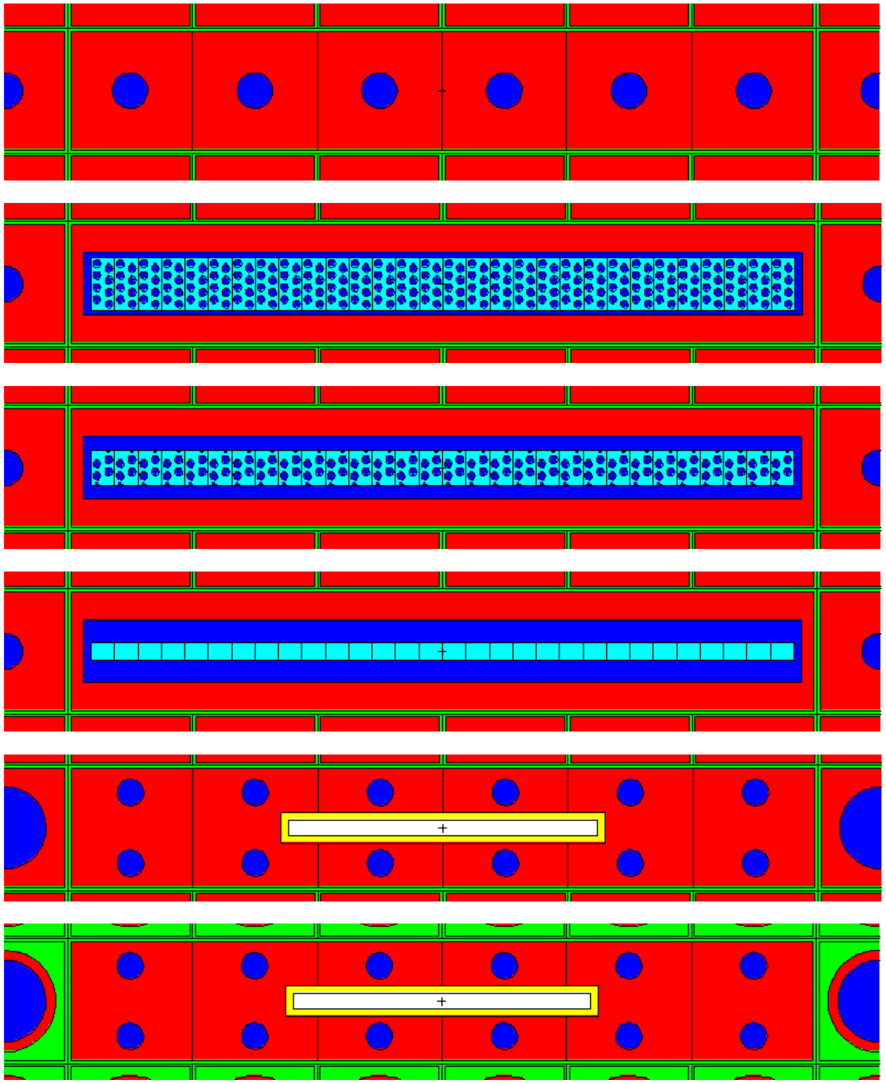
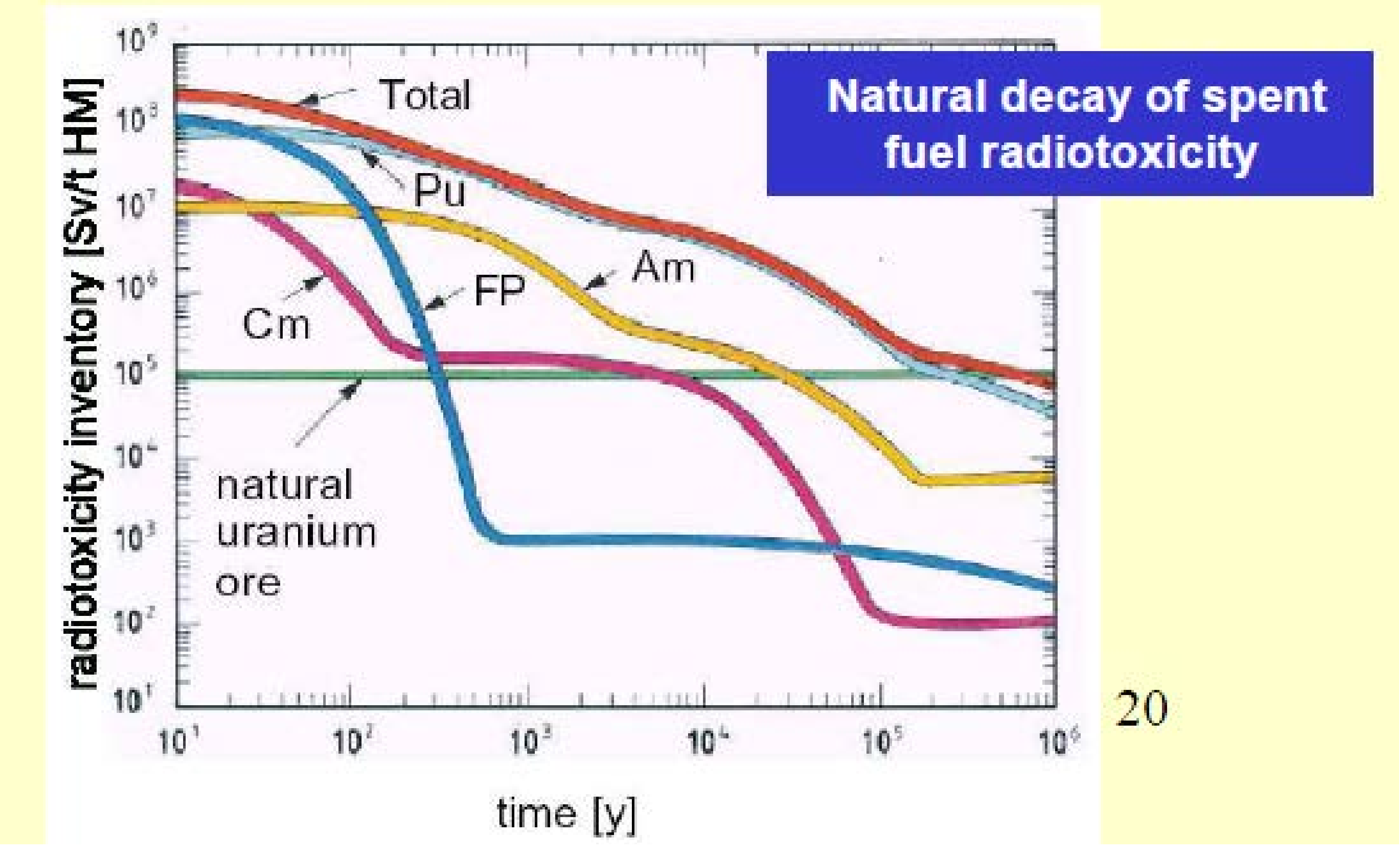
GEM*STAR
Core Design Features



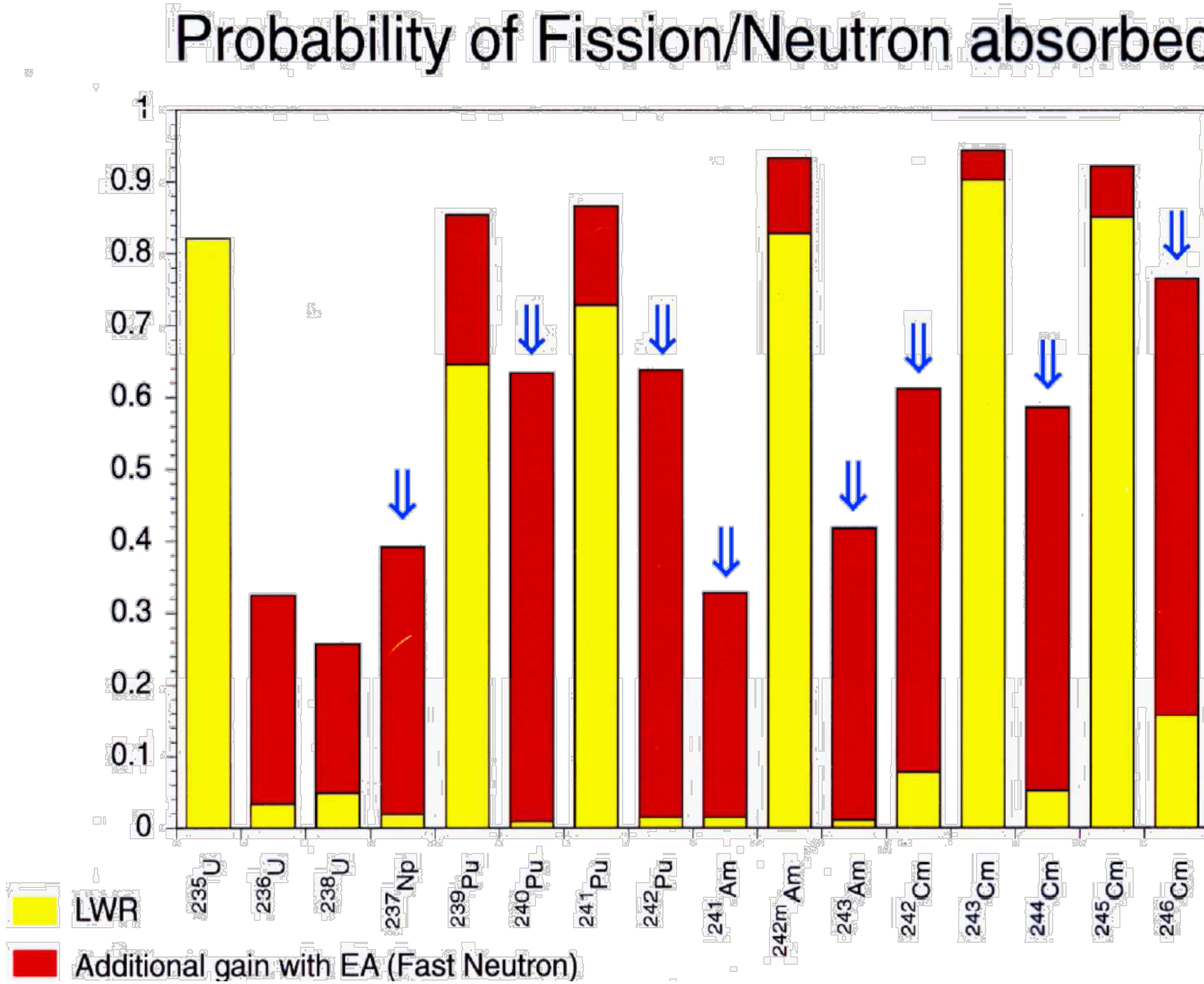
- extractable target region
- individual graphite square tubes separated by He blankets
- no 'reflector' around core
- under-core fuel storage

graphite
MS eutectic
Helium
Uranium
Beryllium

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



Thermal versus fast-spectrum reactors.



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

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

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*

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

$0 = F(v/V) - N_1\phi\,\sigma_{a1} - N_1(v/V)$ 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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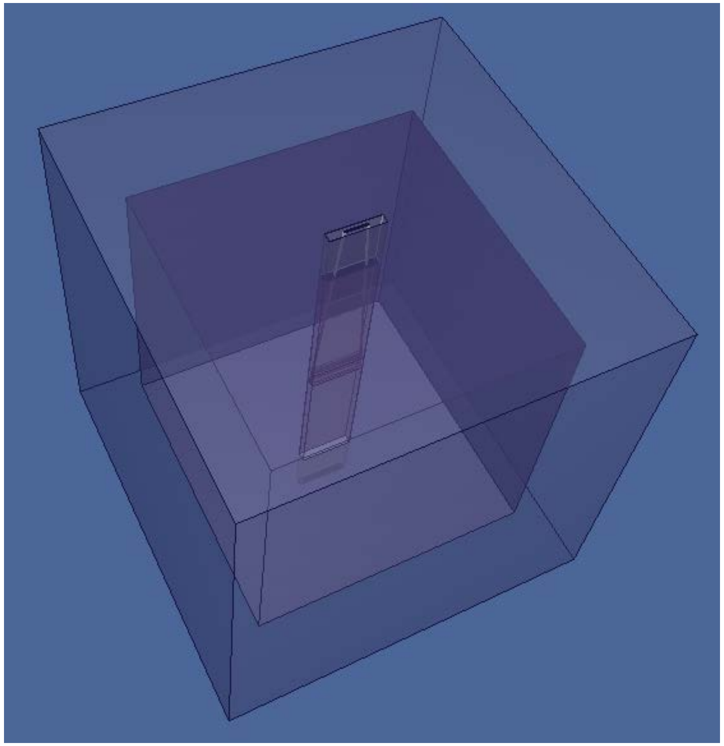
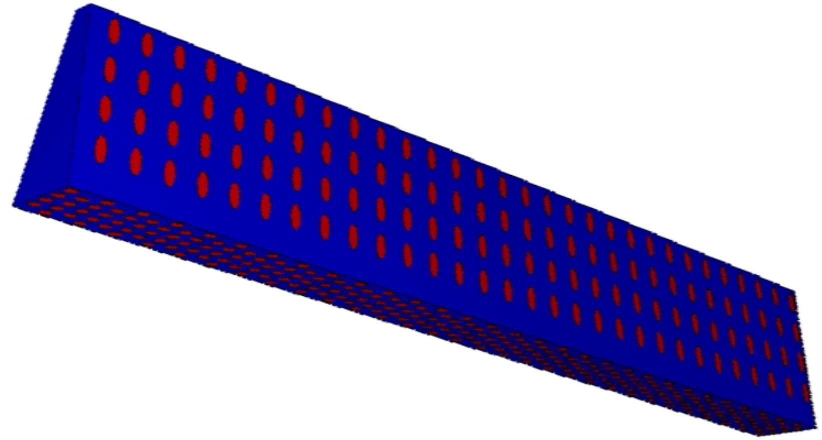
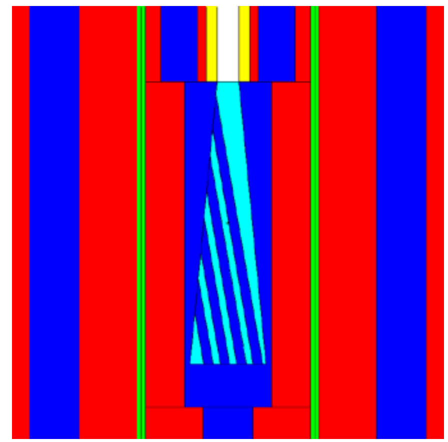
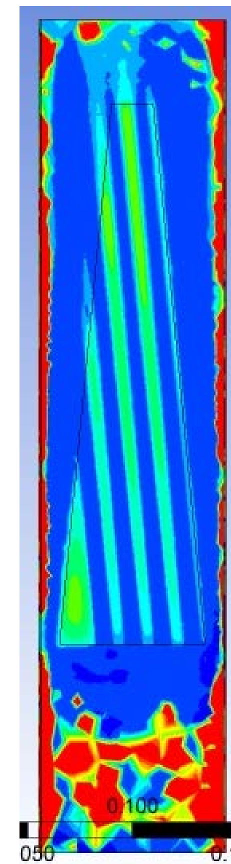
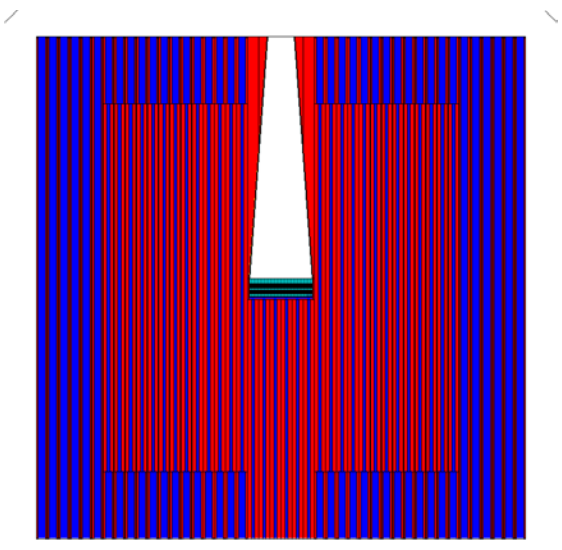










Core and Target Models for MCNPX & FLUENT Calculations

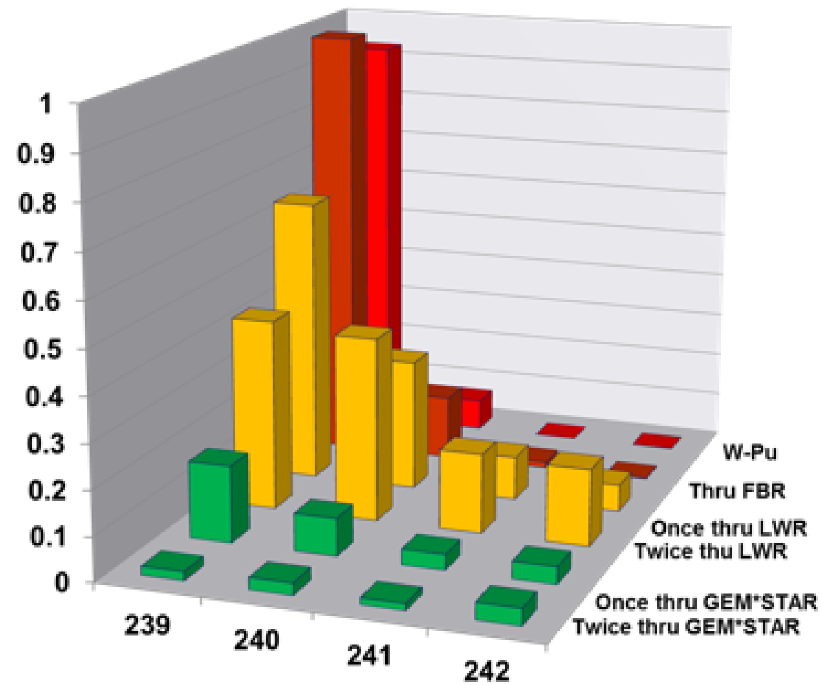
Advantages Over Direct Burial and MOX burning in LWRs

- ✓ **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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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”

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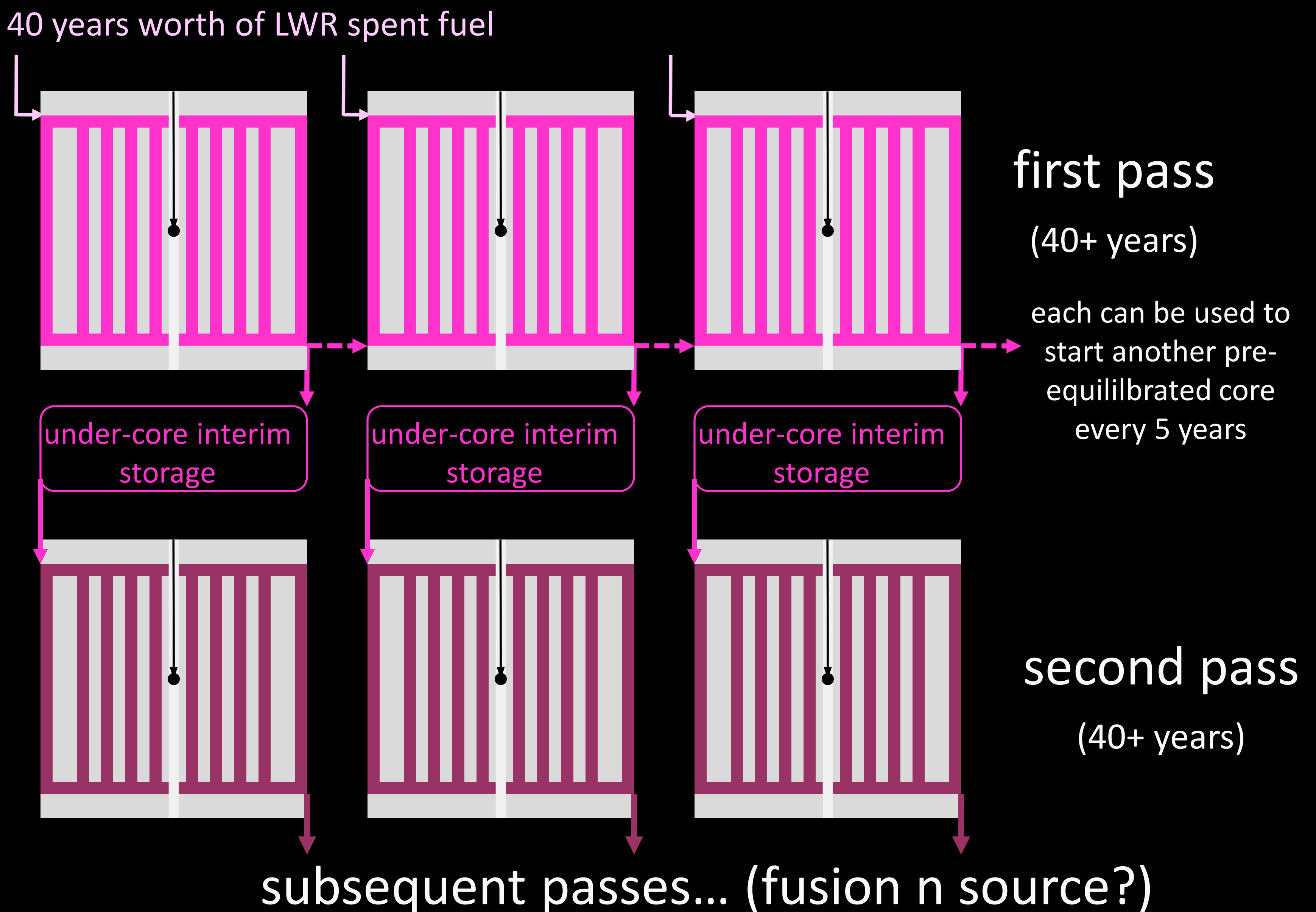
Deployed Civilian Reactor Types

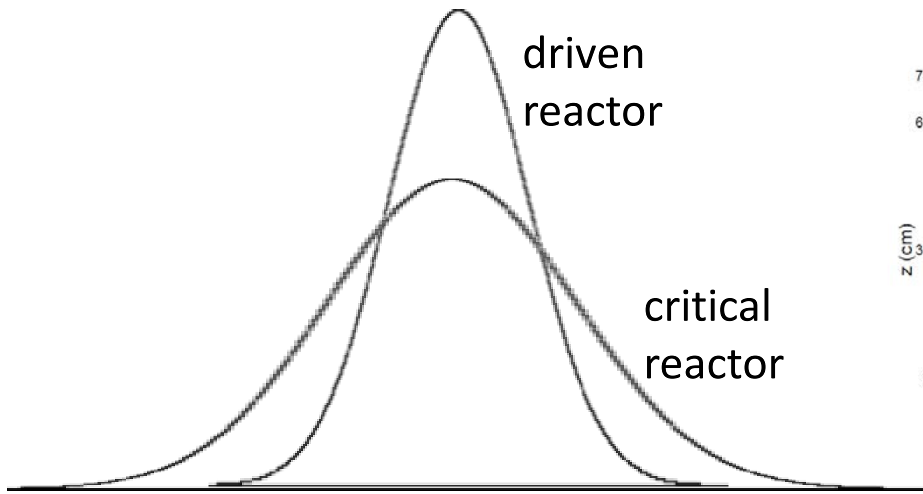
Reactor Type	Main Countries	GWe	Fuel	Coolant	Moderator
Light Water Reactors	US, France, Japan, Russia	337	enriched UO_2	water	water
Heavy Water Reactors	Canada	43	natural UO_2	heavy water	heavy water
Gas-cooled Reactors	UK	18	natural U (metal), enriched UO_2	CO_2	graphite
Light Water/ Graphite Reactors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

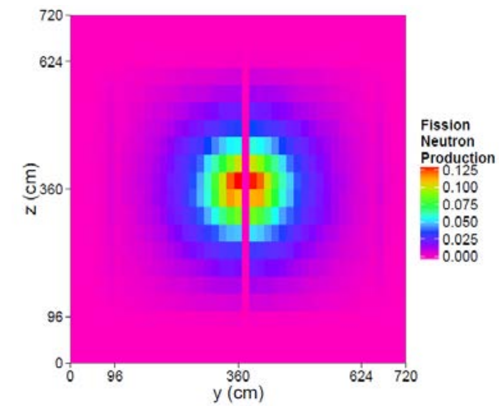
82% are LWRs

Recycling


40 years worth of LWR spent fuel
under-core interim storage
under-core interim storage
under-core interim storage
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?)

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)

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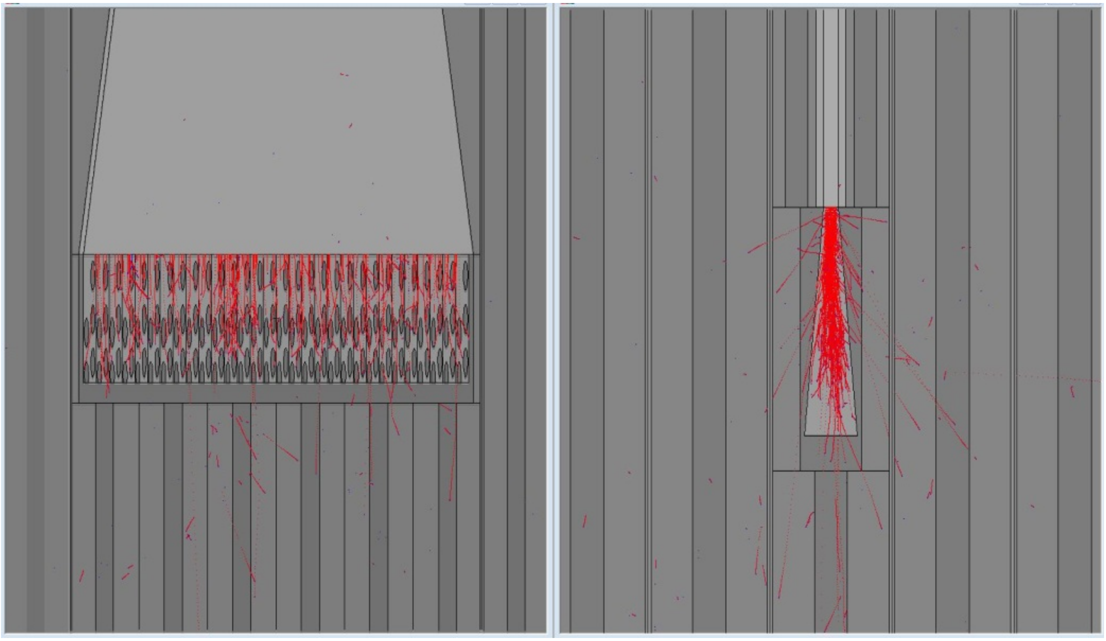
Target Considerations



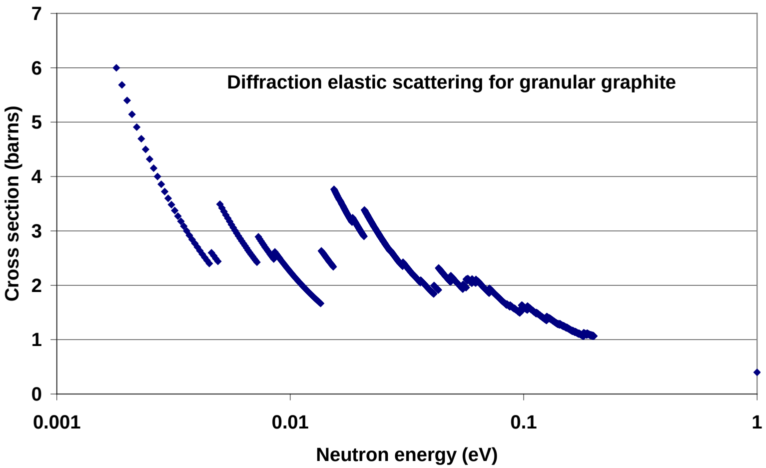
GEM*STAR Internal Target

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

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

new graphite results

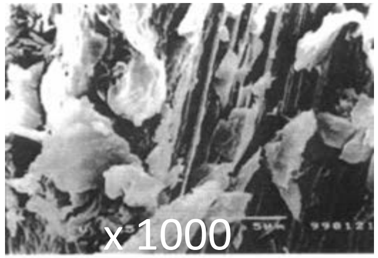
Diffusion/Absorption @ Duke

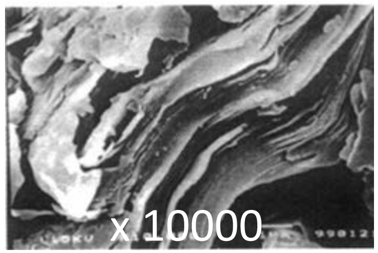


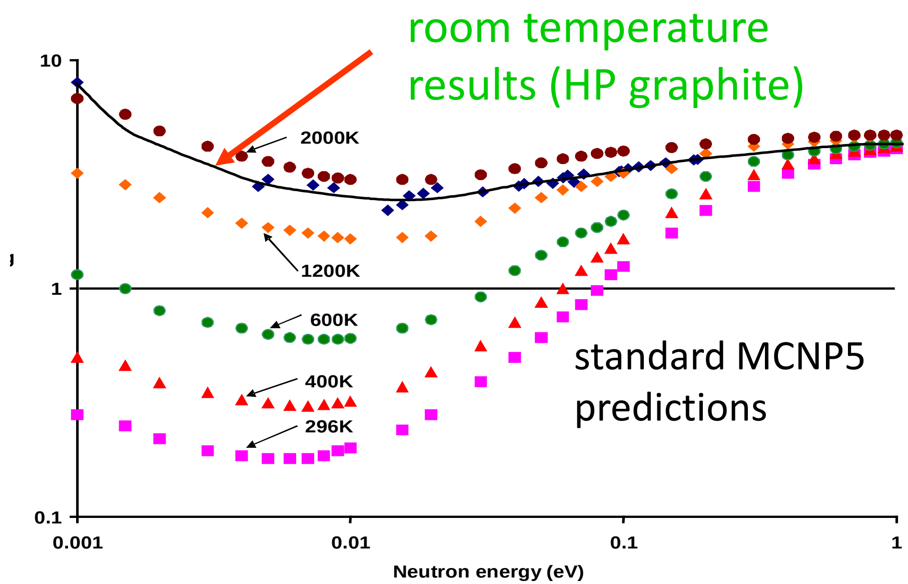
Diffraction @ LANL

“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)

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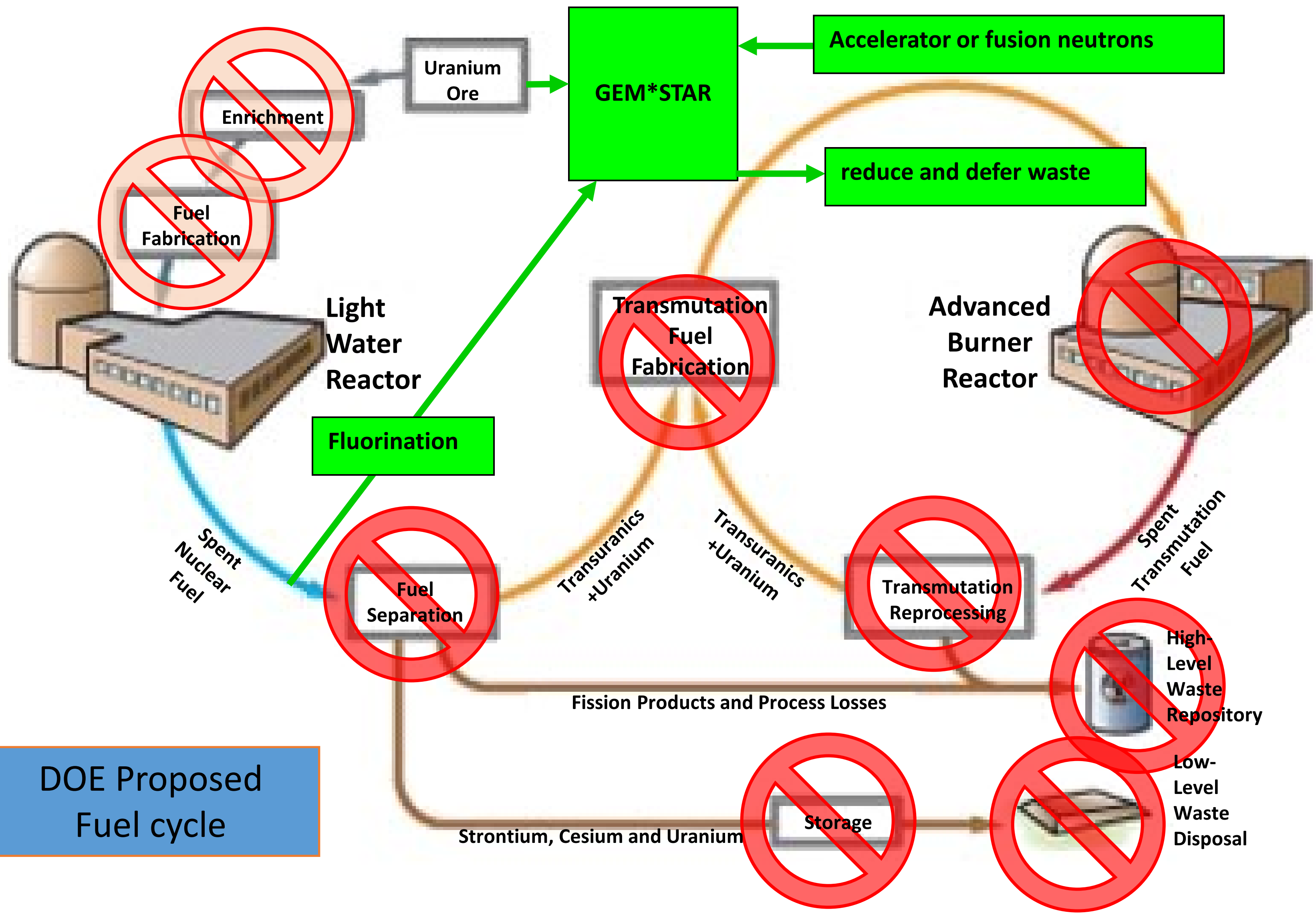

DOE Proposed Fuel cycle

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.

Invent the Future

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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