GEM\*STAR

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

R. Bruce Vogelaar
Virginia Tech
Recent Developments

“At least 40 developing countries have recently approached the U.N. to signal interest in starting nuclear power programs”

Joby Warrick, Washington Post, May 12, 2008

meanwhile…

• Fukushima accident
• Germany shuts down its nuclear plants
• Japan shuts down most of its nuclear plants
• US shuts down San Onofre…
ADNA & GEM*STAR Consortium

Invent the Future

US Energy Flow

Estimated U.S. Energy Use in 2010: ~98.0 Quads

Source: LLNL 2011. Data is based on DOE/EIA-0384(2010), October 2011. 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 flows for hydro, wind, solar and geothermal in Btu-equivalent values by assuming a typical fossil fuel plant “heat rate.” (see EIA report for explanation of change to geothermal in 2010). 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 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL--M1--410527
the classic ‘nuclear’ option
Fission

~200 MeV released per fission

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

On Average: 1 fission $\rightarrow$ 1 fission $\rightarrow$ 1 fission  
$\text{“}k_{\text{eff}} = 1\text{”}$

$k_{\text{eff}} > 1 \rightarrow$ runaway reaction

$k_{\text{eff}} < 1 \rightarrow$ chain has finite length
Sustaining a chain reaction

0.72 % Natural 4.5 % “Low” Enriched > 20 % Weapons Usable

$^{235}\text{U} \text{ fission}$  $^{238}\text{U} \text{ capture}$  $^{238}\text{U} \text{ fission}$

Need to thermalize fission neutrons in U-free region to avoid capture before fission
Possible Fuels

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“Breeder” reactions
Classic (LWR) Operation

- Water Moderation: enriched $^{235}\text{U}$ fuel
- Solid fuel in cladding
- Uses negative feedback
  - 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 $k_{\text{eff}}=1$
- only 0.5% of energy in mined uranium gets used
What are the obstacles?

in the US:
• safety
• waste
• weapons proliferation
• cost

in other countries?
Safety

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

SMR claim $10^{-8}$ events per reactor-year

...that’s 1 event in 1,000,000 reactors over 100 years

...is there a credibility issue...
Waste

- long-lived fission products and actinides
  - bury in Yucca Mountain? (now cancelled!)
  - burn with accelerators?
  - burn in next generation reactors?
  - store on site...current practice

Weapons Proliferation

- enrichment
- reprocessing
## Cost

### current prices for electricity

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

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<th>Energy Source</th>
<th>Price (cents/kwh)</th>
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<td>Coal without CO₂ capture</td>
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<tr>
<td>Natural gas at high efficiency</td>
<td>10.6</td>
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<tr>
<td>Old nuclear</td>
<td>“3.5”</td>
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<tr>
<td>New nuclear</td>
<td>10.8</td>
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<td>Wind in stand alone</td>
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<tr>
<td>Wind with the necessary base line back-up</td>
<td>12.1</td>
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<tr>
<td>Solar source for steam-driven electricity</td>
<td>21.0</td>
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<td>Solar voltaic cells; higher than solar steam electricity</td>
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*NYT, Sunday (3/29/09) by Matthew Wald*

**GEM*STAR**: 4.5 ¢ per kWh with natural uranium fuel
What is being done...

**DOE-NE**
- ‘small modular reactors’
  - safety
  - waste
  - weapons proliferation
  - cost

**DOE-Science**
- ‘high intensity frontier’
  - safety
  - waste
  - weapons proliferation
  - cost

**India**
- PHWR (nat U) →
- FBR (\(^{239}\)Pu & Th) →
- AHWR (\(^{233}\)U & Th)
Are there other avenues to explore?

- to address ‘clean energy’ ‘now’
- that would compete today with coal costs
- not being ‘captured’ by the previous slide
- low enough cost to try without requiring broad ‘consensus’ first
Different Paradigm

Natural Uranium → Enrichment → Thermal Reactors → Reprocessing → Fast Reactors

- Geologic Storage
- Liquid Fuel Recycling Reactor
- With supplemental neutrons
- No enrichment, no reprocessing
- End-of-life waste remnant reduced by x10 and delayed by centuries
Existing Enabling Technologies

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

the key:

proper integration - from the beginning
The cost of neutrons has dropped dramatically.

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

($432M @ 5 ¢/kWh)
Proton Driven Sub-Critical System

$$E_{\text{electric}} = E_{\text{thermal}} \eta_t$$

$$= (E_{\text{beam}} + E_{\text{fission}}) \eta_t$$

$$= \left( E_{\text{beam}} + \frac{E_{\text{beam}}}{\epsilon_n} m \epsilon_f \right) \eta_t$$

$$= E_{\text{beam}} \left( 1 + \frac{\epsilon_f}{\epsilon_n} m \right) \eta_t$$

$$= E_{\text{wall}} \eta_a \left( 1 + \frac{\epsilon_f}{\epsilon_n} m \right) \eta_t$$

$$\eta_a \equiv \text{efficiency of accelerator}$$

$$\epsilon_n \equiv \text{energy to create a neutron}$$

$$m \equiv \text{number of fissions per neutron}$$

$$\epsilon_f \equiv \text{energy per fission}$$

$$\eta_t \equiv \text{efficiency converting thermal to electrical energy}$$

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

Reference parameters:
- $\epsilon_f$ 200 MeV / fission
- $\epsilon_n$ 19 MeV / neutron (for 1 GeV protons on Uranium)
- $m$ 15 fissions / neutron
- $\eta_t$ 44% thermal to electric conversion
- $\eta_a$ 20% accelerator efficiency

$G = 65$ \hspace{1em} (ie: $1\text{MW}_{\text{target}} \rightarrow 65\text{ MW}_e$ net output)
Design criteria: large $m$ (fissions per neutron), reduces need to maximize $\eta_a$ (accelerator efficiency)

eg: changing accelerator efficiency from 20% to 10% only lowers $G$ from 65 to 60

Today’s accelerators are already efficient enough.
Solid Fuel Issues

- non-uniform fuel consumption requires fuel repositioning
- volatile fission-product build-up within cladding
- thermal shock due to beam trips (~800↔320)
Molten Salt Eutectic Fuel

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

High boiling point $\rightarrow$ low vapor pressure

Proven in ORNL MSRE reactor using Modified Hastelloy-N ($^{235}$U, $^{239}$Pu, $^{233}$U)
consider a clear liquid which releases heat when exposed to light, eventually turning a dark purple

Initial fill

increasing light exposure \( \rightarrow \)

with continuous feed-and-bleed beginning here

feed

bleed

color and heat output remains constant indefinitely

\( \rightarrow \) equilibrated isotope fractions throughout core and throughout time

fast internal mixing

10^{-6} \text{ less volatile fission-product build-up in core}
Liquid fuel enables operation with constant and uniform isotope fractions including fission products

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

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

define neutron fluence: $F = \phi(V/v)$; then in equilibrium $dN_1/dt = 0$

$$N_1 = \frac{F}{1 + F \sigma_{a1}}$$

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

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

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.

Feed material:
- LWR spent fuel: 20 GWy
- Acc 1: 40 GWy
- Acc 2: 60 GWy
- etc...

major reduction and deferral of waste
Natural decay of spent fuel radiotoxicity
Recycling

40 years worth of LWR spent fuel

first pass
(40+ years)
each can be used to start another pre-equilibrated core every 5 years

second pass
(40+ years)

subsequent passes… (fusion n source?)
Existing Proton Beam Power

![Graph showing existing proton beam power](image-url)
Target Considerations

• using “k_{eff}” is really very misleading for a driven system

• a driven system should not have the standard neutron reflector around the core
For 50 years, and even today, people argue for fast-spectrum systems. Why?

Faster burn-up of heavy actinides.

Probability of Fission/Neutron absorbed
But Using Thermal Spectrum
0.01 – 0.2 eV

highest tolerance for fission products:

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

\[
\frac{\sigma_{\text{fission}} (^{239}\text{Pu})}{\sigma_{\text{capture}} (\text{f.p.})} \approx 100 \quad (\text{vs } \approx 10 \text{ @ 50 keV})
\]

• \(^{151}\text{Sm}\) (transmuted rapidly to low \(\sigma_c\) nuclei)
• \(^{135}\text{Xe}\) (continuously removed as a gas)

⇒ more than compensates for slower fission of heavy actinides (which are burned anyway)
Fuel: Natural Uranium (MCNPX)

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

Running at x60 gives 70% Pu-239 plutonium
Fuel: un-reprocessed Light-Water-Reactor spent fuel

Running at x140 gives 45% Pu-239 plutonium

Net Electric Power / Power on Target

Additional Fission Fraction (%)

Super Critical

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

feed LWR spent fuel fission product fraction
no enrichment; no reprocessing; can burn MANY fuels (pure, mixed, *including* LWR spent fuel) with no redesign required
High Temperature MS Advantages over LWRs

- no high-pressure containment vessel
- 34% → 44% efficiency for thermal to electric conversion (low-pressure operation)
- match to existing coal-fired turbines, enables staged transition for coal plants, addressing potential “cap-and-trade” issues
- synthetic fuels via modified Fischer-Tropsch methods – very attractive (much more realistic than hydrogen economy)
Coal and Natural Gas to Diesel/Gasoline with GEM*STAR at 500 MWt (~3.4MW on target)

$0.87/gal prod. cost
$1.58/gal at the pump
No CO₂ production
1 mol of coal + 1 mol of CH₄ yields 2 mols of diesel/gasoline

affordable diesel without CO₂ production
What are the obstacles?

- GEM*STAR uses liquid fuel – but NRC is only “comfortable” with solid fuel, despite MSRE success
- Existing commercial deployed fleet of LWRs
- Engineers in nuclear industry have little experience with accelerators; physicists using accelerators have little experience with nuclear power plants ⇒ little cooperation in base programs (vague talk about a distant ATW application)
- Current focus (in US) only on existing and new “modular” reactors (scaled down versions of existing deployed technology)
resulting in policies such as

- **DOE NE** Report to Congress, April 2010, “Nuclear Energy Research and Development Roadmap” does not include the word ‘accelerator’ even once.
- **DOE Science** (HEP & NP) ADS Report (September 17, 2010)
  - Finding #2: Accelerator-driven sub-critical systems offer the potential for safely burning fuels which are difficult to incorporate in critical systems, for example fuel without uranium or thorium. [WHY not U??]
  - Finding #3: Accelerator driven subcritical systems can be utilized to efficiently burn minor actinide waste.
  - Finding #4: Accelerator driven subcritical systems can be utilized to generate power from thorium-based fuels
- MIT Energy Initiative; Obama’s Blue Ribbon Panel
  - 100 year horizon, no new direction, yet continue DOE-NE funding at current level
- **DOE NE** “thinking about an ADS demonstration in 2050” (ie, when I’m 90 😞)
## ADS Technology Readiness Assessment

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</tr>
</tbody>
</table>

Green: “ready”, Yellow: “may be ready, but demonstration or further analysis is required”, Red: “more development is required”.
how is this rationalized?

Table 1: Range of Parameters for Accelerator Driven Systems for four missions described in this whitepaper

<table>
<thead>
<tr>
<th></th>
<th>Transmutation Demonstration</th>
<th>Industrial Scale Transmutation</th>
<th>Industrial Scale Power Generation with Energy Storage</th>
<th>Industrial Scale Power Generation without Energy Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Power</td>
<td>1-2 MW</td>
<td>10-75 MW</td>
<td>10-75 MW</td>
<td>10-75 MW</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>0.5-3 GeV</td>
<td>1-2 GeV</td>
<td>1-2 GeV</td>
<td>1-2 GeV</td>
</tr>
<tr>
<td>Beam trips (t &gt; 5 min)</td>
<td>&lt; 50/year</td>
<td>&lt; 50/year</td>
<td>&lt; 50/year</td>
<td>&lt; 3/year</td>
</tr>
<tr>
<td>Availability</td>
<td>&gt; 50%</td>
<td>&gt; 70%</td>
<td>&gt; 80%</td>
<td>&gt; 85%</td>
</tr>
</tbody>
</table>

...helps motivate “Intensity Frontier” (ie: Project X at Fermilab); but higher efficiency via higher-power beams is not a requirement; $100’s of millions are going into solar and wind which have far greater outages.

DOE-NE: “It takes about 20 years to validate any new fuel system, so 2050 is the earliest one might imagine for ADS.”

...based on input from solid-fuel manufacturers; but consider how this might change if a new system actually addressed waste, proliferation, LWR spent fuel usage, and safety (thus becoming politically, publicly, and financially desirable).
People (and agencies), in the US and India, and pretty much everywhere, are legitimately afraid that if they ‘blink’ they might lose what they already have.

Or that if they don’t first obtain consensus opinion they won’t get new funding.

How can one then even try GEM*STAR in this environment?