GEM*STAR

GEM*STAR

Green Energy-Multiplier

Subcritical-technology
Thermal-spectrum
Accelerator-driven
Recycling-reactor

(my version of acronym)

Transforming the Nuclear Landscape

Bruce Vogelaar (Virginia Tech)

September 27, 2010

ADNA and Virginia GEM*STAR Consortium

The Urgency

Population Growth:

2020 → 8 billion
2100 → 10-12 billion

Energy Availability – vs – poverty:

Sweden – 15,000 kWh_e/(person-yr)
Tanzania – 100 kWh_e / (person-yr)
½ live in poverty; 1/5th under nourished

Energy Source:

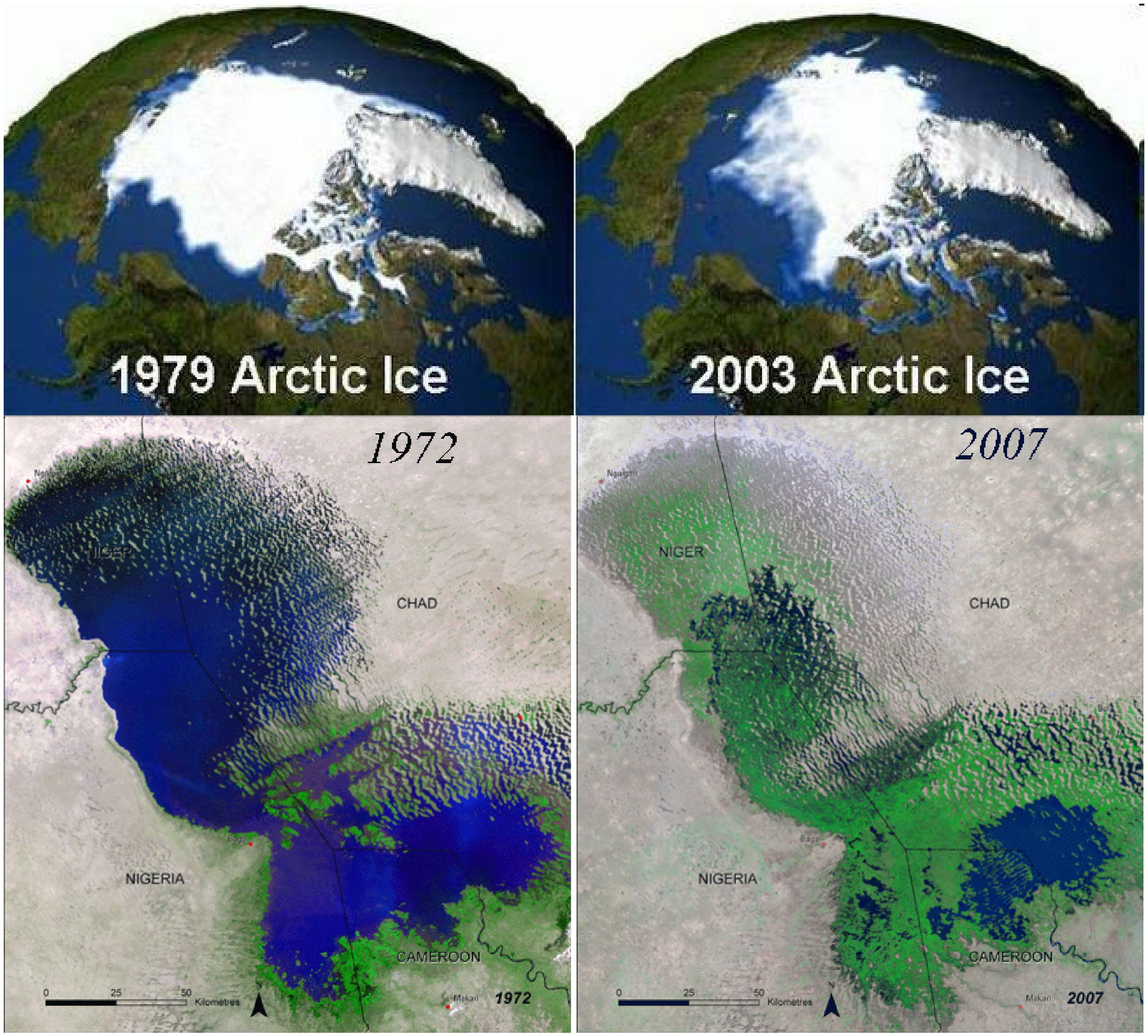
1.6 billion – no electricity
2.4 billion – traditional biomass

Advanced Society Energy Consumption:

0.9 GJ / day / person
10.4 kW /person
32 kg coal / day / person
100 kg CO_2 / day / person

GEM*STAR

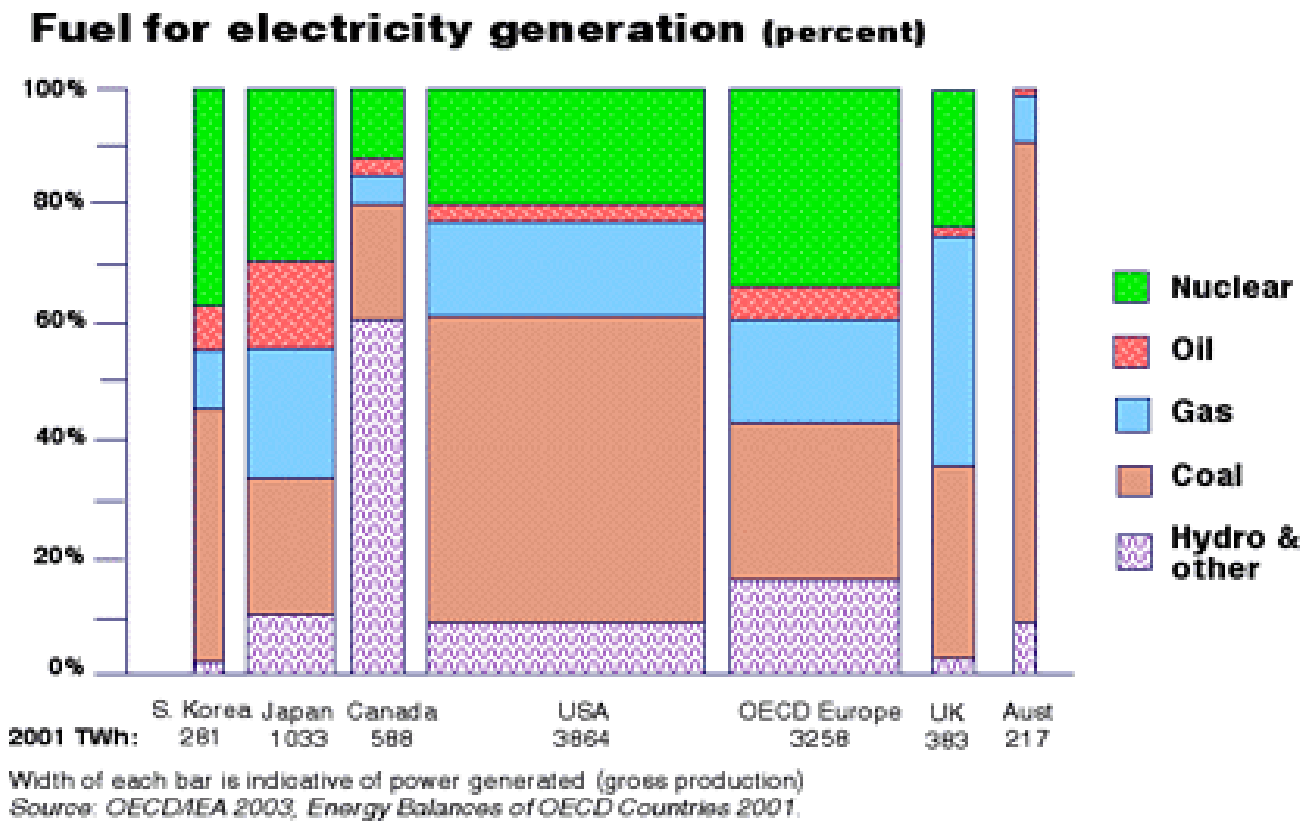
Global Warming is happening *now*



GEM STAR

These are shared challenges – either directly or indirectly

nuclear energy already accounts for 17% of global electricity production



GEM★STAR

GEM STAR

Nuclear Issues Are (and will remain) Unavoidable

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

… At least half a dozen countries are specifically planning to conduct enrichment or reprocessing of nuclear fuel…"

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

Classic Associations with Nuclear Energy

- no CO_2
- low-cost electricity (current fleet)
- engineered safety
- IAEA oversight

- weapons
  - enrichment
  - reprocessing
- waste
- costly political ramifications
- truly catastrophic failure scenarios
- NIMBY

Incremental improvements will not break all these associations
– be they real or imagined, each is a proven show stopper

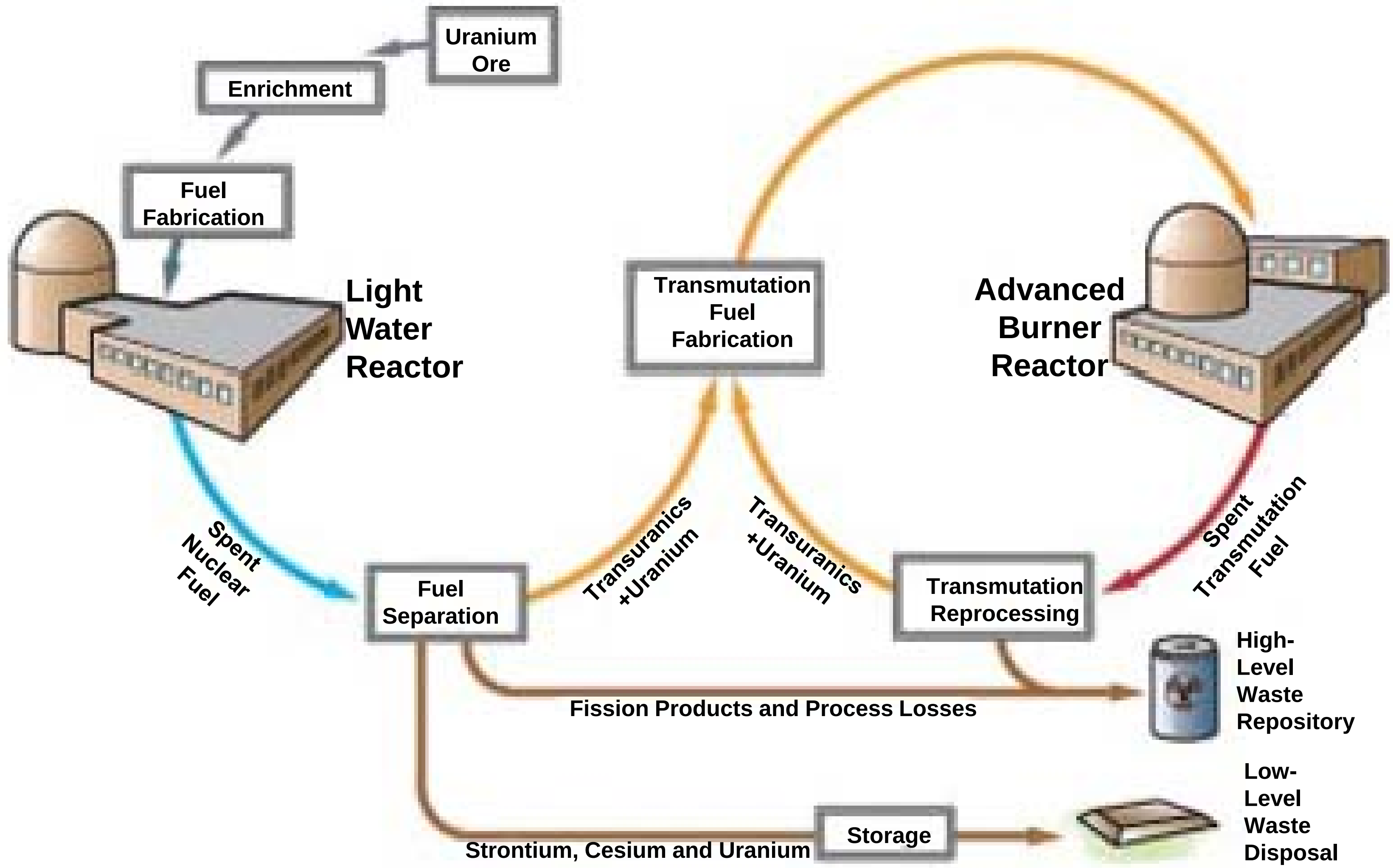
GEM*STAR

GEM STAR

Invent the Future

Invent Solutions to the Realities of Today

Can **accelerators** really make the difference?



NOT if incremental, or pursued in an unmotivated context.

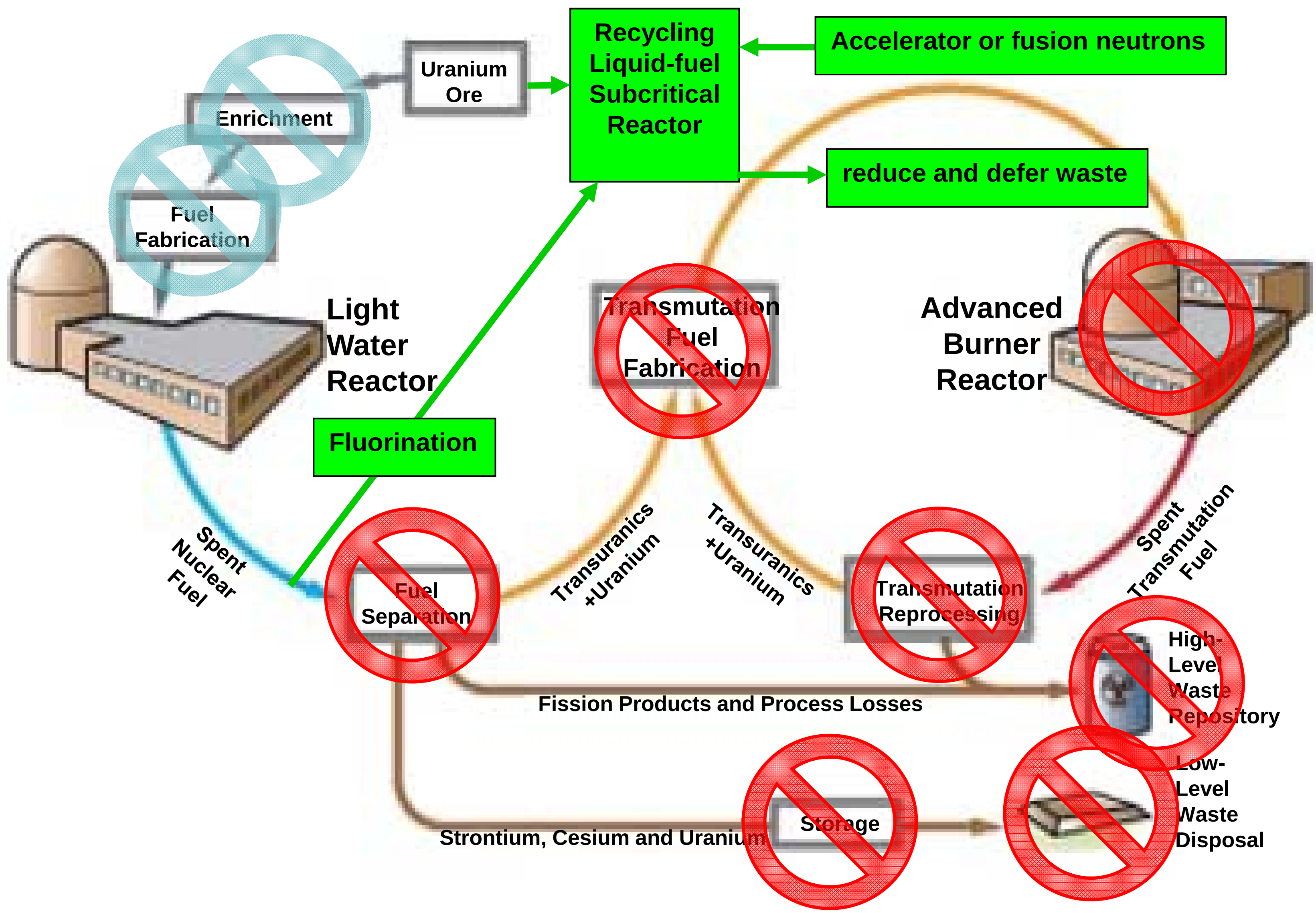
GEM*STAR

ADNA: “re-frame the question”

“What would an optimized accelerator-based nuclear-energy program look like?”

GEM*STAR

graphically…

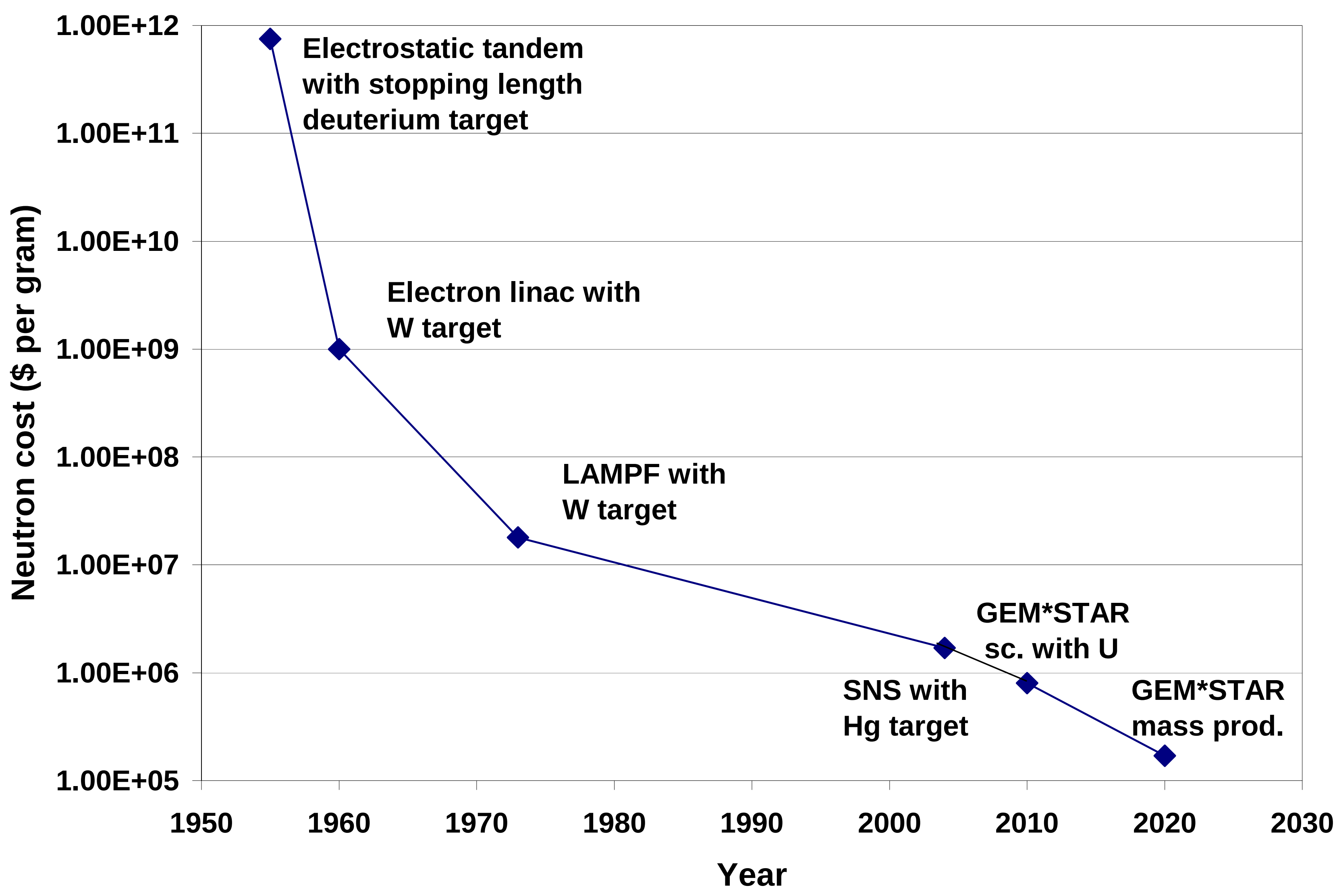


GEM★STAR

GEM✵STAR

the advances and understanding which make this possible *now*…

…despite the real challenges of currently being ‘outside’ traditional programs



Neutron cost ($ per gram)
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1950
1960
1970
1980
1990
2000
2010
2020
2030
Year
Electrostatic tandem with stopping length deuterium target
Electron linac with W target
LAMPF with W target
GEM*STAR sc. with U
SNS with Hg target
GEM*STAR mass prod.

GEM*STAR

Accelerators

Study of a 10-MW Continuous Spallation Neutron Source (BNL, 2003)

Comparison of Super-Conducting Linacs and operation power costs.

	SNS	AGS	ACNS
Kinetic Energy, GeV	1.0	1.2	1.25
Ave. Power, MW	1.0	0.045	10
Duty Factor, %	6.0	0.18	**100**
Repetition Rate, Hz	60	2.5	--
Pulse Length, ms	1.0	0.72	--
Peak Power, MW	16.7	25	10
Ion Source Current, mA	35	35	**10**
Ave. Beam Current, mA	1.0	0.035	**8**
Peak Beam Current, mA	26	21	**8**
Protons / Bunch, x 10^8	4.3	8.7	**1.43**
RF, GHz	0.805	0.805-1,61	0.7 - 1,4
Coupler RF Power, MW	170-350	260 - 400	**80 - 155**
Length, m	158	120	163
Inj. Energy, MeV	185.6	200	200
Cryo. Power (2.1°K), kW	0.5	0.15	**5.3**
Ave. AC Power, MW	3.1	0.28	**23**
Ave. Gradient, MV/m	3.1 - 6.5	5.3-10.0	3.3 - 8.7
Efficiency, %	26 -30	9 - 16	**35 - 40**
Capital Cost, M$	110	97	**85**
Operation Cost, M$ / yr	2.0	0.18	**15.2**

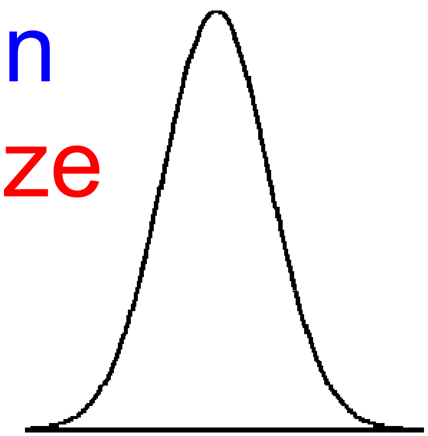
ADS Technology Readiness Assessment

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

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

Solid Fuel Issues

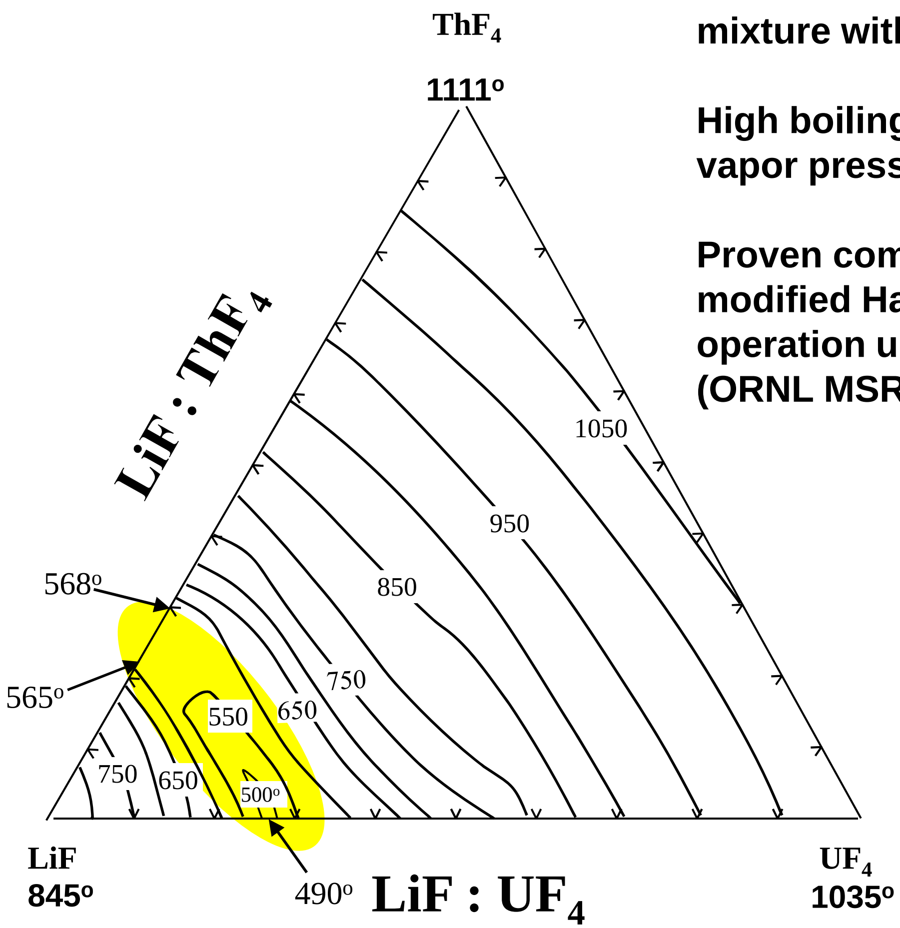
- non-uniform fuel consumption
  - fuel repositioning to optimize burn-up fraction
- fission-product build-up
  - significant inventory of radioactive gasses
- difficult and expensive process to ‘qualify’ new fuels



typical fission distribution for driven systems

GEM*STAR

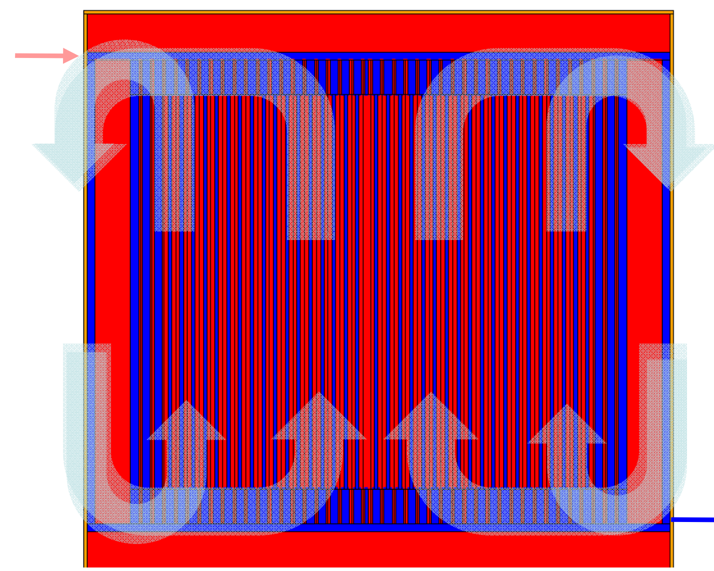
Molten Salt Eutectic Fuel



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

High boiling point → low vapor pressure

Proven compatible with modified Hastelloy-N for operation up to 750C. (ORNL MSRE)



GEM*STAR

Liquid fuel enables operation with constant and uniform isotope fractions

including fission products

consider isotope N_1 present in molten-salt feed:

feed *absorption* *overflow*

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

define neutron fluence: $\mathcal{F} = \phi(V/v)$; then in equilibrium

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

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

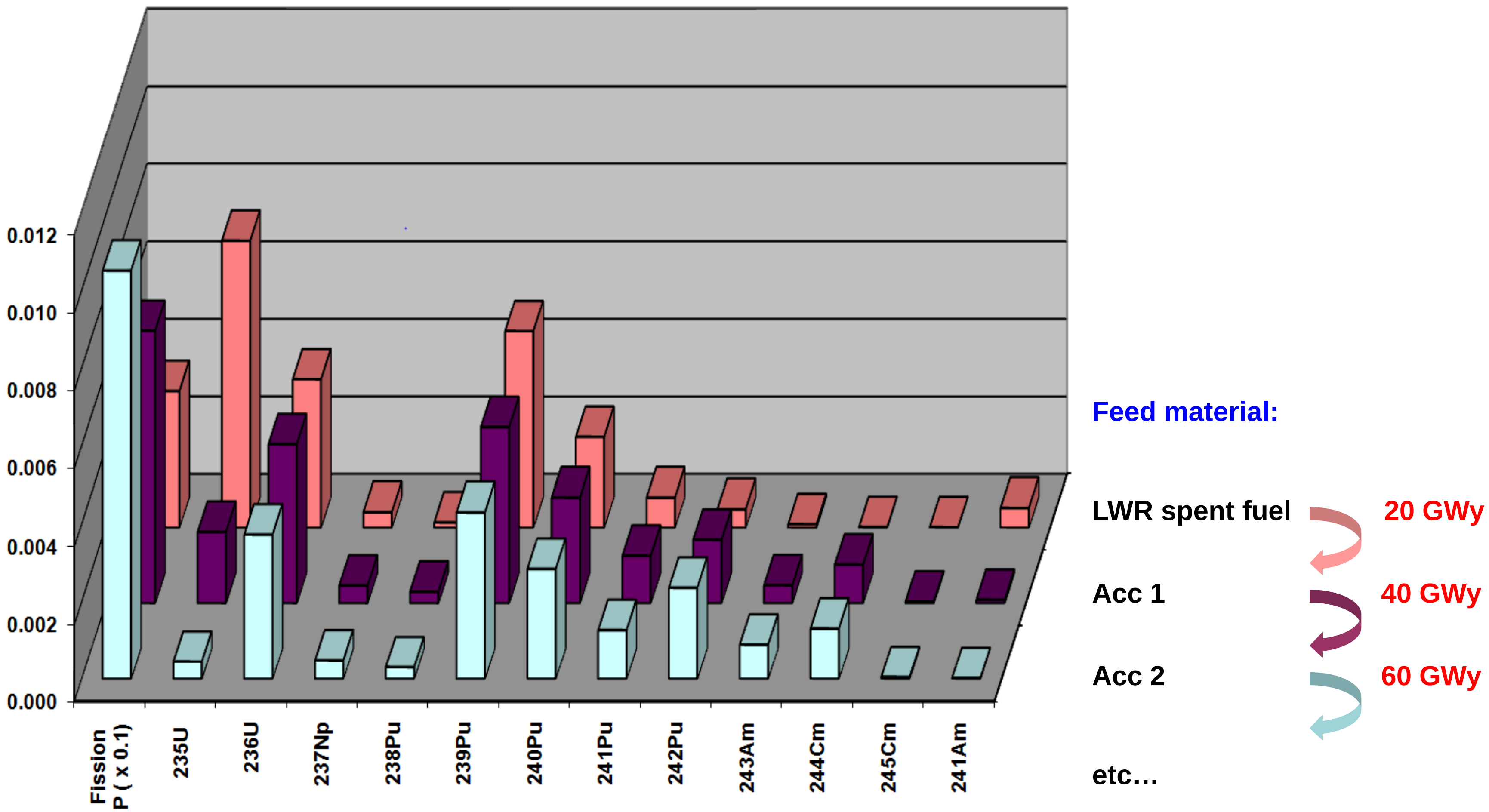
$$N_i \;= N_1\, \Pi_{j=2,i}\{\mathcal{F}\,\sigma_{c(j-1)} /[1 + \mathcal{F}\,\sigma_{aj}]\} \qquad i \geq 2$$

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

note: feed rate is determined by power extracted

GEM*STAR

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



major reduction and deferral of waste

Thermal Spectrum

0.01 – 0.2 eV

highest tolerance for fission products:

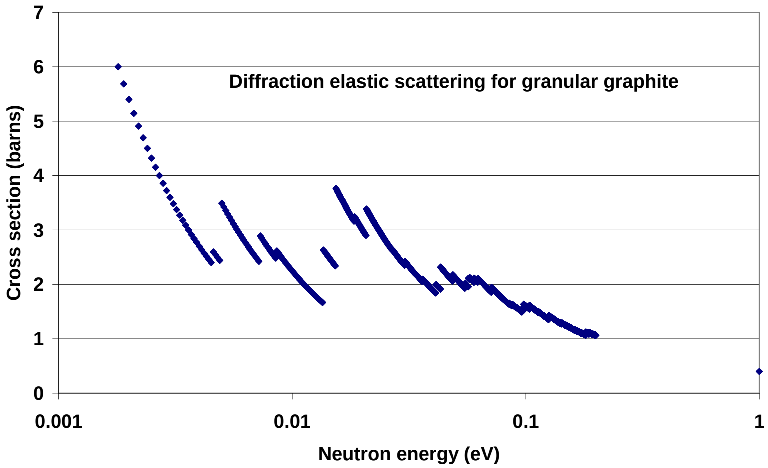
- neutron s-wave strength low for fission products
- $\sigma_f(^{239}Pu)/ \sigma_c(f.p.) \sim 100$

  (versus ~ 10 at 50 keV)
- resonance spacing large compared to width of neutron spectrum
- ^{151}Sm (transmuted rapidly to low σ_c nuclei); ^{135}Xe (continuously removed as a gas)

$\Rightarrow$ more than compensates for slower fission of heavy actinides

New Graphite Results
(ADNA)

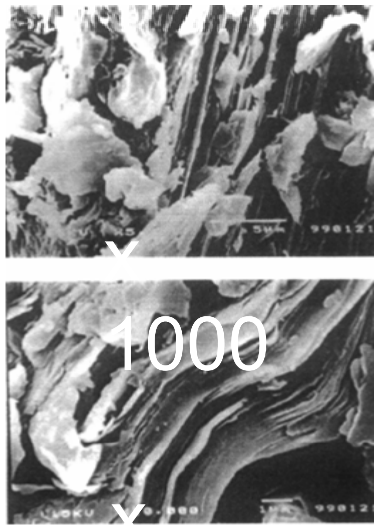
Diffusion/Absorption @ Duke

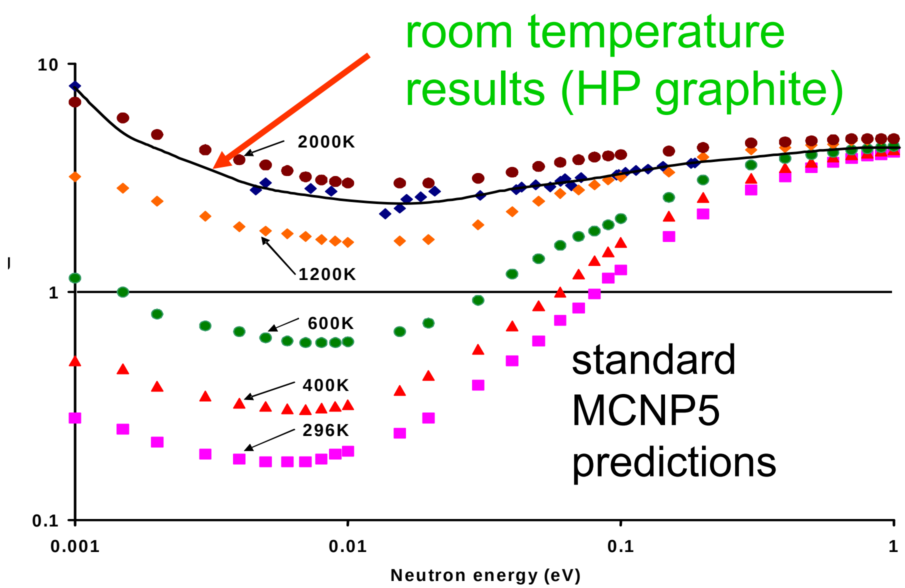


Diffraction @ LANL

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

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



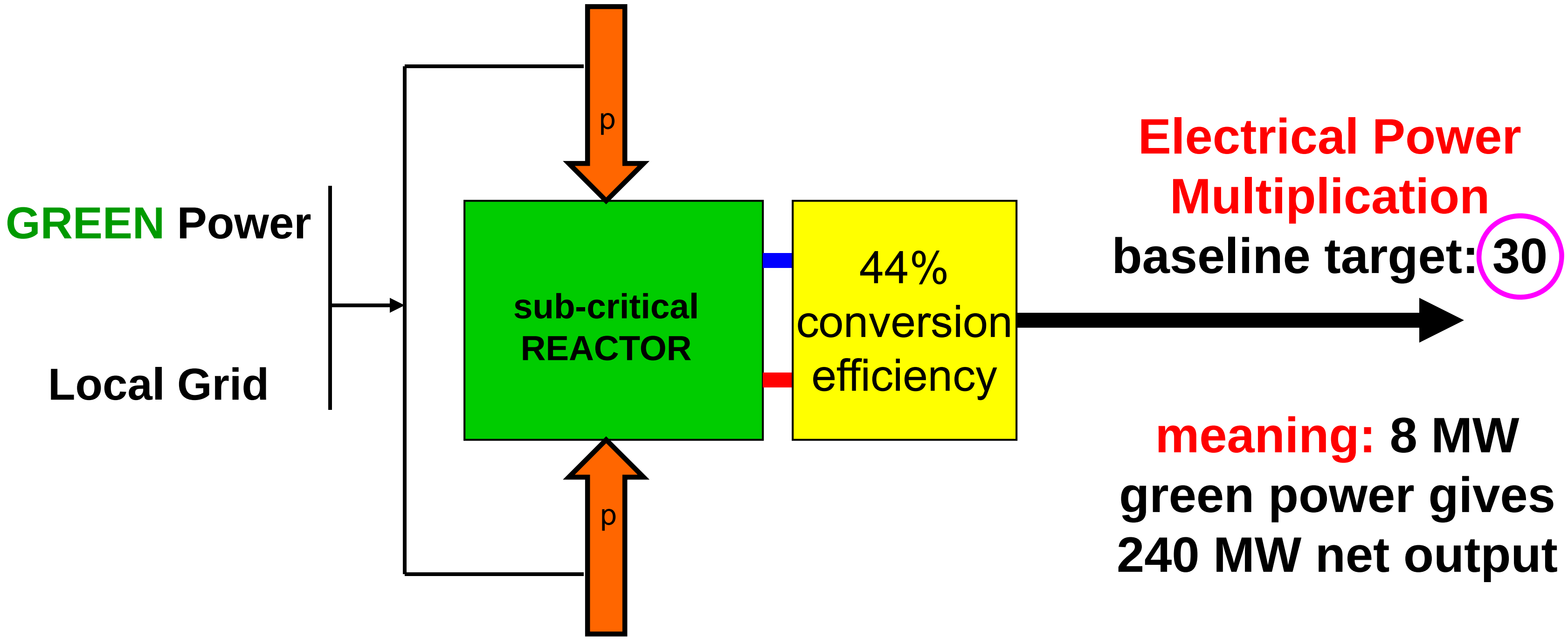


Discovered ***and measured*** a commercial graphite source with:

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

$\Rightarrow$ significant reduction in parasitic neutron absorption

Typical GEM✵STAR System



two proton beams from
accelerators (50% efficient)

meaning: 8 MW green power gives 240 MW net output

Protons -vs- Electrons

$$\frac{P_{beam}}{P_{input}} \cdot \frac{\mathrm{n}}{E(MeV)} \cdot \frac{fission}{\mathrm{n}} \cdot \frac{1}{1-k_s} \cdot \frac{E(MeV)}{fission} \cdot \frac{P_{electric}}{P_{thermal}} \approx M$$

protons (@600 MeV):

$$0.5 \cdot \frac{1}{30MeV} \cdot \frac{1}{2.7} \cdot \frac{1}{1-0.98} \cdot 200MeV \cdot 0.44 = 27$$

electrons (@50 MeV):

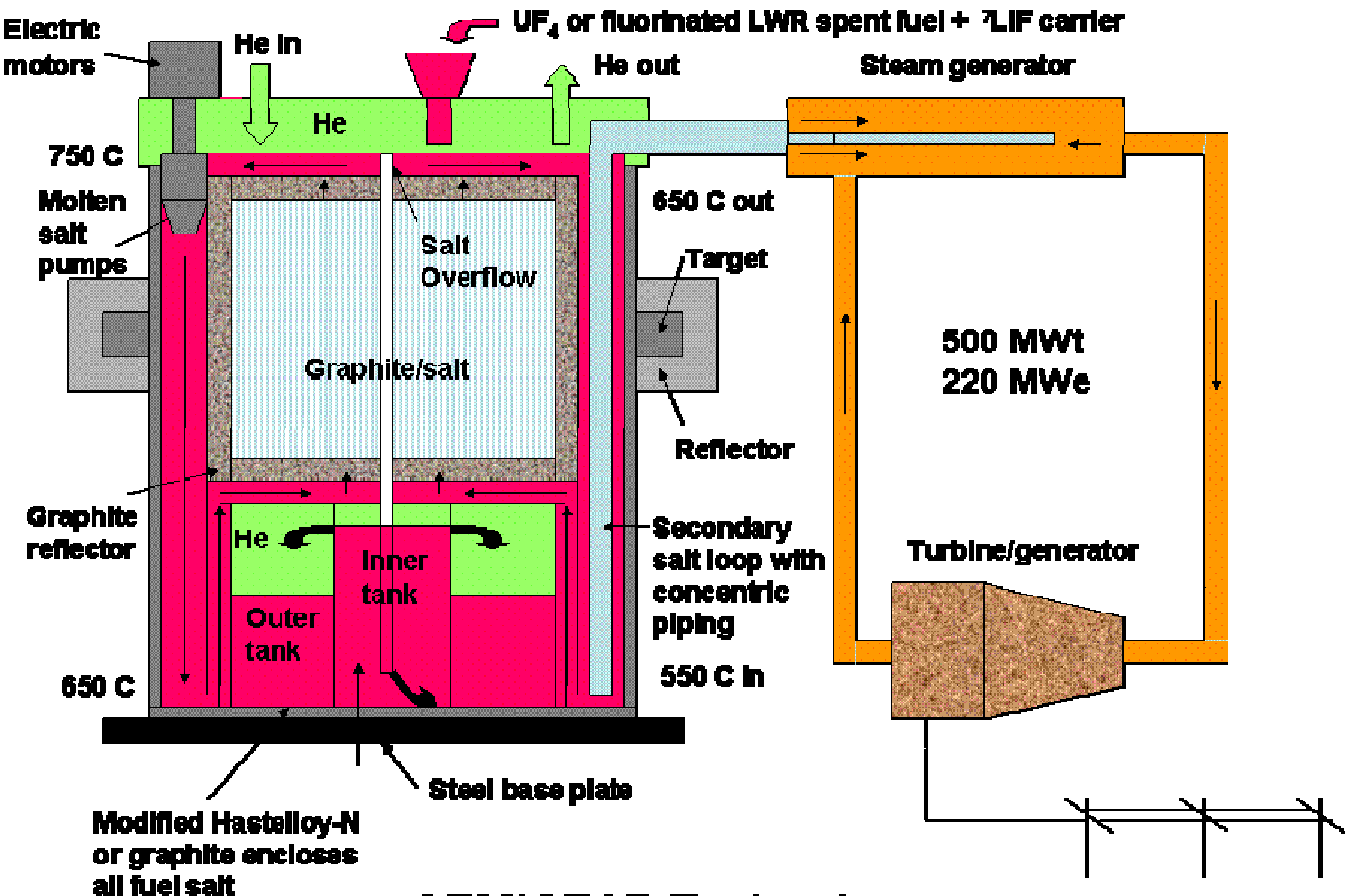
$$0.5 \cdot \frac{1}{3000MeV} \cdot \frac{1}{2.7} \cdot \frac{1}{1-0.98} \cdot 200MeV \cdot 0.44 = 0.27$$

20 n per 1 p
1n per 60 e

$$0.5 \cdot \frac{1}{3000MeV} \cdot \frac{1}{2.7} \cdot \frac{1}{1-0.9996} \cdot 200MeV \cdot 0.44 = 27$$

proton accelerator ~ ¼ capital cost

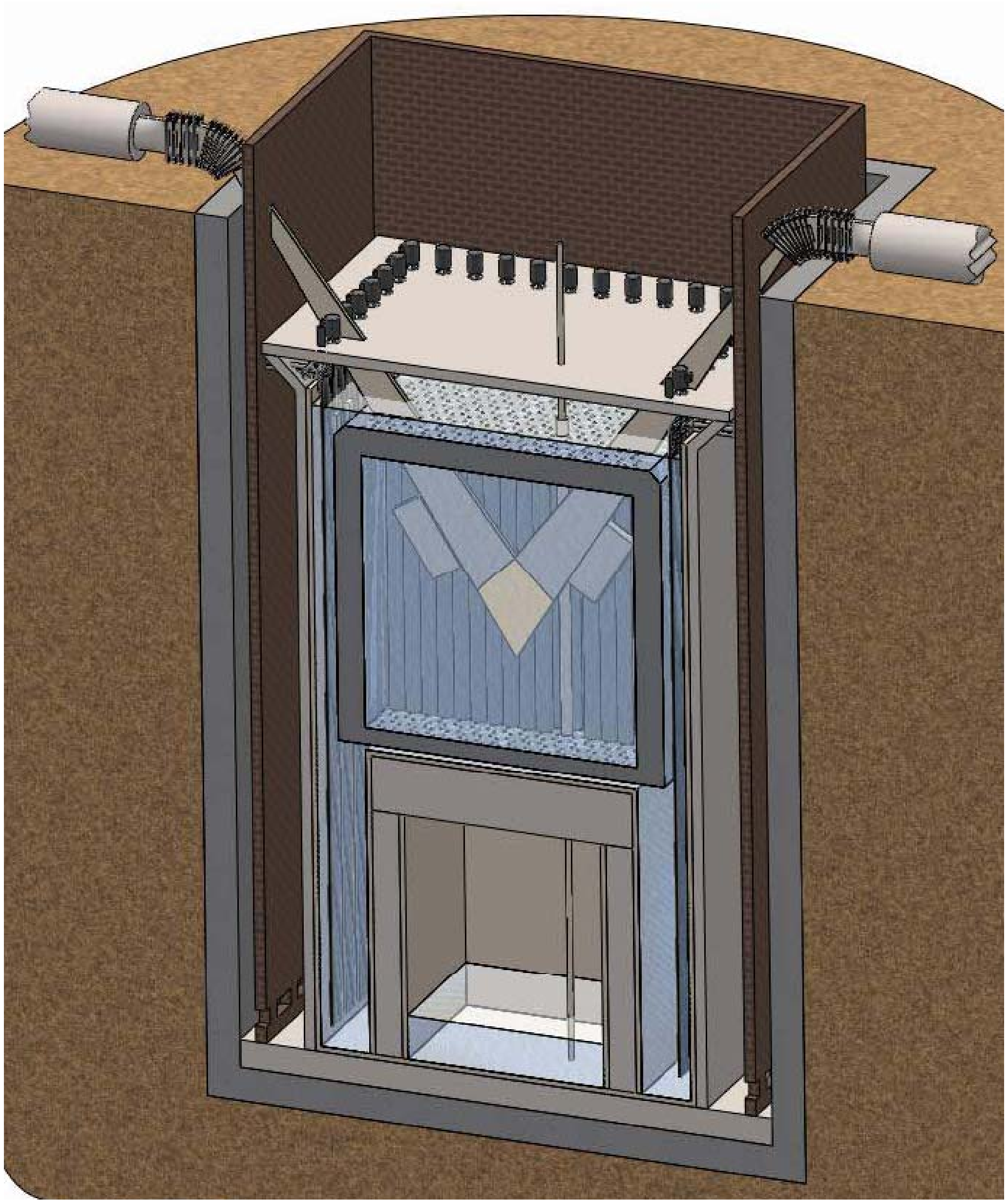
GEM*STAR



GEM*STAR Technology

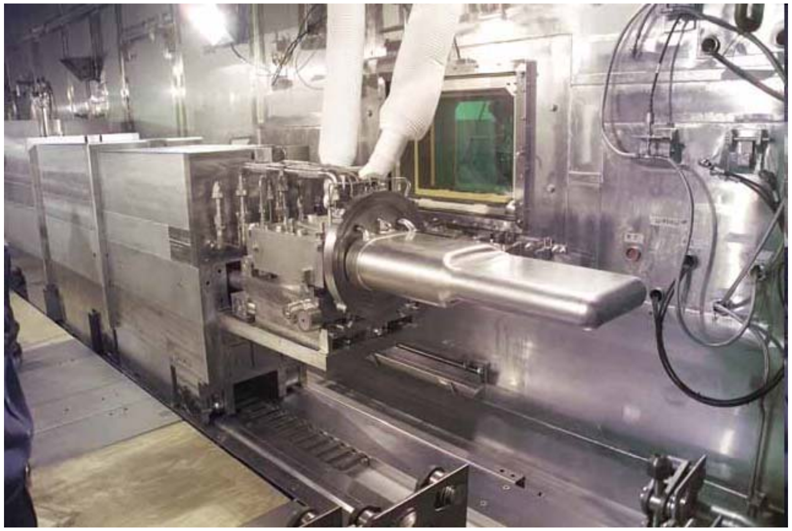
Functional Components

GEM✱STAR



Conceptual Design

Unique Target Considerations



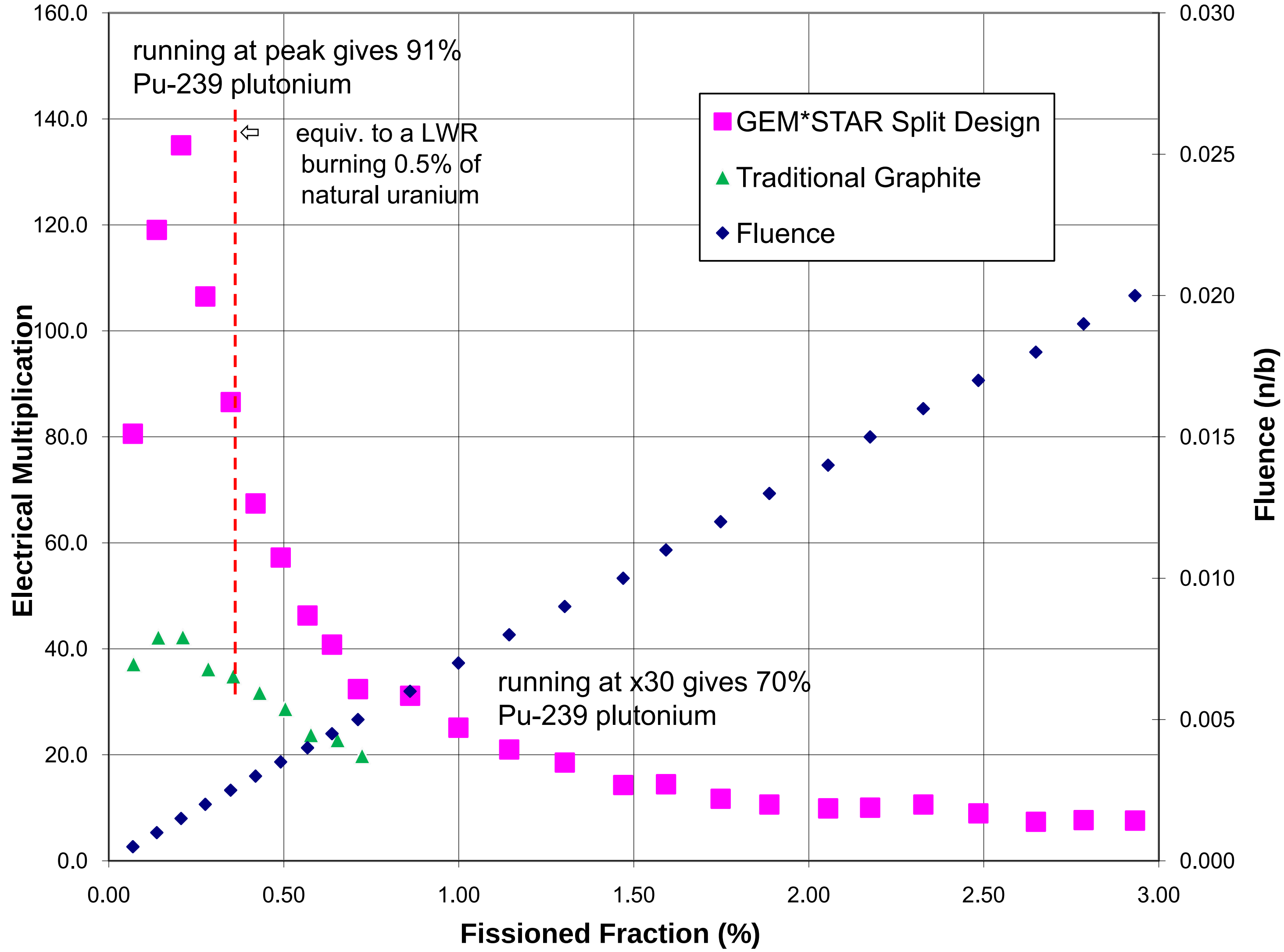
Existing Oak Ridge SNS Molten Hg target

- heat removal; diffuse/ multiple beam targets
- neutron absorption
- local core reactivity
- primary n production
- thermal n escape, fast n fission
- maintenance
- spent target disposal

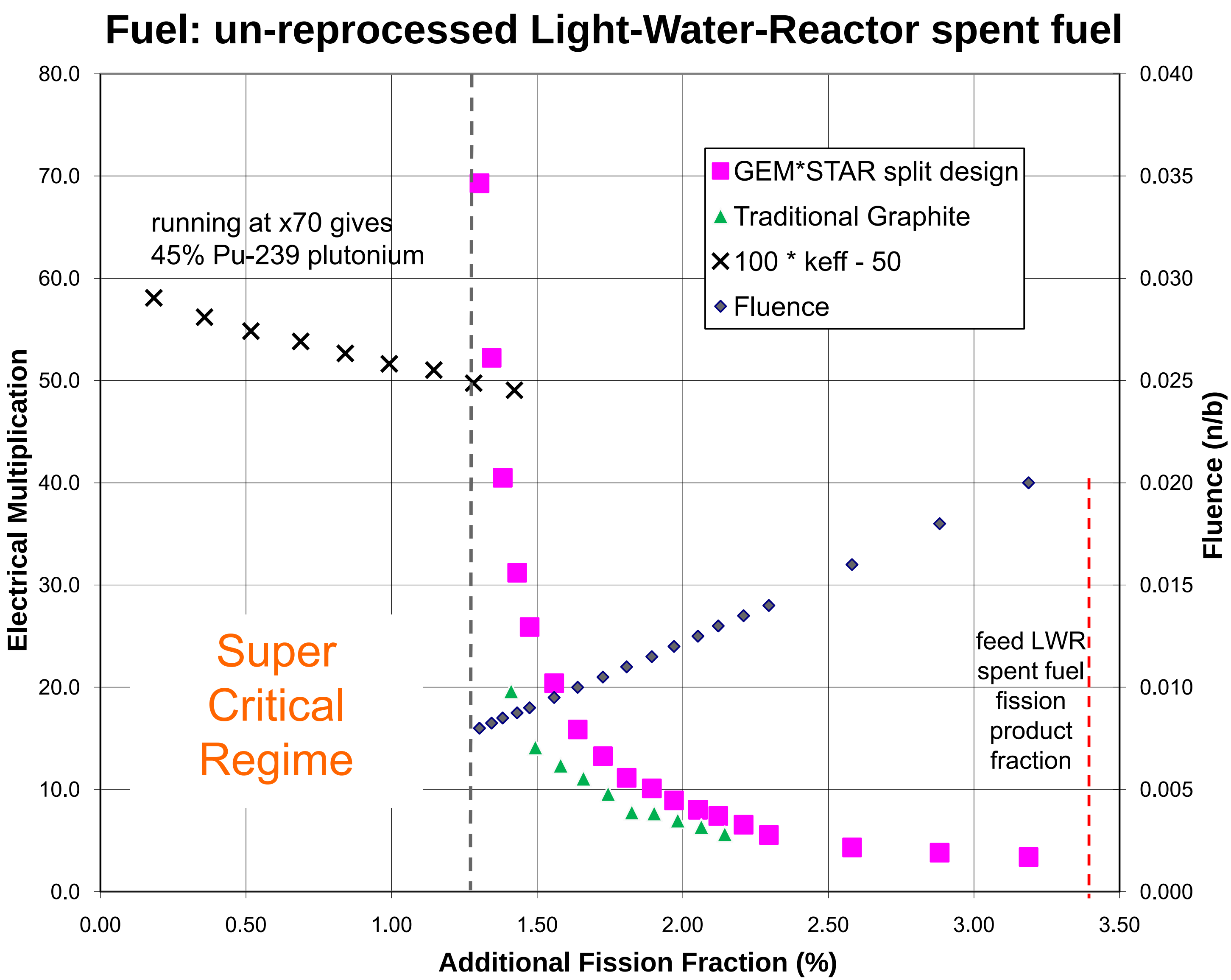
Uranium seems ideal…

GEM*STAR

Fuel: Natural Uranium



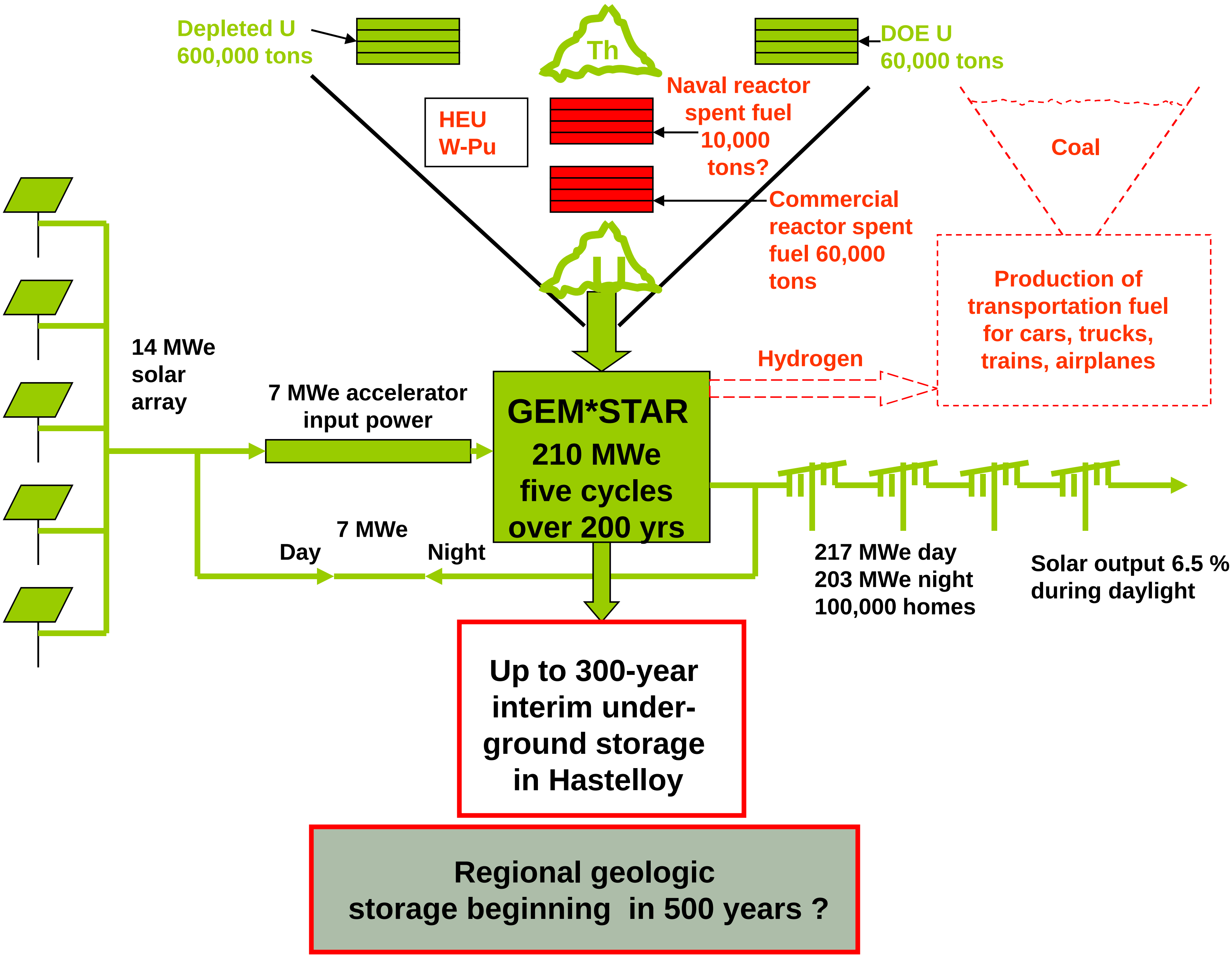
GEM*STAR



Fuel: un-reprocessed Light-Water-Reactor spent fuel
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
Electrical Multiplication
Fluence (n/b)
Additional Fission Fraction (%)
GEM*STAR split design
Traditional Graphite
100 * keff - 50
Fluence
running at x70 gives
45% Pu-239 plutonium
Super
Critical
Regime
feed LWR
spent fuel
fission
product
fraction

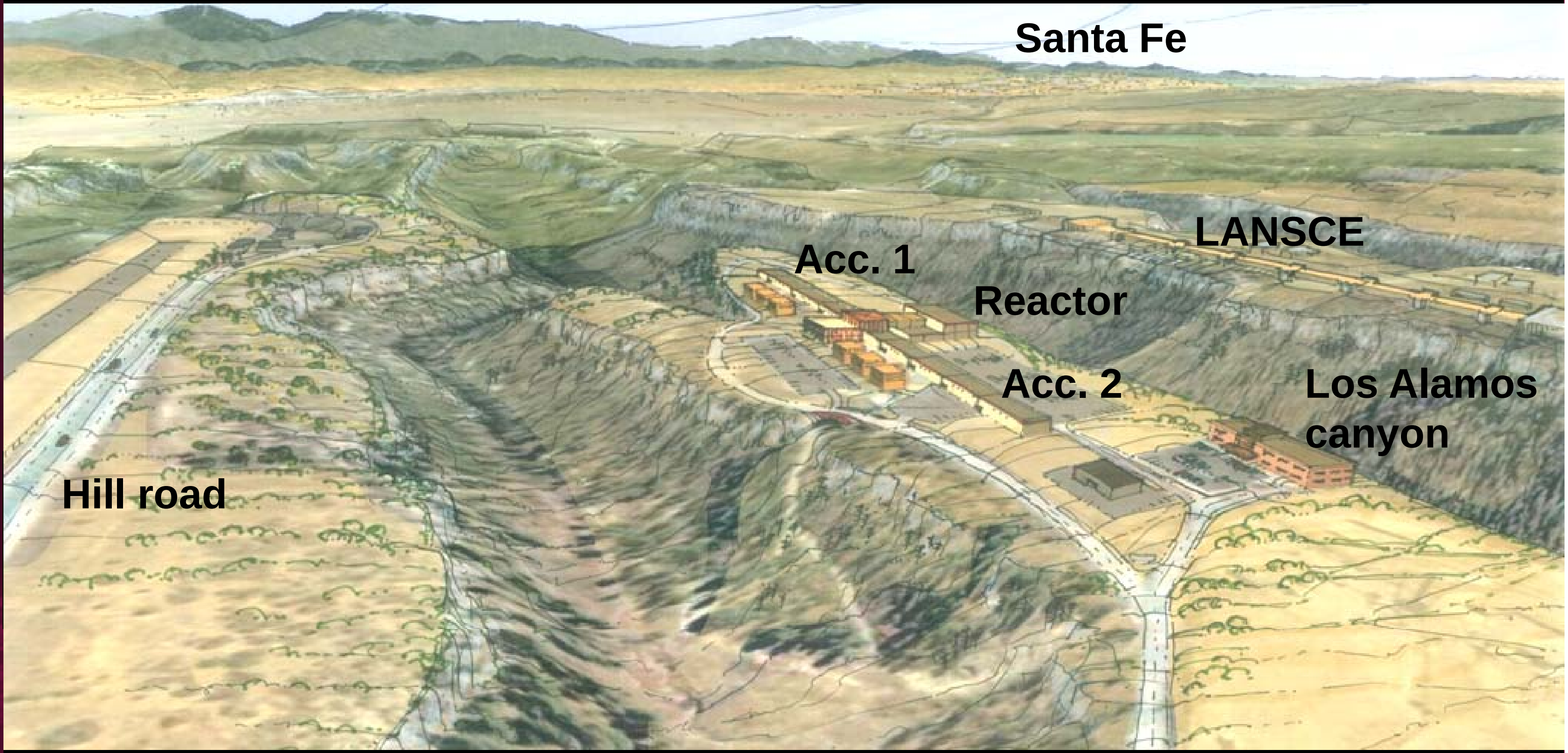
GEM*STAR

GEM*STAR



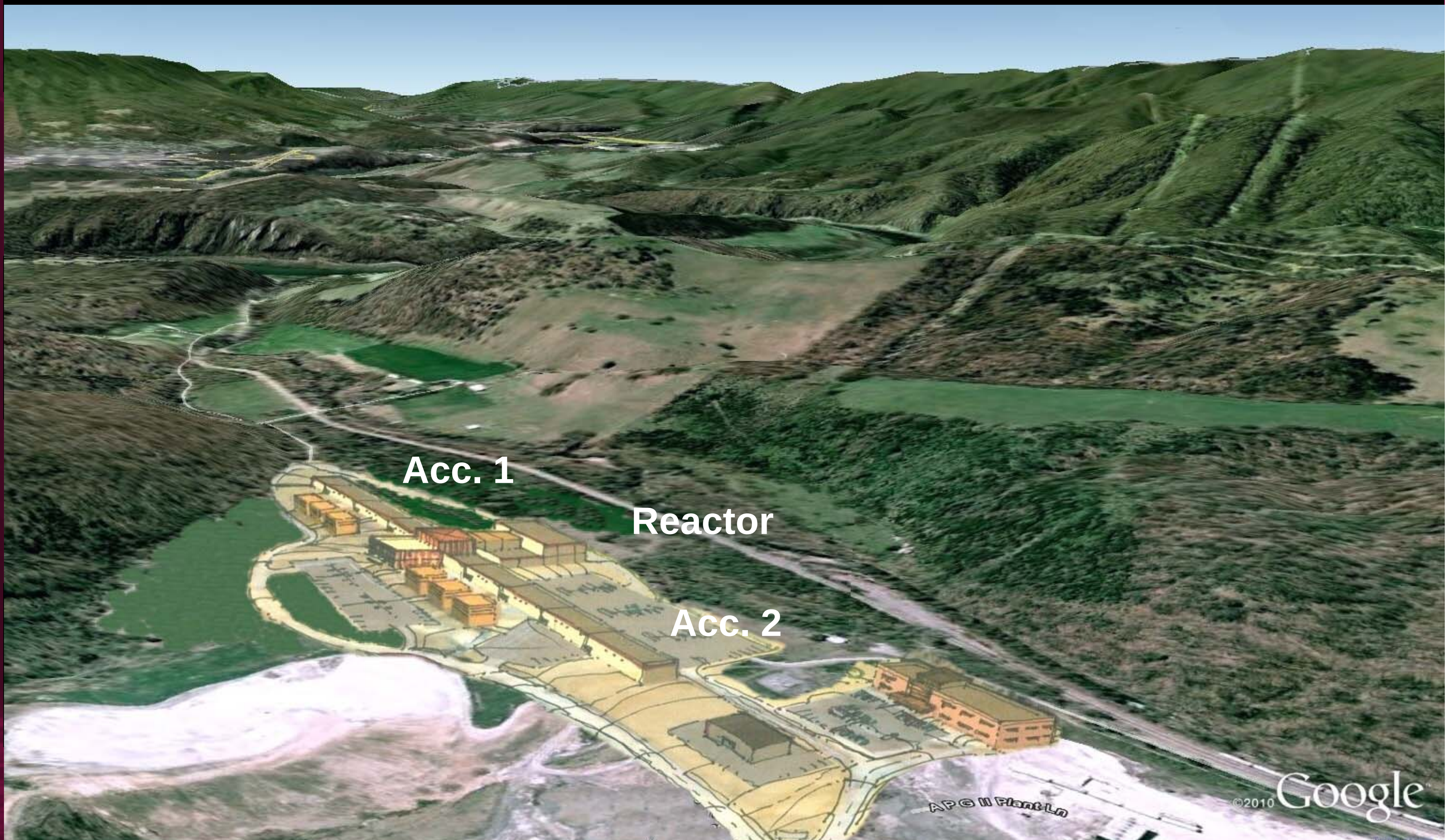
Depleted U
600,000 tons
Th
DOE U
60,000 tons
Naval reactor
spent fuel
10,000
tons?
HEU
W-Pu
Coal
Commercial
reactor spent
fuel 60,000
tons
U
Production of
transportation fuel
for cars, trucks,
trains, airplanes
Hydrogen
14 MWe
solar
array
7 MWe accelerator
input power
GEM*STAR
210 MWe
five cycles
over 200 yrs
7 MWe
Day
Night
217 MWe day
203 MWe night
100,000 homes
Solar output 6.5 %
during daylight
Up to 300-year
interim under-
ground storage
in Hastelloy
Regional geologic
storage beginning in 500 years ?

Next: 60 (120) MW_e Demonstration Facility



a potential site at Los Alamos

GEM*STAR



a potential site in Virginia

GEM STAR

GEM✵STAR System

- intrinsic safety: no critical mass ever present
- no high-pressure containment vessel
- thermal neutrons: better tolerance to fission products
- exceptional neutron economy: allows deeper burning
- higher thermal to electric conversion efficiency

no enrichment; no reprocessing; can burn multiple fuels *including* LWR spent fuel

current prices for electricity

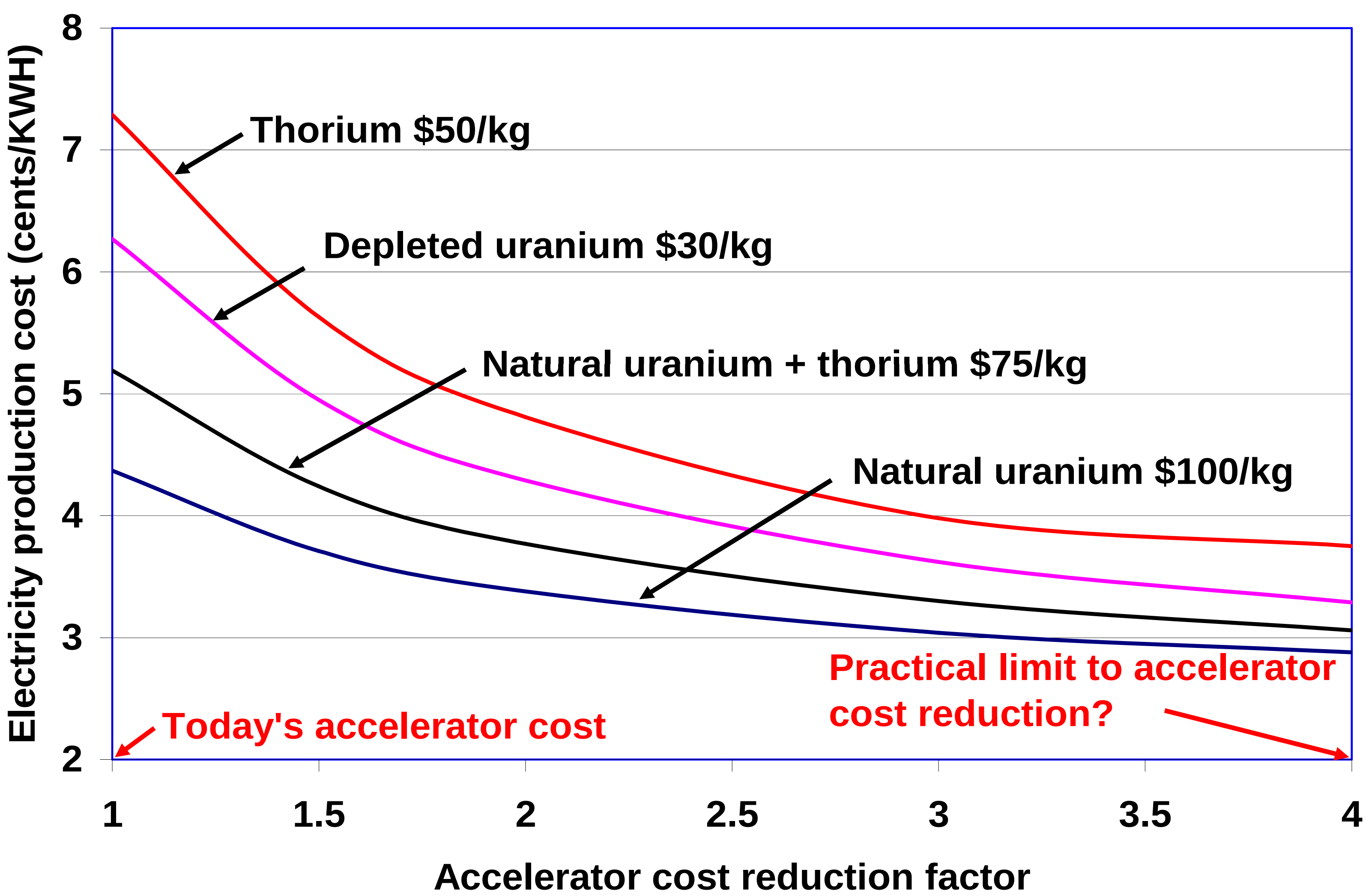
(estimated by Black and Veatch, Overland Park, Kansas)

	cents/kwh
Coal without CO_2 capture	7.8
Natural gas at high efficiency	10.6
Old nuclear	“3.5”
New nuclear	10.8
Wind in stand alone	9.9
Wind with the necessary base line back-up	12.1
Solar source for steam-driven electricity	21.0

Solar voltaic cells; higher than solar steam electricity

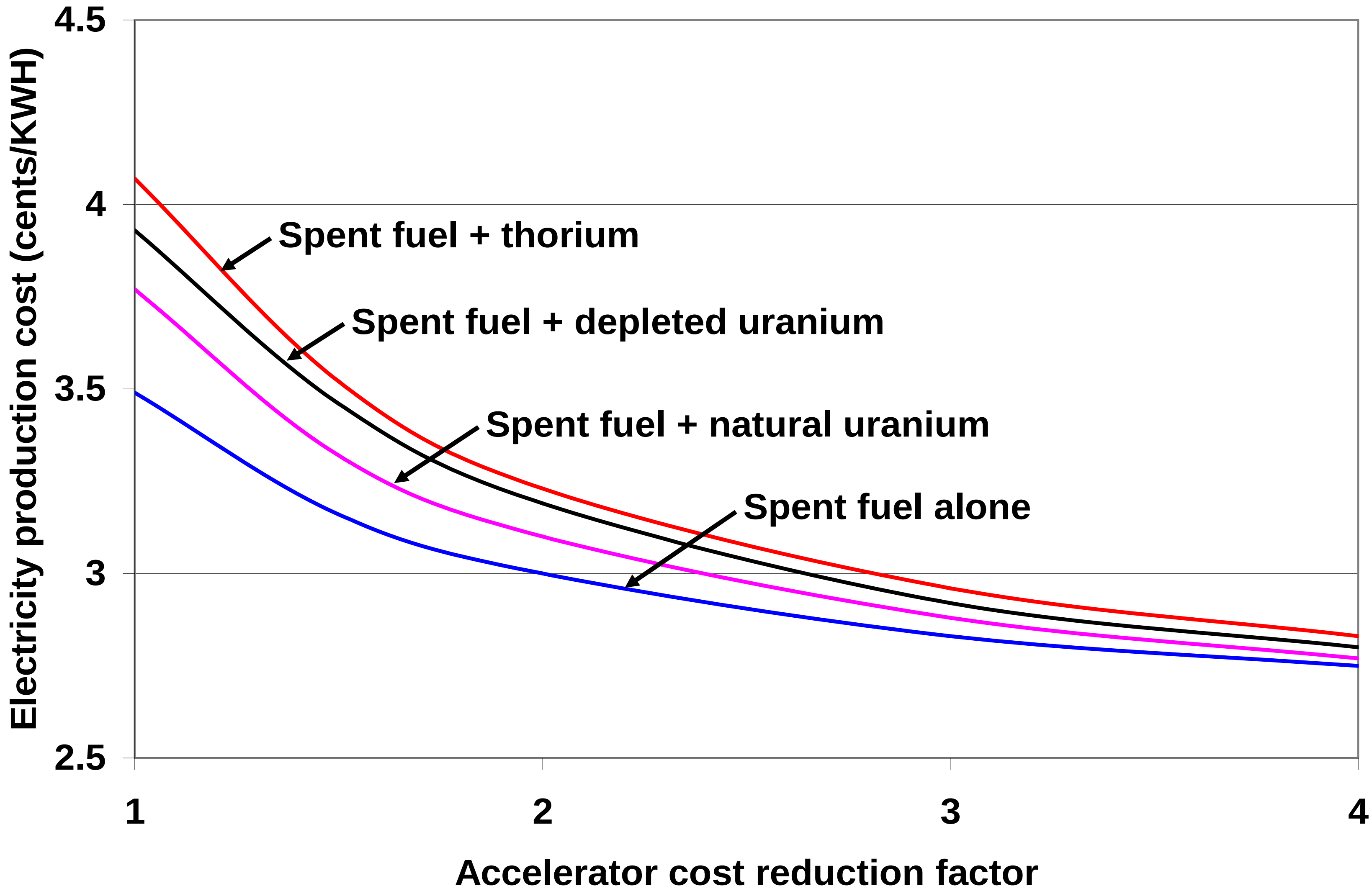
*NYT, Sunday (3/29/09) by Matthew Wald

GEM STAR


Electricity production cost (cents/KWH)
8
7
6
5
4
3
2
Thorium $50/kg
Depleted uranium $30/kg
Natural uranium + thorium $75/kg
Natural uranium $100/kg
Practical limit to accelerator cost reduction?
Today's accelerator cost
1
1.5
2
2.5
3
3.5
4
Accelerator cost reduction factor

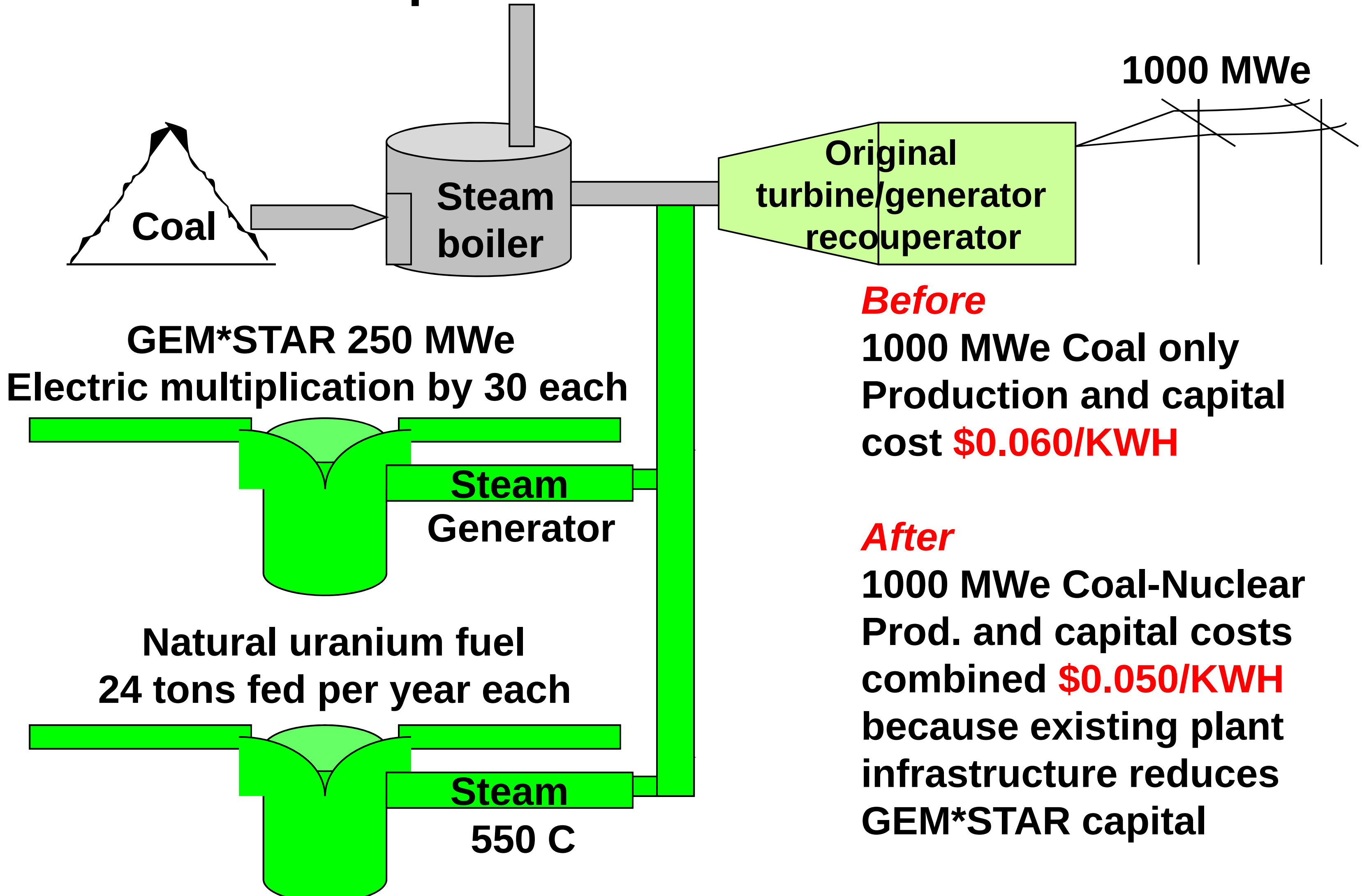
GEM STAR

GEM*STAR



Electricity production cost (cents/KWH)
4.5
4
3.5
3
2.5
1
2
3
4
Accelerator cost reduction factor
Spent fuel + thorium
Spent fuel + depleted uranium
Spent fuel + natural uranium
Spent fuel alone

Coal-Fired Plant Conversion to Half Nuclear
Cap-and-Trade Neutralized



Natural UF_4 fuel \$5.0 million/year
Electricity sales @ 7 ¢/KWH \$550 million/year

Before

1000 MWe Coal only
Production and capital cost **\$0.060/KWH**

After

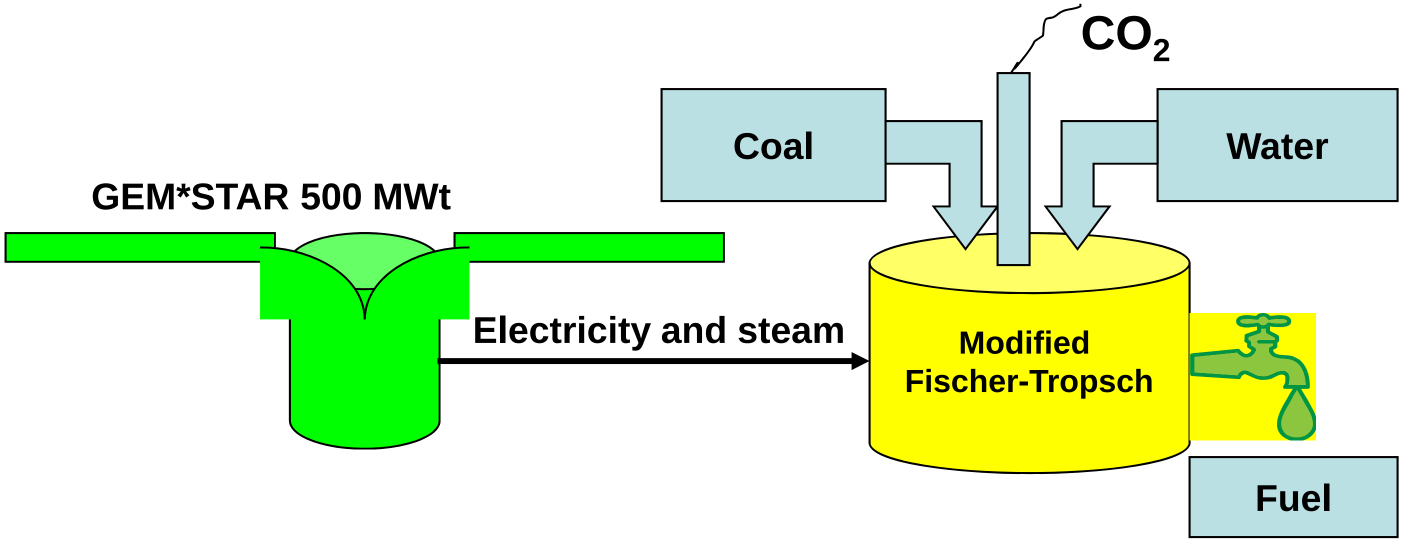
1000 MWe Coal-Nuclear
Prod. and capital costs combined **\$0.050/KWH** because existing plant infrastructure reduces GEM*STAR capital

CO_2 credits transferred internally

GEM*STAR

GEM*STAR

Diesel and Gasoline from GEM*STAR



$6H_2O + 3C \rightarrow 3CO_2 + 6H_2 \rightarrow 2(\text{-}CH_2\text{-}) + 4\,H_2O + CO_2$

Estimate of Diesel Price at the Pump

Steam and electricity from GEM*STAR	\$ 0.53/gallon
Feed coal @ \$100/ton (twice the current price)	0.37
Conversion facility operations costs	0.19
Construction mortgage payments for conv. facil.	0.15
Liquid fuel production profit @ 15 %	0.19
Wholesale price	\$ 1.43/gallon
Distribution and sales	0.24
Federal excise tax*	0.25
State excise tax*	0.22
Total	\$2.14/gallon

Water (680,000 gallons/d)
+ Coal (3000 tons/d

↓

Diesel (680,000 gallons/d
+ CO_2 (1000 tons/d C (1/3 of feed))

Obviously railroad site required

*U. S. Energy Information Administration averages for the U. S.

GEM✵STAR

will transform the nuclear policy landscape:

- not a ‘niche’, but rather base-line capable (green) energy source
- no enrichment necessary
- burns Light-Water-Reactor spent fuel directly (including fission products and actinides)
- burns multiple-fuels (including Th)
- low-cost electricity for consumer
- significant international and non-proliferation implications

GEM✵STAR