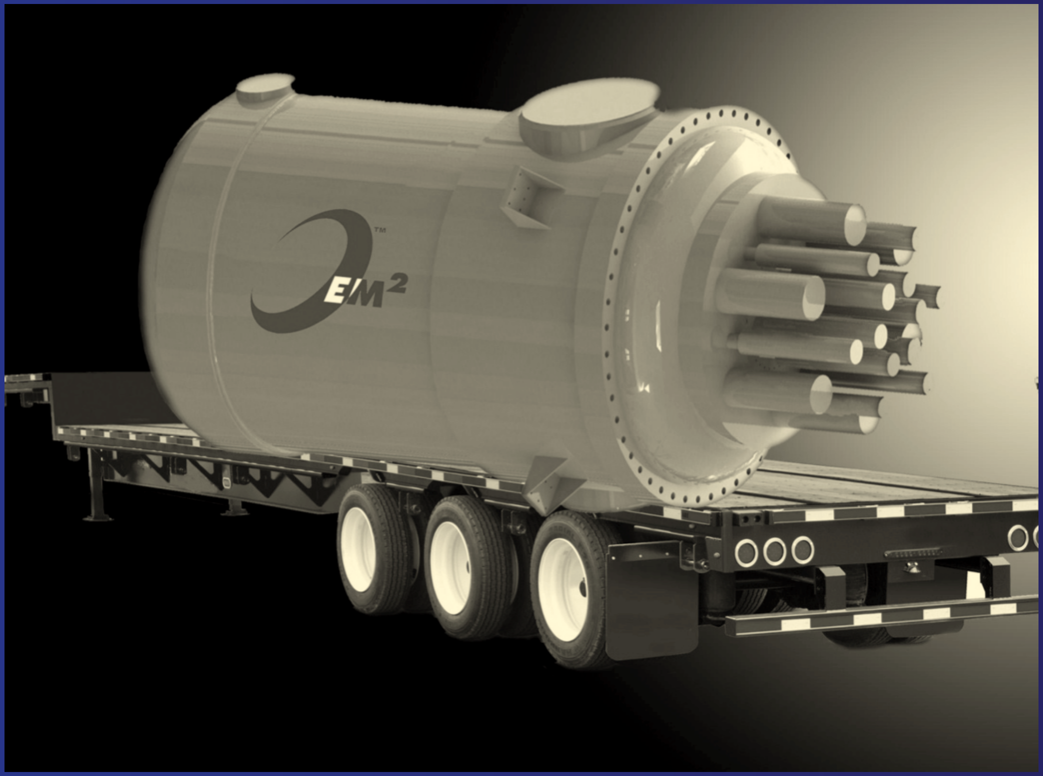
EM^2: Nuclear Power for the 21st Century

Presented at the Canon Institute for Global Studies Climate Change Symposium



Climate Change and the Role of Nuclear Energy

By

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February 5, 2016

This material is based upon work supported by GA IR&D.

GENERAL ATOMICS

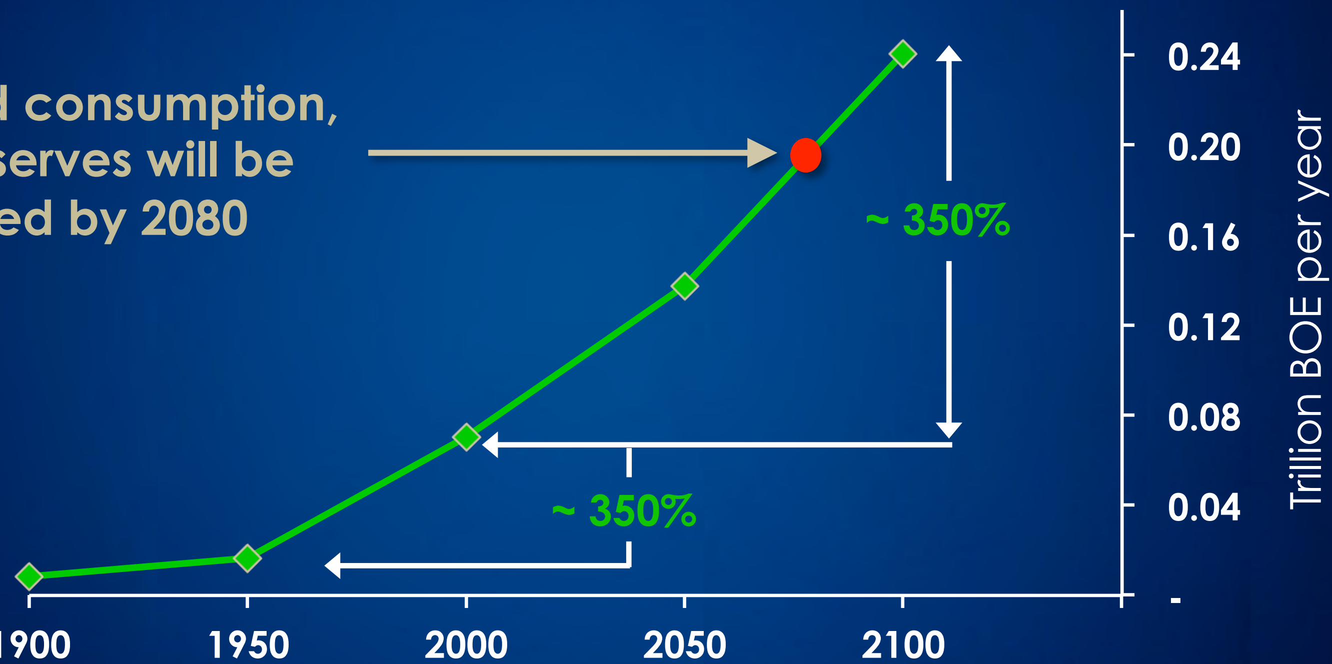
For Nuclear Power To Play a Vital Role In Low Carbon Emissions, 21st Century Challenges Must Be Met

- Energy Resources
- Economic Competitiveness
- Siting Flexibility
- Waste Disposal

World Energy Requirements Present Major Challenges and Large Opportunities

Global Energy Consumption
EIA and Harvard Projections

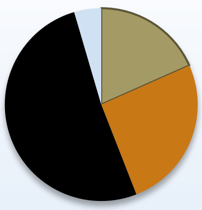
At projected consumption, proven reserves will be exhausted by 2080



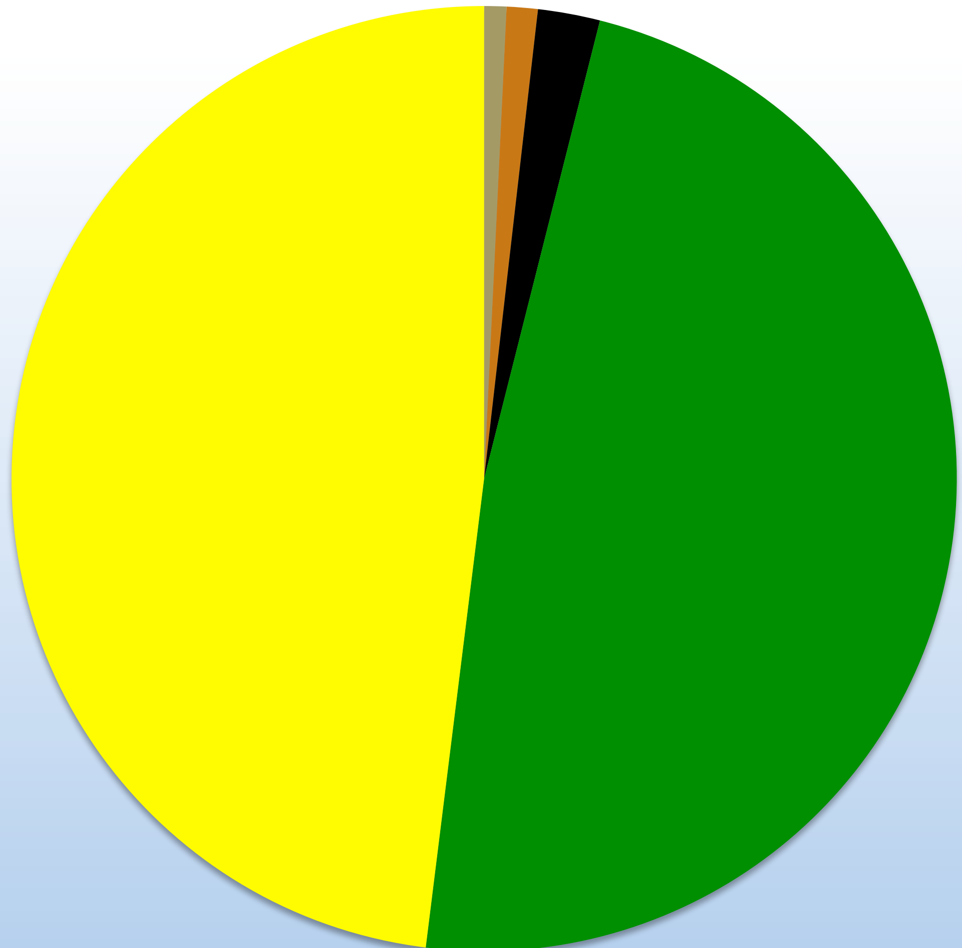
Nuclear can be a major clean-energy factor in supporting this growth

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

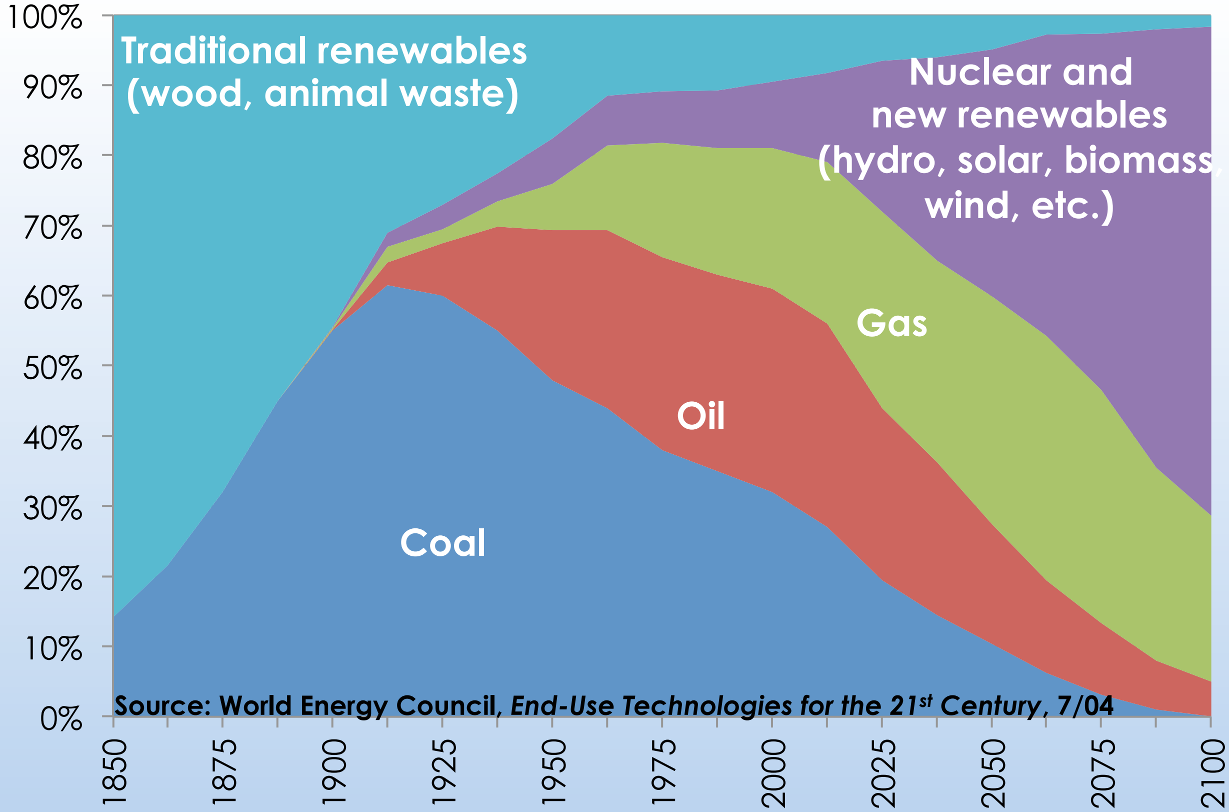


198 trillion BOE with fast fission reactors

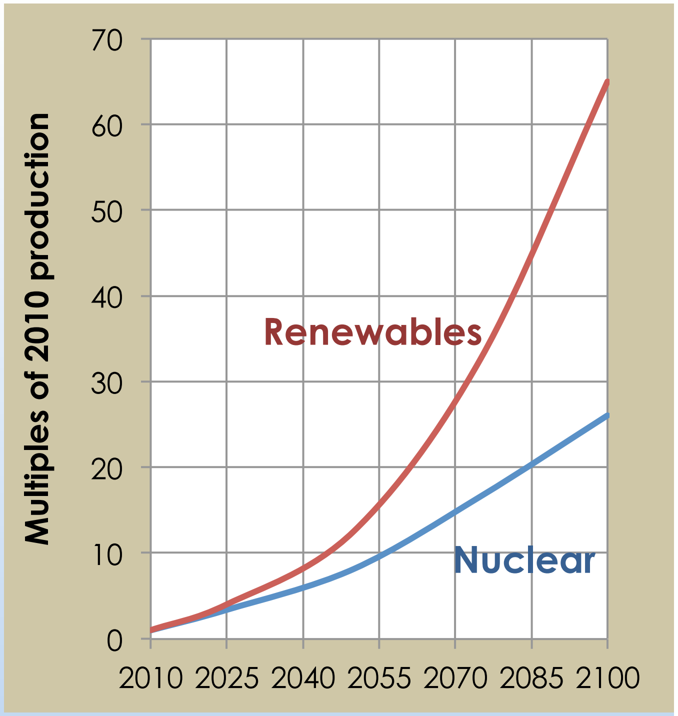
- Oil
- Natural Gas
- Coal
- Uranium Thermal Reactor
- Uranium Fast Closed Cycle
- Thorium Fast Closed Cycle

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

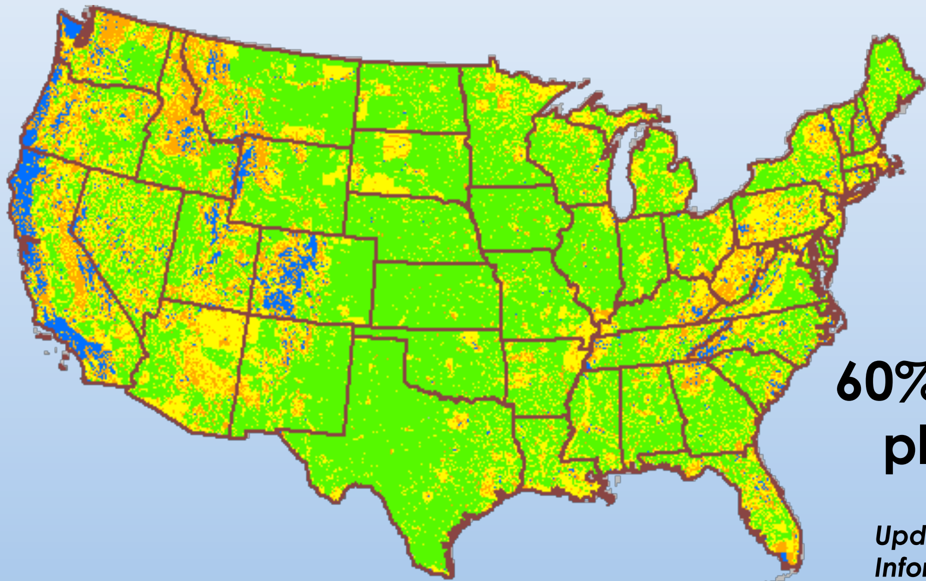
GENERAL ATOMICS

Siting Flexibility

Dry Cooling Greatly Increases Available Sites

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

Site Requirement	4 x EM^2	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 EM^2 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

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 (EM^2) is a Compact Fast Gas Reactor Optimized for 21st Century Grid

Below-ground construction negates many physical threats and improves security

1060 MWe EM^2 plants fits on 9 hectares

- 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

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

Two reactor systems on one seismically isolated module

Specifications:

- 265/240 MWe per reactor 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 converted MOX
  - Fertile: depleted U, natural U, spent LWR fuel or thorium

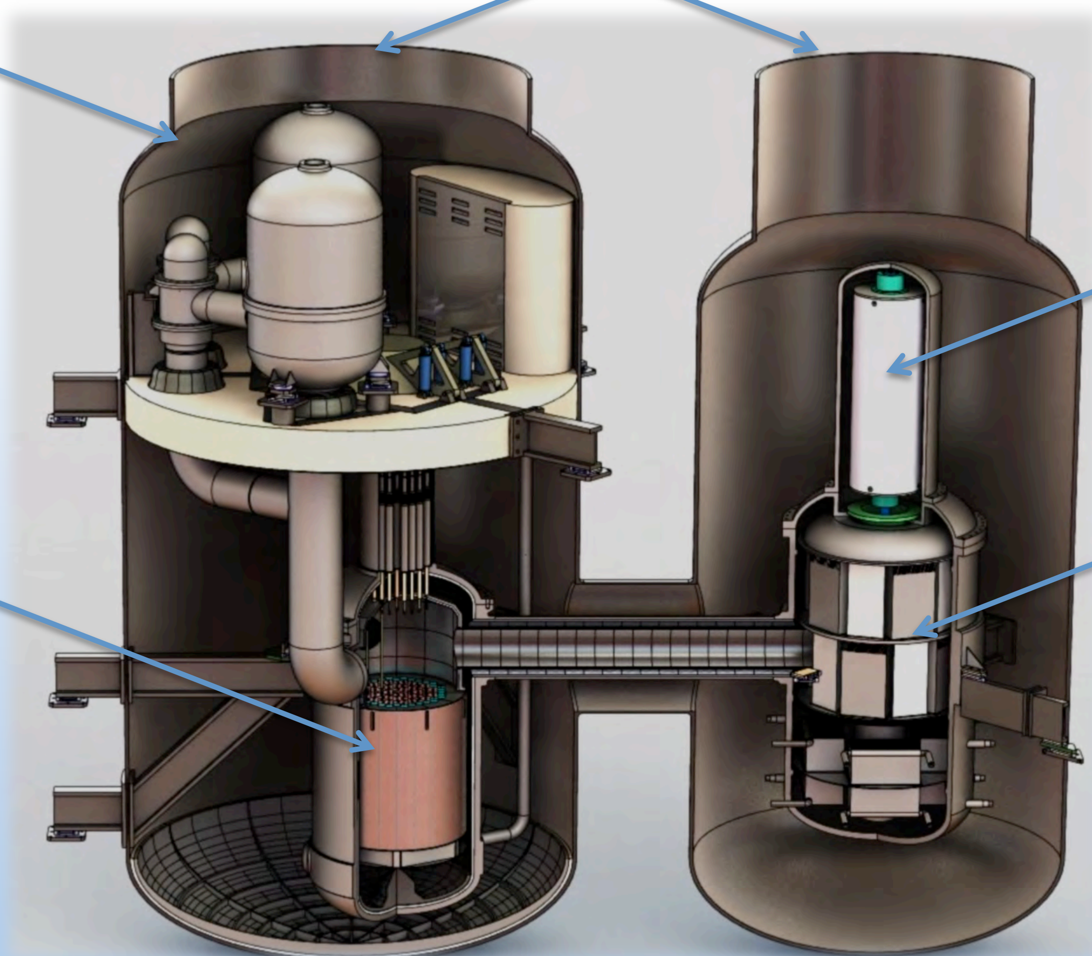
Reduced Capital Cost: Use Building Block Module Pair to Reduce Construction Time to 42 Months

EM² module pair

EM² reactor aux. bldg.

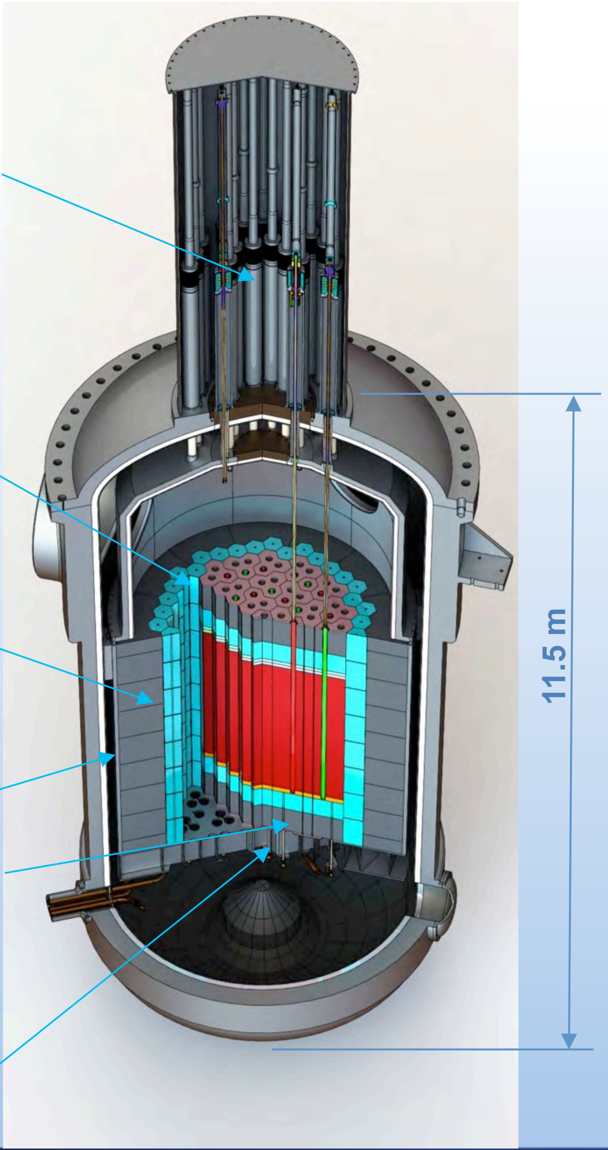
AP1000 reactor auxiliary building (China installation) same size as entire EM² module pair

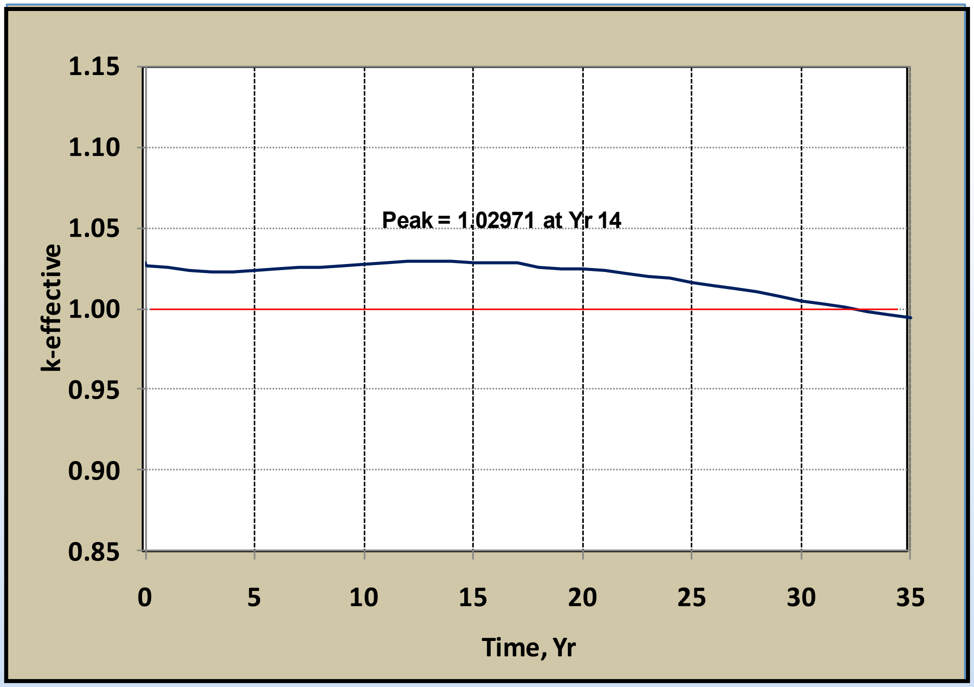
EM[2] Primary Coolant System Includes Power Conversion within 2-Chamber Containment



GENERAL ATOMICS

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



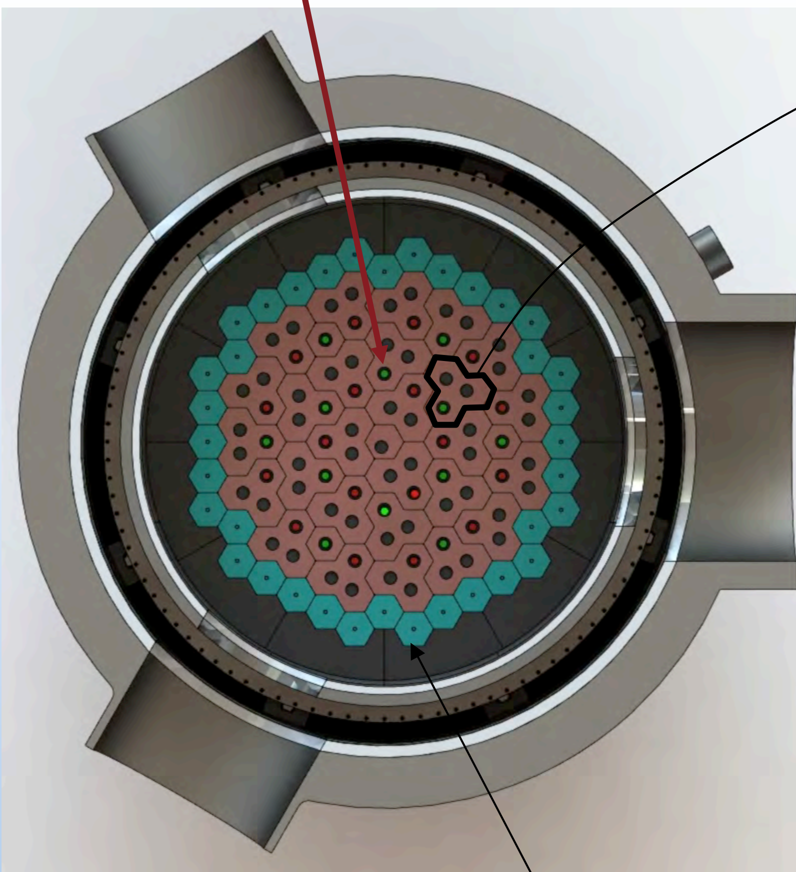


Starter	Fertile
LEU: ~ 11.6%	Depleted uranium
Transuranics	Used nuclear fuel
Mixed U/Pu oxides	Natural uranium
Recycled EM^2 discharge	Thorium

GENERAL ATOMICS

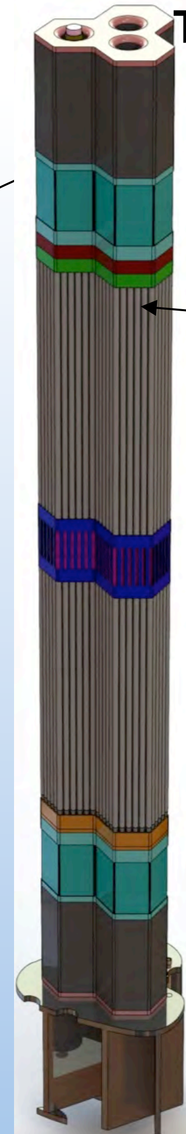
EM^2 Fuel is Designed to Meet the Challenge of a 30-Year Burn

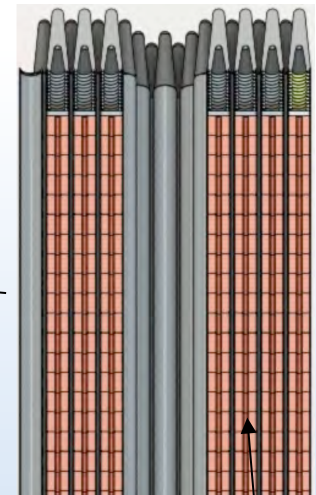
Active core



Reflector

Tri-bundle





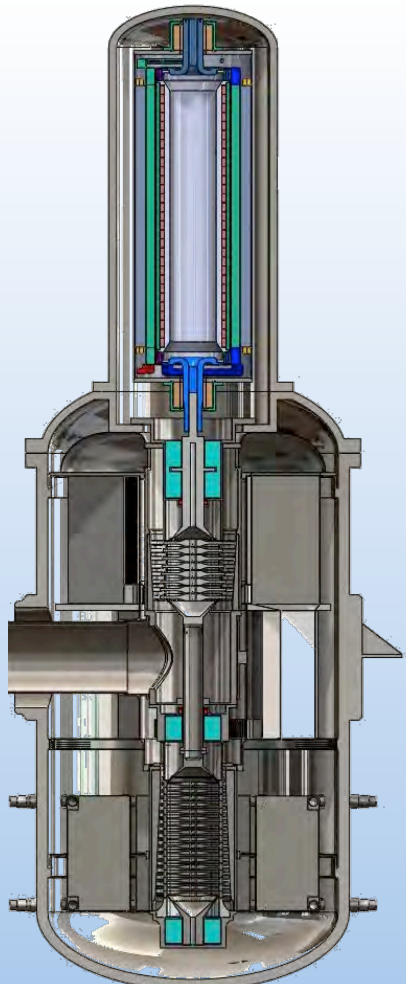
91 rods per hex-bundle

UC fuel pellet in SiC-SiC clad

GENERAL ATOMICS

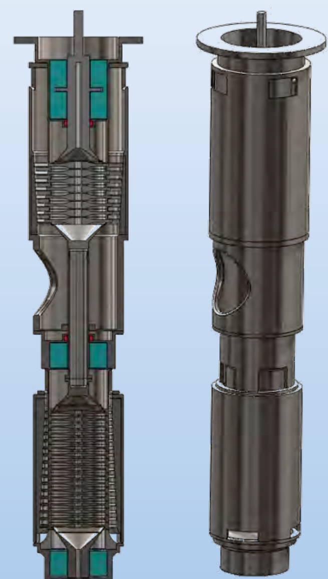
High Efficiency: High Temperature + Combined Brayton/Organic Rankine Cycle

Power conversion unit

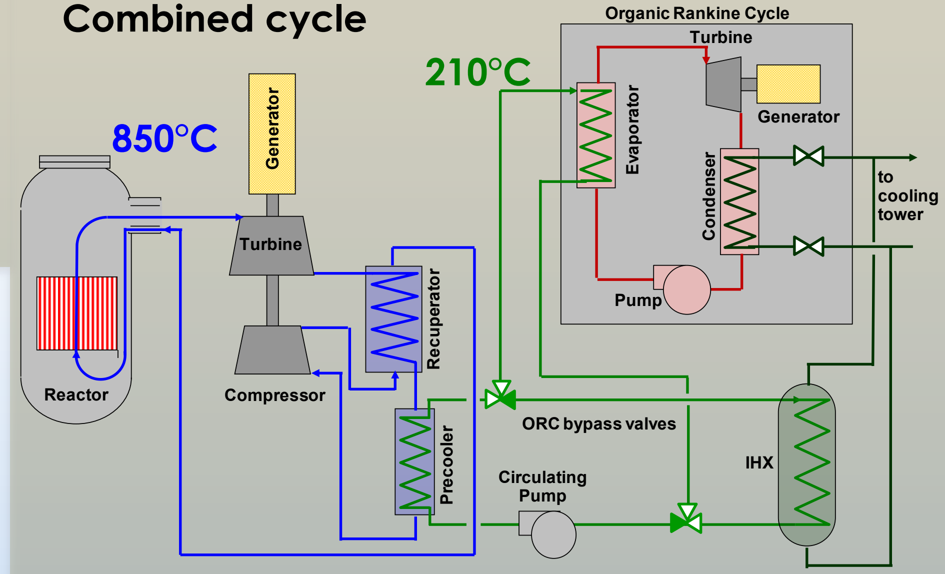


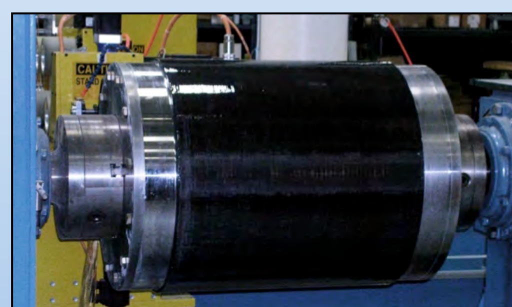
53% net (water cooling)
48% net (dry cooling)*

Turbo-compressor cartridge



Combined cycle

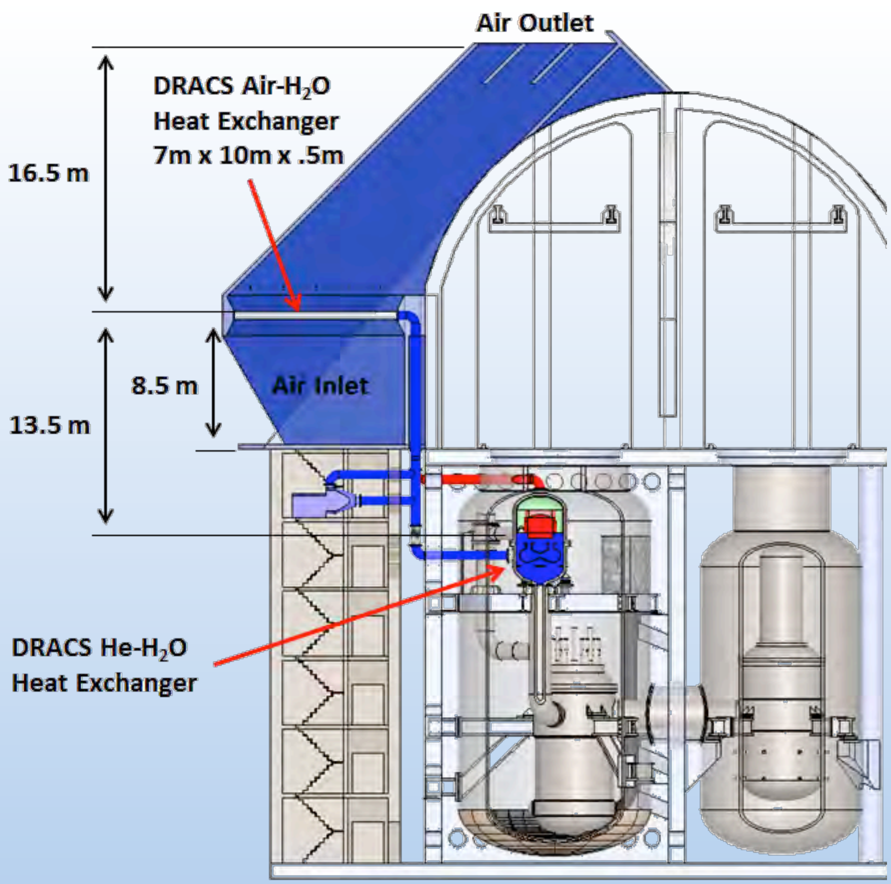


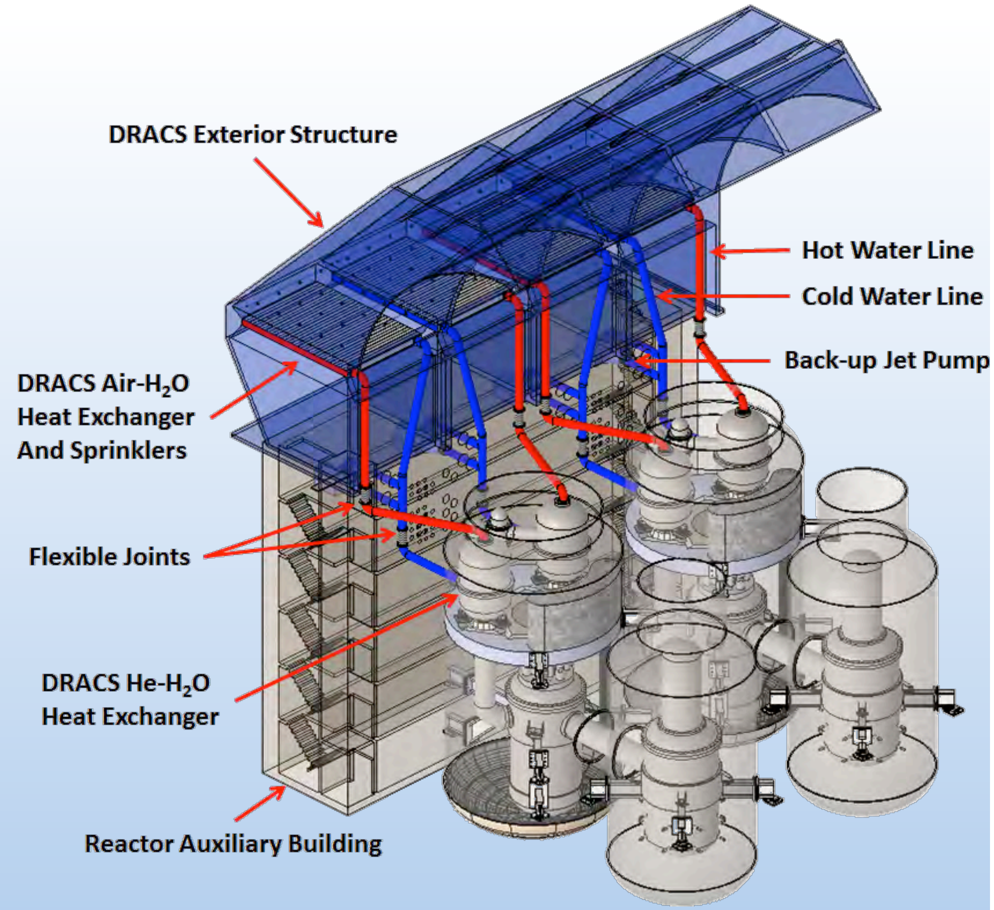


Test of high-speed permanent magnet rotor

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

EM^2 DRACS Based on Natural Circulation Cooling

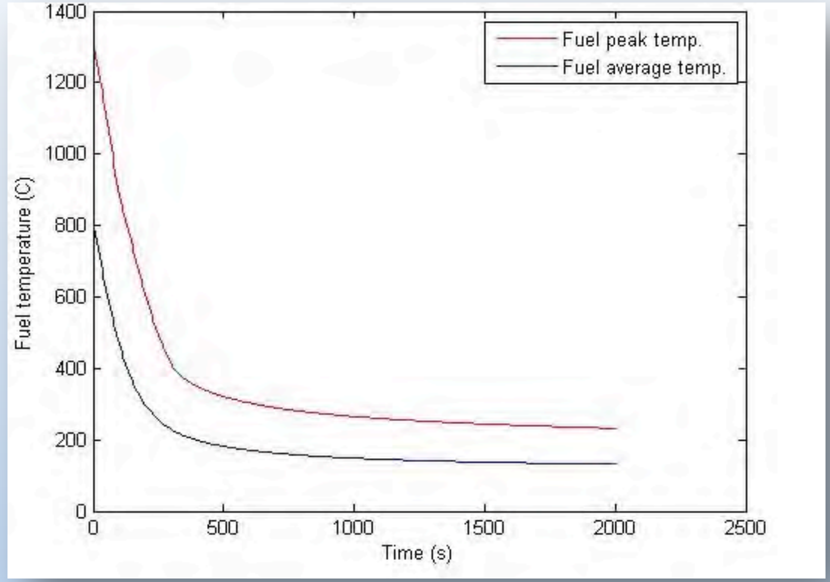




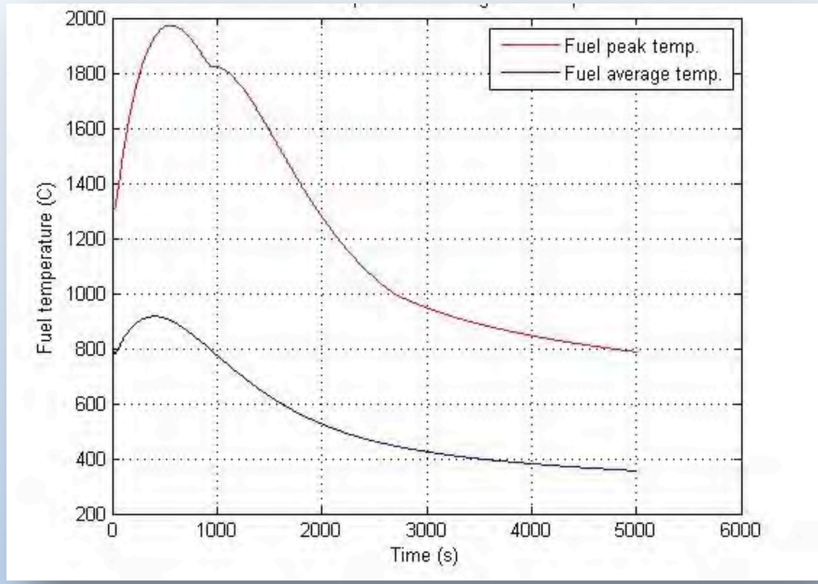
GENERAL ATOMICS

DRACS Passive Cooling Performance

Station Blackout
Cooldown on only one DRACS loop



500 CM² Primary System Breach
Cooldown on only one DRACS loop;
Containment pressure reaches 100 psig



GENERAL ATOMICS

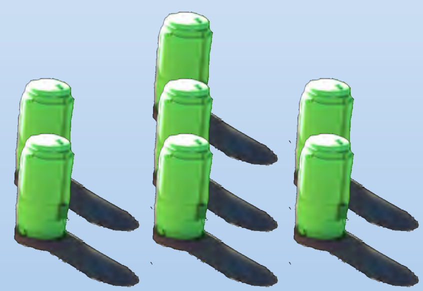
Waste Reduction: Benefits from High Temperature and Radiation Resistant Materials

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

$$\frac{1}{1.6} \times \frac{1}{3} \simeq \frac{1}{5}$$

- $\frac{1}{1.6}$: 60% more efficient than LWR
- $\frac{1}{3}$: Higher burnup
- $\frac{1}{5}$: The fuel of LWR

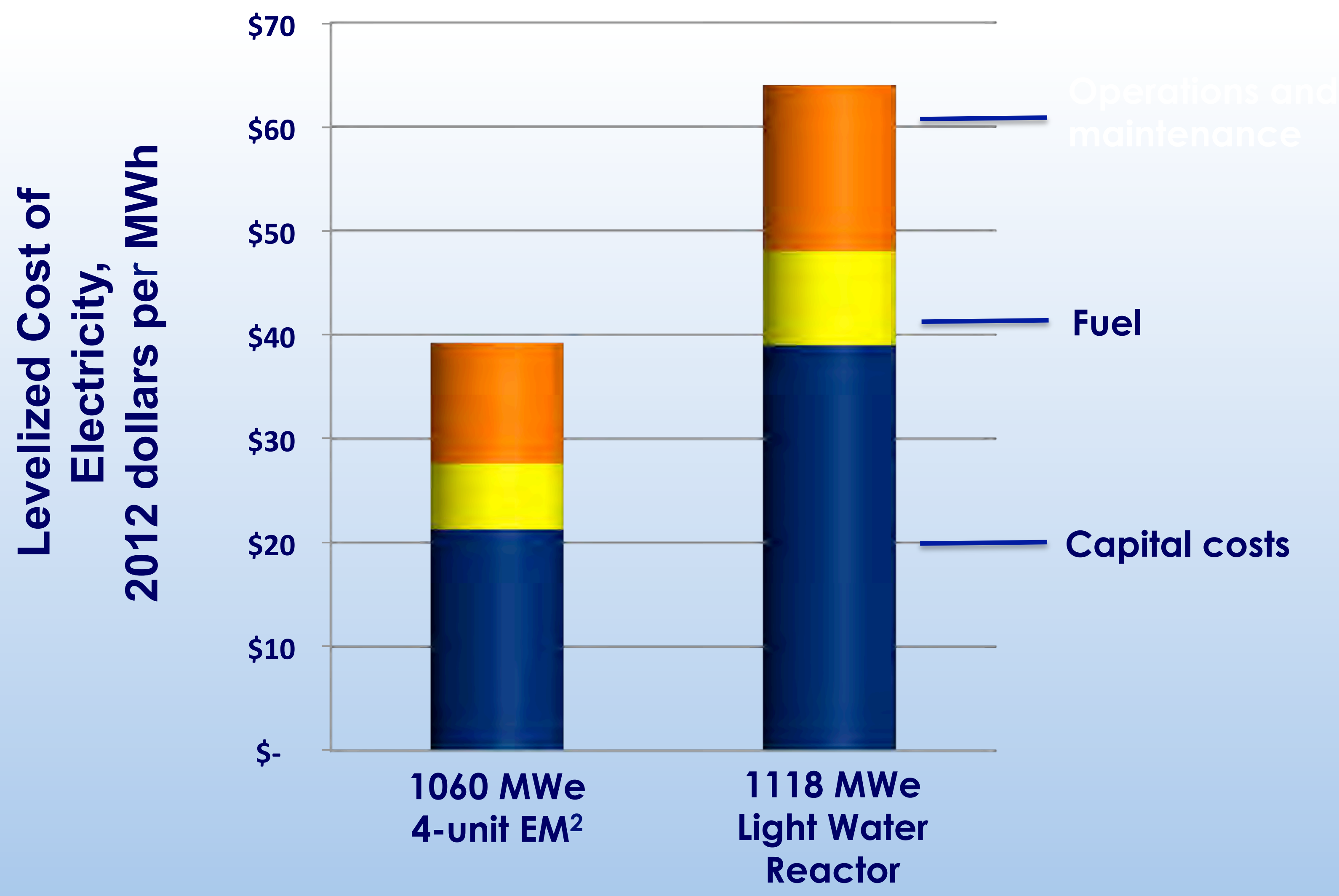
4-unit EM² produces 80% less waste over the same period



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

EM^2 Cuts Energy Costs by 40%

5% Cost of Capital



GENERAL ATOMICS

EM^2 Provides a Firm Basis for the Nuclear Power to Reduce CO_2 Emissions

- **Energy Resources** - EM^2 burns ^{238}U and ^{232}Th thereby extending nuclear energy resources by a factor of thousands.
- **Economically Viable** – EM^2 reduces the cost of electricity to make it affordable in the world market
- **Water Resources** – EM^2 does not require water cooling thereby enabling siting in more locations and preserving precious water resources
- **Waste Reduction** – EM^2 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.