The Liquid-Salt-Cooled Advanced High-Temperature Reactor for Hydrogen and Electricity

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Outline

Reactors Before Their Time

What Has Changed?

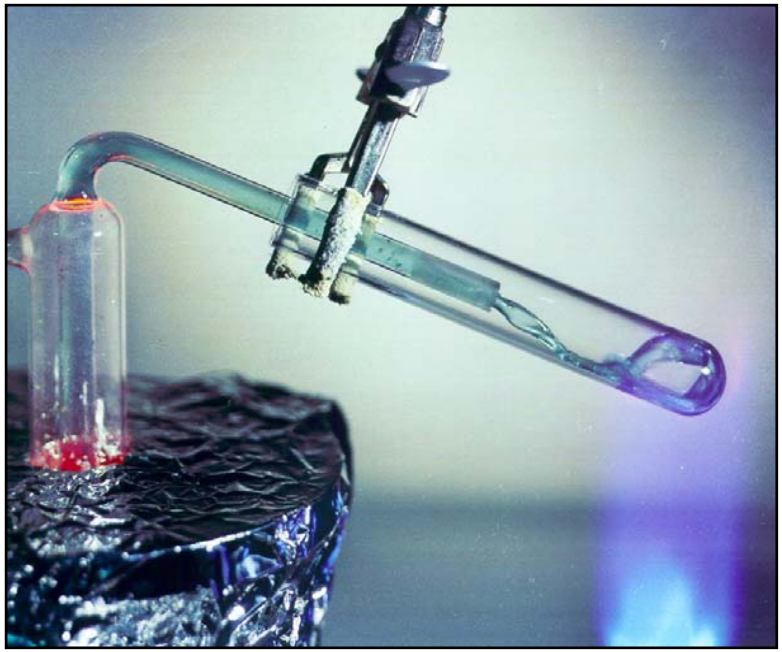
Back to the Future!

The High-Temperature Reactor Rebirth

The Advanced High-Temperature Reactor

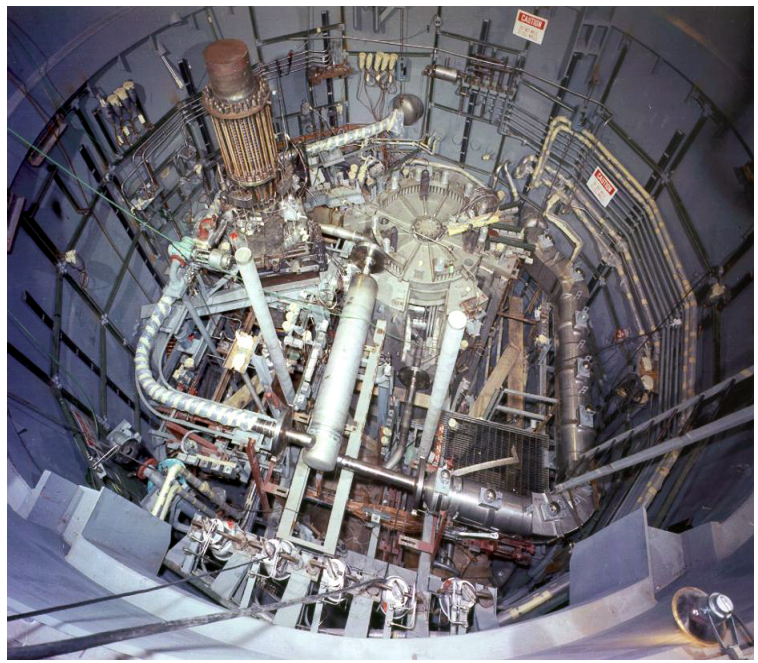
Reactors Before Their Time

Molten Salt Reactors Were Developed from the 1950s to the Mid 1970s



Liquid Salts

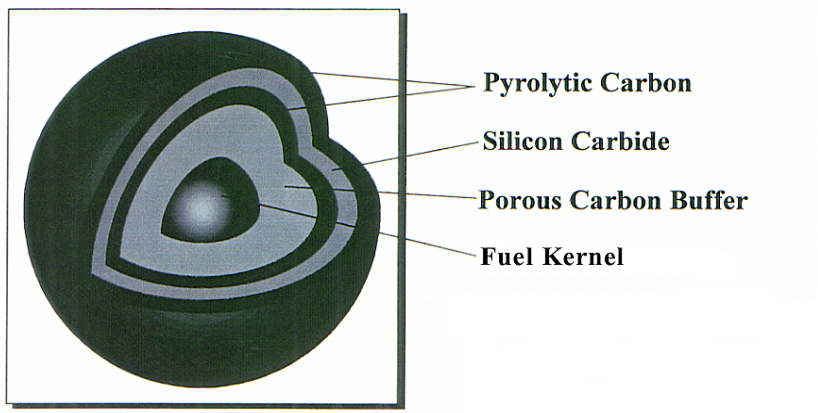
← Melting points: 350 to 500ºC
Boiling points: >1200ºC



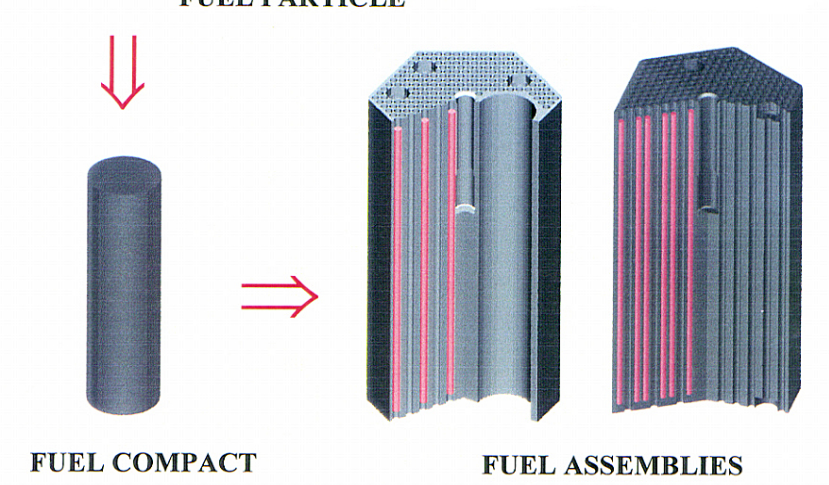
Molten Salt Breeder Reactor Program

ORNL Molten Salt Reactor Experiment
Power level: 8 MW(t) →

High-Temperature Gas-Cooled Reactors Were Developed in the 1970s



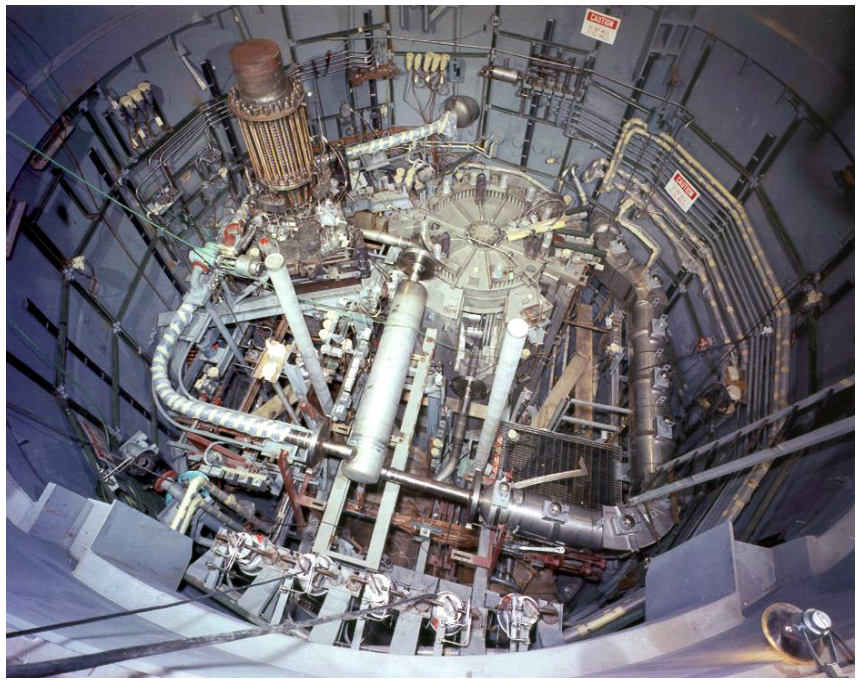
FUEL PARTICLE



PEACH BOTTOM 1: 1967–1974

FORT ST. VRAIN: 1976–1989

The Reactor Technologies Were Developed



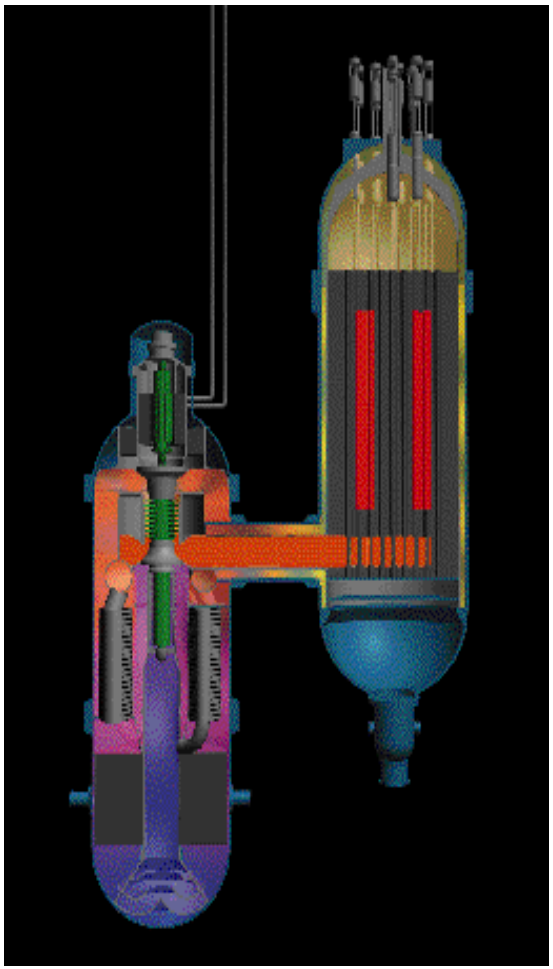
Molten Salt Reactors

High-Temperature Reactors

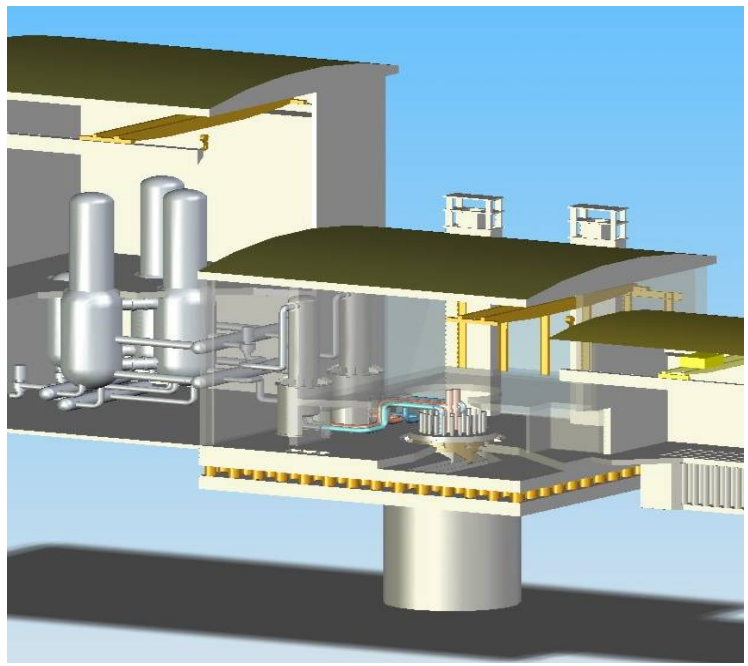
And Then They Were Abandoned....

Back to the Future

Rebirth of High-Temperature Reactors and the Birth of the Advanced High Temperature Reactor (AHTR)



New Needs and New Technologies Enable Rebirth of Old Technologies in a New Form



What Has Changed?

Electricity Production

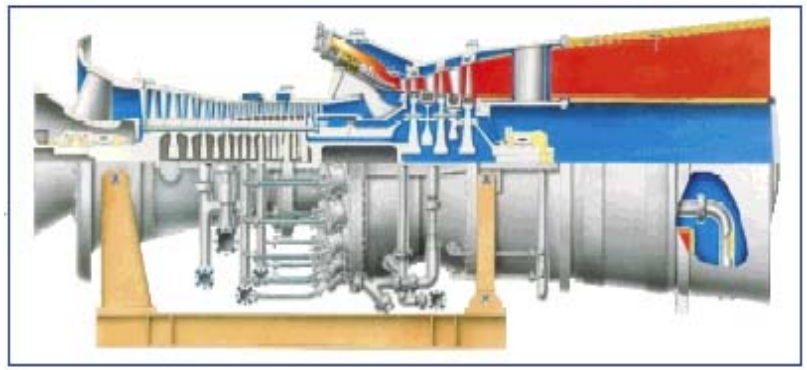
A New Technology Makes an Old Technology Useful by More Efficiently Converting High-Temperature Heat to Electricity

The Water-Energy Nexus

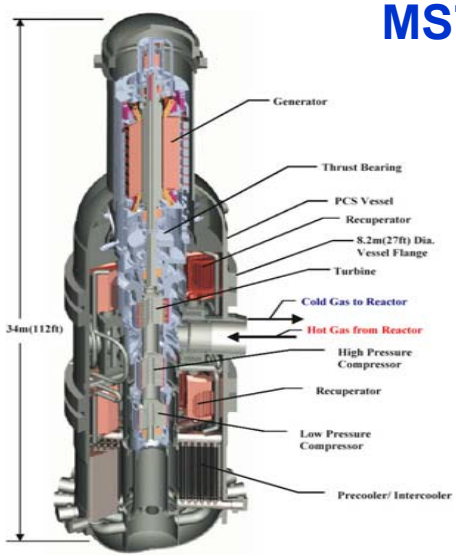
Brayton Power Cycles Make High-Temperature Utility Power Systems Viable

(Helium or Nitrogen Brayton Power Cycles)

- **High-temperature heat is only useful if it can be converted to electricity**
- **Steam cycle limit ~ 550ºC**
- **New utility-grade Brayton cycles operate efficiently at higher temperatures**
- **The technology now exists to economically convert high-temperature heat to electricity**



GE Power Systems MS7001FB



General Atomics GT-MHR Power Conversion Unit (Russian Design)

High-Temperature Utility Power Systems Enable Dry Cooling

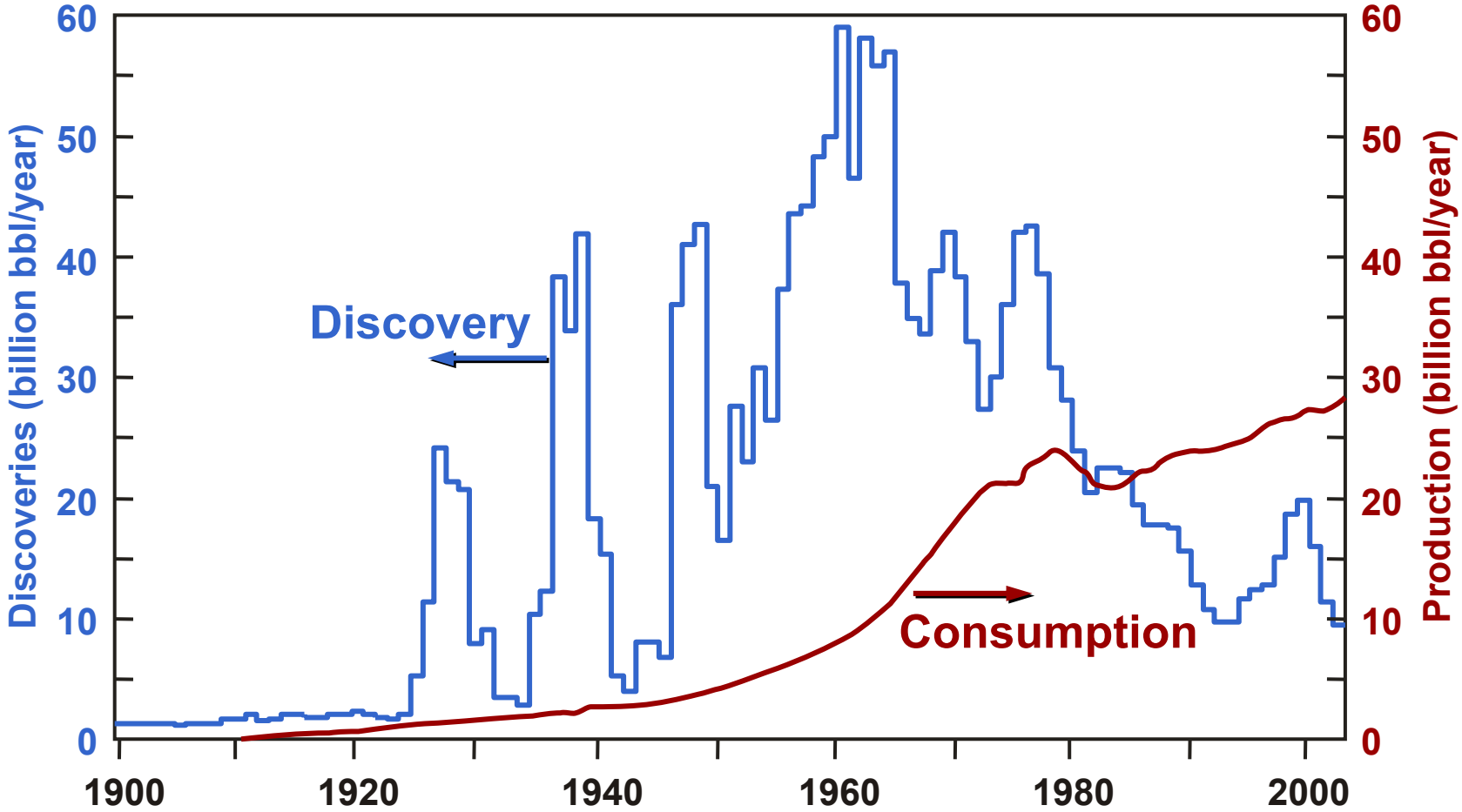
Thermal Power Plant Dry Cooling
ACC at PacifiCorp's Wyodak Power Plant
(Courtesy of R. Garan)

- **Dry cooling avoids water-power-people conflicts**
- **Dry cooling is expensive**
  - **Planned Nevada Toquop Supercritical Coal Plant**
    - **Dry cooling**
    - **$1600/kW(e)**
  - **Higher efficiency reduces heat rejection costs**
    - **LWR: 2 kW(t) rejection per kW(e)**
    - **HTR: 1 KW(t) per KW(e)**
- **Strong incentives for high-temperature reactors**

Liquid Transport Fuels

(New Need for Alternative Fuel Sources)

The Age of Oil for Fuels is Closing



Oil and Gas J.; Feb. 21, 2005

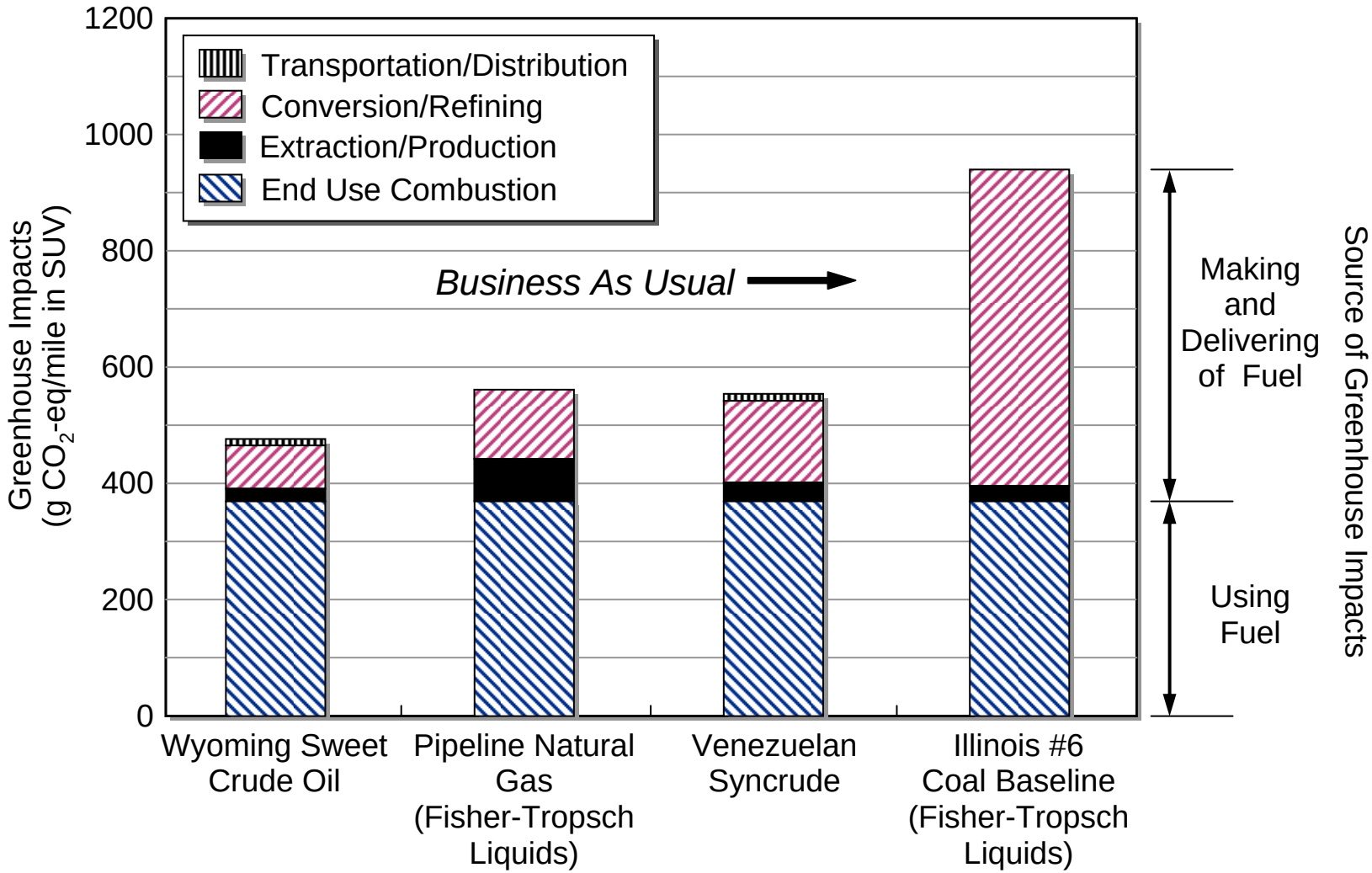
Conventional Futures: Liquid Fuels will be Made from Heavy Oils and Tar Sands

(Lower Hydrogen-to-Carbon Ratios)

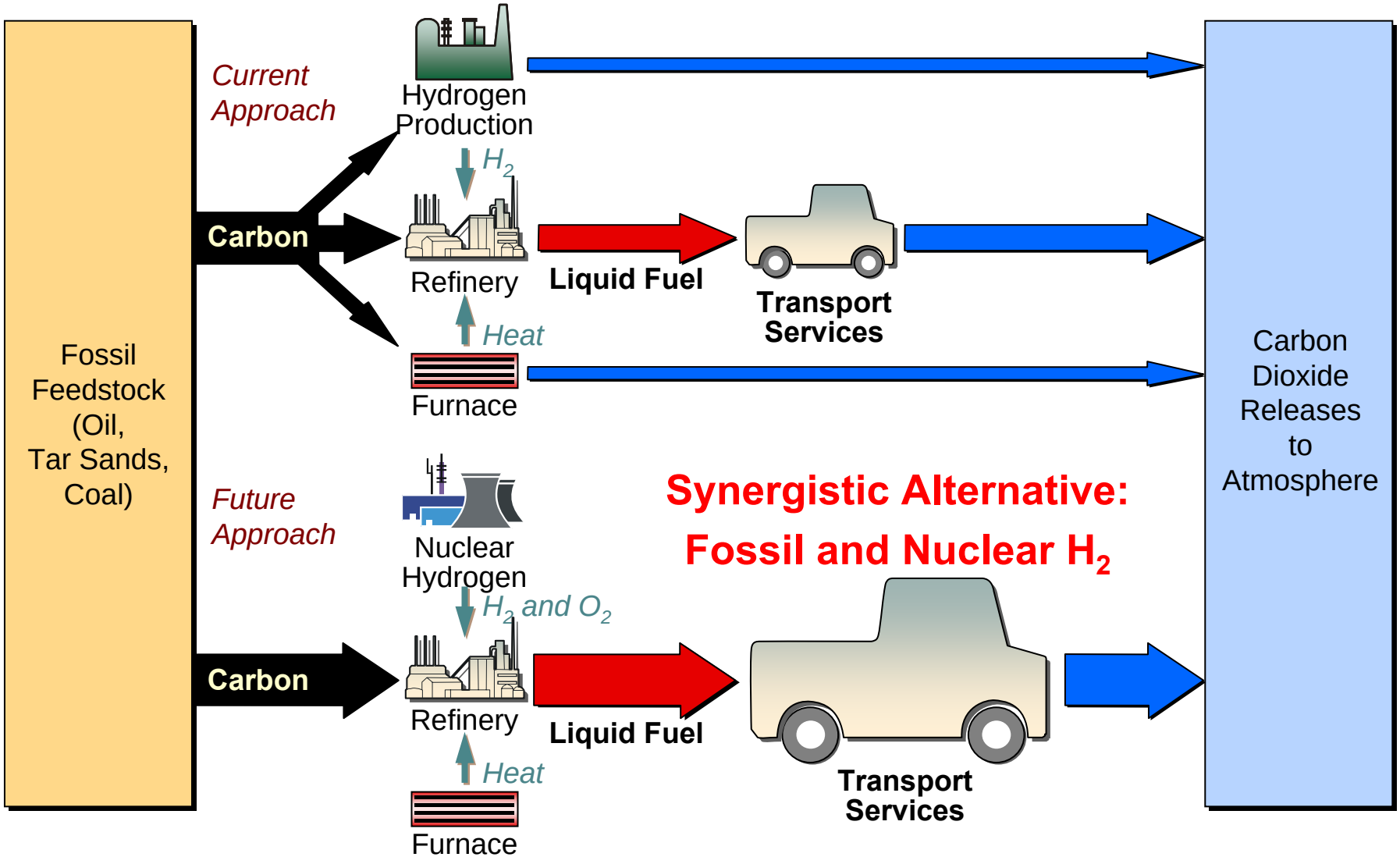
Syncrude Canada Ltd.
Tar Sands Operations

- **Tar sands and heavy oils are converted to liquid fuels by:**
  - **Addition of hydrogen**
  - **Removal of carbon with carbon dioxide ultimately to the atmosphere**
- **Implies major increases in greenhouse gas releases (CO_2) per vehicle mile**

Conventional Futures Imply Increasing Greenhouse Emissions per Mile Traveled



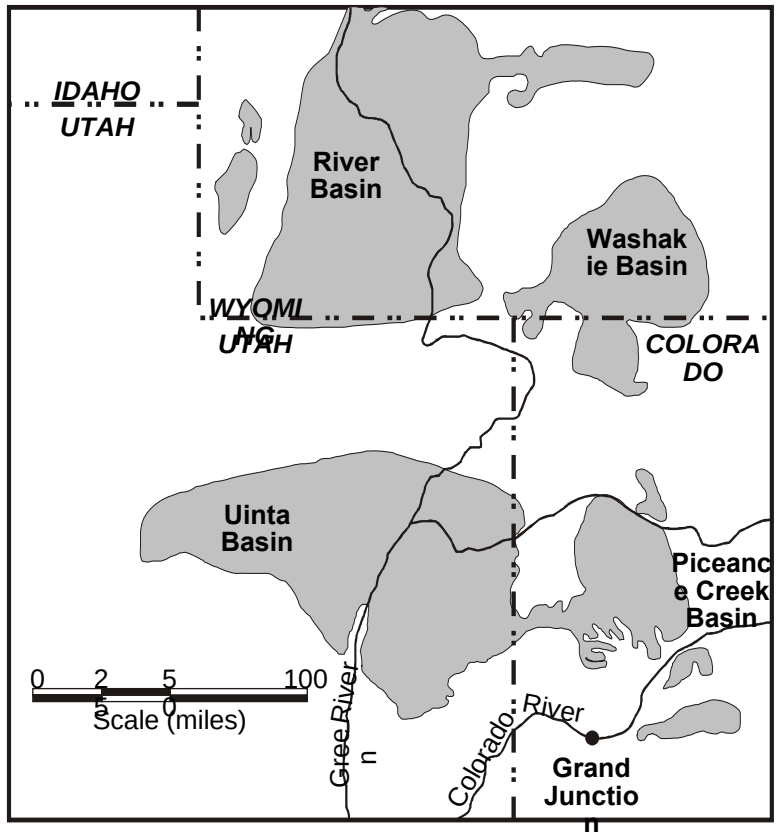
Nuclear Hydrogen can Increase Liquid Fuel per Unit of Feedstock and Reduce Emissions



Hydrogen sources: nuclear (cold electrolysis or high-temperature heat with high-temperature electrolysis or thermochemical cycles), renewables, and coal with carbon dioxide sequestration

Shale Oil Recovery Requires Massive Quantities of High-Temperature Heat

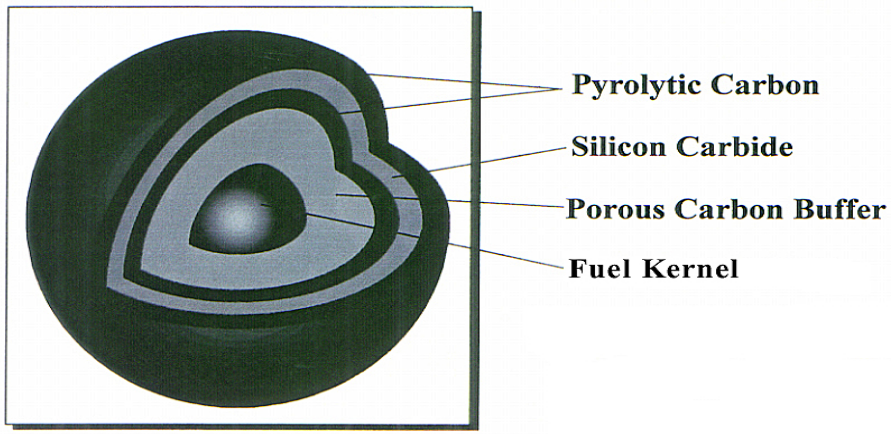
- **~100-year oil supply for the United States**
- **Oil Shale + High-Temperature Heat → Shale Oil**
- **Current strategy is electric heat**
- **Alternative**
  - **High-temperature reactor heat to the oil shale**
  - **Avoid heat → electricity → heat inefficiencies**



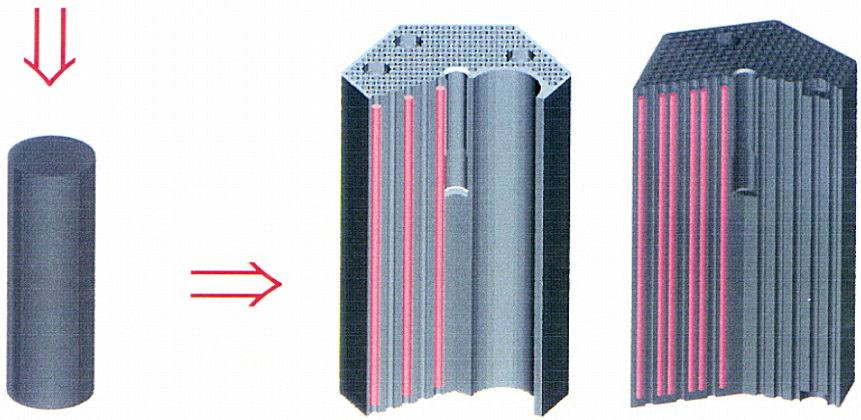
Because of Changes in Technology and Markets, Its Back to the Future with:

High Temperature Reactors

There is One Demonstrated High-Temperature Reactor Fuel



FUEL PARTICLE



FUEL COMPACT

FUEL ASSEMBLIES

- **No choice on high-temperature fuel**
- **Coated particles of uranium oxides or carbides**
- **Graphite matrix fuel**
- **Multiple fuel geometries**
  - **Blocks**
  - **Pebbles**
  - **Stringers**

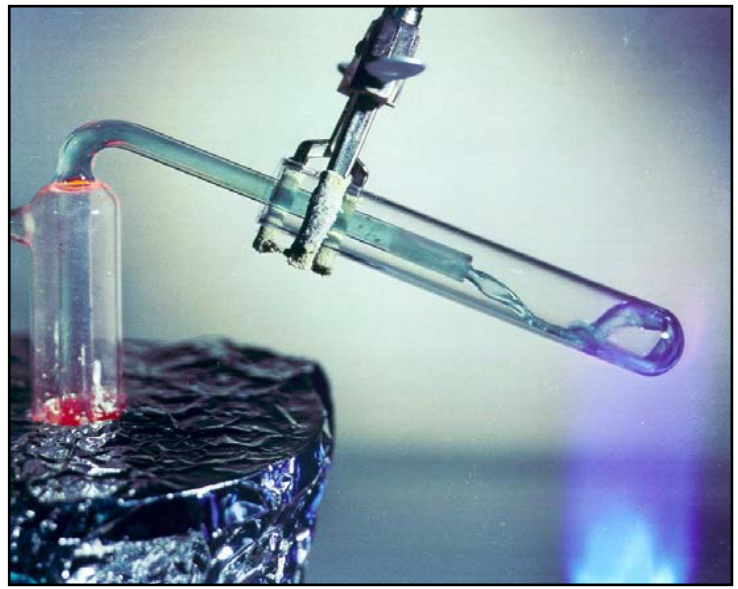
Two Reactor Coolants are Chemically Compatible with Graphite-Matrix Fuel

Modular High-Temperature Gas-Cooled Reactor

Helium

(High Pressure/Transparent)

Advanced High-Temperature Reactor



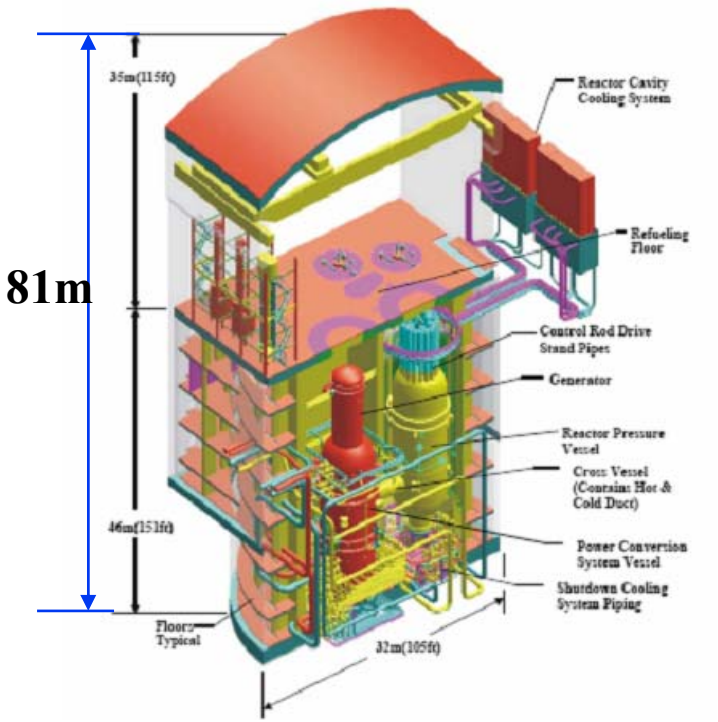
Liquid Fluoride Salts

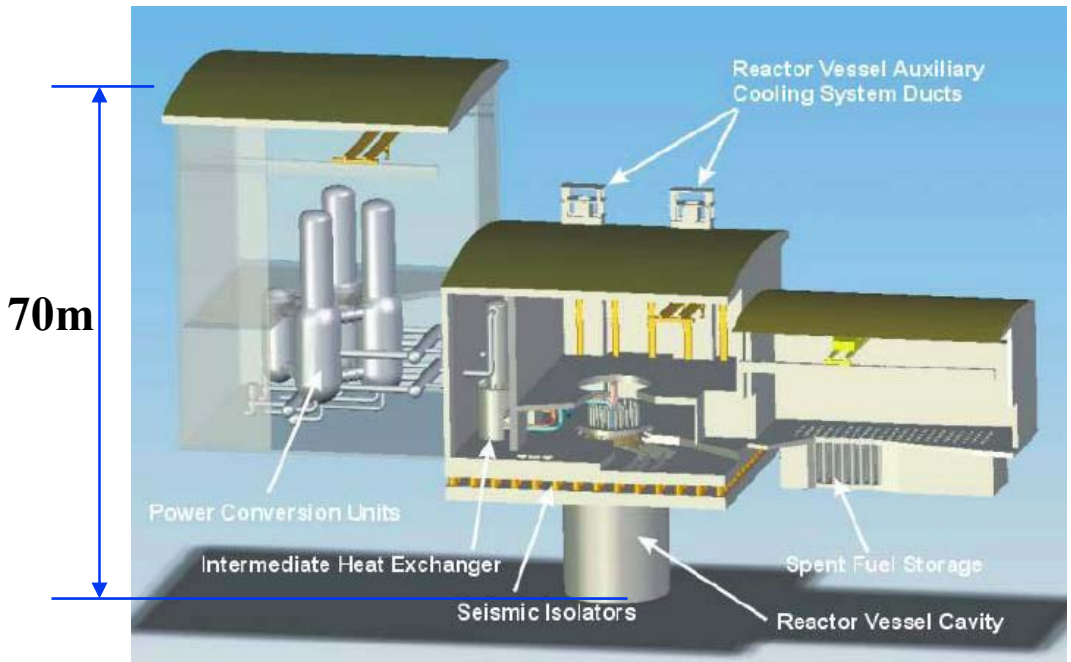
(Low Pressure/Transparent)

Two Reactor Options Based on Choice of Coolant

Two Types of High-Temperature Reactors are being Developed

(MHTGR Near-term; AHTR Midterm)





Modular High-Temperature Gas-Cooled Reactors

Gas-Cooled: 600 MW(t); Near-Term Option

Advanced High-Temperature Reactor

Liquid-Salt-Cooled: 2400 MW(t)

Longer-term Option

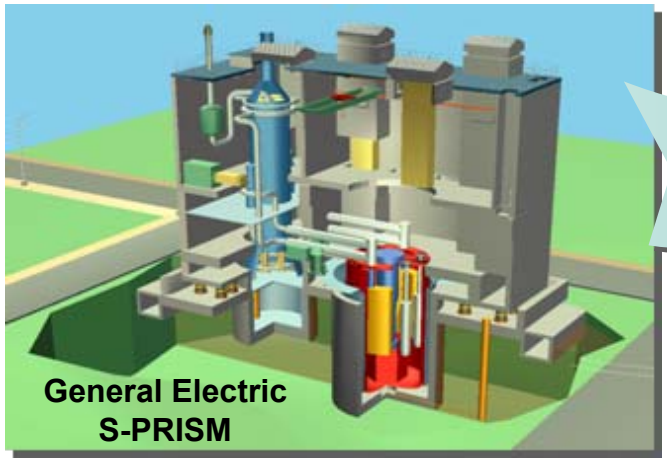
The Advanced High-Temperature Reactor

(The Liquid-Cooled Option)

Combining Different Technologies in a New Way

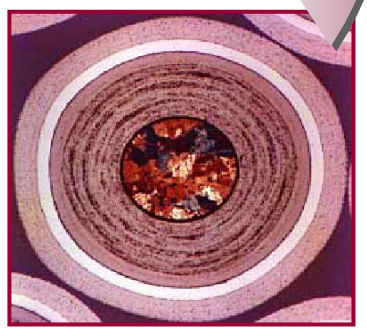
The Advanced High-Temperature Reactor

The Near-Term Option That Combines Four Existing Technologies



Passively Safe Pool-Type Reactor Designs

Brayton Power Cycles

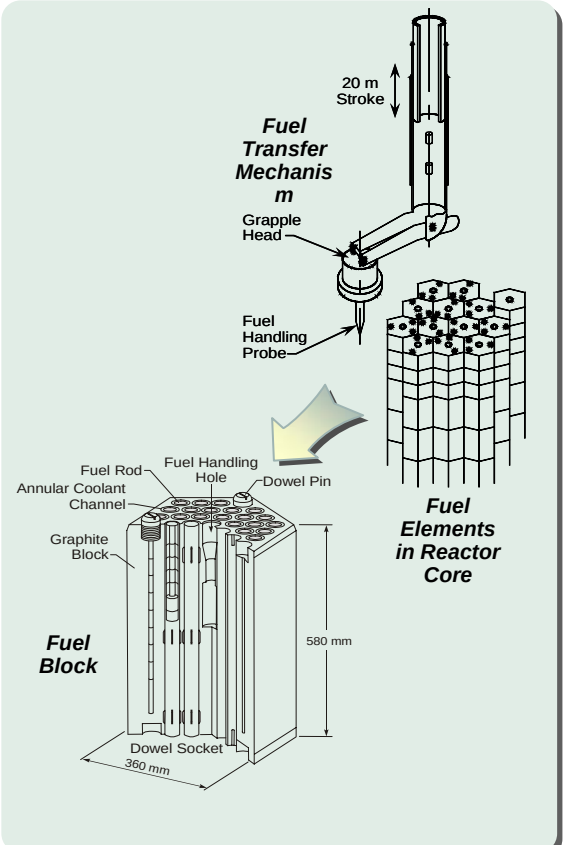


High-Temperature Coated-Particle Fuel

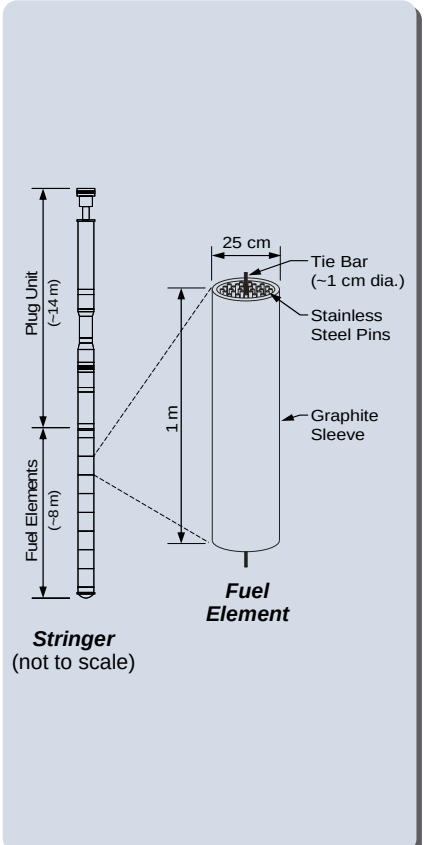
High-Temperature, Low-Pressure Transparent Liquid-Salt Coolant

The AHTR Uses High-Temperature Graphite-Matrix Fuel

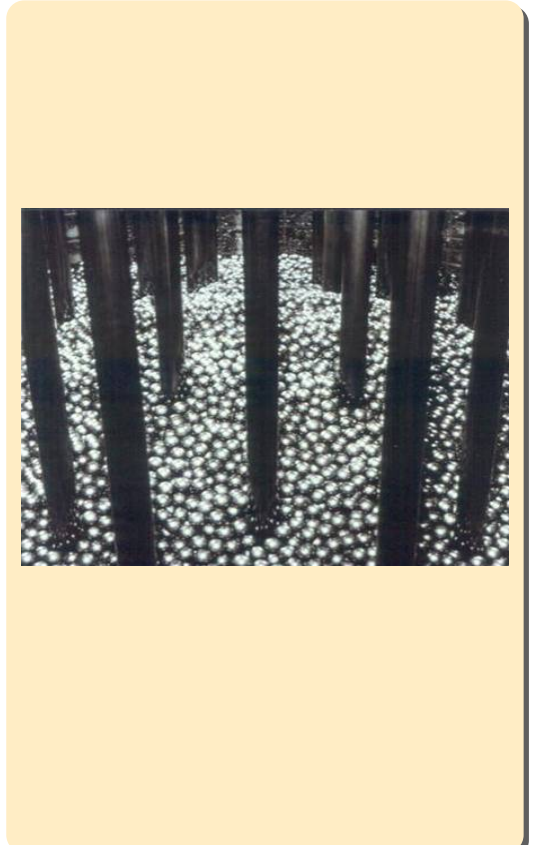
Evaluating Three Alternative Fuel Geometries



Prismatic Fuel Block



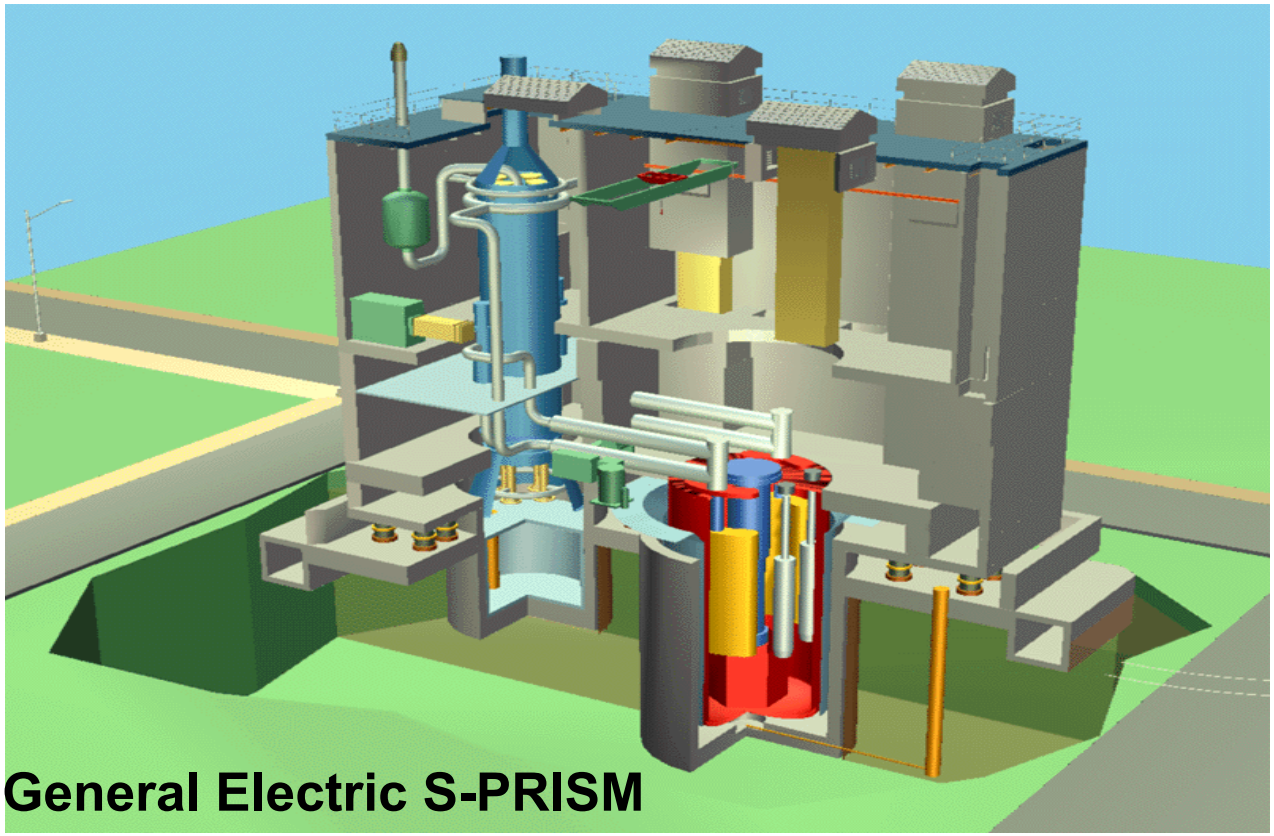
Stringer



Pebble Bed

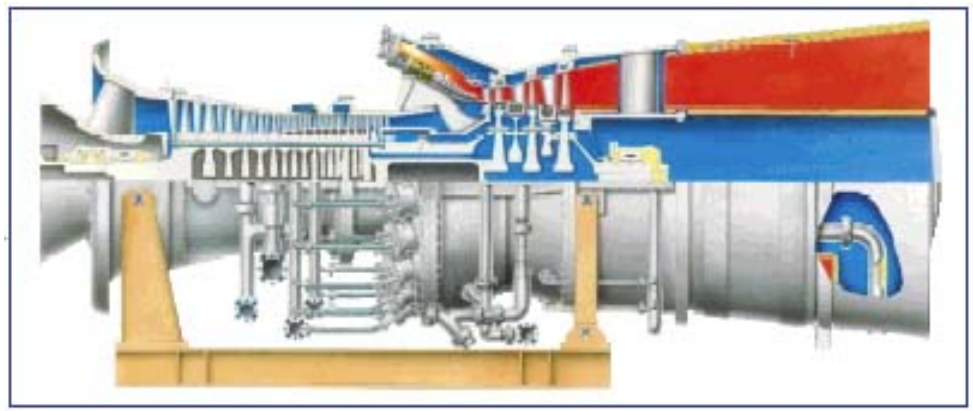
AHTR Facility Layouts are Based on Sodium-Cooled Fast Reactors

Low Pressure, High Temperature, Liquid Cooled

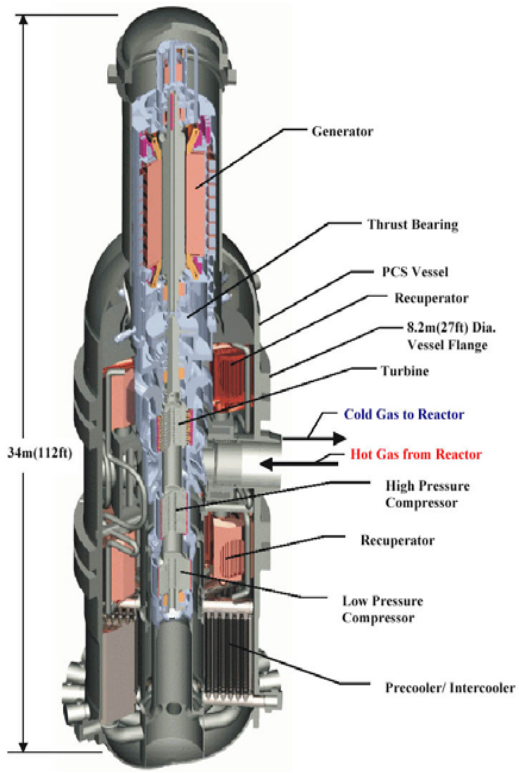


The AHTR Uses Brayton Power Cycles to Convert Heat to Electricity

Matches AHTR heat at temperatures from 700 to 950ºC



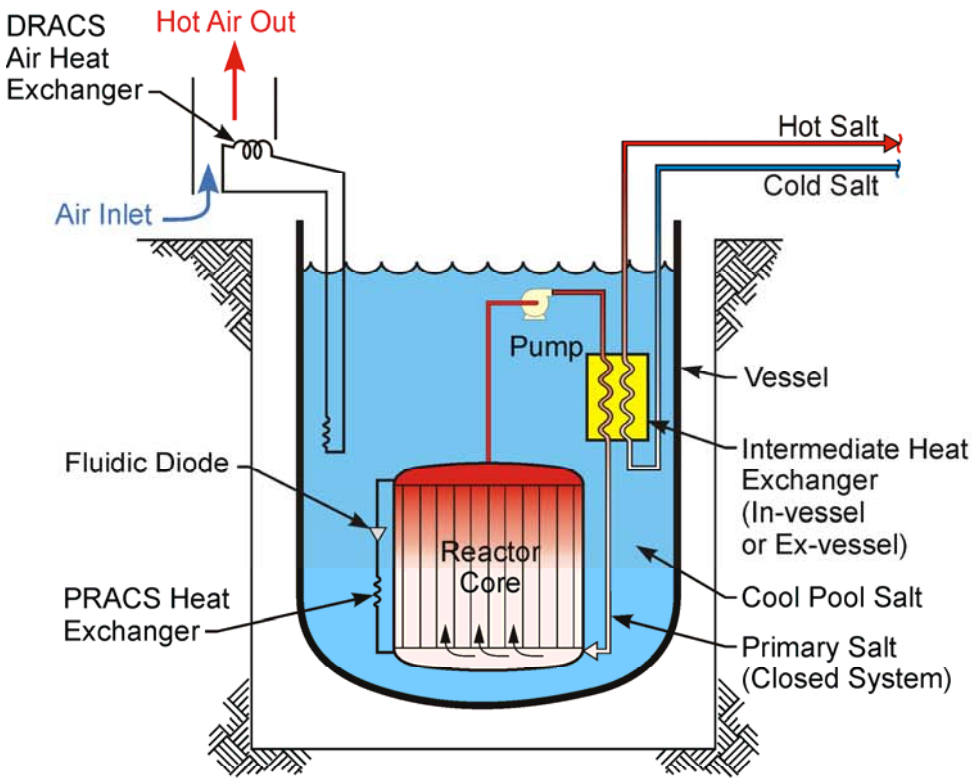
GE Power Systems MS7001FB

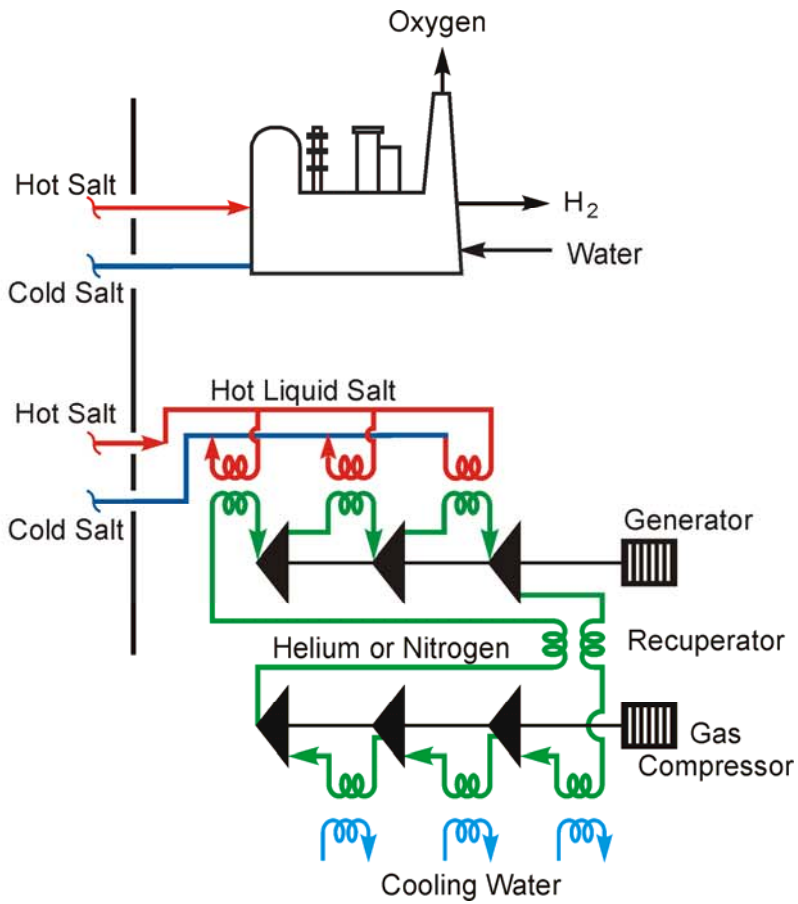


General Atomics GT-MHR Power Conversion Unit (Russian Design)

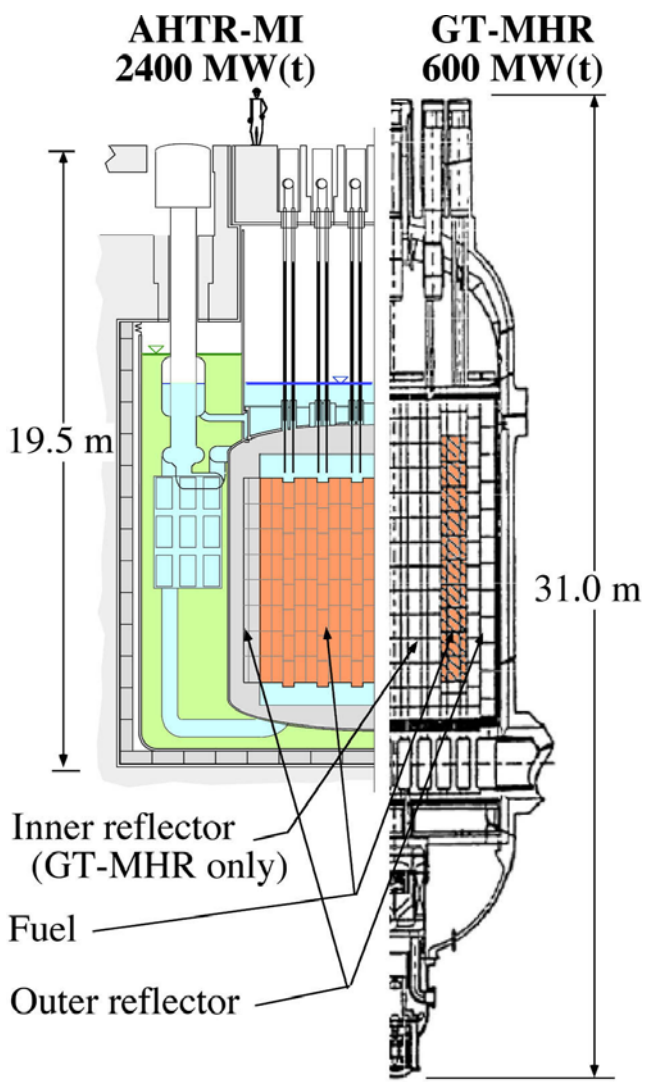
The Advanced High-Temperature Reactor

Passive Decay Heat Removal **Reactor** **Hydrogen/Brayton Electricity Production**





Economics Drives Design Choices



- **Economics drives real-world decisions**
- **Electricity production**
  - **Match electric output of a large ALWR in 2025**
  - **~2000 MW(e); ~4000 MW(t)**
  - **Peak Coolant: ~750°C**
- **Hydrogen production**
  - **2400 MW(t)**
  - **Peak coolant: 950°C**
- **Achievable economic goals based on analysis**
  - **Capital costs 50 to 60% of those for modular reactor per kW(e)**
  - **Capital costs one-third less than an ALWR per kW(e)**

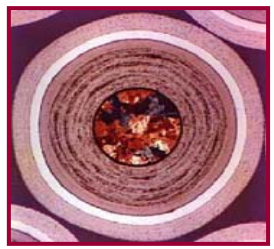
ALWRs will improve with time thus advanced reactor goals must exceed expected ALWR technology in 2025

Potential Improvements in Economics are Based on Several Technical Factors

Salt cooling: High-power reactor, Small plant, Simple containment, Passive safety

Cost/KW(e)

Choice of Coolant: Economics of Scale



High-temperature for high heat-to-electricity conversion

Higher Efficiency (~50%)

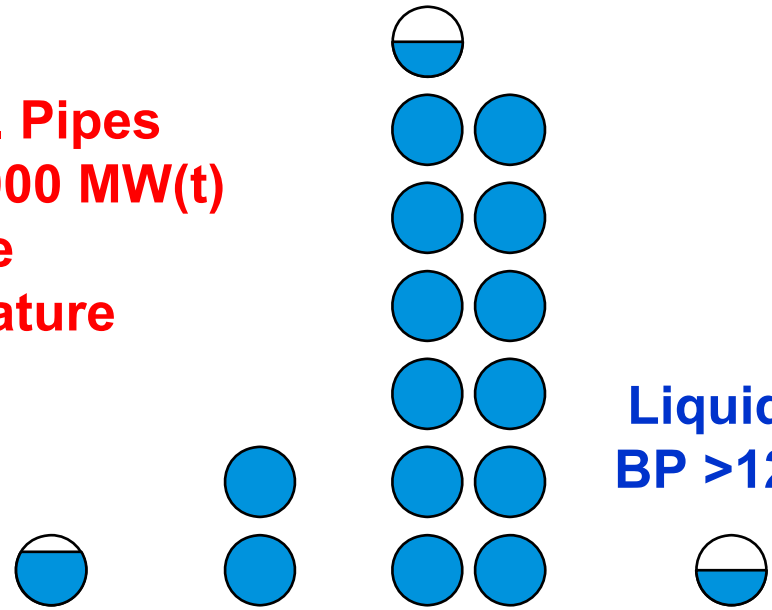
Lower Cost Systems

Brayton power cycles for lower costs

Salt Coolant Properties Reduce Equipment Size and Costs

(Determine Pipe, Valve, and Heat Exchanger Sizes)

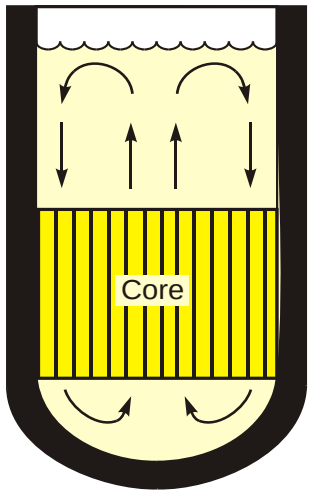
Number of 1-m-diam. Pipes Needed to Transport 1000 MW(t) with 100ºC Rise in Coolant Temperature



	Water (PWR)	Sodium (LMR)	Helium	Liquid Salt
Pressure (MPa)	15.5	0.69	7.07	0.69
Outlet Temp (ºC)	320	540	1000	1000
Coolant Velocity (m/s)	6	6	75	6

Liquid Cooling Enables Passively-Safe More Economic High-Power Reactors

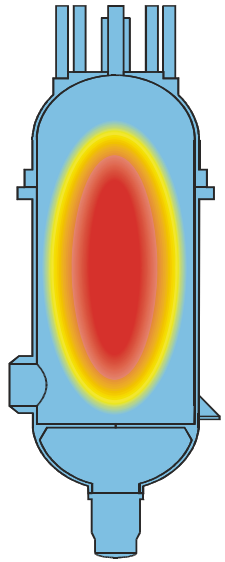
Liquid
[1000s of MW(t)]



Decay Heat Removal Limited by Convective Cooling

(Added benefit of full use of internal heat capacity)

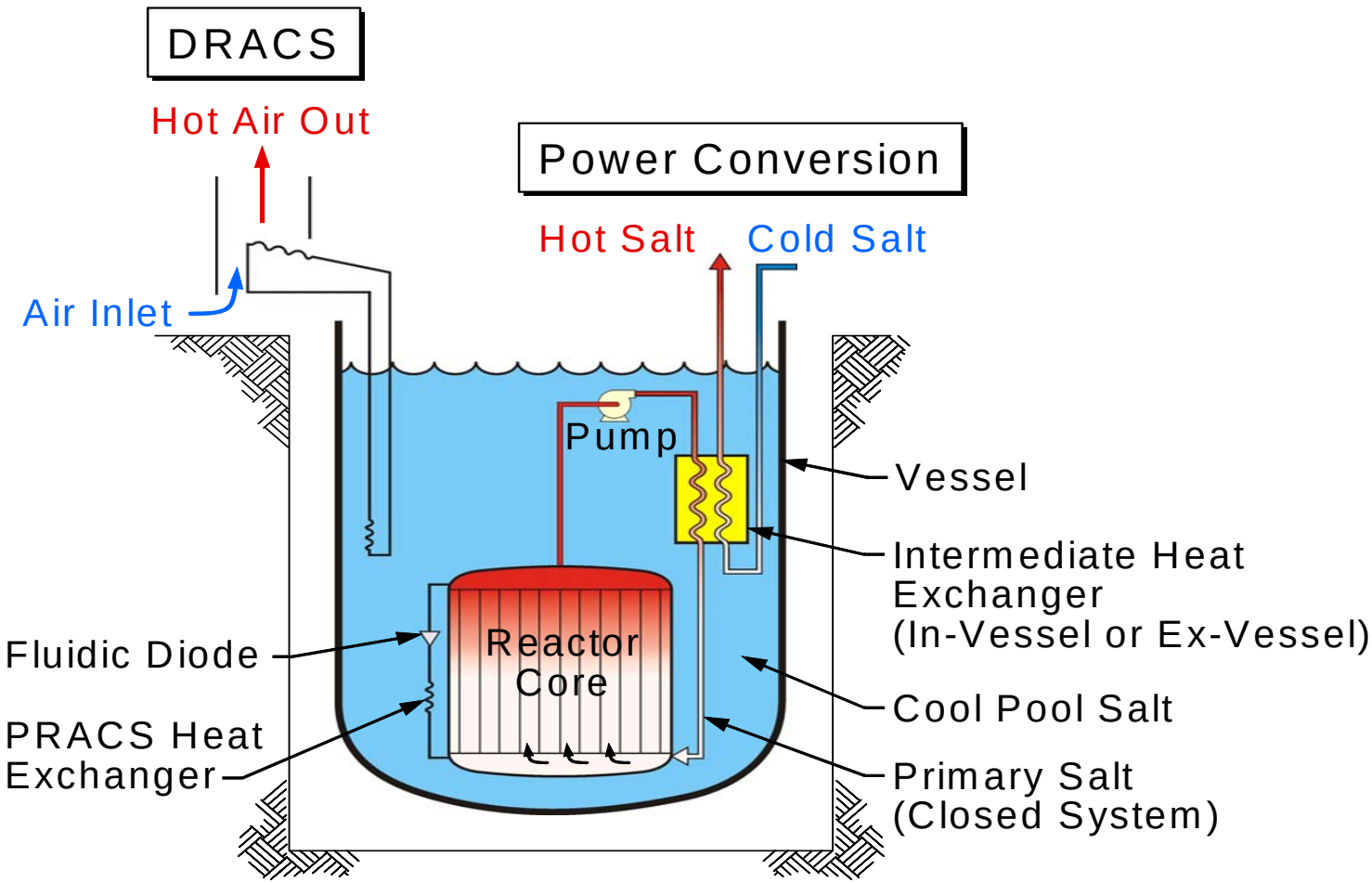
Gas
[~600 MW(t)]



Decay Heat Removal Limited by Conduction Cooling

Decay Heat Removal System Enables Passive Safety and High-Power Levels

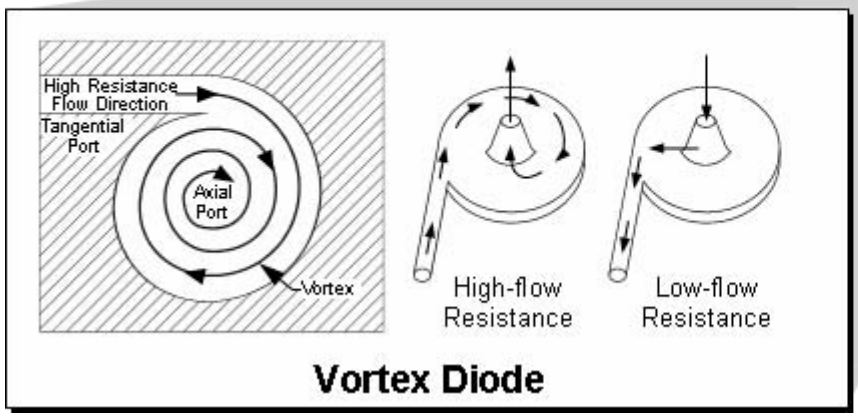
(Pool Reactor Auxiliary Cooling System: PRACS)

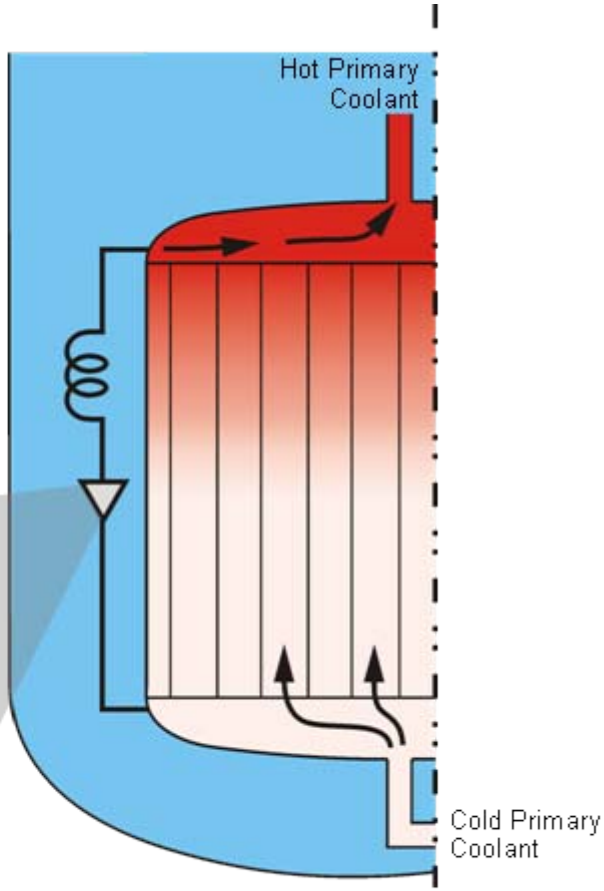


Three decay heat systems evaluated;
PRACS is the current design basis

PRACS Heat Exchanger and Valve Dumps Decay Heat to the Pool Salt

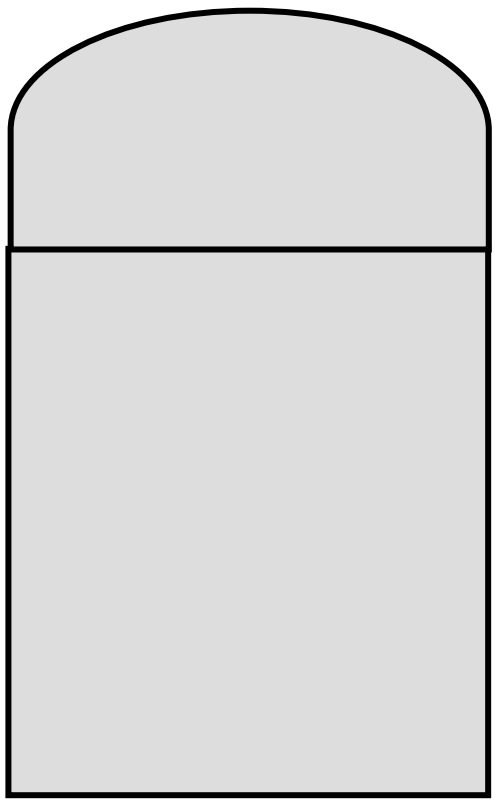
- **Low flow in upward direction during normal operations**
- **High flow in reverse direction after pump shutdown and natural circulation flow startup**
- **Flow resistance 50 times higher in one direction than the other**





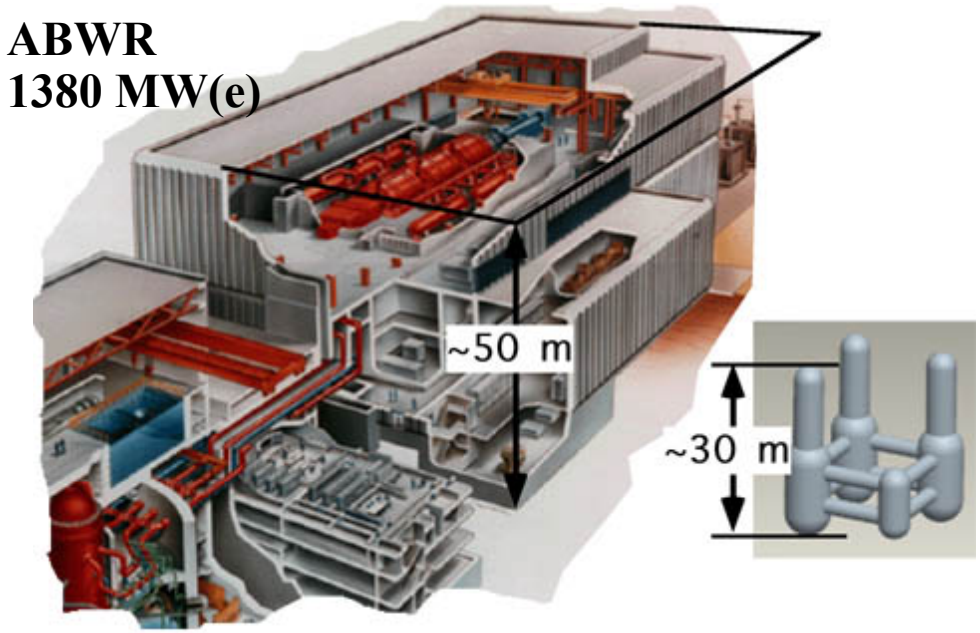
Multiple fluidic valve options

Coolant Properties Reduce Containment and Related Costs



- **No high-pressure fluids**
  - **No Helium**
  - **No Steam**
  - **No chemical gas generators (sodium)**
- **No major chemical heat sources**
- **Salts dissolve non-noble fission products and actinides**
  - **Added safety barrier under accident conditions**
  - **Based on experience with molten salt reactors**

Brayton Power Cycles Imply Lower Capital Costs and Higher Efficiency

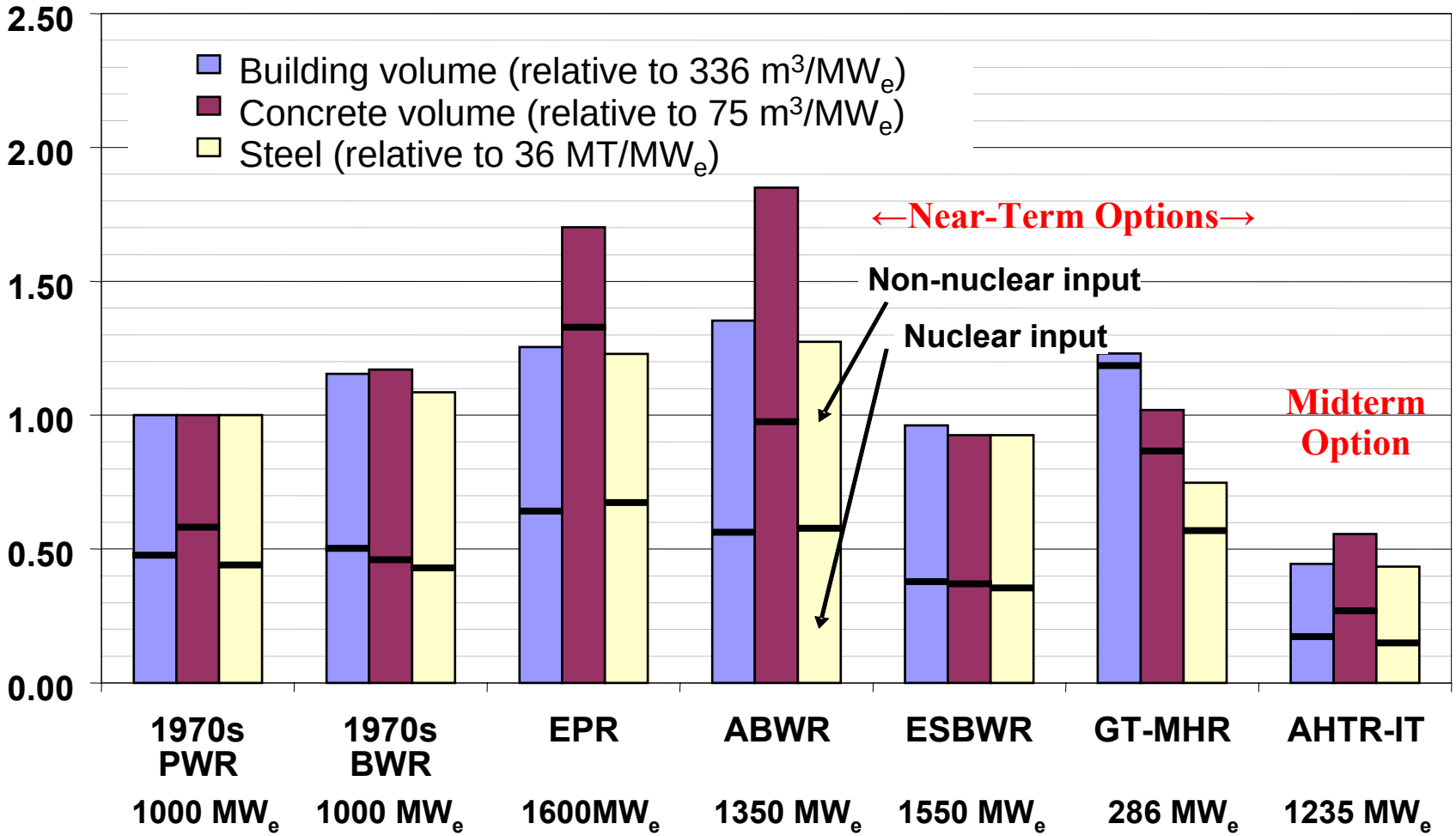


AHTR: ~1300 MW(e) Helium-Brayton cycle with 3 power conversion units similar to GT-MHR

- **Power system size depends upon gas pressures**
  - **Steam systems have large low-pressure turbines and condensers**
  - **Closed Brayton cycles operate at high pressures**
- **High-temperature AHTR requires ~1100 MW(t) of cooling water capacity, compared to 2800 MW(t) for the lower-temperature ABWR**

Reactor Comparison of Building Volume, Concrete, and Steel Consumption Per MW(e)

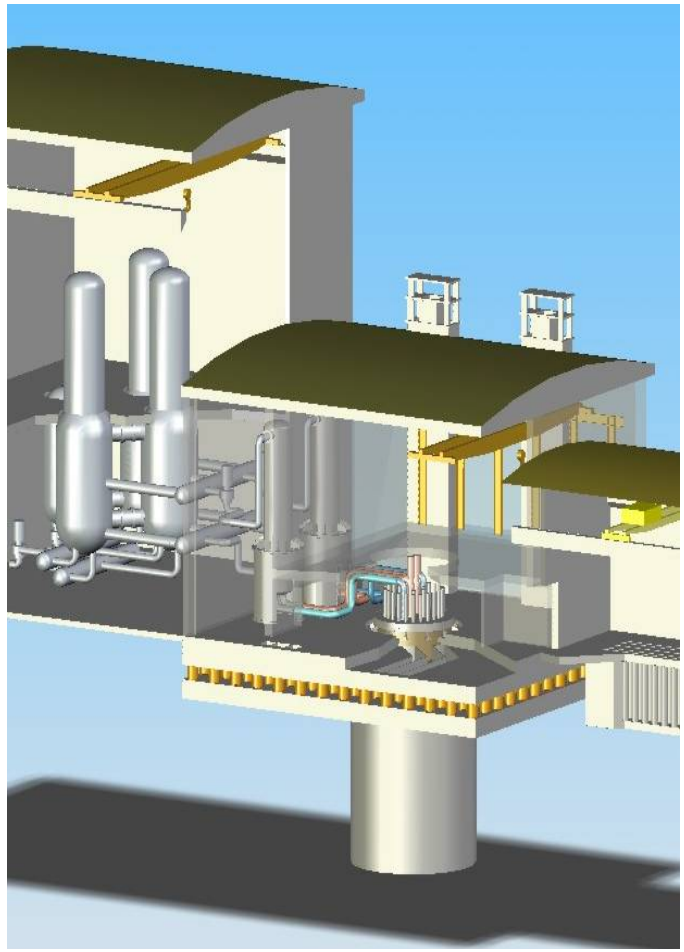
(High-Temperature Reactors are Potentially Competitive Sources of Energy)



Per Peterson (Berkeley): American Nuclear Society 2004 Winter Meeting

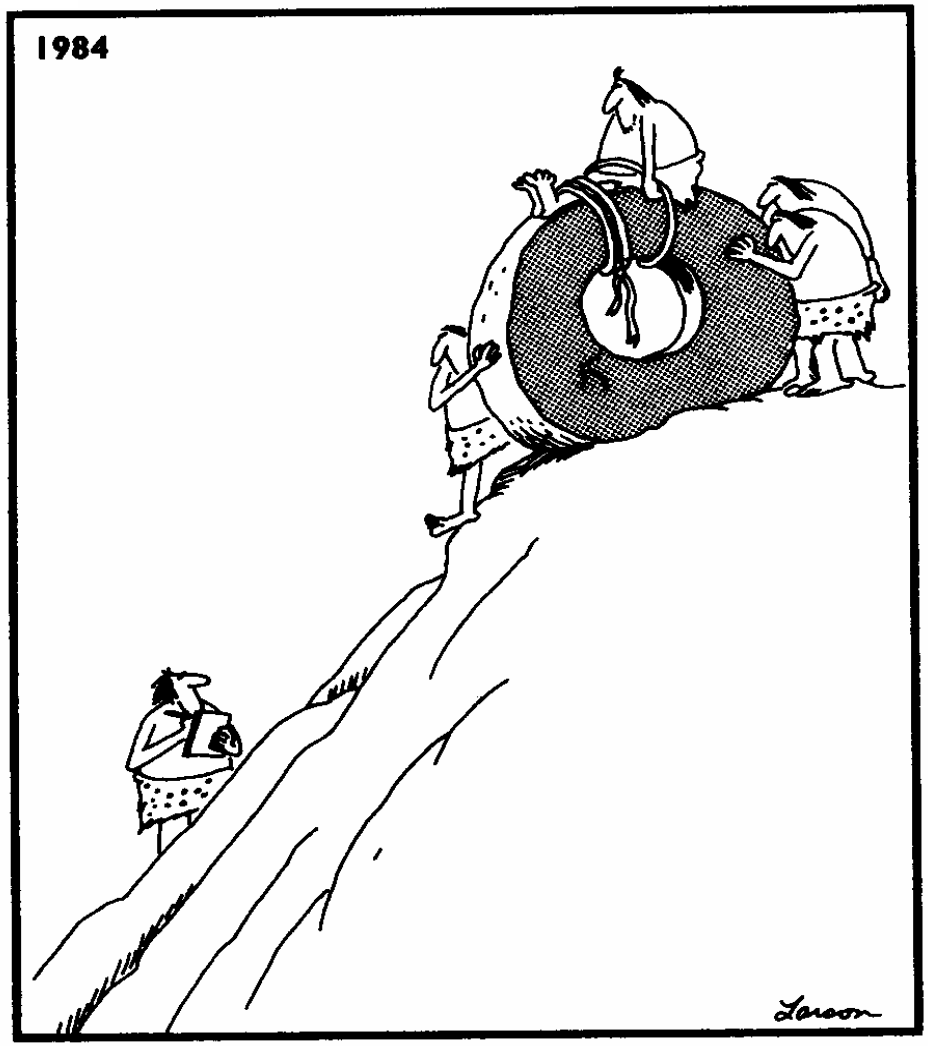
Conclusions

- **The High-Temperature Reactor rebirth is driven by:**
  - **Efficient methods to convert heat to electricity**
  - **Need for liquid transport fuels**
  - **Need to reduce water use**
- **AHTR goals**
  - **High temperature**
  - **Passive safety**
  - **Superior economics**
- **Vendor interest**
- **Early in development**



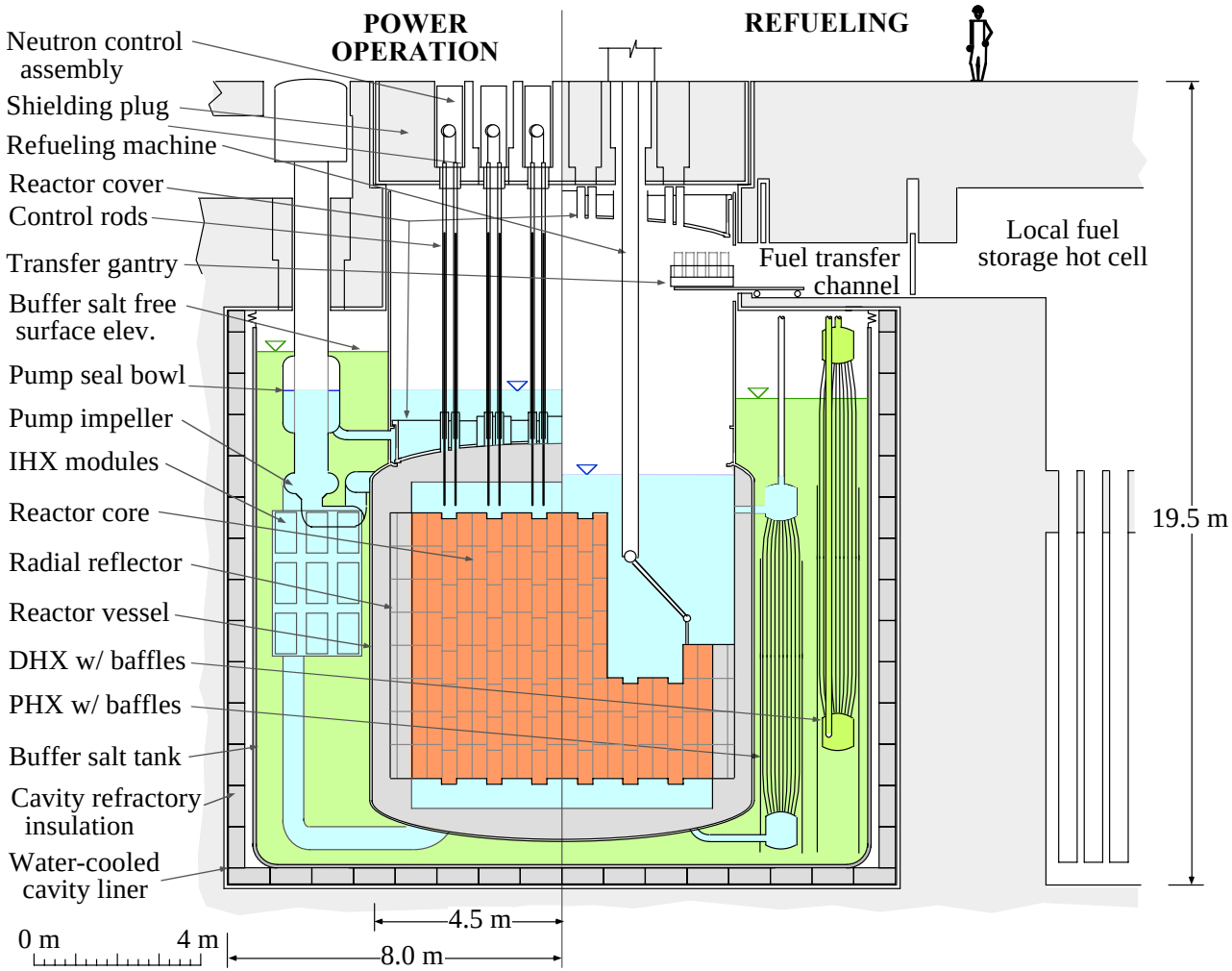
The AHTR

A good idea that still needs some work



Questions?

(2400-MW(t) AHTR Schematic)



Biography: Charles Forsberg

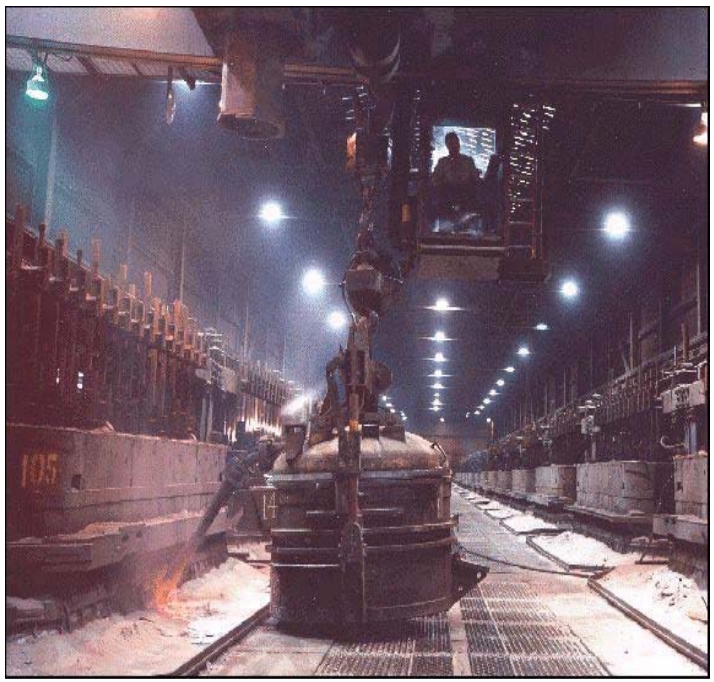
Dr. Charles Forsberg is a Corporate Fellow at Oak Ridge National Laboratory, a Fellow of the American Nuclear Society, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and the Oak Ridge National Laboratory Engineer of the Year Award. Dr. Charles Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. After working for Bechtel Corporation, he joined the staff of Oak Ridge National Laboratory, where he is the Senior Reactor Technical Advisor. Dr. Forsberg has been awarded 10 patents and has published over 200 papers in advanced energy systems, waste management, and hydrogen futures.

The AHTR Uses the Salt Coolant Technology Developed for MSRs

The AHTR Uses a Clean Salt Coolant and Solid Fuel

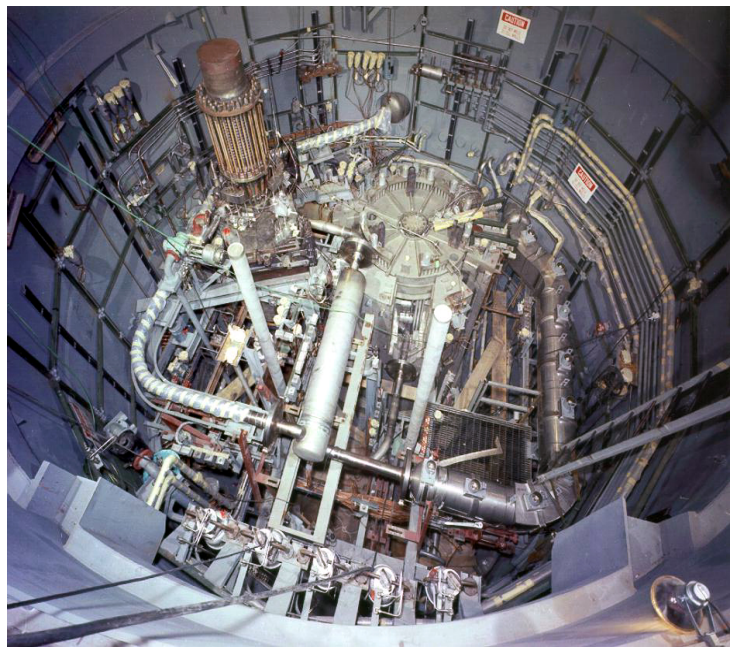
Molten Salt Reactor Dissolved the Fuel in the Coolant

Technology developed in the 1950s and 1960s



Molten Fluoride Salts are Used to Make Aluminum in Graphite Baths at 1000°C

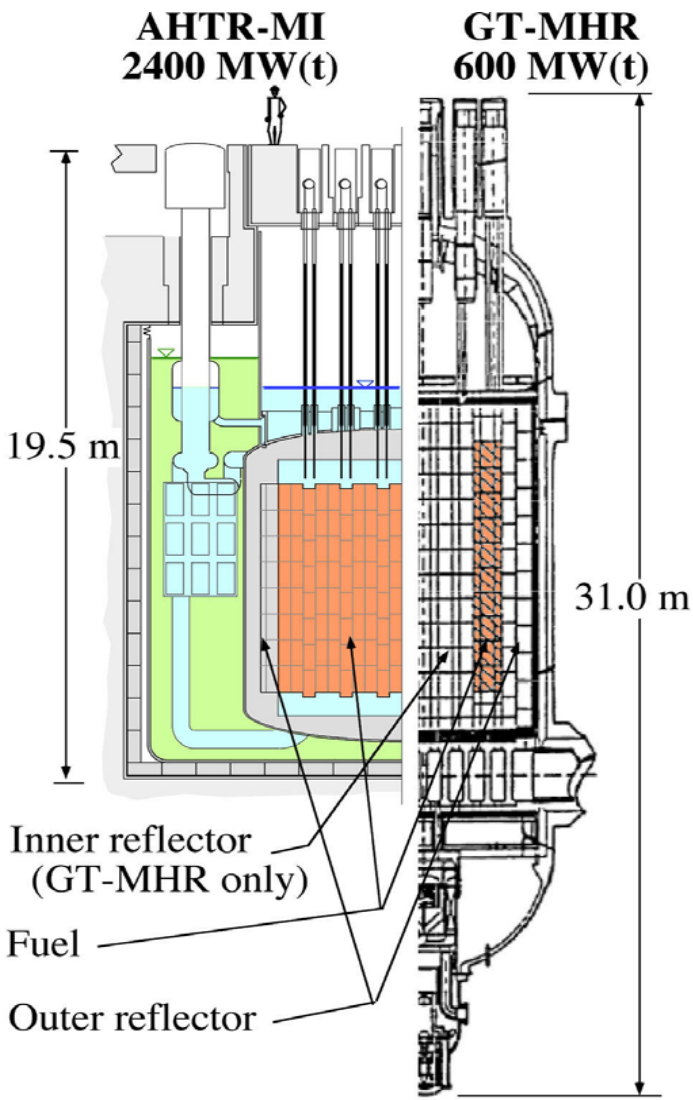
Liquid Fluoride Salts were Used in Molten Salt Reactors with Fuel in Coolant



Alloys of construction were developed to ~750ºC for the MSR. For the AHTR, very low corrosion rates and a wider choice of alloys because clean liquid salts (like clean water, sodium, and helium) have very low corrosion rates compared to coolants with high impurity levels. Impurities usually control corrosion rates.

AHTR Goal

A Large High-Temperature Reactor With Superior Economics and the Same Safety Goals as a Modular HTGR

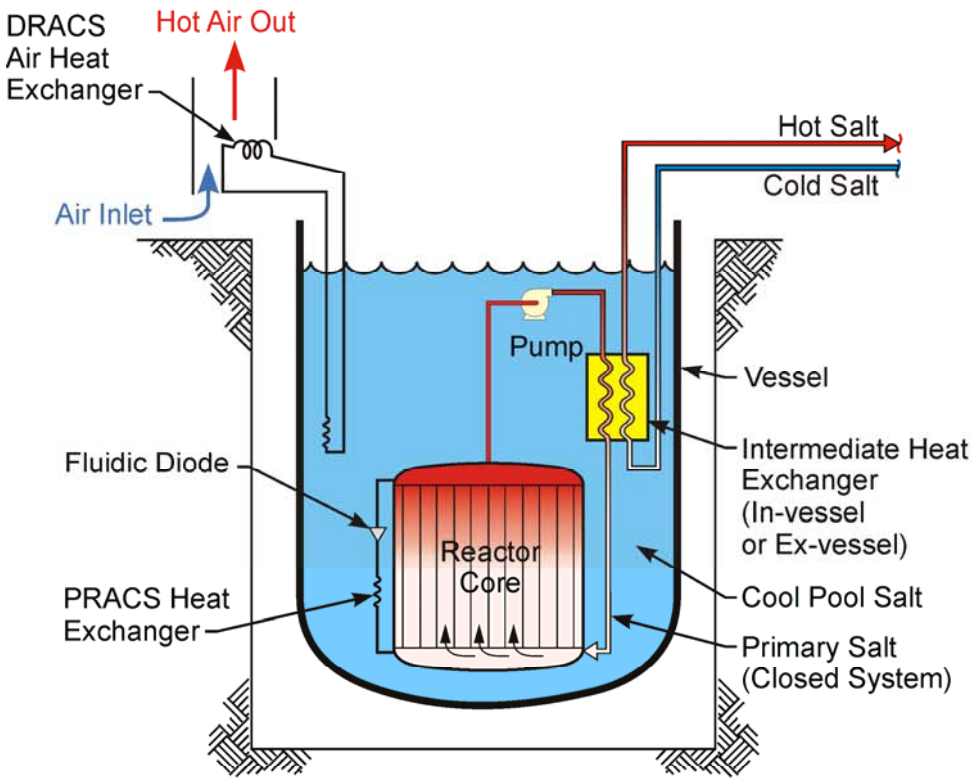


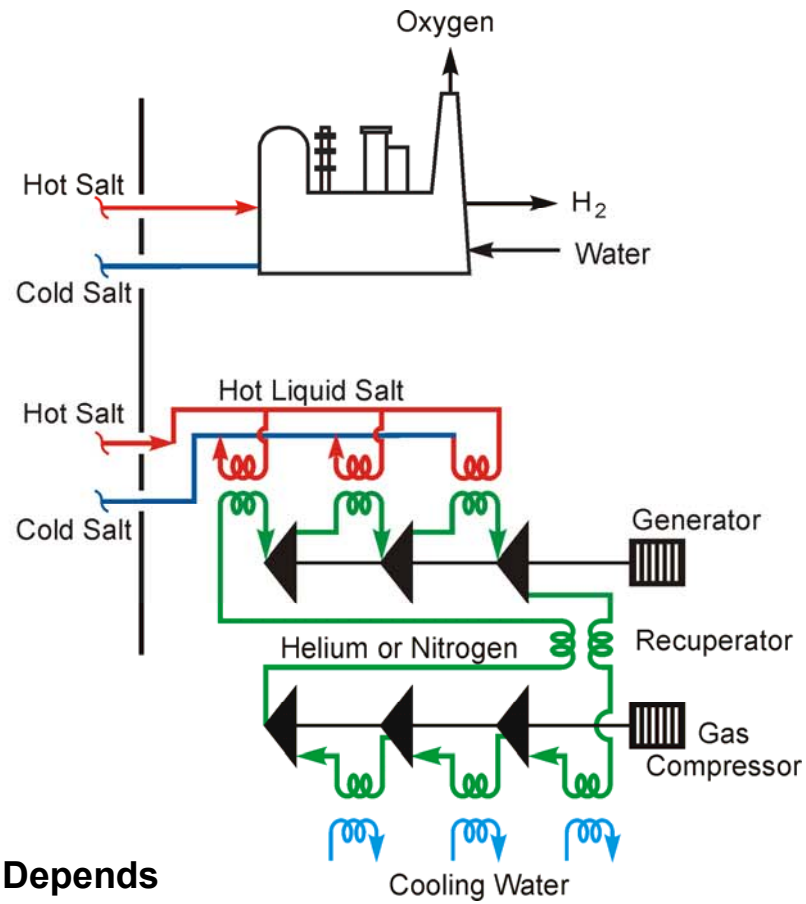
Initial Coolant Options Have a Wide Range of Melting Points and Properties

Alkali Fluorides	***ZrF_4 – salts***	***BeF_2 – salts***
	$LiF\text{-}ZrF_4$ 509°C $NaF\text{-}ZrF_4$ 500°C	
LiF-KF 492°C LiF-RbF 470°C		
LiF-NaF-KF 454°C		$LiF\text{-}BeF_2$ 460°C
LiF-NaF-RbF 435°C	$LiF\text{-}NaF\text{-}ZrF_4$ 436°C	$LiF\text{-}BeF_2\text{-}ZrF_4$ 428°C
	$RbF\text{-}ZrF_4$ 410°C	
	$KF\text{-}ZrF_4$ 390°C	
		$NaF\text{-}BeF_2$ 340°C $LiF\text{-}NaF\text{-}BeF_2$ 315°C

The Advanced High-Temperature Reactor

Passive Decay Heat Removal **Reactor** **Hydrogen/Brayton Electricity Production**



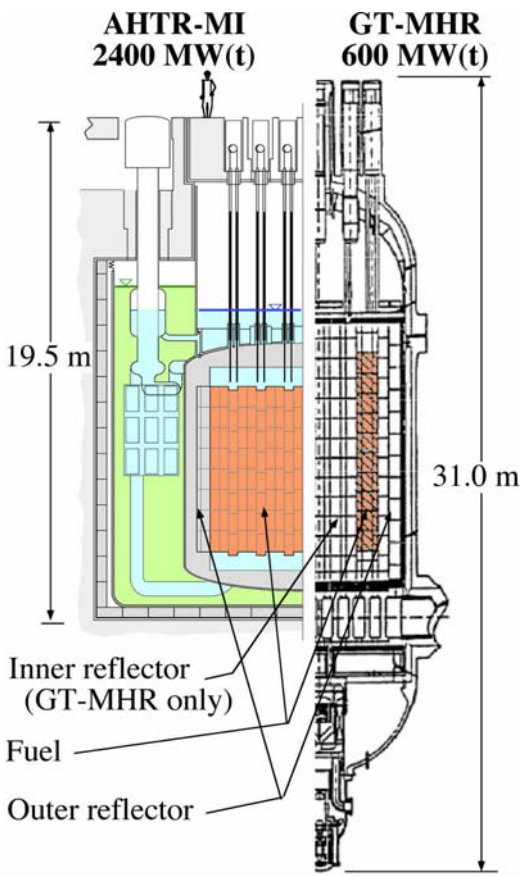


Efficiency Depends upon Temperature:

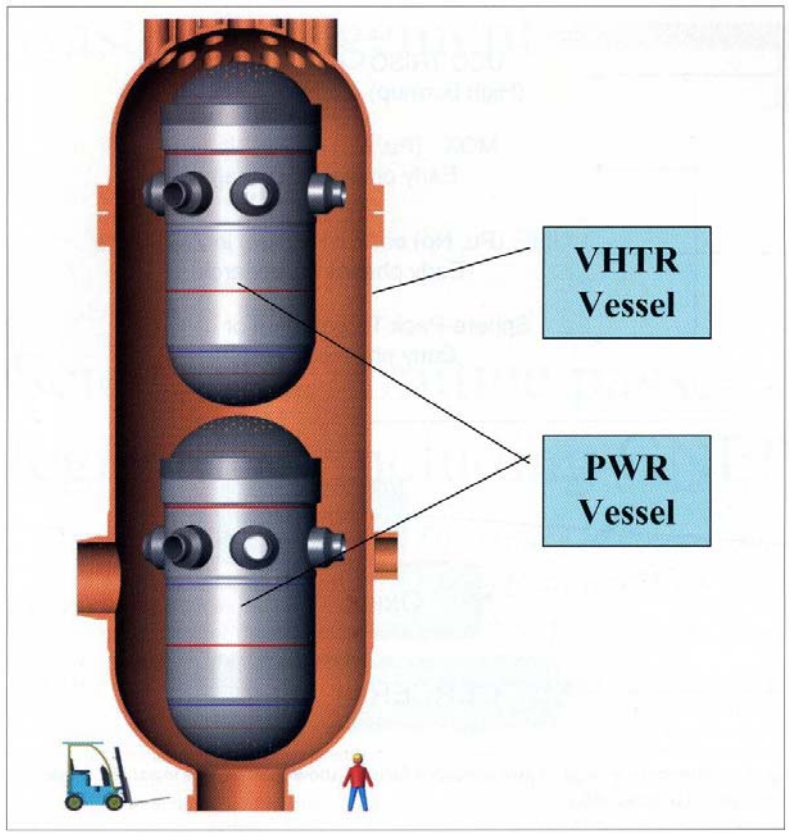
705ºC: 48.0%
800ºC: 51.5%
1000ºC: 56.6%

Reactor Vessel Comparisons

2400-MW(t) AHTR (Low Pressure) Versus 600-MW(t) GT-MHR

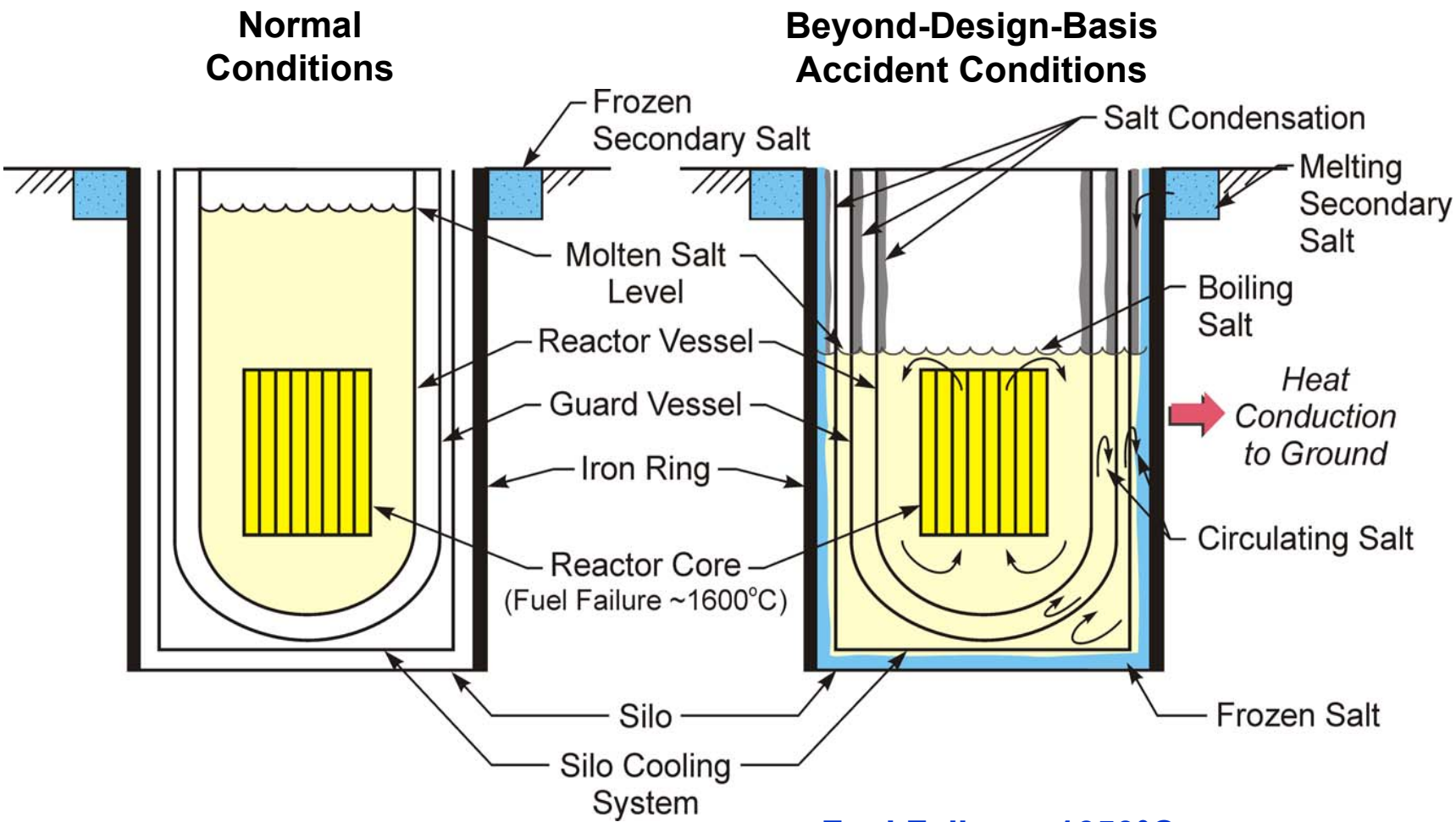


300-MW(e) VHTR Versus 2 Standard PWRs



PWRs have steam generators in addition to the pressure vessel. Some variants of the VHTR have equivalent intermediate heat exchangers and vessels; others have direct power cycles.

Beyond-Design-Basis Accident Avoids Major Fuel Failure by Decay-Heat to Soil

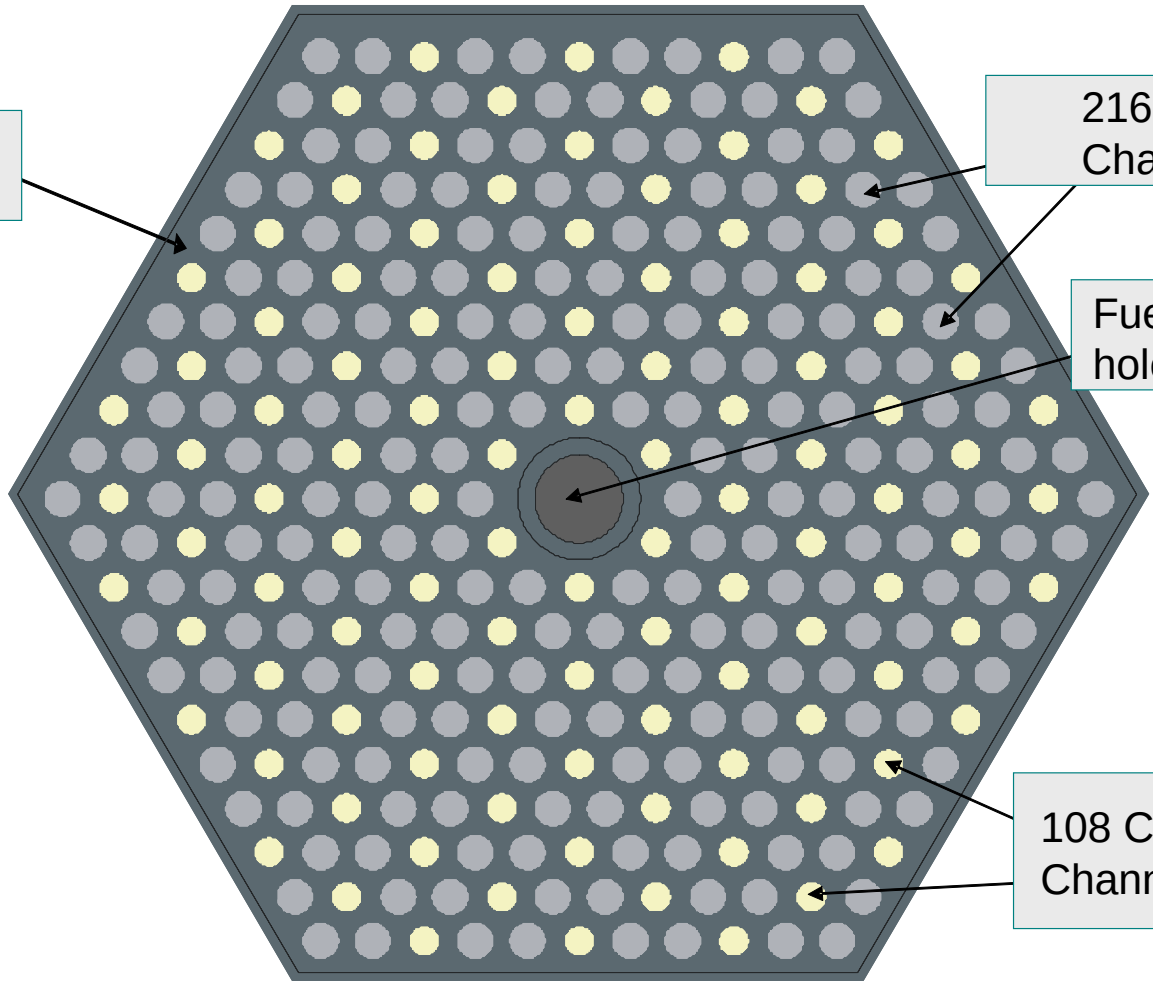


Fuel Failure >1650°C
Coolant BP>1400°C

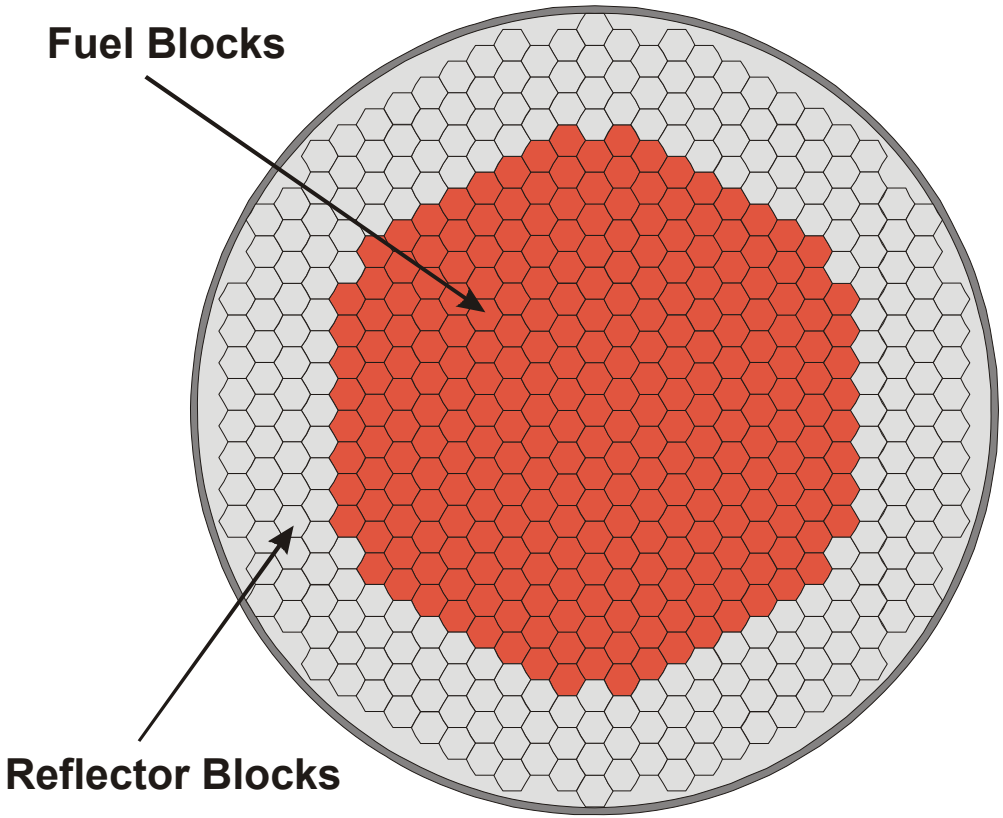
Reactor Physics Summary

- Neutronics similar to High-Temperature Gas-Cooled Reactors
- Many salt coolant options
- Nuclear reactivity effects
  - Void coefficient (+/-) depends upon salt composition
  - Coolant density coefficient (+/-) depends upon the salt composition
  - System has very negative fuel and moderator Doppler coefficients
- Reactor safety requires that the sum of all effects assure power levels decrease under accident conditions
  - PWR
    - Negative void coefficient under most conditions
    - Positive void coefficient under some cold startup conditions
      - Acceptable because other reactivity coefficients assure safety
  - Three AHTR core design strategies
    - Select salt with negative void coefficient
    - Select design with a negative void coefficient
    - Select design with overall negative coefficients
  - AHTR fuel and salt have very large temperature margins (hundreds of ºC) before fuel failure or coolant boiling
    - Allows use of negative Doppler to shut down system under many conditions
    - Option not available in most other reactor systems
- Added information
  - K. Clarno, "Physics Analysis of the LS-VHTR: Salt Coolant and Fuel Block Design," PHYSOR 2006,American Nuclear Society, September 10-14, 2006

Base Case AHTR Block Design



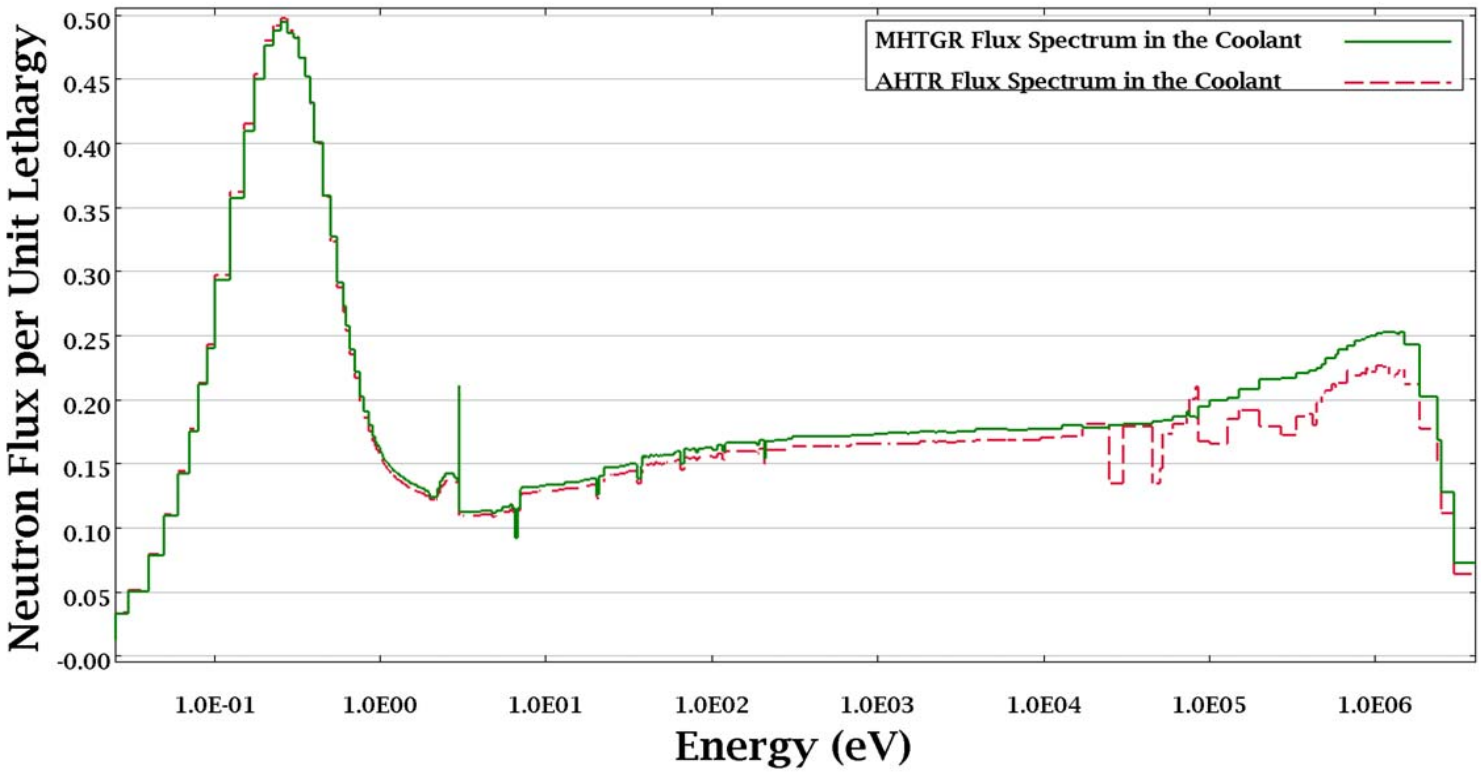
Base Case Core Design



2006 Design

265 Fuel Columns
10.0 MW/m^{-3} Power Density

The AHTR and MHTGR Reactor Core Characteristics are Nearly Identical



Example Void and Temperature Reactivity Coefficients for Different Salts

(Negative Temperature Coefficients Can Overcome Positive Void Coefficients Because the AHTR Has Very Large Temperature Margins Before Fuel Damage)

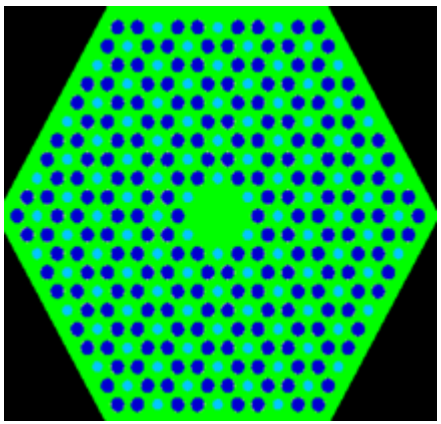
Salt	Salt Composition (Eutectic)	Temperature Reactivity Coefficient	Total Coolant Void Reactivity
	Atom %	Dollars per 100ºC	Dollars
$^{7}LiF\text{-}BeF_2$	67-33	-$2.54	-$0.11
$NaF\text{-}BeF_2$	57-43	-$2.26	$2.45
$^{7}LiF\text{-}NaF\text{-}ZrF_4$	26-37-37	-$2.23	$2.89
$NaF\text{-}ZrF_4$	59.5-40.5	-$2.15	$3.44
$NaF\text{-}RbF\text{-}ZrF_4$	33-23.5-43.5	-$1.99	$4.91

Erbium Case; 7% Coolant Fraction

Erbium (Burnable Absorber) Improves Non-Coolant Coefficients

Salt	Composition Mole%	Coefficients of Reactivity ($/100ºC)					
		----------Coolant----------			--------Non-Coolant-------		
		Temp.	Density	Total	Fuel	Graphite	Total
No Erbium							
$^{7}LiF-BeF_2$	**67-33**	**-0.01**	**0.01**	**0.00**	**-0.46**	**-0.12**	**-0.58**
$NaF-BeF_2$	**57-43**	**0.00**	**0.06**	**0.07**	**-0.41**	**0.02**	**-0.39**
$^{7}LiF-NaF-ZrF_4$	**26-37-37**	**0.00**	**0.09**	**0.09**	**-0.41**	**0.00**	**-0.41**
$NaF-ZrF_4$	**59.5-40.5**	**0.00**	**0.11**	**0.11**	**-0.39**	**0.05**	**-0.35**
$NaF-RbF-ZrF_4$	**33-23.5-43.5**	**0.00**	**0.14**	**0.13**	**-0.37**	**0.12**	**-0.25**
Erbium							
$^{7}LiF-BeF_2$	**67-33**	**-0.09**	**0.00**	**-0.09**	**-0.92**	**-1.54**	**-2.45**
$NaF-BeF_2$	**57-43**	**-0.08**	**0.06**	**-0.01**	**-0.86**	**-1.40**	**-2.25**
$^{7}LiF-NaF-ZrF_4$	**26-37-37**	**-0.05**	**0.09**	**0.04**	**-0.87**	**-1.41**	**-2.27**
$NaF-ZrF_4$	**59.5-40.5**	**-0.05**	**0.11**	**0.06**	**-0.85**	**-1.37**	**-2.21**
$NaF-RbF-ZrF_4$	**33-23.5-43.5**	**-0.05**	**0.15**	**0.11**	**-0.82**	**-1.29**	**-2.10**

Example: Axial-layering of Er_2O_3 Poison Reduces the CVR



Cooled Eigenvalue	1.259	1.250	1.250	1.250
Voided Eigenvalue	1.265	1.240	1.241	1.241
CVR ($)	$0.54	-$0.94	-$0.83	-$0.88
1	Reflector	Reflector	Reflector	Reflector
2	Fuel	Poison	Poison	Poison
3	Fuel	Poison	Poison	Fuel
4	Fuel	Fuel	Fuel	Fuel
5	Fuel	Fuel	Fuel	Poison
6	Fuel	Poison	Poison	Poison
7	Fuel	Poison	Fuel	Fuel
8	Fuel	Poison	Poison	Poison
9	Fuel	Fuel	Fuel	Poison
10	Fuel	Fuel	Fuel	Fuel
11	Fuel	Poison	Poison	Fuel
12	Fuel	Poison	Poison	Poison
13	Reflector	Reflector	Reflector	Reflector

Variant Case: Safety control strategy must be integrated with burnable absorbers to adjust reactivity versus time

AHTR: The Potential to Meet GenIV Goals

- **AHTR Cost per kW(e)**
  - **60–70% of an ALWR**
  - **50–60% of MHTGR**
- **Sustainability**
  - **Exceed ALWR and MHTGR**
- **Safety**
  - **Match MHTGR**
  - **Exceed ALWR**
- **Proliferation**
  - **Match MHTGR**
  - **Exceed ALWR**

Goal Areas	Goals
Economics	EC1 Life Cycle Cost EC2 Risk to Capital
Sustainability	SU1 Resource Utilization SU2 Waste Minimization and Management
Safety and Reliability	SR1 Operational Safety and Reliability SR2 Core Damage SR3 Offsite Emergency Response
Proliferation Resistance and Physical Protection	PR1 Proliferation Resistance and Physical Protection

AHTR Teams

Organization	Experimental
Oak Ridge National Laboratory	X
U.C. Berkeley	X
Areva-NP	
Argonne National Laboratory	
U. of Wisconsin	X
Westinghouse	
U. of Tennessee	
Idaho National Laboratory	
Sandia National Laboratory	
U. of Nevada	
Netherlands (Delft U. of Tech.)	
Sweden (KTH)	