The Indian High Temperature Reactor Programme

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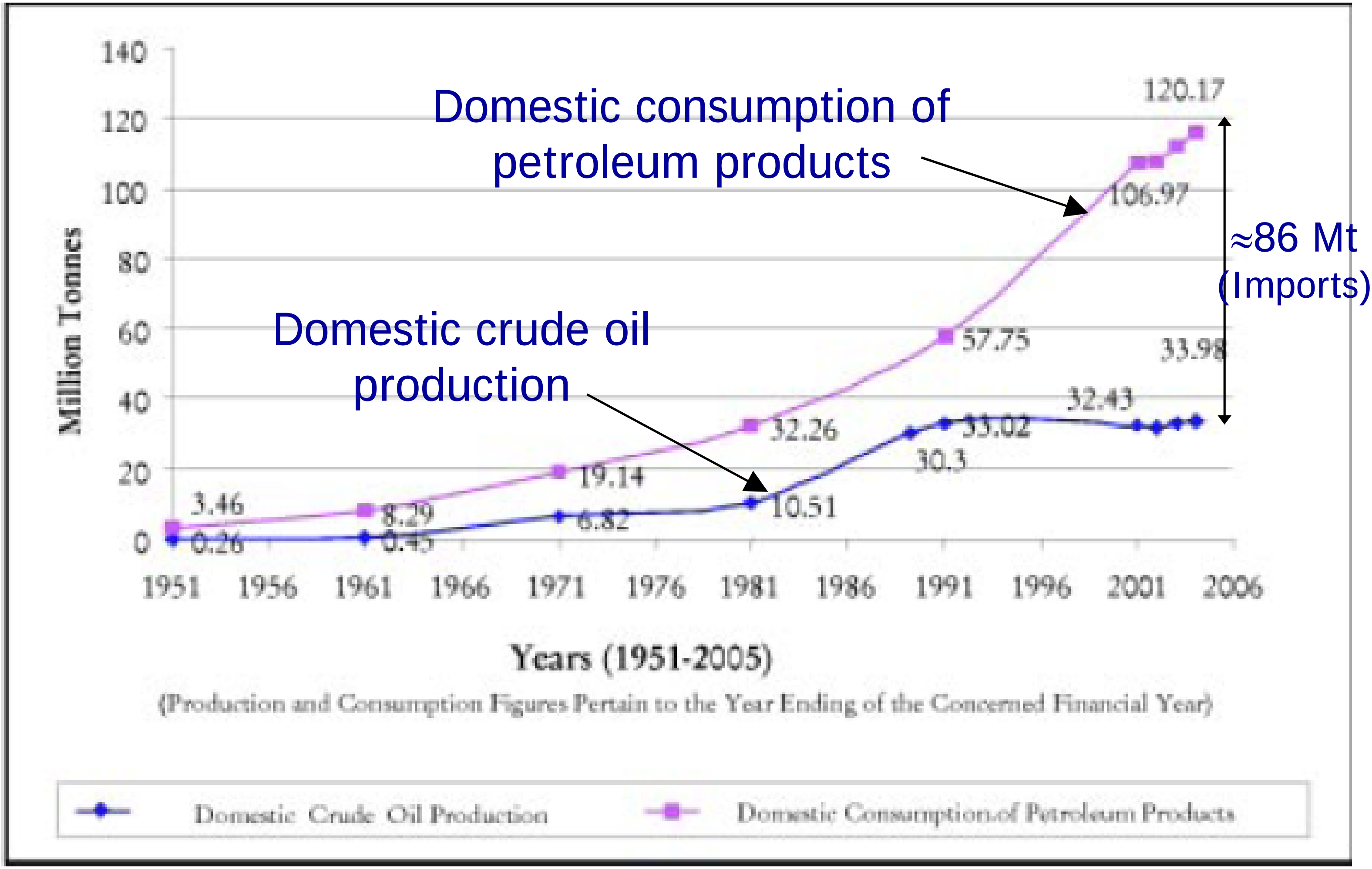
In Indian context, the need for high temperature reactors are mainly to facilitate sustainable long term production of alternate fuel for transport sector

Indian fossil fuel based energy resources are rather limited

Source	Amount	Thermal Energy			Electricity Potential
		EJ (10^{18} J)	TWh (10^{12} Wh)	GWYr	GWeYr
Fossil Fuel:					
Coal	53.9 Bln. t	913	253,540	28,944	10,419
Hydrocarbon	12 Bln. t	511	141,946	16,204	5,833
Non-Fossil:					
Nuclear					
Uranium metal	61,000 t				
In PHWR		28.9	7,992	913	328
In Fast Reactors		3,699	1,027,616	117,308	42,231
Thorium metal	2,25,000 t				
In Breeders		13,622	3,783,886	431,950	155,502
Renewable	**Potential (Installed capacity)**				**(Effective capacity)**
Hydro	150 GWe	6.0	1,679	192	69
Non-conventional & renewable	100 GWe	1.8	487	56	20

Ref: A strategy for growth of electrical energy in India, Department of Atomic Energy, Document no. 10 (Data related to coal has been modified based on latest information)

Indian production, consumption and projected demand of petroleum products



Domestic consumption of petroleum products

Domestic crude oil production

≈86 Mt (Imports)

2031-32, Projected demand: ≈ 486 Mt

Imports ≈ 450 Mt

Source: Ministry of Petroleum & Natural Gas, India

Source: Integrated Energy Policy – Report of the expert committee, Planning commission of India, August 2006

Options for transport fuel

1) Natural gas – Limited domestic resources

2) Other options for natural gas production:

   a) Coal bed methane: Limited reserves

   b) Gas hydrates: Technology for safe extraction, Economics, environmental impacts

3) Coal – synthetic fuel production: Viable option in the interim period

4) Bio-fuel and bio-mass gasification: Can contribute only a small part of total requirement – Limited land usage

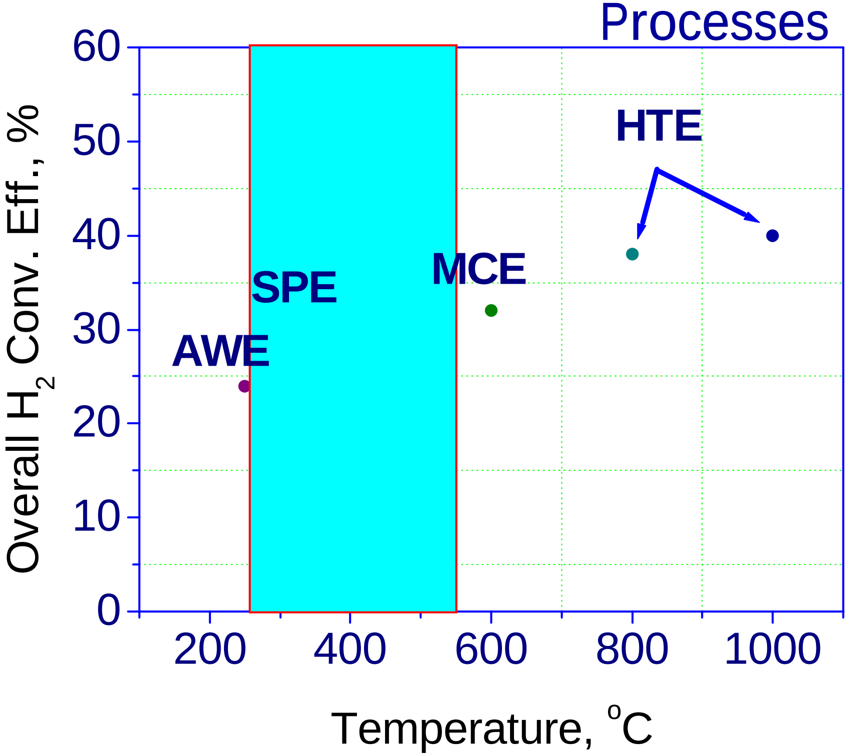
5) Nuclear and solar energy assisted hydrogen – Viable and long term sustainable option

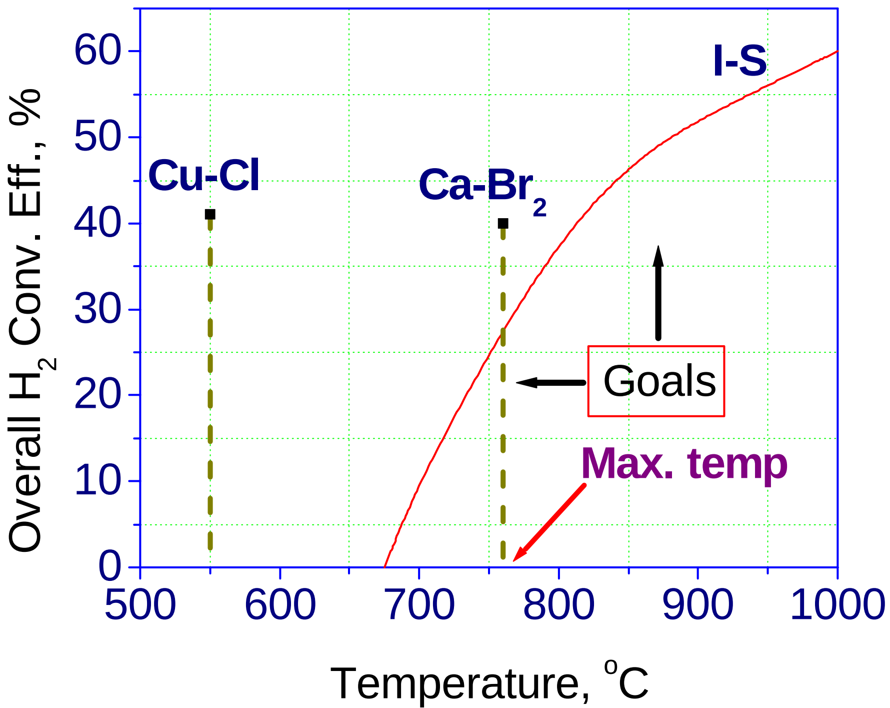
Source: Integrated Energy Policy – Report of the expert committee, Planning commission of India, August 2006

Options for production of hydrogen using nuclear energy

Electrolysis ← Water → Thermo-chemical cycle

Processes shown are indicative





Electrolysis Processes:
AW: Alkali Water, MC: Molten Carbonate
SP: Solid Polymer, HT: High Temperature

Ref: IAEA-TECDOC-1085: Hydrogen as an energy carrier and its production by nuclear power

Thermo-chemical Processes:
Cu-Cl: Copper - Chlorine, $Ca-Br_2$: Calcium-Bromine, I-S: Iodine-Sulfur Process

Ref: High Efficiency Generation of Hydrogen Fuels Using Nuclear Power, G.E. Besenbruch, L.C. Brown, J.F. Funk, S.K. Showalter, Report GA–A23510 and ANL reports

Indian High Temperature Reactor Development Programme – The focus is on hydrogen production

Compact High Temperature Reactor (CHTR)- Technology Demonstrator

- 100 kW_{Th}, 1000 °C, Portable, TRISO coated particle fuel
- Several passive systems for reactor safety and heat removal - unattended operation
- Prolonged operation without refuelling

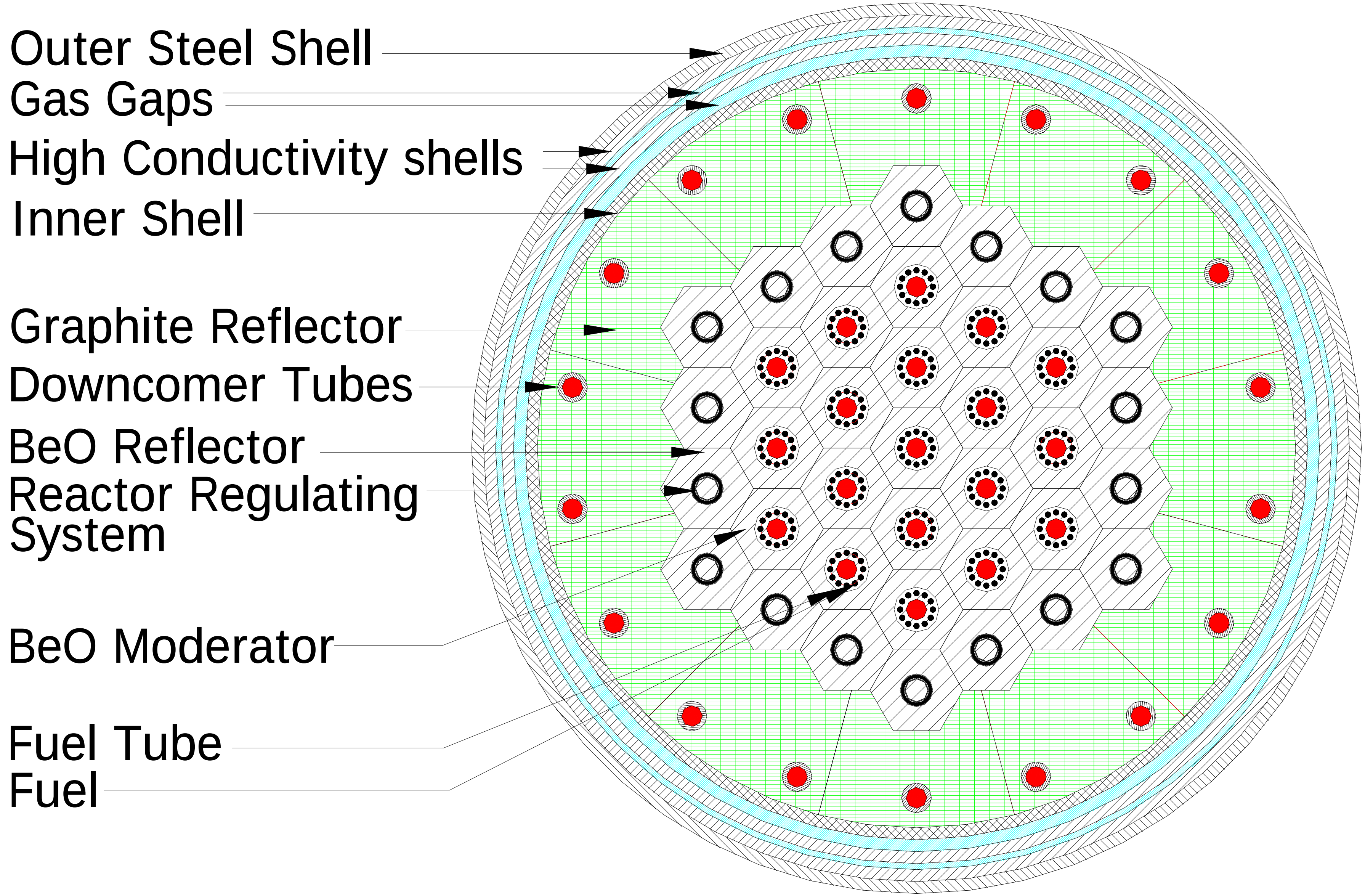
Status: Feasibility studies carried out. Materials, fuel and experimental setups under development

Indian High Temperature Reactor for Hydrogen Production (IHTR-H)

- 600 MW_{Th} , 1000 °C, TRISO coated particle fuel
- Combination of active and passive systems for control & cooling
- Medium life core

Status: Options being evaluated for the design

CHTR has an all ceramic core containing mainly BeO and carbon based components



Outer Steel Shell

Gas Gaps

High Conductivity shells

Inner Shell

Graphite Reflector

Downcomer Tubes

BeO Reflector

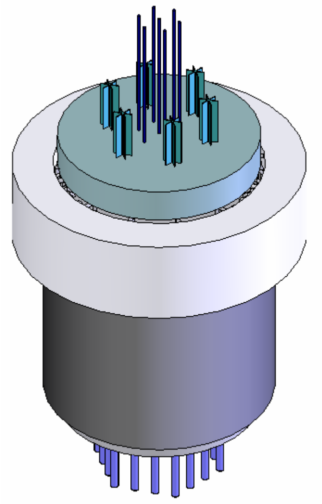
Reactor Regulating System

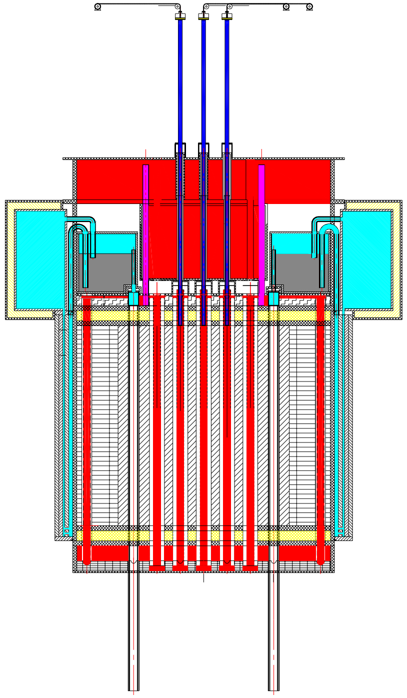
BeO Moderator

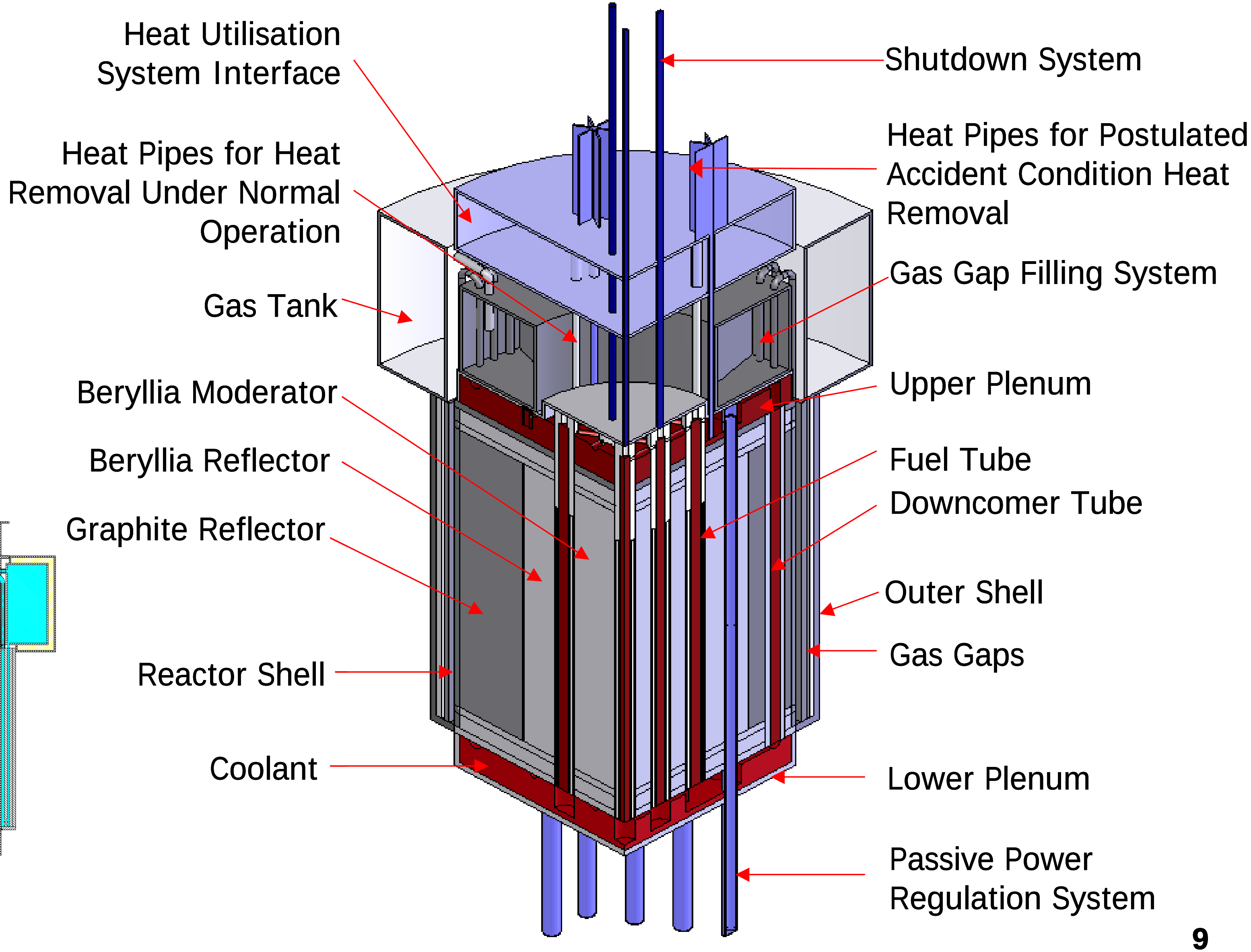
Fuel Tube

Fuel

Several innovations in the areas of fuel, materials, passive reactor safety, efficient heat removal systems & liquid heavy metal coolant technology mark CHTR configuration







Heat Utilisation System Interface

Heat Pipes for Heat Removal Under Normal Operation

Gas Tank

Beryllia Moderator

Beryllia Reflector

Graphite Reflector

Reactor Shell

Coolant

Shutdown System

Heat Pipes for Postulated Accident Condition Heat Removal

Gas Gap Filling System

Upper Plenum

Fuel Tube

Downcomer Tube

Outer Shell

Gas Gaps

Lower Plenum

Passive Power Regulation System

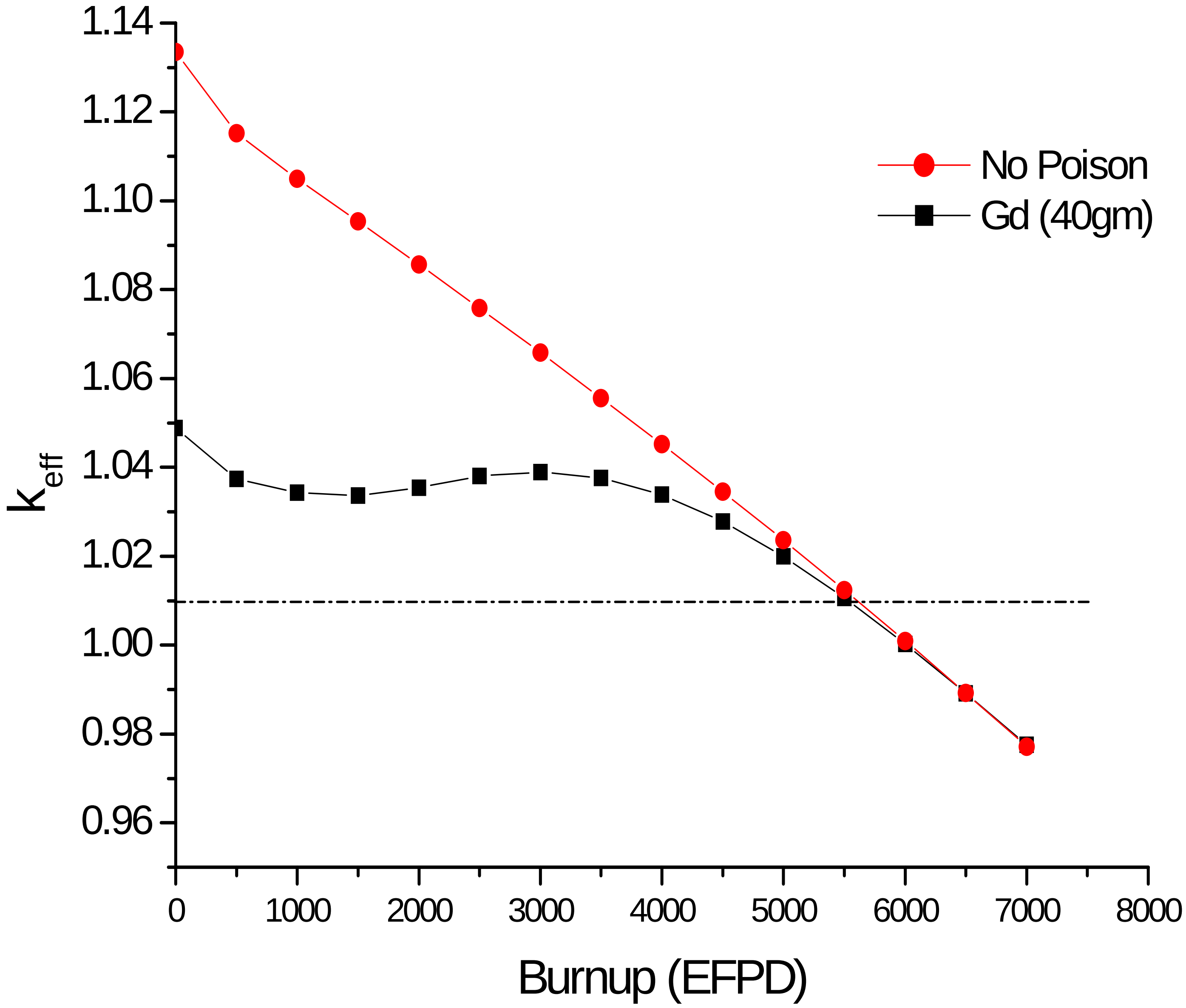
Important Design Parameters of CHTR

Reactor power	100 kW_{Th}
Core configuration	Vertical, Natural circulation type
Coolant	Molten Pb-Bi eutectic
Fuel tubes	Graphite - 19 nos. with 75 mm OD and 35 mm ID
Fuel	$^{233}UC_2$+ ThC_2 based TRISO Coated fuel particles (900 micron in diameter) made into fuel compacts
Enrichment	33.75 wt %
Burnup	68000 MWd/t of heavy metal
Refuelling interval	15 EFPYs
Moderator	BeO
Reflector	BeO and Graphite
Fuel heated length	0.70 m
Total core flow rate	6.78 kg/s
Coolant inlet temp.	900 ^{o}C
Coolant outlet temp.	1000 ^{o}C
Core diameter	1.27 m
Core height	1.0 m

Development programme for technologies related to CHTR

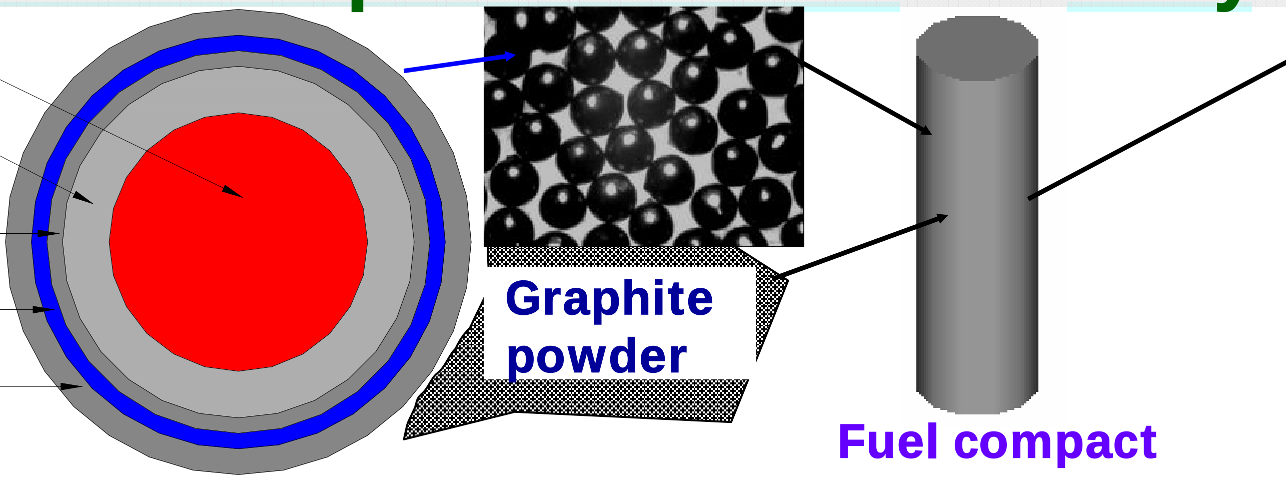
- Development of neutronics design tools for compact cores
- TRISO coated particle fuel development
- Development of reactor core materials
- Development of corrosion resistant materials and their coatings
- Development of thermal hydraulic design tools
- Development of passive systems for reactor safety and core heat removal
- Development of liquid metal related technologies including material compatibility issues
- High temperature heat removal technologies

Indigenous codes developed for Reactor Physics Analysis of CHTR



- Fuel Configuration: 2.7 kg ^{233}U + 5.3 kg ^{232}Th+ 40 gm Gd (only central fuel tube)
- Fuel Life (Refueling period): 5500 EFPD
- Negative fuel and moderator temperature coefficient –

TRISO coating facility established and trials on surrogate materials and simulation to optimize the parameters is underway



Fuel kernel

PyC buffer layer

Inner PyC layer

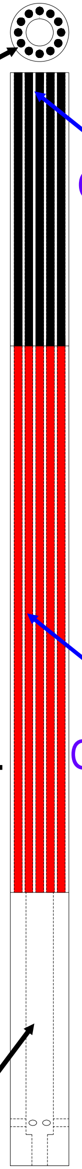
SiC layer

Outer PyC layer

TRISO coated particle fuel

Graphite powder

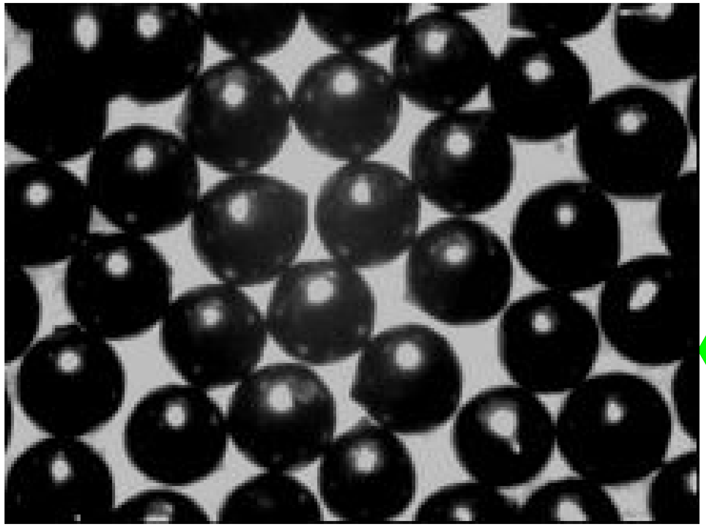
Fuel compact
(ϕ10 mm, 35 mm long)



Graphite

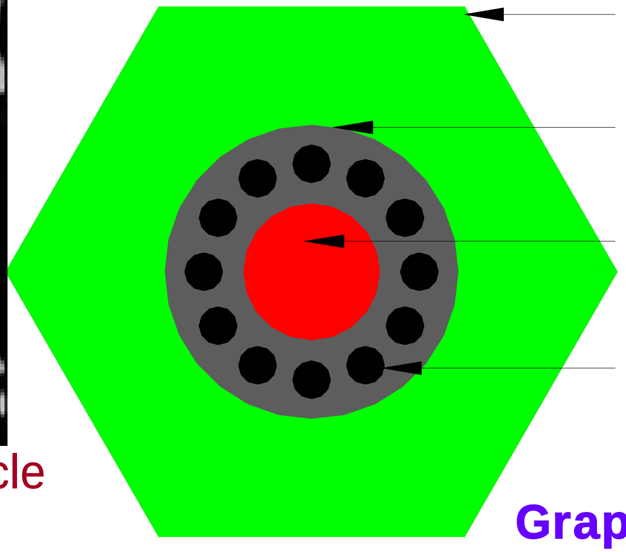
Fuel Compacts

Graphite fuel tube



PyC (30 μ) coated spherical particle of stabilized zirconia (500 μ)

CHTR - Single fuel bed



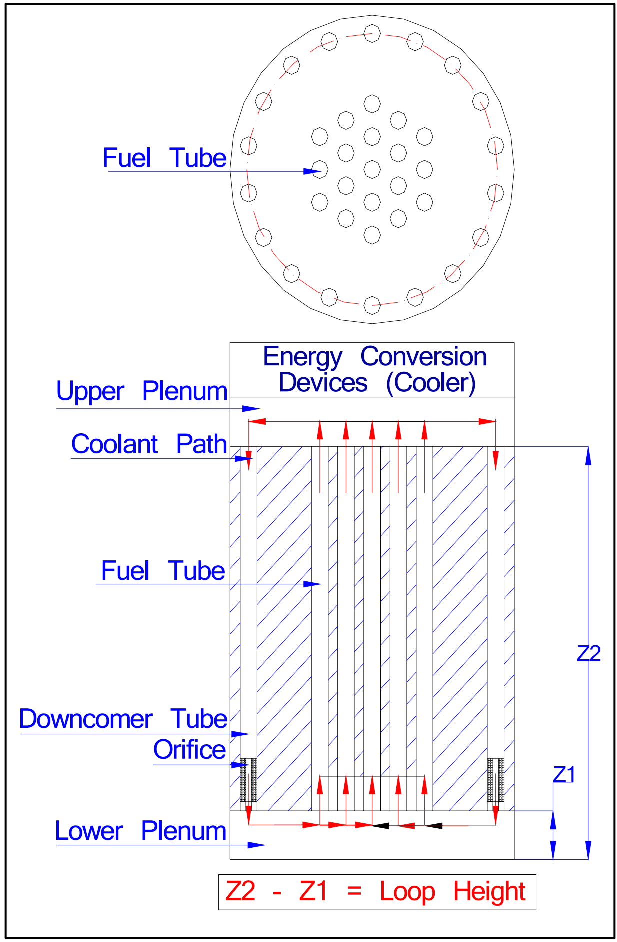
BeO

Graphite Fuel Tube

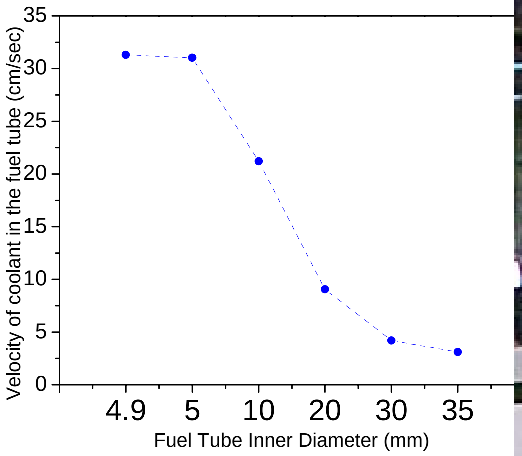
Pb-Bi Coolant

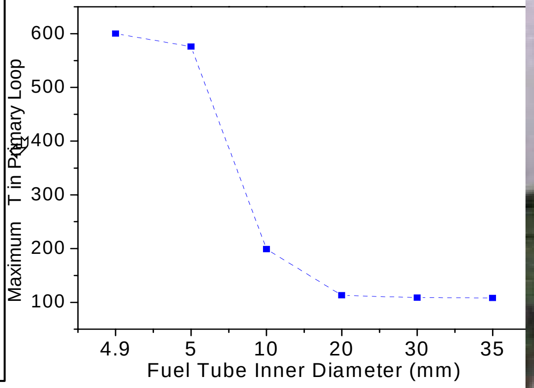
Fuel Comapct

Passive normal operation heat removal from CHTR core by natural circulation of coolant



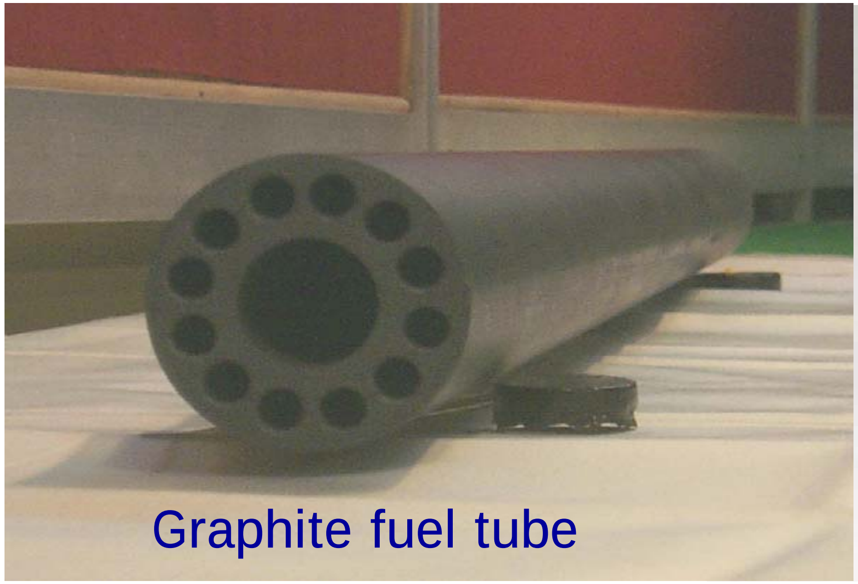
Simplified thermal–hydraulics loop used for analysis





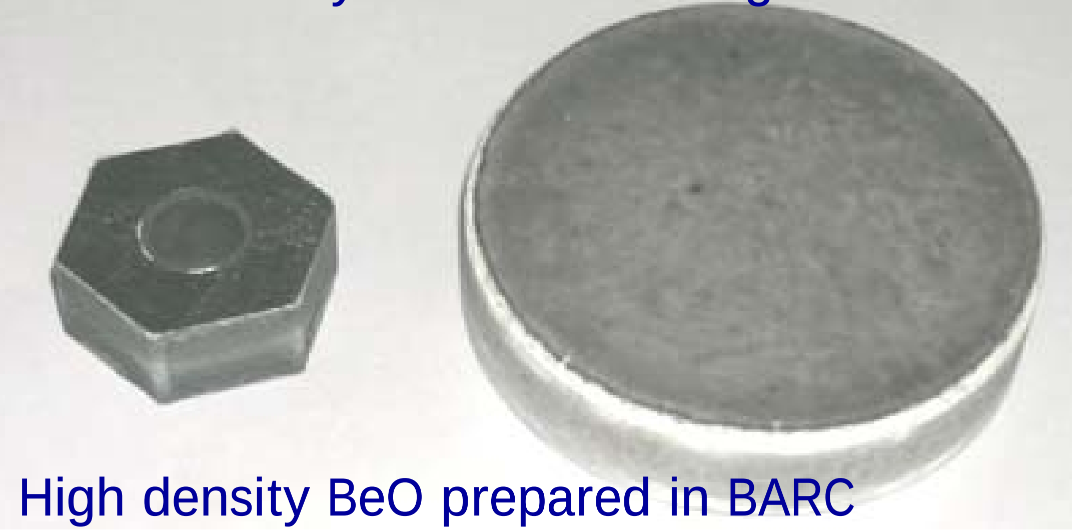
Materials - Development of materials, coatings, joining technologies, compatibility and irradiation studies are underway

Materials	**Reactor Components/ Systems**
High density nuclear grade BeO	Moderator and reflector
High density, isotropic, nuclear grade graphite	Long fuel tube & down comer tube, large size reflector blocks, plenum flow guide blocks
Carbon-carbon composites	Heat pipes, alternate fuel tubes
Refractory metals and their alloys	Inner reactor shell, coolant plenums, heat utilisation vessels, Passive power regulation system, heat pipes, shutdown system
Oxidation and corrosion resistant Coatings	PyC, SiC, Silicides etc.



Graphite fuel tube

Density achieved > 2.9 gm/cc



High density BeO prepared in BARC

CHTR has been designed to have several inherent safety features

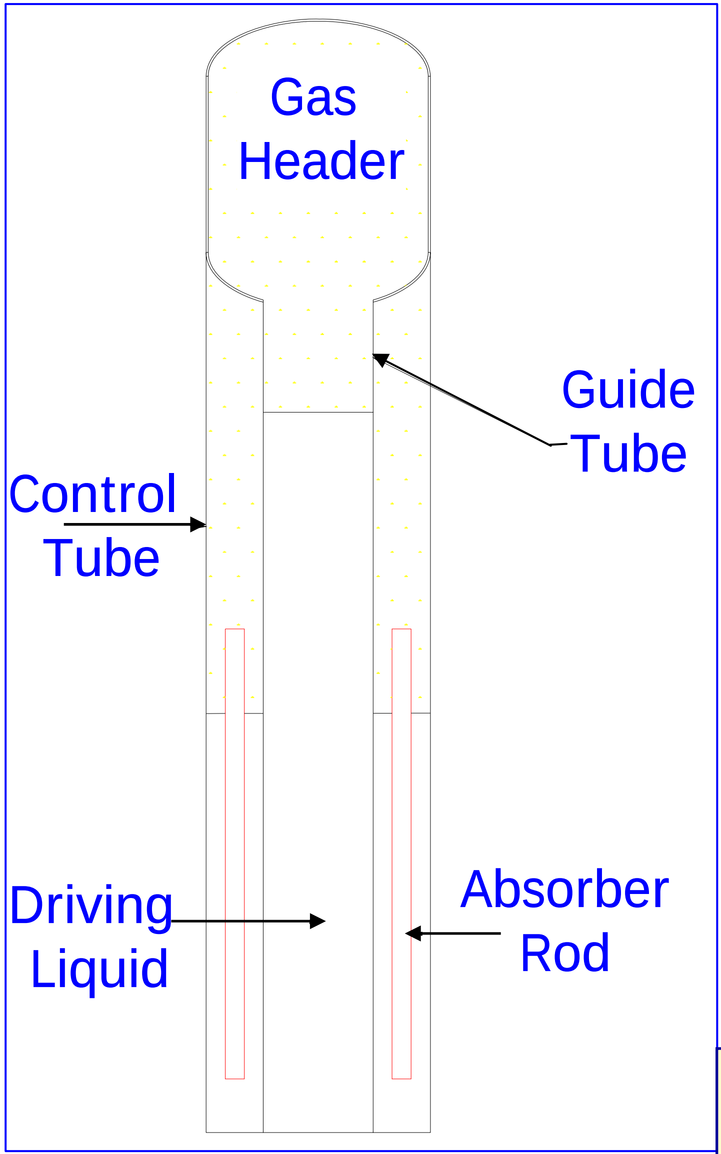
- Reactivity drops with increase in fuel temperature
- High thermal inertia of all-ceramic core and low core power density
- Large margin between the normal operating temperature of fuel (1100 °C) and the leak tightness limit of the TRISO coated particle fuel (1600 °C)
- High boiling point (1670 °C), large thermal margin to Pb-Bi boiling
- Low pressure operation of Pb-Bi coolant
- Low pressure makes possible use of graphite fuel tube, improving neutronics of the reactor
- Low thermal energy stored in coolant – Low energy release in case of a leak or accident
- Pb-Bi is chemically inert with air and water
- In case of leakage, the coolant retains iodine and other radionucleides and itself solidifies preventing further leakage
- Pb-Bi coolant - The reactivity effects (void, power, temperature, etc.) are negative
- Negative moderator temperature coefficient

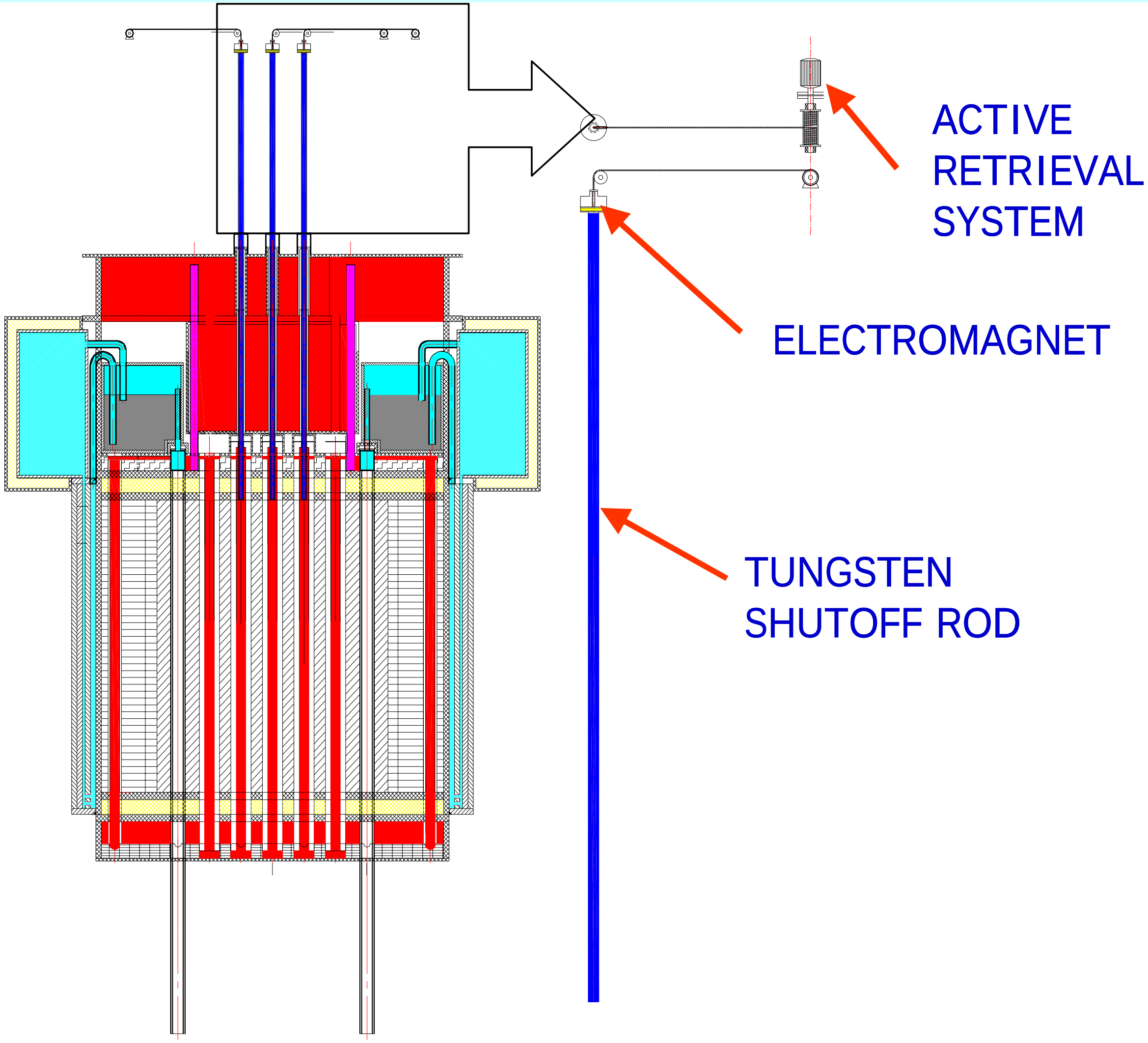
Emphasis has been put on development of passive systems for most of the safety and heat removal systems

- Natural circulation of coolant
- Passive regulation of reactor power under normal operation
- Passive shutdown for postulated accidental conditions
- Passive system for conduction of heat from reactor core by filling of gas gaps by liquid metal
- Removal of heat from upper plenum, under both normal and postulated accidental conditions by heat pipes
- Removal of heat from the core by C/C composite heat pipes under postulated accidental conditions with LOCA

Several of these features will be retained for the Indian High Temperature Reactor for Hydrogen production

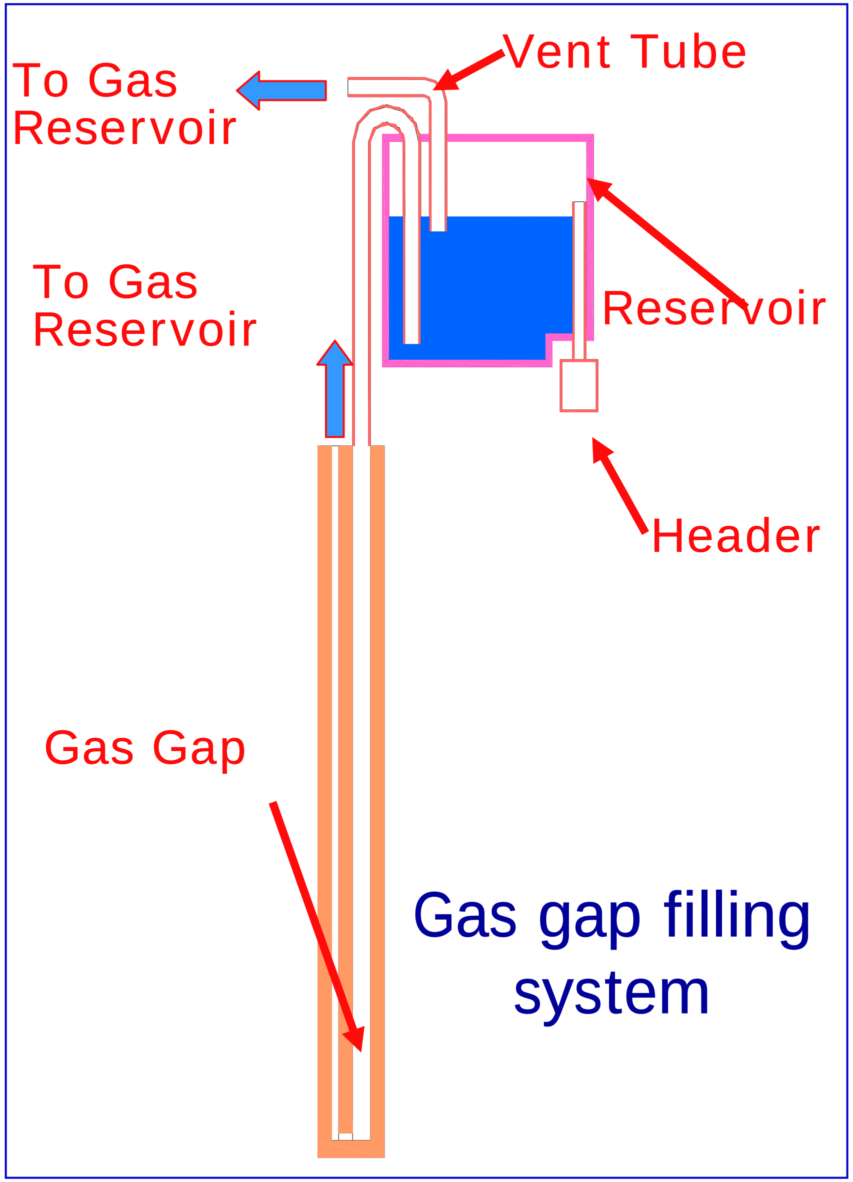
CHTR has passive power regulation and reactor shutdown system





Experimental setups for these systems are under various stages of development

Under postulated accident condition, core heat can be released to atmosphere by passive means



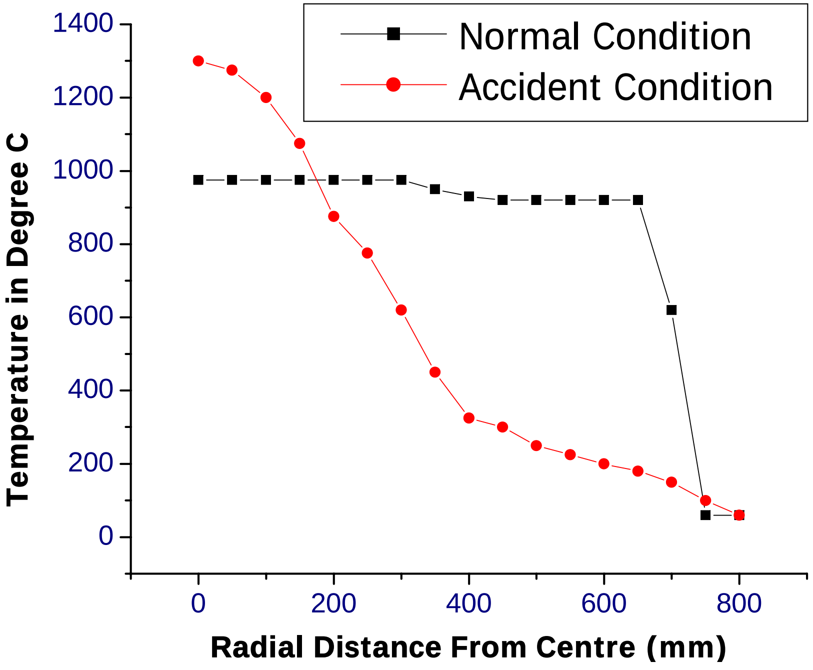
Gas gap filling system

Passive systems provided are

- Gas gap liquid metal filling system
- Heat pipe based systems

Gas gap liquid metal filling system

- Conduction pathway between the reactor core and outside heat sink
- Passive system activation based on increase of coolant exit temperature
- Siphon action to transfer molten metal to the gas-gaps



Status of Important Research & Development Areas

Objective	Enabling Technologies	Status of Development
Development of TRISO coated particle fuel	Production of fuel kernels by sol-gel technique	The technique exists
	Technology for development of multi-layer coatings	Coating trials initiated on surrogate material
Development of BeO based moderator and reflector	Manufacture of high density BeO blocks	Sample pieces manufactured
Development of liquid metal coolant technology	Natural circulation of Pb-Bi coolant in the primary circuit	Experimental loop under commissioning
	Validated codes for simulation of thermal-hydraulic behaviour of Pb-Bi coolant in primary circuit	
	Compatibility of materials with Pb-Bi coolant	
	Instrumentation and components like electro-magnetic pumps and flow meters for liquid metal coolant	Technology available
Development of PPRS	Validated computer codes to simulate operation of passive power regulation system	Experimental set up under commissioning
Development of passive heat removal systems	Manufacture of heat pipes	Experimental set-ups under design
	Testing of heat pipes	
	Gas gap filling system	
Development of carbon based materials	High density isotropic graphite	Available
Development of high temperature structural materials	Refractory metals and their alloys	Under development
Development of coatings	PyC, SiC, Silicide etc. based coatings development	Many sample pieces coated
Development of codes for design of brittle materials	Validated codes and databases for design of brittle materials	Under development

Indian High Temperature Reactor for Hydrogen Production (IHTR-H)

- 600 MWTh, 1000 °C, TRISO Fuel
- Combination of active and passive systems for control & cooling
- Medium life core

Status: Options being evaluated for the design

Fuel configuration:

- Prismatic block
- Pebble bed

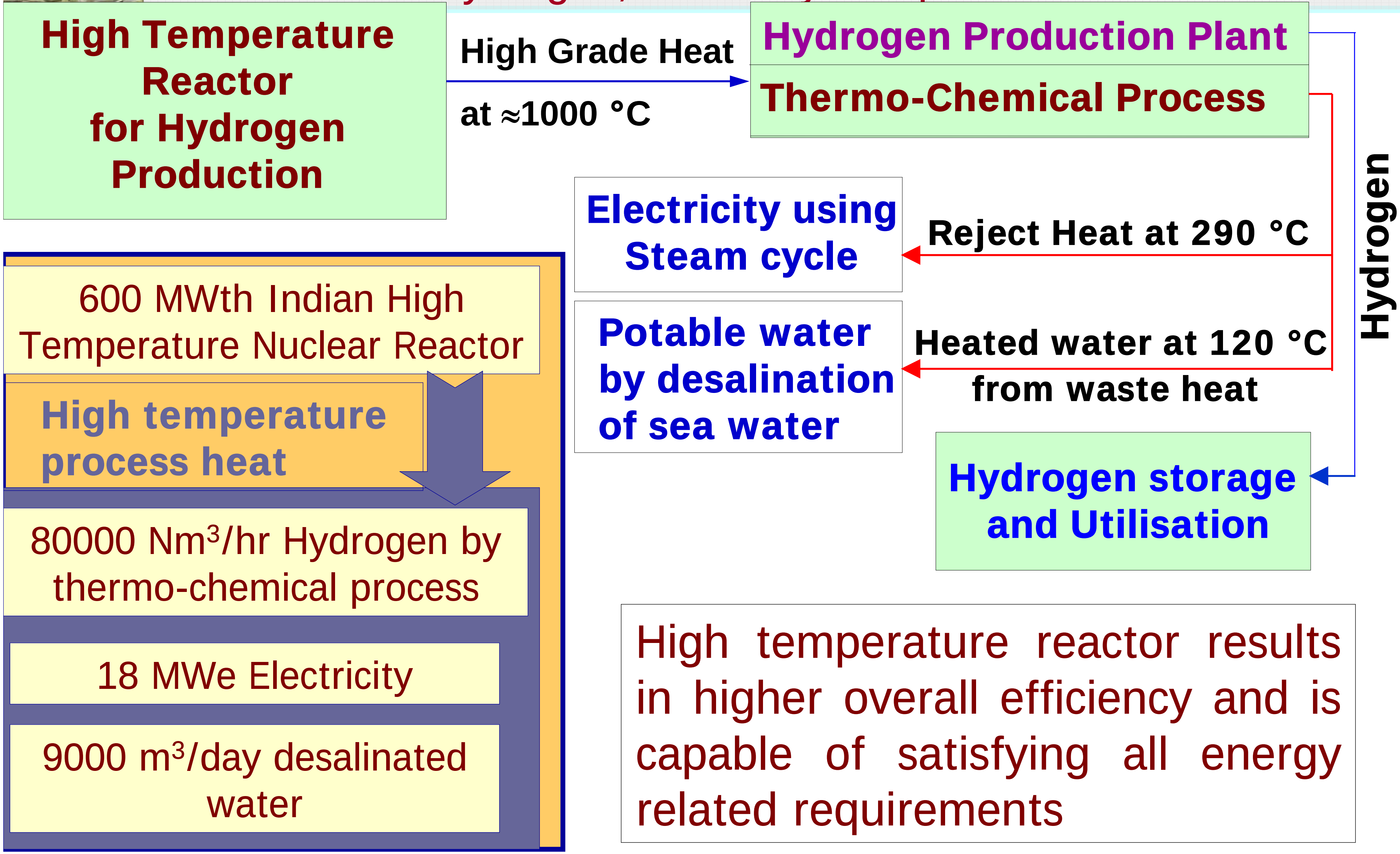
Coolant configuration:

- Pressurized Helium
- Molten Pb/ molten salt

Proposed Broad Specifications of Indian High Temperature Reactor for Hydrogen Production (IHTR-H)

Reactor power	600 MWth for following deliverables (Optimised for hydrogen production) ▪Hydrogen: 80,000 Nm^3 /hr ▪Electricity: 18 MWth ▪Drinking water: 375 m^3/hr
Coolant outlet temperature	1000°C
Moderator	Graphite
Coolant	Pb/ Molten salt
Reflector	Graphite
Mode of cooling	Natural circulation of coolant
Fuel	$^{233}UO_2$ & ThO_2 based high burn-up TRISO coated particle fuel
Refueling period	2-3 years
Control	Passive power regulation and reactor shutdown systems
Energy transfer systems	Intermediate heat exchangers for heat transfer to Helium or other medium for hydrogen production + High efficiency turbo-machinery based electricity generating system + Water desalination system for potable water
Hydrogen production	High efficiency thermo-chemical processes

The high temperature reactor based nuclear hydrogen production system aims to satisfy total energy needs of a region in the form of hydrogen, electricity and potable water



High Temperature Reactor for Hydrogen Production

High Grade Heat

at ≈1000 °C

Hydrogen Production Plant

Thermo-Chemical Process

Electricity using Steam cycle

Reject Heat at 290 °C

Potable water by desalination of sea water

Heated water at 120 °C from waste heat

Hydrogen

Hydrogen storage and Utilisation

600 MWth Indian High Temperature Nuclear Reactor

High temperature process heat

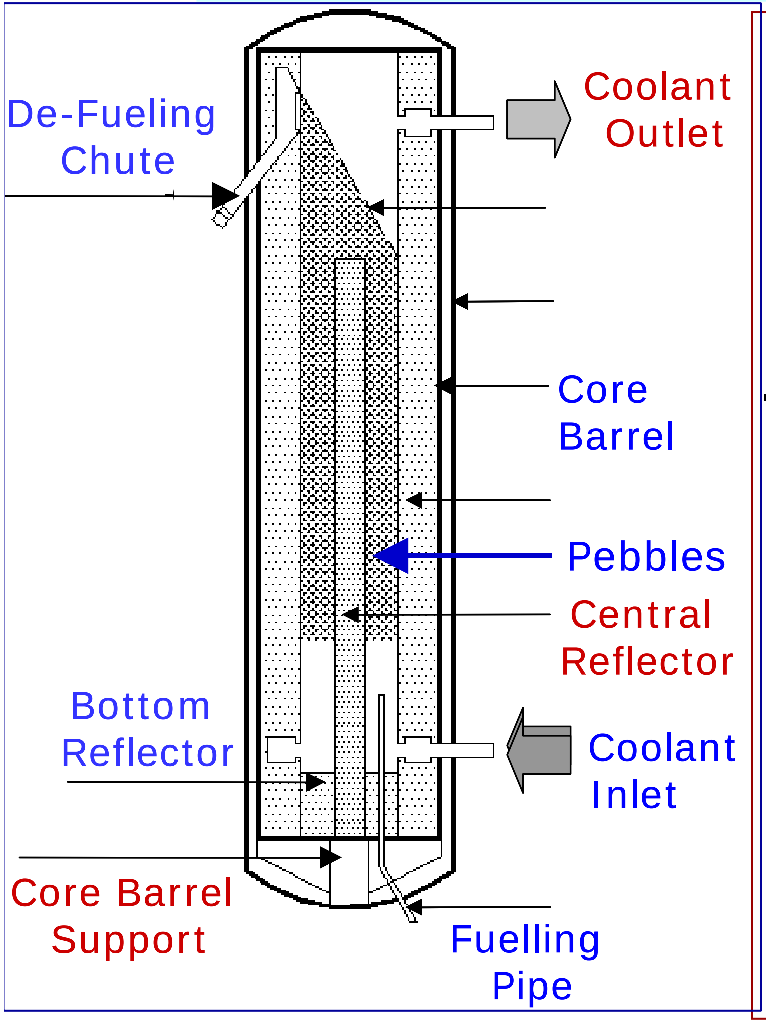
80000 Nm^3/hr Hydrogen by thermo-chemical process

18 MWe Electricity

9000 m^3/day desalinated water

High temperature reactor results in higher overall efficiency and is capable of satisfying all energy related requirements

Pebble bed reactor with molten lead/ molten salt coolant selected for detailed design and development work (Preliminary design stage)



De-Fueling Chute

Coolant Outlet

Core Barrel

Pebbles

Central Reflector

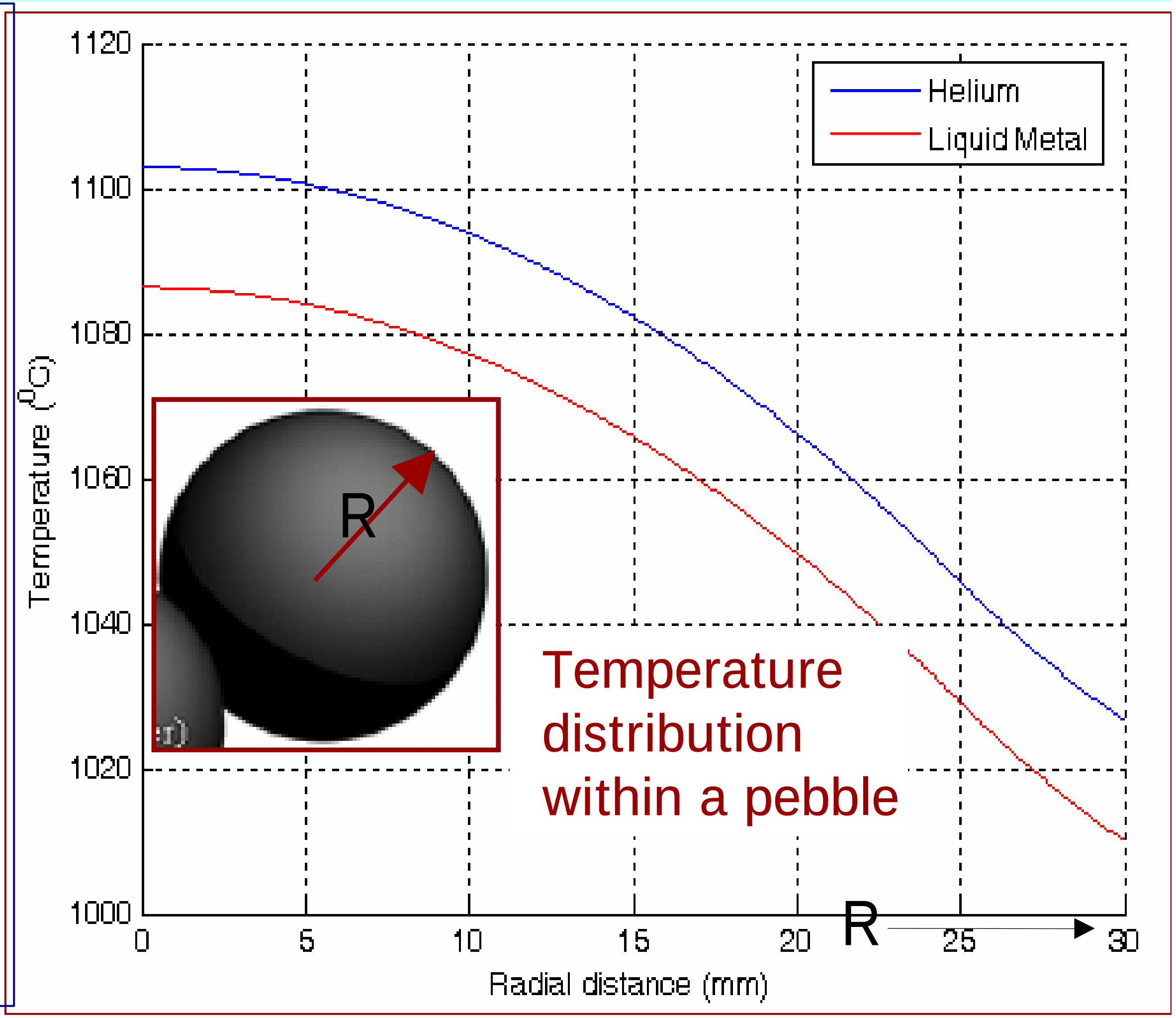
Bottom Reflector

Coolant Inlet

Core Barrel Support

Fuelling Pipe

Schematic of the reactor



Temperature distribution within a pebble

A large number of R & D activities are being planned for the development of this reactor

These activities are broadly in the areas of reactor component development, fuel development, materials & coating development, development of characterization techniques, molten lead/molten salt based coolant technologies, interface systems between nuclear and chemical plants, and safety & seismic studies

Programme includes analytical and experimental studies

- Development of reactor core and other components
- Development of systems for pebble loading and unloading
- Development of pebble fuel based on TRISO coated particles
- Development of materials and coatings
- Large size and coated graphite components
- Compatibility issues of materials with molten lead/ salt based coolant
- Irradiation and high temperature behaviour of materials
- Seismic design related issues
- Development of interface systems between nuclear reactor and hydrogen production plant
- Materials and coatings for interface systems between hydrogen plant and nuclear reactor
- Safety studies including issues related to combined operation of a nuclear and a hydrogen production plant

Summary

1. In future Indian energy scenario, nuclear energy assisted hydrogen production is expected to play a significant role
2. Development of technologies related to high temperature nuclear reactors is an important step in that direction
3. These reactors pose new challenges as regards fuel and materials are concerned
4. Emphasis is on inclusion of passive design features to the extent possible
5. R & D work have been initiated for most of the developmental work
6. An internationally accepted design as well as safety guidelines/code for components of high temperature reactors would help in addressing many safety related issues in more effective manner

Thank you