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Climate Change and the Role of Nuclear Energy

By
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Is Nuclear Power Required for Carbon-Free Power Production?

- World energy demand likely to increase by 50% by 2040

- Current non-carbon energy consumption:
  - Hydro: 3.8%
  - Geothermal: 0.1%
  - Nuclear: 2.6
  - Solar, wind: 0.8
  - Total: 7.3%

- Solar and wind can, in principle, meet most energy needs but requires large land consumption, more networks and expensive energy storage.

- Nuclear can be a base-load option but must be economically competitive.

Failure to develop safe, economically competitive nuclear plants and versatile use of nuclear energy will prolong use of fossil fuels.
## Desirable Characteristics for a 21st Century Nuclear Plant in Combination with Non-Carbon Renewables

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Very Safe</strong></td>
<td>Major accident probability $&lt; 10^{-6}$/reactor-yr</td>
</tr>
<tr>
<td>Competitive economics</td>
<td>Power cost must be $&lt; \text{fossil fuel power cost}$</td>
</tr>
<tr>
<td>Greatly reduced waste</td>
<td>More efficient use of fuel resources</td>
</tr>
<tr>
<td>Better fuel flexibility</td>
<td>$^{235}\text{U}$, $^{238}\text{U}$, transuranics, thorium, LWR waste</td>
</tr>
<tr>
<td>Siting flexibility</td>
<td>Water cooling not required</td>
</tr>
<tr>
<td>Proliferation resistant</td>
<td>No heavy element separation (e.g. plutonium)</td>
</tr>
<tr>
<td>Load following</td>
<td>Pick up load from solar and wind fluctuations</td>
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</table>
New Technologies Are Key to Assuring Nuclear Power’s Place in Meeting Future World Energy Demands

- Convert-and-burn core physics
- Silicon carbide composite structures
- Advanced fuels
- High temperature systems
- Asynchronous, high-speed generators
- Proliferation resistant spent fuel recycling
General Atomics Is Developing an Advanced Reactor for the 21st Century to Fit with Non-Carbon Renewables

Four-module EM² plant:
• 1,060 MWe for evaporative cooling
• 960 MWe for dry-cooling
• 9 hectares

Characteristics
• High fuel utilization (5 x LWR for single cycle)
• Reduced high level waste (1/5 x LWR for single cycle)
• High thermal efficiency (water -53%; no water -48%)
• Total passive safety; (licensable by U.S. NRC)
• Rapid load following
• 42-month construction, (road shippable modules)
• Secure, protected, below-grade construction
• Competitive power cost
EM² is a Modular, Gas-Cooled, “Convert and Burn”, Fast Reactor

Specifications:
- 265/240 MWe per module 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 MOX fissile
  - Fertile: depleted U, natural U, spent LWR fuel or thorium
Reduced Capital Cost: Use Building Block Module Pair to Reduce Construction Time to 42 Months

EM² module pair

EM² reactor aux. bldg.

Seismic isolation

AP1000 reactor auxiliary building (China installation) same size as entire EM² module pair
EM² Primary Coolant System Includes Power Conversion within 2-Chamber Containment
Reactor System: Long-Burn Core Extracts Most of Its Energy From Fertile Uranium or Thorium

- Control drum drive
- Shutdown rod drive
- Top neutron shield
- Top reflector
- Control drum
- Bottom reflector
- Bottom neutron shield
- Coolant flow
- Core barrel
- Core support floor
- Outer flow annulus
- Side neutron shield
- Side reflector
- To/from PCU

Graph:
- $k_{effective}$ vs Time, Yr
- Peak = 1.02971 at Yr 14

Table:

<table>
<thead>
<tr>
<th>Starter</th>
<th>Fertile</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEU: ~ 12%</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 EM$^2$ 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 assembly

SiC composite clad

UC fuel pellet in SiC-SiC clad

Control drums

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

Power conversion unit

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

Combined cycle

850°C

210°C

React to cooling tower

Turbo-compressor cartridge

Test of high-speed permanent magnet rotor

* Based on U.S. geographical and seasonal mean temps
GA Has Established a State-of-the-Art Fuel Fabrication Laboratory

Prototypes have been fabricated and samples prepared for irradiation.
Silicon Carbide Composite (SiC-SiC) Has High Temperature Strength Like Ceramic and Ductility Like Metal

Crystalline SiC_β fiber

Pyrocarbon interface

SiC_β matrix infiltration

SiC_β-SiC_β component

Fuchishima

Both Zircaloy and SiC_β/SiC_β meet design condition

SiC-SiC cladding does not melt during loss of cooling accident
Accident Tolerant Fuel (ATF) Improves Safety and Fuel Cycle Economics for Many Nuclear Technologies

Fuels:
- UC
- UN
- UCO
- UCO
- UO₂ (<1200°C)
- THC
EM² is 100% Passively Safety with Redundant and Backup Safety Features

- Two 100% passive core cooling loops with active backup
- Two independent and diverse reactivity shutdown mechanisms
- Sealed containment rated at 100 psig peak
- High negative temp coefficient can reduce power to zero if core heats up within fuel damage limits
- Volatile fission products removed from the core
- Core catcher to prevent re-criticality
- Passive containment liner cooling
DRACS Passive, Redundant Core Heat Rejection to Air – No Need for Water Resupply

2 independent passive systems reject afterheat to air

- Air duct
- Water-to-air HX
- Reactor auxiliary bldg
- Back-up Jet pumps

Pressurized Primary System

- Temperature °C
- Time (Seconds)

Depressurized Primary System

- Temperature °C
- Time (Seconds)

Fuel limit
Clad limit
EM² Meets the Desired Characteristic of “Very Safe” without Compromising Economic Competitiveness

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<tr>
<th>Accident</th>
<th>EM² Response</th>
<th>Result</th>
</tr>
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<tr>
<td>Station blackout (Fukushima)</td>
<td>DRACS passive heat rejection to air</td>
<td>No fuel failure – plant restart</td>
</tr>
<tr>
<td>Station blackout plus loss of coolant accident</td>
<td>DRACS passive heat rejection to air</td>
<td>No fuel failure – plant restart after inspection</td>
</tr>
<tr>
<td>Station blackout plus failure to SCRAM</td>
<td>Large neg. temp coef reduces power to near zero – DRACS passive heat rejection to air</td>
<td>No fuel failure – plant restart after inspection</td>
</tr>
<tr>
<td>Station blackout plus loss of coolant plus loss of DRACS</td>
<td>1 hour to fuel failure; 12 hours to vessel failure; heat removal via containment cooling</td>
<td>Containment remains intact – no fission product release</td>
</tr>
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</table>
Better Resource Utilization

EM² Closes the Fuel Cycle to Reduce Waste

1st Generation

LOW ENRICHED URANIUM STARTER

SNF* - AIROX - EM² Fuel

ENERGY

DISCHARGE

No Need for Uranium Enrichment After 1st Generation

2nd Generation

Heavy Metals, Actinides & Balance of Fission Products

SNF* - AIROX - EM² Fuel

ENERGY

Nth Generation

Fission Products Removed by AIROX

STORAGE

*Spent Nuclear Fuel
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
Discharge Waste Comparison: 1.1 GWe LWR vs. EM\(^2\)

Waste after 30 years

- **Uranium**
- **Plutonium**
- **Fission products**

**LWR discharge waste is primarily actinides**

**EM\(^2\) discharge is fission products**

Only 3% of LWR waste

Fission product activity and heat generation decays much faster than actinides
Voloxidation (AIROX): Dry-Gas Extraction Is a Proliferation Resistant Method of Recycling Spent Fuel

Disassemble LWR/EM² used fuel

Pierce or shear cladding

Cycle oxidation/reduction to separate clad & achieve particle size
- $O_2$ in Ar, 400° C
- $H_2$ in Ar, 600° C

Volatile fission product release:
(up to 100% $^3$H, $^{14}$C, I, Kr, Xe, Cs, Rb, ...)

Milling & blending with recycled EM² fuel

Spent hard-ware

Demonstration plant built by KAERI

Feedstock

EM² New Fuel Fabrication
Archimedes: A Proliferation Resistant Method to Addressing Spent Fuel

- Separates fission products from actinides (avoids difficult chemistry)
- Not capable of TRU separation by element or isotopes (non-proliferation)
- Supportive of new reprocessing-free closed fuel cycle options
Reducing Proliferation Risk

- Enrichment only for the first generation
- Convert and burn in situ with a conversion ratio of approximately one (no breeding) and produce a discharge that is self-protecting for decades
- Improved fuel utilization through a closed fuel cycle without heavy metal separation
- Fission product waste stream with no proliferation value
Factors Affecting the Cost of Nuclear Power

Tornado chart for ± 10% variation from base

- **Cost of Capital**: Reduce the risk premium
- **Net Efficiency**: Increase net efficiency
- **Nonfuel Capital Cost**: Reduce components, increase system power density
- **Operating Cost**: Reduce staffing
- **Fuel Cost**: Increase burnup

Mean of Net Present Value
EM² Levelized Power Cost vs Cost of Capital
(Based on U.S. Construction and Risk Premiums)

- EM² at 8.4%
- EM² at 8.4%
- Nat. gas CCGT - U.S.
- Non-nuclear construction
- Lower risk SMR construction
- Large LWR construction

ALWR at 9.7%
1) LWR sites are limited due to need for water cooling.
2) EM² has substantially more siting opportunities due to dry-cooling ability

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<tr>
<th>Site Requirement</th>
<th>4 x EM²</th>
<th>ALWR</th>
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<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>
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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