Very High Temperature Gas Reactor (VHTR) Technology

Dr. David Petti

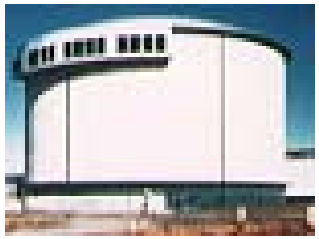
Laboratory Fellow
Director VHTR Technology Development Office

Idaho National Laboratory

Background

HTGR Technology Well Established

PROTOTYPE PLANTS



DRAGON – 20 MWt
(U.K.)
1964 1975

AVR – 46 MWt
(FRG)
1967 1988

PEACH BOTTOM 1 – 115 MWt
(U.S.A.)
1967 1974

HTTR – 30 MWt
(JAPAN)
1999 - present

HTR-10 – 10 MWt
(CHINA)
2000 - present

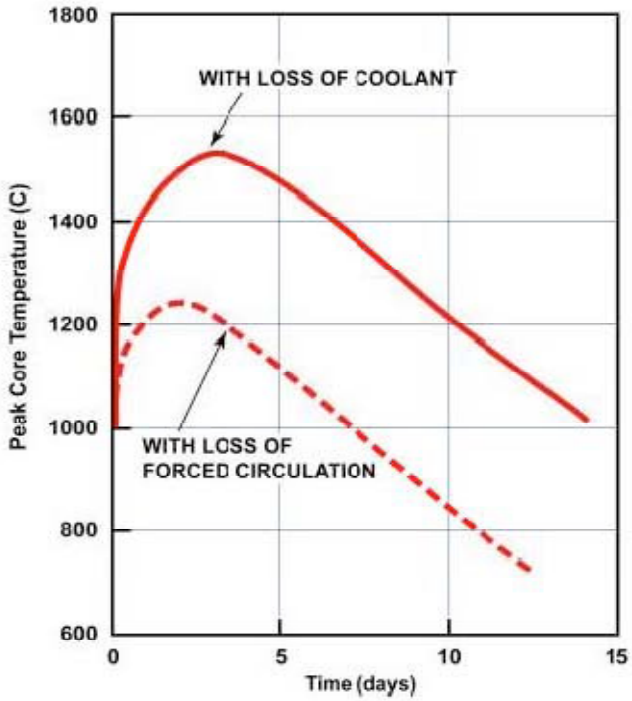
DEMONSTRATION PLANTS

FORT ST. VRAIN – 842 MWt
(U.S.A.)
1976 1989

THTR – 750 MWt
(FRG)
1986 1989

Photos courtesy of GA

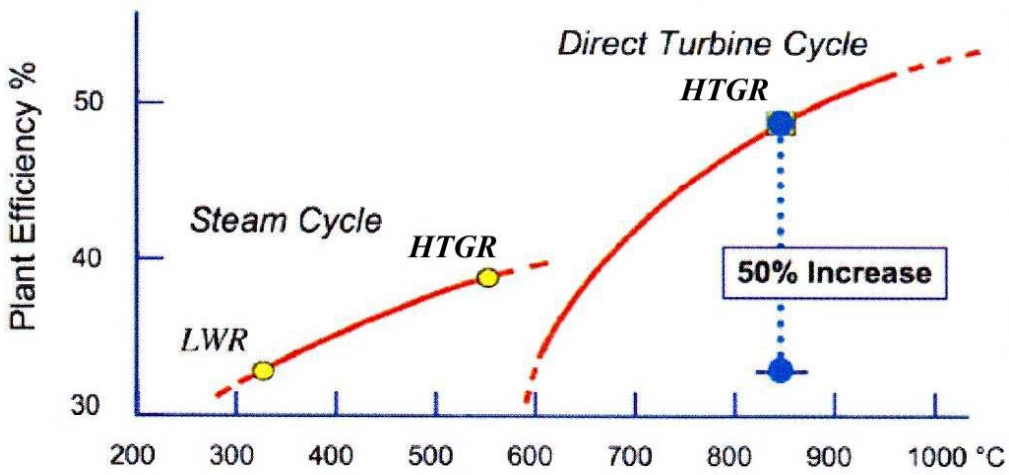
HTGRs Feature Passive Safety



- Inert single-phase helium coolant
- Massive graphite core moderator
  - High temperature
  - Large heat capacity
  - Low power density
- Coated particle fuel
  - High temperature
  - Fission particle retention
- Large negative temperature coefficient

Figure courtesy of GA

HTGRs Offer Economic Advantages

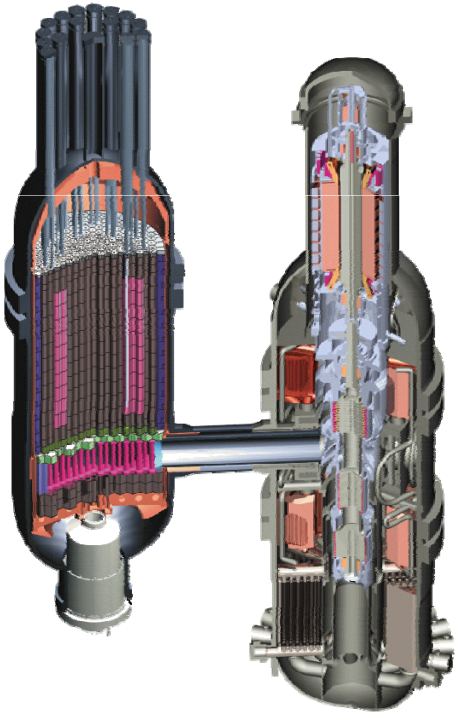


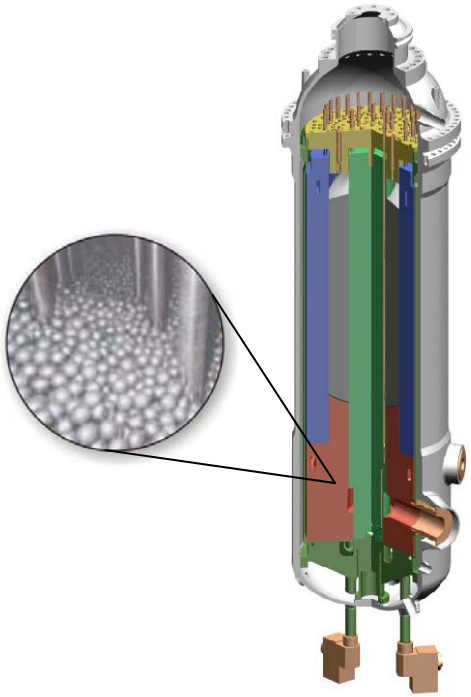
- High thermal efficiency
- Reduced emergency planning costs
- Simplified safety systems
- Lower component contamination levels

Increased public acceptance

Figure courtesy of GA

HTGR Design Dependent On Fuel Form





Prismatic
(Dragon, Peach Bottom, FSV, etc.)

Pebble-bed
(AVR, THTR, SA PBMR, China, etc.)

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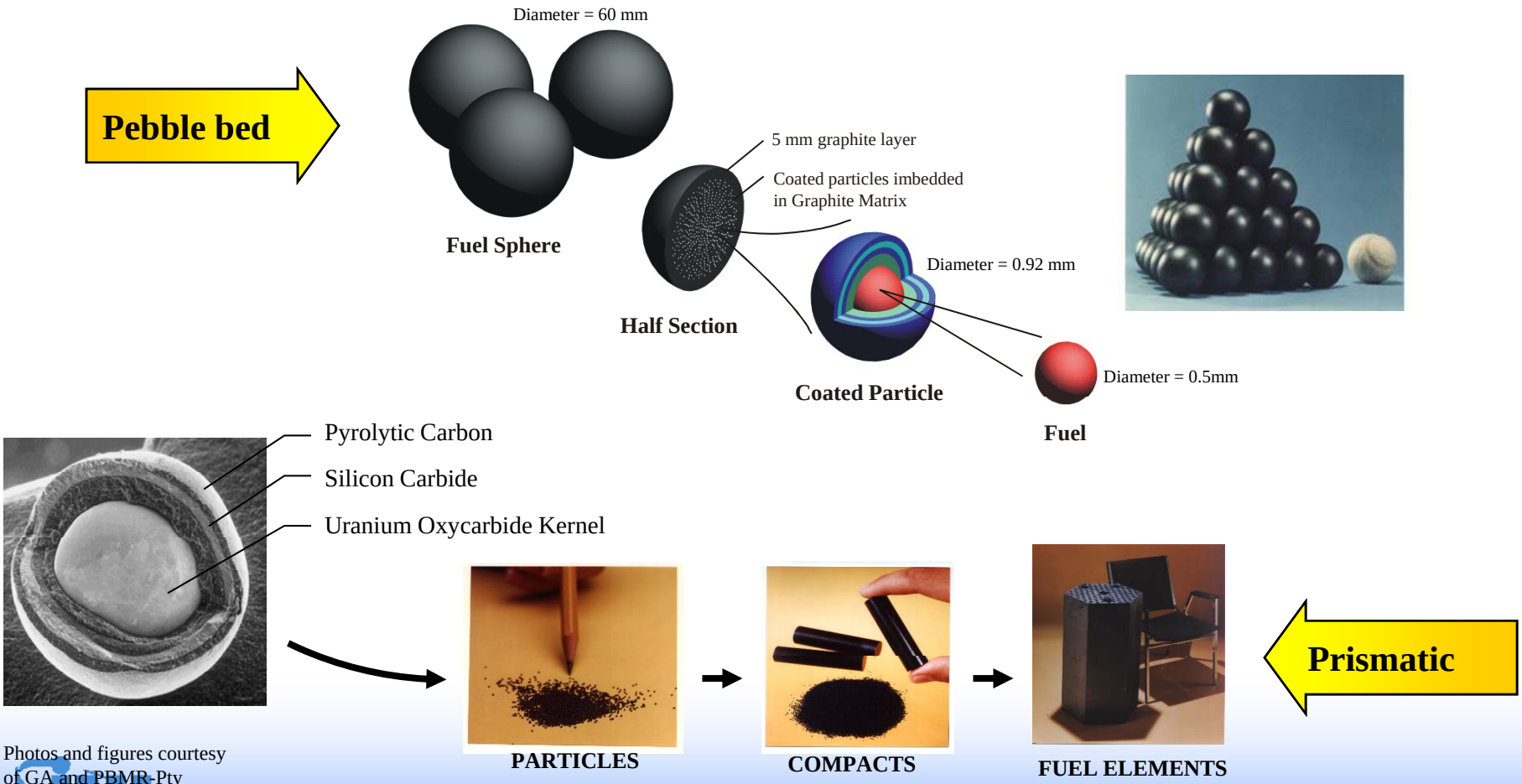
Photos and figures courtesy of GA and PBMR-Pty

Background

All HTGRs Rely on Coated Particle Fuel



Photos and figures courtesy of GA and PBMR-Pty

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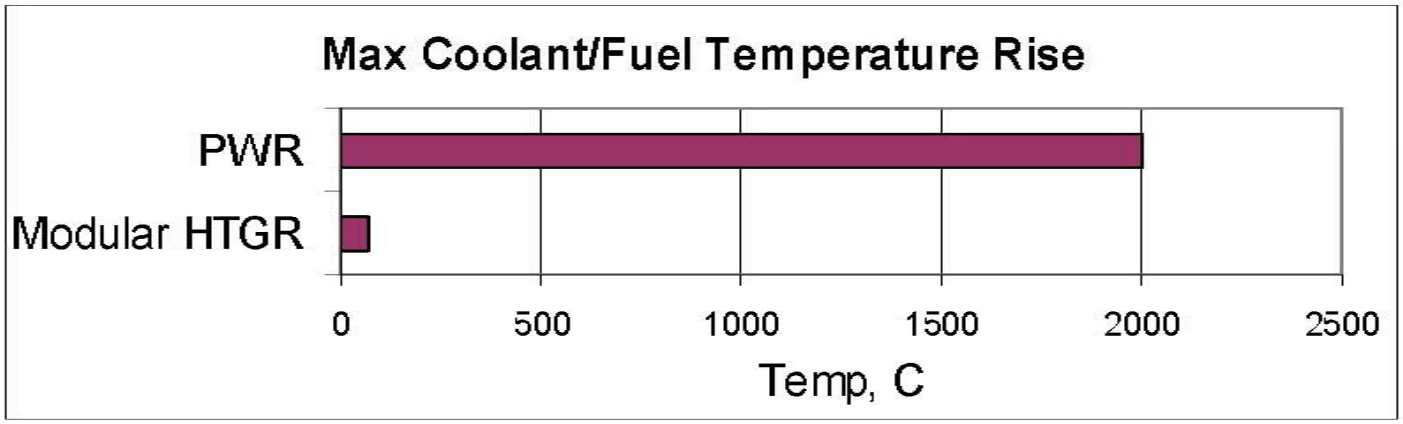
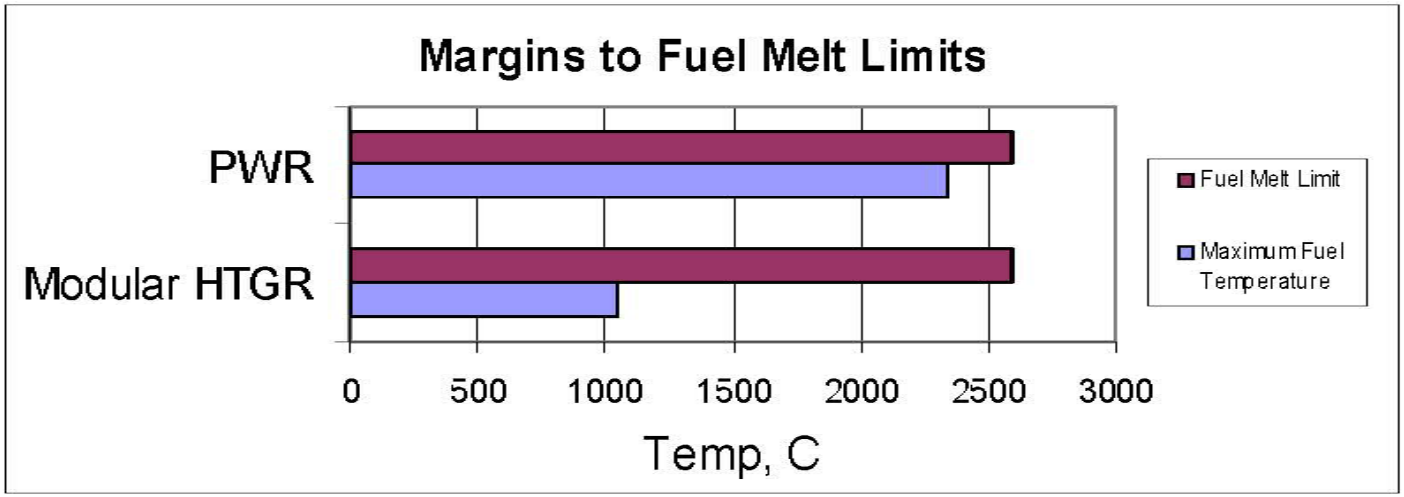
TRISO coating primary barrier for fission product release

Advantages of VHTRs: Safety Advantage of VHTRs





Courtesy Global Virtual LLC

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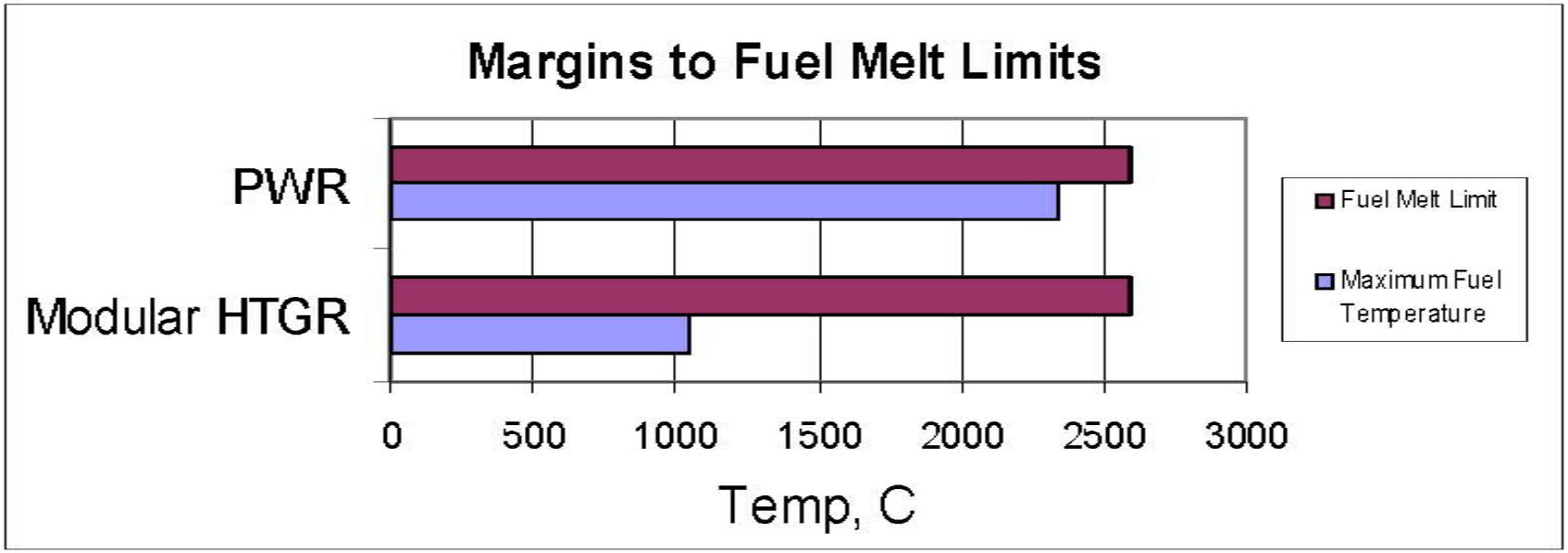
Advantages of VHTRs: Large Margin to Fuel Integrity Limits



Courtesy Global Virtual LLC

Advantages of VHTRs: Robust High Performance Fuel

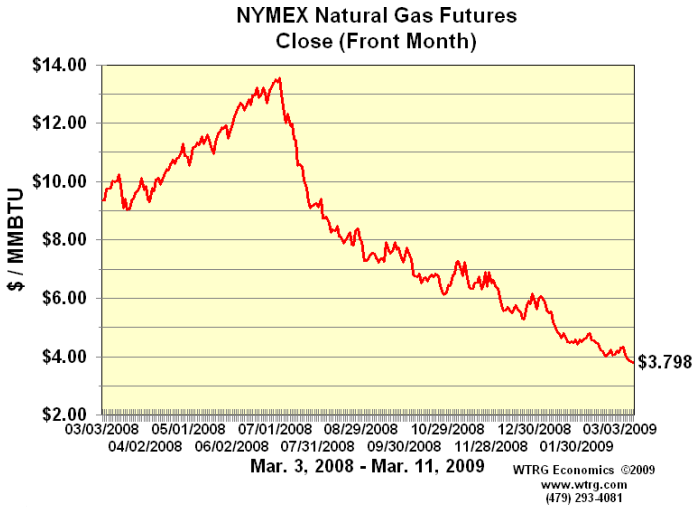
Parameter	LWR	PBMR	GT-MHR
Discharge burn up (MWt-day/kg)	55	92	160
Fuel enrichment (%)	5.0	9.4	15
Thermal efficiency (%)	33	42	45
Natural uranium consumption (kg/MWe-day)	0.630	0.573	0.497
Separative work consumption (SWU/MWe-day)	0.397	0.415	0.385
Depleted uranium generation (kg/MWe-day)	0.575	0.547	0.483
Relative natural uranium consumption	1.00	0.91	0.79
Relative SWU consumption	1.00	1.05	0.97
Relative spent fuel volume per unit of electricity generated	1.00	0.47	0.25

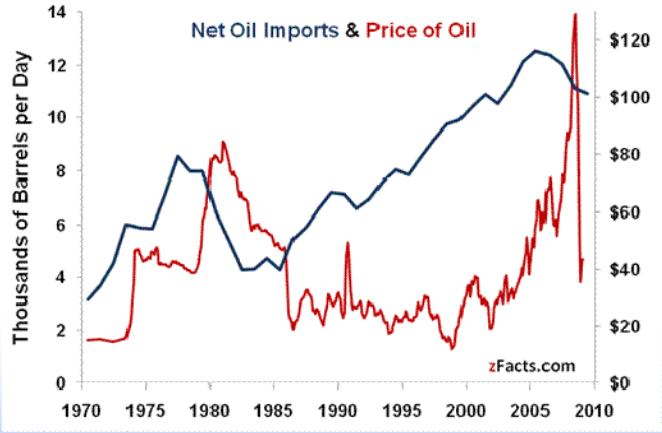
Several Factors Motivate Recent U.S. HTGR Interest

- High temperature applications
  - Process heat
  - Hydrogen production
- Inherent safety
  - Simplified licensing and emergency planning requirements
  - Reduced safety requirements
  - More flexible siting requirements
- Political
  - Reduce greenhouse gas emissions
  - Energy Policy Act of 2005 (EPAct)
  - Energy independence
  - Grow US nuclear infrastructure
  - Increased public acceptance

Addressing the Energy Challenge…

- **Volatile prices for oil and natural gas**
- **Dependence on foreign sources**
- **Increased risk of climate change with burning of fossil fuels**





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60% of oil and 16% of natural gas used in US is imported

Using High Temperature Reactors to Produce Process Heat and Hydrogen

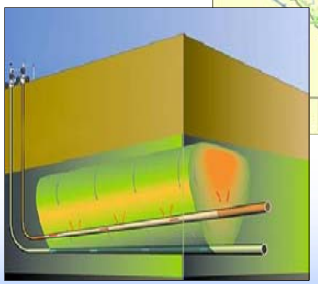
If all industrial coal heating and 50% of natural gas heating were replaced with nuclear heat from HTGR's (by 2050):

- **GHG emissions from this sector could be reduced to *~28% below current levels, and 37% below business as usual levels in 2050***
- **Would require ~550 HTGR's be deployed to this sector**

Petrochemical

Petroleum Refining

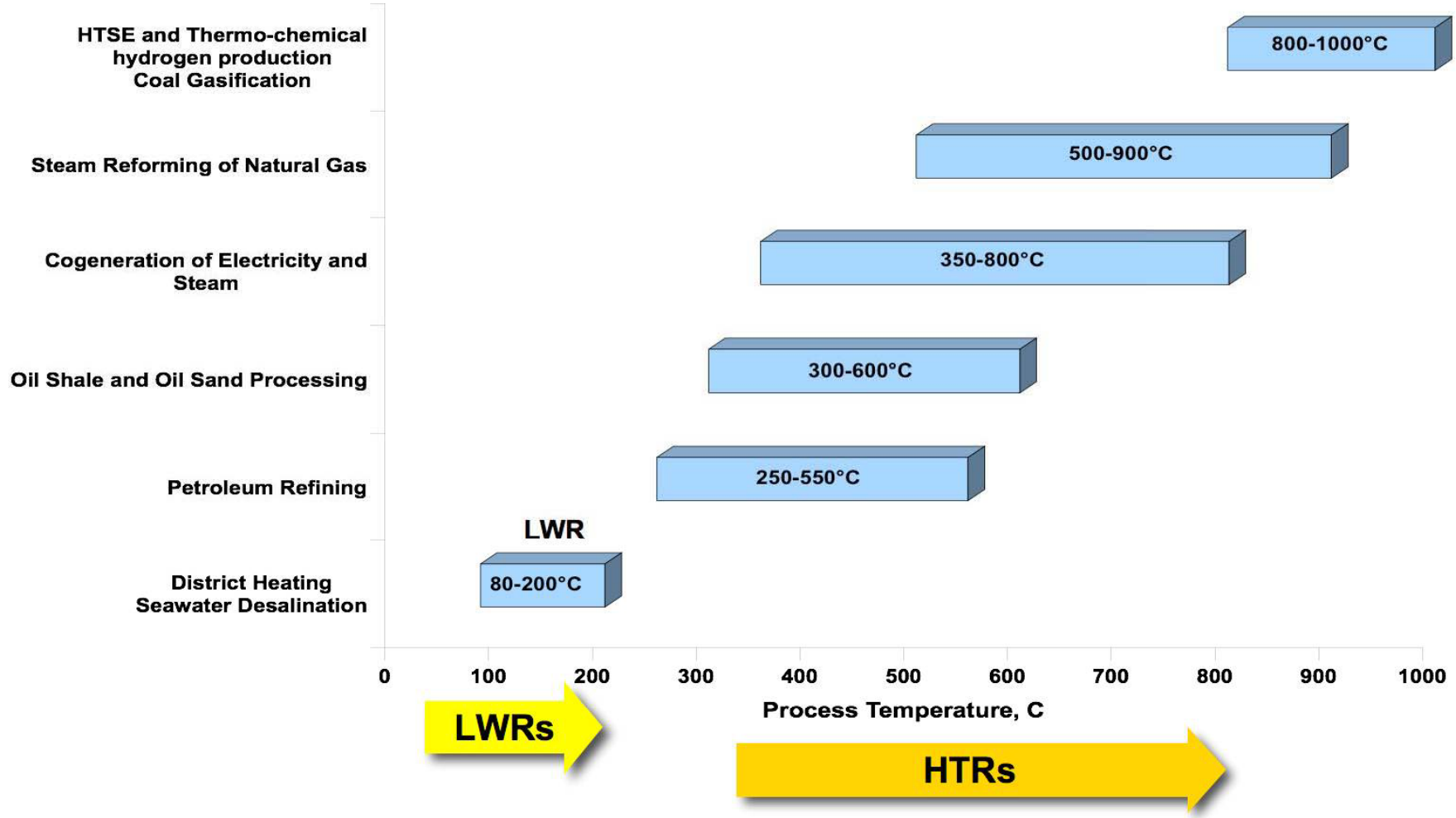
Fertilizers/Ammonia



Oil Sands/Shale

Coal-to-Liquids

Several Industrial Processes Require Temperatures Only Attainable by HTRs



Energy Policy Act of 2005

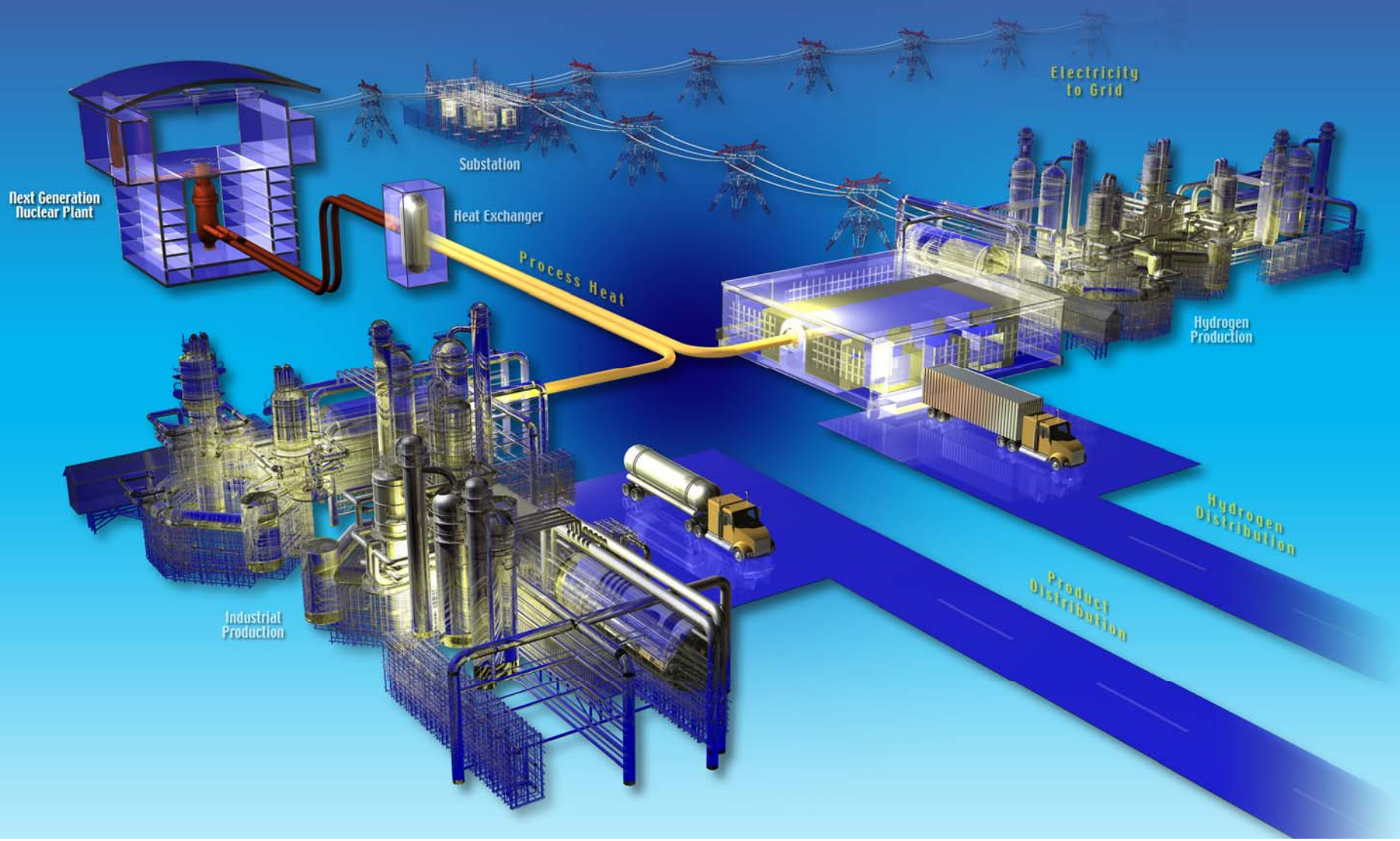
- **NGNP Project as authorized by the Energy Policy Act of 2005 to be built at INL by 2021.**
- **Use VHTR technology to:**
  - **Produce electricity, and**
  - **Process heat for hydrogen production and other applications**
- **Conceived as a public/private partnership**
  - **Demonstrate the basis for commercialization**
  - **U.S. nuclear industry expected to play integral part in advancing VHTR technologies**
- **Will be licensed by NRC**

Next Generation Nuclear Plant (NGNP)

- 600 MWt (upper limit), helium cooled high temperature reactor
- Outlet temperature from 850 to 950°C
- Process heat demonstration - hydrogen production by thermo-chemical cycle or high temperature electrolysis
- Electricity generation
- 60-year design life - however, components can be replaced

NGNP Commercialization

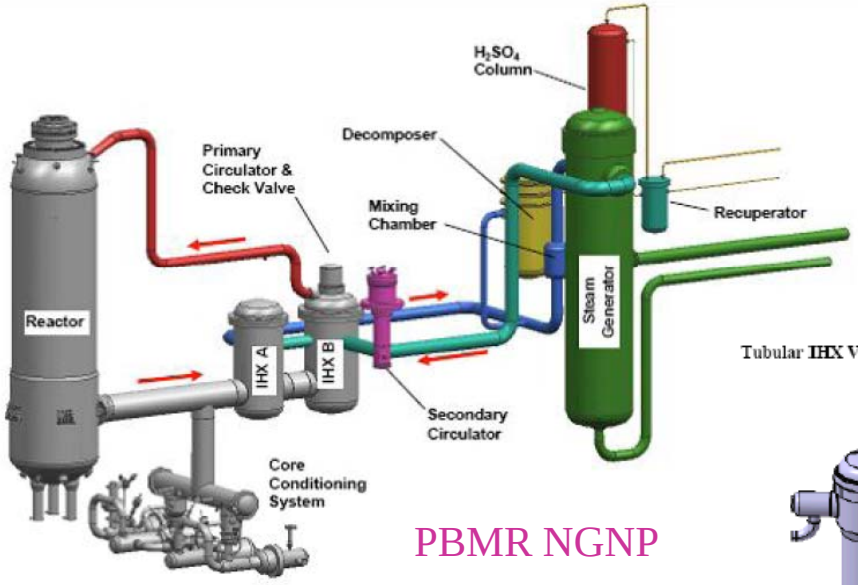
NGNP will enable commercialization of High Temperature Gas-Cooled Reactor technology to provide process heat



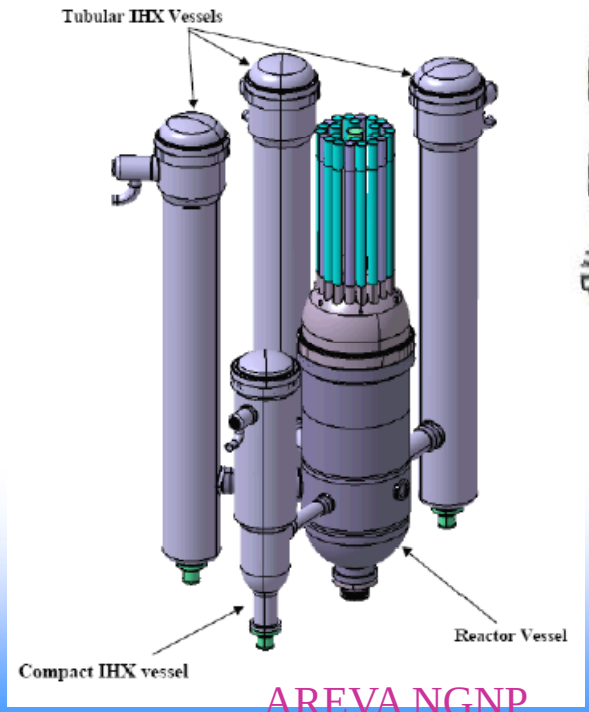
Current NGNP Project Status

- Current plan is for DOE to enter into a financial assistance agreement with private sector to share risks and costs
- Current emphasis is on R&D, reduction of high technical risks and licensing planning issues until the Financial Offer of Assistance is sent by DOE to proceed with Conceptual Design (2 concepts)
- Completion of NGNP demonstration plant scheduled for early 2020s

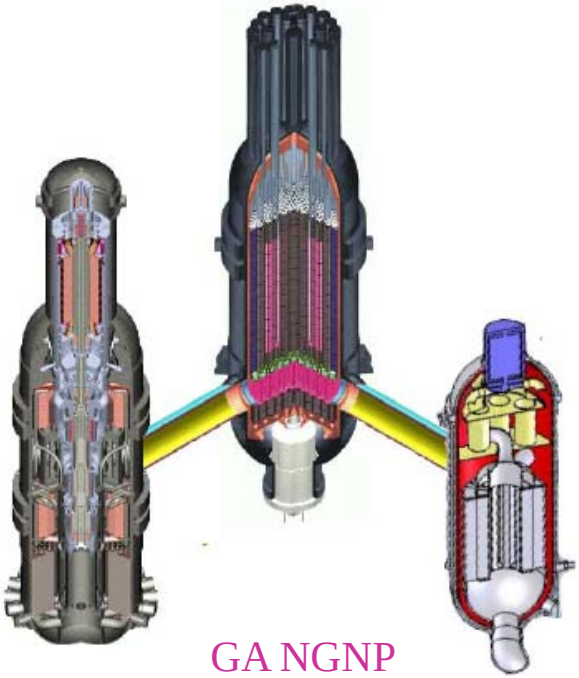
Industry Design Efforts Guide Technology Development



PBMR NGNP

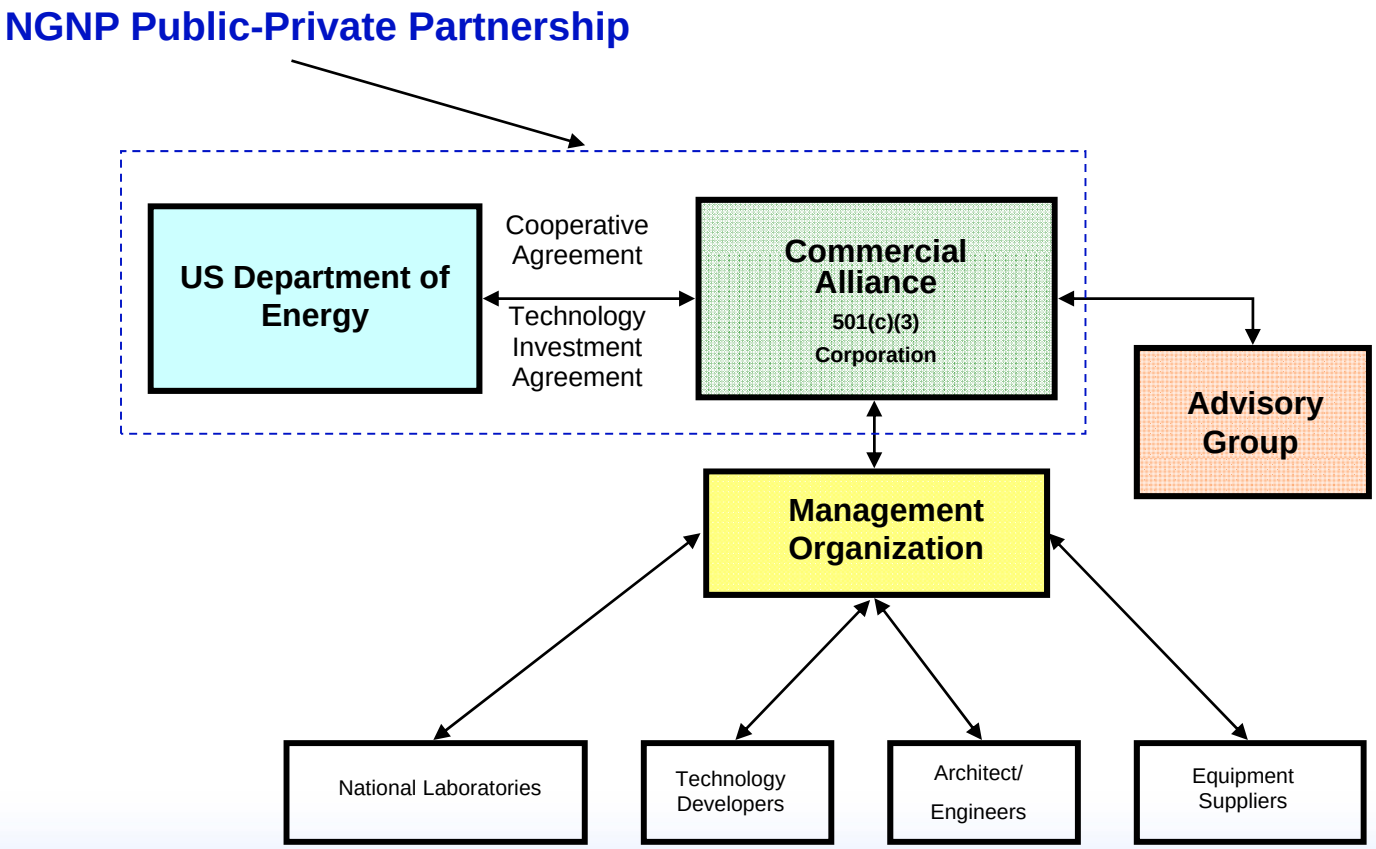


AREVA NGNP



GA NGNP

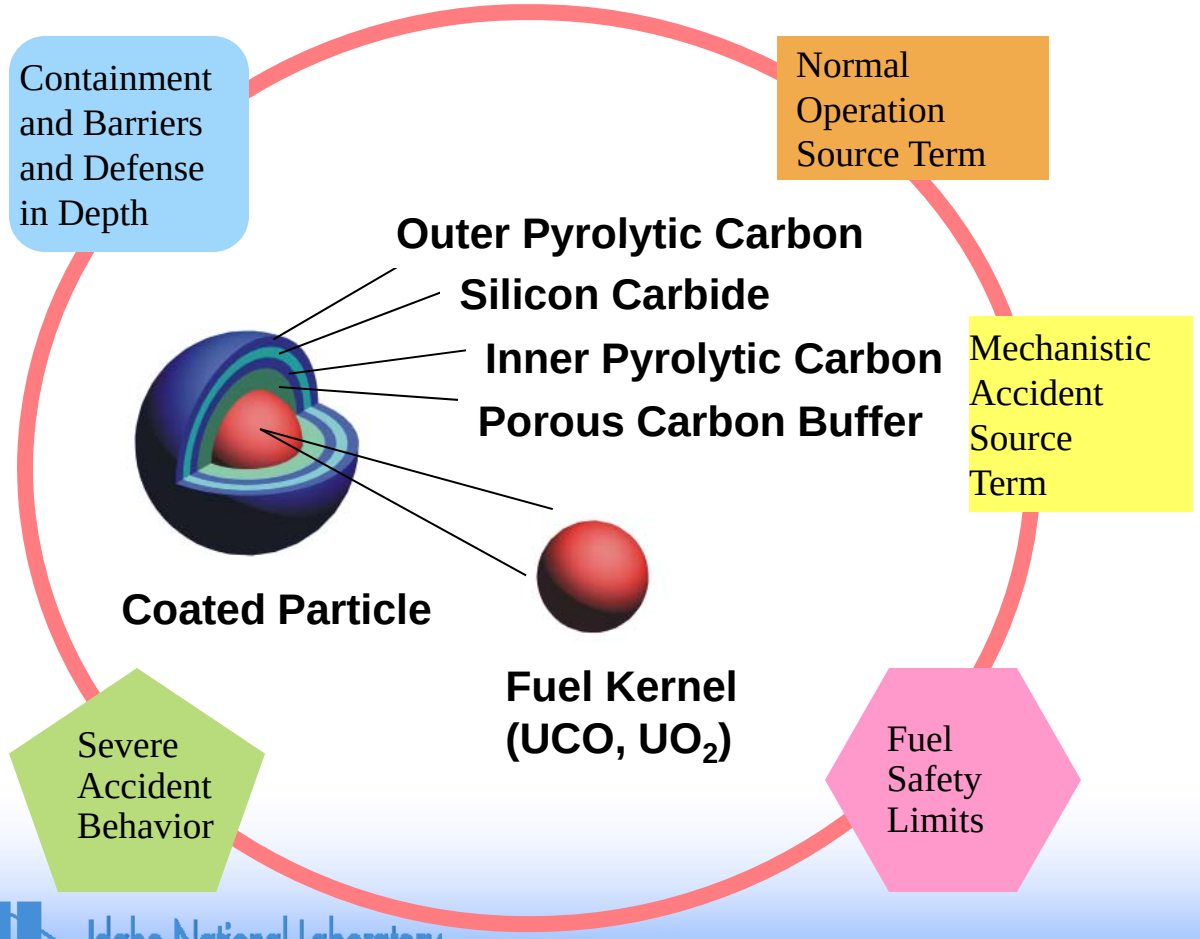
Proposed Partnership Organization



NGNP Technology Development Addresses Technical Risks

- Qualification and Fabrication of
  - Fuel
  - Graphite (Fuel and Structural)
  - Metals (Ductwork, IHX, Vessel)
- Design and Safety Methods and Validation
- Instrumentation Development and Qualification
- Hydrogen Production Process Development

Coated Particle Fuel Qualification Identified as Key Technology Need



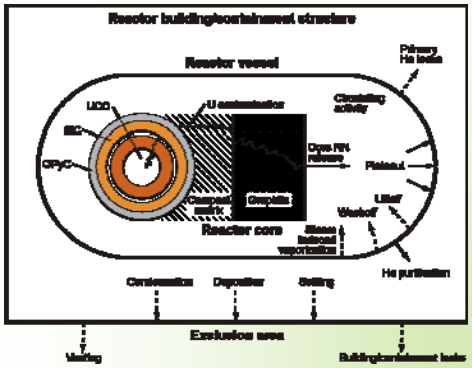
PARTICLES

COMPACTS

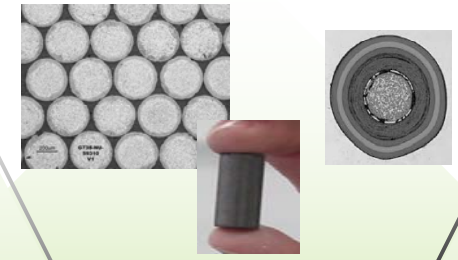
FUEL ELEMENTS

Photos and figures courtesy of GA

Program Elements Address Fuel Technology Needs



Fission Product Transport & Source Term

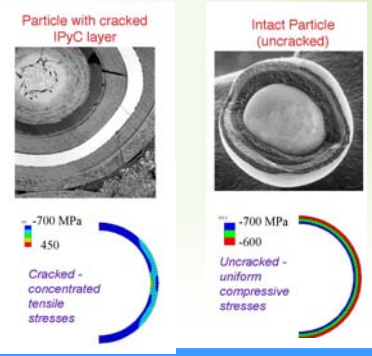


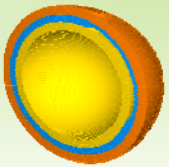
Fuel Supply

Fuel and Materials Irradiation

- **Coated Particle Fuel Fabrication**
- **Fuel Qualification**
- **Analysis Methods Development & Validation**

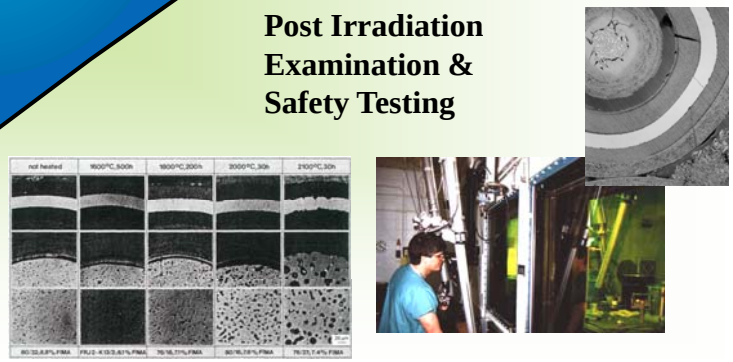
Fuel Performance Modeling



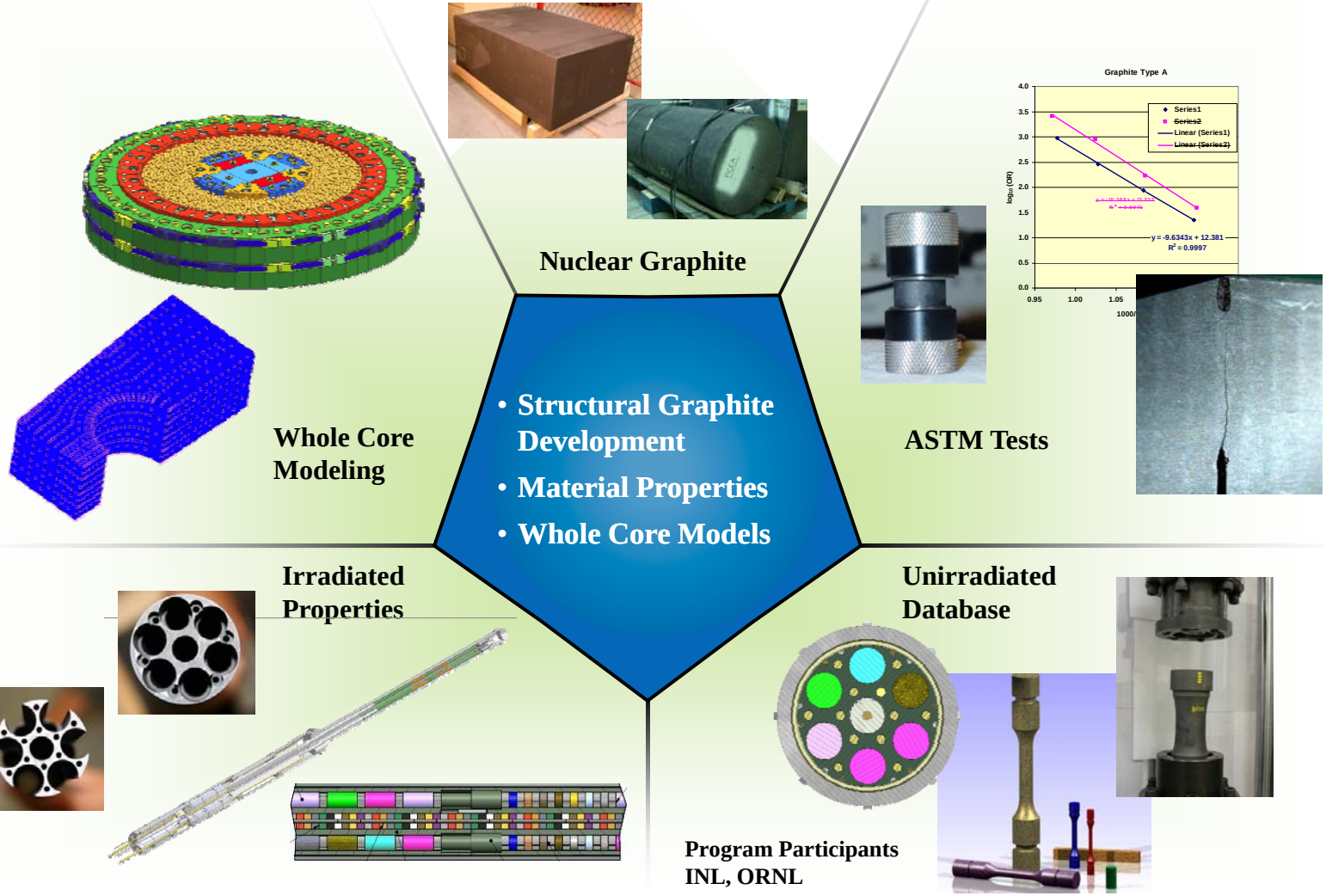


Program Participants
INL, ORNL, BWXT, GA

Post Irradiation Examination & Safety Testing



Program Elements Address Graphite Technology Needs



High Temperature Qualification Data Needed for IHX Alloy

Development of Material Properties, Design Rules,

and

ASME Codification

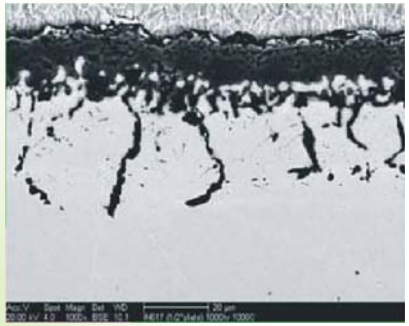
Materials:

- **Pressure vessel steels**
- **Alloys for heat exchangers (up to 800°C)**
- **Control rod sleeves and other core internals**

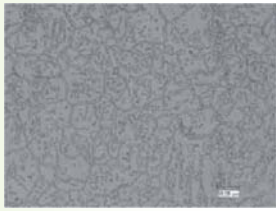
Ni from Watts bath plating

Cr Oxide surface layer

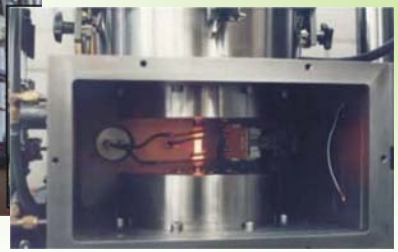
Al Oxide intergrowth



Material Characterization



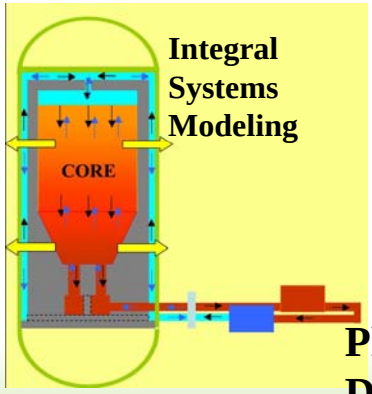
Mechanical Testing



Environmental Testing

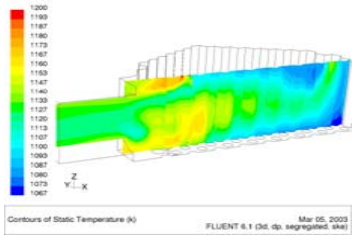
Program Participants INL, ORNL

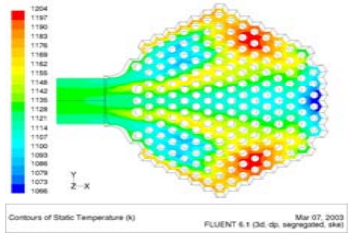
NGNP Methods Program Elements



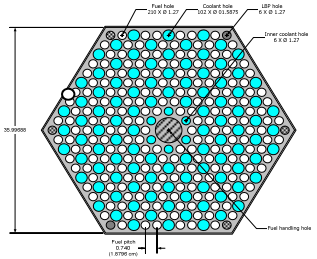
Integral Systems Modeling

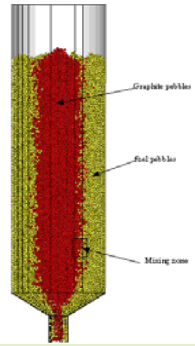
Multi-dimensional CFD Simulations





Pebble and Prismatic Physics Methods





Physics, Thermal and System Safety Methods & Code Development and Application

Design and Safety Analysis Methods Development & Validation

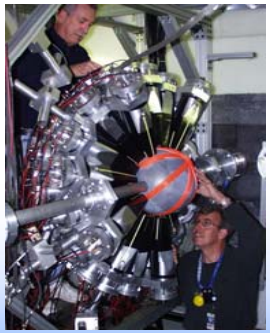
Separate Effects & Integral Testing Under Normal & Off-Normal Conditions

Scaled Vessel Testing

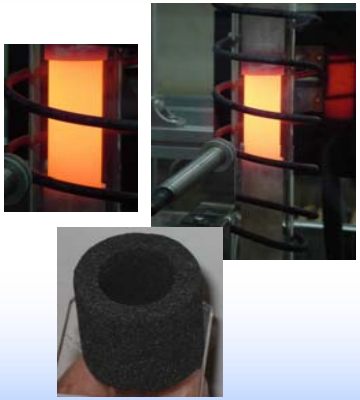
ANL Facility to Validate VHTR Reactor Cavity Cooling System Behavior

INL's Matched Index of Refraction (MIR) Facility to Study 3-D Flow Effects in Plena

Cross-section Measurements at LANL



Program Participants LANL, ANL, INL



Graphite/Air Reaction Rate Testing

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Summary

- **Prior experience demonstrates HTGR technology offers unique safety and economic benefits.**
  - **High efficiency power production**
  - **High temperatures for process heat and hydrogen production**
  - **Inherent safety**
- **The U.S. NGNP Project defined to:**
  - **Develop and implement technologies important to achieving design and performance requirements through collaboration with commercial end-users**
  - **Demonstrate basis for commercialization of nuclear system, hydrogen production facility and power conversion concepts**
  - **Establish basis for licensing commercial version of NGNP by NRC by licensing prototype**
- **R&D focused to address technical risks identified in industry / regulatory / laboratory interactions**

End-users are Defining the HTGR Commercial Concept

Energy Delivery

- **Co-generation of process steam and electricity of more immediate interest**
- **Intermediate Nuclear System outlet temperature (~750°C) may suffice**
- **Hydrogen (and oxygen) production – of interest in selected applications – potentially drives higher Nuclear System outlet temperature requirement**

Business Model – nuclear owner/operator in long term business relationship with end-user

Schedule – 2021 operational date for NGNP demonstration at far end of acceptable schedule