Goals, Requirements, and Design Implications for the Advanced High-Temperature Reactor

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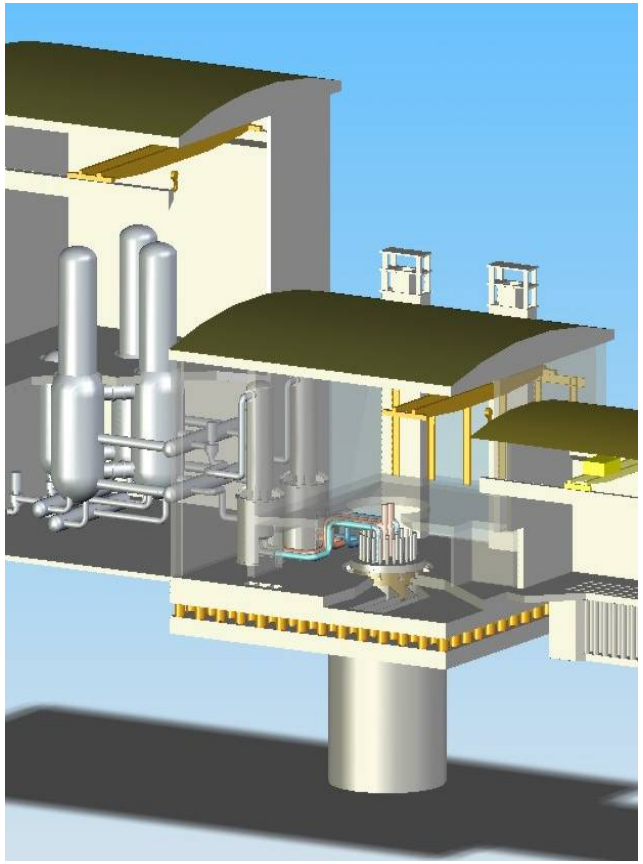
14th International Conference on Nuclear Energy
Paper: ICONE 14-89305
American Society of Mechanical Engineers
July 17–20, 2006
Miami, Florida



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ABSTRACT: ICONE14-89305
GOALS, REQUIREMENTS, AND DESIGN IMPLICATIONS FOR THE ADVANCED HIGH-TEMPERATURE REACTOR

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The Advanced High-Temperature Reactor (AHTR), also called the liquid-salt-cooled Very High-Temperature Reactor (LS-VHTR), is a new reactor concept that has been under development for several years. The AHTR combines four existing technologies to create a new reactor option: graphite-matrix, coated-particle fuels (the same fuel as used in high-temperature gas-cooled reactors); a liquid-fluoride-salt coolant with a boiling point near 1400°C; plant designs and decay-heat-removal safety systems similar to those in sodium-cooled fast reactors; and a helium or nitrogen Brayton power cycle. This paper describes the basis for the selection of goals and requirements, the preliminary goals and requirements, and the analysis that indicates these goals are potentially achievable.

For electricity production, the draft AHTR goals include peak coolant temperatures between 700 and 800°C and a maximum power output of about 4000 MW(t), for an electrical output of ~2000 MW(e). The electrical output matches that expected for a large advanced light-water reactor (ALWR) built in 2025. Plant capital cost per kilowatt electric is to be at least one-third less than those for ALWRs with the long-term potential to significantly exceed this goal. For hydrogen production, the peak temperatures may be as high as 950°C, with a power output of 2400 MW(t). The safety goals are to equal or surpass those of the modular high-temperature gas-cooled reactor with a beyond-design-basis accident capability to withstand large system and structural failures (vessel failure, etc.) without significant fuel failure or off-site radionuclide releases. These safety goals may eliminate the technical need for evacuation zones and reduce security requirements and significantly exceed the safety goals of ALWRs. The plant design should enable economic dry cooling to make possible wider nuclear-power-plant siting options. Uranium consumption is to be less than that for an ALWR, with major improvements in repository performance and nonproliferation characteristics.

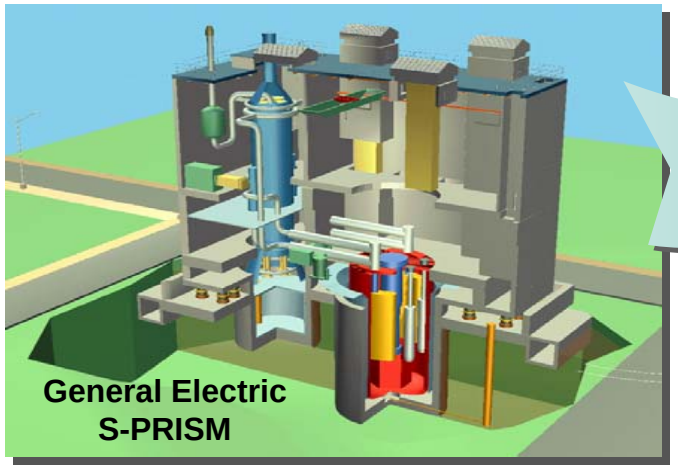
The Advanced High-Temperature Reactor

A New Reactor Concept That Has Been Under Development For Several Years

Oak Ridge National Laboratory (ORNL), Idaho National Laboratory (INL), Argonne National Laboratory (ANL), Sandia National Laboratory (SNL), the University of California at Berkeley, The University of Tennessee, the University of Wisconsin, Areva-NP, and Others

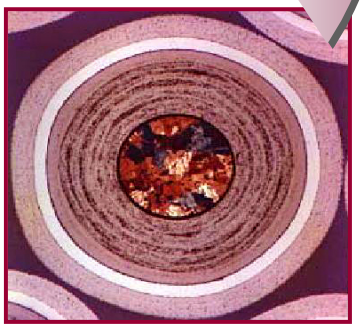
The Advanced High-Temperature Reactor

Combining Four Existing Technologies in a New Way



Passively Safe Pool-Type Reactor Designs

Brayton Power Cycles

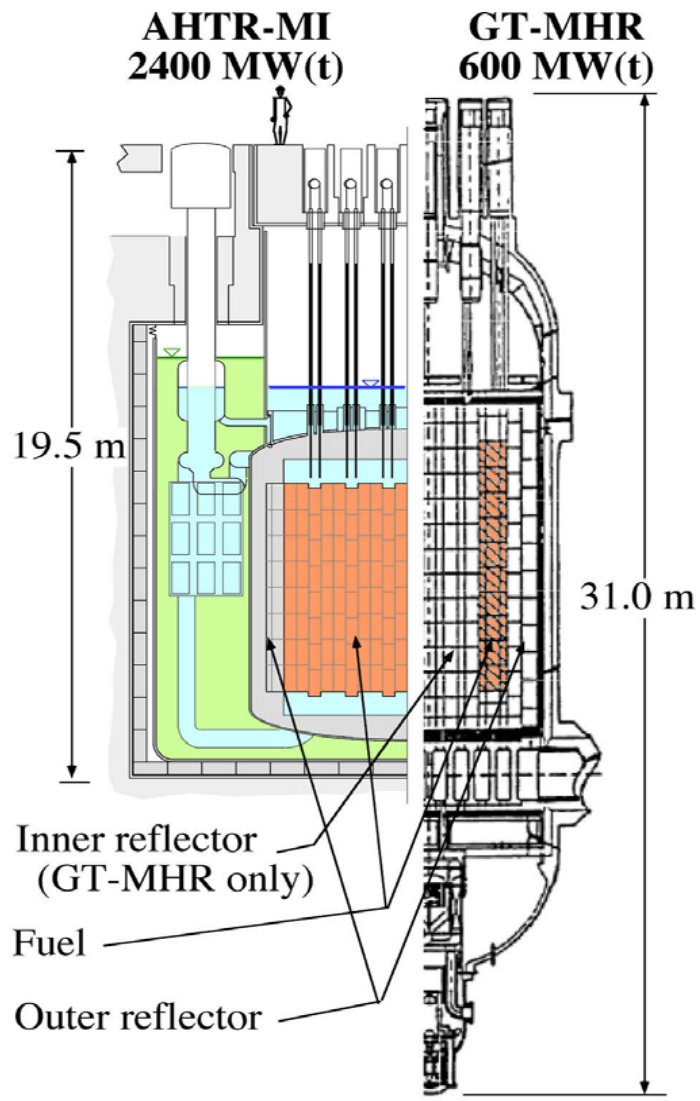


High-Temperature Coated-Particle Fuel

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

AHTR Goal

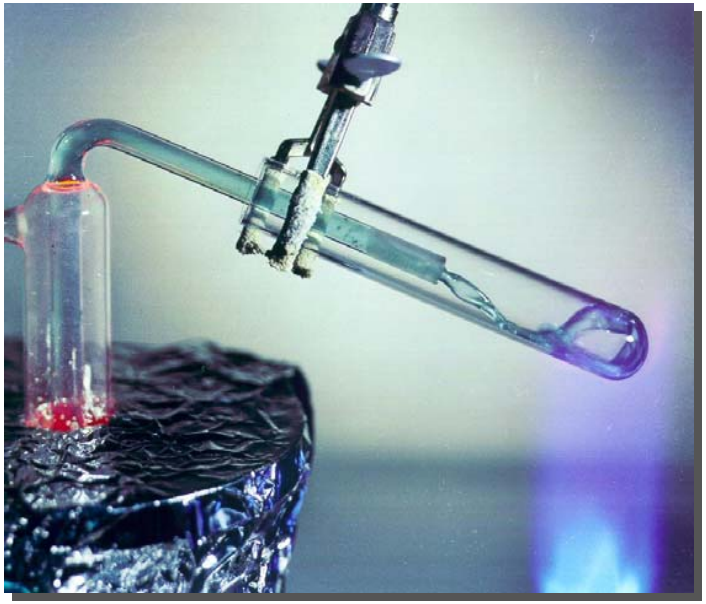
A Large High-Temperature Reactor With Superior Economics and the Same Safety Goals as an MHTGR



The AHTR Uses a Liquid Salt Coolant

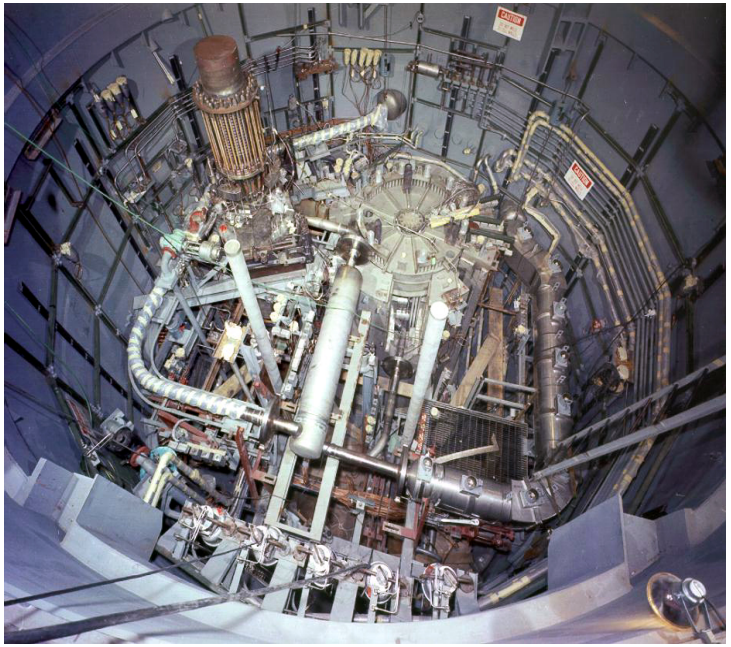
The AHTR Uses a Clean Low-Pressure Salt Coolant and Solid Fuel

The Technology was Developed in the 1950s and 1960s for the Molten Salt Reactor (Fuel Dissolved in the Coolant)



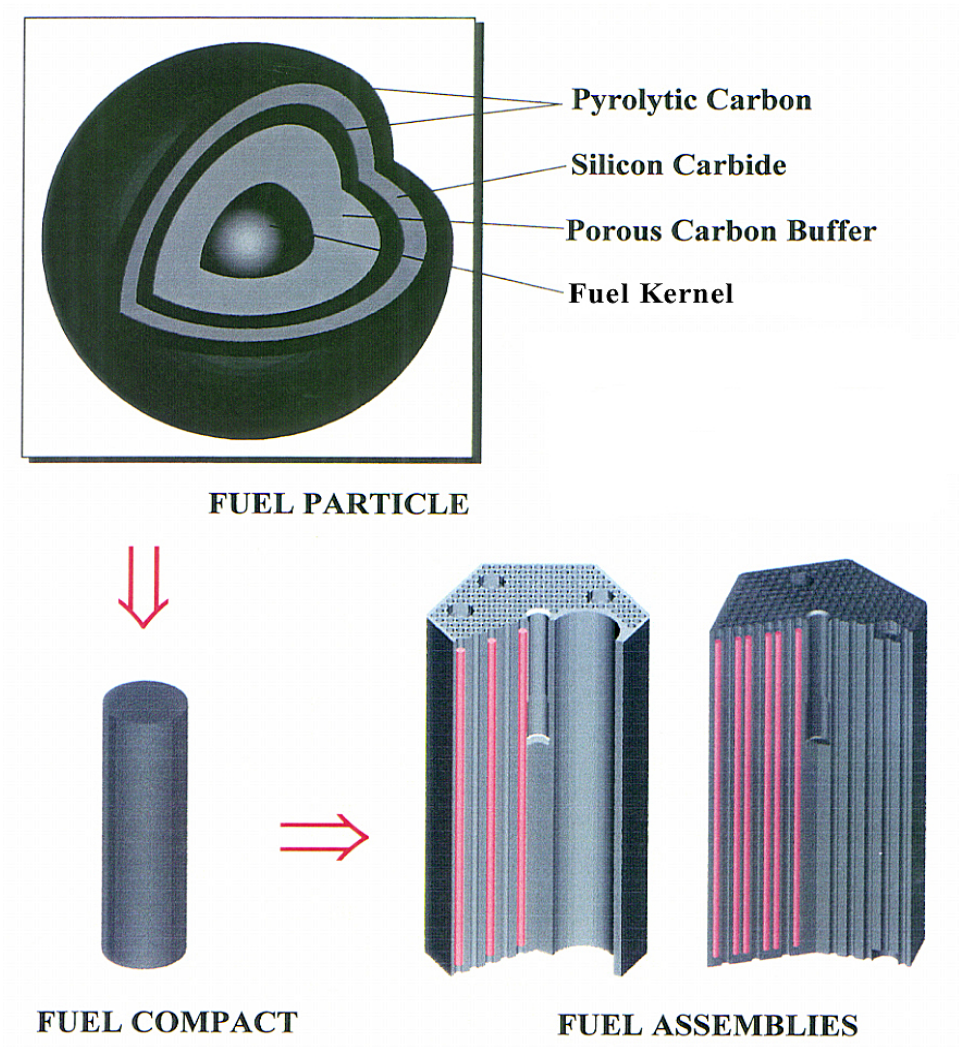
Liquid Fluoride Salt; Transparent; Liquid; BP >1200°C

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



The AHTR Uses High-Temperature Graphite-Matrix Fuel

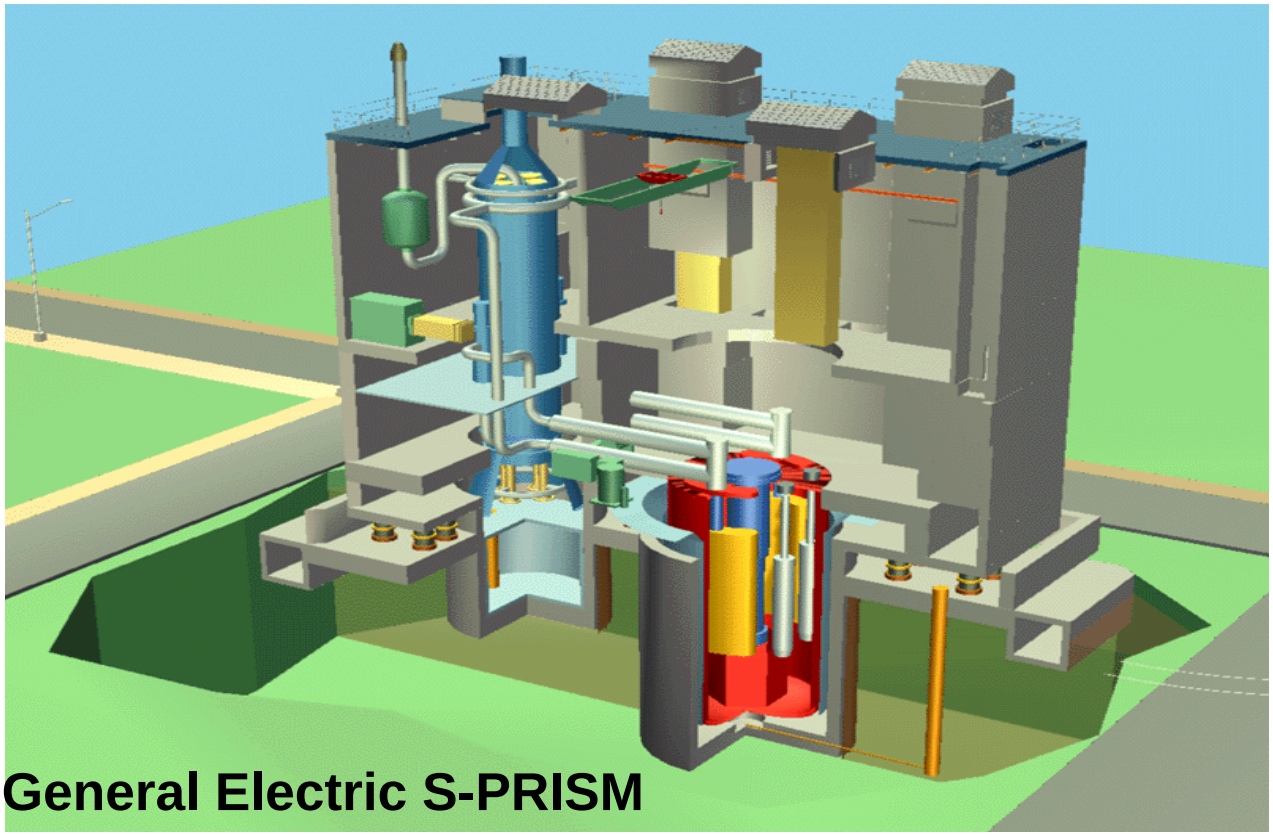
Developed for Gas-Cooled Reactors in the 1960s and 1970s



Peak Operating Temperature ~1250°C
Failure Temperature ~1650°C

AHTR Facility Layouts are Based on Sodium-Cooled Fast Reactors

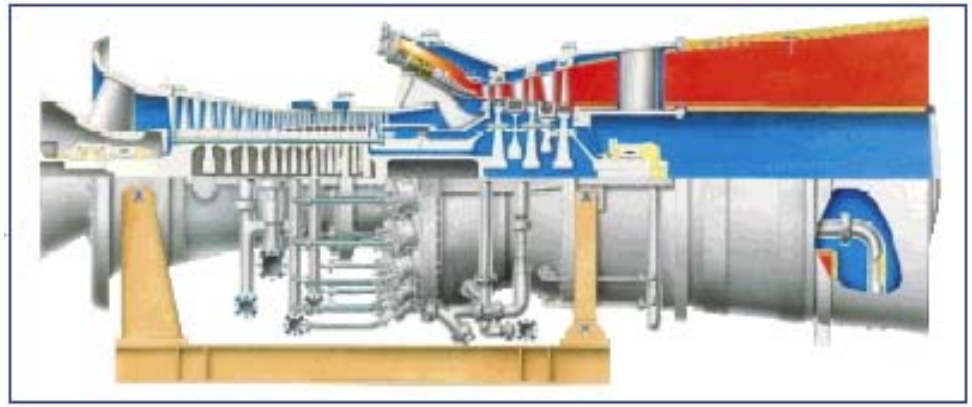
Common Characteristics: Low Pressure, High Temperature, Liquid Cooled



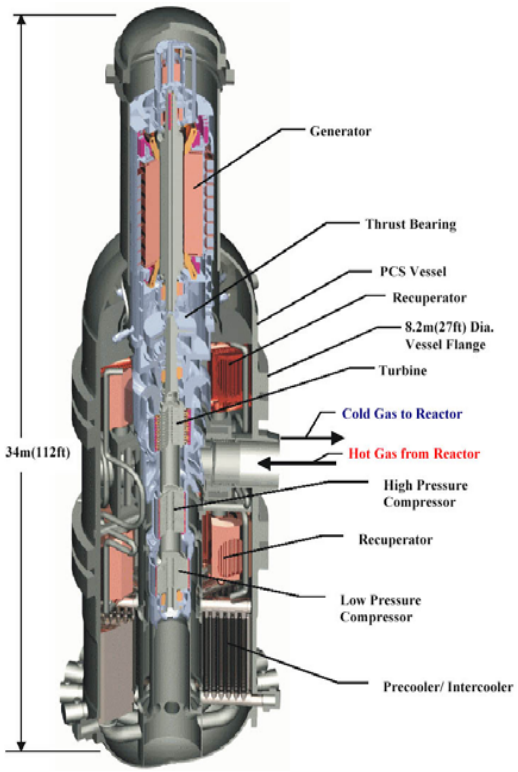
The Technology was Developed in the 1970s and 1980s

The AHTR Uses a Closed Brayton Cycle to Convert Heat to Electricity

- **Matches AHTR coolant temperatures from 700 to 950ºC**
- **Utility-grade Brayton cycles were developed in the 1980s and 1990s**



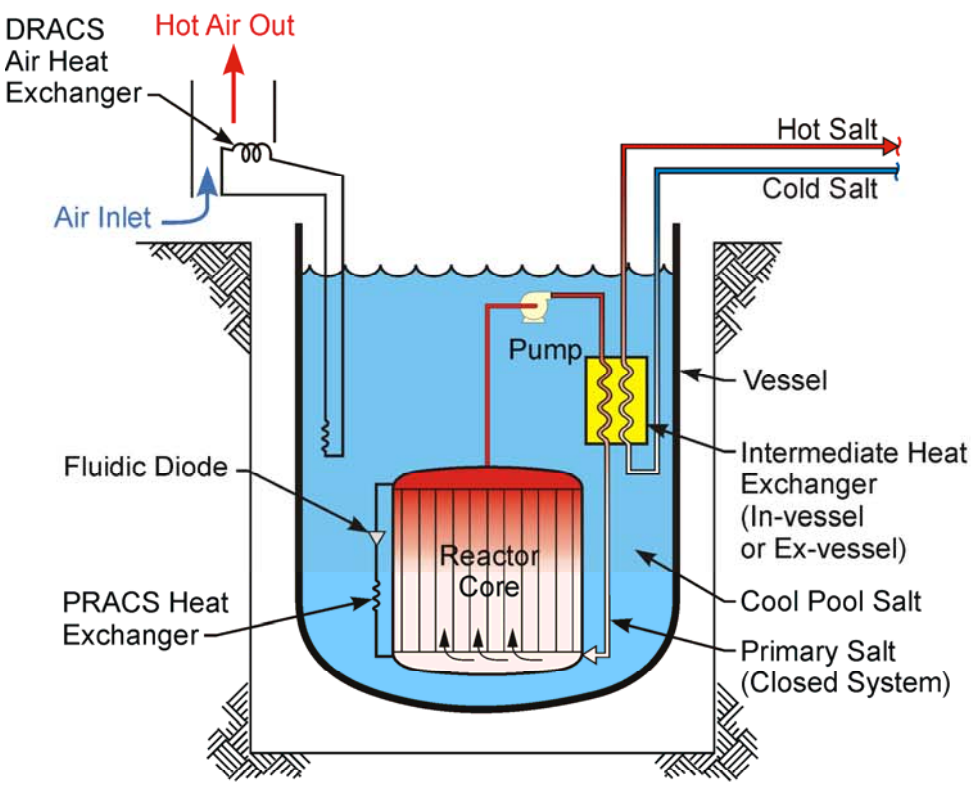
GE Power Systems MS7001FB



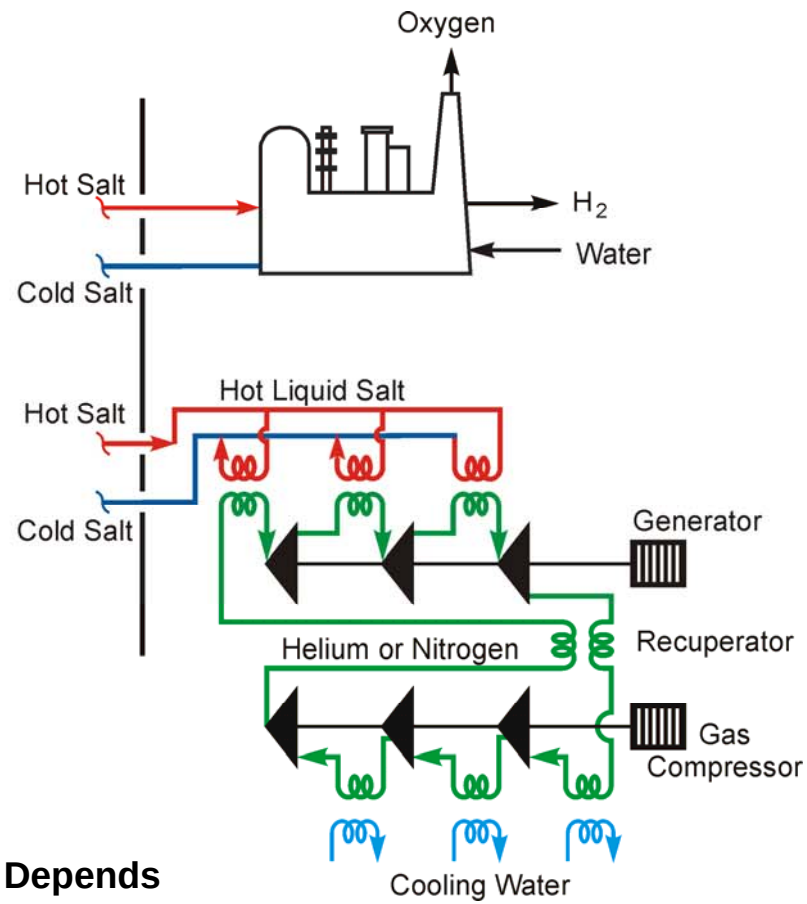
General Atomics GT-MHR Power Conversion Unit (Russian Design)

The Advanced High-Temperature Reactor

Passive Decay Heat Removal **Reactor**



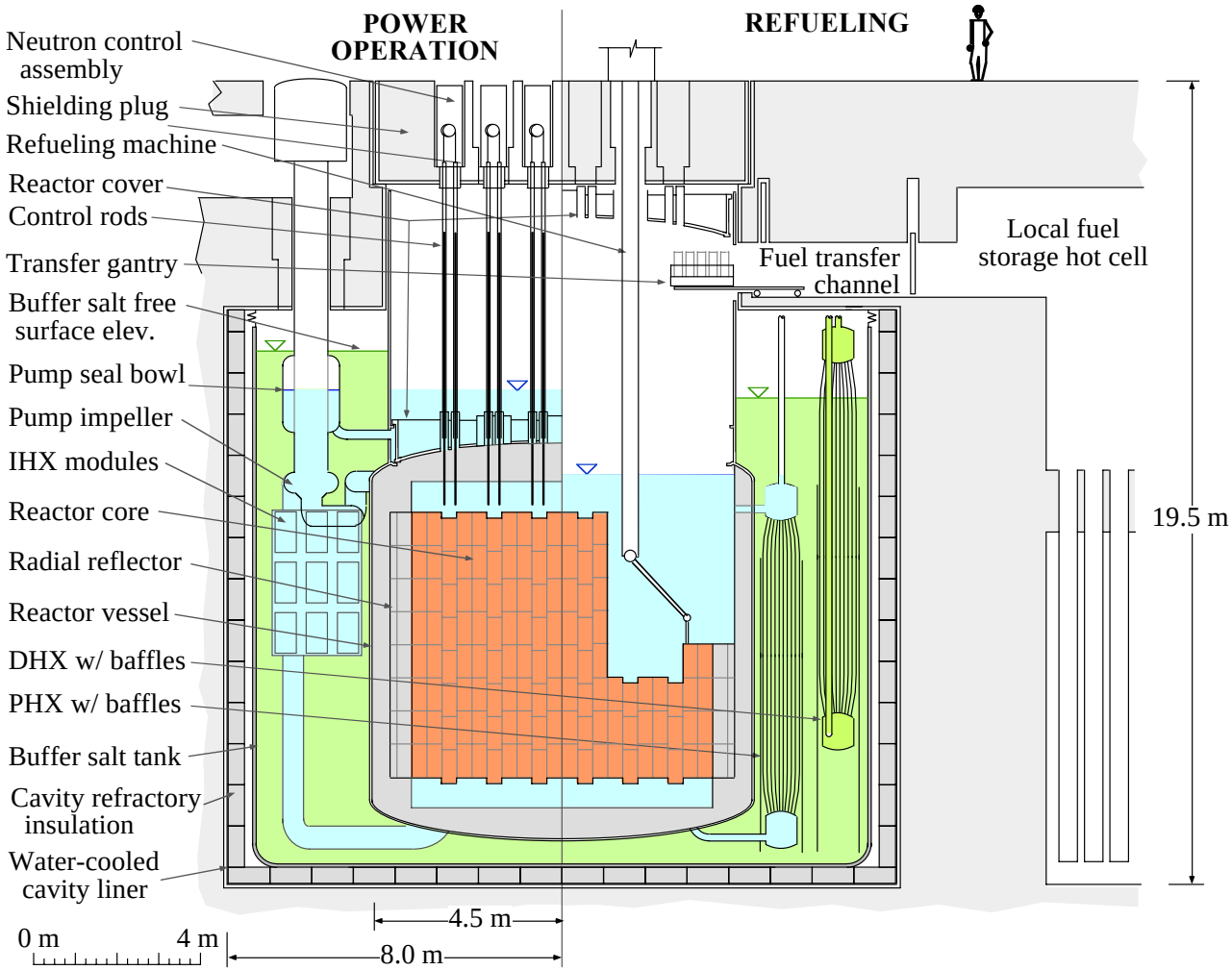
Hydrogen/Brayton Electricity Production



Efficiency Depends upon Temperature:

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

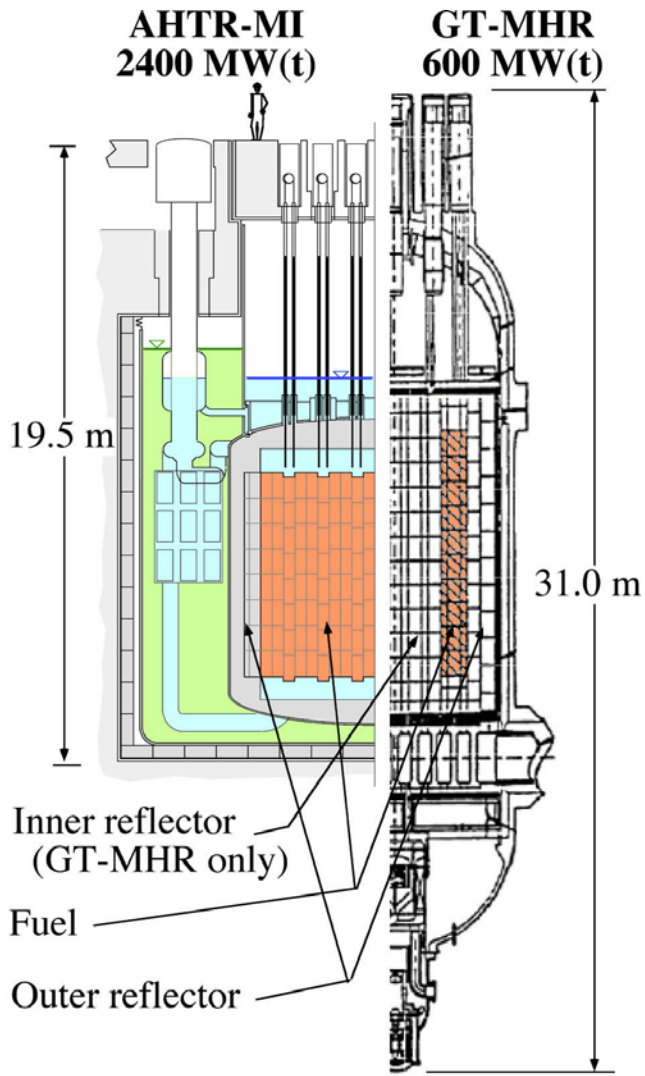
2400-MW(t) AHTR Schematic



Goals and the Technical Basis to Meet the Goals

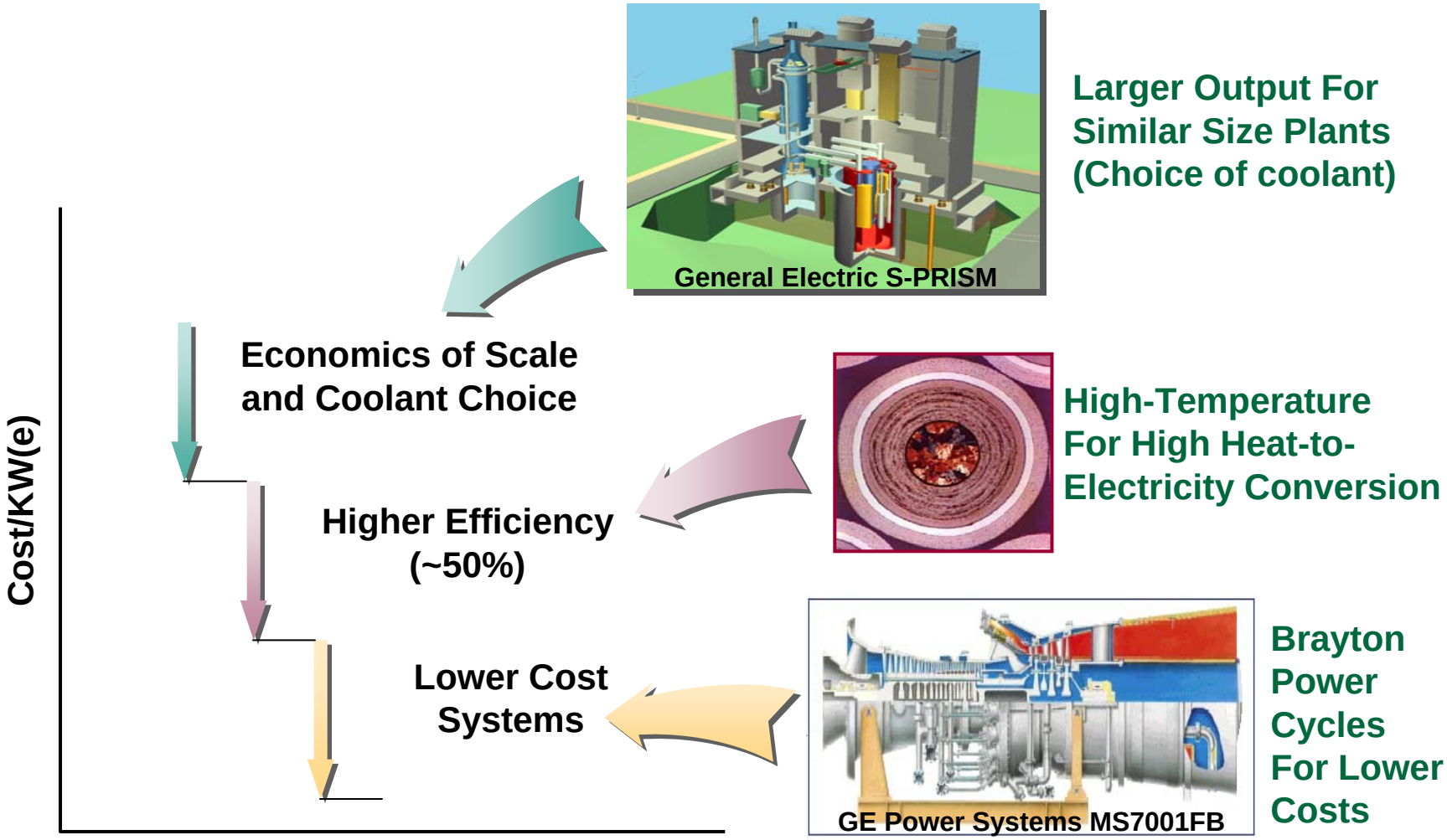
AHTR Economic Goals

Goal: Superior AHTR Economics with Large Reactors



- **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(t)**
  - **Capital costs one-third less than an ALWR**

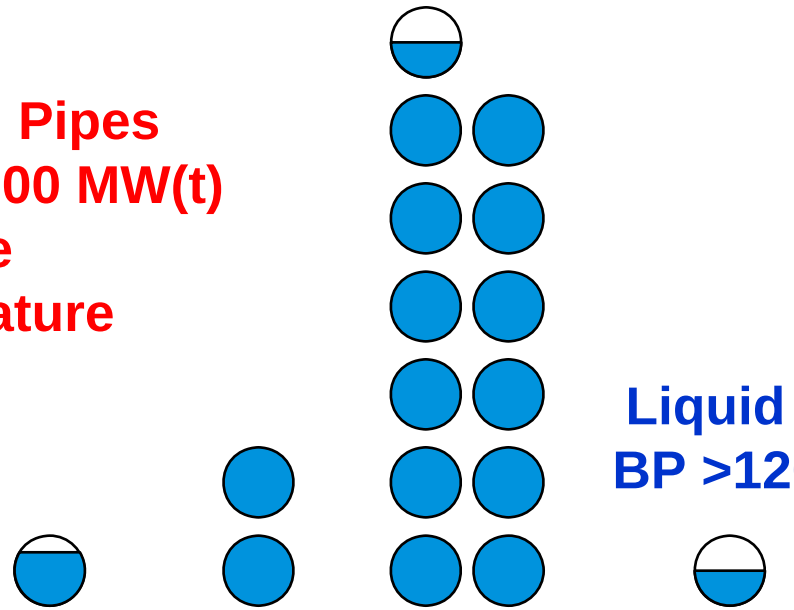
The Potential Improvements in Economics are Based on Several Factors



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

AHTR Plant Size for H_2 Production is Based on H_2 Industry Needs

- **H_2 plant size is increasing**
- **Largest natural gas-to-H_2 plant (4 trains) under construction will have an output of $15.6 \cdot 10^6$ m^3/day**
- **Equals H_2 by electrolysis from three 1000-MW(e) nuclear power plants**
- **4600 MW(t) of nuclear heat required for thermochemical H_2 production**

Browns Ferry Nuclear Power Plant
(Courtesy of TVA)

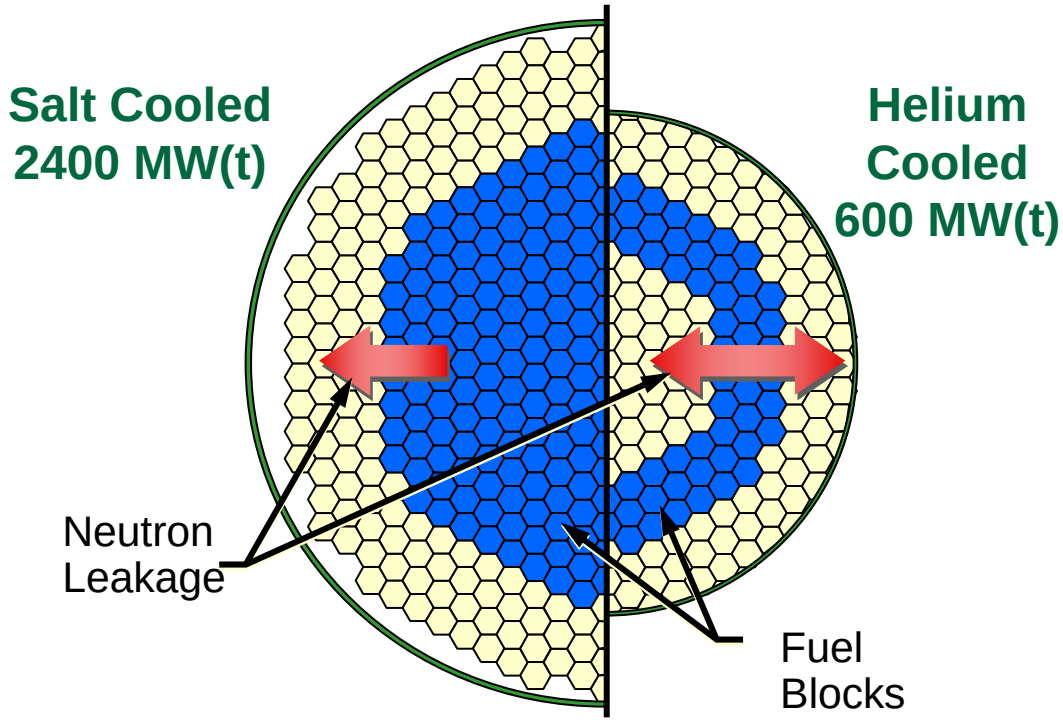
Need for Multiunit Stations (Reliable Delivery)
AHTR Size for H_2 Production: 2400 MW(t)
Coolant Exit Temperature: 950°C

AHTR Sustainability Goals

Exceed ALWRs and MHTGRs

The AHTR Uranium Consumption is Better than an ALWR or a MHTGR

- **Relative uranium consumption per kW(e)**
  - **AHTR (best)**
  - **ALWR**
  - **MHTGR (worst)**
- **Basis for lower uranium consumption**
  - **High efficiency in converting heat to electricity (similar to MHTGR)**
  - **Large low-neutron-leakage core**



High-Temperature Reactors Increase Repository Capacity (Good) and Waste Volume (Bad)

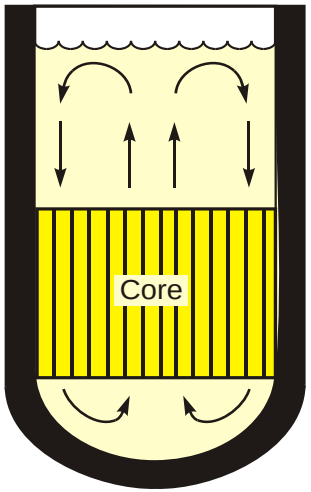
Property	PWR	MHTGR	AHTR
Fuel burnup [GWd(t)/ton uranium]	50	100	150
Electrical efficiency (%) [Measurement of Relative Repository Capacity Because a Repository Capacity Is Limited by Decay Heat]	33	50	50
Electricity per unit volume of fuel [GWd(e)/m^3]	20	3.3	5

AHTR Safety Goals

Exceed ALWR and Match MHTGR

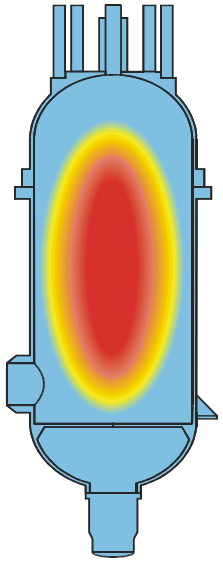
Liquid Cooling Enables Design of Large Reactors with Passive Decay-Heat Cooling Systems

Liquid
[1000s of MW(t)]



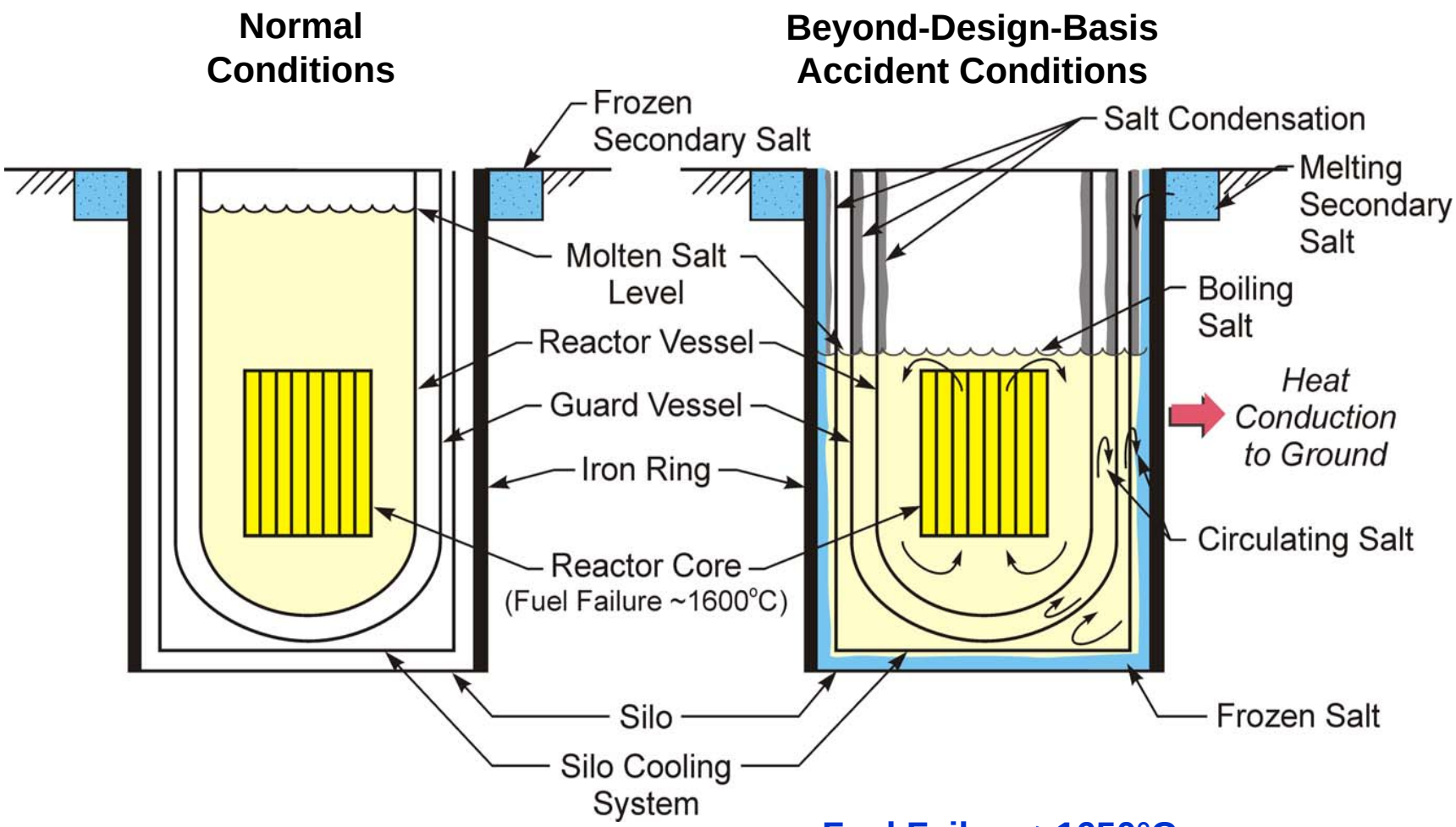
Fuel Design Controlled by Convective Cooling Requirements

Gas
[~600 MW(t)]



Fuel Design Controlled by Conduction Cooling Requirements

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



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

AHTR Conclusions: 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**

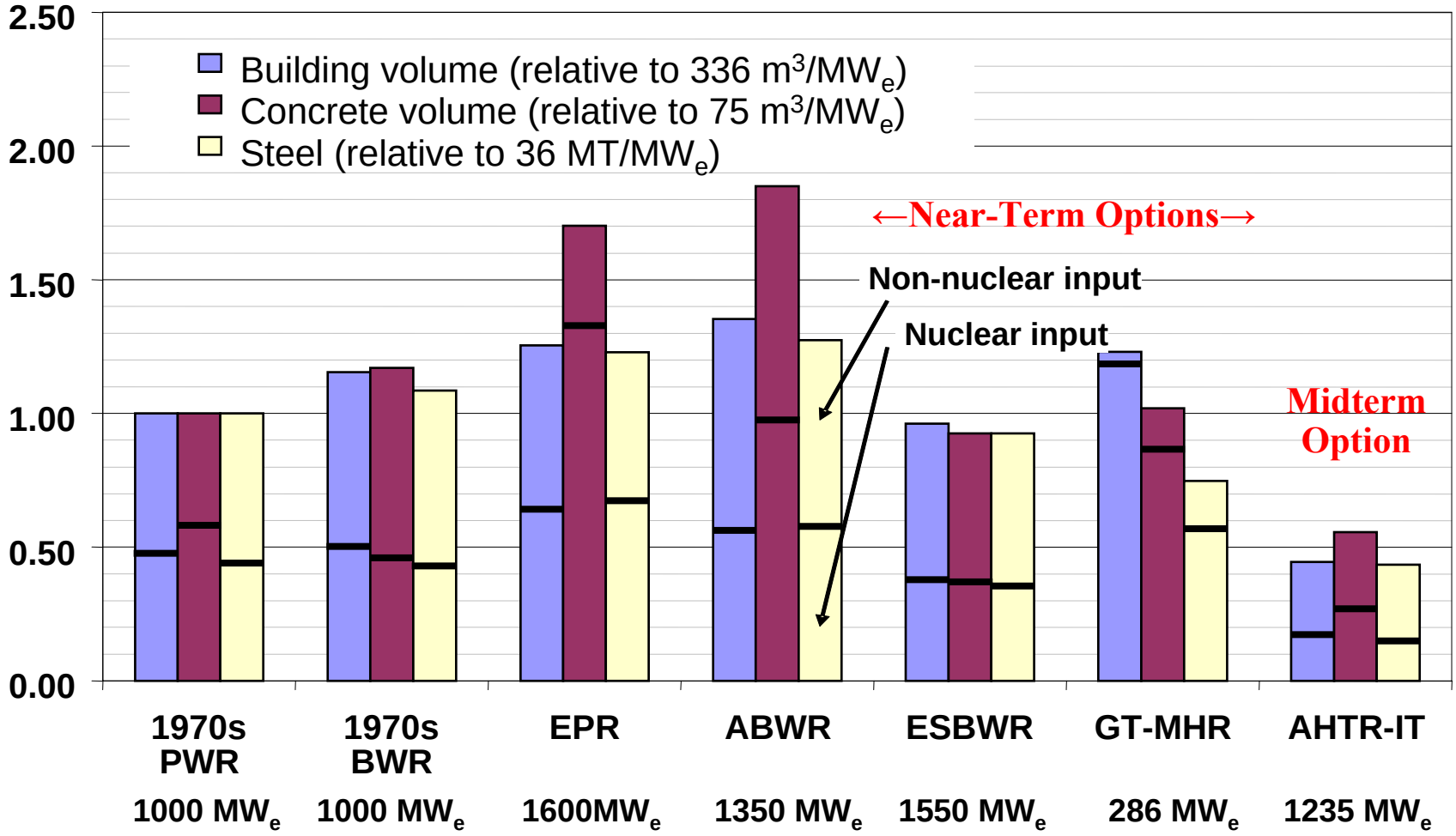
Goal Areas	Goals
Economics	EC1 Life Cycle Cost EC2 Risk to Capital
Sustainability	SU1 Resource Utilization SU2 Waste Minimization and Management
Safety and Reliability	SR1 Operational Safety and Reliability SR2 Core Damage SR3 Offsite Emergency Response
Proliferation Resistance and Physical Protection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

Biography: Charles Forsberg

Dr. Charles Forsberg received 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 presently a senior scientist and the Senior Reactor Technical Advisor. Dr. Forsberg is a fellow of the American Nuclear Society and received the American Nuclear Society special award for innovative nuclear reactor design. In 2005 he received the American Institute of Chemical Engineers Nuclear Energy Division Robert E. Wilson Award for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and other technologies to use nuclear energy. He also received the Oak Ridge National Laboratory Engineer of the Year Award in 2005. Dr. Forsberg has been awarded 10 patents and has published over 200 papers, many on hydrogen futures.

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