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 CO₂ / day / person
Global Warming is happening now
These are shared challenges – either directly or indirectly

nuclear energy already accounts for 17% of global electricity production

Fuel for electricity generation (percent)

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 CO₂
- low-cost electricity (current fleet)
- engineered safety
- IAEA oversight

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

- weapons
  - enrichment
  - reprocessing
- waste
- costly political ramifications
- truly catastrophic failure scenarios
- NIMBY
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.
ADNA: “re-frame the question”

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

- Uranium Ore
  - Enrichment
  - Fuel Fabrication
  - Accelerator or fusion neutrons
  - Recycling Liquid-fuel Subcritical Reactor
  - reduce and defer waste

- Light Water Reactor
  - Fluorination
  - Transmutation Fuel Fabrication
  - Transmutation Reprocessing
  - High-Level Waste Repository
  - Low-Level Waste Disposal

- Spent Nuclear Fuel
- Transuranics + Uranium
- Transuranics + Uranium

- Advanced Burner Reactor
  - Spent Transmutation Fuel
- Fuel Separation
- Strontium, Cesium and Uranium
- Storage
- Fission Products and Process Losses

- Advanced Transmutation Fuel Fabrication
- Advanced Transmutation
- Transmutation
- Light Water Reactor
- Fluorination

- GE Fuel Separation
- High-Transmutation Reprocessing
- Low-Transmutation

- Strontium, Cesium and Uranium

- Waste Disposal Storage
- Strontium, Cesium and Uranium

the advances and understanding which make this possible now…

…despite the real challenges of currently being ‘outside’ traditional programs
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06

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.

Year


Neutron cost ($ per gram)
Accelerators

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

Comparison of Super-Conducting Linacs and operation power costs.

<table>
<thead>
<tr>
<th></th>
<th>SNS</th>
<th>AGS</th>
<th>ACNS</th>
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<tbody>
<tr>
<td>Kinetic Energy, GeV</td>
<td>1.0</td>
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<td>Ave. Power, MW</td>
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<td>Duty Factor, %</td>
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<td>Repetition Rate, Hz</td>
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<td>Pulse Length, ms</td>
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<td>Ion Source Current, mA</td>
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<td>35</td>
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<td>Ave. Beam Current, mA</td>
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<td>Peak Beam Current, mA</td>
<td>26</td>
<td>21</td>
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<td>Protons / Bunch, x 10^8</td>
<td>4.3</td>
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<td>RF, GHz</td>
<td>0.805</td>
<td>0.805-1.61</td>
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<td>Coupler RF Power, MW</td>
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<td>260 - 400</td>
<td><strong>80 - 155</strong></td>
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<td>Length, m</td>
<td>158</td>
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<td>Inj. Energy, MeV</td>
<td>185.6</td>
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<td>Cryo. Power (2.1°K), kW</td>
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<td>0.15</td>
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<td>Ave. AC Power, MW</td>
<td>3.1</td>
<td>0.28</td>
<td><strong>23</strong></td>
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<td>Ave. Gradient, MV/m</td>
<td>3.1 - 6.5</td>
<td>5.3-10.0</td>
<td>3.3 - 8.7</td>
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<td>Efficiency, %</td>
<td>26</td>
<td>9 - 16</td>
<td><strong>35 - 40</strong></td>
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<tr>
<td>Capital Cost, M$</td>
<td>110</td>
<td>97</td>
<td>85</td>
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<tr>
<td>Operation Cost, M$ / yr</td>
<td>2.0</td>
<td>0.18</td>
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## ADS Technology Readiness Assessment

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

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*
Molten Salt Eutectic Fuel

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

High boiling point $\rightarrow$ low vapor pressure

Proven compatible with modified Hastelloy-N for operation up to 750°C. (ORNL MSRE)
Liquid fuel enables operation with constant and uniform isotope fractions including fission products

consider isotope $N_1$ present in molten-salt feed:

\[
\frac{dN_1}{dt} = F\left(\frac{v}{V}\right) - N_1 \phi \sigma_{a_1} - N_1 (v/V) = 0
\]

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

\[
N_1 = \frac{F}{1 + \mathcal{F} \sigma_{a_1}}
\]

and its $n_{\text{capture}}$ and $\beta_{\text{decay}}$ daughters are given by

\[
N_i = N_1 \prod_{j=2,i} \left\{ \mathcal{F} \sigma_{c(j-1)} / [1 + \mathcal{F} \sigma_{a_j}] \right\} \quad i \geq 2
\]

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

note: feed rate is determined by power extracted
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
  \( \frac{\sigma_f(^{239}\text{Pu})}{\sigma_c(f.p.)} \approx 100 \)  
  (versus \( \sim 10 \) at 50 keV)
  
• resonance spacing large compared to width of neutron spectrum
  
• \(^{151}\text{Sm}\) (transmuted rapidly to low \( \sigma_c \) nuclei);
  \(^{135}\text{Xe}\) (continuously removed as a gas)

⇒ more than compensates for slower fission of heavy actinides
New Graphite Results
(ADNA)

“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 $10^7$

⇒ significant reduction in parasitic neutron absorption
Typical GEM STAR System

GREEN Power

Local Grid

sub-critical REACTOR

44% conversion efficiency

two proton beams from accelerators (50% efficient)

Electrical Power Multiplication
baseline target: 30

meaning: 8 MW green power gives 240 MW net output
Protons -vs- Electrons

\[
\frac{P_{\text{beam}}}{P_{\text{input}}} = \frac{n}{E(\text{MeV})} \cdot \frac{\text{fission}}{n} \cdot \frac{1}{1-k_s} \cdot \frac{E(\text{MeV})}{\text{fission}} \cdot \frac{P_{\text{electric}}}{P_{\text{thermal}}} \approx M
\]

protons (@600 MeV):

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

electrons (@50 MeV):

\[
0.5 \cdot \frac{1}{3000\text{MeV}} \cdot \frac{1}{2.7} \cdot \frac{1}{1-0.98} \cdot 200\text{MeV} \cdot 0.44 = 27
\]

20 n per 1 p
1n per 60 e

proton accelerator ~ ¼ capital cost
GEM*STAR Technology

Functional Components
Unique Target Considerations

- 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…
Fuel: Natural Uranium

- Running at peak gives 91% Pu-239 plutonium.
- Equivalent to a LWR burning 0.5% of natural uranium.

- Running at x30 gives 70% Pu-239 plutonium.

Graph showing electrical multiplication and fluence as functions of fissioned fraction.
Fuel: un-reprocessed Light-Water-Reactor spent fuel

running at x70 gives 45% Pu-239 plutonium

- GEM*STAR split design
- Traditional Graphite
- 100 * keff - 50
- Fluence

Super Critical Regime
Naval reactor spent fuel
HEU W-Pu
Commercial reactor spent fuel 60,000 tons
DOE U 60,000 tons
Depleted U 600,000 tons

GEM*STAR
210 MWe five cycles over 200 yrs

14 MWe solar array
7 MWe accelerator input power
7 MWe Day
Night

217 MWe day
203 MWe night
100,000 homes

Up to 300-year interim underground storage in Hastelloy
Regional geologic storage beginning in 500 years?

Coal

Production of transportation fuel for cars, trucks, trains, airplanes

Solar output 6.5% during daylight
Next: 60 (120) MW_e Demonstration Facility

a potential site at Los Alamos
a potential site in Virginia
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)

<table>
<thead>
<tr>
<th>Source</th>
<th>Price/cent/kwh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal without CO₂ capture</td>
<td>7.8</td>
</tr>
<tr>
<td>Natural gas at high efficiency</td>
<td>10.6</td>
</tr>
<tr>
<td>Old nuclear</td>
<td>“3.5”</td>
</tr>
<tr>
<td>New nuclear</td>
<td>10.8</td>
</tr>
<tr>
<td>Wind in stand alone</td>
<td>9.9</td>
</tr>
<tr>
<td>Wind with the necessary base line back-up</td>
<td>12.1</td>
</tr>
<tr>
<td>Solar source for steam-driven electricity</td>
<td>21.0</td>
</tr>
<tr>
<td>Solar voltaic cells; higher than solar steam electricity</td>
<td></td>
</tr>
</tbody>
</table>

*NYT, Sunday (3/29/09) by Matthew Wald*
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
Electricity production cost (cents/KWH)

Accelerator cost reduction factor

- Spent fuel + thorium
- Spent fuel + depleted uranium
- Spent fuel + natural uranium
- Spent fuel alone

Accelerator cost reduction factor

3.5

Spent fuel + thorium

Spent fuel + depleted uranium

Spent fuel + natural uranium

Spent fuel alone

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

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 250 MWe
Electric multiplication by 30 each

Natural uranium fuel
24 tons fed per year each

Steam boiler

Steam
Generator

550 C

Natural UF$_4$ fuel $5.0$ million/year

Electricity sales @ 7 ¢/KWH $550$ million/year
6H₂O + 3C → 3CO₂ + 6H₂ → 2(-CH₂-) + 4 H₂O + CO₂

Water (680,000 gallons/d) + Coal (3000 tons/d)
\[ \text{Diesel (680,000 gallons/d)} + \text{CO}_2 \text{ (1000 tons/d C (1/3 of feed))} \]

Obviously railroad site required

**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
- Construction and mortgage payments for conv. facil.: 0.19
- Conversion facility operations costs: 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

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