Nuclear Energy: 1996, 2006, 2016

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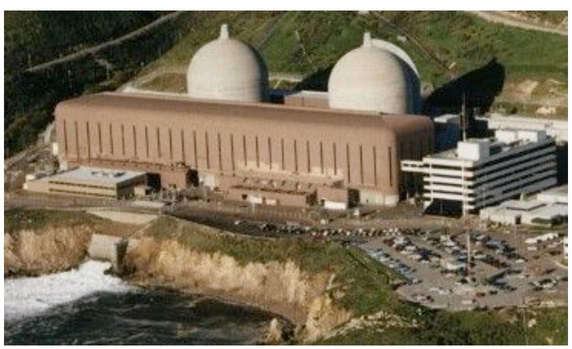
April 10, 2006



Overview

- **Current events for nuclear energy**
- **Liquid salts for high temperature nuclear heat transfer**
- **Nuclear waste management and Yucca Mountain**

Context: Recent Events

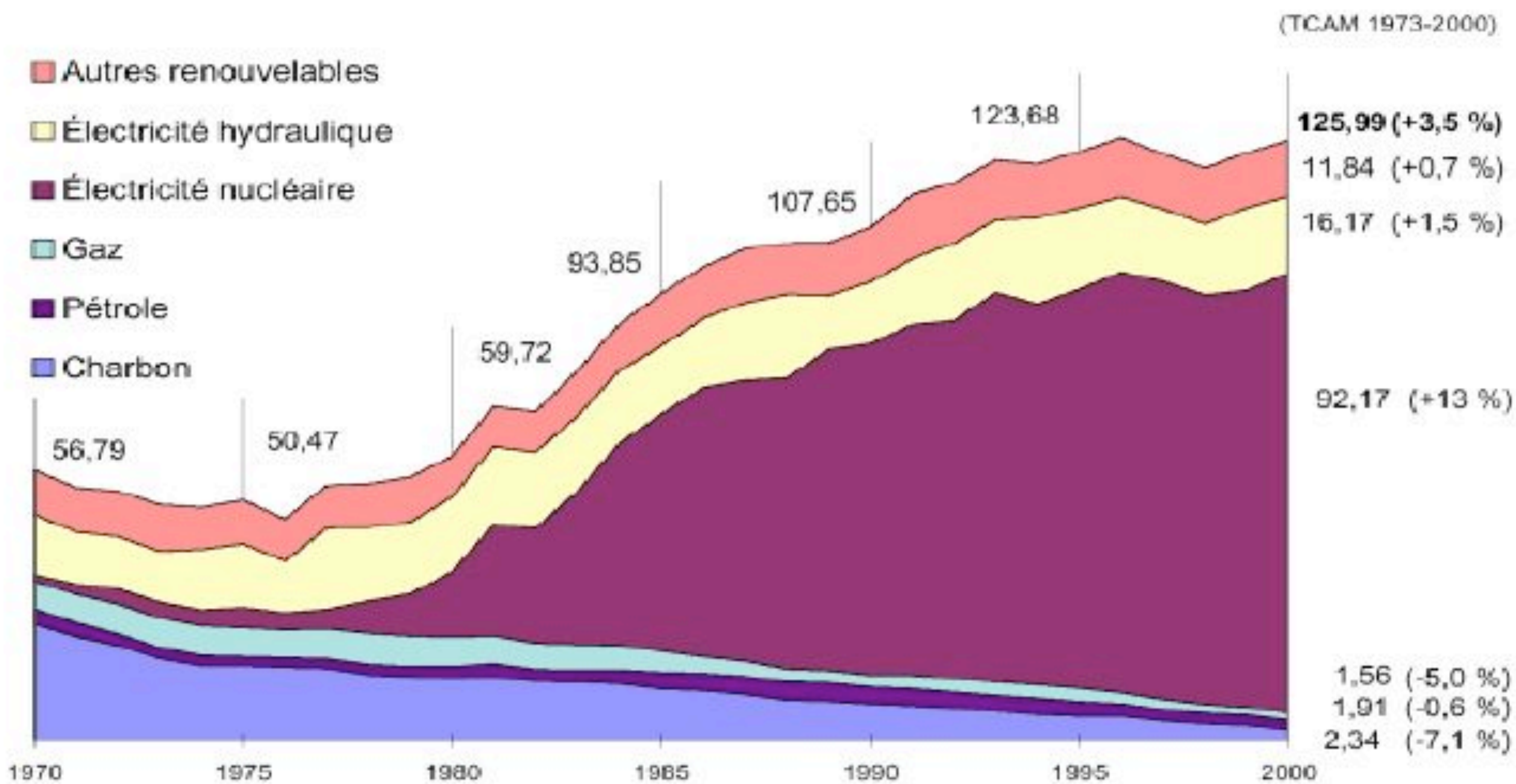
- **Important recent events**
  - Global coal consumption reaches 5.4 billion tons per year in 2002
  - In 2004, average production cost of nuclear electricity reaches 1.7 cents/kWhr, average capacity factor 90.7%, 70% fraction of all non-fossil energy produced in United States
  - As of September 2005, 33 U.S. plants had received 20-year license renewals, 16 were under review, and 27 were planned for submission by 2010 (73% of U.S. plants total). Nuclear Regulatory Commission announces plans to hire 300 engineers (October 2005)
  - 2005 Energy Bill provides major incentives for:
    - » new near-term commercial reactor construction, and
    - » authorizes funding for the U.S. Generation IV program to build a demonstration high-temperature reactor at Idaho National Laboratory to produce electricity and hydrogen
  - Announcements for new Combined Construction and Operating Licenses (as of January, 2006):
    - » 10 utilities
    - » 11 plant sites
    - » 16 plants (4 dual unit AP-1000's)
  - U.S. Senate selects Yucca Mountain as site for national repository, July 2002, NRC license application submission planned for 2008

What’s happening

- **For sure**
  - **Transformed operation of existing reactors—now the lowest production cost of any electricity source besides hydro**
- **Likely**
  - **New construction, with capital costs below $1500. First focus on commodity, base load electricity generation**
- **Hopeful**
  - **License application submission for Yucca Mountain in 2008**
  - **Congressional action to remove 70,000 MTIHM cap**
  - **Construction license for baseline design, subsequent improvements implemented through license amendments**
- **Longer term**
  - **Global Nuclear Energy Partnership technology development leads to technology to cap spent fuel accumulation inside the capacity of one repository site**
    - » **Improved repository science, source term reduction, and recycle all play roles**

France closed its last coal mine in April, 2004

Primary energy production in France (Mtoe – million tons of oil eq.)



Germany has perfected coal strip mining

45,500-ton German Krupp earth mover, can mine 76,455 cubic meters (100,000 large 40 cu. yd. dump trucks) per day

Resource inputs will affect future capital costs and competition

- **Nuclear: 1970's vintage PWR, 90% capacity factor, 60 year life [1]**
  - **40 MT steel / MW(average)**
  - **190 m^3 concrete / MW(average)**
- **Wind: 1990's vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life [2]**
  - **460 MT steel / MW (average)**
  - **870 m^3 concrete / MW(average)**
- **Coal: 78% capacity factor, 30 year life [2]**
  - **98 MT steel / MW(average)**
  - **160 m^3 concrete / MW(average)**
- **Natural Gas Combined Cycle: 75% capacity factor, 30 year life [3]**
  - **3.3 MT steel / MW(average)**
  - **27 m^3 concrete / MW(average)**

Concrete + steel are >95% of construction inputs, and become more expensive in a carbon-constrained economy

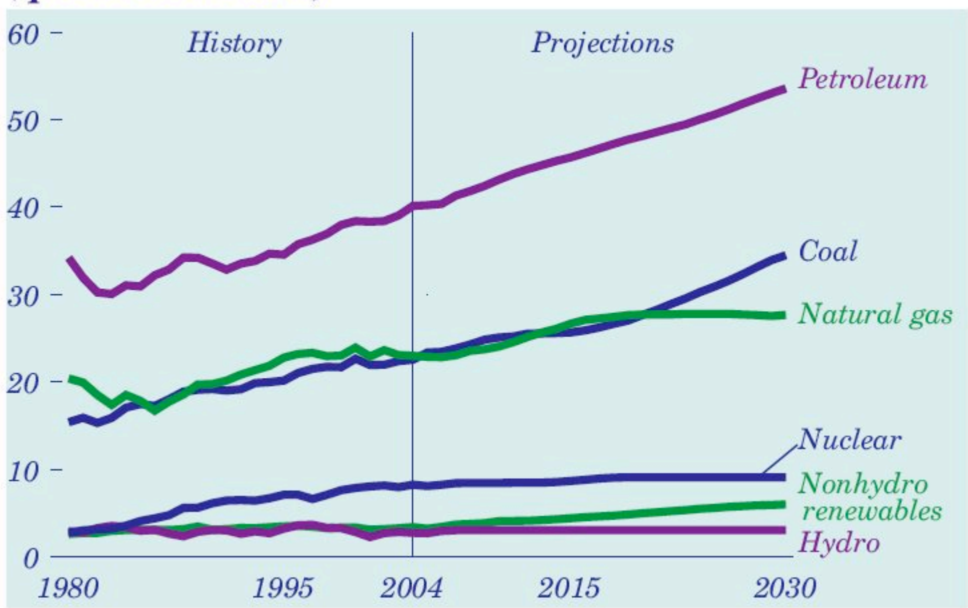
1. R.H. Bryan and I.T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant," Oak Ridge National Laboratory, TM-4515, June (1974)
2. S. Pacca and A. Horvath, *Environ. Sci. Technol.*, **36**, 3194-3200 (2002).
3. P.J. Meier, "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," U. WisconsinReport UWFDM-1181, August, 2002.

DOE Energy Information Agency's electricity projections depend strongly upon assumed capital cost of nuclear power plants

- **2006 EIA Energy Outlook report**
  - **"Reference" case: $1901/kW declining by 10% by 2025 - 6 GW new nuclear plants**
  - **"Advanced nuclear": $1818/kW declining 28% - 34 GW new nuclear plants by 2030**
  - **"Vendor estimate": $1604/kW declining 38% - 77 GW new nuclear plants by 2030**
- **General Electric statements (9/05) on fixed-price, turn-key bids**
  - **New ABWR's (nth-of-a-kind): $1450 to $1550/kW**
  - **New ESBWR's (1st-of-a-kind): approximately $1350/kW**

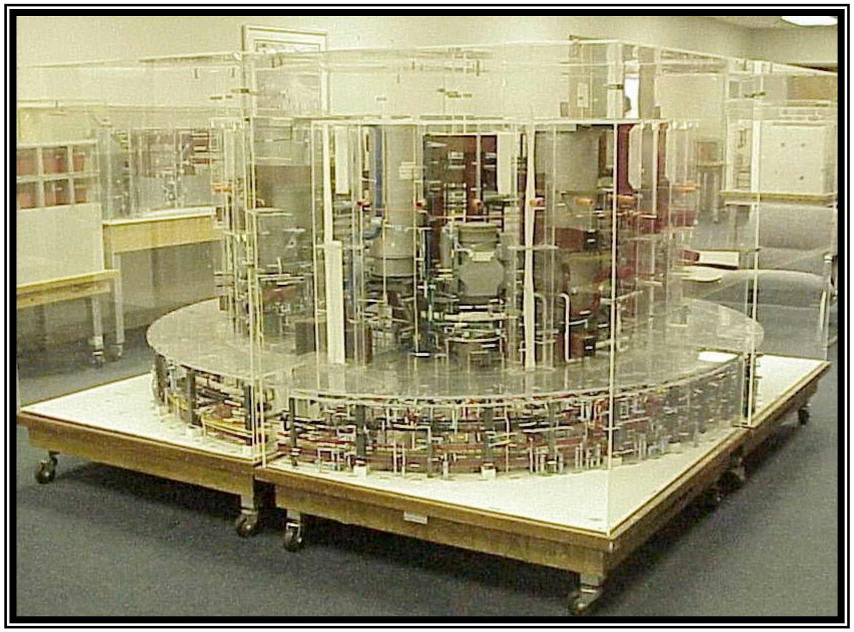
If General Electric's cost estimates prove correct, most new U.S. capacity built up to 2030 may be nuclear rather than coal or natural gas

Figure 3. Energy consumption by fuel, 1980-2030 (quadrillion Btu)



New nuclear infrastructure will be more highly optimized

1978: Plastic models on roll-around carts



McGuire Nuclear Station Reactor Building Models.

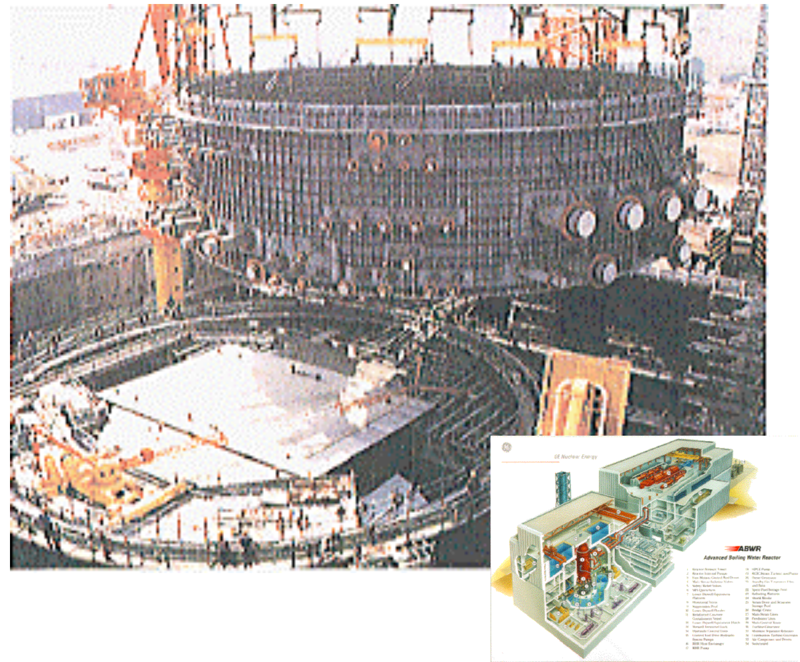
2002 NRC processing time for 20-year license renewal: ~18 months

2000: 4-D computer aided design and virtual walk-throughs

1000 MW Reactor (Lianyungang Unit 1)

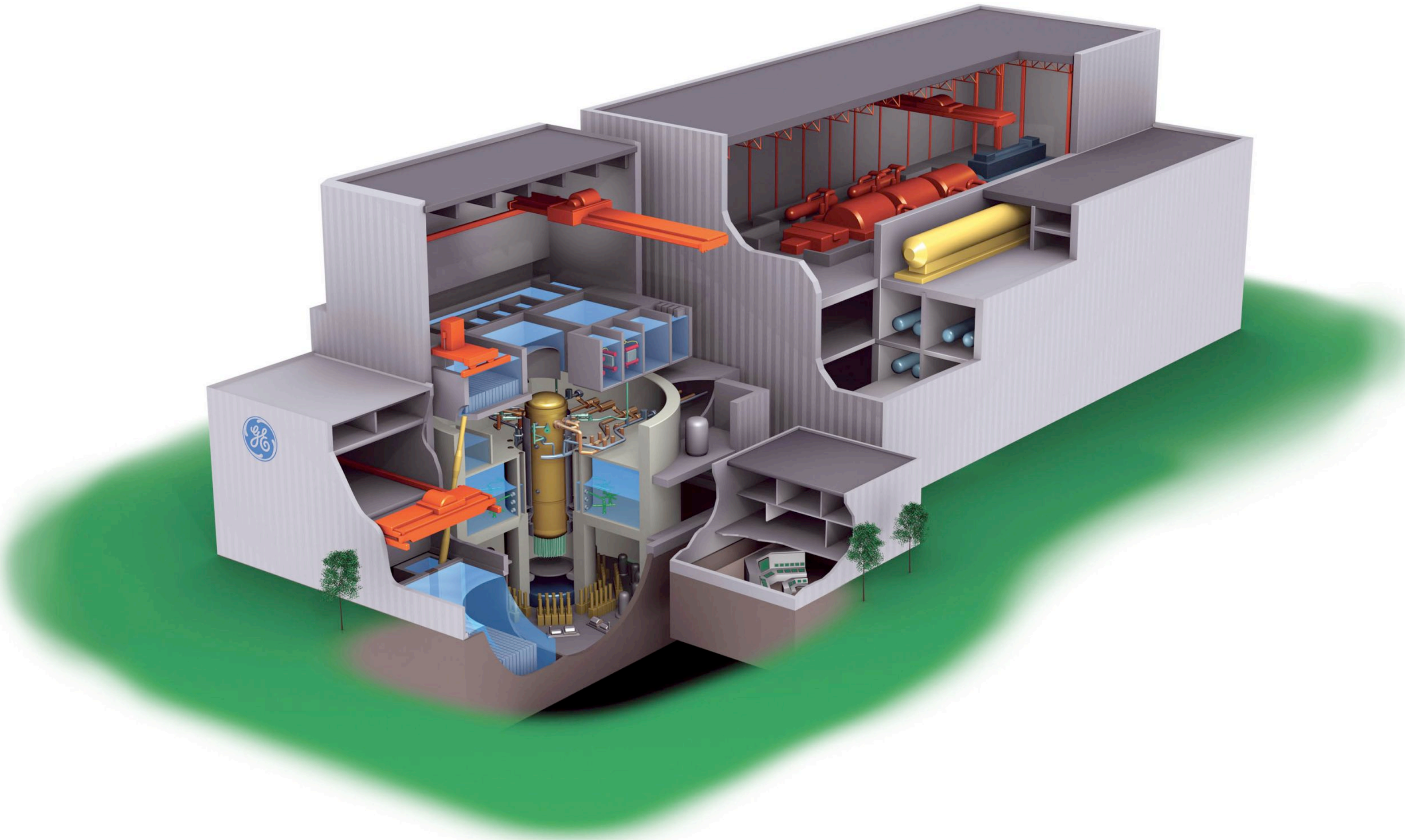
“Modular” design no longer requires “cookie cutter” construction

Modern cruise-ship construction using 3-D computer aided design and automated manufacturing

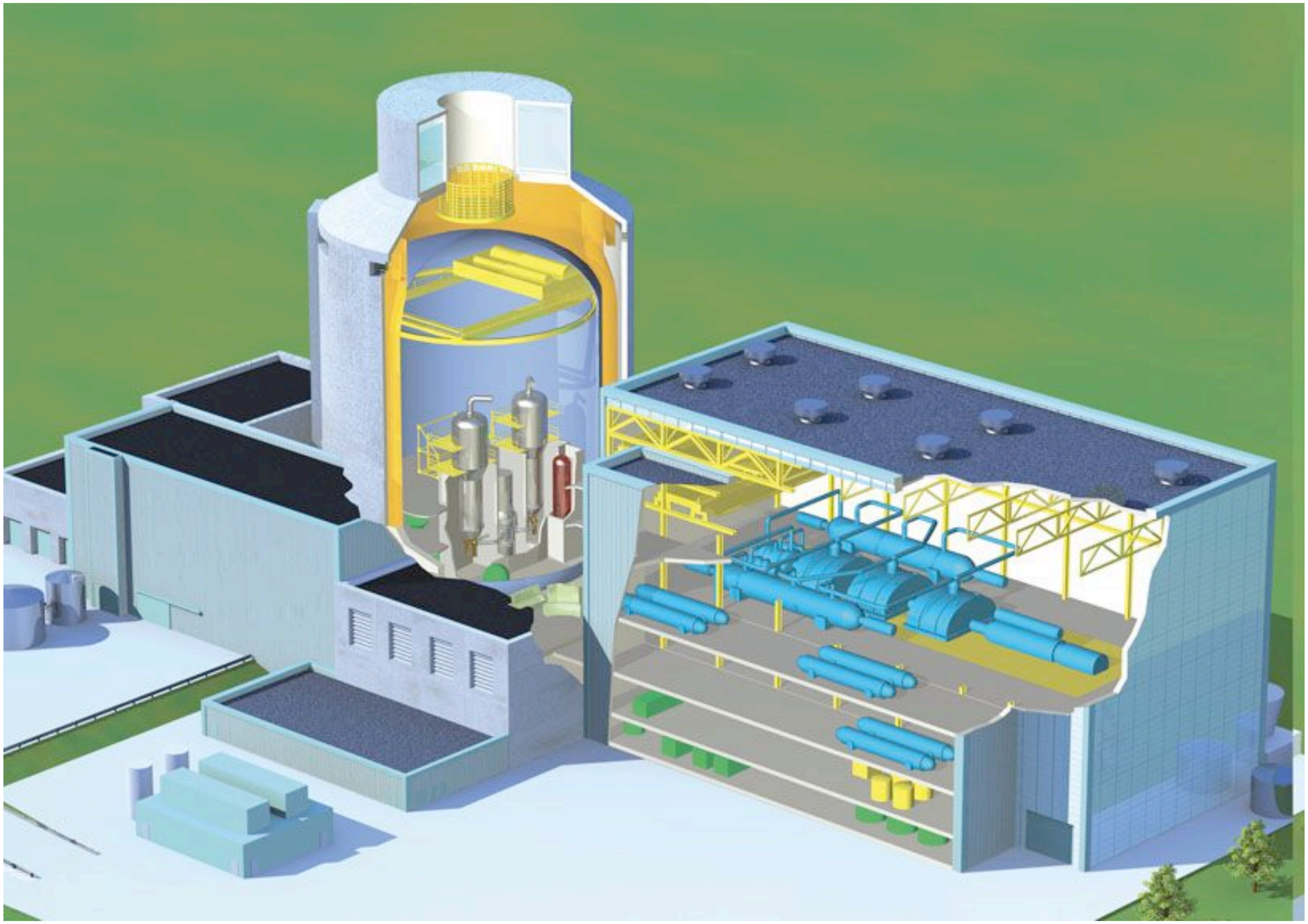


ABWR modular assembly reduces construction time to <u>52 months</u>

Gen III+: The ESBWR

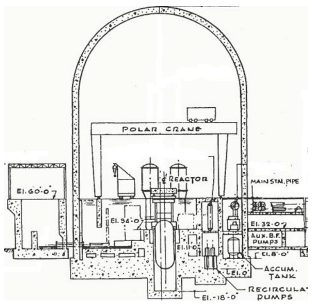


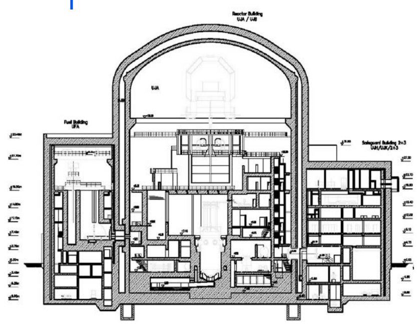
Gen III+: The AP-1000

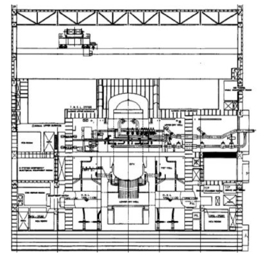


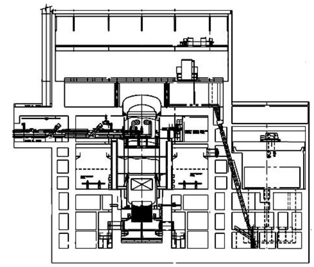
Economics will be strong influenced by design optimization to increase power while reducing structures/equipment

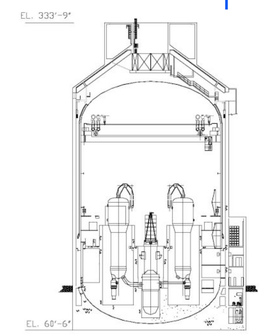
Gen II | **Gen III - Active** | **Gen III+ - Passive**

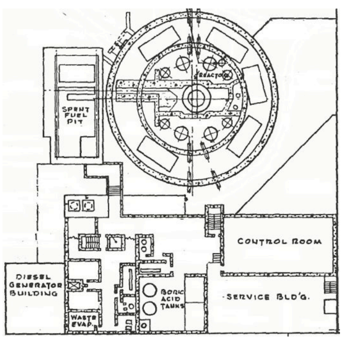


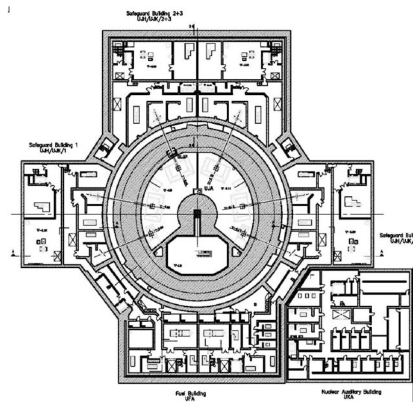


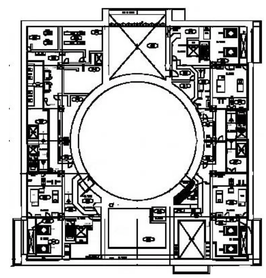


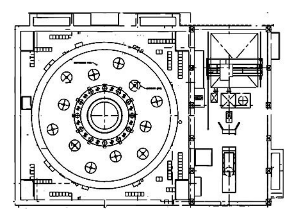


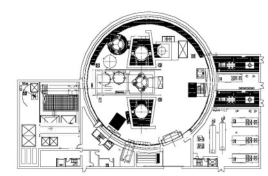








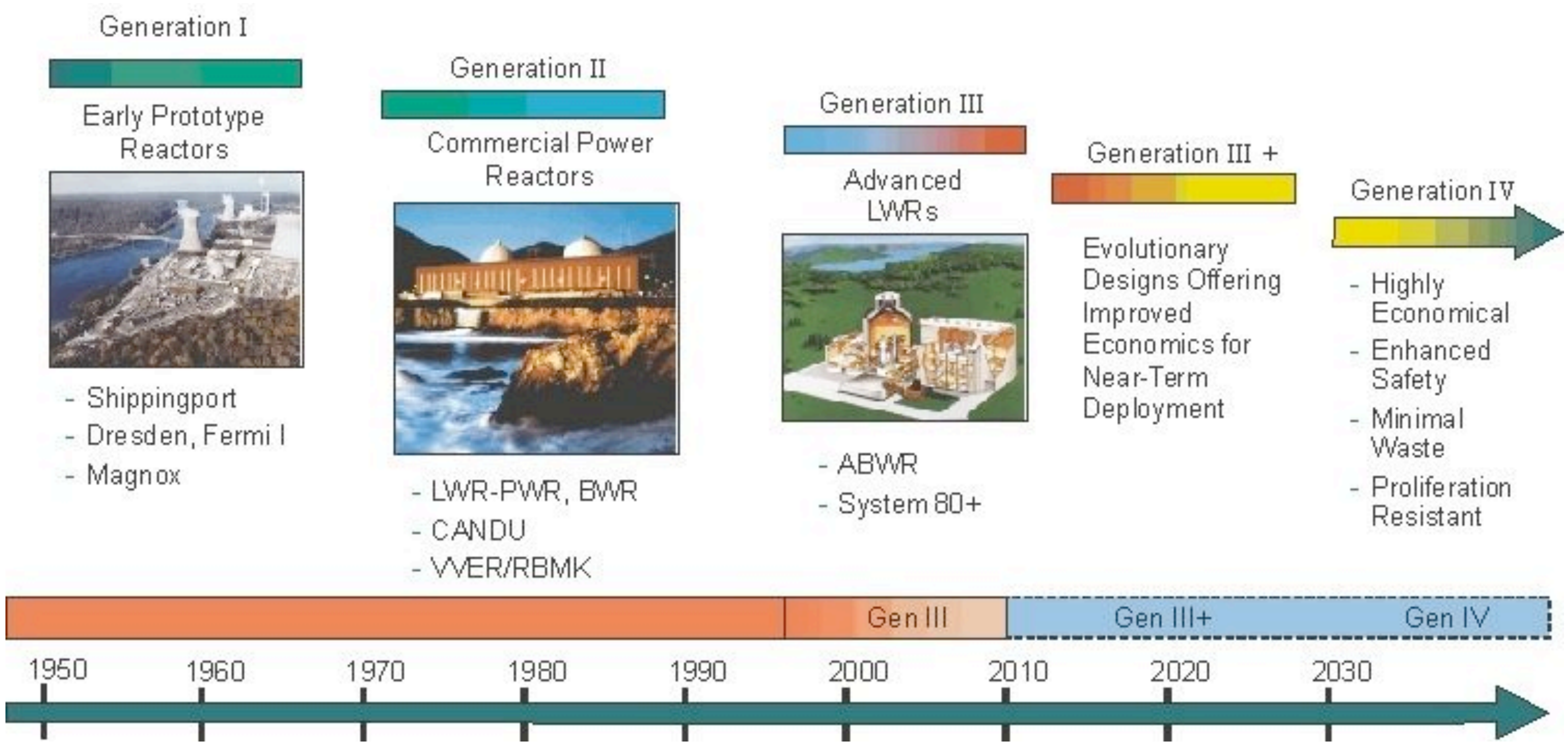




1970's PWR	EPR	ABWR	ESBWR	AP-1000
1000 MWe	1600 MWe	1380 MWe	1550 MWe	1090MWe
40 MT_{steel}/MW	49 MT_{steel}/MW	51 MT_{steel}/MW	__ MT_{steel}/MW	42 MT_{steel}/MW

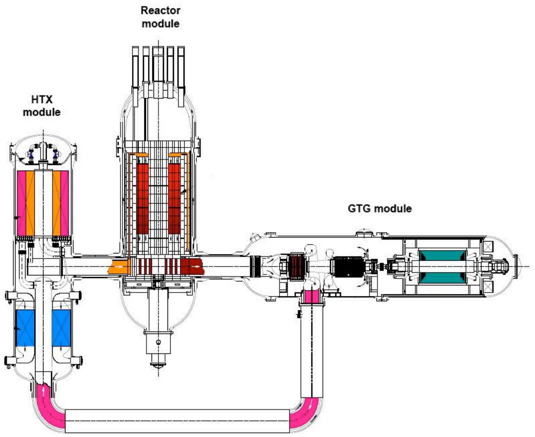
Large light water reactors with passive safety features will be difficult to beat for commodity electricity generation

The Generations of Nuclear Energy

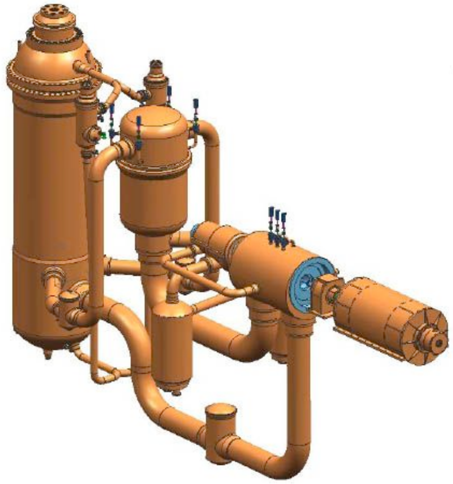


Source: DOE Generation IV Project

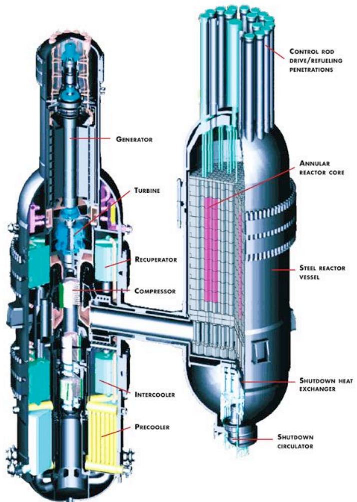
High-temperature Gen IV reactors can achieve higher efficiency/power density



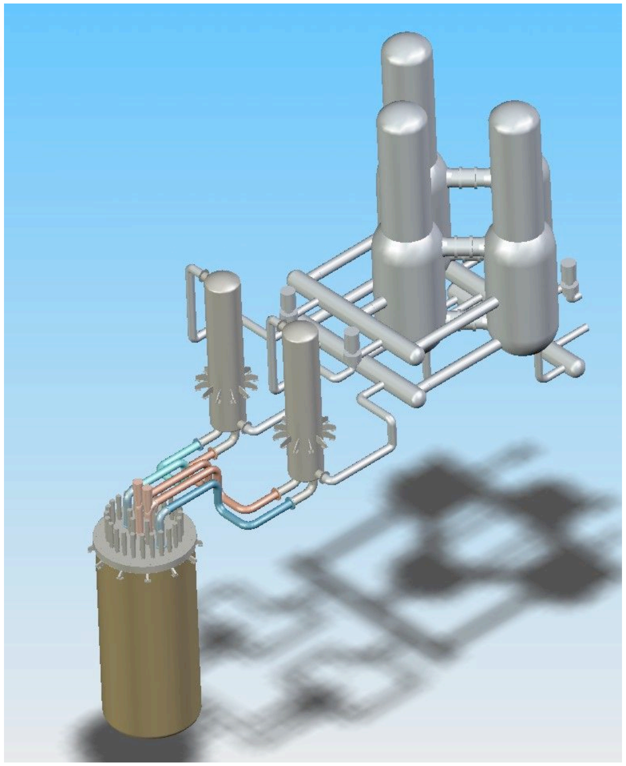
HTR-300
274 MWe



PBMR
165 MWe

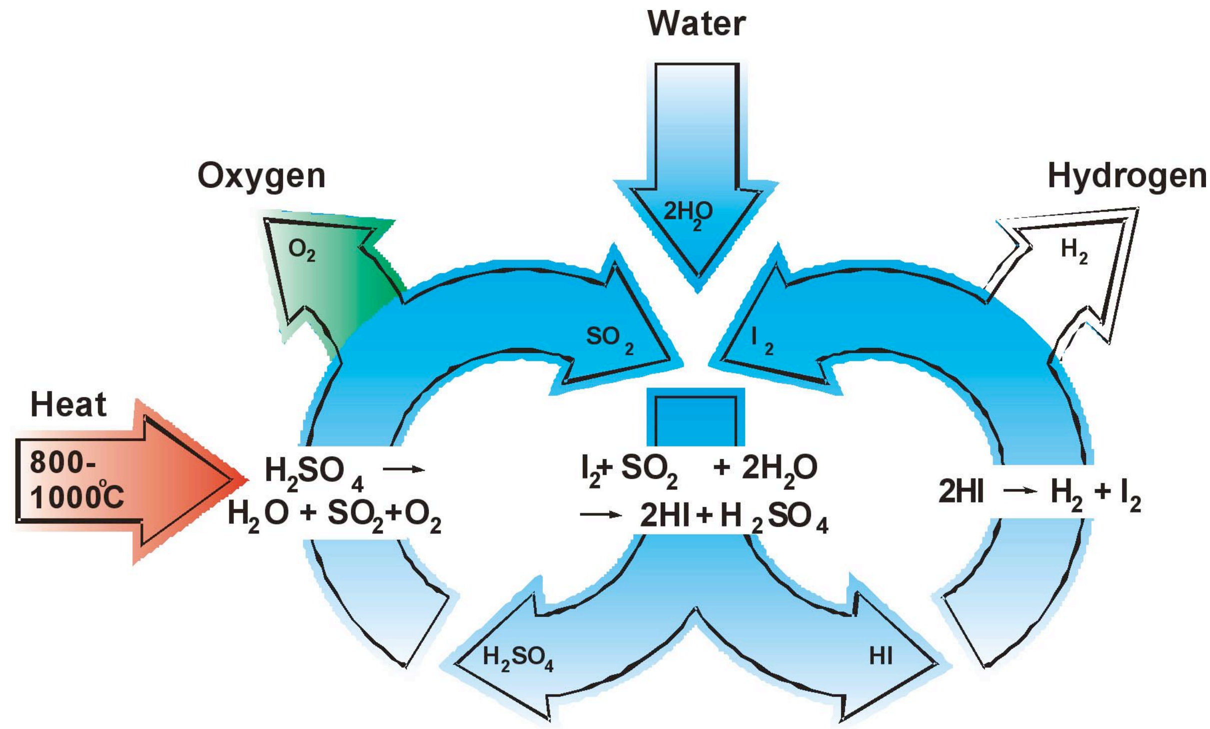


GT-MHR
286 MWe



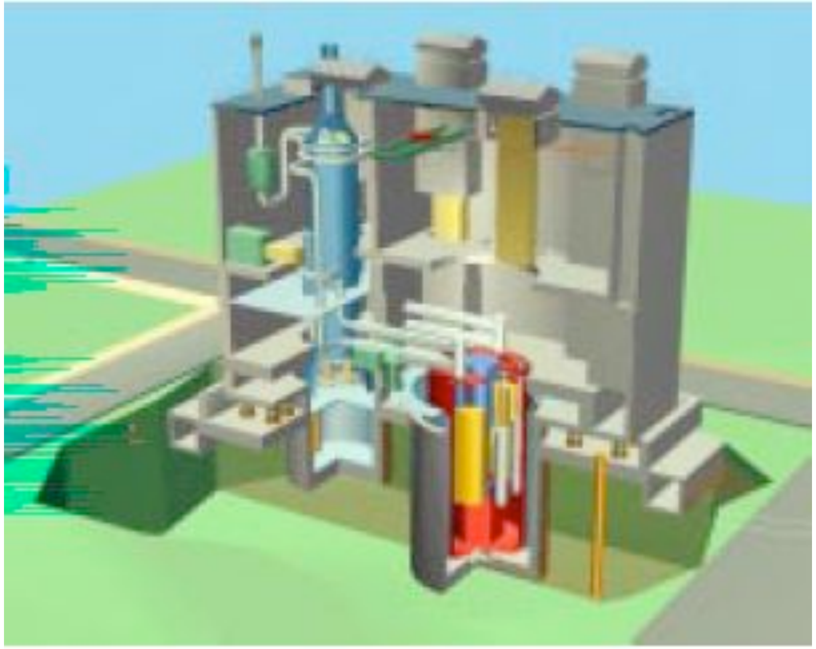
AHTR-IT-MCGC
1235 MWe

When upgraded to higher core outlet temperature, AHTR-MI can make hydrogen using the thermo-chemical process



ORNL DWG 2001-102R

Fission Reactors: The Sodium Fast Reactor



General Electric S-Prism Reactor

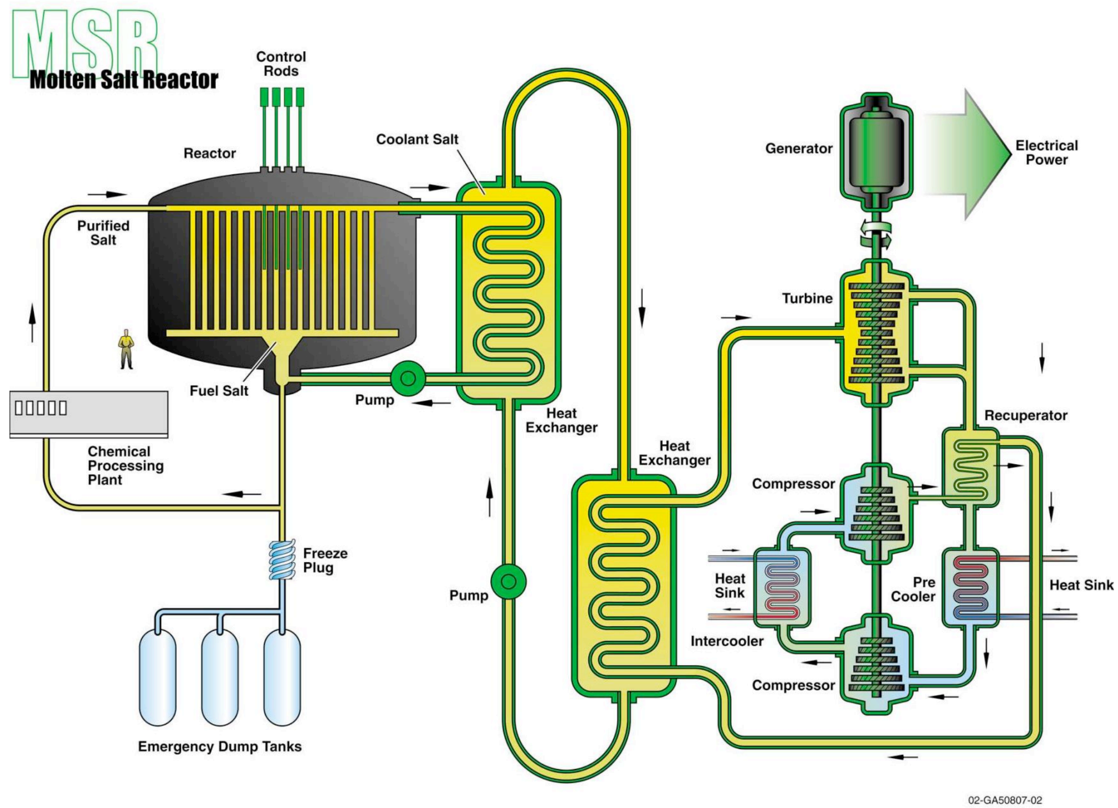
The Molten Salt Reactor (MSR) provides an alternative technology for actinide management

Characteristics

- Fuel: liquid Na, Zr, U and Pu fluorides
- 700-800°C outlet temperature
- 1000 MWe
- Low pressure (<0.5 MPa)

•Benefits

- Waste minimization
- Avoids fuel development
- Proliferation resistance through low fissile material inventory



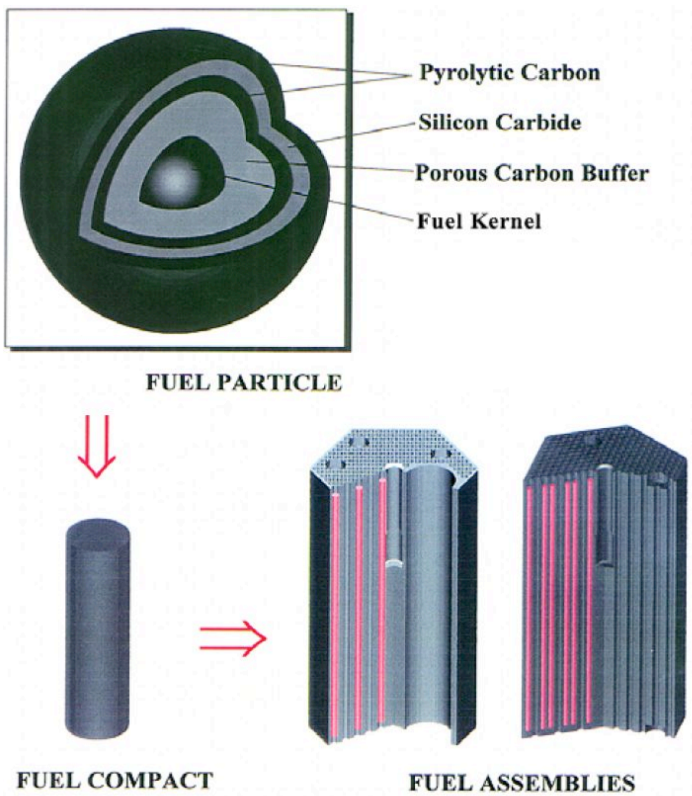
Fission Safety Fundamental Requirements

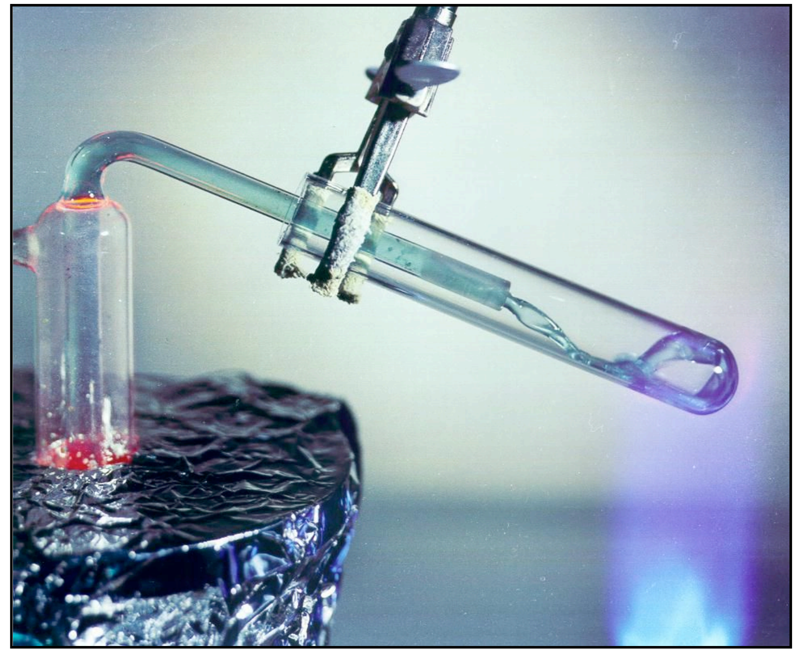
- **Negative Core Power Temperature/Void Coefficient**
  - **Heating causes fission reactions to shut off**
- **Heat Removal**
  - **Passive/active mechanisms to remove fission and decay heat**
  - **Desired directions:**
    - » **High core/coolant thermal inertia**
    - » **Highly predictable heat transfer phenomena**
    - » **Diversity/redundancy**
- **Radionuclide Confinement**
  - **Multiple/independent barriers to release of radioactive material**
  - **Defense in depth**
- **Isolation from External Events**
  - **Missiles**
  - **Seismic loading**
  - **Floods and hurricanes**

The Advanced High-Temperature Reactor (AHTR) combines two older technologies

Coated particle fuel

Same as gas-cooled reactors
Peak temperatures ~1600ºC

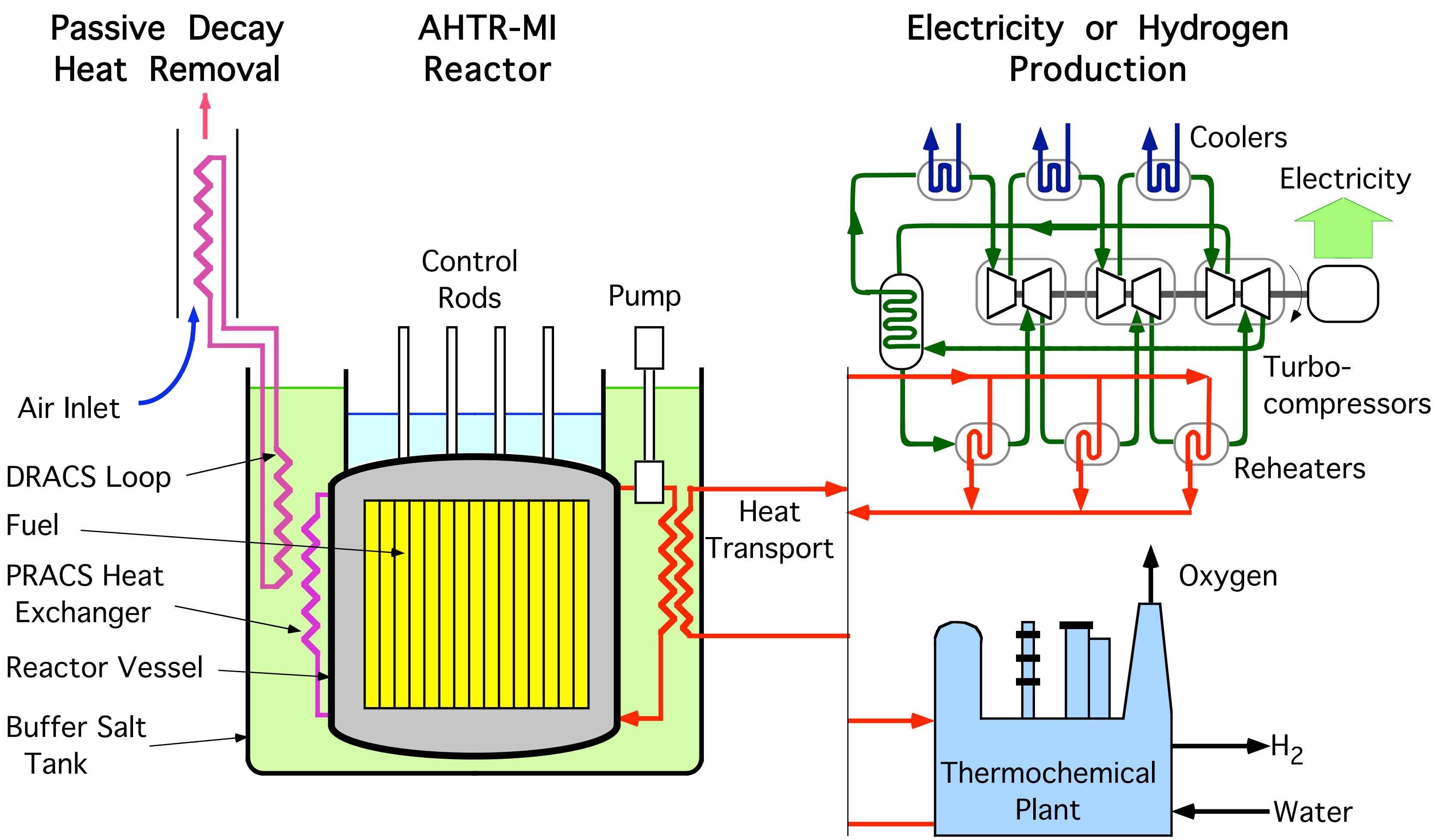




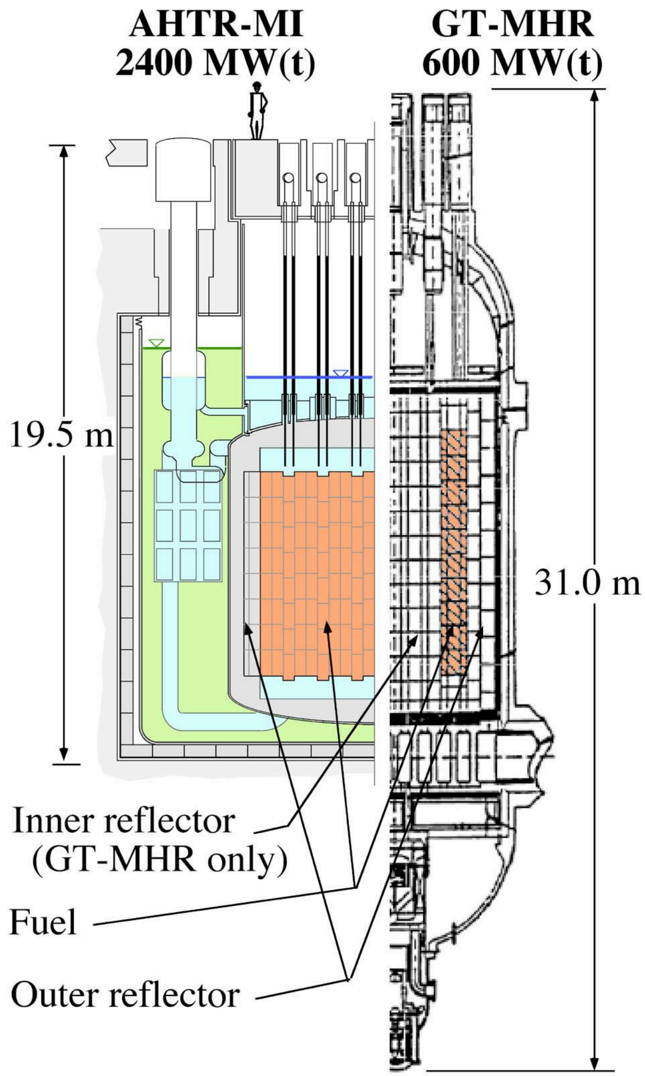
Liquid fluoride salt coolants

Boiling point ~1400ºC
Reacts very slowly in air
Excellent heat transfer
Transparent, clean fluoride salt

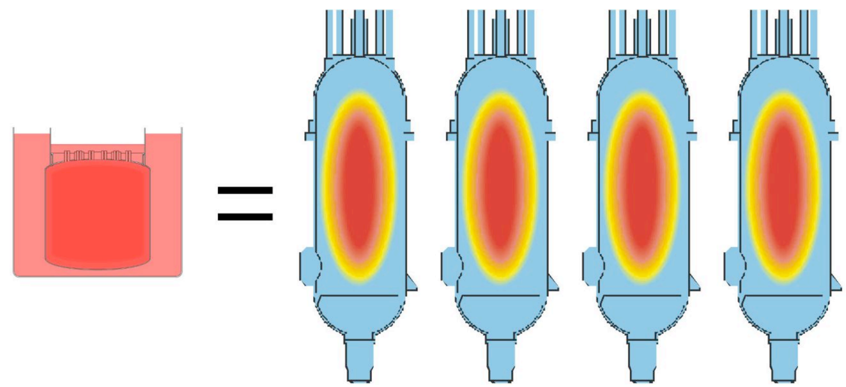
The Advanced High-Temperature Reactor (AHTR-MI) can produce electricity or hydrogen



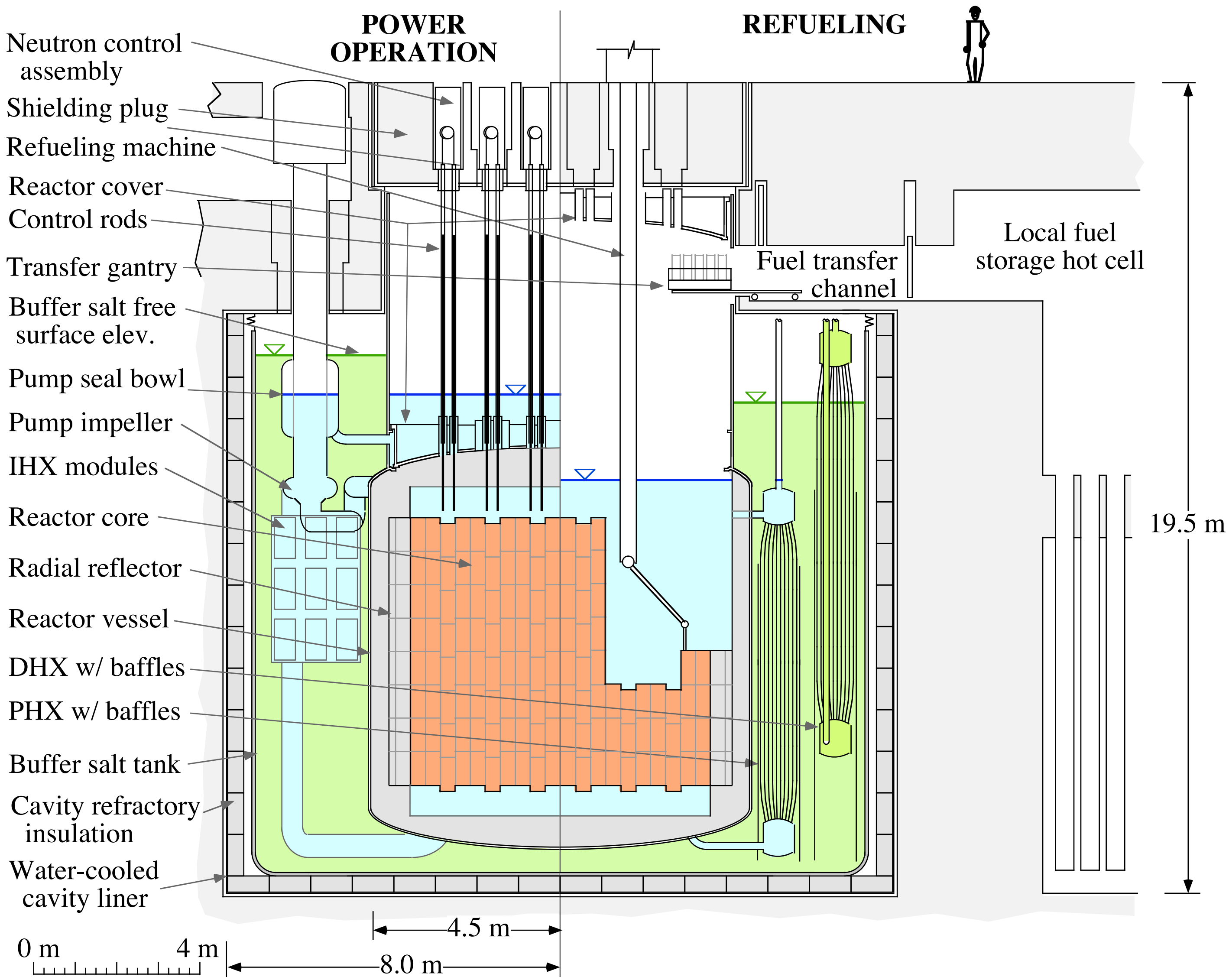
Advanced High Temperature Reactor: AHTR-MI



- **Passive safety (equivalent to modular gas-cooled reactors)**
  - **Natural circulation of primary and buffer salts increases total thermal inertia**
- **Large power output: ~2400 MW(t)**
- **Potentially superior economics-of-scale**



The AHTR-MI


POWER OPERATION
REFUELING
Neutron control assembly
Shielding plug
Refueling machine
Reactor cover
Control rods
Transfer gantry
Buffer salt free surface elev.
Pump seal bowl
Pump impeller
IHX modules
Reactor core
Radial reflector
Reactor vessel
DHX w/ baffles
PHX w/ baffles
Buffer salt tank
Cavity refractory insulation
Water-cooled cavity liner
Fuel transfer channel
Local fuel storage hot cell
19.5 m
4.5 m
8.0 m
0 m
4 m

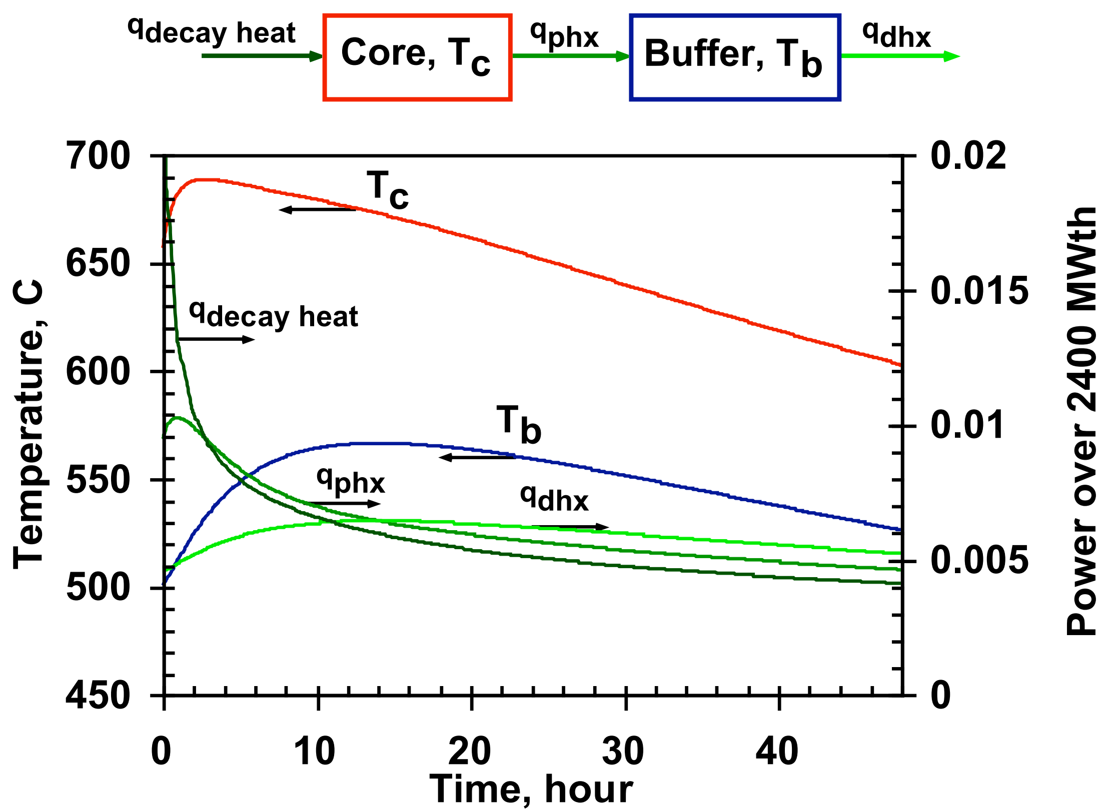
The AHTR-MI variant uses a closed primary loop

- **The mass of primary salt is greatly reduced**
  - **Primary salt can be relatively expensive (NaF/BeF_2 or $^7LiF/BeF_2$ are the baseline AHTR-MI primary salt selections)**
  - **Buffer salt is very inexpensive (sodium fluoroborate)**

		Mass (MT)	Thermal Capacity (GJ/°C)
Primary loop	Graphite/fuel	920	1.6
	Metal: reactor vessel, HX's, pumps	720	0.3
	Primary salt : NaF/BeF_2	190	0.4
Buffer tank	Buffer salt: $NaF/NaBF_4$	2500	3.8

- **The number of components exposed to high salt temperature is controlled and minimized**
  - **Only hot ducts, reactor cover, IHX, PHX and pumps see peak temperatures**
  - **Large components (reactor vessel, buffer salt tank) operate at much lower temperature, and can use less expensive materials**

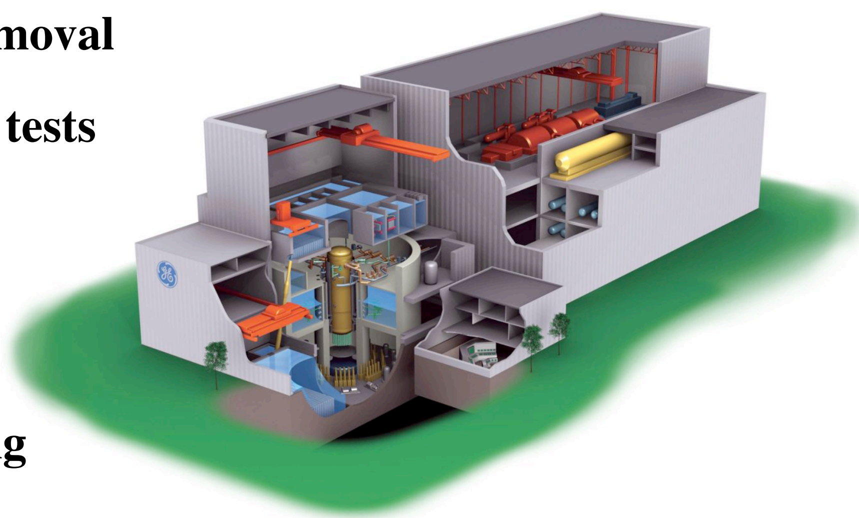
A lumped capacity model provides a first-order estimate for the AHTR-MI response to LOFC



- **Thermal inertia comes primarily from graphite and buffer salt**
- **Total primary temperature rise <50°C**

New reactor concepts should be designed to simplify safety analysis for NRC licensing

- ESBWR provides an important example
  - In pre-certification review, NRC approved GE safety codes and supporting experimental validation in only 6 months
  - ESBWR was the first reactor to be designed using the Code Scaling, Applicability, and Uncertainty Method (CSAU)
  - Phenomena Identification and Ranking used to determine experimental validation needs
    - » Modular decay heat removal simplifies reduced area scaling and component tests
  - Major goal: Simplicity
    - » Component tests
    - » Separate effects tests
    - » Integral effects tests
    - » Maximize use of existing experimental data



Phenomena Identification and Ranking Tables

- **Identify NPP and scenario (e.g. initiating event)**
- **Disaggregate system and transient response into:**
  - **Spatial regions**
    - » **choose boundaries that give logical boundary conditions (e.g. LOCA fuel rods, core, upper plenum, hot leg, etc.)**
  - **Temporal phases**
    - » **Choose time phases where transitions in dominant phenomena occur (e.g. LOCA blowdown, refill, reflood)**
- **Systematically identify and rank phenomena that are important in each spatial region and temporal phase**
- **Define the experiments required to validate modeling tools**
  - **Scaled separate effects experiments**
    - » **boundary and initial conditions for a region and phase are imposed artificially to replicate a phenomena**
  - **Scaled integral effects experiments**
    - » **coupled phenomena for multiple regions and/or phases are generated in scaled experiments, or**
    - » **experiments are performed using a prototypical system**

Example: PANDA integral effects test for SBWR

- **Major experimental facility used to provide IET data for code validation for SBWR**
  - **Full height, reduced area experiment**
- **For liquid salts, Dowtherm and Therminol heat transfer fluids can reproduce liquid salt fluid mechanics and heat transfer**
  - **can match Pr, Re, Gr, Fr simulataneously**

Panda experiment, PSI, before building was constructed around the vessels

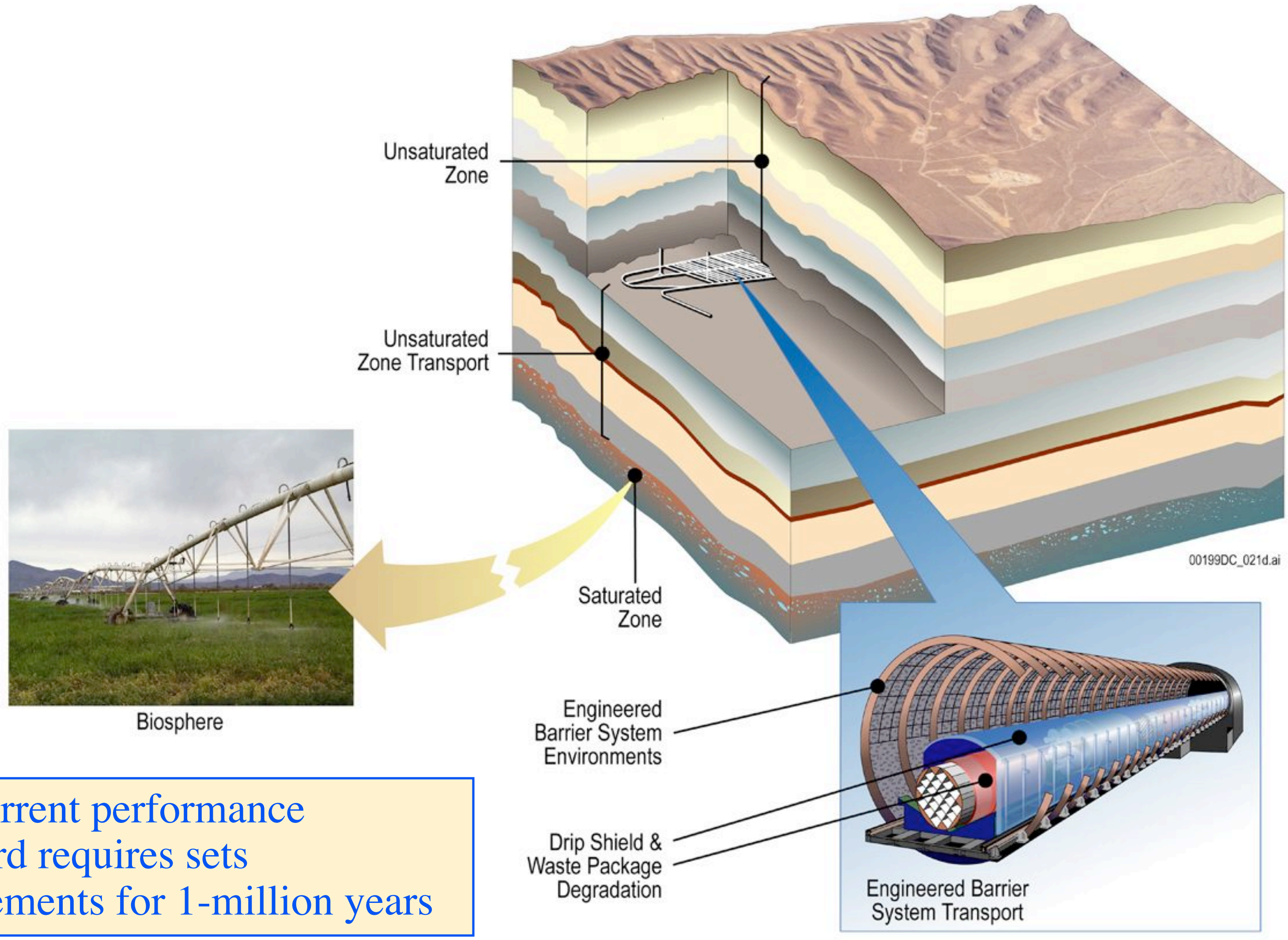
Liquid salt heat transfer/fluid mechanics can be simulated at low temperature with Dowtherm

Scaling parameters to match Pr, Re, Gr, and Fr for flibe and Dowtherm A

Flibe Temperature [°C]		600	650	700	750	800	850
Dowtherm A Temperature [°C]		63	82	104	129	157	191
Length scale	l_m/l	0.52	0.51	0.49	0.46	0.44	0.41
Velocity scale	u_m/u	0.72	0.72	0.70	0.68	0.66	0.64
ΔT scale	$\Delta T_m/\Delta T$	0.30	0.30	0.30	0.30	0.29	0.29
Heat conductivity	λ_m/λ	0.14	0.13	0.13	0.12	0.12	0.11
Ther. diffusivity	α_m/α	0.37	0.35	0.33	0.31	0.28	0.26
$\beta\Delta T$	$(\beta\Delta T)_m/\beta\Delta T$	1.00	1.00	1.00	1.00	1.00	1.00
$\gamma\Delta T$	$(\gamma\Delta T)_m/\gamma\Delta T$	0.81	0.94	1.06	1.13	1.13	1.04
$\kappa\Delta T$	$(\kappa\Delta T)_m/\kappa\Delta T$	-0.84	-0.86	-0.89	-0.92	-0.95	-0.99
Pumping power	$P_{p,m}/P_p$	5.2%	5.0%	4.2%	3.4%	2.8%	2.1%
Heating power	$P_{q,m}/P_q$	2.1%	2.1%	1.9%	1.7%	1.5%	1.3%

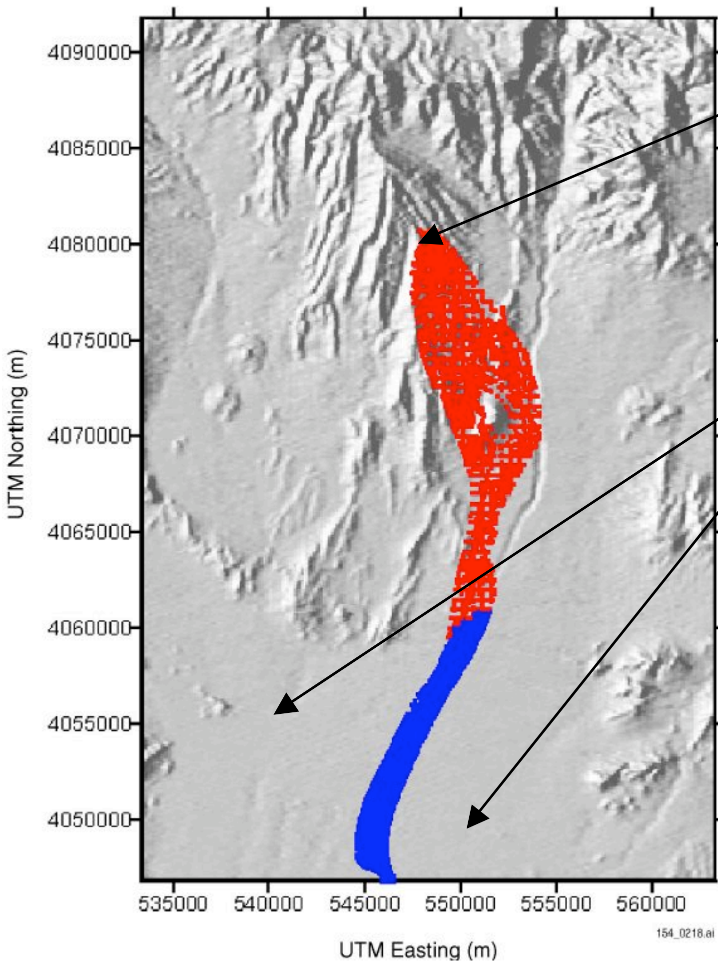

Yucca Mountain
00199DC_043.ai

Overview of Yucca Mountain repository system



The current performance standard requires sets requirements for 1-million years

Projected Contaminant Path in the Groundwater



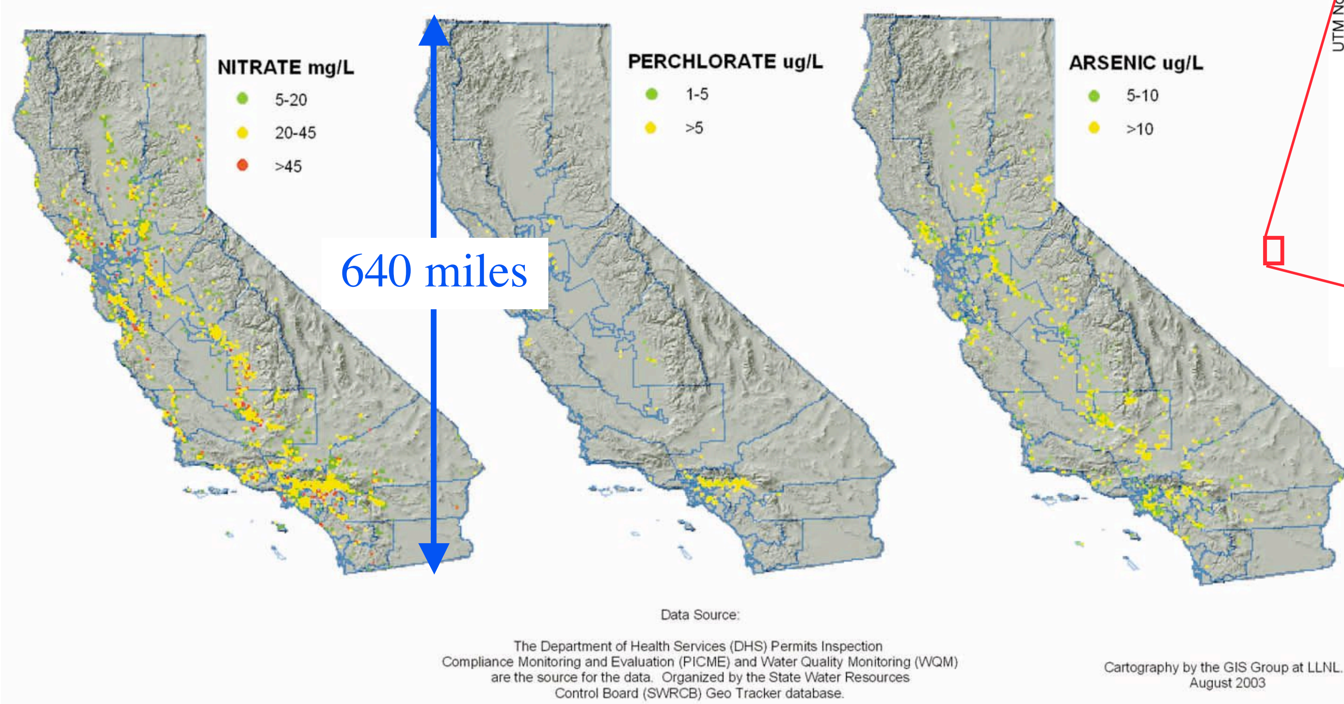
Yucca Mountain

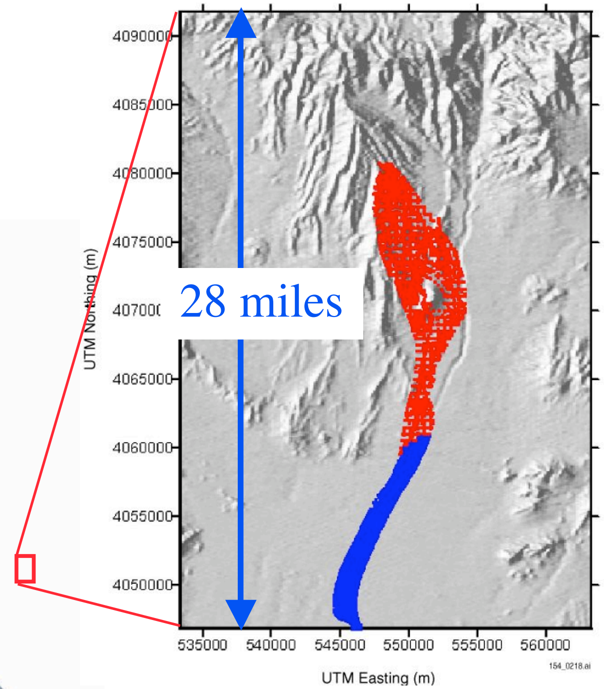
Amargosa Valley

At the current legal capacity limit of 63,000 MT, spent fuel in Yucca Mountain produced the energy equivalent of 5 billion tons of coal

Chemical contamination of groundwater from natural and human sources is extensive

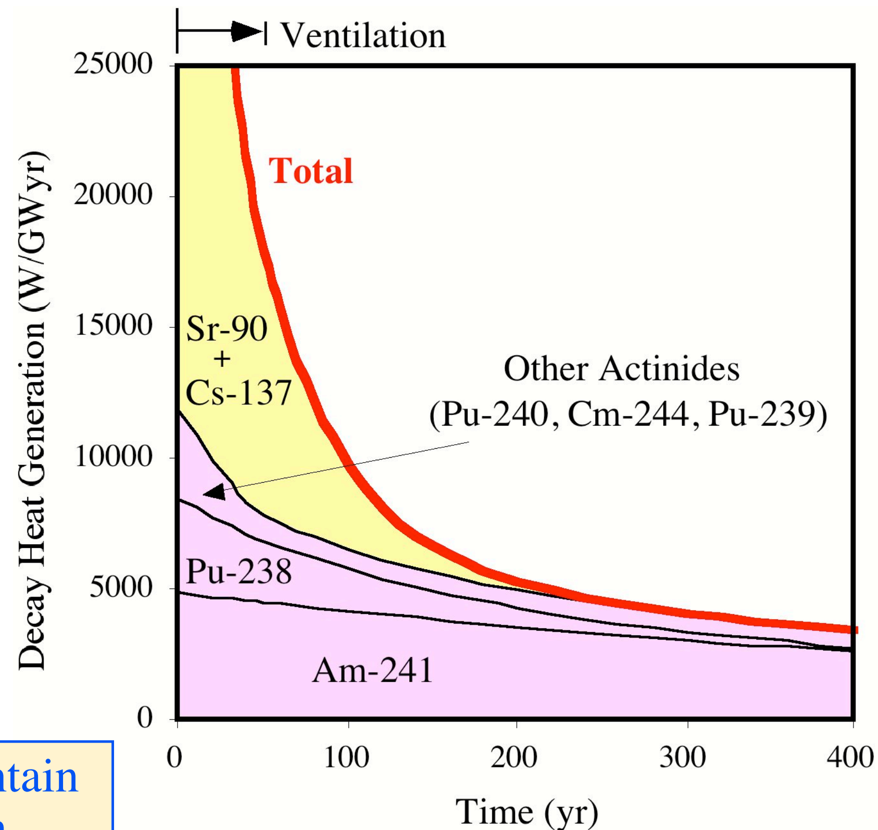
Scaled comparison of California wells with current nitrate, perchlorate, and arsenic groundwater contamination, to the potential groundwater plume that might be generated at Yucca Mountain





Advanced fuel cycles can impact repository performance

- **Yucca Mountain's current legal capacity limit is 63,000 MT of spent fuel**
  - **Current U.S. plants will reach this limit in 2014**
- **Technical limit for the current 4200 acre repository footprint is between 105,000 and 300,000 MT of spent fuel**
- **Advanced fuel cycles that recycle the heavy elements in spent fuel would increase this capacity by a factor of ~ 50x.**



LWR Spent Fuel Heat Generation

Under advanced fuel cycles, Yucca Mountain could potentially hold 500 kg/m of fission products in 800 km of drifts (4200 acres), equal to 1.0-trillion tons of coal

Conclusions

- **Recent activity in nuclear energy has been substantial**
  - **Waste repository site selected in United States**
  - **Over 50% of U.S. reactors to receive 20-year license renewals by 2007**
  - **11 U.S. sites applying for combined construction and operating, multiple new reactor designs in queue with NRC for certification**
  - **2005 Energy Bill provisions for new nuclear construction and R&D**
  - **New nuclear power plant orders in Europe and Asia**
  - **New research to demonstrate high-efficiency electricity and hydrogen production**
  - **New conceptual designs with very low capital cost**
  - **Global Nuclear Energy Partnership**