HTGR Technology Course for the Nuclear Regulatory Commission

May 24 – 27, 2010

Module 2a

History and Evolution of the HTGR

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General Atomics

Outline

- Evolution of HTGR designs including licensing and operational experience
- Overview of current HTGR design concepts
- NGNP Project

HTGR Acronyms

HTGR – High-Temperature Gas-Cooled Reactor
HTR – High-Temperature Reactor

PB: Peach Bottom
FSV: Fort St. Vrain
MHTGR: Modular HTGR
NP-MHTGR: New Production MHTGR
GT-MHR: Gas-Turbine Modular Helium Reactor
HTTR: High Temperature Engineering Test Reactor

AVR: Arbeitsgemeinschaft Versuchs Reactor
THTR: Thorium High Temperature Reactor
PBMR: Pebble Bed Modular Reactor
PBMR DPP: PBMR Demonstration Power Plant
PBMR-CG: PBMR Co-Generation Plant

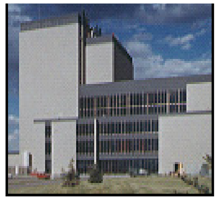
NGNP – Next Generation Nuclear Plant
VHTR – Very High Temperature Reactor

Gas-Cooled Reactors by Country

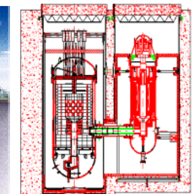
	CO_2	He
United Kingdom	41	1
France	8	--
Italy, Spain	1,1	--
USA	--	2
Germany	--	2
Japan	1	1
China	--	1
	52	7

Several Helium Cooled HTGRs Built World-Wide

Power Reactors | Research Reactors



	Peach Bottom 1 1966-1974	Fort St Vrain 1976-1989	THTR 1986-1989	Dragon 1966-1975	AVR 1967-1988	HTTR 2000-	HTR-10 2003-
Power Level: MW(t)	115	842	750	20	46	30	10
MW(e)	40	330	300	-	15		--
Coolant: Pressure, Mpa	2.5	4.8	4	2	1.1	4	3
Inlet Temp, °C	344°C	406°C	250°C	350°C	270°C	395°C	250°C/300°C
Outlet Temp, °C	750°C	785°C	750°C	750°C	950°C	850°C/950°C	700°C/900°C
Fuel type	$(U\text{-}Th)C_2$	$(U\text{-}Th)C_2$	$(U\text{-}Th)O_2$	$(U\text{-}Th)C_2$	$(U\text{-}Th)O_2$	$(U\text{-}Th)O_2$	$(U\text{-}Th)O_2$
Peak fuel temp, °C	~1000°C	1260°C	1350°C	~1000°C	1350°C	~1250°C	
Fuel form	Graphite compacts in hollow rods	Graphite Compacts in Hex blocks	Graphite Pebbles	Graphite Hex blocks	Graphite Pebbles	Graphite compacts in Hex blocks	Graphite Pebbles

Peach Bottom Experience (1966-1974)

- **Peach Bottom 1 - very successful - 40 MW(e)**
  - Demonstrated variety of nuclear industry performance records
  - Average gross efficiency - 37.2%
  - Availability - 85%
  - No steam generator tube failures
  - Operator doses less than 10 man-rem/year
  - Load following demonstrated
  - Post examination of materials performed

- **Lessons learned**
  - Fuel element and coated particle design improvements

AVR Experience (1967-1988)

- **AVR very successful - 15 MW(e)**
  - Prototype for pebble bed core and refueling
  - High availability over 21 years of operation to 1988
  - Core outlet temperature up to 950°C
  - On-line fuel irradiation test bed
  - Loss of cooling accident with ATWS demonstrated with passive shutdown via negative temperature coefficient
  - Very low maintenance doses
- **Lessons learned**
  - Coolant core bypass flows
  - Dust generation, behavior
  - Water ingress mitigation

Fort St. Vrain Experience (1976-1989)

- **Demonstrated excellent fuel performance, low operator doses, and core physics**
- **Demonstrated fuel handling / refueling approach**
- **Lessons learned**
  - Separation of safety and non-safety cooling systems
  - He circulator and seals leaked bearing water
  - Water cooling pump cavitation
  - Reserve shutdown malfunction
  - Hot helium bypass on control rod drives
  - Core thermal fluctuations
  - Core support floor - liner cooling system

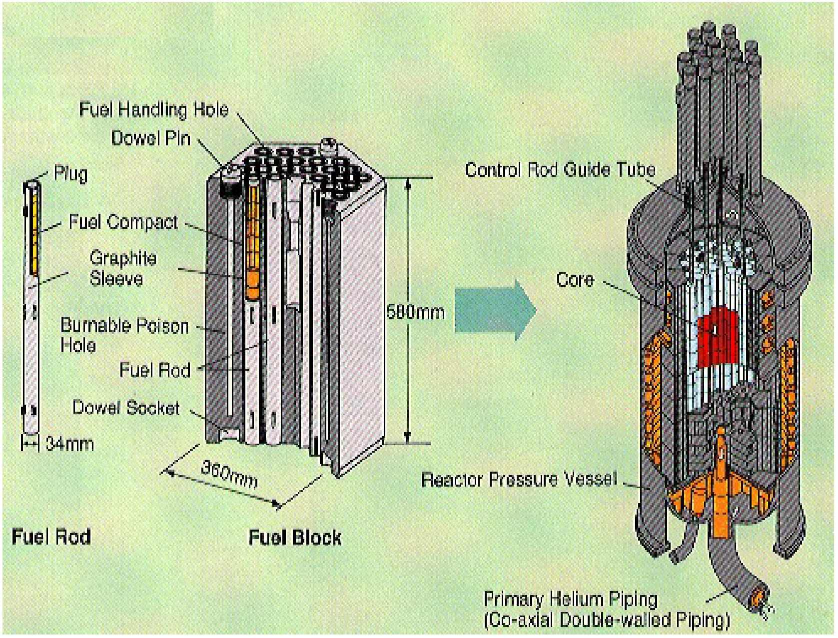
THTR Experience (1986-1989)

- **Commercial scale demonstration plant**
- **Co-located with coal fired plant – shared turbine hall**
- **Dry cooling**
- **Very low maintenance doses**

- **Lessons learned**
  - Costly licensing changes and delays - major redesign
  - In-core control rods and pebble breakage
  - Thermal barrier attachment failures

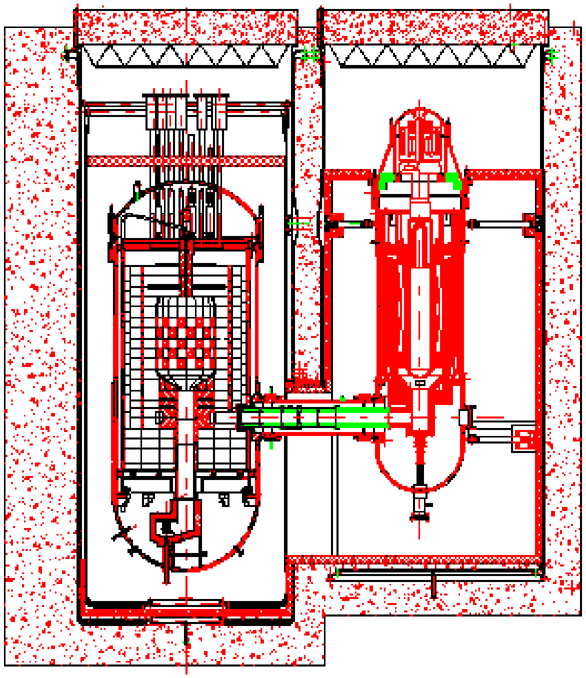
Two Research HTGRs Are Currently Operating in Asia

Prismatic-Block HTTR in Japan



HTTR reached outlet temperature of 950°C at 30 MW on April 19, 2004

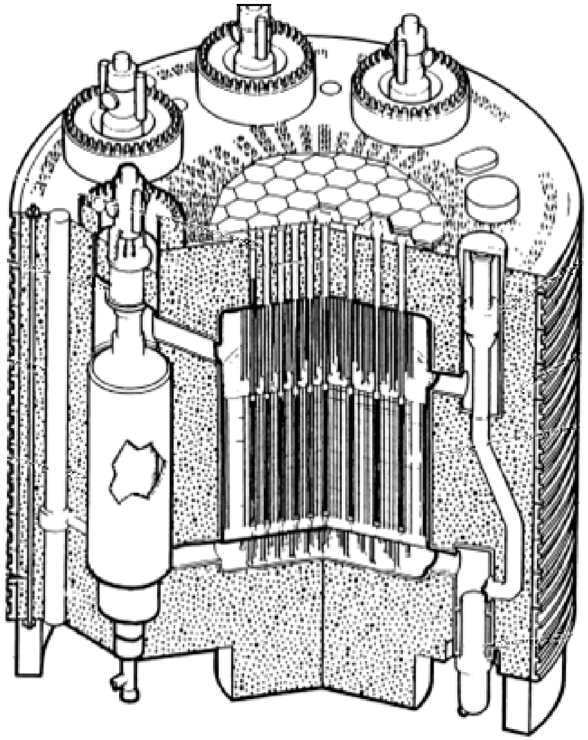
Pebble-Bed HTR-10 in China



Reached full power with 750°C outlet temperature in Jan 2003

Large HTGR Orders in the U.S. (1971 - 1974)

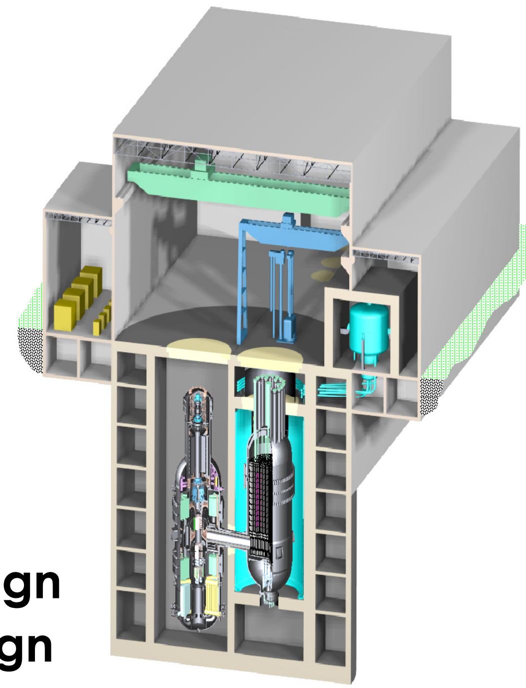
Utilities	Power Level (MWe)
Delmarva P&L	2 x 770
Philadelphia Electric	2 x 1160
Ohio Edison	2 x 1160
Louisiana P&L	2 x 1160
Southern Cal. Edison	1 x 1300



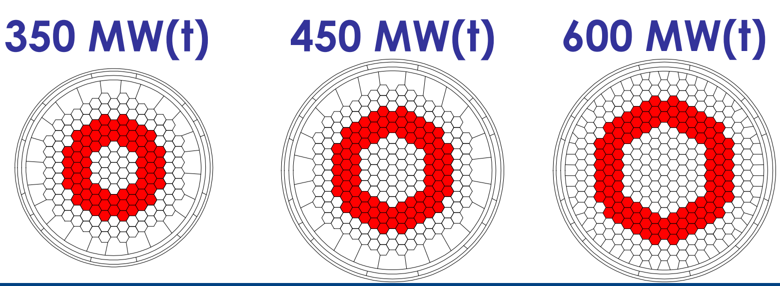
Oil embargo and economic downturn resulted in order cancellation (HTGRs and LWRs)

Transition to Prismatic Modular HTGR

- 1984 DOE Modular HTGR program begins
- 1985 350 MW(t) Prismatic MHTGR steam cycle
- 1986 MHTGR PSID submitted
- 1988 DOE selects MHTGR as NPR design
- 1990 450 MW(t) MHTGR steam cycle
- 1992 Pu consumption MHR study
- 1993 GT-MHR chosen as reference design
- 1994 600 MW(t) power level selection
- 2001 Completion of Russian GT-MHR conceptual design
- 2003 Completion of Russian GT-MHR preliminary design
- 2005 Energy Policy Act establishes NGNP Project



GT-MHR



Transition to Pebble Bed Modular HTGR

Major Projects	Power (MWt)	Status
HTR 100 (Germany)	250	Preliminary Design
HTR Modul (Germany)	200	Preliminary Design
PBMR DPP (South Africa)	400	Preliminary Design
HTR-10 (China)	10	Operating
HTR-PM (China)	250	Construction Underway
PBMR-CG (South Africa)	250	Conceptual Design Underway

U.S. HTGR Licensing Experience

Project	MW(e)	Status
Peach Bottom 1	40	Lic/Built/Decom.
Fort St. Vrain	330	Lic/Built/Decom.
Summit 1 & 2	770 ea.	Limited Work Auth
Fulton 1 & 2	1160 ea.	Const Appl Sub
GASSAR	1160	Submitted
MHTGR	4x133	PSID - Draft PSER
PBMR DPP	165	Pre-app Review
NGNP	Generic	Ongoing pre-licensing review

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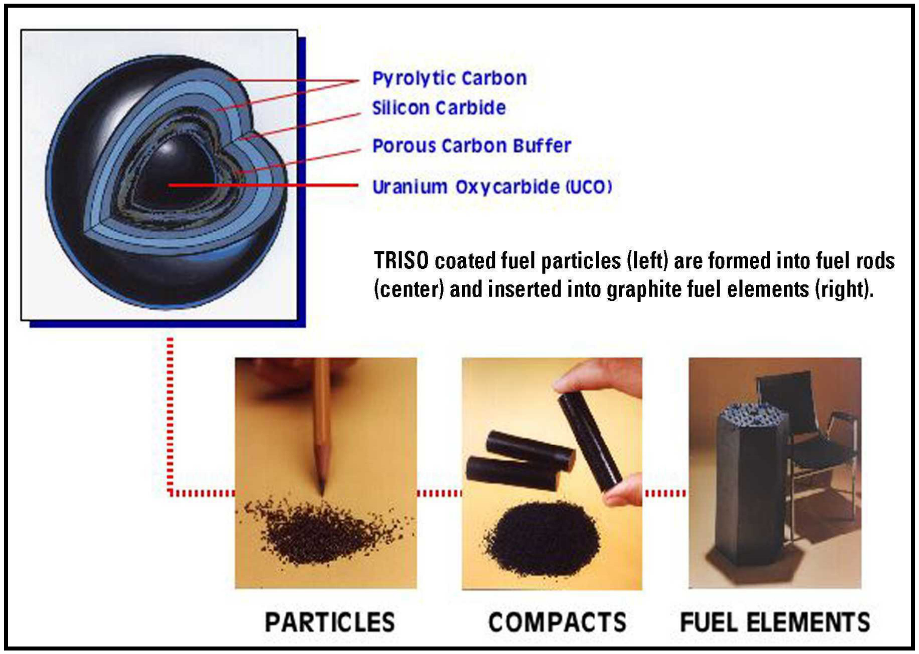
HTGR / LWR Comparison

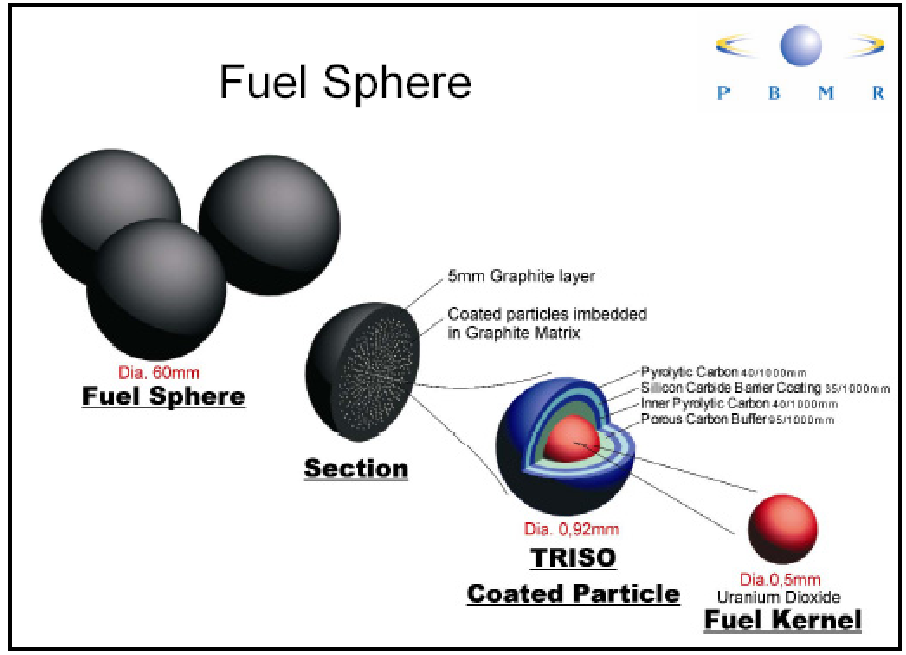
Item	HTGR	LWR
Moderator	Graphite	Water
Coolant	Helium	Water
Avg coolant exit temp.	700-950°C	310°C
Structural material	Graphite	Steel
Fuel clad	SiC & PyC	Zircaloy
Fuel	UO_2,UCO	UO_2
Fuel damage temperature	>1800°C	1260°C
Power density, W/cm^3	4 to 6.5	58 - 105
Linear heat rate, kW/ft	1.6	19
Migration length, cm	57	6

TRISO Coated Particle Fuel Common to Prismatic and Pebble Bed HTGRs

Prismatic Fuel



Pebble Bed Fuel

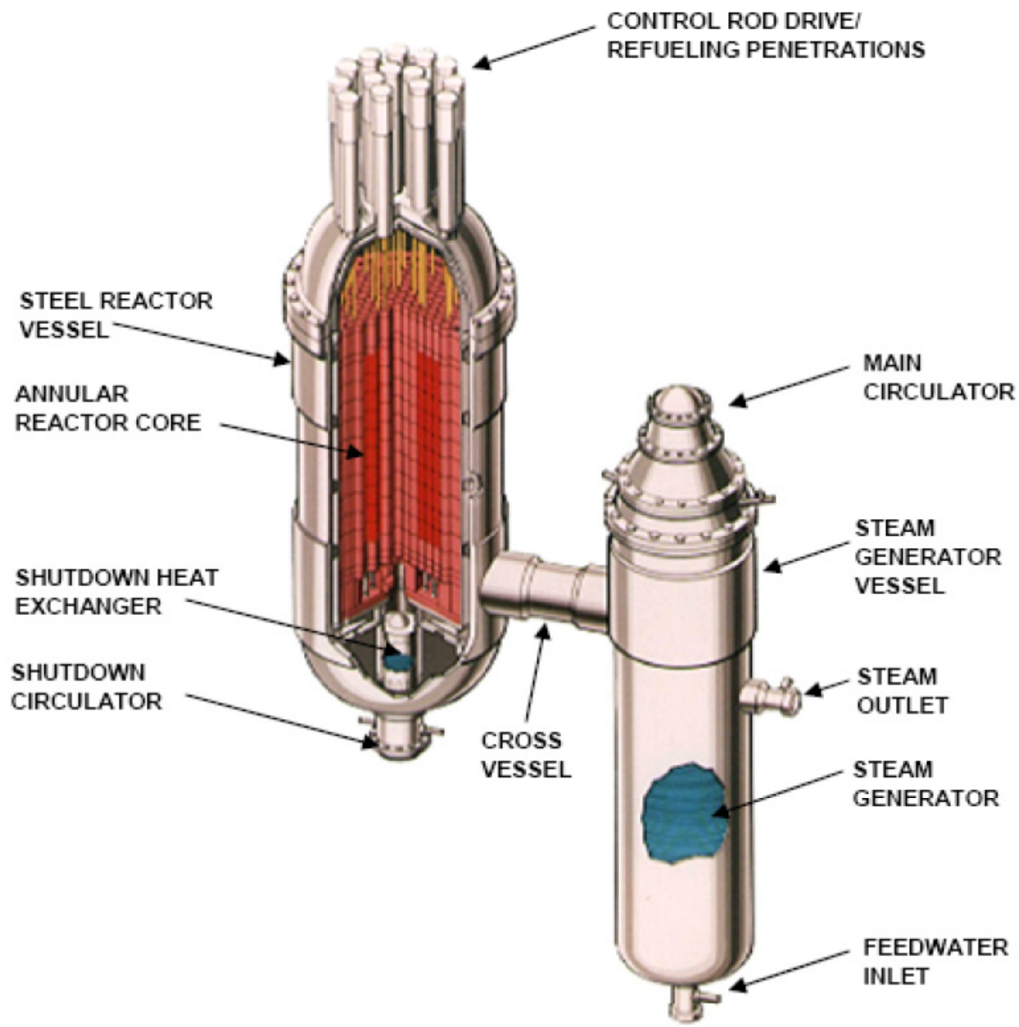


Prismatic and Pebble Bed Designs Share Generic Base of Components/Systems and Infrastructure

- Graphite core structures
- Steel reactor pressure vessels
- Steam generators
- He circulators
- He purification system
- Control rods and drives
- Intermediate heat exchanger
- Licensing framework and approach
- Industry codes

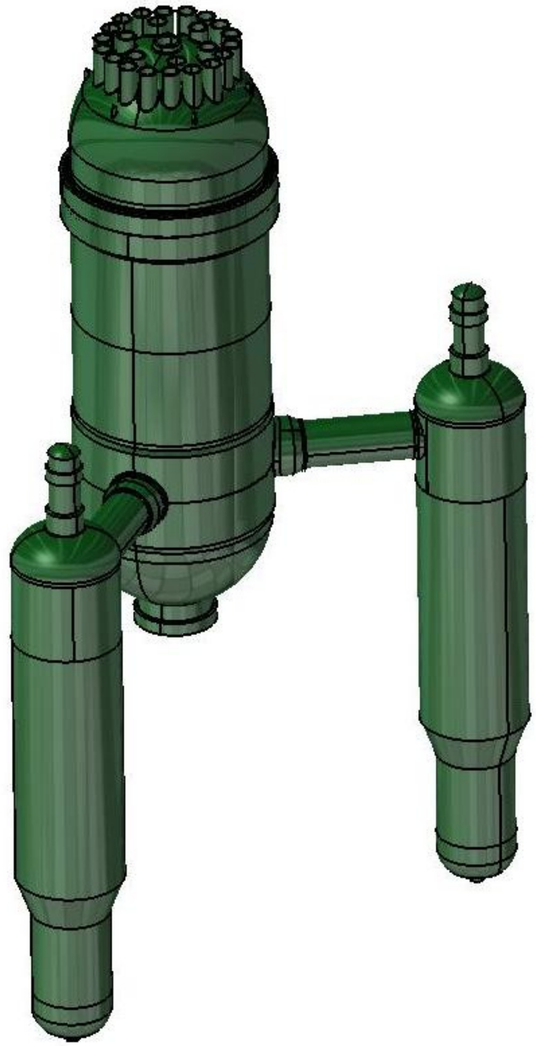
Major Features of GA Prismatic HTGR Design

- **Modular Nuclear Heat Supply System (NHSS)**
  - 350 MWt annular core
  - TRISO coated particle fuel
  - Helium cooled
  - Graphite moderated
  - 750°C core outlet temp
  - 540°C/17.3 MPa steam heat
- **NHSS contained in 2 steel vessels, RV and SGV, interconnected by a cross vessel**



AREVA Prismatic HTGR Design Concept

- **Simple HTGR heat source**
- **Delivers steam at 550 C for variety of applications**
  - **Electricity**
  - **Process heat**
  - **Cogeneration**



Current parameters:

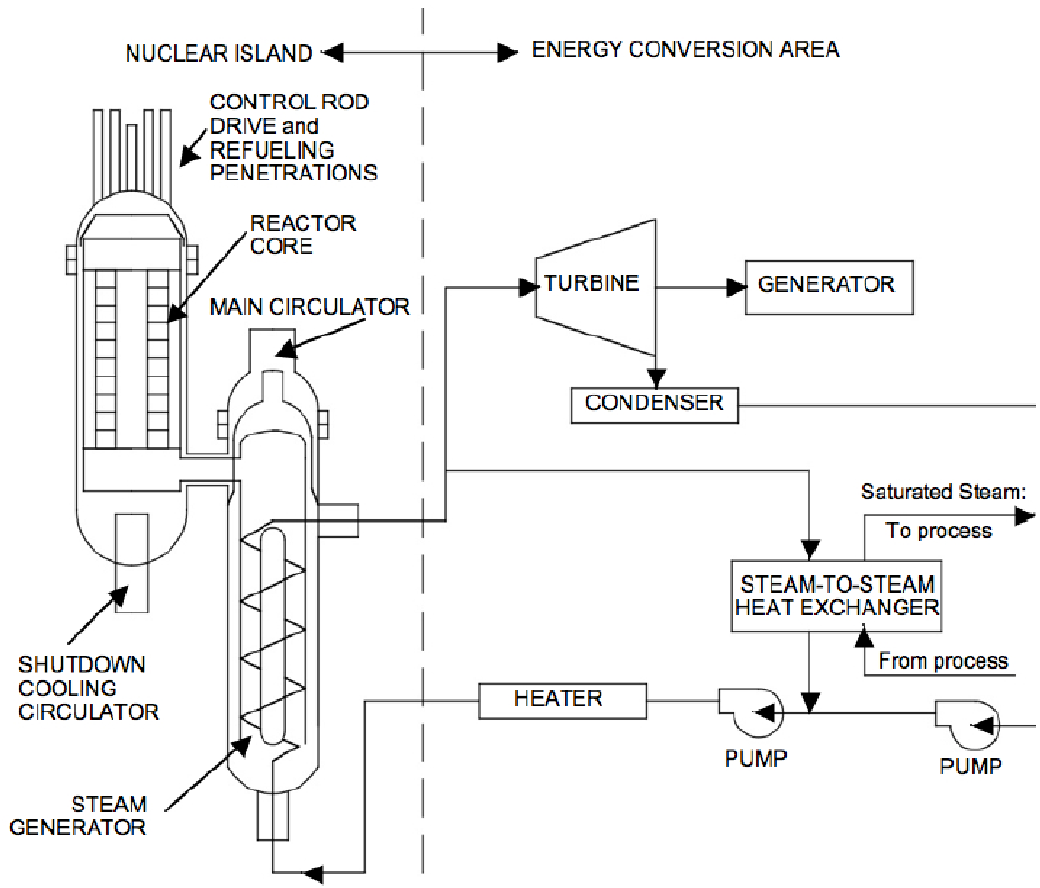
Reactor 625 MWt

SGs – 2 x 315 MWt

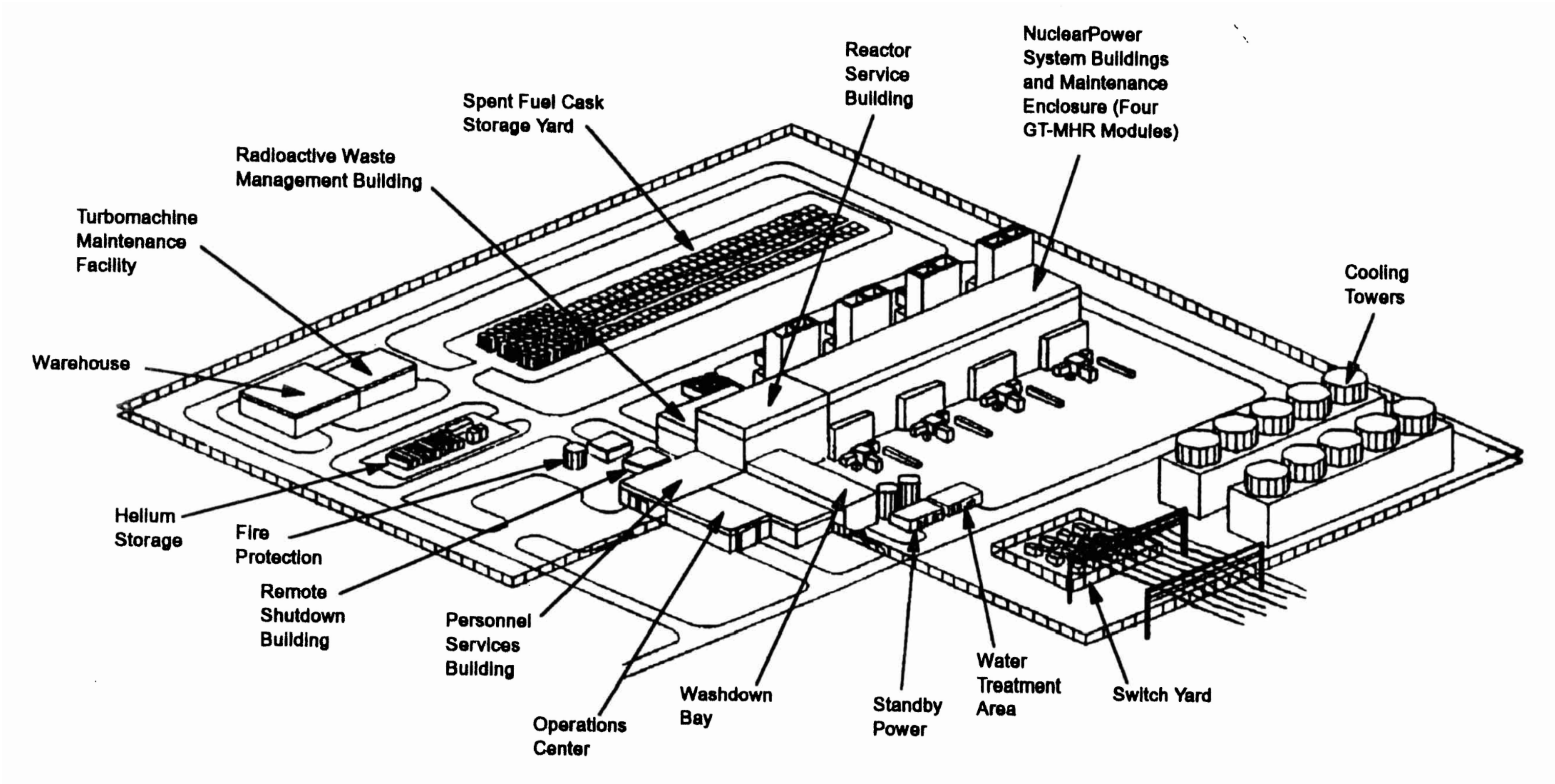
Circulators – 2 x 4.0 MWe

Co-Generation of Electricity and Process Steam from NHSS

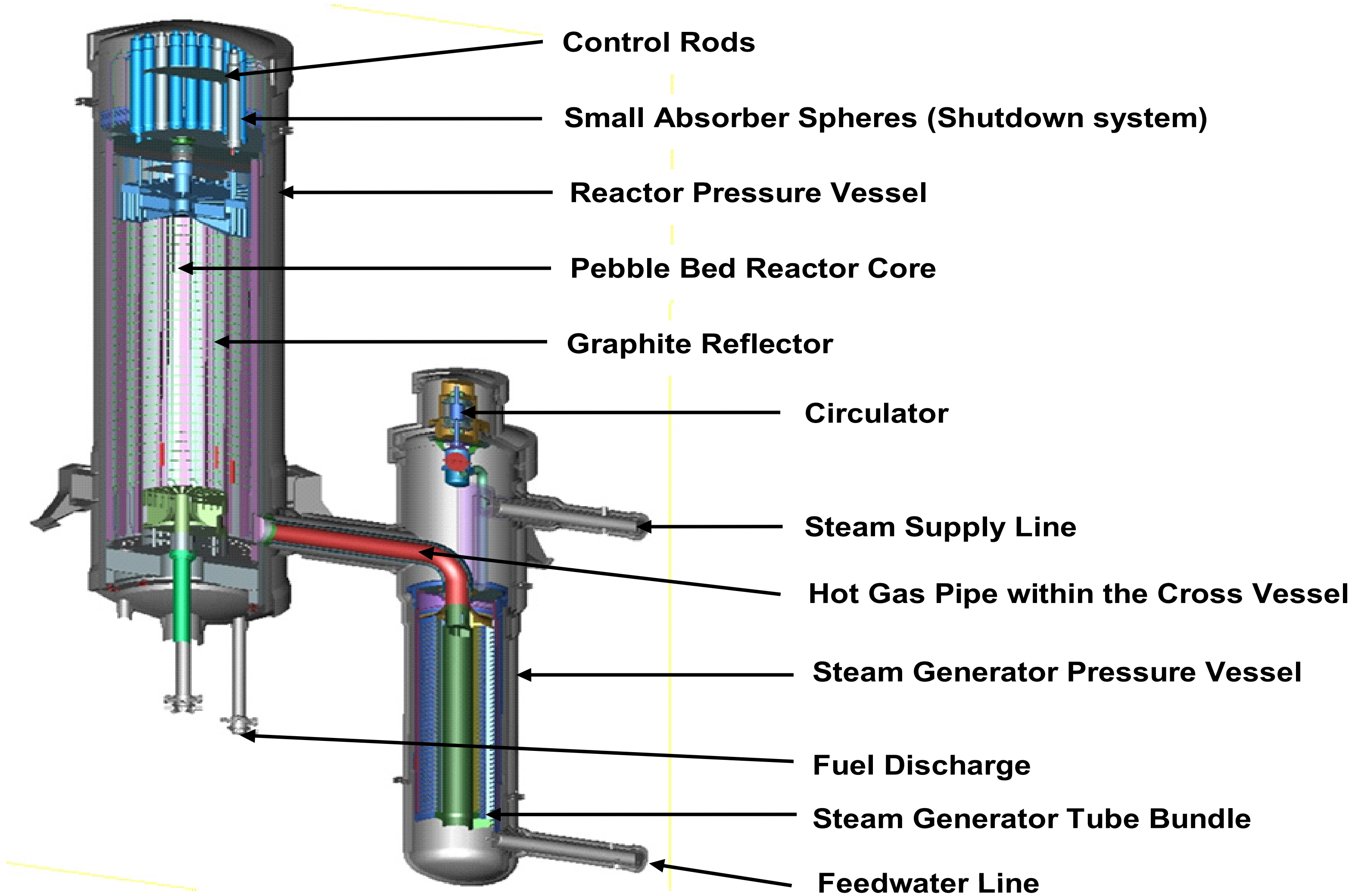
- **Electricity/steam split not yet selected**
- **Process steam produced in tertiary steam-to-steam HX:**
  - Provides additional barrier against Tritium migration to process system
  - Protects against contamination of secondary system water by process
  - Secondary steam source could be main steam line (shown) or turbine extraction steam



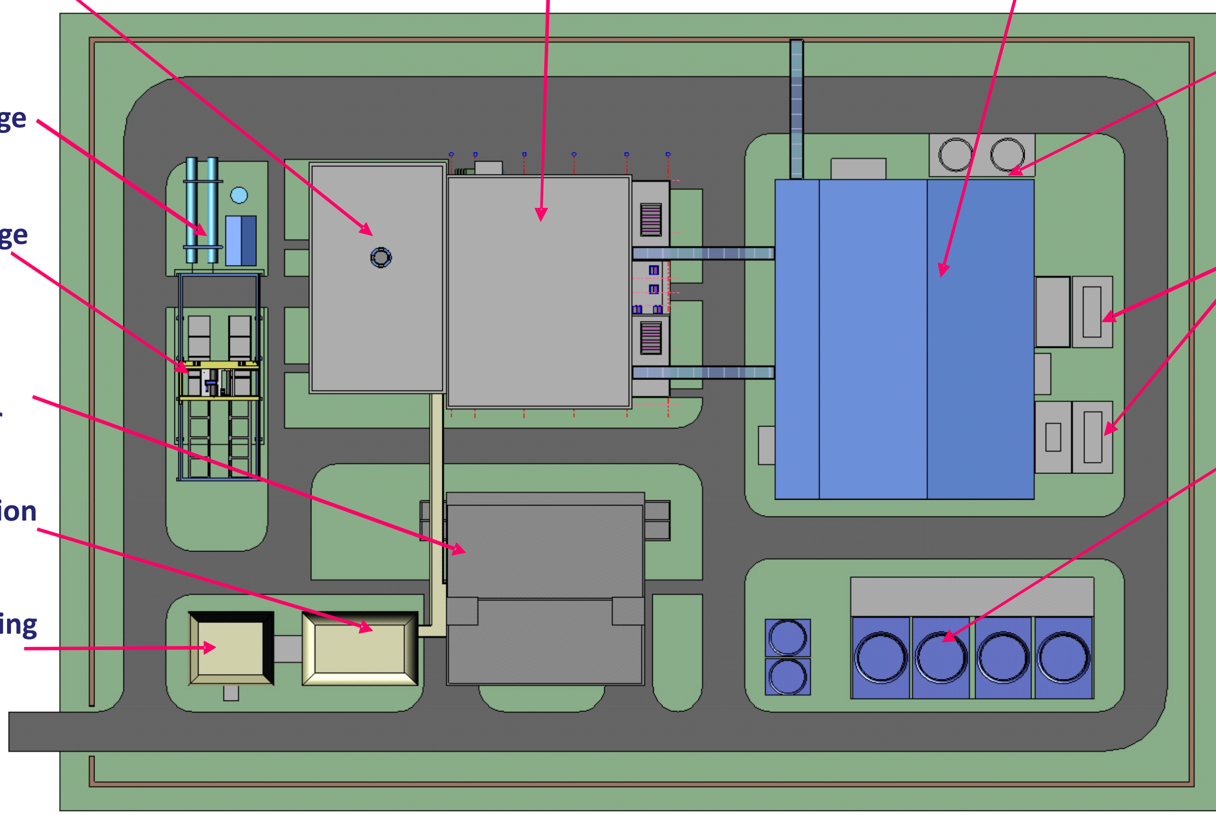
Four Modules Comprise Standard MHTGR Plant



Pebble Bed Steam Cycle HTR Module



PBMR Electrical Plant Plan View - Standard NI for Range of Target Applications



Nuclear Island ⟺ Conventional Island

Outline

- Evolution of HTGR designs including licensing and operational experience
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Overview of NGNP Project

- Energy Policy Act of 2005 established Next Generation Nuclear Plant project to build demonstration of HTGR technology by 2021
- Pre-Conceptual Designs by three vendor teams completed in 2007
- Funding Opportunity Announcement (FOA) issued Sept 18, 2009 for Phase 1 NGNP conceptual design, cost and schedule estimates, and business plan preparation
- FOA awardees announced March 8, 2010

NGNP Project Pre-Conceptual Design Studies

- **Refined operating point and initial application**
- **Concluded pre-conceptual designs for different reactor types**
- **Established target project plan and schedule**
- **Began pre-licensing engagement with NRC per DOE-NRC agreed strategy**
- **Conducted studies in support of R&D plan alignment with technical and regulatory needs**

NGNP Project – Phase 1

- **Phase I scope completion projected for early 2011**
  - Conceptual design
  - Advance pre-licensing program with the NRC
  - Cost and schedule estimates
  - Business Plan development
  - Nuclear Energy Advisory Committee review and recommendations re Phase II
- **Alignment with NGNP technology development programs**
  - Fuel and graphite testing and qualification
  - Testing to support design code validation
  - Enhancing technology for higher temperature applications
- **Continue Project development through NGNP Alliance - owner, operator, end-user interactions**

Summary

- HTGR technology has an extensive base of design, licensing and operating experience with valuable lessons learned
- Prismatic and pebble bed systems share large common base of technology, systems and components
- Current NGNP design concepts build on previous design, licensing and operational experience

Suggested Reading

- Moore, R. A. et al., “HTGR Experience, Programs, and Future Applications,” Nucl. Eng. Des., 72, 153, 1982.
- “High Temperature Gas Cooled Reactor Technology Development,” IAEA-TECDOC-988, November 1996.
- “Current Status and Future Development of Modular High Temperature Gas Cooled Reactor Technology,” IAEA-TECDOC-1198, February 2001.
- “Next Generation Nuclear Plant Pre-Conceptual Design Report,” INL-EXT-07-12967, September 2007.