EM²: Nuclear Power for the 21st Century

Presented at the Canon Institute for Global Studies Climate Change Symposium

Climate Change and the Role of Nuclear Energy

By Dr. Christina Back

February 5, 2016

This material is based upon work supported by GA IR&D.
For Nuclear Power To Play a Vital Role In Low Carbon Emissions, 21st Century Challenges Must Be Met

- Energy Resources
- Economic Competitiveness
- Siting Flexibility
- Waste Disposal
World Energy Requirements Present Major Challenges and Large Opportunities

Global Energy Consumption
EIA and Harvard Projections

At projected consumption, proven reserves will be exhausted by 2080

~ 350%

Nuclear can be a major clean-energy factor in supporting this growth
World’s Uranium and Thorium Have almost 300 Times More Energy than all Proven Oil Reserves

Exhausted by 2080

8.2 trillion BOE with thermal reactors

198 trillion BOE with fast fission reactors

- Oil
- Natural Gas
- Coal
- Uranium Thermal Reactor
- Uranium Fast Closed Cycle
- Thorium Fast Closed Cycle
Competition, Fossil Depletion and Environmental Costs Will Create Market for Nuclear and Renewables

Projected composition of energy Consumption to meet world demand

Required growth in nuclear & renewables to meet demand

However, nuclear power must be able to fill energy demand at a reasonable price
Dry Cooling Greatly Increases Available Sites

1) LWR sites are limited due to need for water cooling.
2) EM² has substantially more siting opportunities due to dry-cooling ability

<table>
<thead>
<tr>
<th>Site Requirement</th>
<th>4 x EM²</th>
<th>ALWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power, MWe</td>
<td>1060</td>
<td>1117</td>
</tr>
<tr>
<td>Minimum land area, acres</td>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>Minimum cooling water makeup, gpm</td>
<td>negligible</td>
<td>200,000</td>
</tr>
<tr>
<td>Max distance to rail, mi</td>
<td>N/A</td>
<td>20</td>
</tr>
<tr>
<td>Safe shutdown earthquake acceleration, g</td>
<td>0.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Green = no siting challenges
Yellow = 1 siting challenge
Orange = 2 siting challenges
Blue = 3 or more siting challenges

60% of U.S. is available for siting an EM² plant; only 13% is available to LWRS

The Nuclear Industry Requires a Technology Upgrade

LWRs are the workhorse for the nuclear industry, but can 60-year old technology meet the huge world energy demand in 21st century and beyond?

Problems

- **Uranium**: LWRs require large natural U resources for $^{235}$U enrichment
- **Efficiency**: Low electric output to fuel energy consumed (~33%)
- **Waste**: Low fuel utilization/efficiency result in high waste production
- **Water**: Lack of abundant cooling water inhibits nuclear power siting
- **High Cost**: LWRs cannot compete with fossil fuels in most countries
Energy Multiplier Module (EM²) is a Compact Fast Gas Reactor Optimized for 21st Century Grid

Below-ground construction negates many physical threats and improves security

• 30-year fuel life – high burnup
• Multi-fuel capable
• Reduced waste stream
• Cost competitive
• Flexible siting, no need for water cooling
• Factory built, truck transportable
• Higher efficiency – 53% net

1060 MWe EM² plants fits on 9 hectares
EM² is a Modular, Gas-Cooled, “Convert and Burn”, Fast Reactor

Specifications:

- 265/240 MWe per reactor for water/dry cooling
- 500 MWt reactor power
- 4 modules per standard plant
- 60 year plant life; 30 year core life
- 60 year dry fuel storage
- 14% average fuel burnup
- Multi-fuel capable
  - Fissile: low-enriched U or converted MOX
  - Fertile: depleted U, natural U, spent LWR fuel or thorium

Two reactor systems on one seismically isolated module
Reduced Capital Cost: Use Building Block Module Pair to Reduce Construction Time to 42 Months

EM² module pair

EM² reactor aux. bldg.

AP1000 reactor auxiliary building (China installation) same size as entire EM² module pair
EM² Primary Coolant System includes Power Conversion within 2-Chamber Containment

Passive Direct Reactor Auxiliary Cooling System (DRACS)

Containment

Generator

Turbo-Compressor and Recuperator

Reactor Core

Power Conversion Unit (PCU)

Reactor Module
Reactor System: Long-Burn Core Extracts Most of Its Energy From Fertile Uranium or Thorium

<table>
<thead>
<tr>
<th>Starter</th>
<th>Fertile</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEU: ~ 11.6%</td>
<td>Depleted uranium</td>
</tr>
<tr>
<td>Transuranics</td>
<td>Used nuclear fuel</td>
</tr>
<tr>
<td>Mixed U/Pu oxides</td>
<td>Natural uranium</td>
</tr>
<tr>
<td>Recycled EM² discharge</td>
<td>Thorium</td>
</tr>
</tbody>
</table>
EM² Fuel is Designed to Meet the Challenge of a 30-Year Burn

Active core

Tri-bundle

91 rods per hex-bundle

UC fuel pellet in SiC-SiC clad

Reflector
High Efficiency: High Temperature + Combined Brayton/Organic Rankine Cycle

53% net (water cooling)
48% net (dry cooling)*

Combined cycle

850°C
210°C

* Based on U.S. geographical and seasonal mean temps

Test of high-speed permanent magnet rotor

* Based on U.S. geographical and seasonal mean temps
EM² DRACS Based on Natural Circulation Cooling

- Air Outlet
- DRACS Air-H₂O Heat Exchanger 7m x 10m x .5m
- DRACS Exterior Structure
- Hot Water Line
- Cold Water Line
- Back-up Jet Pump
- Flexible Joints
- DRACS Air-H₂O Heat Exchanger
- DRACS He-H₂O Heat Exchanger
- Reactor Auxiliary Building
- DRACS He-H₂O Heat Exchanger And Sprinklers
- Air Inlet
- DRACS He-H₂O Heat Exchanger

Dimensions:
- 16.5 m
- 8.5 m
- 13.5 m
Station Blackout
Cooldown on only one DRACS loop

500 CM² Primary System Breach
Cooldown on only one DRACS loop;
Containment pressure reaches 100 psig
Waste Reduction: Benefits from High Temperature and Radiation Resistant Materials

One LWR produces ~600 tonnes of nuclear waste over 30 years

4-unit EM² produces 80% less waste over the same period

For EM² closed cycle, waste is further reduced to 97%

\[
\begin{align*}
\frac{1}{1.6} \times \frac{1}{3} & \approx \frac{1}{5} \\
60\% \text{ more efficient than LWR} & \quad \text{Higher burnup} \quad \text{The fuel of LWR}
\end{align*}
\]
EM\textsuperscript{2} Cuts Energy Costs by 40%

5\% Cost of Capital

Levelized Cost of Electricity, 2012 dollars per MWh

<table>
<thead>
<tr>
<th>System</th>
<th>Cost (2012 dollars/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1060 MWe 4-unit EM\textsuperscript{2}</td>
<td>$20 - $40</td>
</tr>
<tr>
<td>1118 MWe Light Water Reactor</td>
<td>$50 - $70</td>
</tr>
</tbody>
</table>

- Fuel
- Capital costs
- Operations and maintenance
EM² Provides a Firm Basis for the Nuclear Power to Reduce CO₂ Emissions

- **Energy Resources** - EM² burns $^{238}\text{U}$ and $^{232}\text{Th}$ thereby extending nuclear energy resources by a factor of thousands.

- **Economically Viable** – EM² reduces the cost of electricity to make it affordable in the world market

- **Water Resources** – EM² does not require water cooling thereby enabling siting in more locations and preserving precious water resources

- **Waste Reduction** – EM² reduces the amount of nuclear waste relative to current thermal reactor technology by a factor of five for once through and by a factor of 30 for recycle.