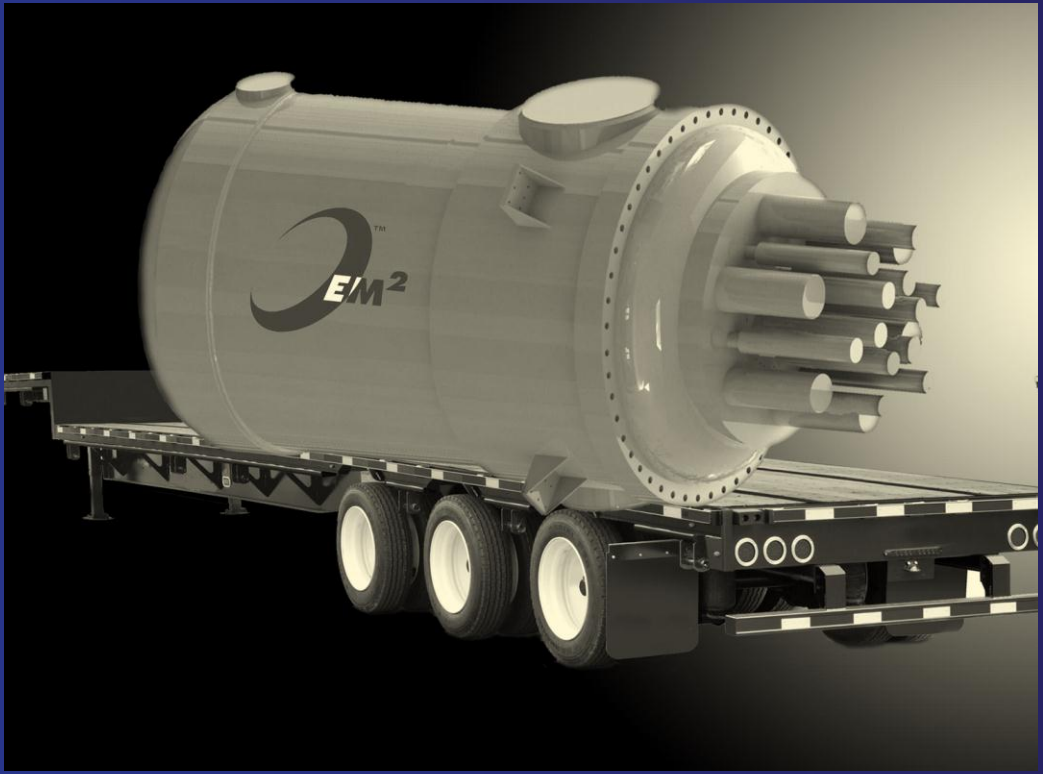
EM²: A Compact Gas-Cooled Fast Reactor for the 21st Century

Presented at the Canon Institute for Global Studies Climate Change Symposium

Climate Change and the Role of Nuclear Energy



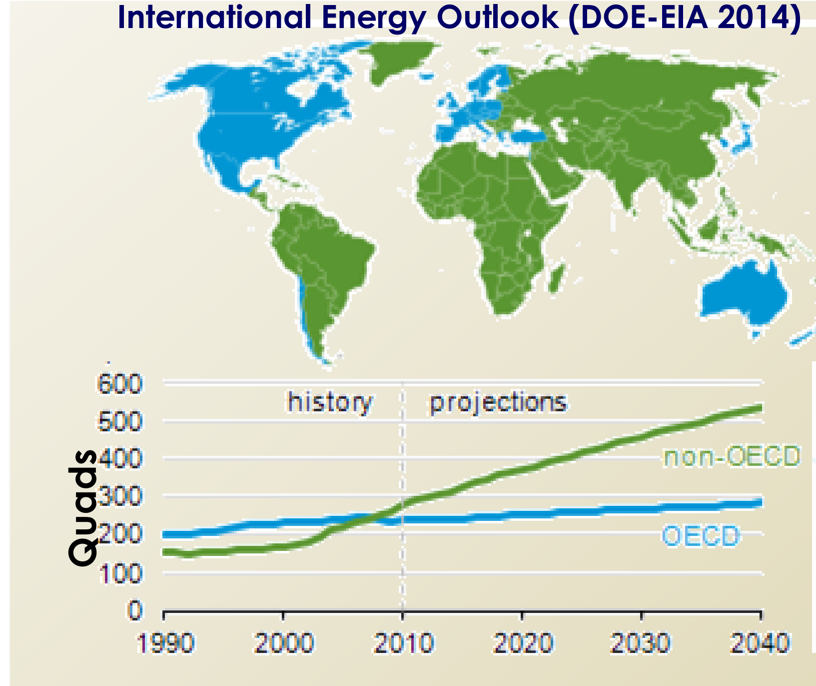
By

Dr. Robert W. Schleicher

February 3, 2015

GENERAL ATOMICS

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
	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

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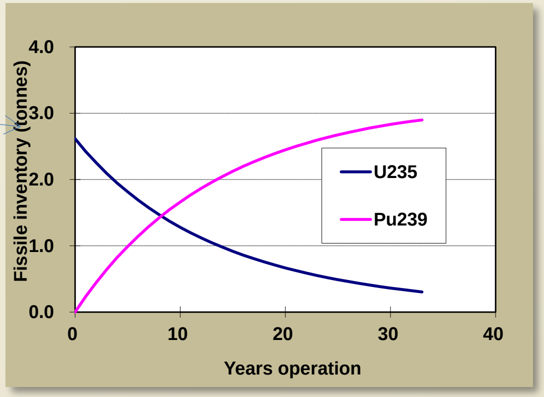
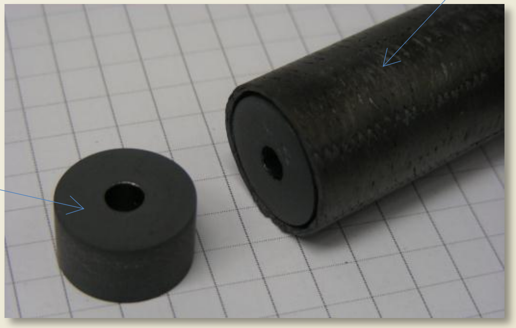
Desirable Characteristics for a 21st Century Nuclear Plant in Combination with Non-Carbon Renewables

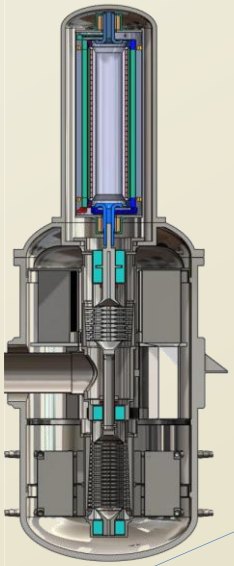
Very Safe	Major accident probability < 10^{-6}/reactor-yr
Competitive economics	Power cost must be ≤ fossil fuel power cost
Greatly reduced waste	More efficient use of fuel resources
Better fuel flexibility	^{235}U, ^{238}U, transuranics, thorium, LWR waste
Siting flexibility	Water cooling not required
Proliferation resistant	No heavy element separation (e.g. plutonium)
Load following	Pick up load from solar and wind fluctuations

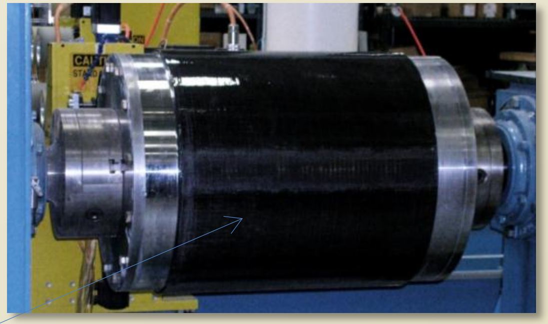
New Technologies Are Key to Assuring Nuclear Power's Place in Meeting Future World Energy Demands

- Convert-and-burn core physics
- Silicon carbide composite structures
- Advanced fuels
- High temperature systems
- Asynchronous, high-speed generators
- Proliferation resistant spent fuel recycling





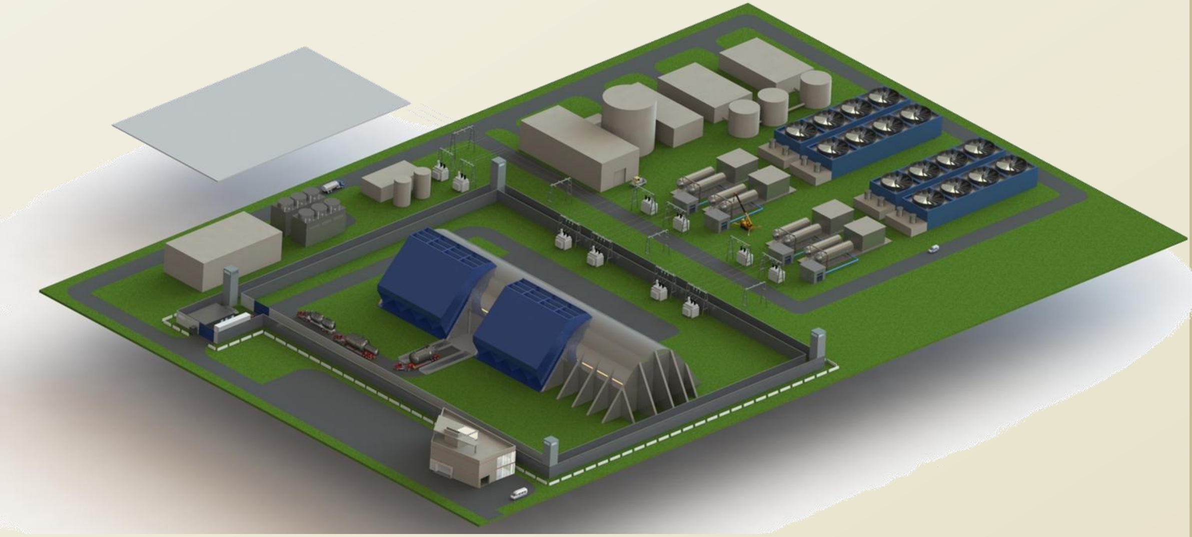




General Atomics Is Developing an Advanced Reactor for the 21st Century to Fit with Non-Carbon Renewables

Four-module EM² plant:

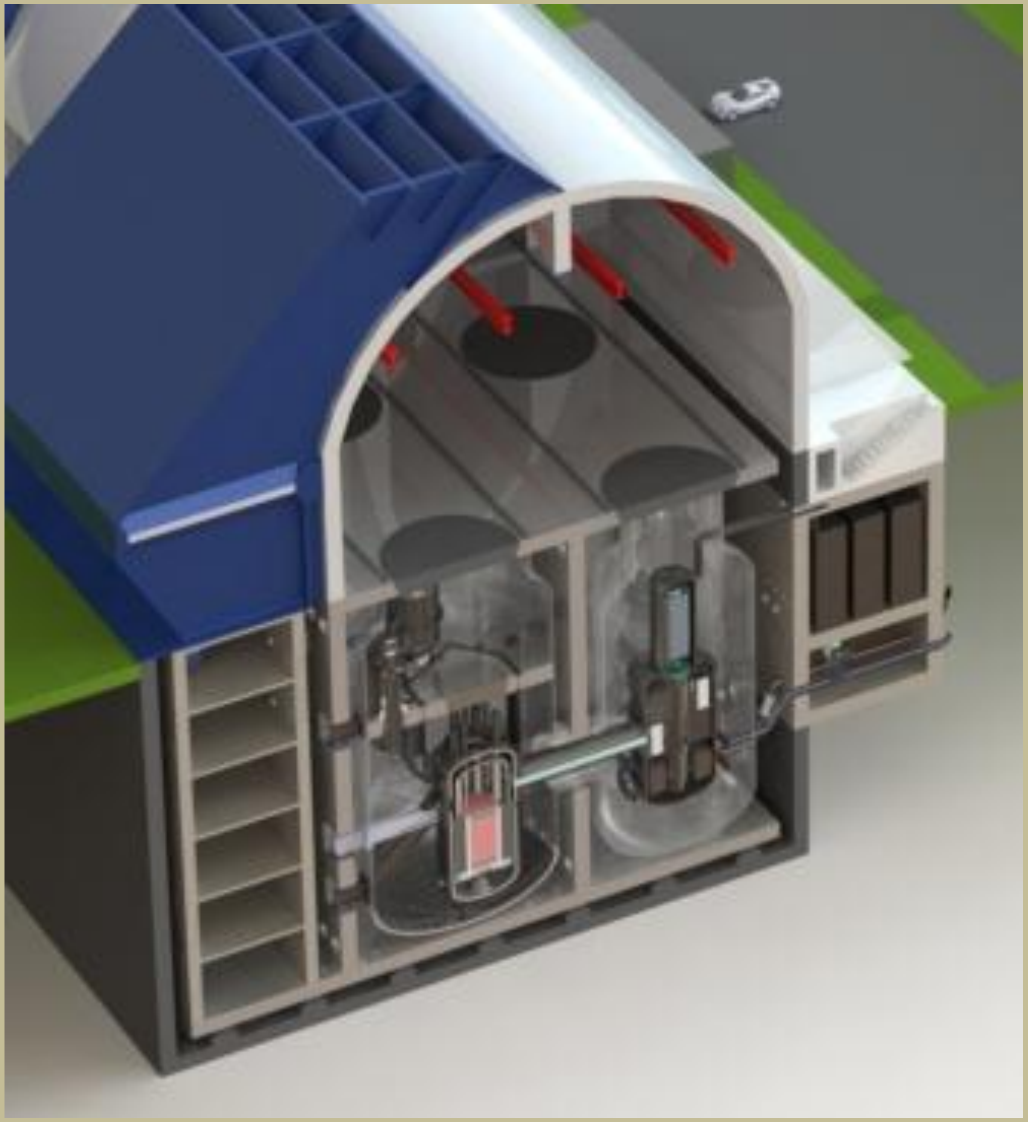
- 1,060 MWe for evaporative cooling
- 960 MWe for dry-cooling
- 9 hectares



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

EM^2 is a Modular, Gas-Cooled, "Convert and Burn", Fast Reactor



Specifications:

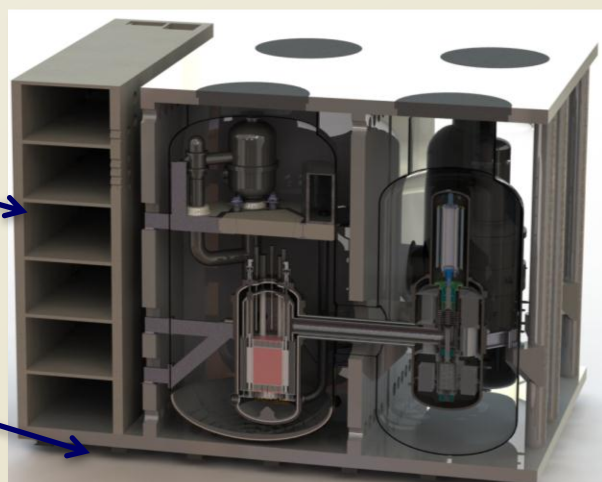
- 265/240 MWe per module for water/dry cooling
- 500 MW_t reactor power
- 4 modules per standard plant
- 60 year plant life; 30 year core life
- 60 year dry fuel storage
- 14 % average fuel burnup
- Multi-fuel capable
  - Fissile: low-enriched U or MOX fissile
  - Fertile: depleted U, natural U, spent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

Reduced Capital Cost: Use Building Block Module Pair to Reduce Construction Time to 42 Months

EM^2 module pair

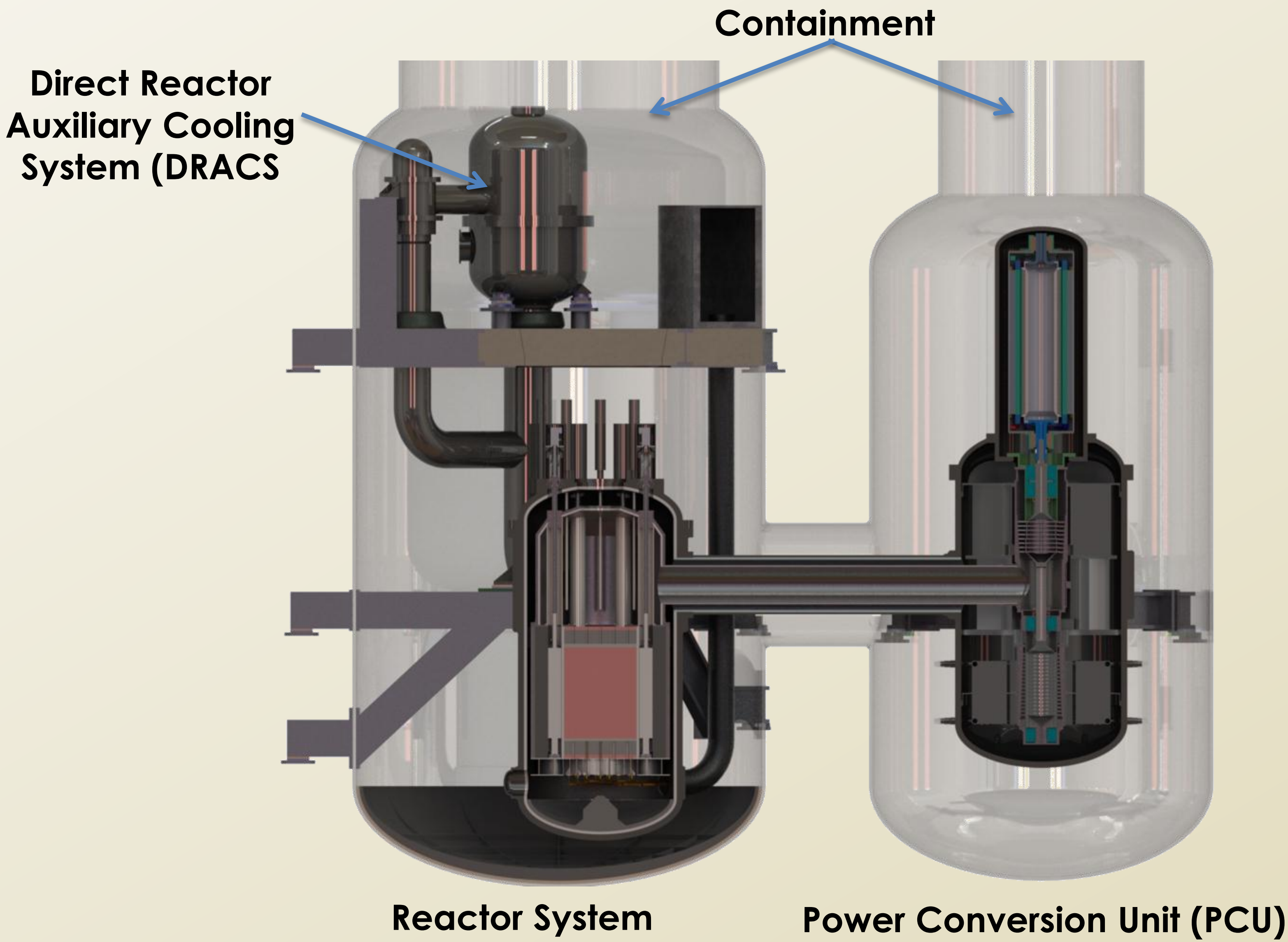
EM^2 reactor aux. bldg.

Seismic isolation

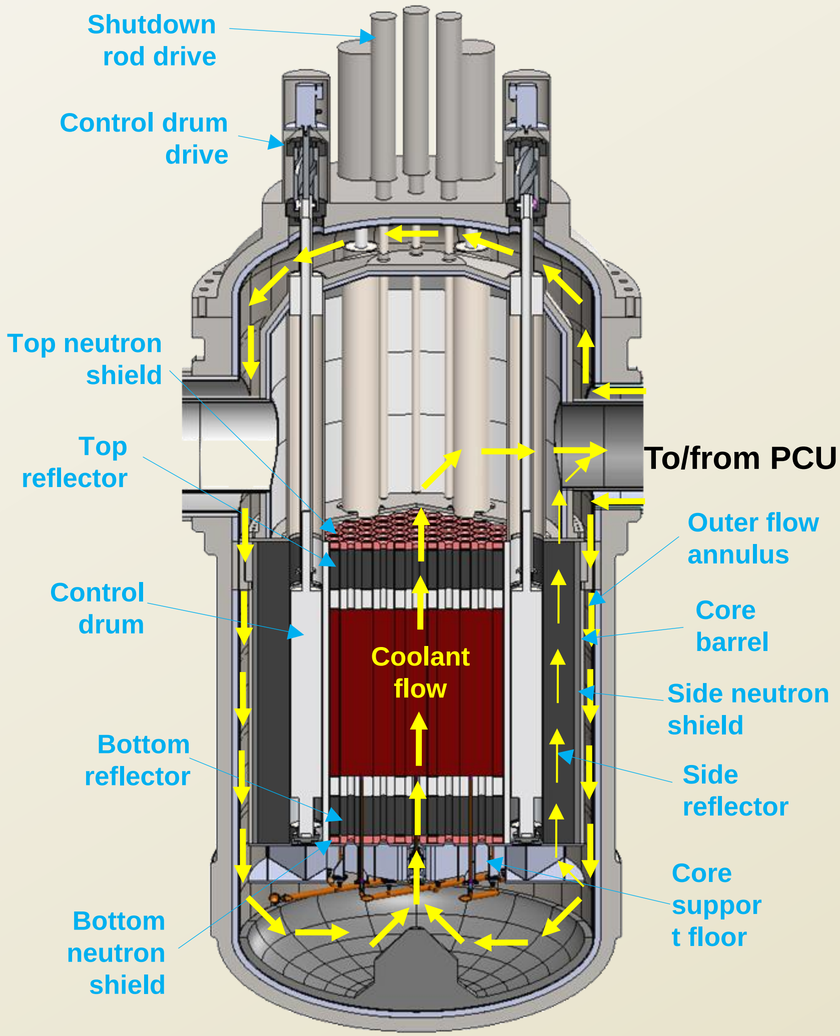


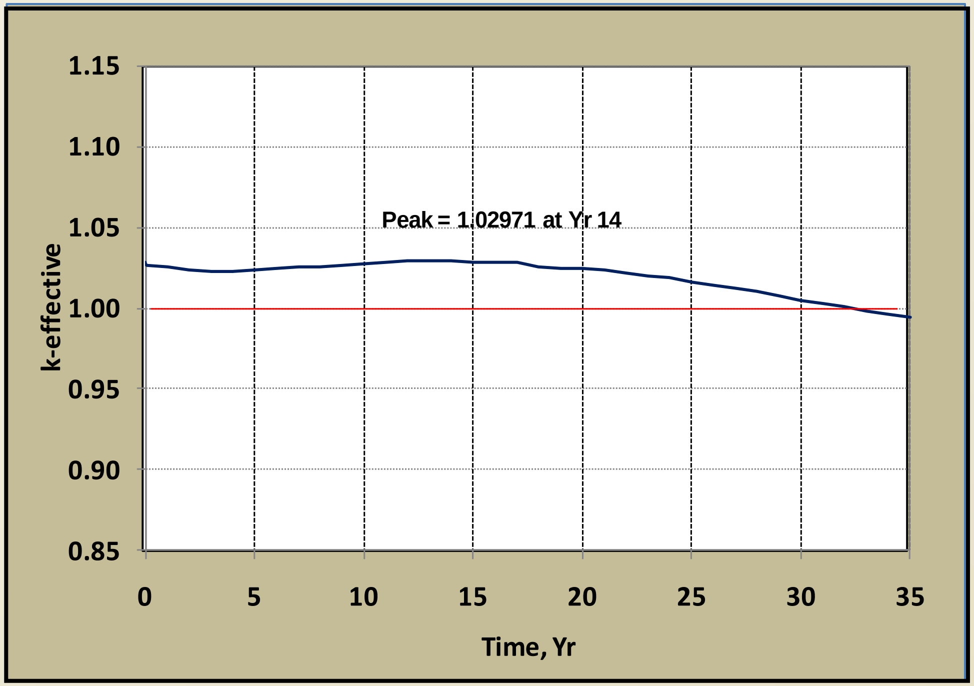
AP1000 reactor auxiliary building (China installation) same size as entire EM^2 module pair

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





Starter	Fertile
LEU: ~ 12%	Depleted uranium
Transuranics	Used nuclear fuel
Mixed U/Pu oxides	Natural uranium
Recycled EM^2 discharge	Thorium

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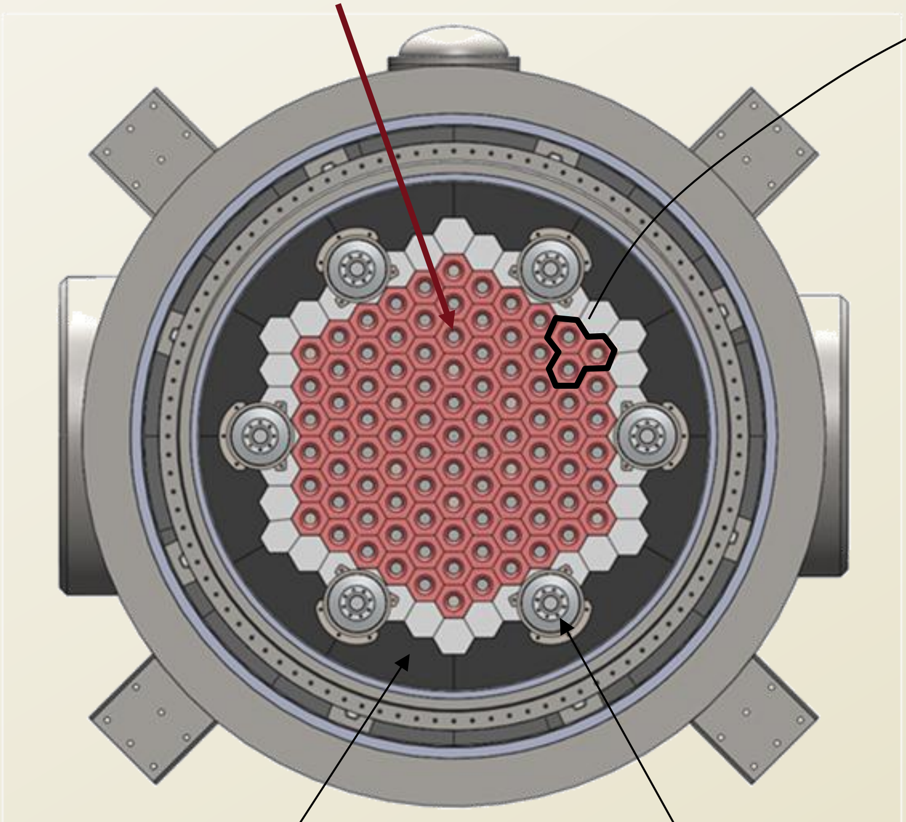
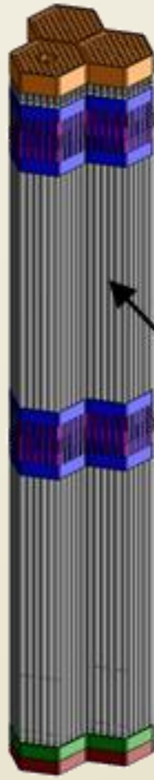
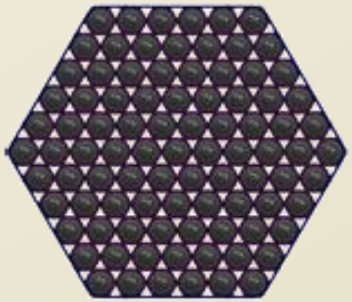
EM^2 Fuel is Designed to Meet the Challenge of a 30-Year Burn



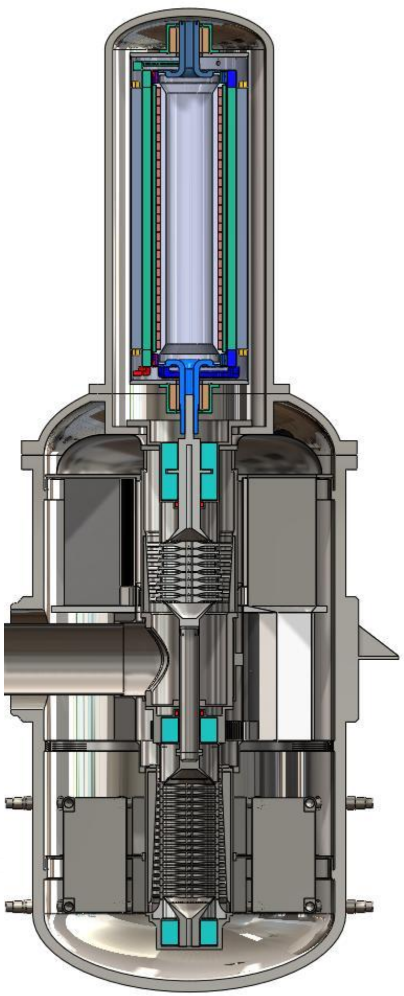




UC fuel pellet in SiC-SiC clad

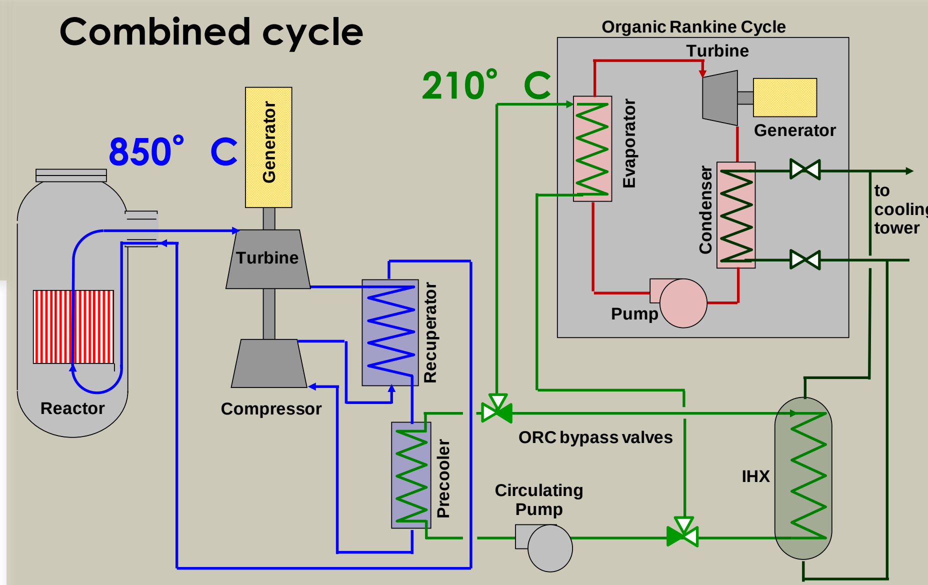
High Efficiency: High Temperature + Combined Brayton/Organic Rankine Cycle

Power conversion unit

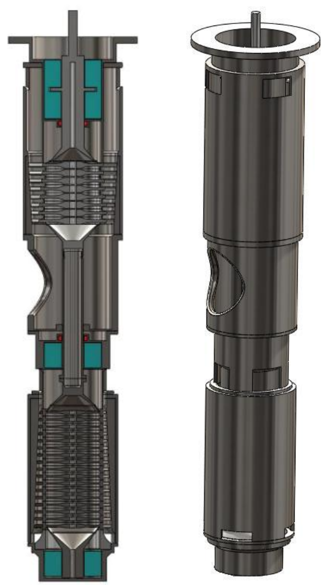


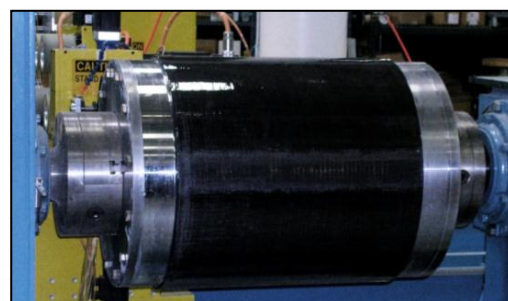
53% net
(water cooling)
48% net
(dry cooling)*

Combined cycle



Turbo-compressor cartridge





Test of high-speed permanent magnet rotor

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

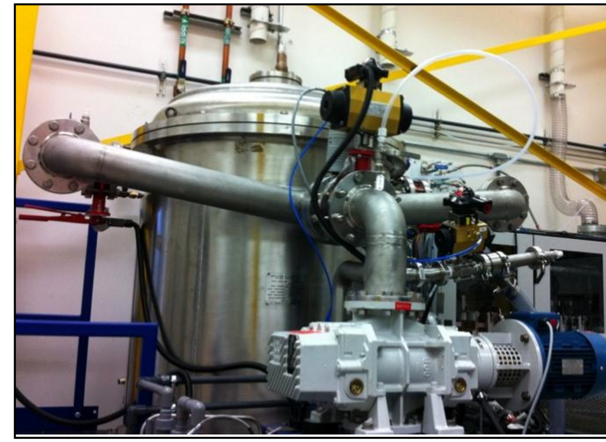
GA Has Established a State-of-the-Art Fuel Fabrication Laboratory

Sol-gel column

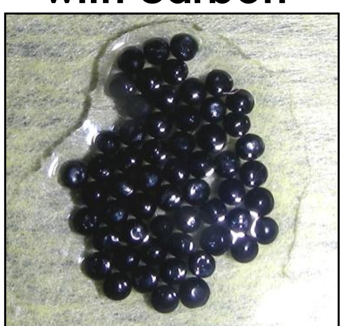
Sintering

Hot press

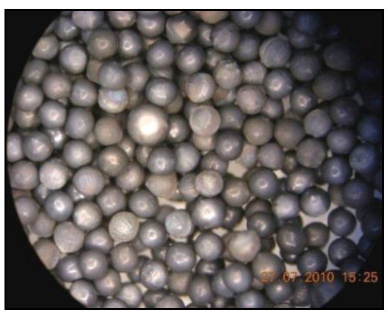
SiC coater



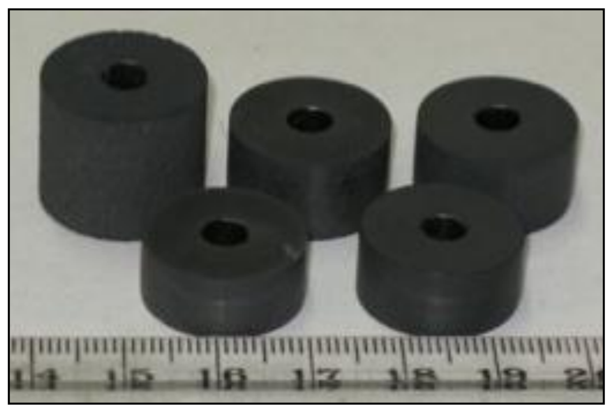
Gel particles with carbon



UC kernels



Sintered pellets

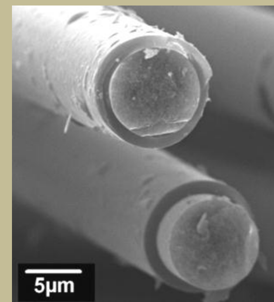


SiC composite fuel cladding

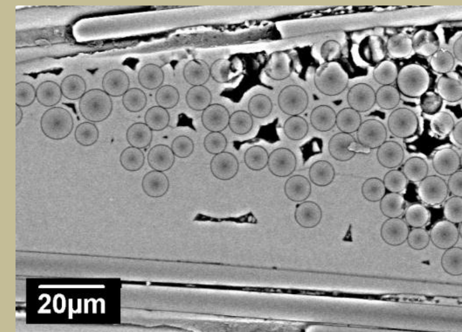
Prototypes have been fabricated and samples prepared for irradiation

Silicon Carbide Composite (SiC-SiC) Has High Temperature Strength Like Ceramic and Ductility Like Metal

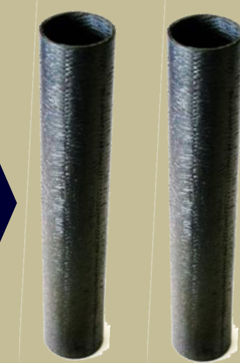
Crystalline SiC_β fiber



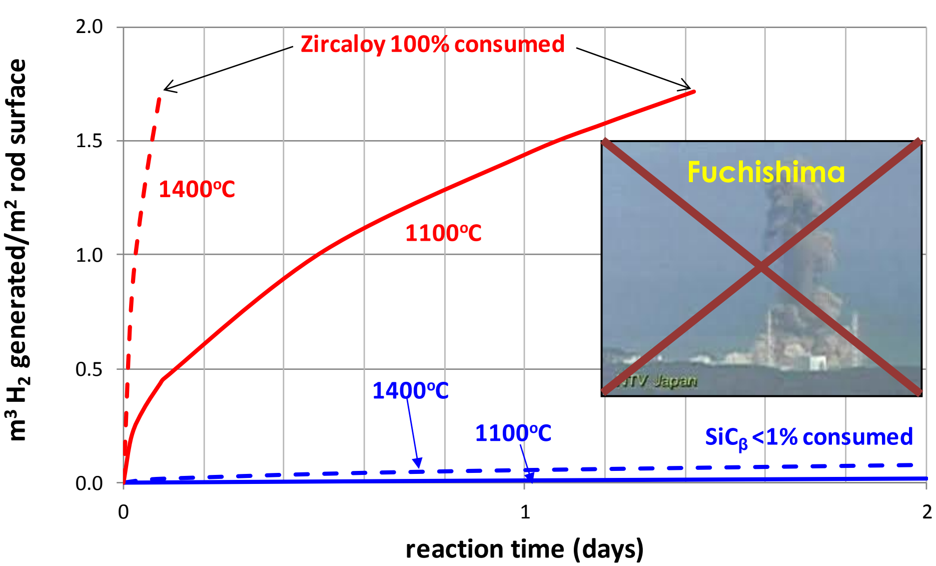
Pyrocarbon interface

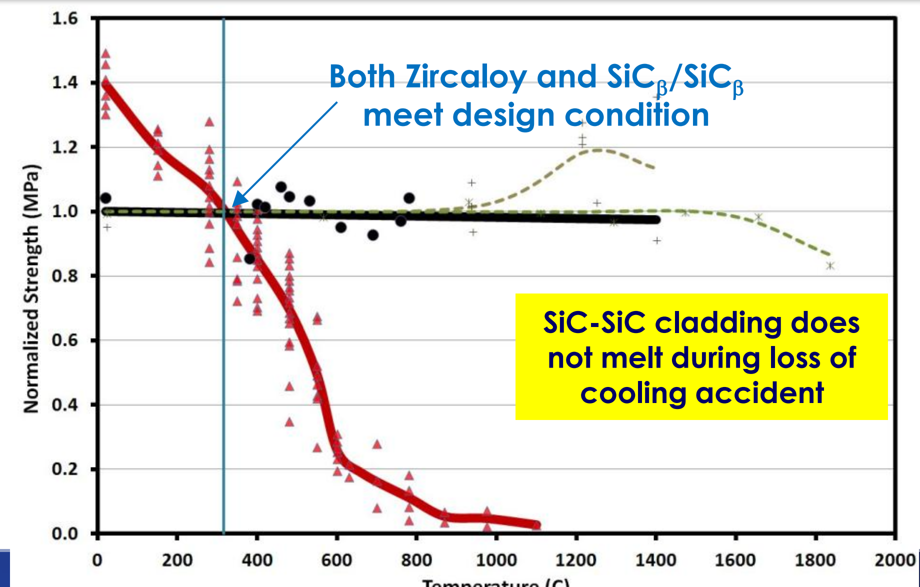


SiC_β matrix infiltration



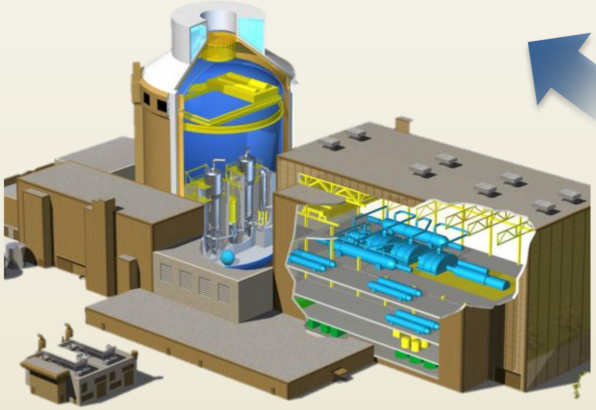
SiC_β-SiC_β component



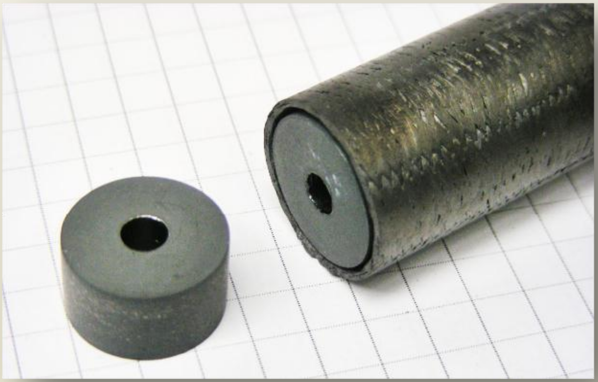


Accident Tolerant Fuel (ATF) Improves Safety and Fuel Cycle Economics for Many Nuclear Technologies

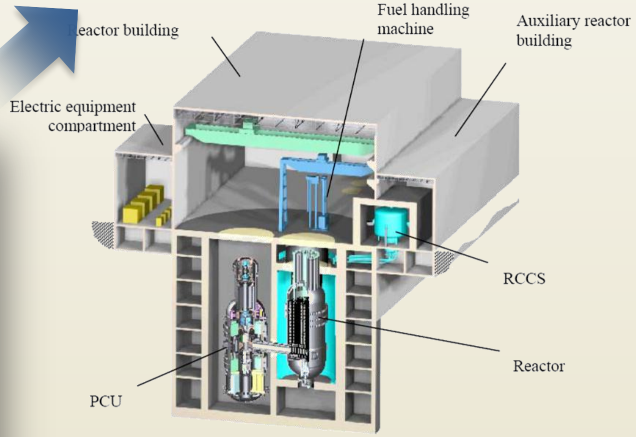
Light water reactor



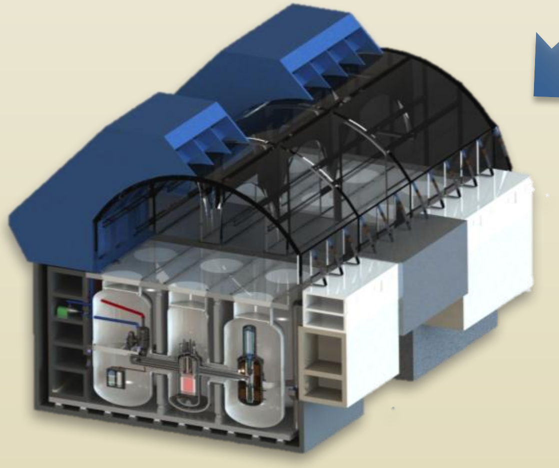
SiC composite cladding



Modular helium reactor



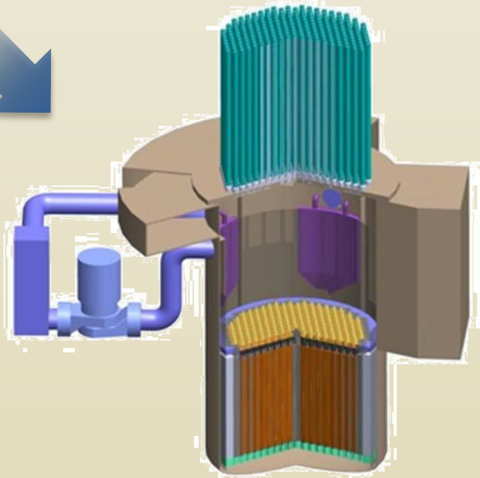
Gas-cooled fast reactor



Fuels:

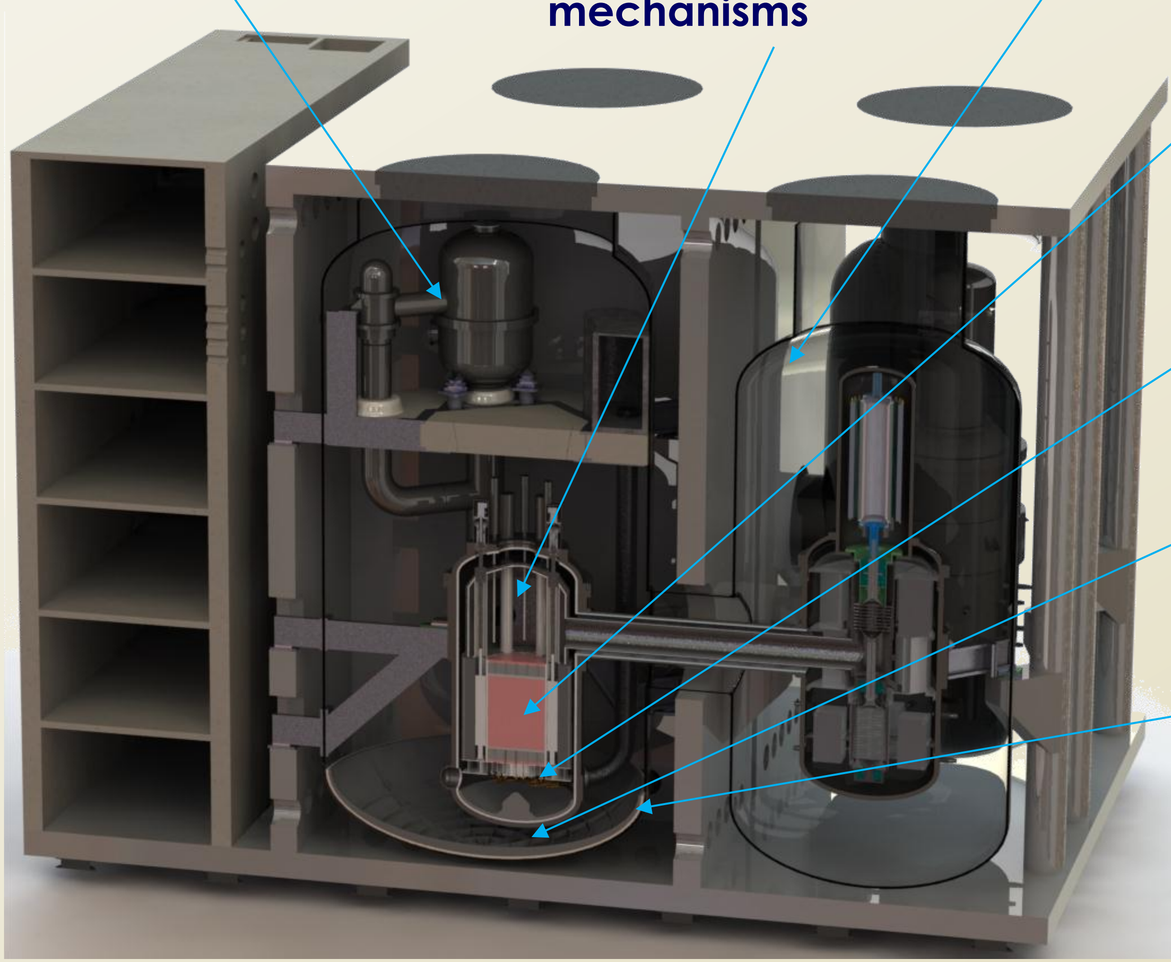
- UC
- UN
- UCO
- UO_2 (<1200°C)
- THC

Molten salt reactor



Safety

EM^2 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

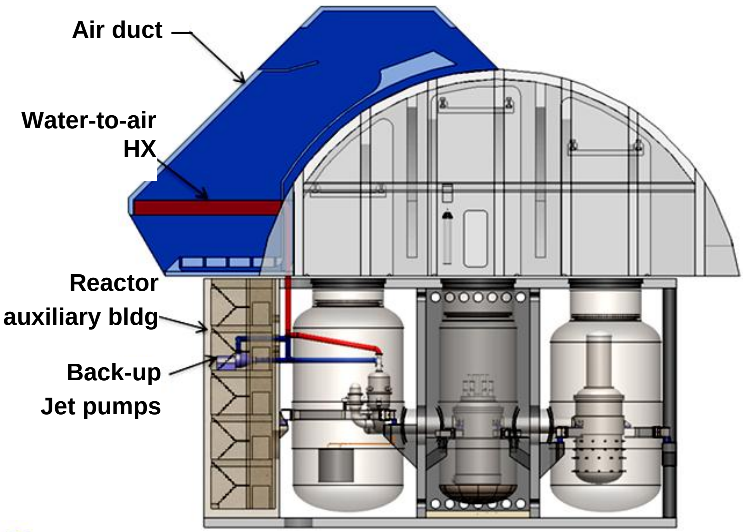
Volatile fission products removed from the core

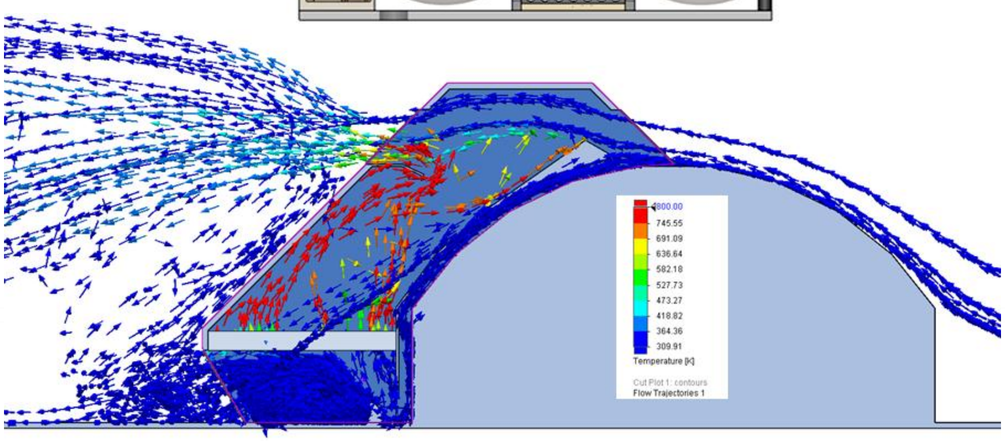
Core catcher to prevent re-criticality

Passive containment liner cooling

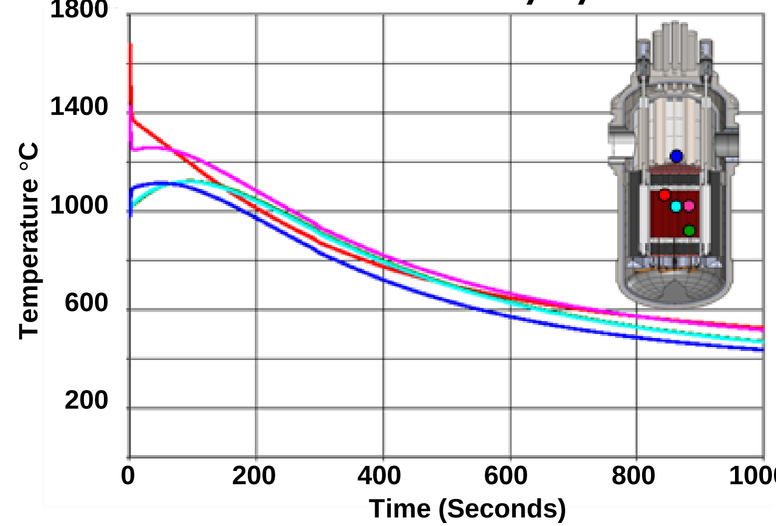
DRACS Passive, Redundant Core Heat Rejection to Air – No Need for Water Resupply

2 independent passive systems reject afterheat to air

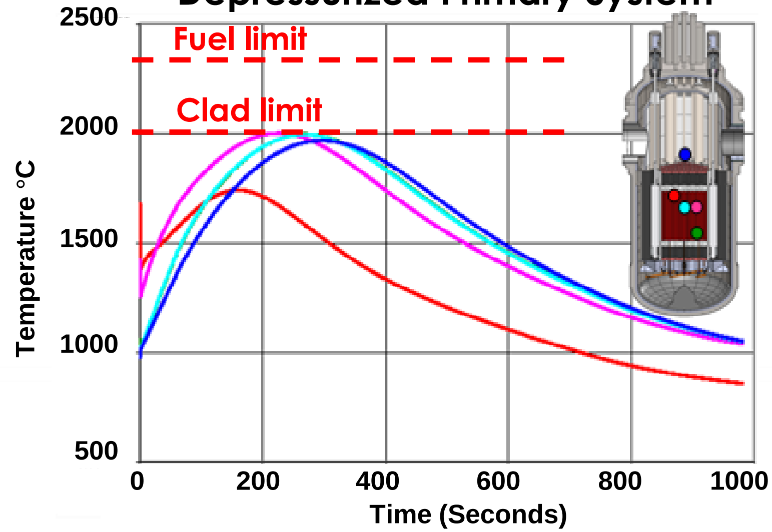




Pressurized Primary System



Depressurized Primary System

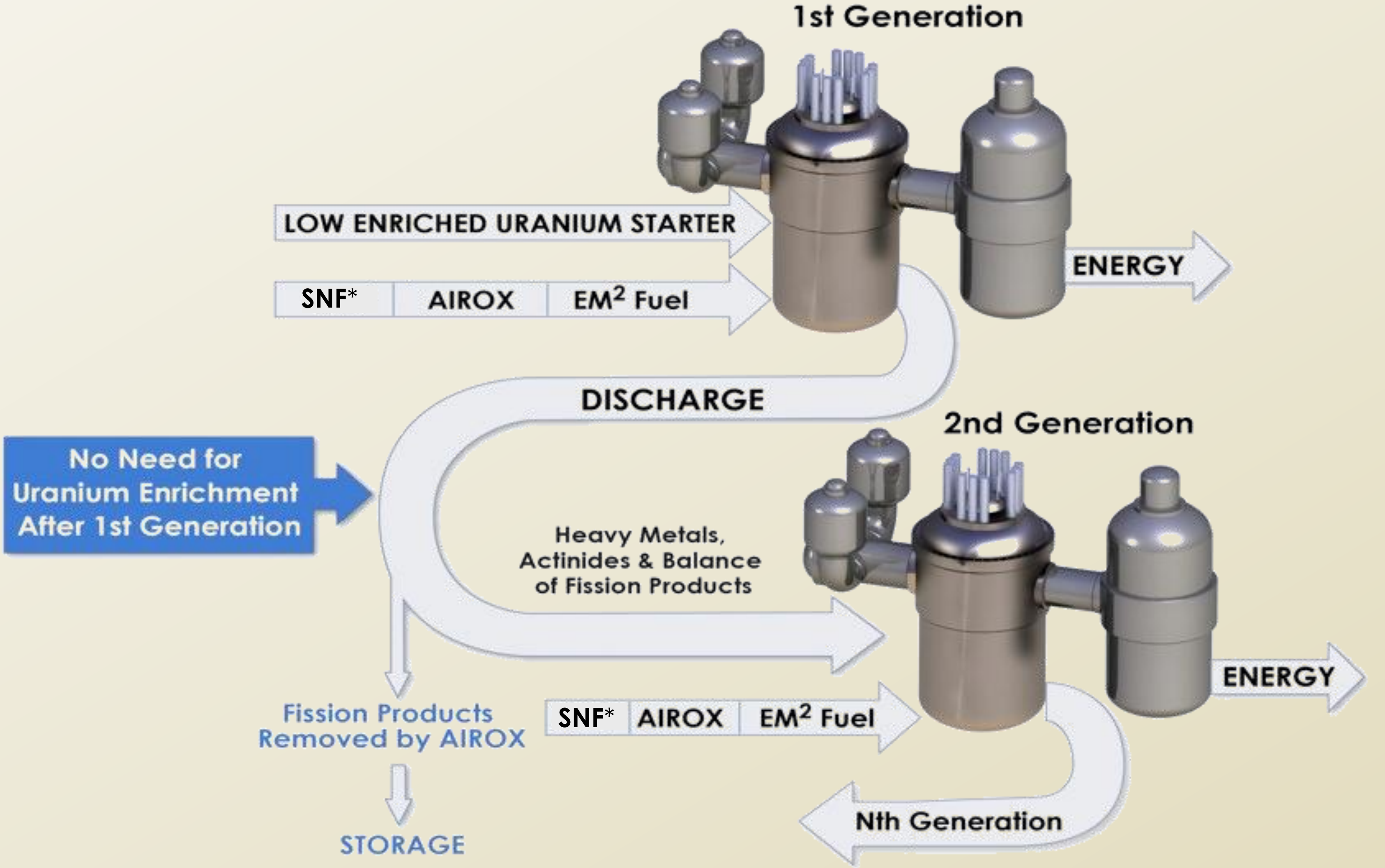


EM² Meets the Desired Characteristic of "Very Safe" without Compromising Economic Competitiveness

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

Better Resource Utilization

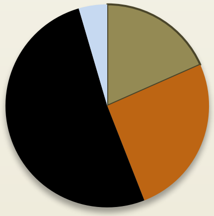
EM² Closes the Fuel Cycle to Reduce Waste



*Spent Nuclear Fuel

World's Uranium and Thorium Have almost 300 Times More Energy than all Proven Oil Reserves

Exhausted by 2080

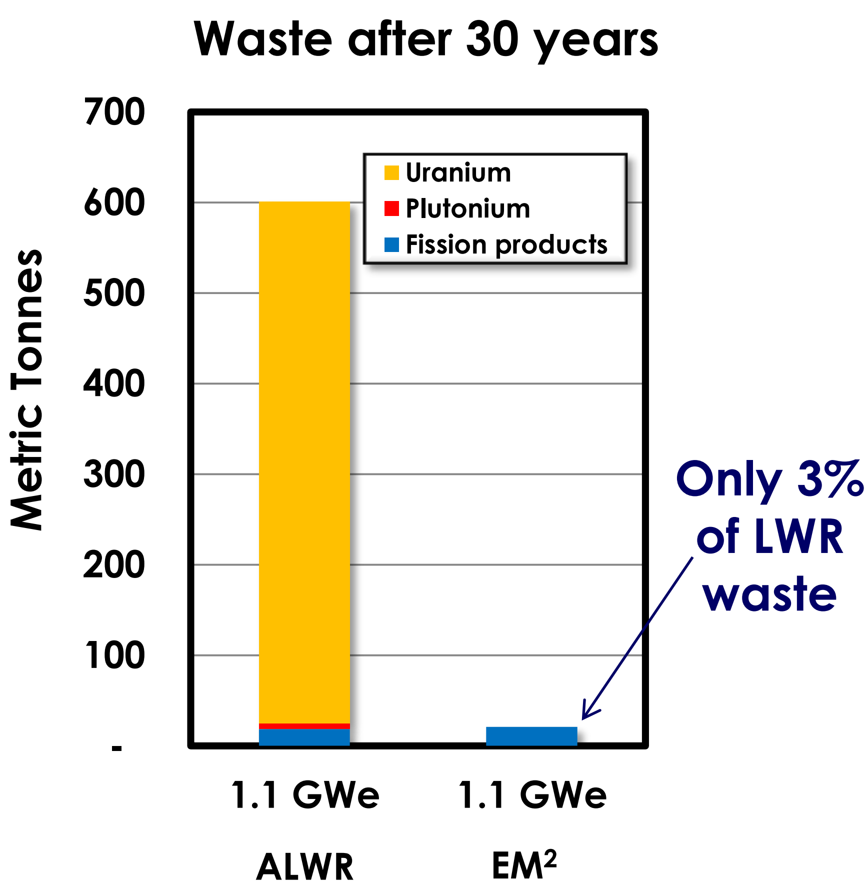


8.2 trillion BOE with thermal reactors

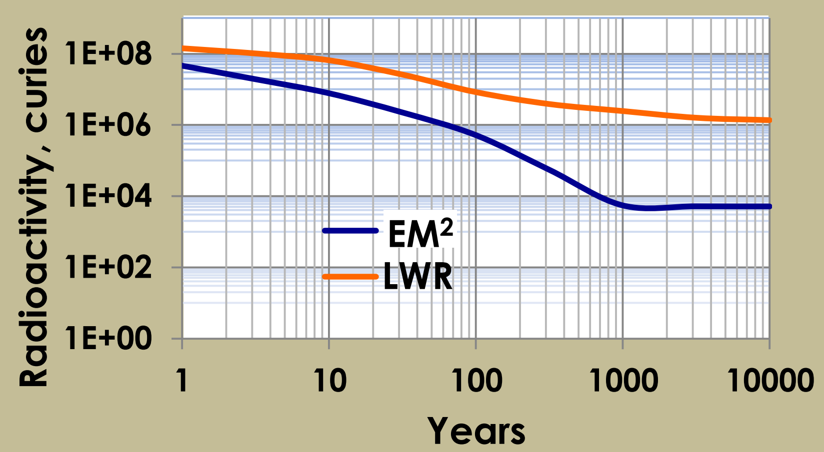
198 trillion BOE with fast fission reactors

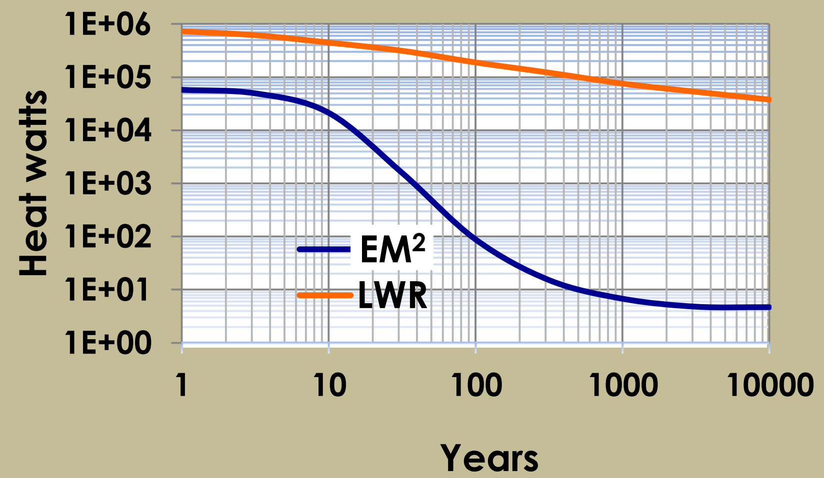
- Oil
- Natural Gas
- Coal
- Uranium Thermal Reactor
- Uranium Fast Closed Cycle
- Thorium Fast Closed Cycle

Discharge Waste Comparison: 1.1 GWe LWR vs. EM²



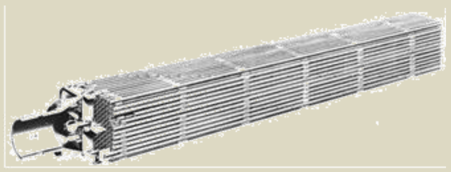
LWR discharge waste is primarily actinides
EM² discharge is fission products





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/EM^2 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

Spent hard-ware

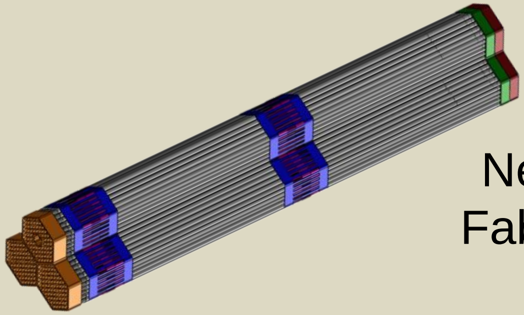
Volatile fission product release:

(up to 100% ^3H, ^{14}C, I, Kr, Xe, Cs, Rb, ...)

Feedstock

Milling & blending with recycled EM^2 fuel

Demonstration plant built by KAERI



EM^2 New Fuel Fabrication

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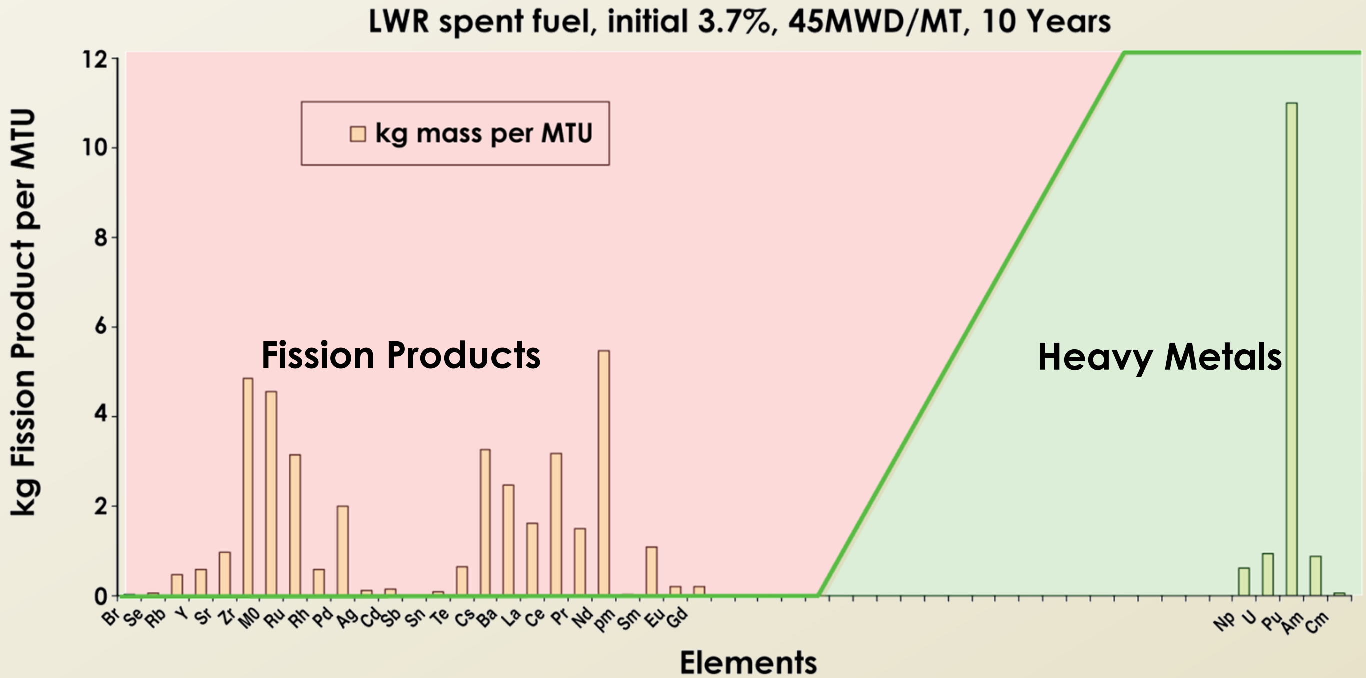
Archimedes: A Proliferation Resistant Method to Addressing Spent Fuel



- 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

Archimedes

Proliferation Resistance

Reducing Proliferation Risk

Uranium enrichment

Dry cask storage

Spent fuel storage pools

- 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

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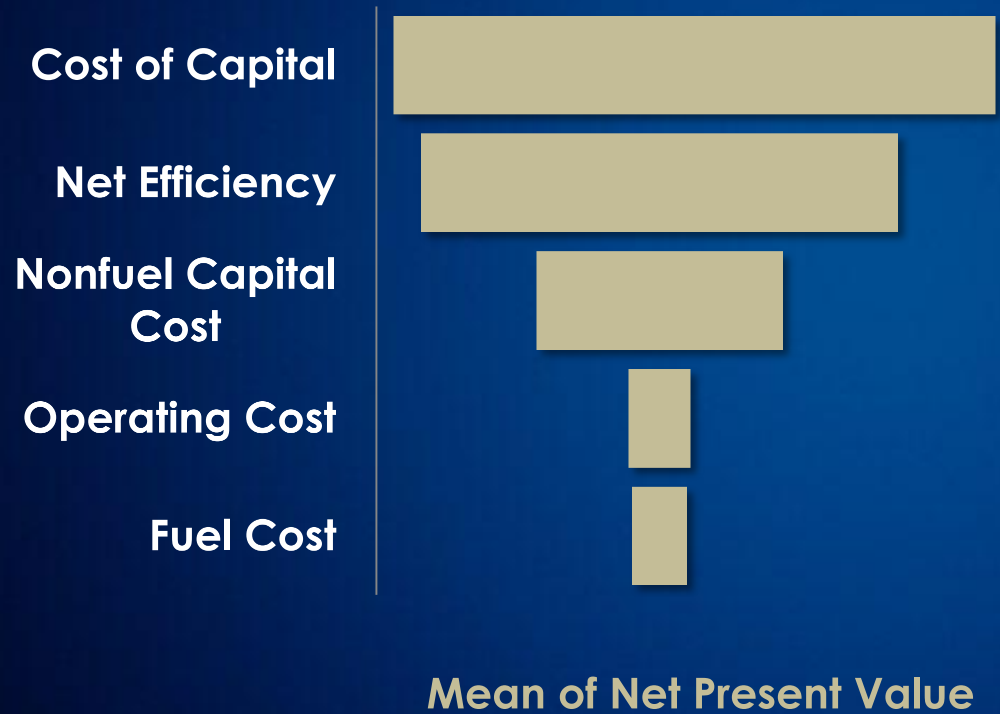
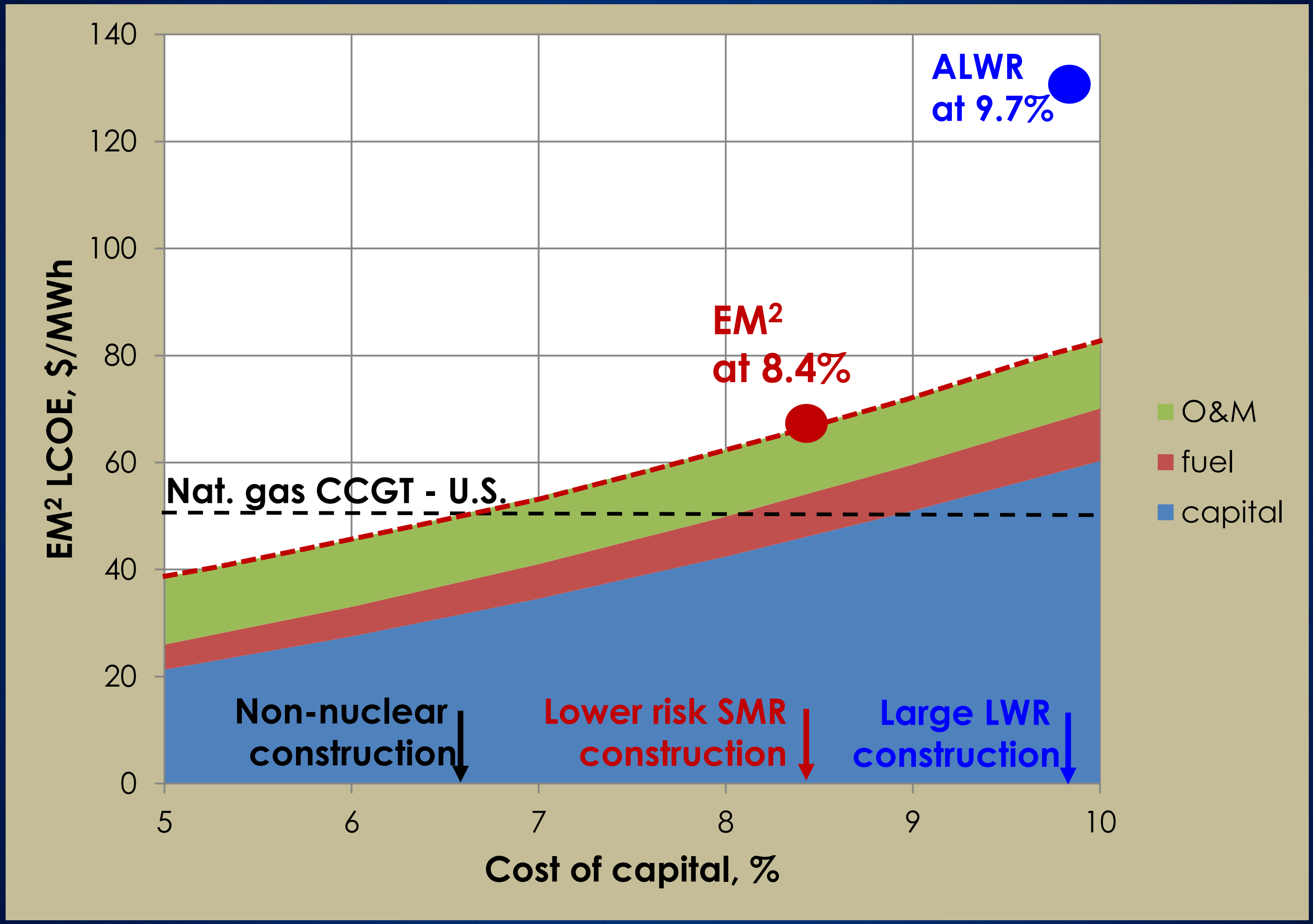
Factors Affecting the Cost of Nuclear Power

Tornado chart for ± 10% variation from base



- Reduce the risk premium
- Increase net efficiency
- Reduce components, increase system power density
- Reduce staffing
- Increase burnup

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



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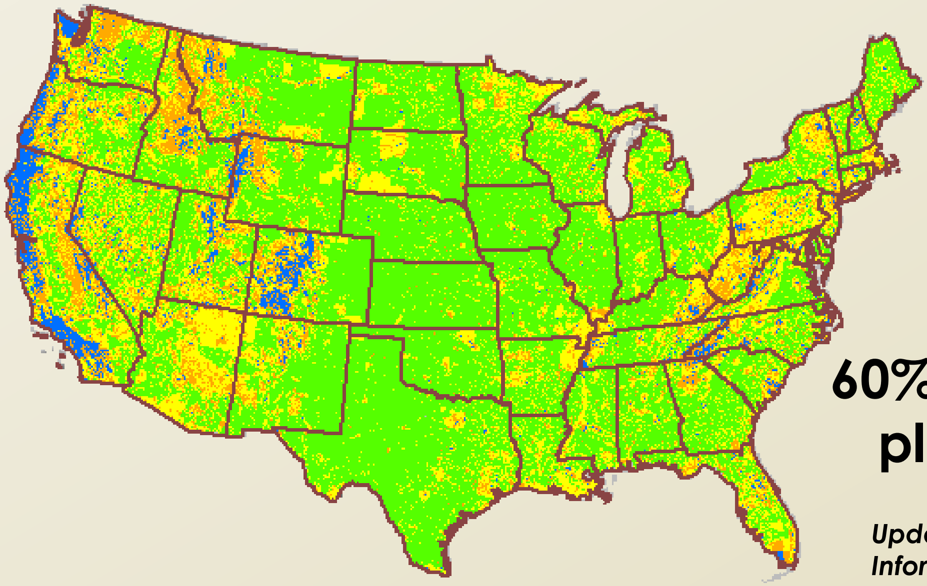
Siting Flexibility

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**

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



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

***Updated Application of Spatial Data Modeling and Geographical Information Systems (GIS) fo Identification of Potential Siting Options for Small Modular Reactors*, ORNL TM-2012/403, Sept, 2012**

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