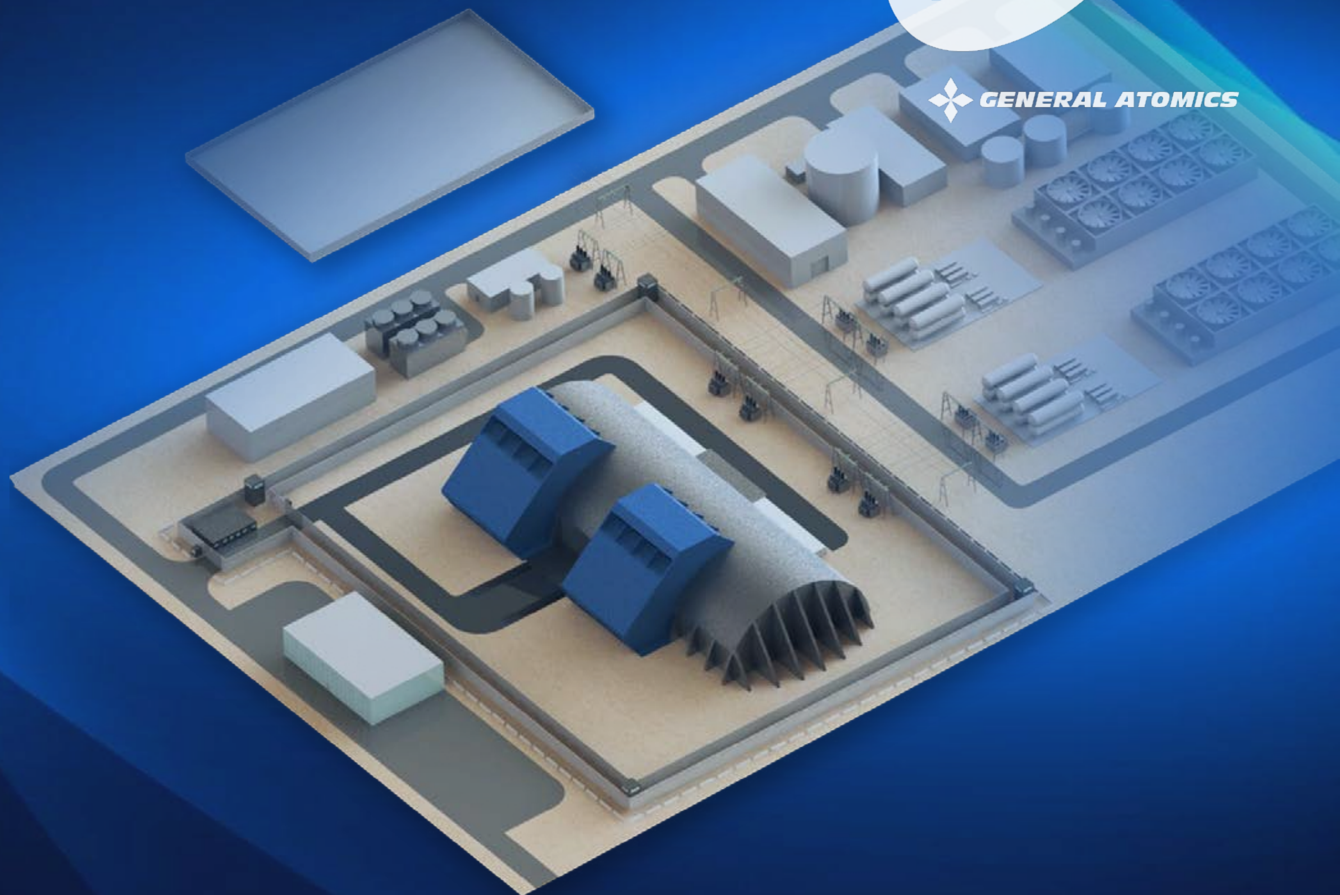
Changing the Game in Nuclear Energy

Presented to

San Diego American Nuclear Society

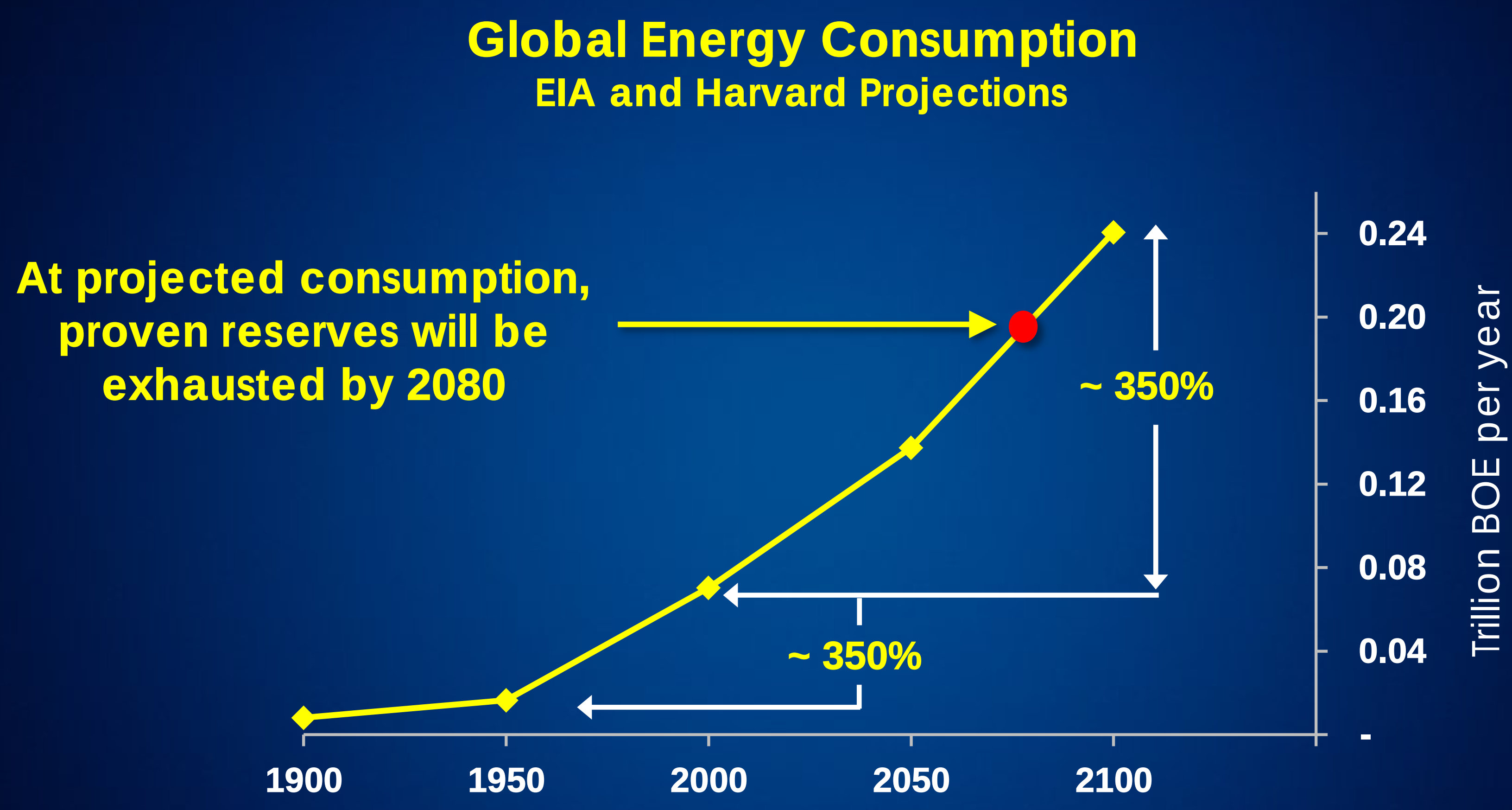


by

Bob Schleicher
Senior Scientist

July 23, 2014

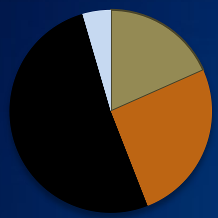
World Energy Requirements Present Major Challenges and Large Opportunities



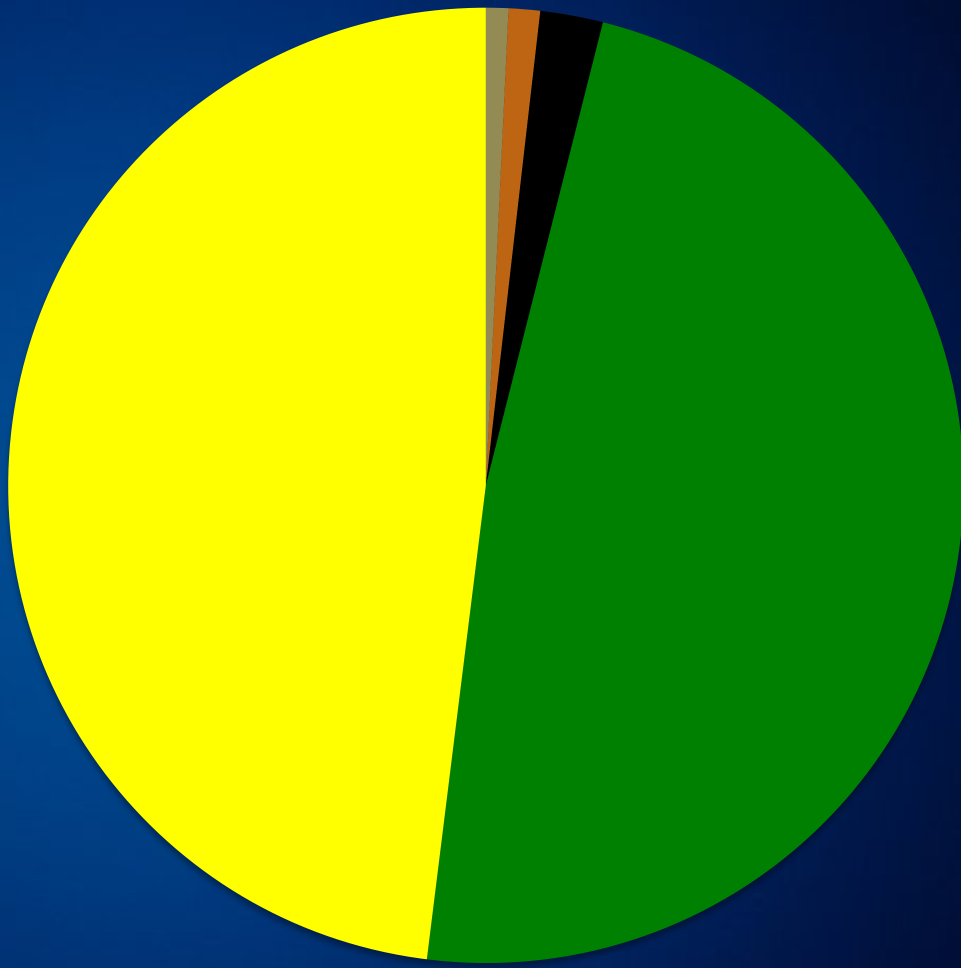
Nuclear can be a major clean-energy factor in supporting this growth

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

Exhausted by 2080



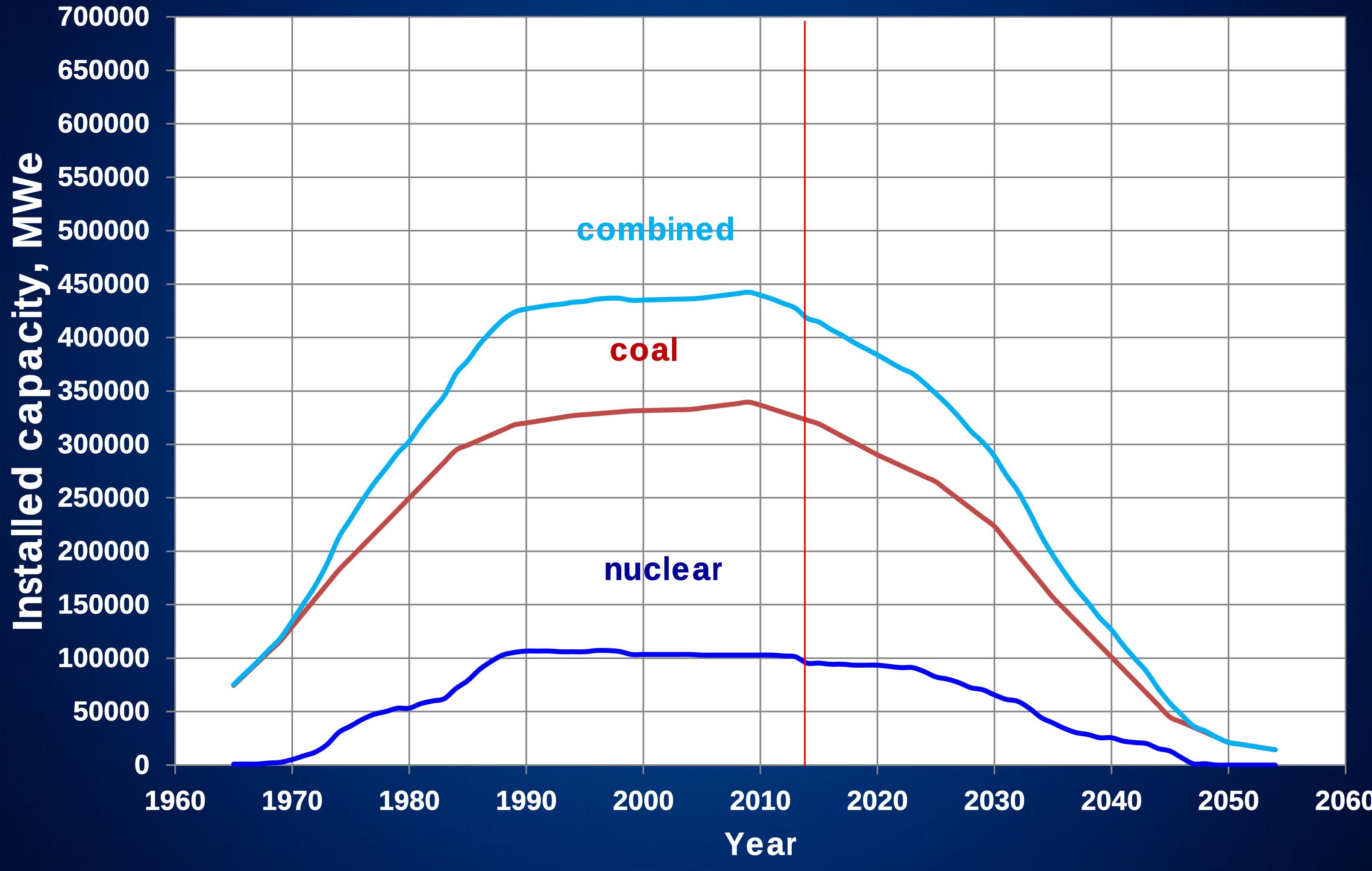
8.2 trillion BOE with thermal reactors



198 trillion BOE with fast fission reactors

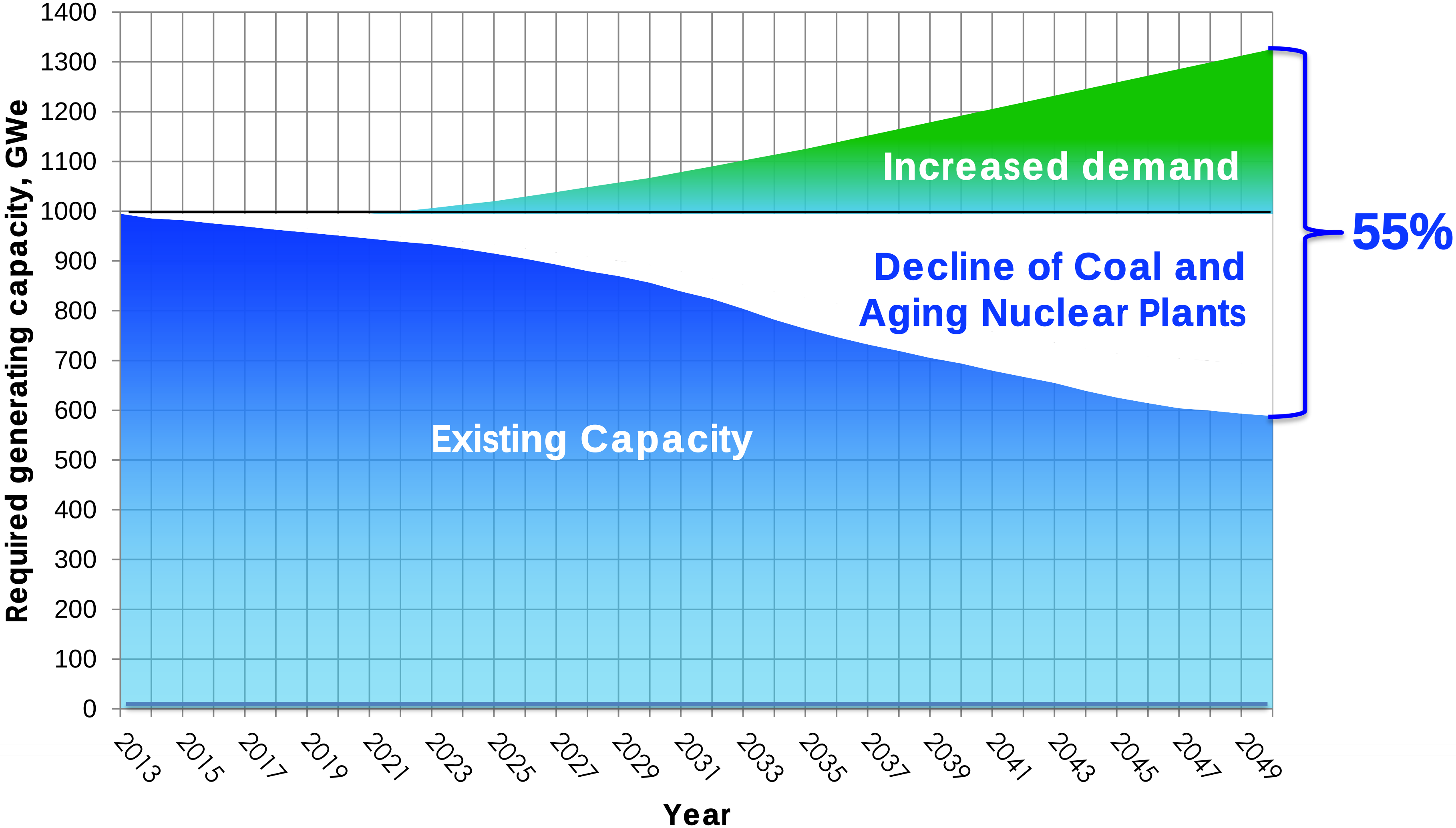
- Oil
- Natural Gas
- Coal
- Uranium Thermal Reactor
- Uranium Fast Closed Cycle
- Thorium Fast Closed Cycle

Aging U.S. Nuclear and Coal Plants Will Be Retired Over Next 30 Years



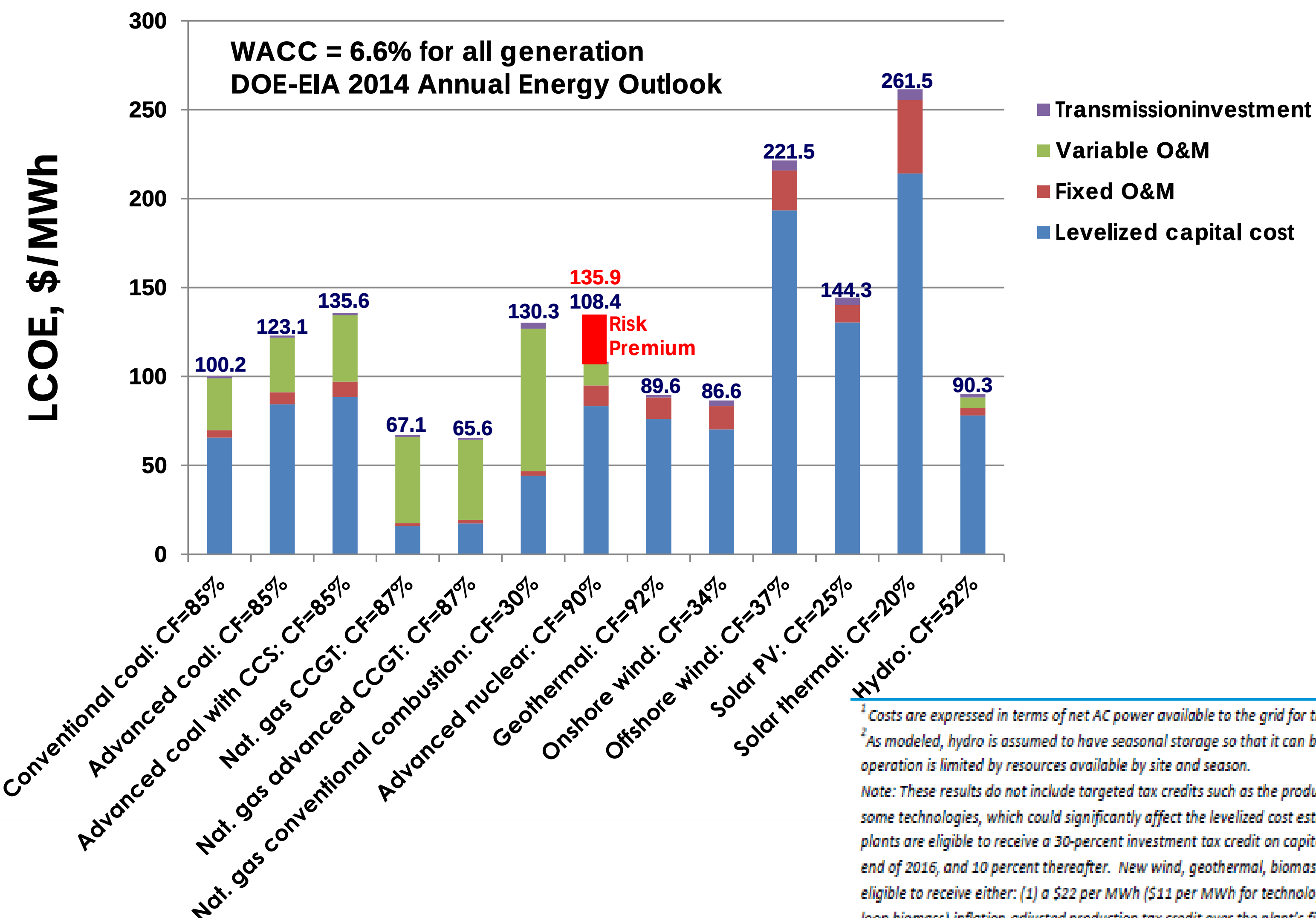
GENERAL ATOMICS

The US Could Have a Potential Shortfall of 55% in Electricity Supply



DOE EIA 2014 Annual Energy Outlook

2014 Levelized Cost of Electricity (for plants entering service in 2018)



[1] Costs are expressed in terms of net AC power available to the grid for the installed capacity.

[2] As modeled, hydro is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.

Note: These results do not include targeted tax credits such as the production or investment tax credit available for some technologies, which could significantly affect the levelized cost estimate. For example,new solar thermal and PV plants are eligible to receive a 30-percent investment tax credit on capital expenditures if placed in service before the end of 2016, and 10 percent thereafter. New wind, geothermal, biomass, hydroelectric, and landfill gas plants are eligible to receive either: (1) a $22 per MWh ($11 per MWh for technologies other than wind, geothermal and closed-loop biomass) inflation-adjusted production tax credit over the plant's first ten years of service or (2) a 30-percent investment tax credit, if placed in service before the end of 2013 (or 2012, for wind only).

EM^2 is the Power Source for the 21st Century and Beyond

LWRs are the workhorse for the nuclear industry, but

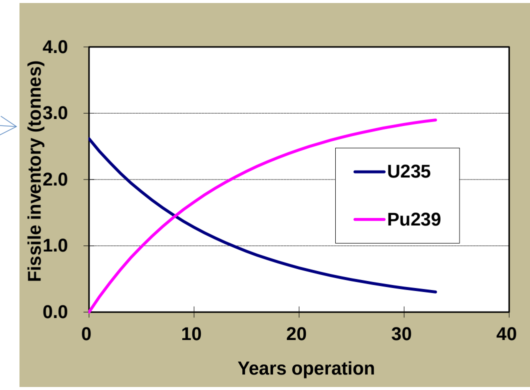
can 60-year old technology meet the huge world energy demand in 21st century and beyond?

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

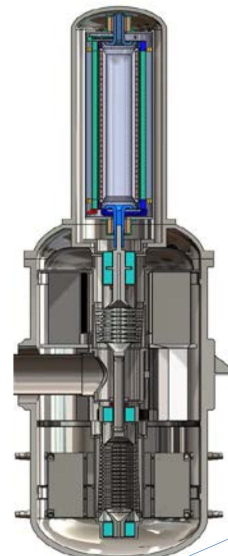
New Technologies Are Key to Assuring Nuclear Power's Place in Meeting Future World Energy Demands

- **Convert-and-burn core physics**

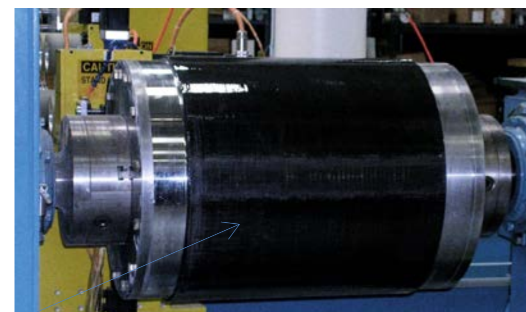


- **Silicon carbide composite structures**

- **Advanced fuels**



- **High temperature systems**



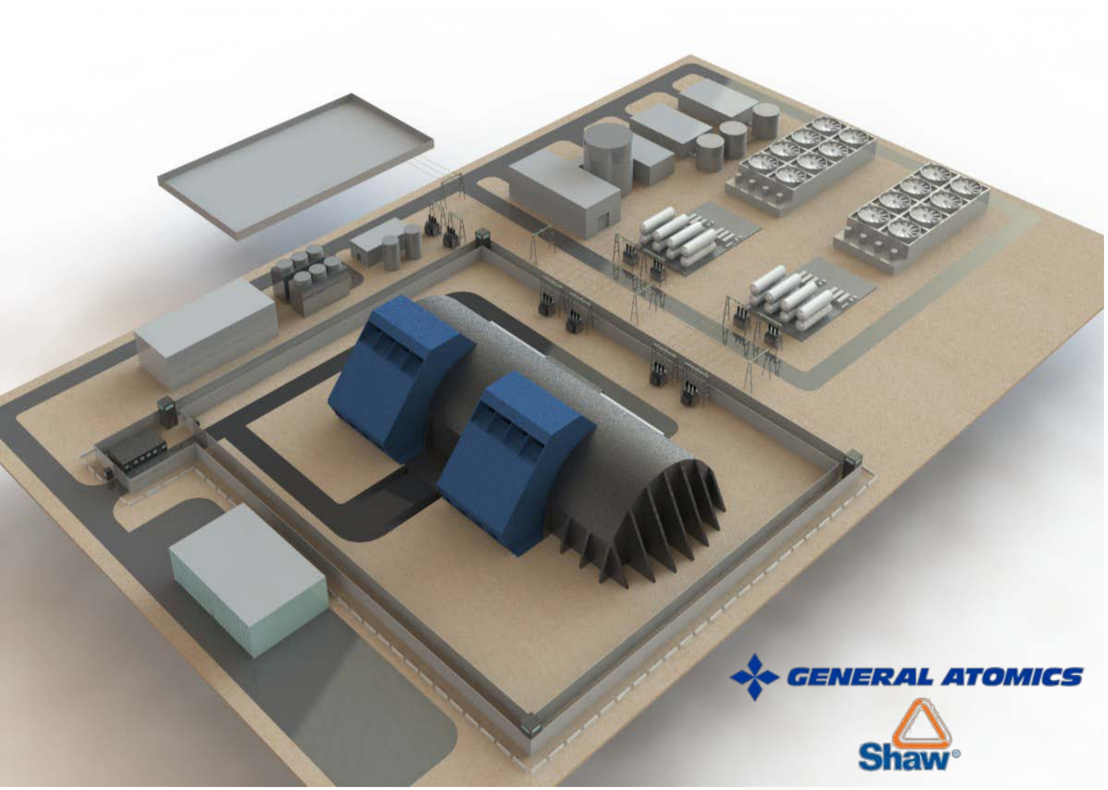
- **Asynchronous, high-speed generators**

- **Non-aqueous spent fuel recycling**

EM^2 is a Convert-and-Burn Fast Reactor

Four-module EM^2 plant

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

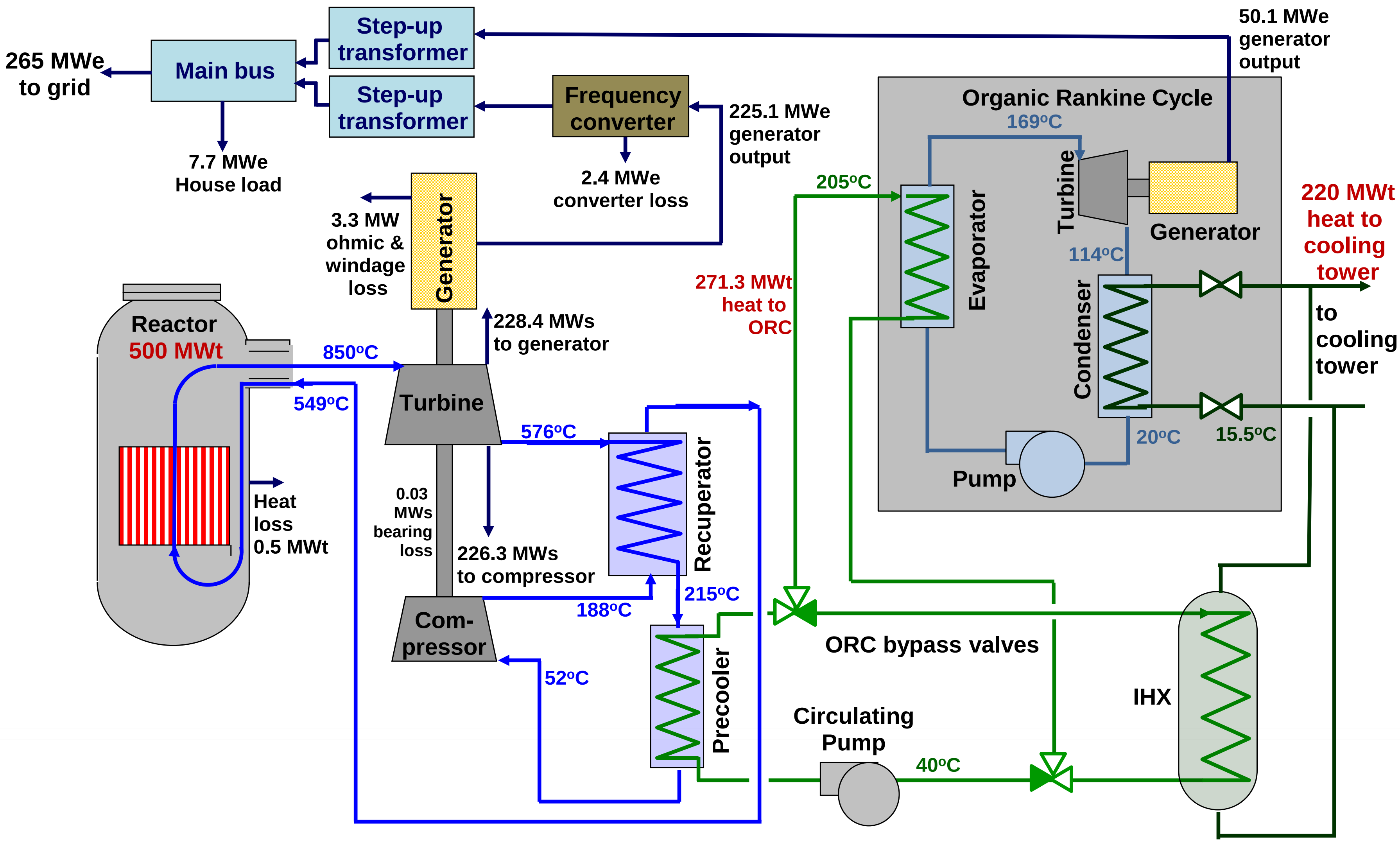


Major specifications

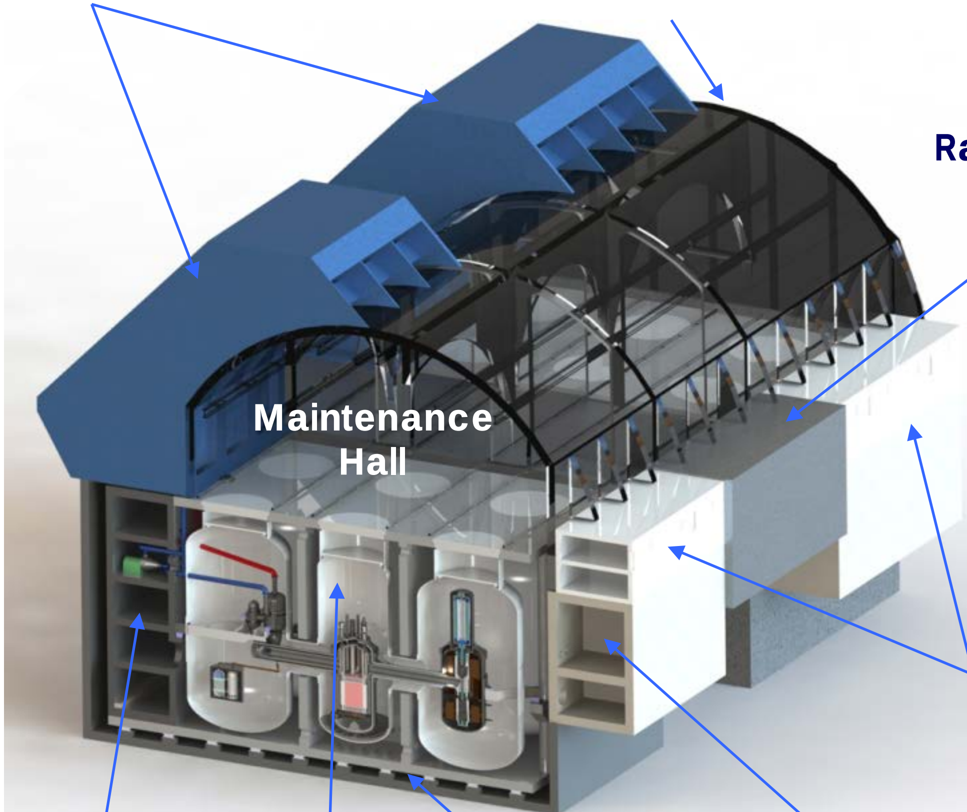
- 30-yr core life – no reshuffling
- 850ºC He-cooled fast reactor
- 53% net efficiency – combined Brayton/ Rankine cycle
- 42-month construction time 4 modules
- 60-yr passive fuel storage
- Burns LEU, DU, Thorium, spent LWR fuel
- Passively safe, licensable by U.S. NRC

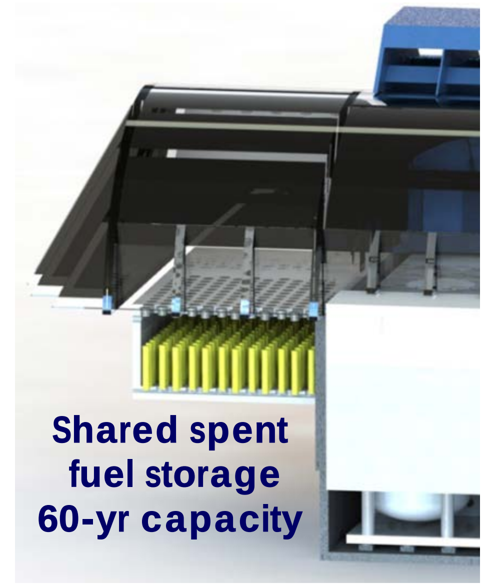
Plant Process Arrangement

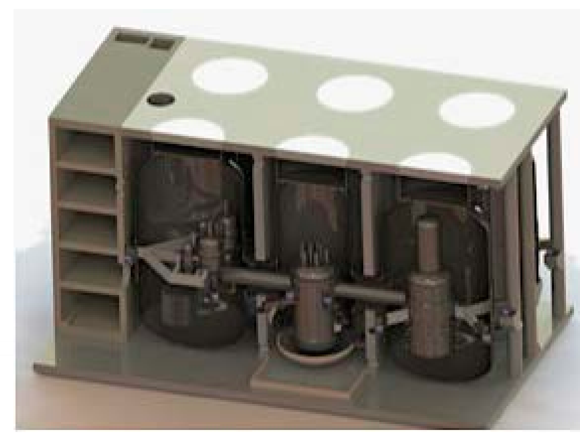
(Values apply to evaporatively cooled plant)



Reactor Building Physical Arrangement With Below-Grade, Seismically Isolated Containments



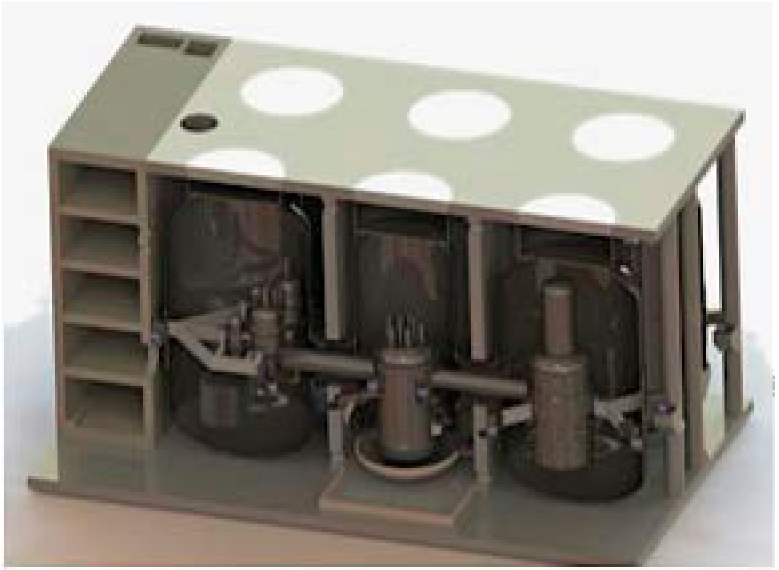




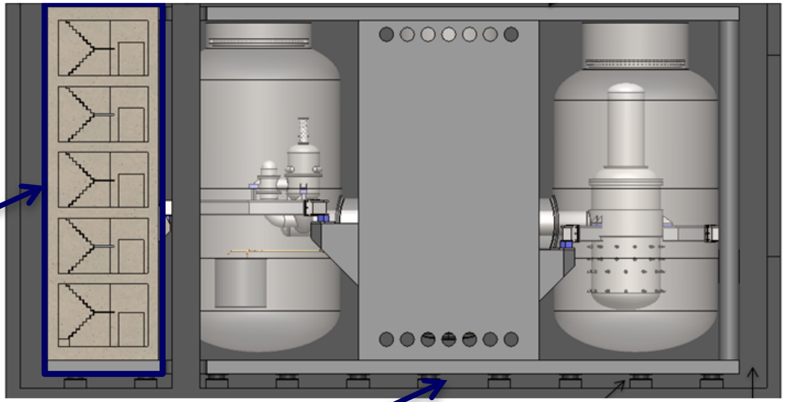
Installation module with 2 reactor systems on a seismic isolation platform

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

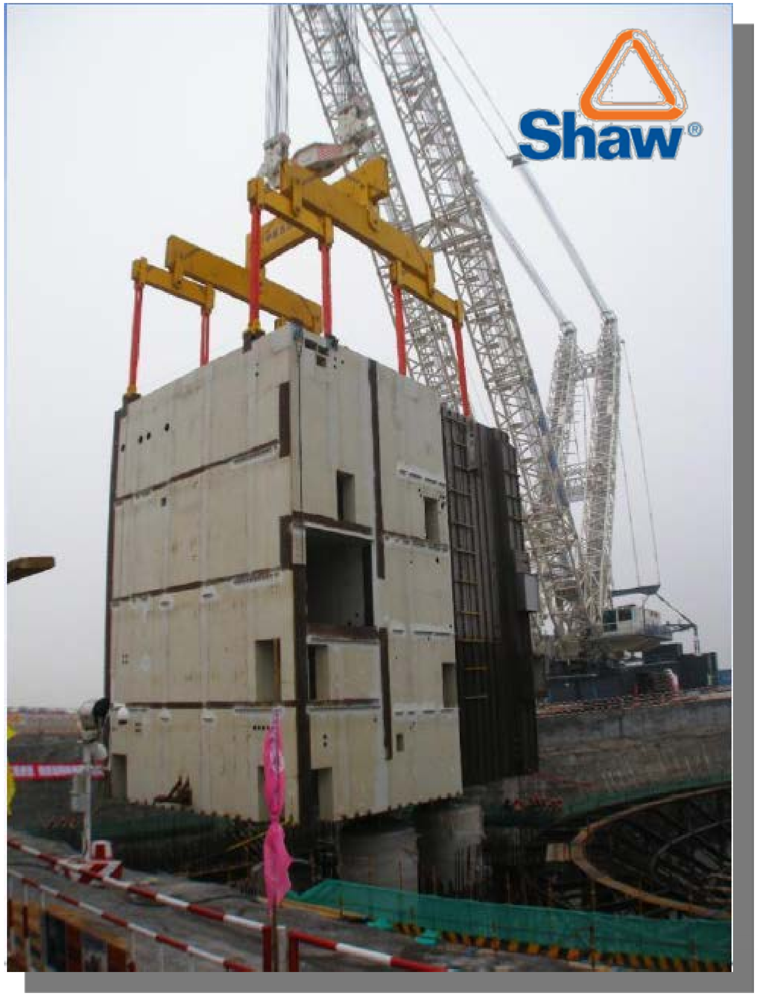
EM² module pair



EM² reactor aux. bldg.

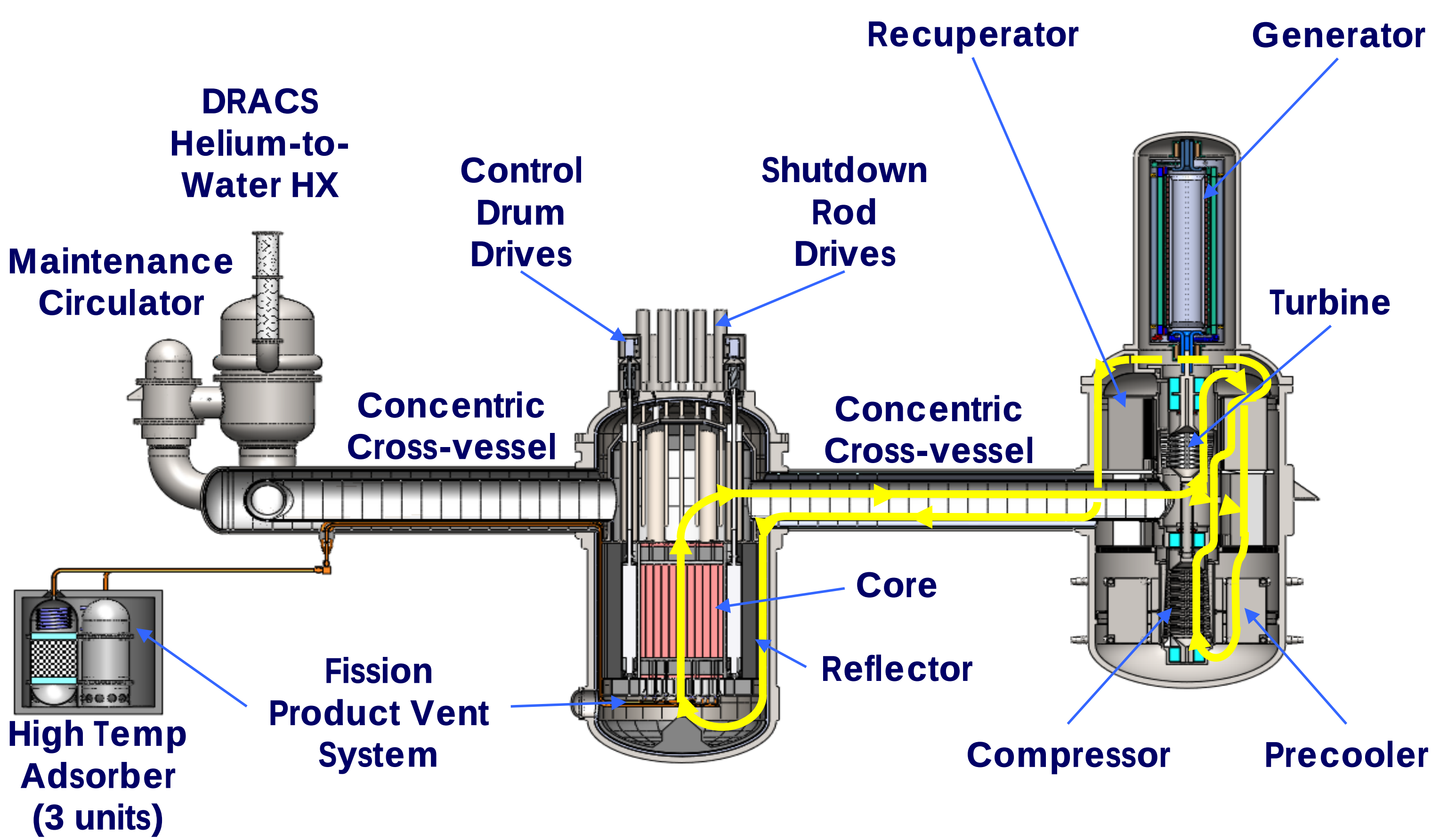


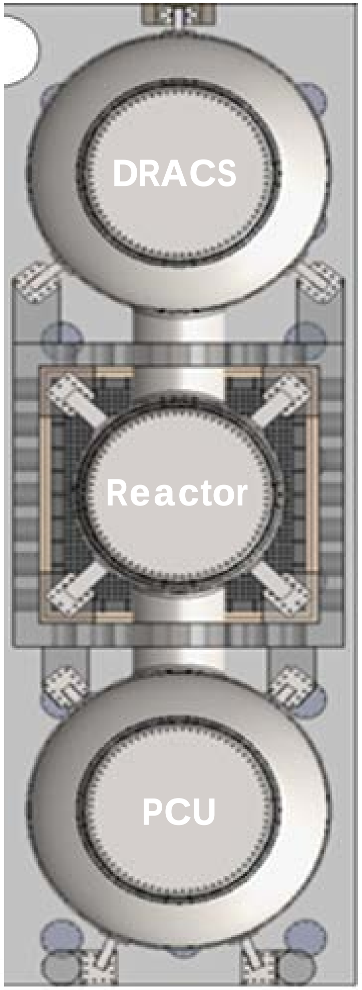
Seismic isolation



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

Primary Coolant System Arrangement





Direct Reactor Auxiliary Cooling System (DRACS

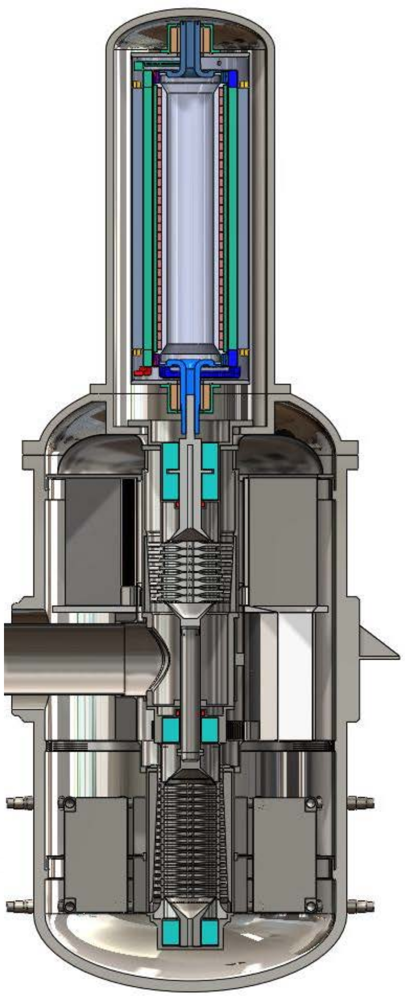
Reactor System

Power Conversion Unit (PCU)

Containment

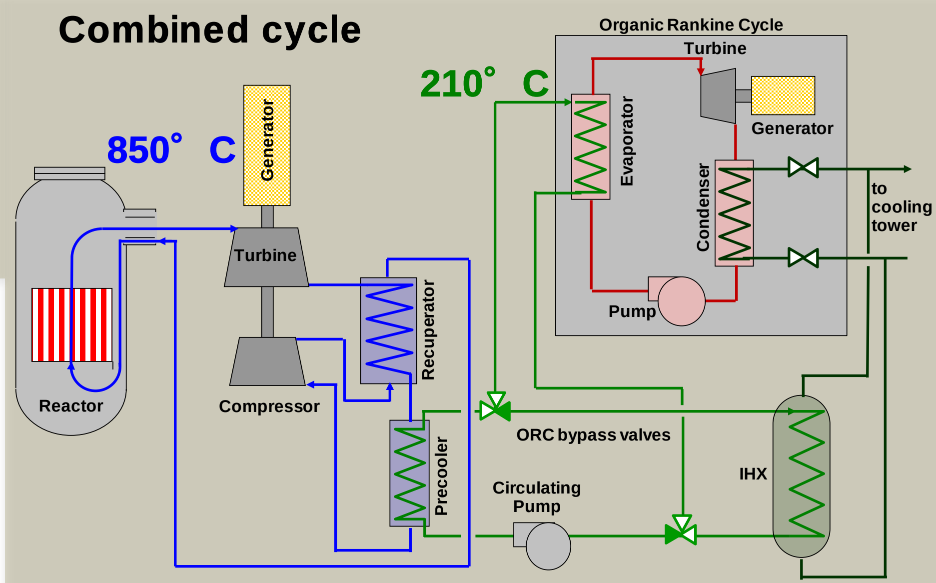
High Efficiency: High Temperature + Combined Brayton/Organic Rankine Cycle

Power conversion unit

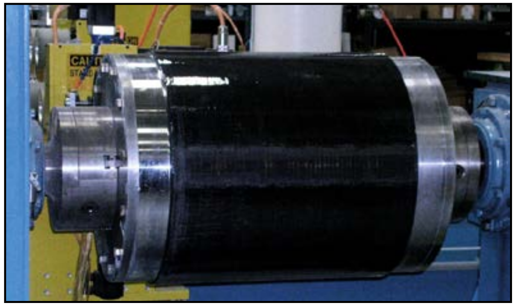


53% net (water cooling)
48% net (dry cooling)*

Combined cycle



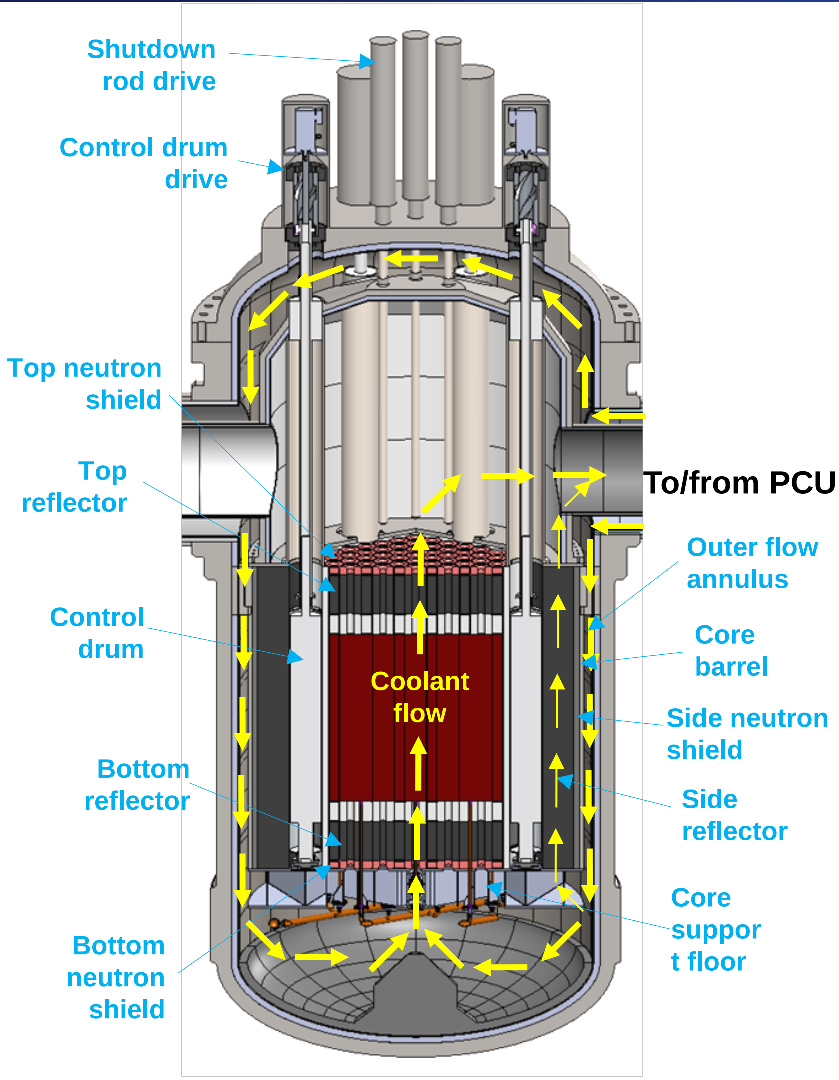
Turbo-compressor cartridge

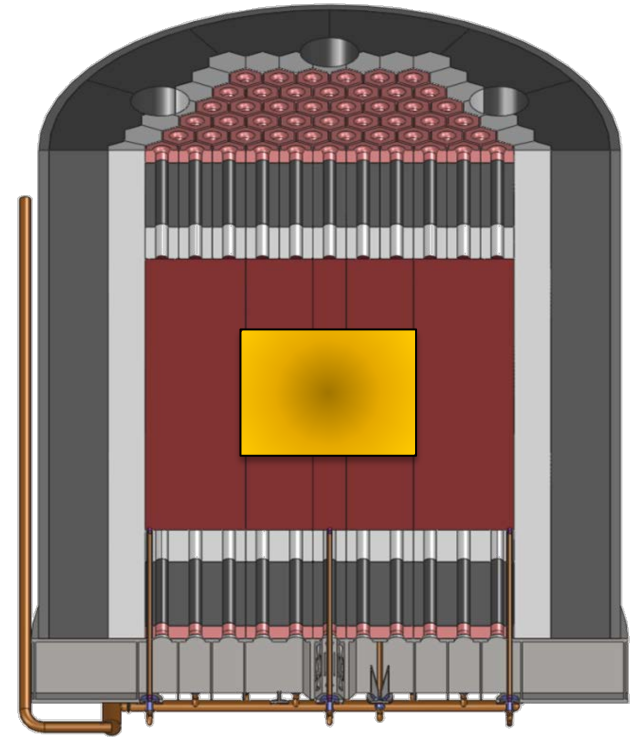


Test of high-speed permanent magnet rotor

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

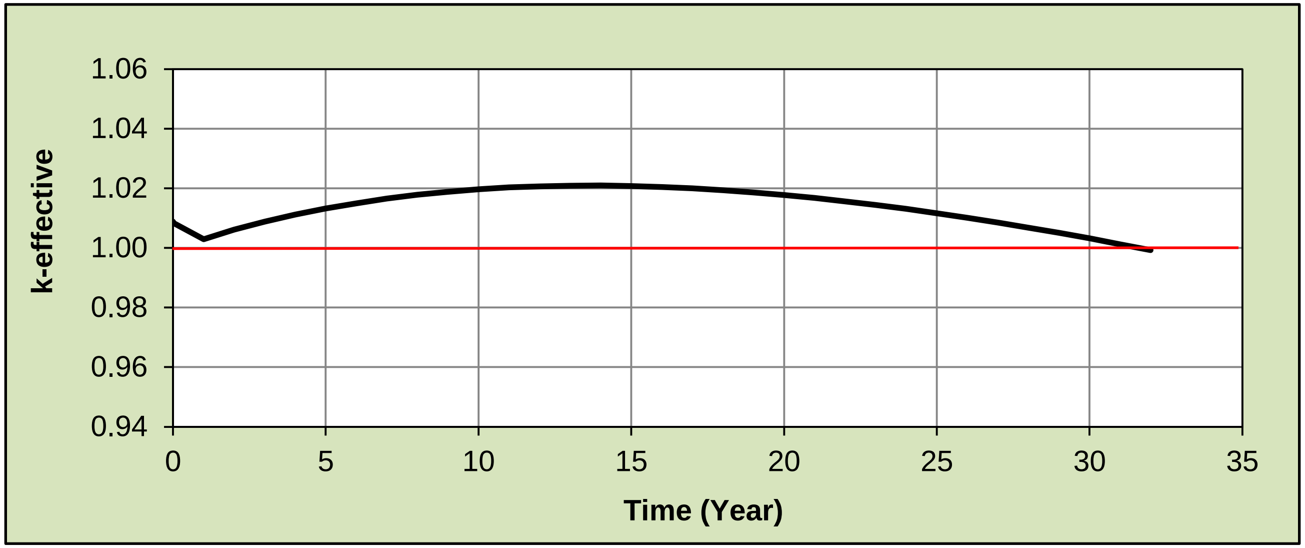
Reactor Elevation and Core Cross-Section





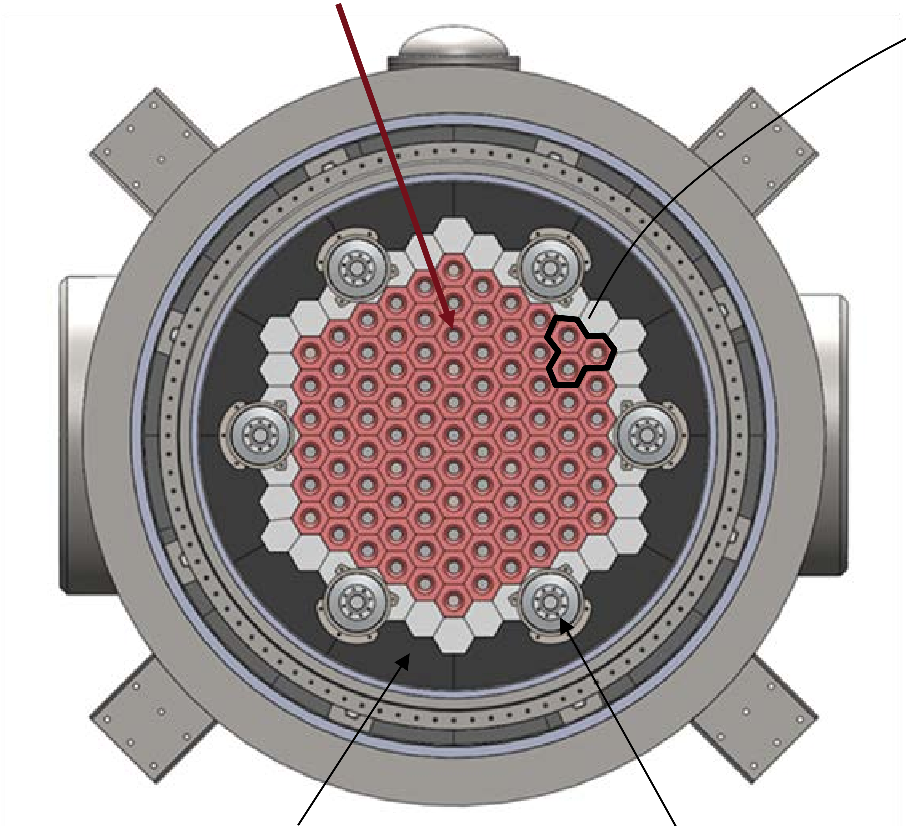
Starter	Fertile
LEU: ~ 12%	Depleted uranium
Transuranics	Used nuclear fuel
Mixed U/Pu oxides	Natural uranium
Recycled EM^2 discharge	Thorium

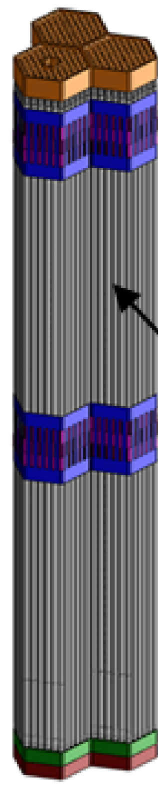
EM^2 Has Low Excess Reactivity and a Large Negative Reactivity Coefficient

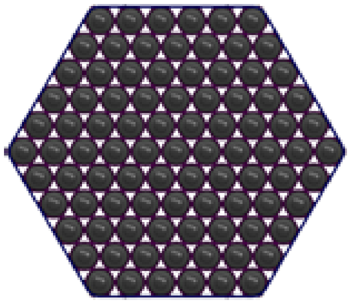


	EM^2	GFR	SFR
Reactor power (MWth)	500	600	1523
Fuel type	UC	(U,Pu)C	U-TRU-10%Zr
Cycle length	32 yrs	2.1 yrs	1.5 yrs
Burnup reactivity swing (%Δk)	2.1	1.5	0.06
Doppler coefficient (pcm/K)	-12.9/-8.6	-2.2/-1.8	-1.5/-0.9
Void reactivity (pcm)	106/210	169/205	2618/2659

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







UC fuel pellet in SiC-SiC clad

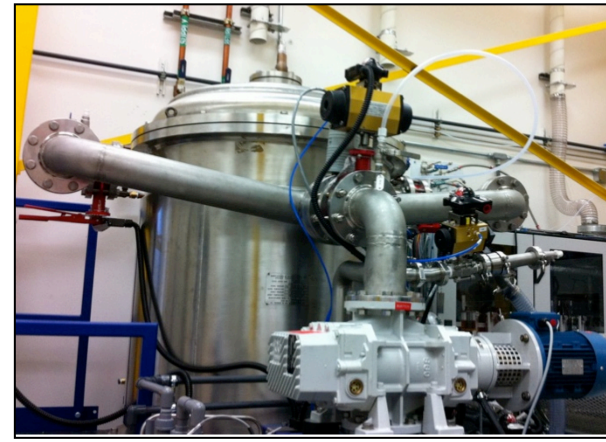
GA Has Established a State-of-the-Art Fuel Fabrication Laboratory

Sol-gel column

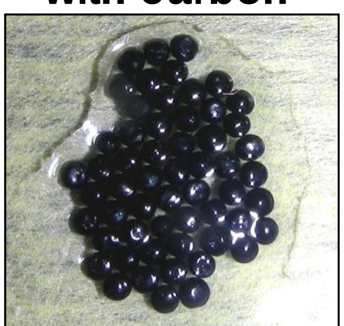
Sintering

Hot press

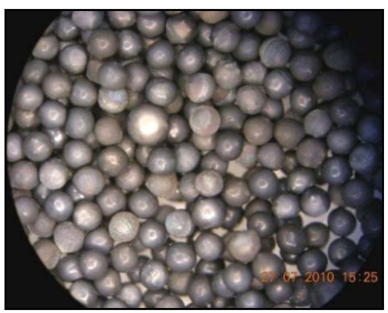
SiC coater



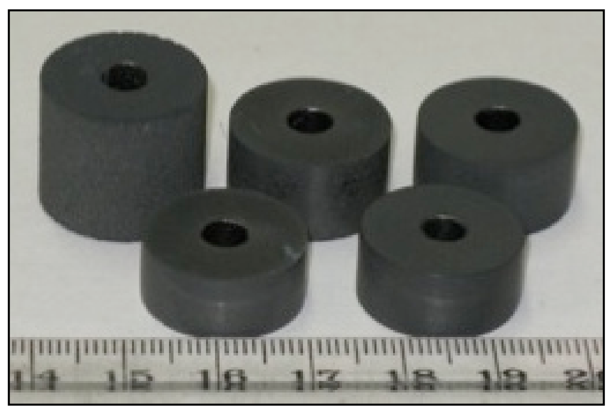
Gel particles with carbon



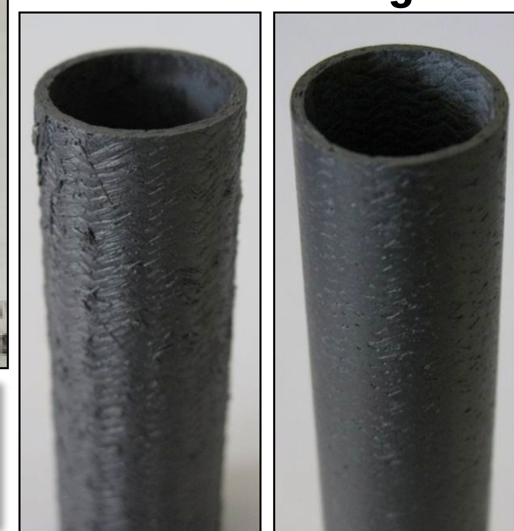
UC kernels



Sintered pellets

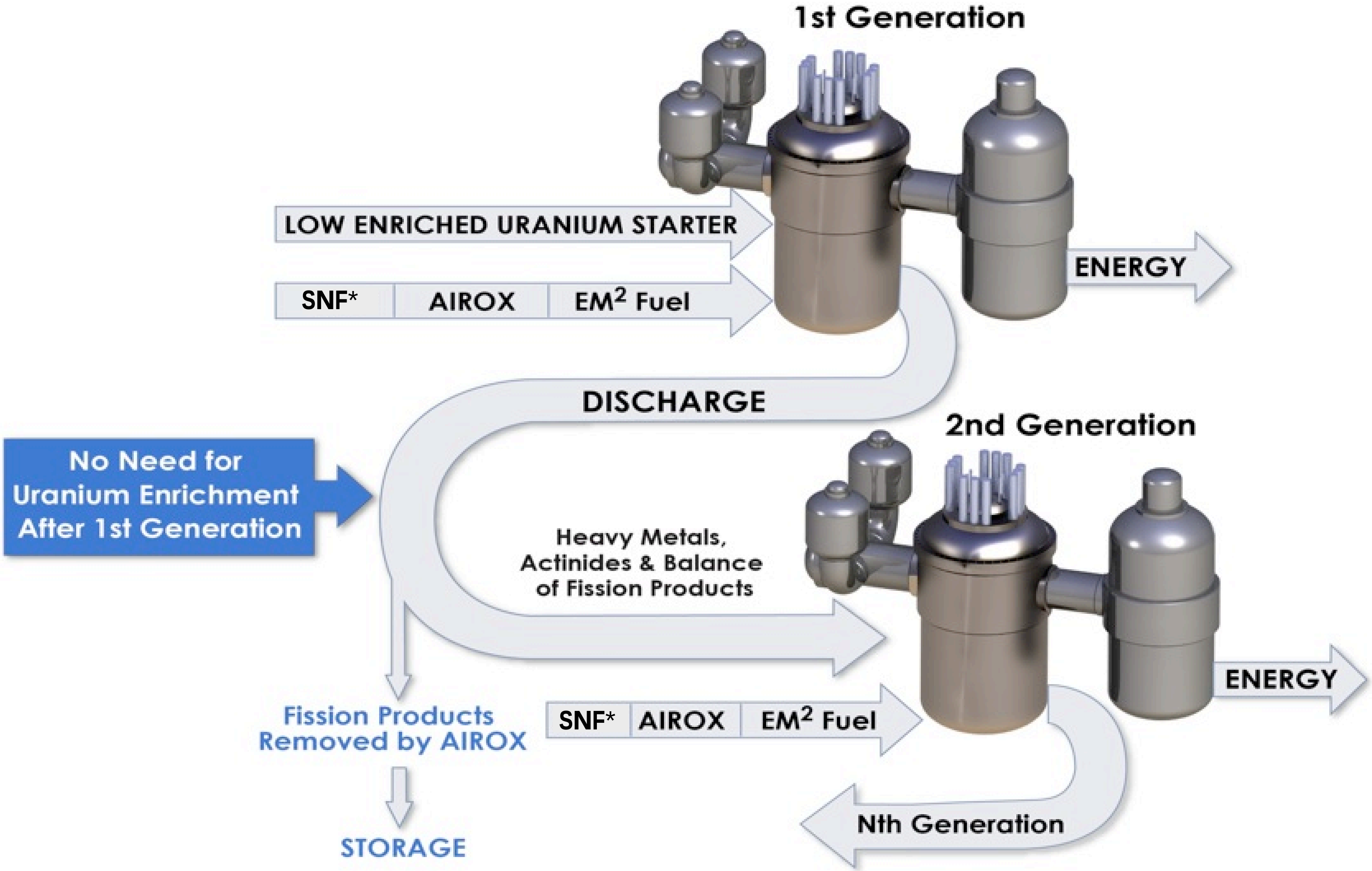


SiC composite fuel cladding



Prototypes have been fabricated and samples prepared for irradiation

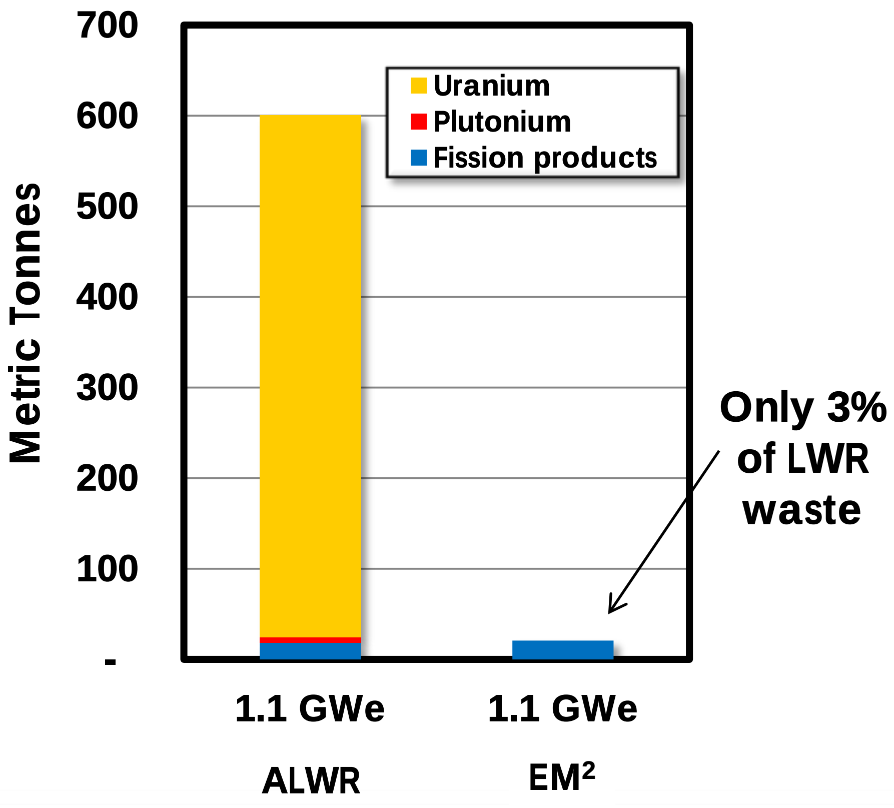
EM² Closes the Fuel Cycle to Not Only Reduce Waste, But Consume Waste



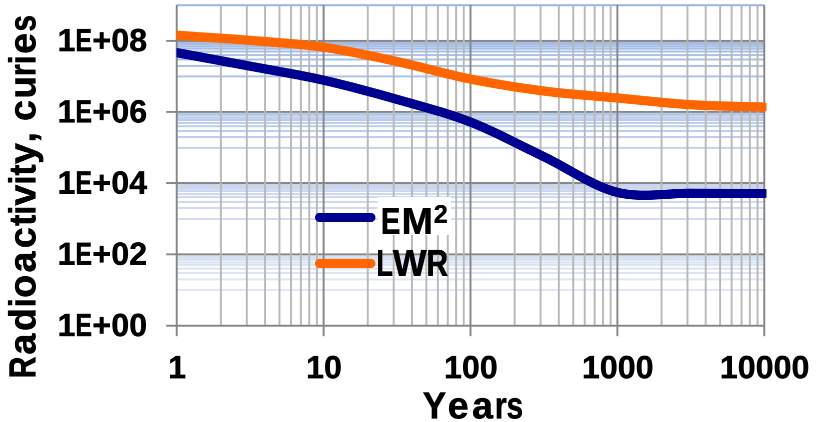
*Spent Nuclear Fuel

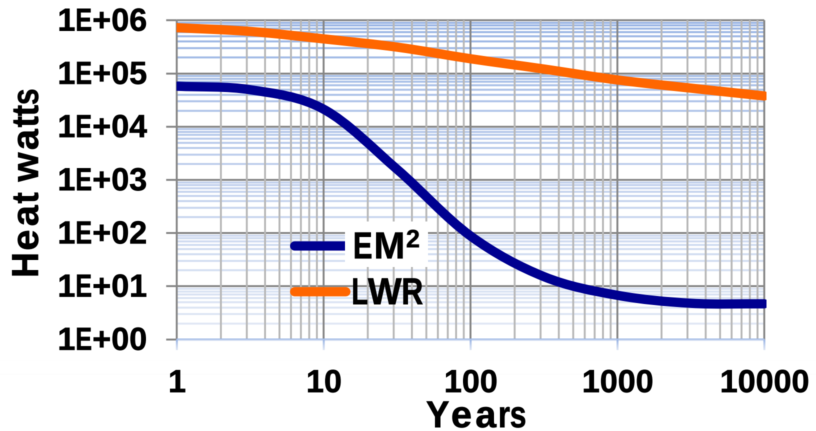
Discharge Waste Comparison: 1.1 GWe LWR vs. EM²

Waste after 30 years



Fission product activity and heat generation decays much faster than actinides



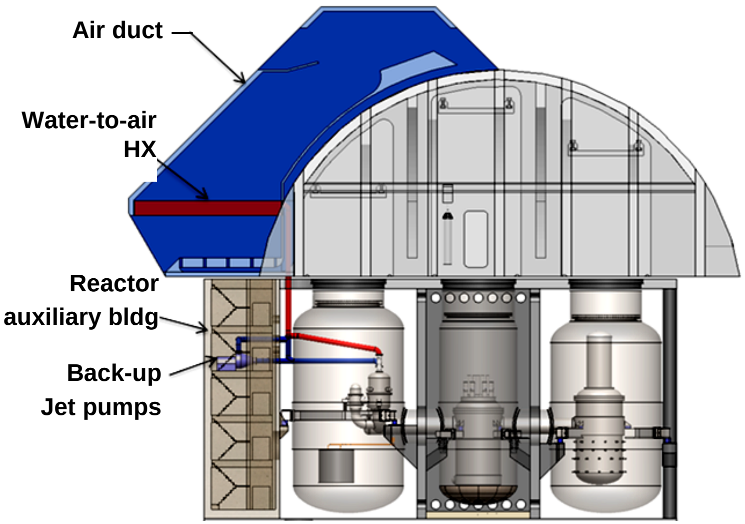


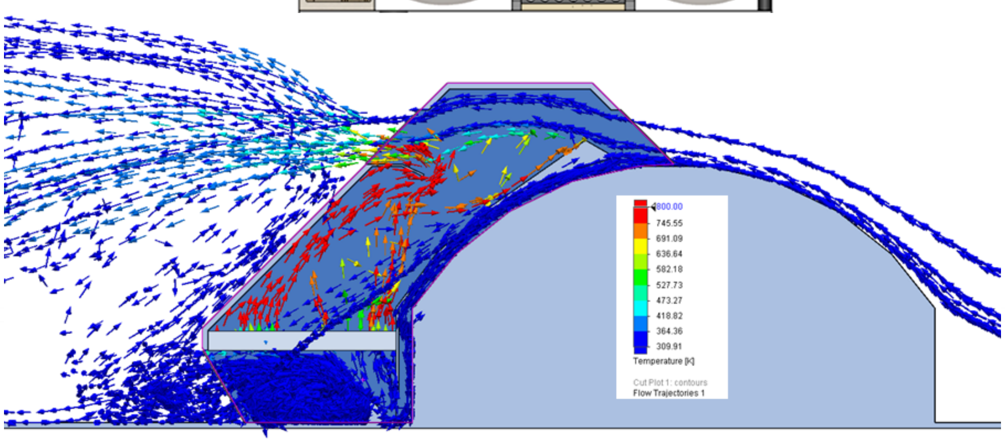
LWR discharge waste is primarily actinides; EM² discharge is fission products

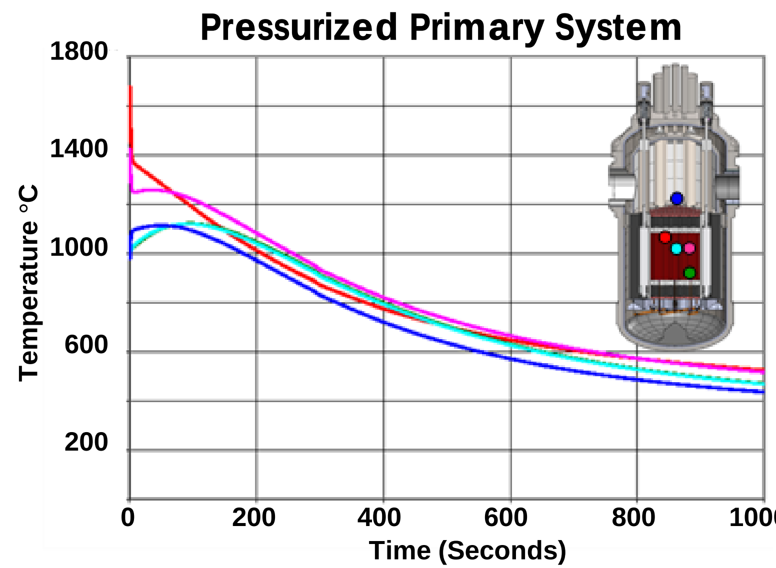
GENERAL ATOMICS

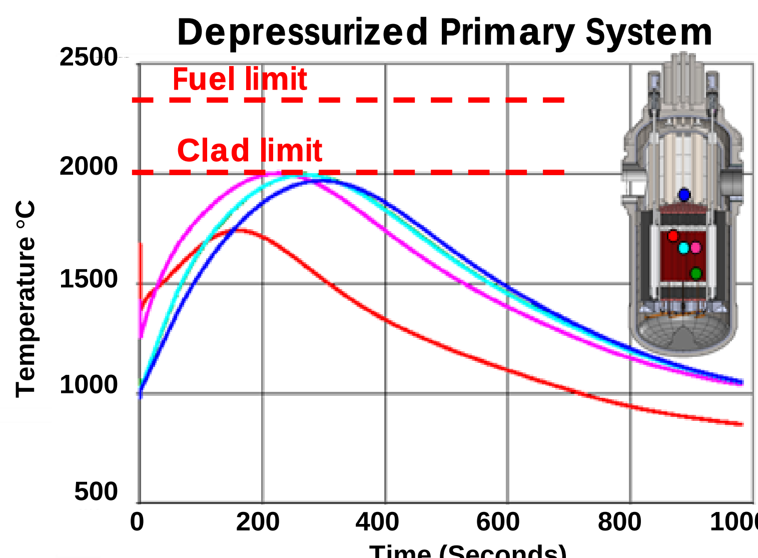
Engineered Safety Features
DRACS

2 independent passive systems reject afterheat to air



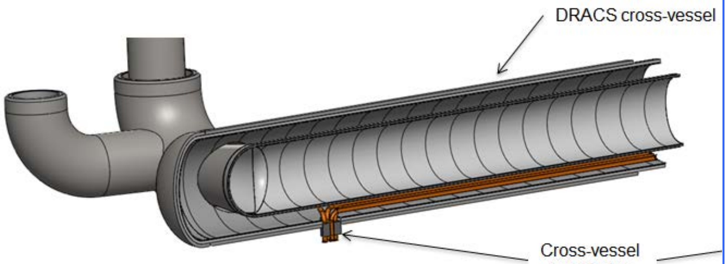




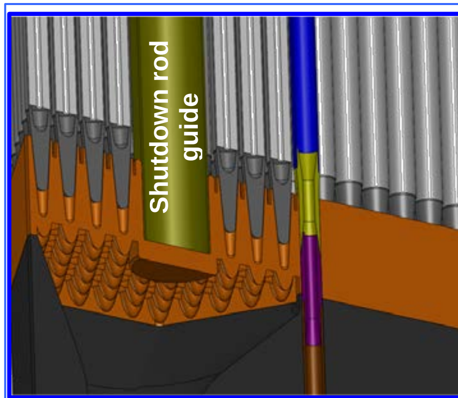


GENERAL ATOMICS

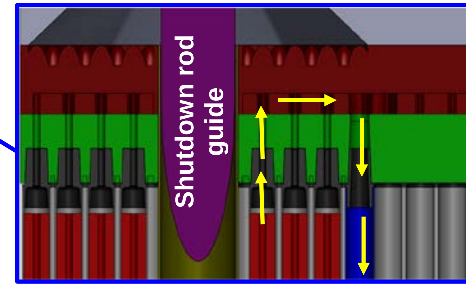
Fission Product Vent System Is an Engineered Safety Feature That Protects Fuel and Removes Volatile Fission Products



DRACS Cross-vessel



Bottom grid showing vent system downcomer

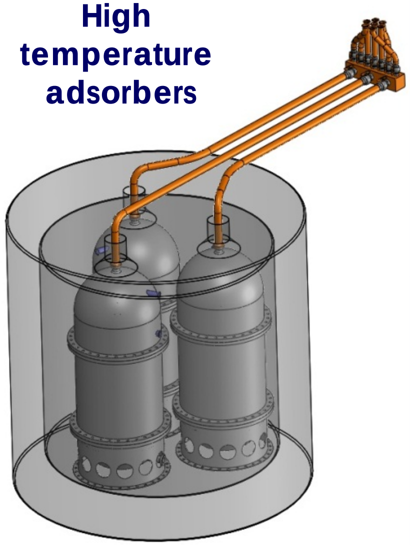


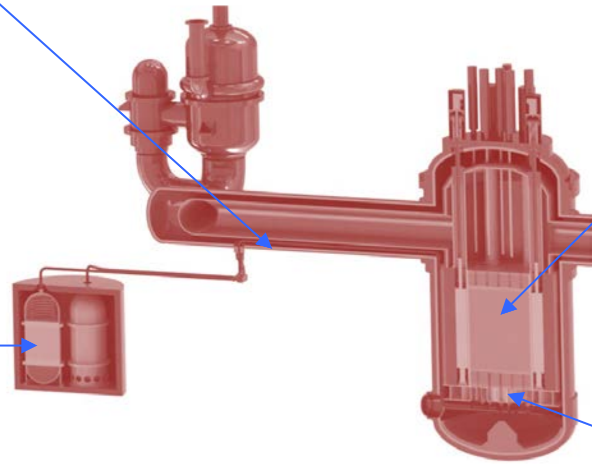
Top grid manifolds of fuel rod vents into central downcomer

Tri-bundle assembly

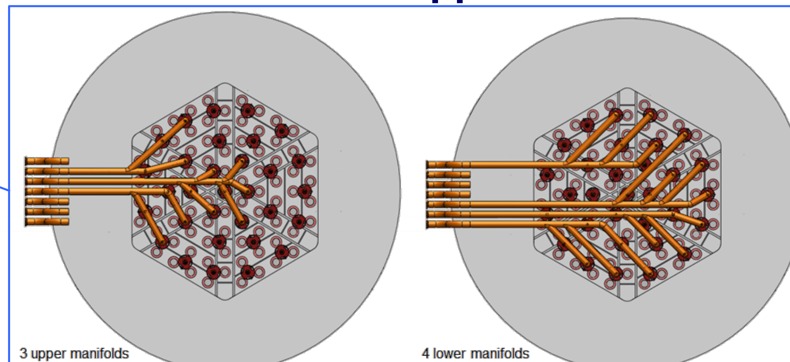
Fuel assembly

High temperature adsorbers





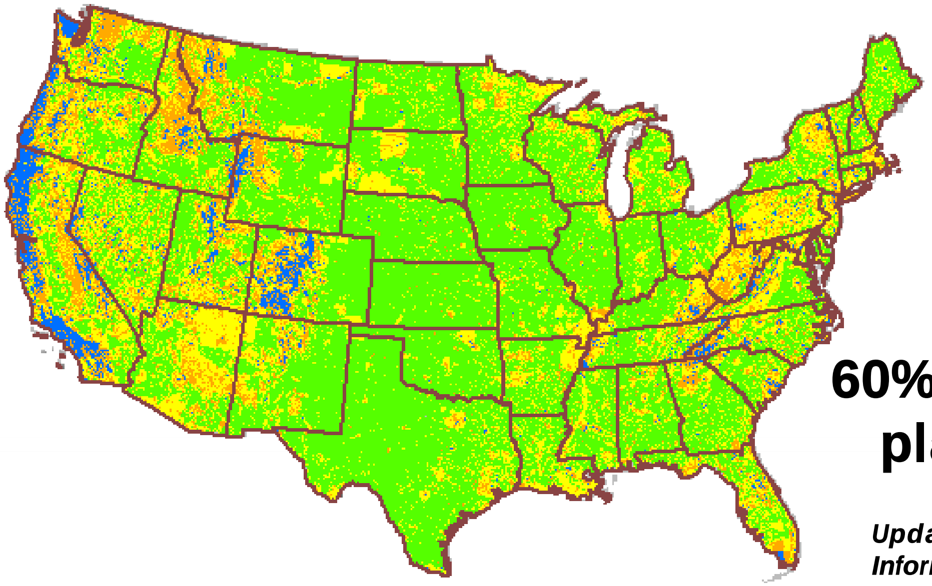
Core support floor



The Best Safety Feature for EM^2 is Distance

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

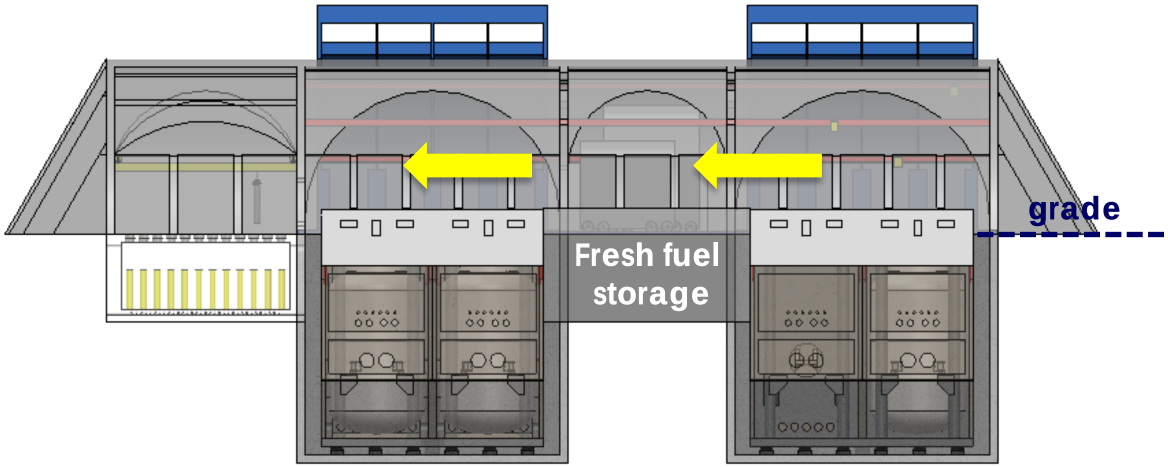
60% of U.S. is available for siting an EM^2 plant; only 13% is available to LWRS

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

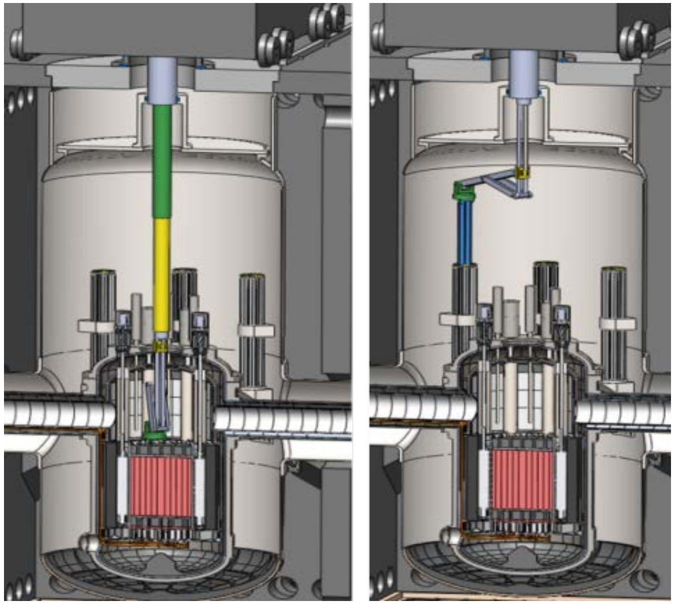
Operations and Maintenance

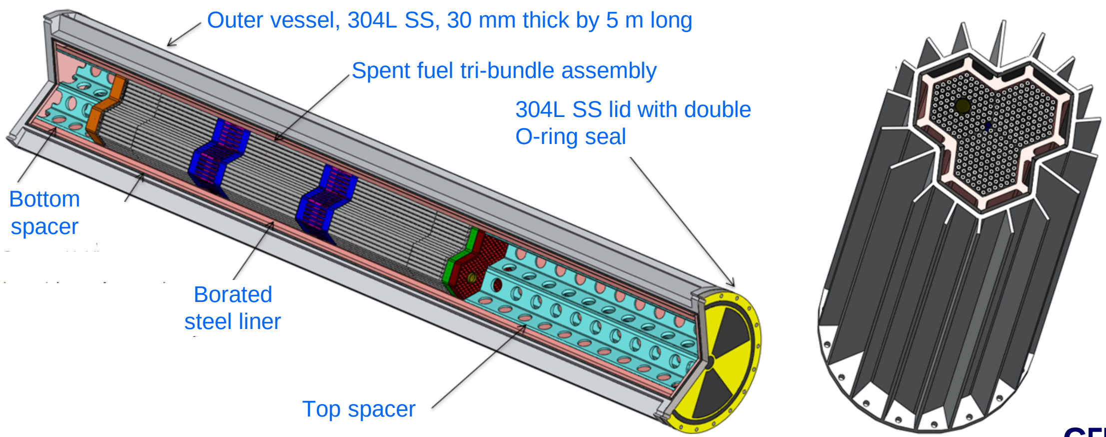
Fuel Handling and Storage

Spent fuel is transported laterally to storage area

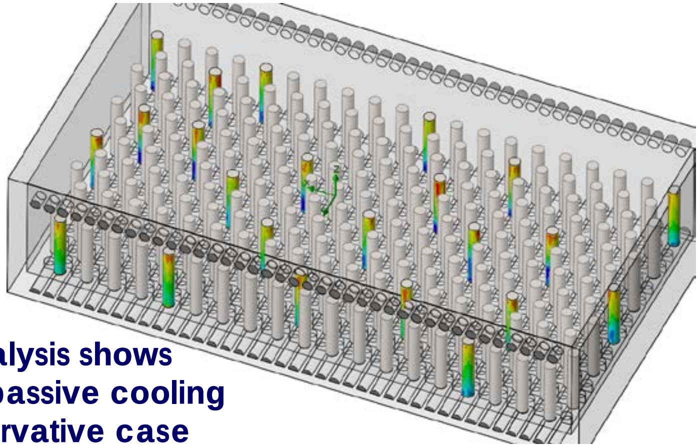


Fuel removal



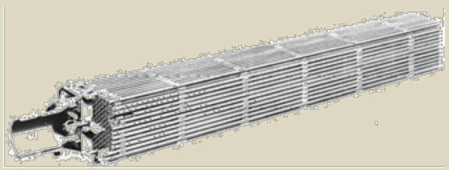


Spent fuel transfer/storage cask for passive dry cooling



CFD analysis shows adequate passive cooling for conservative case

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

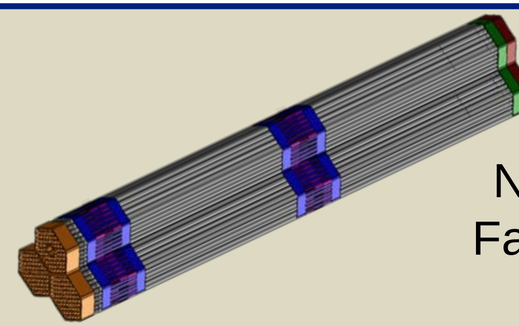
Spent hard-ware

Volatile fission product release:

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

Feedstock

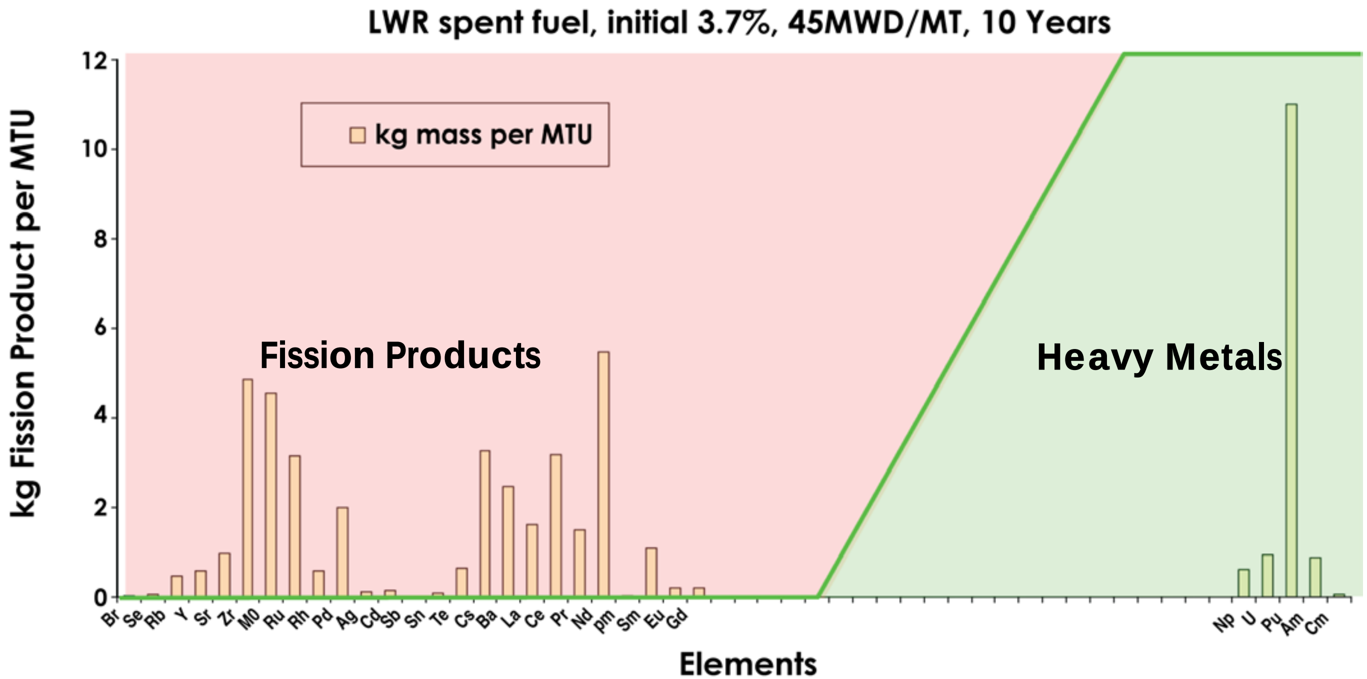
Milling & blending with recycled EM^2 fuel



EM^2 New Fuel Fabrication

Demonstration plant built by KAERI

Archimedes: A Proliferation Resistant Method to Addressing Spent Fuel

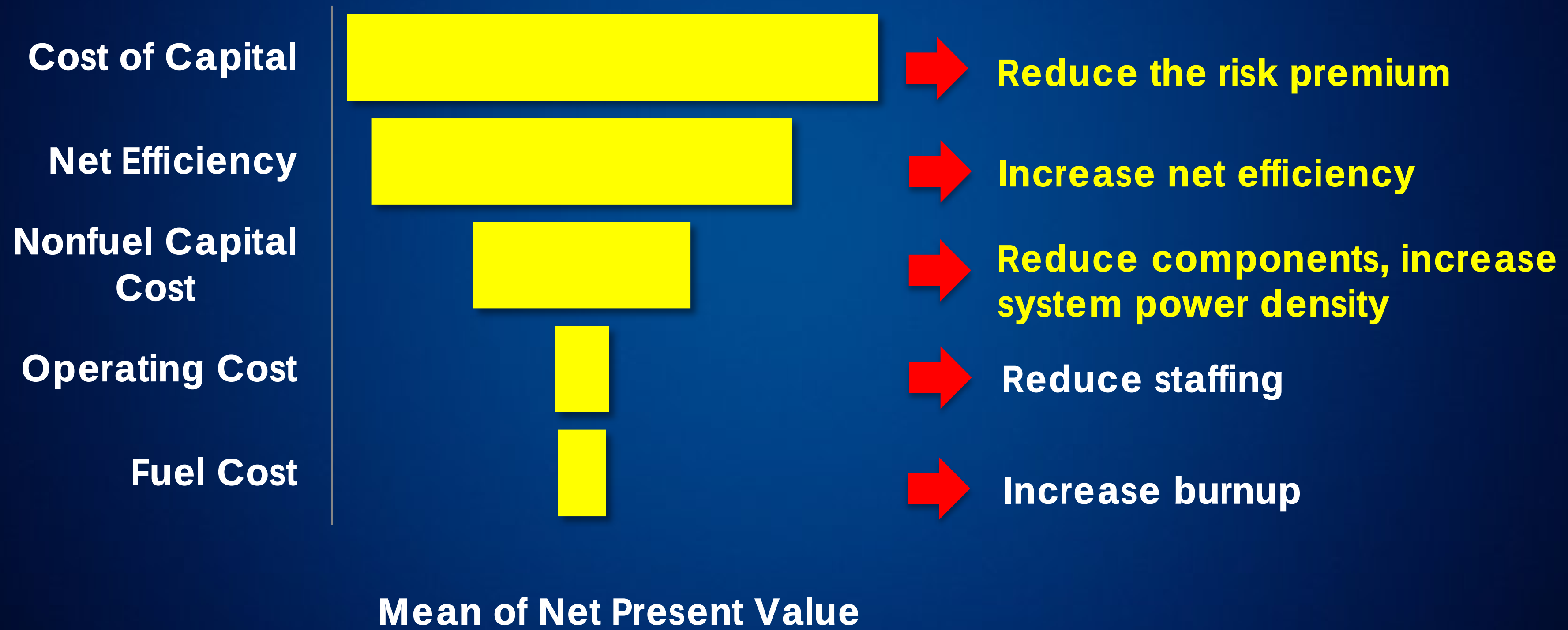


- **Separates fission products from actinides (avoids difficult chemistry)**
- **Not capable of TRU separation by element or isotopes (non-proliferation)**
- **Supportive of new reprocessing-free closed fuel cycle options**

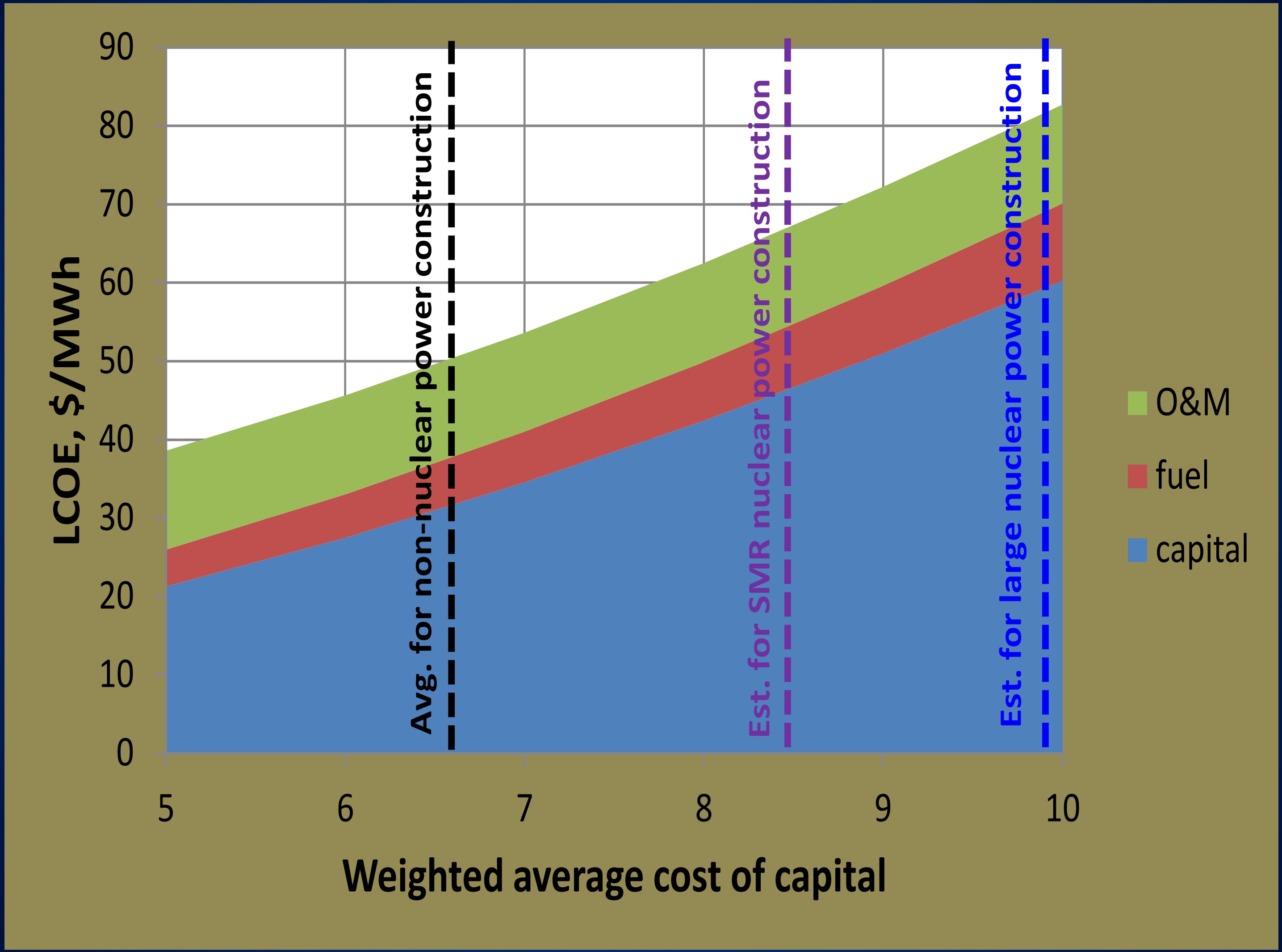
Archimedes

Major Factors Affecting the Cost of Nuclear Power
Economics

Tornado chart for ± 10% variation from base



EM² Levelized Power Cost vs Cost of Capital



GENERAL ATOMICS