GEN IV International Forum

VERY HIGH TEMPERATURE REACTORS

Carl Sink

U.S. Department of Energy, Office of Nuclear Energy

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MEET THE PRESENTER

Carl Sink has been working for the U.S. Department of Energy (DOE) for 24 years in various roles. He is currently a Program Manager for Advanced Reactor Deployment within the Office of Nuclear Energy, and is responsible for coordinating cooperative research, development and demonstration projects conducted by DOE national laboratories and U.S. nuclear industry partners. Since 2004 he has been closely associated with the Next Generation Nuclear Plant Project, the DOE initiative to develop and demonstrate a high temperature gas-cooled reactor (HTGR). From 2006 through 2009 he was the program manager for the Nuclear Hydrogen Initiative, coordinating DOE efforts to develop high temperature water-splitting technologies to take advantage of HTGR outlet temperatures.

Within GIF, Mr. Sink has served on the VHTR System Steering Committee since 2008, and currently chairs that group. He previously served on and chaired the GIF VHTR Hydrogen Production Project Management Board.

Mr. Sink holds a Masters Degree in Engineering Management from the Catholic University of America, and is a graduate of the United States Naval Academy with a degree in Electrical Engineering. Before joining the Department of Energy in 1992, Mr. Sink spent nine years as a qualified Nuclear Engineering Officer in the United States Navy, with reactor operations assignments in a nuclear powered cruiser and a nuclear powered aircraft carrier.

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OUTLINE

Description and History of HTGRs

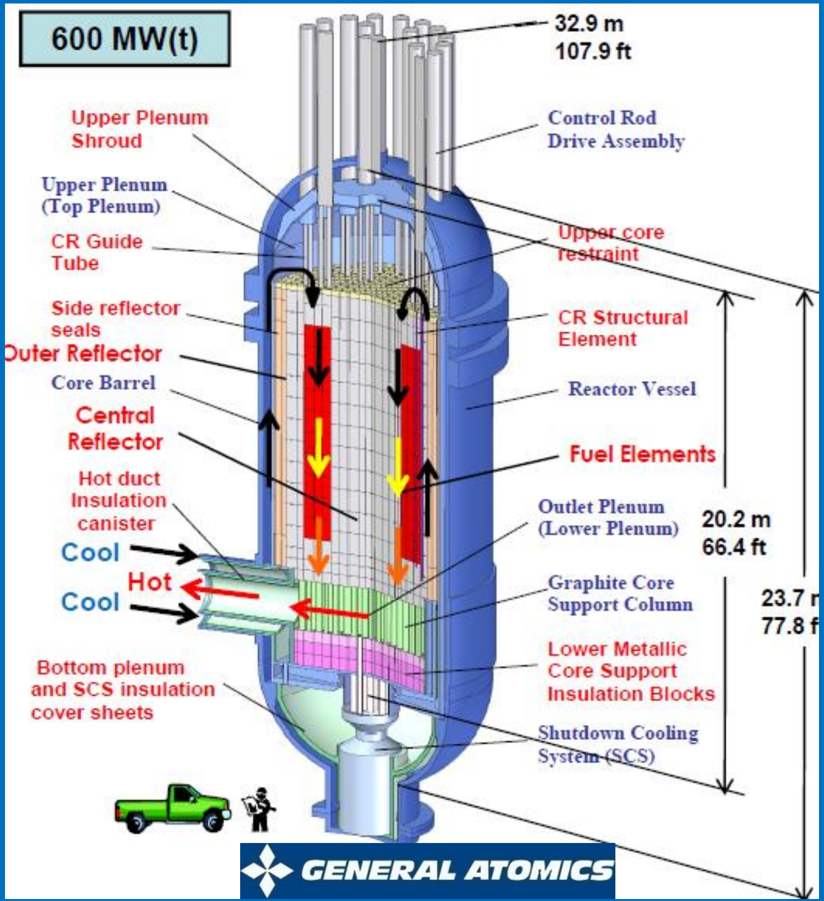
HTGR Safety Design Approach

HTGRs for Cogeneration and Process Heat

WHY HTGRS ?

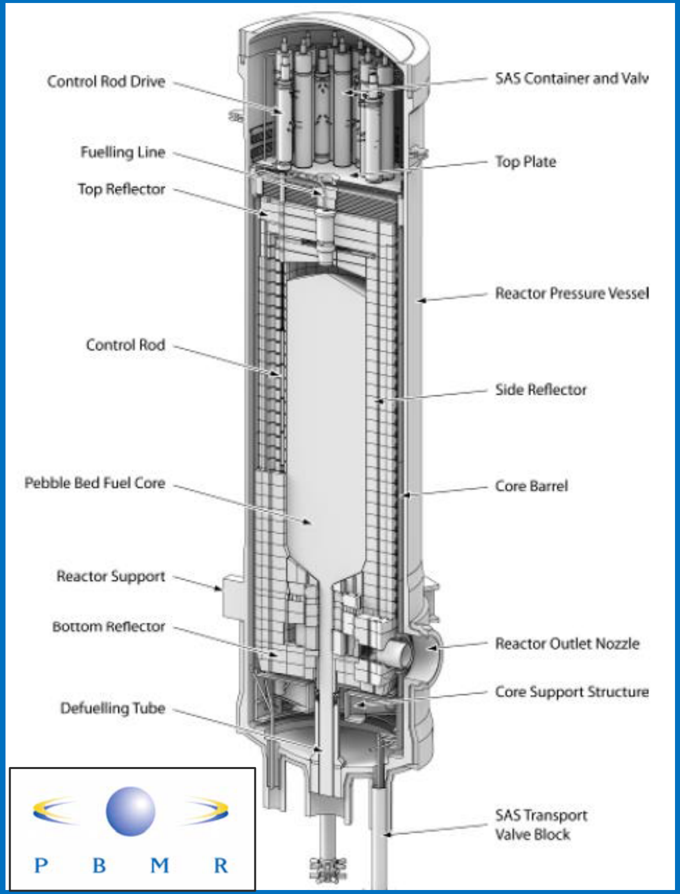
- **Inherent safety characteristics**
  - Ceramic fuel particles – won't melt
  - Graphite core – stable moderator and thermal buffer
  - Helium coolant – inert gas does not interact with fuel, graphite or structural metals
- **Diverse industrial applications in addition to electricity**
  - High efficiency power conversion capability: modern Rankine cycle (Eff ~40%) to advanced closed cycle Brayton (efficiency up to ~47%)
  - High temperature process steam and process heat capability offer cogeneration opportunities now; very high temperatures in future
- **Proliferation resistant, high burnup fuel cycle with growth potential for advanced fuels and cycles (e.g. Plutonium, Thorium), including deep burn cycles with LWR spent fuel**

HTGR DESIGN VARIANTS



Prismatic Block Design

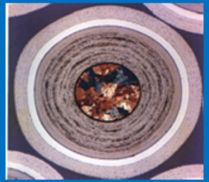
- **Other Design Options:**
  - Power output
  - Rankine or Brayton cycle energy conversion
  - Direct or indirect heat transfer (use of intermediate heat exchanger (IHX))

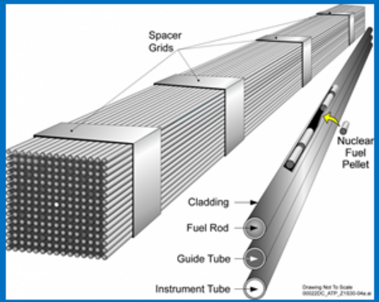


Pebble Bed Design

HTGR / LWR COMPARISON

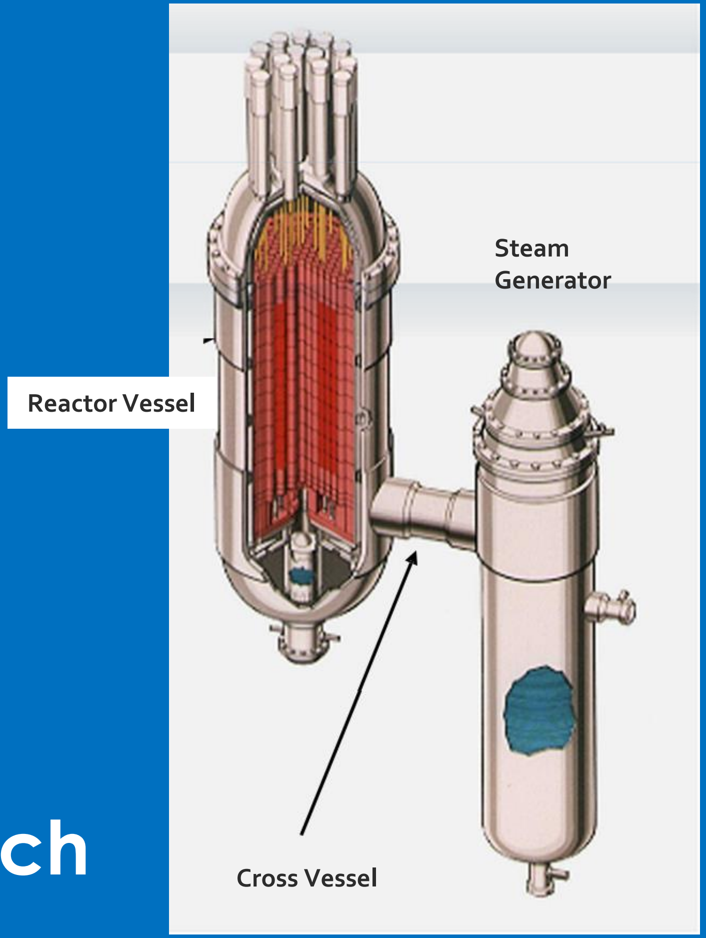
Item	HTGR	LWR
Moderator	Graphite	Water
Coolant	Helium	Water
Avg coolant exit temp.	700-950°C	310°C
Structural material	Graphite	Steel
Fuel clad	SiC & PyC	Zircaloy
Fuel	UO_2,UCO	UO_2
Fuel damage temperature	1600-1800C (design dependent)	1260°C (due to Zircaloy clad properties)
Power density, W/cm^3	4 to 6.5	58 - 105
Linear heat rate, kW/ft	1.6	19
Neutron migration length	57 cm	6 cm





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



SEVERAL HELIUM COOLED HTGRS BUILT WORLD-WIDE

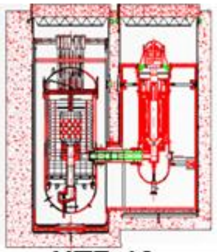
GEN IV International Forum℠

Power Reactors | Research Reactors





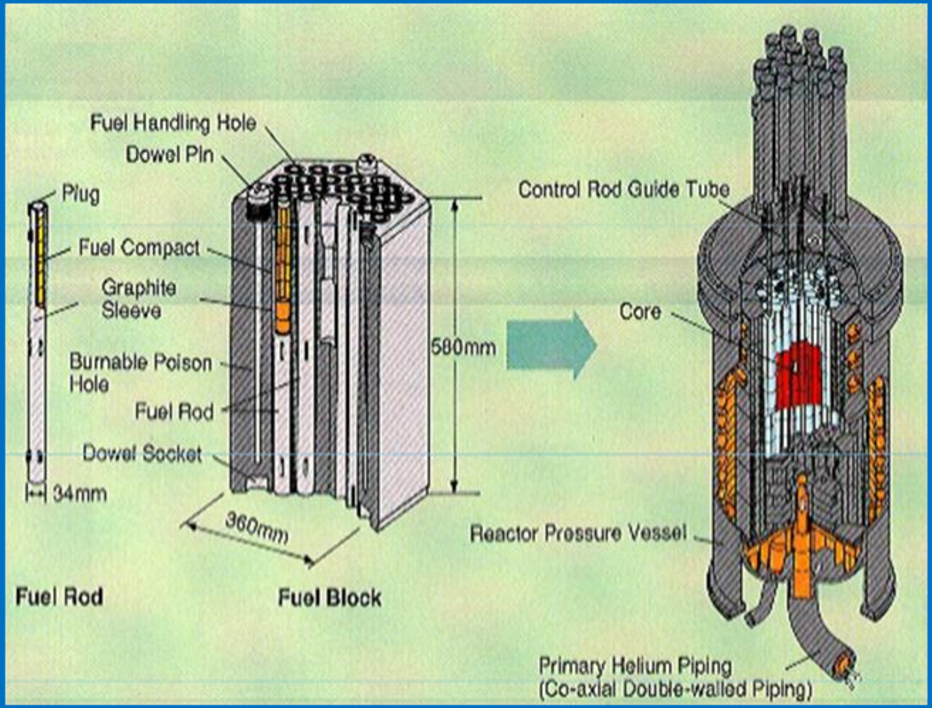




	Power Reactors			Research Reactors			
	Peach Bottom 1 1966-1974	Fort St Vrain 1976-1989	THTR 1986-1989	Dragon 1966-1975	AVR 1967-1988	HTTR 2000-	HTR-10 2003-
Power Level: MW(t)	115	842	750	20	46	30	10
MW(e)	40	330	300	-	15		--
Coolant: Pressure, Mpa	2.5	4.8	4	2	1.1	4	3
Inlet Temp, °C	344°C	406°C	250°C	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

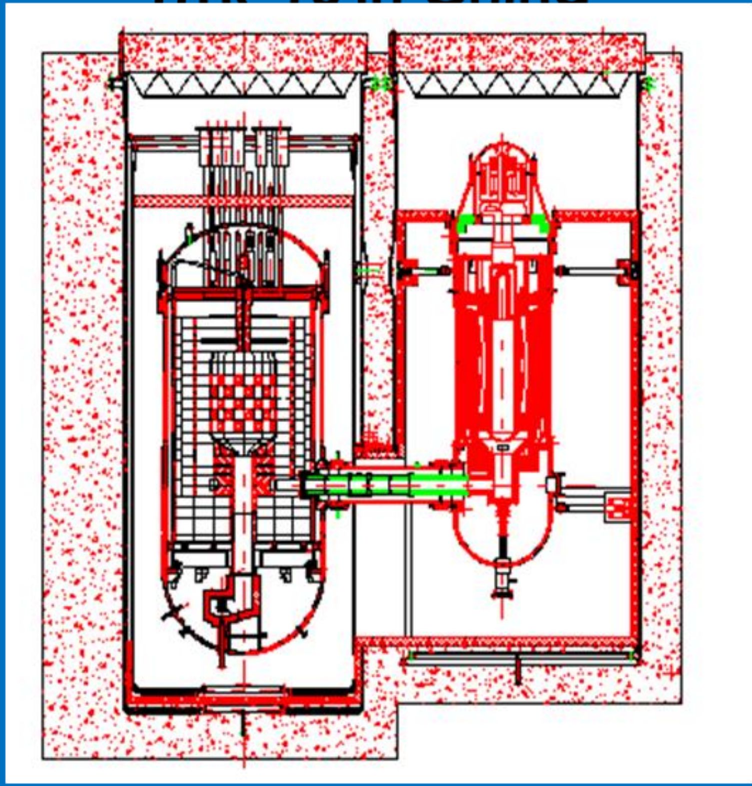
TWO RESEARCH HTGRS IN ASIA

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



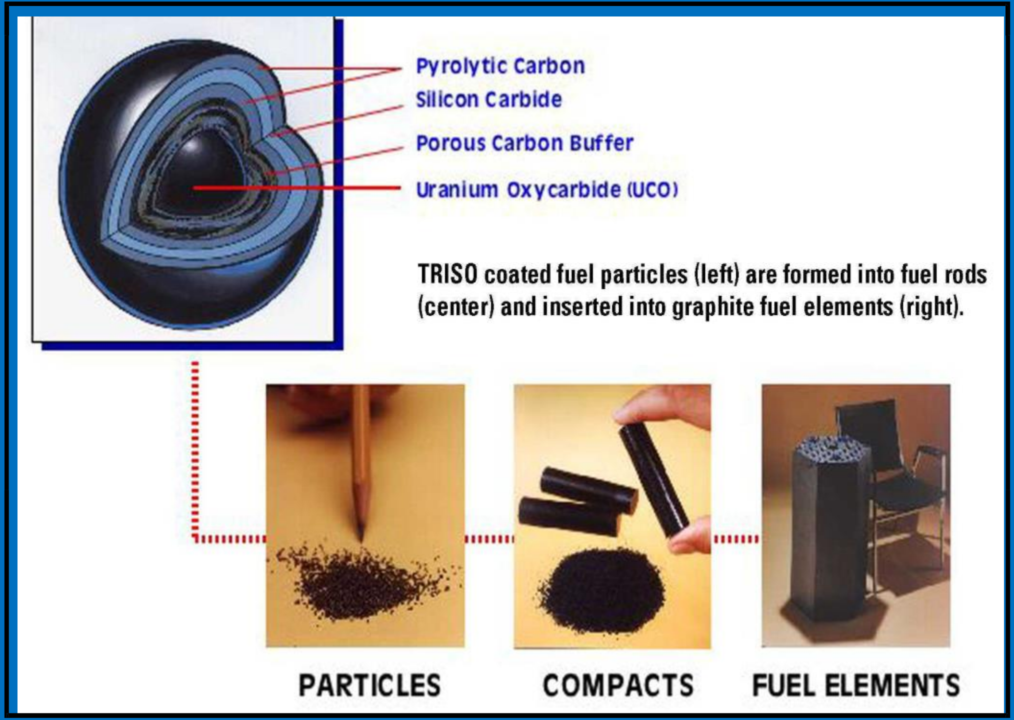
Reached full power with 750°C outlet temperature in Jan 2003

HTGR FUEL TYPES

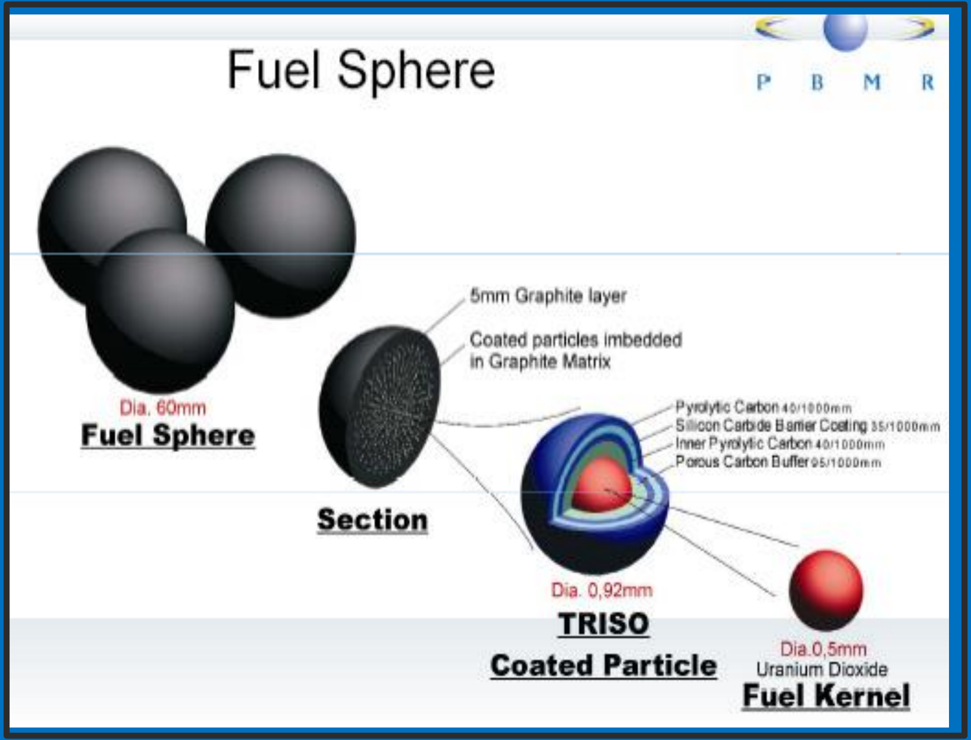
- **HTGRs can use many fuel types**
  - Fissile: UC_2, PuO_x, UO_2, UCO
  - Fertile: ThC_2, ThO_2
- **UO_2 has been the most widely used fuel type**
  - Used in AVR (Germany), HTTR (Japan), HTR-10 (China)
  - Extensive irradiation and heating test data base from German HTGR Program
  - Reference fuel type for PBMR, HTR-PM
- **UCO offers improved fuel performance at higher fuel burnup**

TRISO COATED-PARTICLE FUEL

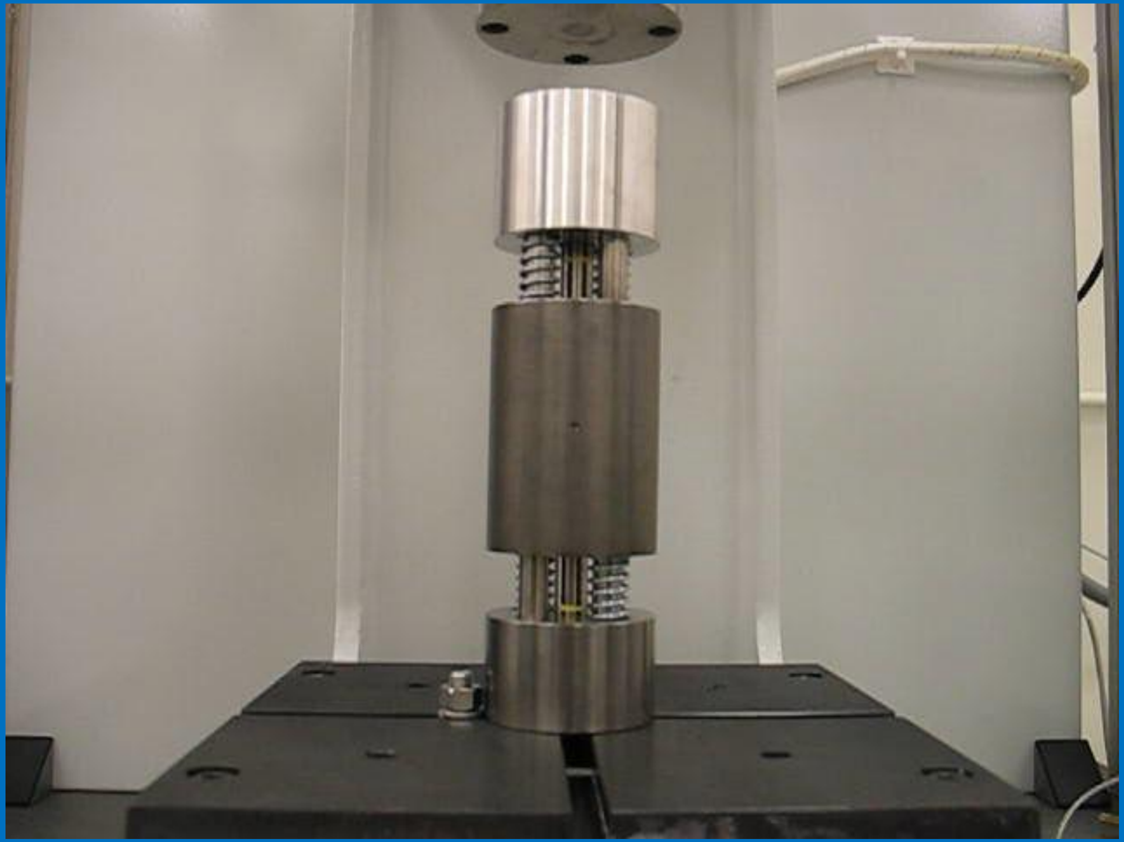
Prismatic Fuel

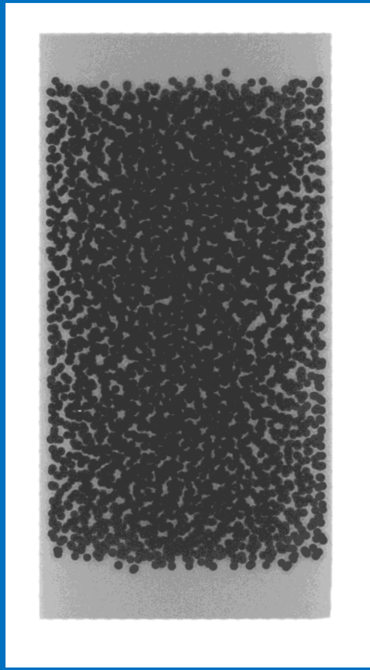


Pebble Bed Fuel

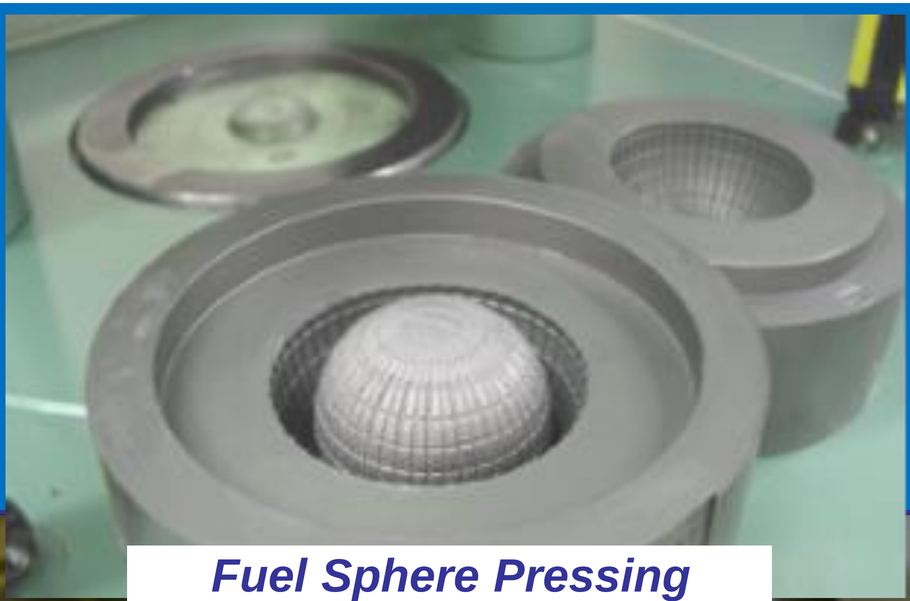


COMPACTING CYLINDRICAL FUEL ELEMENTS



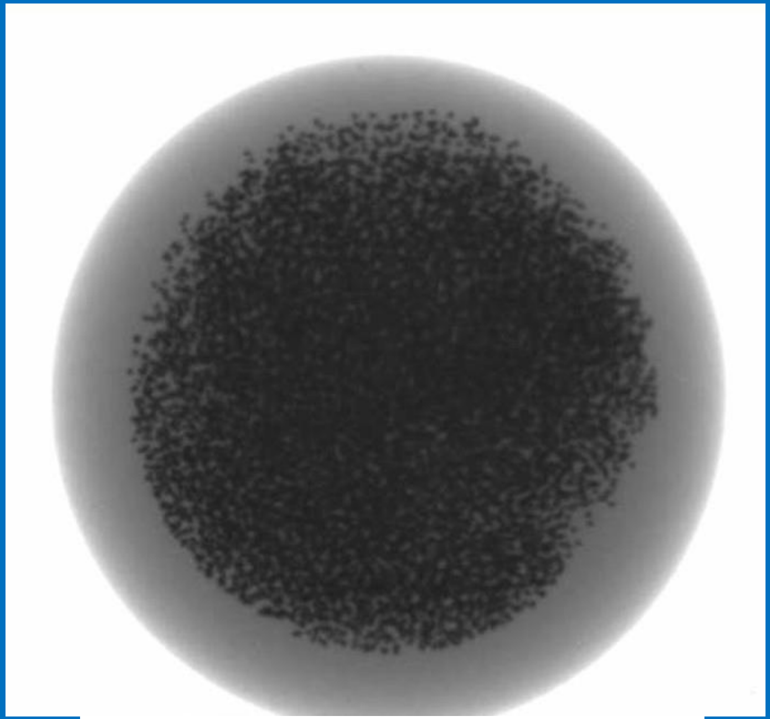


COMPACTING SPHERICAL FUEL ELEMENTS



Fuel Sphere Pressing

Finished (Machined) Fuel Spheres

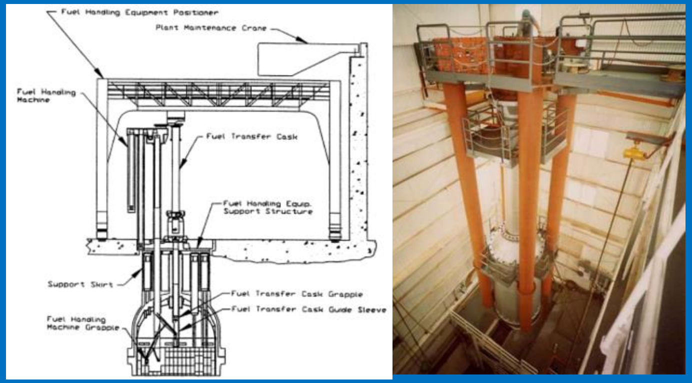


Radiograph of Pebble

HTGR FUEL MANAGEMENT STRATEGIES

- Prismatic HTGR fuel assemblies are **FIXED** and can be moved in **BATCHES**.

    The fresh/spent fuel loading patterns are adjusted at beginning of life to produce flatter axial and radial flux profiles.

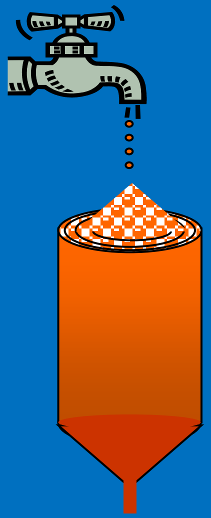


Fort St. Vrain Fuel Handling Machine

- Pebble Bed Reactors have **MOVING** fuel spheres:

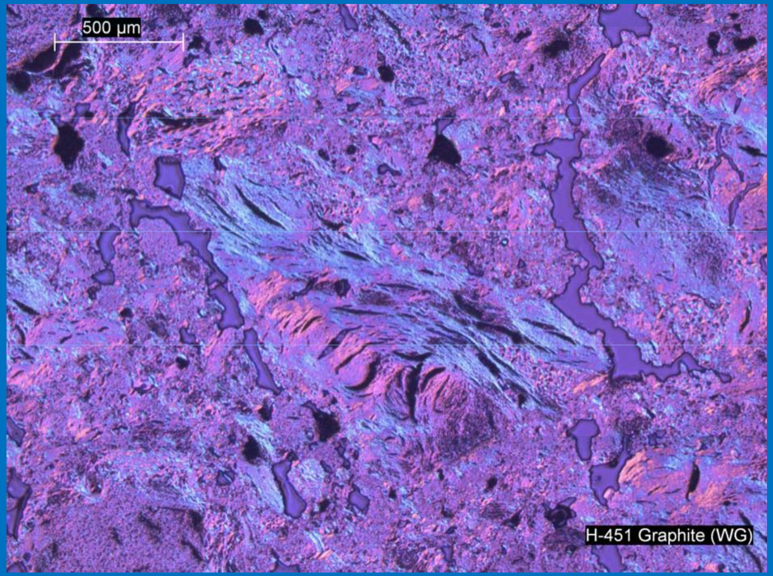
    Multiple Pass Scheme: pebbles repeatedly circulated through reactor core -- homogeneous mixture, uniform power density and larger core height can be achieved.

    Single Pass OTTO (Once-through-then Out cycle): asymmetrical axial power distribution, power and coolant temperature distribution matches well, but power tilt limits core height



ROLE OF GRAPHITE IN HTGRS: NEUTRONIC

- **Neutron moderator (carbon & graphite)**
  - Thermalize fast neutrons to sufficiently low energies that they can efficiently fission U-235
- **Neutron reflector – returns neutrons to the active core**
- **Graphite (nuclear grade) has a low neutron capture cross section**
- **High temperature tolerant material**



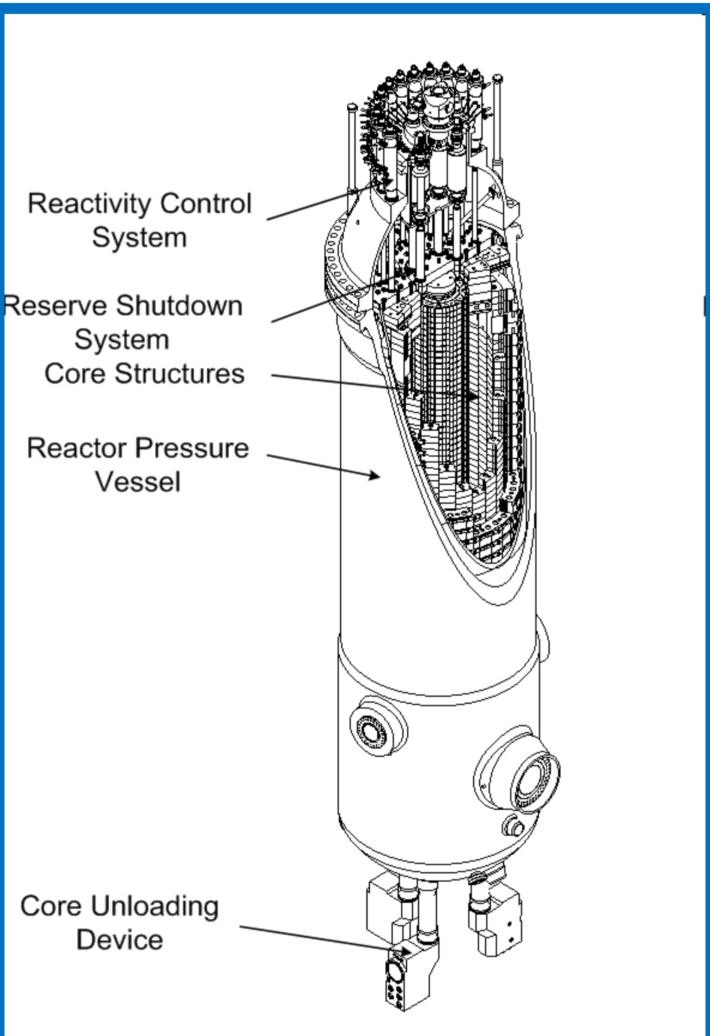
ROLE OF GRAPHITE IN HTGRS: STRUCTURAL

- Prismatic HTGR cores are constructed from graphite blocks
- In prismatic cores, graphite fuel element blocks retain the nuclear fuel compacts
- In a pebble bed reactor, a graphite reflector structure retains the fuel pebbles
- The graphite reflector structure contains vertical penetrations for reactivity control
- Reactivity control channels are also contained in prismatic graphite fuel elements

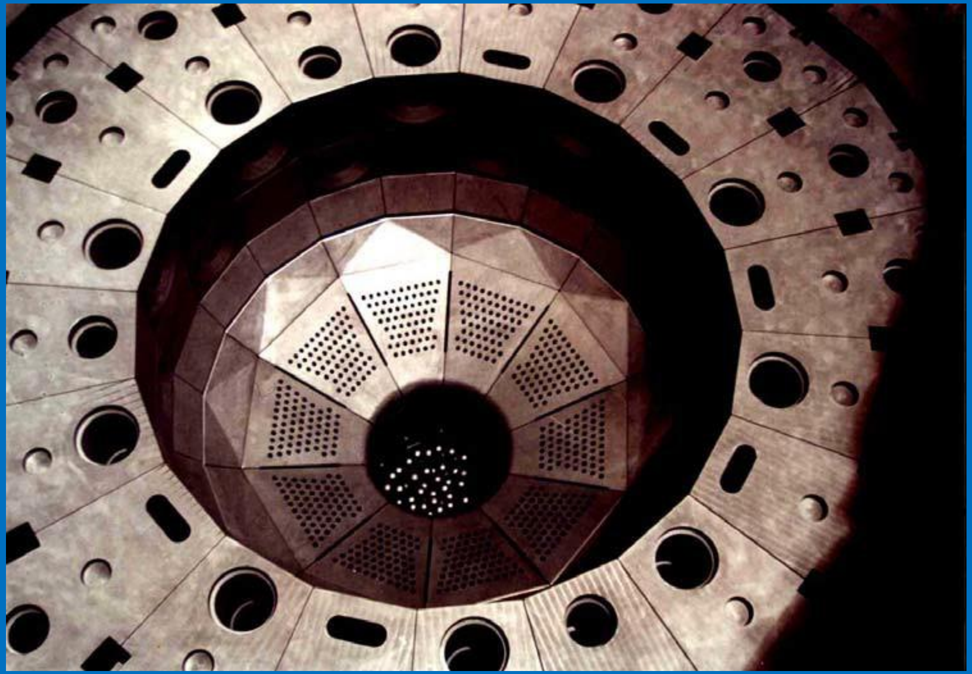
GRAPHITE CORE COMPONENTS – PEBBLE TYPE HTGR (PBMR)

NGB-18 Graphite blocks form the PBMR outer reflector

Reflector penetrations are for the control rods and reserve shutdown system

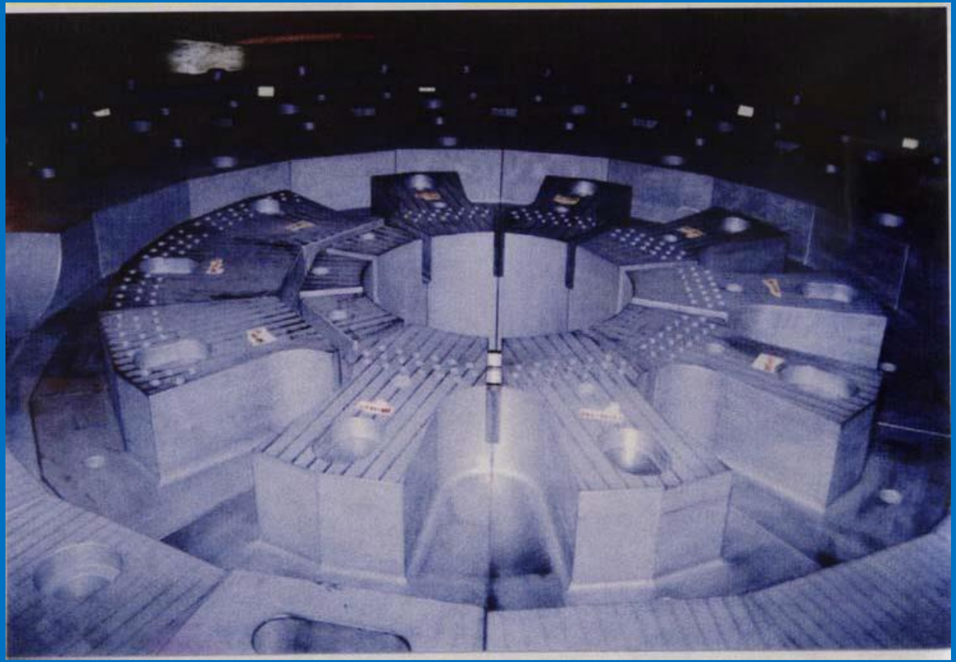


HTR-10 GRAPHITE REACTOR INTERNAL STRUCTURES (GRADE IG-110)

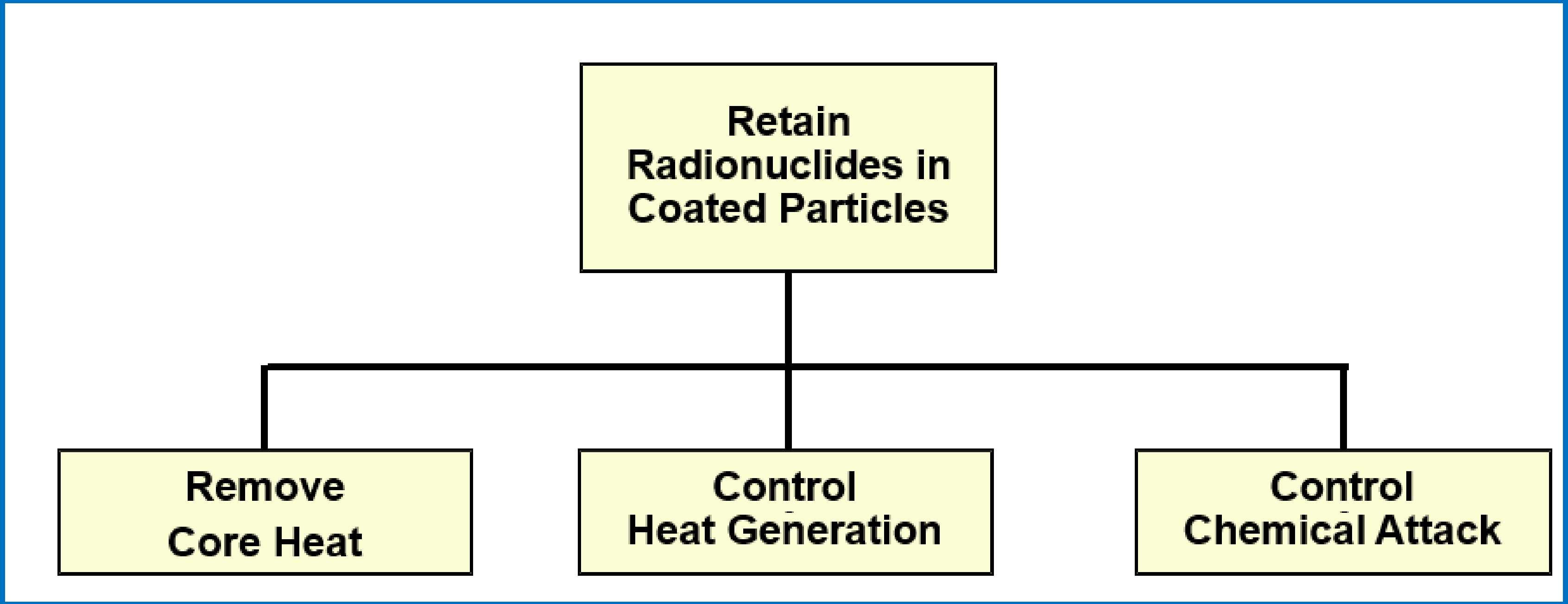


Core bottom of the HTR- 10 showing the fuel pebble collection area

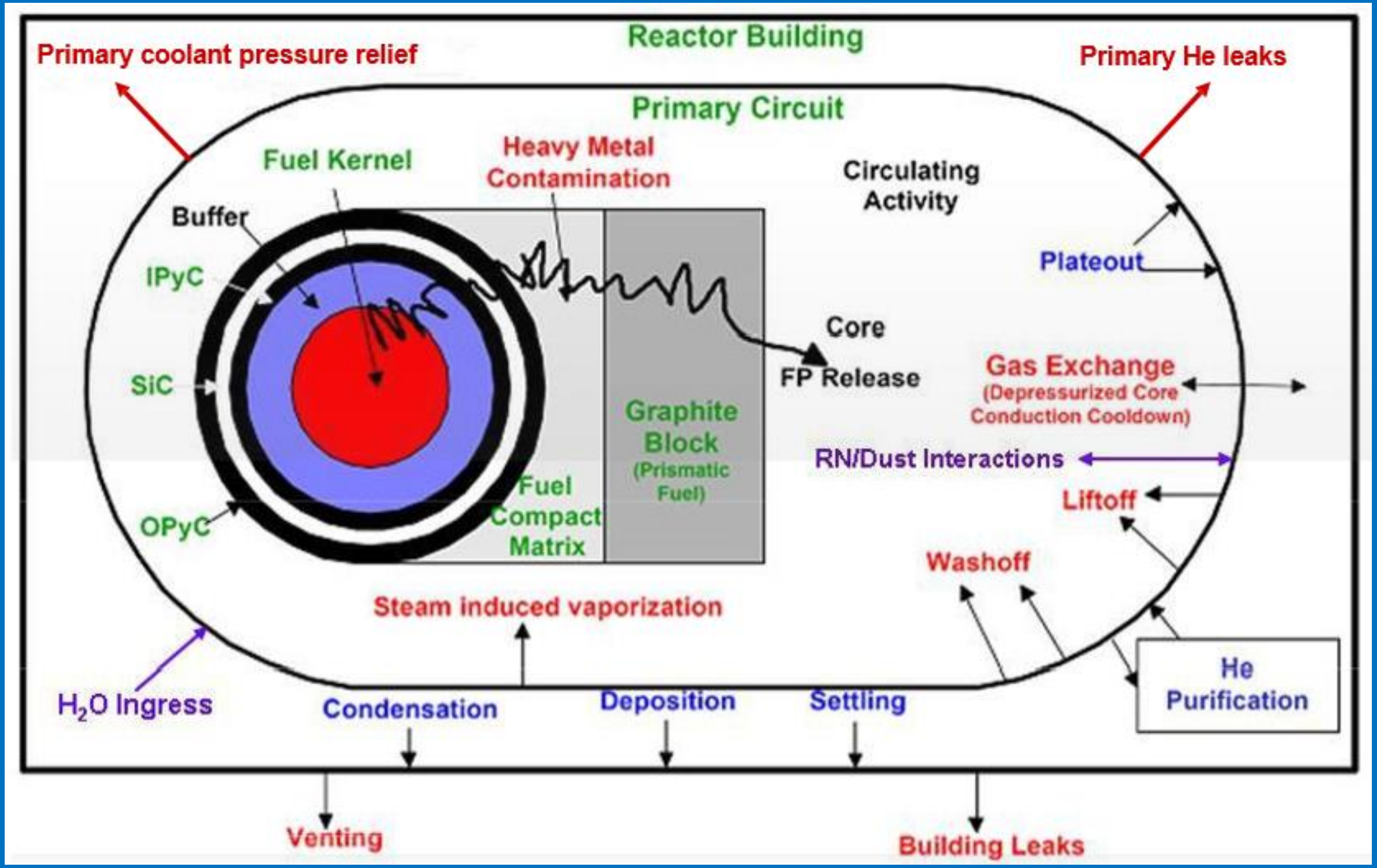
Top of the graphite core of HTR-10



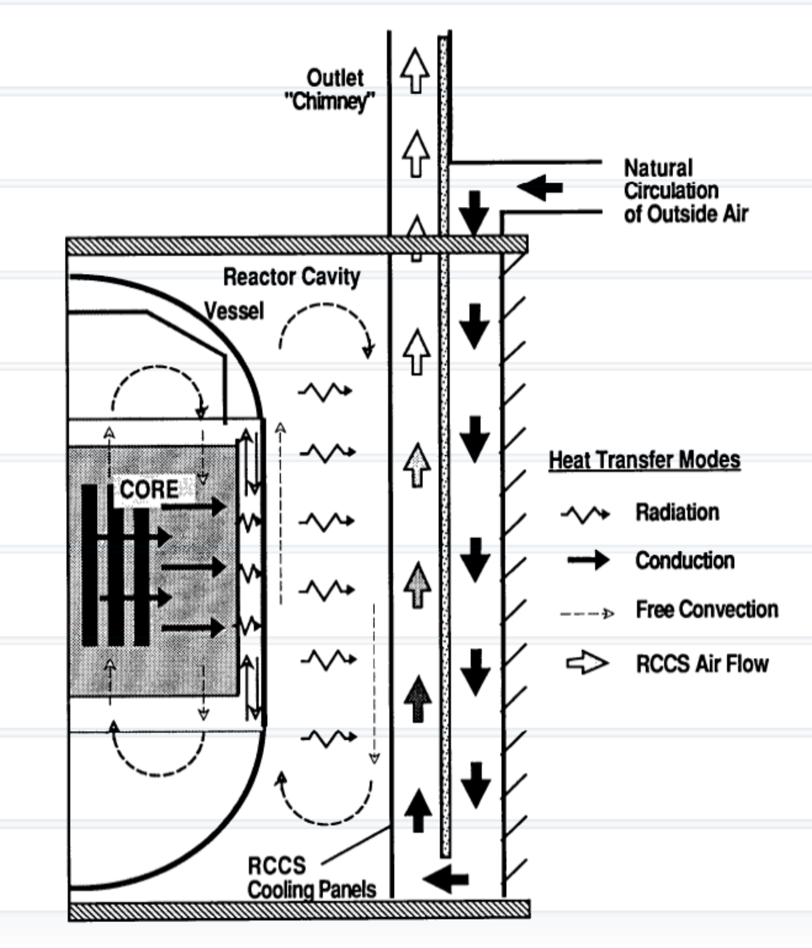
HTGR SAFETY PHILOSOPHY BASED ON THREE FUNCTIONS



HTGR RADIONUCLIDE FUNCTIONAL CONTAINMENT



PASSIVE HEAT TRANSFER TO REACTOR CAVITY COOLING SYSTEM (RCCS)



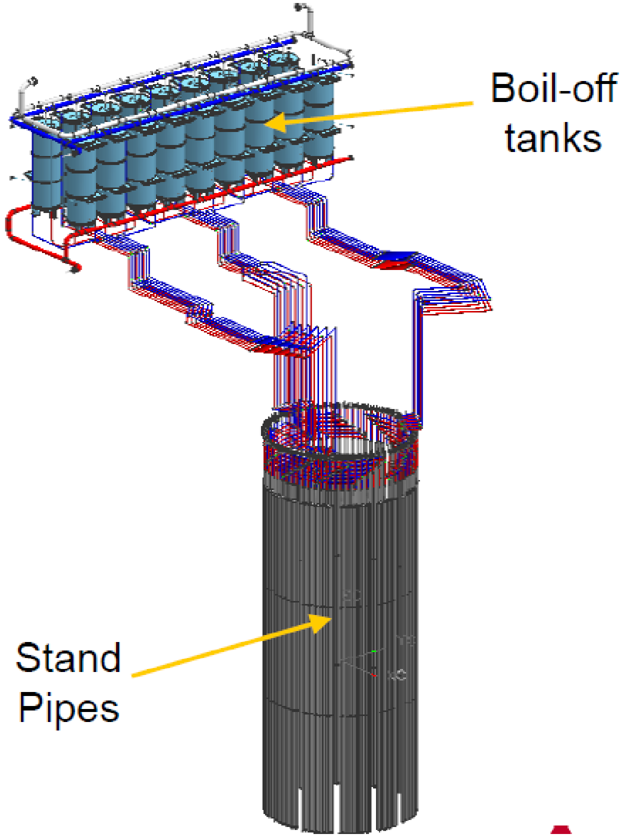
Air-cooled RCCS concept

RCCS SYSTEM FUNCTIONS AND REQUIREMENTS

- **Normal operation**
  – Control cavity concrete temperatures
  – Cool reactor vessel (for some concepts)
- **Accident conditions**
  – Control cavity concrete temperatures
  – Control reactor vessel temperatures
  – Residual heat removal
- **Passive operation during accidents (typical)**
- **Safety-related heat removal system (typical)**
- **Redundant loops (typical)**

WATER-COOLED RCCS CONCEPT

- **Water-cooled**
- **Standpipes surround vessel**
- **18 independent circuits**
  - 1 tank
  - 4 standpipes
- **Active and passive modes**



HTGR TEMPERATURE COEFFICIENT OF REACTIVITY

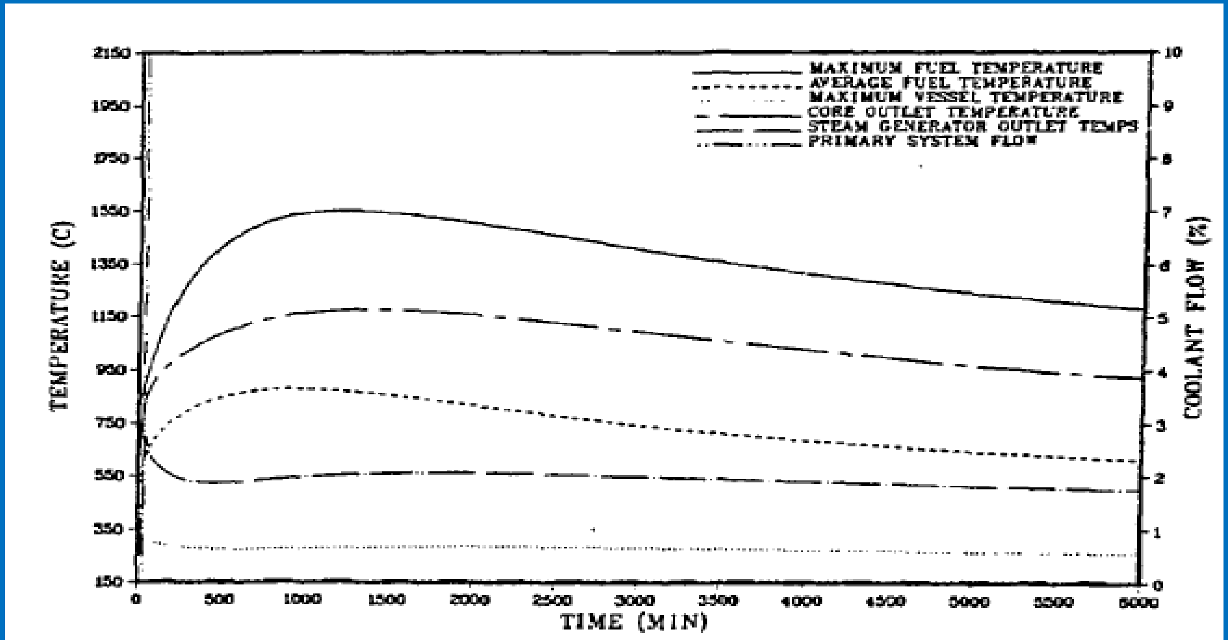
- **Except for control rod motion, changes in core temperature are only significant reactivity effect in prismatic HTGR**

- **Reactivity always decreases as core temperature increases:**
  - **Negative feedback effect in both the fuel and moderator**
  - **Ensures the passive safety of the system**

- **This effect is caused by the Doppler broadening of the U-238 and Pu-240 resonance absorption cross sections as the neutron spectrum changes with increasing core temperature**

HTGR CONTROL OF HEAT GENERATION

- **Continued functioning of reactor shutdown system only necessary for long-term shutdown**
  - **Negative temperature coefficient of reactivity**
    - **Temperature differential of 750K is maintained between operational and maximum allowable fuel temperature**
    - **Reactor shuts itself down before maximum fuel temperature reached**
  - **Limited excess reactivity**
  - **Integrity of core structures**
    - **Ceramic core structures and fuel elements**
    - **Simple and robust core structure design**

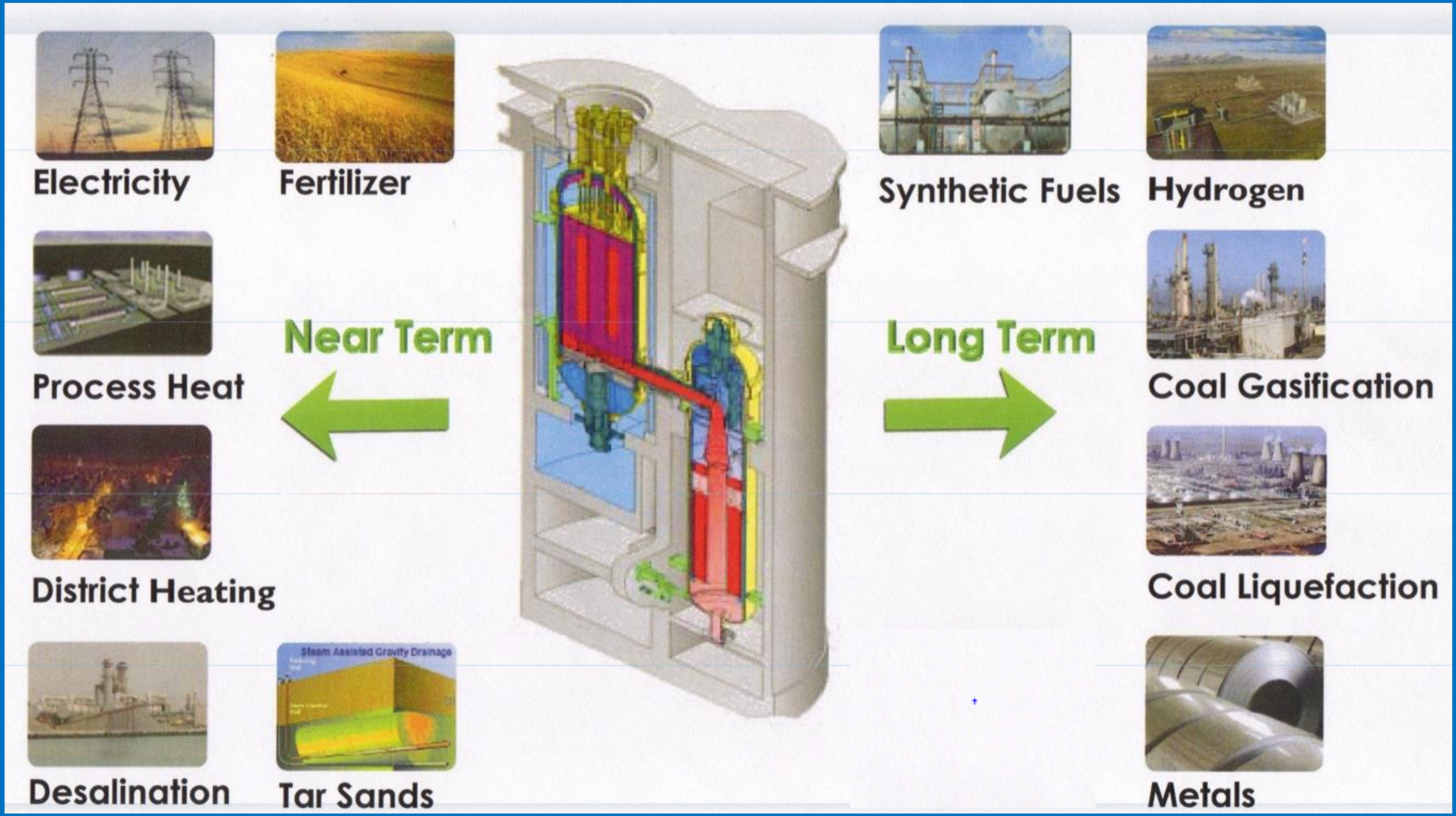


LOFC with depressurization and loss of feedwater

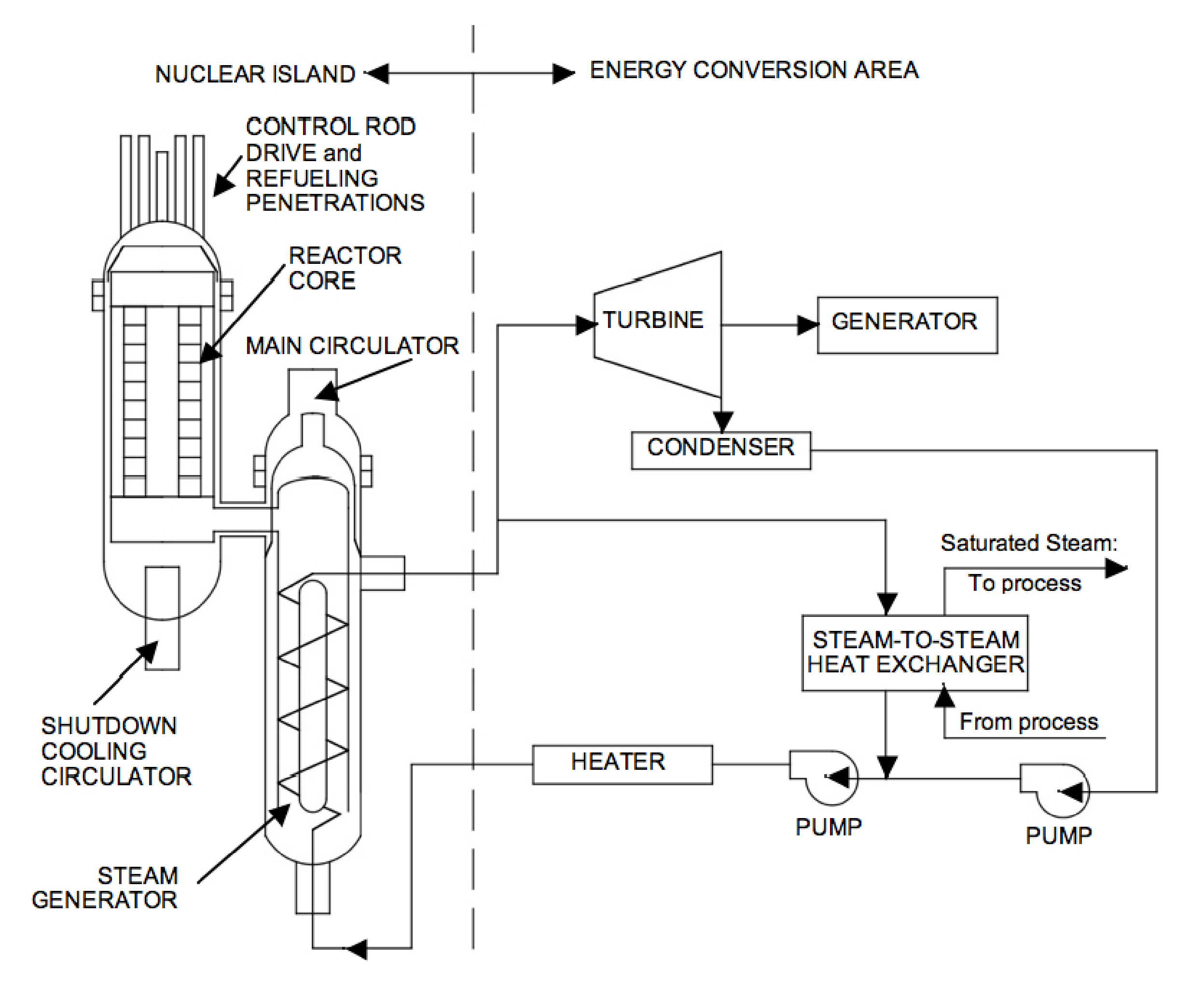
IMPORTANT HTGR SAFETY PARADIGM *SHIFTS*

- The fuel, helium coolant, and graphite moderator are chemically compatible under all conditions
- The fuel has very large temperature margins in normal operation and during accident conditions
- Safety is not dependent on the presence of the helium coolant
- Response times of the reactor are very long (days as opposed to seconds or minutes)
- Loss of forced cooling tests have demonstrated the potential for walk-away safety
- There is no inherent mechanism for runaway reactivity excursions or power excursions
- The HTGR has multiple, nested, and independent radionuclide barriers
- An LWR-type containment is neither advantageous nor necessarily conservative.

HTGRS FOR PRODUCTION OF A WIDE VARIETY OF ENERGY AND COMMERCIAL PRODUCTS



A FIRST STEP – HTGR FOR PROCESS STEAM AND COGENERATION

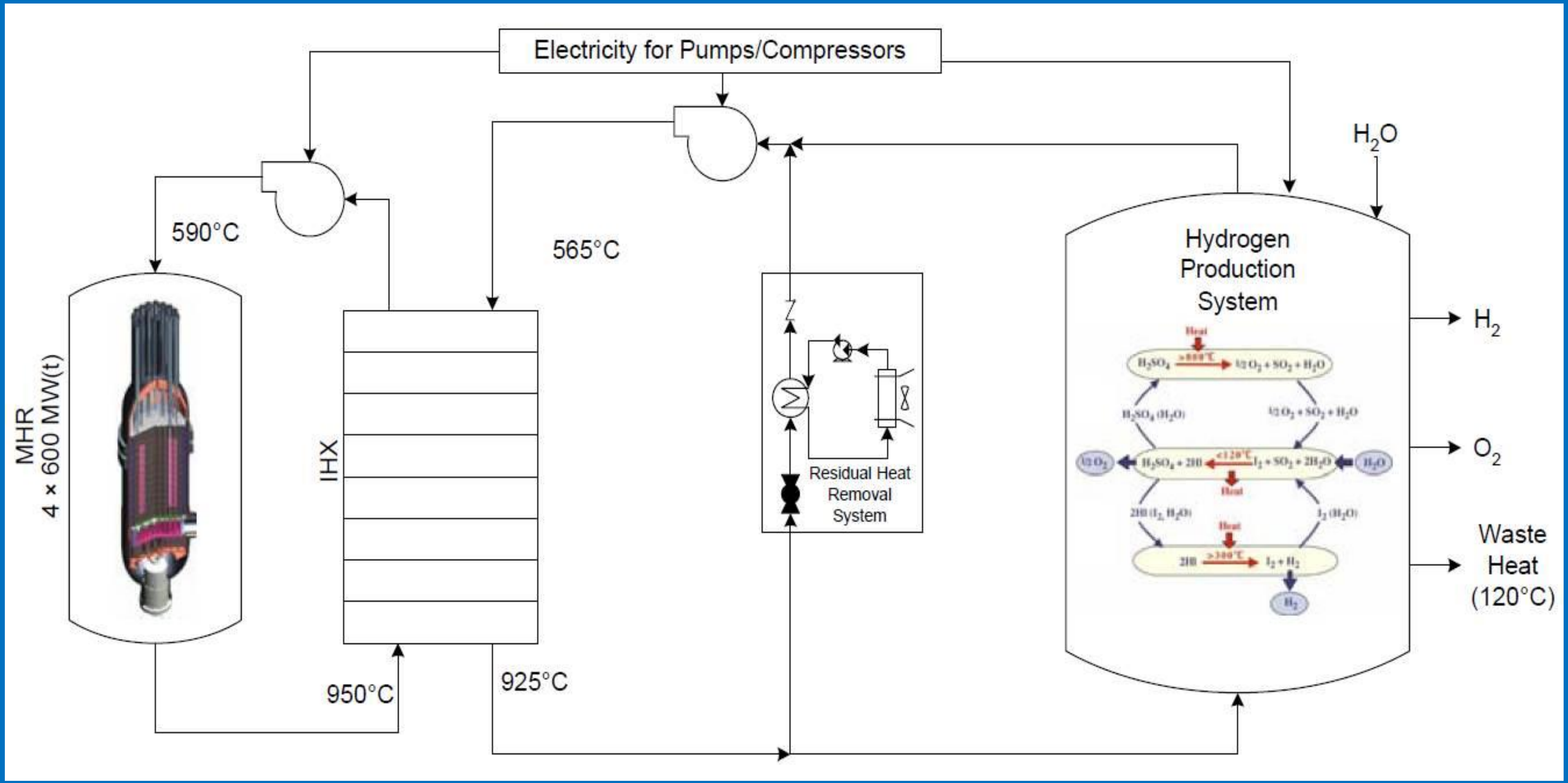


Applications

- **Heavy oil recovery**
- **Oil from tar sands**
- **Industrial process steam**
- **Coal liquefaction**
- **Coal gasification**

The market for process steam < 600C is already very large (87 GWth in Europe alone)

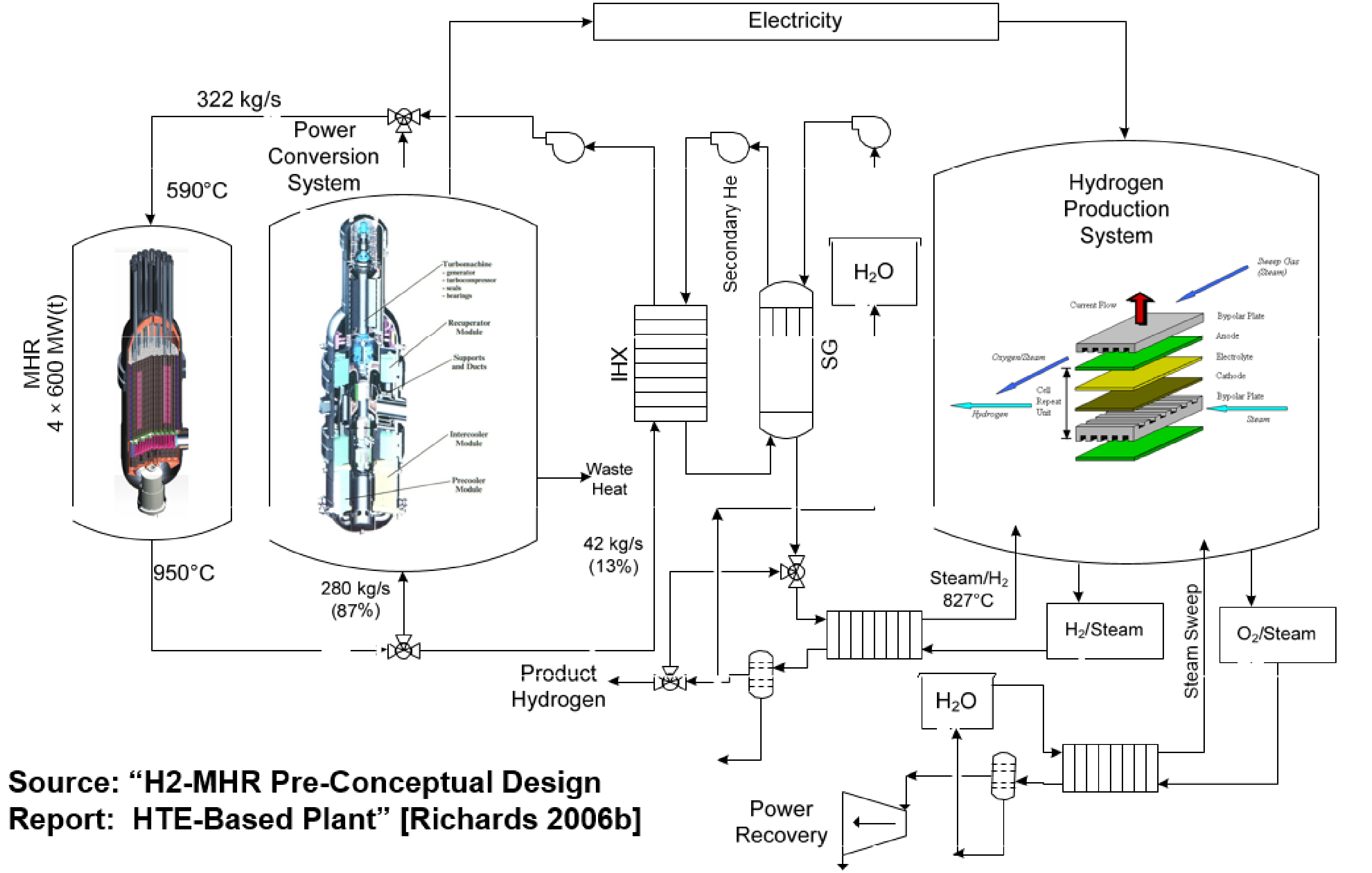
THE FUTURE - VHTR PLANT FOR HIGH TEMP. HYDROGEN PRODUCTION



Source: “H2-MHR Pre Conceptual Design Report: S-I Based Plant” [Richards 2006]

Similar configurations for Hybrid Sulfur (Westinghouse) thermochemical cycle or High Temperature Steam Electrolysis with very high temperature process heat

THE FUTURE - VHTR PLANT FOR HIGH TEMP. HYDROGEN PRODUCTION



Source: "H2-MHR Pre-Conceptual Design Report: HTE-Based Plant" [Richards 2006b]

SUMMARY

- HTGR technology has high technical readiness level with extensive base of design, licensing, and operating experience providing valuable lessons learned
- Prismatic and pebble bed systems share large common base of technology, systems and components
- HTGR has inherent safety characteristics due to ceramic fuel particles, graphite core and inert helium coolant
- The HTGR can play important role for near-term and long-term process heat applications

HTR-PM in China expected online in 2017

Questions?

UPCOMING WEBINARS

22 February 2017	**Gas Cooled Fast Reactor**	**Dr. Alfredo Vasile, CEA, France**
28 March 2017	**Supercritical Water Reactors**	**Dr. Laurence Leung, CNL, Canada**
27 April 2017	**Fluoride-Cooled High-Temperature Reactors**	**Prof. Per Peterson, UC Berkeley, USA**

INSTN- INTERNATIONAL COURSE ON GEN IV NUCLEAR REACTOR SYSTEMS FOR THE FUTURE

- **Date: June 19-23, 2017**
- **Place: INSTN CEA Saclay - France**
- The course is targeting scientists already involved in Gen IV systems activities or planning to work in such areas. The course covers the 6 systems, and cross-cutting aspects (energy conversion, materials, safety, and fuel cycle).
- The course offers lectures by renowned subject matter experts in the various areas, as well as tutorials (how to “design” a fast neutron reactor using simple calculations).
- **GENERAL INFORMATION AND REGISTRATION**
- Number of participant is limited to 20. Course fee includes lectures, documentation, lunches and coffee breaks. **Language**: English **Full rate: €2100 Student rate: €1470**
- **Contact:** Program manager: claude.renault@cea.fr Course organizer: nadia.nowacki@cea.fr
- http://www-instn.cea.fr/en/education-and-training/continuing-education/short-courses/generation-iv-nuclear-reactor-systems-for-the-future%2C1907613.html