COMPACT HIGH TEMPERATURE REACTOR (CHTR)

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Summary

CHTR is a mainly ^{233}U-Thorium fuelled, lead-bismuth cooled and beryllium oxide moderated reactor. This reactor, initially being developed to generate about 100 kW_{Th} power, will have a core life of 15 years and will have several advanced passive safety features to enable its operation as compact power pack in remote areas not connected to the electrical grid. The reactor is being designed to operate at 1000°C, to also facilitate demonstration of technologies for high temperature process heat applications such as hydrogen production from water. Larger power reactors would be designed subsequently.

1.0 Introduction

In the long term, nuclear energy would emerge as the primary source of energy replacing fossil fuels. Thus, in addition to producing electricity, it would provide necessary energy for producing alternate fuel or energy carrier for transport applications. Considering very small petroleum reserves and increasing oil prices worldwide, it is prudent that India find an alternative to oil for its transport applications. High temperature reactor assisted fluid fuel production is a long-term sustainable alternative. CHTR, being developed in BARC, is a prototype technology demonstrator reactor in the direction of fulfilling these objectives.

2.0 Description

The reactor core [1] consists of nineteen prismatic beryllium oxide (BeO) moderator blocks. These 19 blocks contain centrally located graphite fuel tubes. Each fuel tube carries fuel inside 12 equi-spaced longitudinal bores made in its wall. The fuel tube also serves as coolant channel. The fuel is based on TRISO coated particle fuel, which can withstand very high temperature (1600°C). These particles are mixed with graphite powder as a matrix and made into cylindrical fuel compacts. The fuel compacts are packed in fuel bores in the walls of each of the nineteen fuel tubes. Eighteen blocks of beryllium oxide reflector surround the moderator blocks. These eighteen blocks have central holes to accommodate passive power regulation system. This system works on temperature feedback, and in case of rise of coolant outlet temperature beyond design value, inserts negative reactivity inside the core. Graphite reflector blocks surround these beryllium oxide reflector blocks. This part of the reactor is contained in a shell of a material resistant to corrosion against Pb-Bi eutectic alloy coolant, and suitable for high temperature applications. Top and bottom closure plates of similar material close this reactor shell. The fuel, moderator, and reflector blocks are contained in a reactor shell made of high temperature and liquid metal corrosion resistant material. Top and bottom closure plates of the same material close the reactor shell. Above the top cover plate and below the bottom cover plate, plenums are provided for core-outlet and core-inlet coolant respectively. These plenums have graphite flow guiding blocks, having passages for coolant flow, to increase the velocity of the coolant between the fuel tube and down comer tube. The reactor shell is surrounded by two gas gaps that act as insulators during normal reactor operation and reduce heat loss in the radial direction. There is an outer steel shell, surrounded by heat sink. This outer shell has fins to improve heat dissipation. Schematic of a single fuel bed and cross-sectional layout of the reactor core are shown respectively in Figure-1 and Figure-2 below:

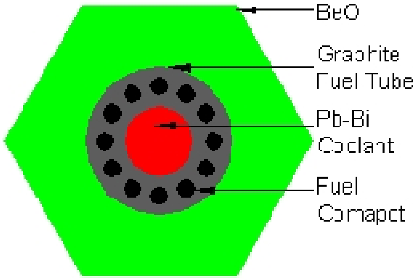


Figure-1: Single CHTR fuel bed

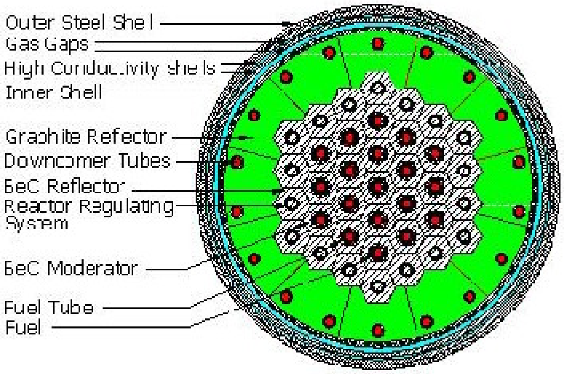


Figure-2: CHTR core cross-sectional layout

A passive system has been provided to fill the gas gaps with molten metal in case of abnormal rise in coolant outlet temperature so as to facilitate a conduction path for the reactor heat to outside heat sink. Nuclear heat from the reactor core is removed passively by a lead-bismuth eutectic alloy coolant, which flows due to natural circulation between the bottom and top plenums, upward through the fuel tubes and returning through the downcomer tubes. On top of the upper plenum, the reactor has multi-layer heat utilisation vessels to provide an interface to systems for high temperature heat applications. A set of sodium heat pipes is in the upper plenum of the reactor to passively transfer heat from the upper plenum to the heat utilisation vessels with a minimum drop of temperature. Another set of heat pipes transfers heat from the upper plenum to the atmospheric air in the case of a postulated accident. To shut down the reactor, a set of seven shut-off rods has been provided, which fall by gravity in the central seven coolant channels. Instrumentation like neutron detectors; sensors; and auxiliary systems such as a cover gas system, purification systems, etc. would be incorporated in the design. CHTR component layout is shown in Figure-3. Major design and operating characteristics of CHTR are shown in Table-1.

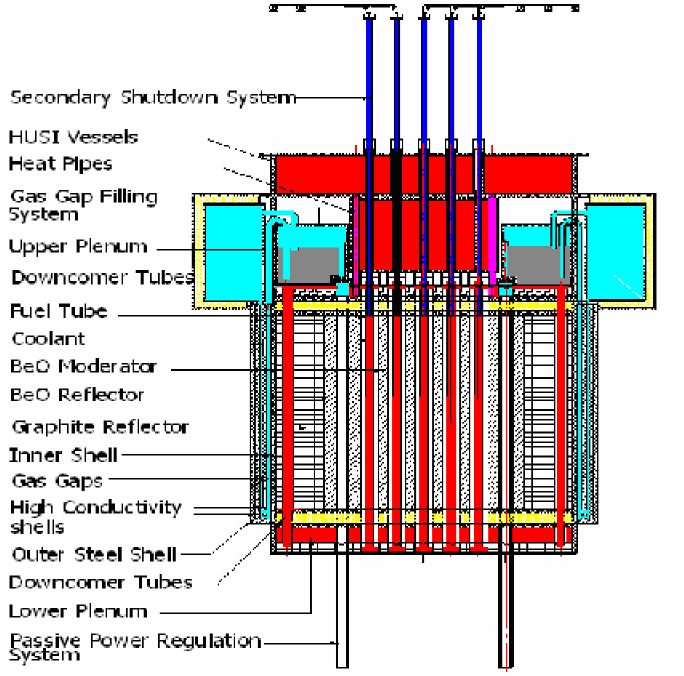


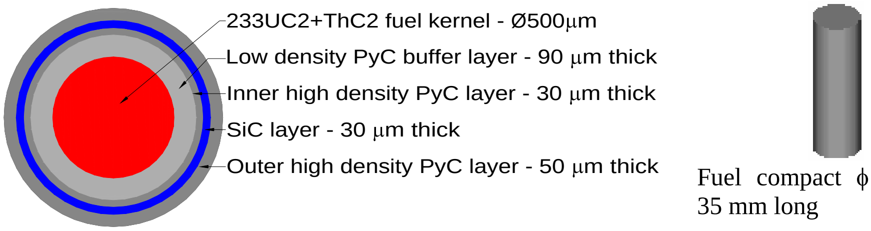
Figure-3: CHTR components layout

Table -1: Major design and operating characteristics of CHTR

Attributes	Design Parameters
Reactor power	100 kW(th)
Core configuration	Vertical, prismatic block type
Fuel	$^{233}UC_2$+ ThC_2 based TRISO coated fuel particles shaped into fuel compacts with graphite matrix
Fuel enrichment by ^{233}U	33.75 weight %
Refuelling interval	15 effective full power years
Fuel Burnup	≈ 68000 MWd/t of heavy metal
Moderator	BeO
Reflector	Partly BeO and graphite
Coolant	Molten Pb-Bi eutectic alloy (44.5% Pb and 55.5% Bi)
Mode of core heat removal	Natural circulation of coolant
Coolant flow rate through core	6.7 kg/s
Coolant inlet temperature	900 °C
Coolant outlet temperature	1000 °C
Loop height	1.4 m (actual length of the fuel tube)
Core diameter	1.27 m (including radial reflectors)
Core height	1.0 m (Height of the fuelled part and axial reflectors)
Primary shutdown system	18 floating annular B_4C elements of passive power regulation system
Secondary shutdown system	7 mechanical shut-off rods

3.0 Fuel Elements

Cylindrical fuel compacts are packed in fuel bores located in the walls of each fuel tube. These fuel compacts comprise TRISO coated fuel particles embedded in graphite matrix. Figure-4 shows schematic of TRISO coated particle fuel and fuel compact.



Fuel compact ϕ10 mm, 35 mm long

Figure-4: Schematic of a TRISO coated particle fuel and fuel compact

4.0 Passive Power Regulation System (PPRS) and Shutdown System [2]

CHTR incorporates a Passive Power Regulation System (PPRS). This system works on the principle of increase of gas pressure with temperature thereby pressurising and forcing a column of molten metal with floating absorbing material into the core. This introduces negative reactivity in the core. Depending on the temperature rise sensed, the system would stabilize at a particular value of reactivity insertion. The PPRS operation was analyzed using an in-house developed computer code. CHTR has been provided with a passive secondary shutdown system. Under normal operation this system has a set of seven shut-off rods held on top of the reactor core by individual electro-magnets, which are passively released under abnormal conditions when the temperature of the core goes up.

5.0 Passive Core Heat Removal Under Normal Operation

During normal operation of the reactor, the core heat is removed by natural circulation of lead-bismuth eutectic alloy coolant. The coolant at 900° C enters the fuel tube in lower plenum, takes the reactor heat, and at 1000° C it is delivered to the upper plenum. Heat is transferred from the upper plenum to a system of heat utilising vessels by heat pipes [3]. Thermal hydraulic analyses were carried out to study natural circulation of the primary loop. A computer model based on the law of conservation of momentum was developed for this analysis. The mass flow rate of coolant and velocity in the fuel tube was found to be 6.7 kg/sec and 0.04 m/sec respectively.

6.0 Passive Heat Removal Under Accident Conditions [3]

CHTR has three independent and redundant passive heat removal systems to cater to different postulated accident conditions. These heat removal systems, which are individually capable of removing neutronically limited power of 200 $kW_{Th,}$ may operate together or independently to prevent the temperature of the core and coolant from increasing beyond a set point. For the loss of load condition, when coolant circuit is intact, a system of six variable conductance heat pipes delivers heat to atmosphere. A system of twelve carbon-carbon composite variable conductance heat pipes provided in reactor core caters to the need when coolant is lost. Another passive heat removal system involves filling of the gas gaps by siphon with a molten metal to provide a conduction heat path from reactor core to heat sink provided outside the outer steel shell.

7.0 Inherent safety features and passive safety systems

CHTR is being designed to have many features, which make it inherently safe. In addition, many passive systems for reactor control, reactor shutdown and reactor heat removal under normal and postulated accident conditions, have been incorporated. These are listed below:

7.1 CHTR has following inherent safety features:

i) A strong negative Doppler coefficient of the fuel for any operating condition;
ii) High thermal inertia of the all-ceramic core and low core power density;
iii) A large margin between the normal operating temperature of the fuel (around 1100 °C) and the leak tightness limit of the TRISO coated particle fuel (1600 °C) to retain fission products and gases;
iv) A negative moderator temperature coefficient;
v) Due to the use of the Pb-Bi coolant, which operates at low pressure, there is no over pressurisation and no chance of reactor thermal explosion due to coolant overheating;
vi) Due to a very high boiling point (1670 °C), there is a very large thermal margin to Pb-Bi boiling. This also eliminates the possibility of heat exchange crisis and increases the reliability of heat removal from the core;
vii) There is a negligible thermal energy stored in the coolant and available for release in the event of a leak or accident;
viii) The high temperature Pb-Bi coolant is chemically inert. Even in the eventuality of contact with air or water, it does not react violently with explosions or fires;
ix) No pressure in the coolant allows the use of a graphite coolant channel, improving neutronics of the reactor;
x) A low induced long-lived gamma activity of the coolant; in case of a leakage, the coolant retains iodine and other radionucleides.
xi) For Pb-Bi coolant, the reactivity effects (void, power, temperature, etc.) are negative.

7.2 CHTR employs following passive systems:

- i) Natural circulation of coolant to remove reactor heat during normal operation;
- ii) Passive regulation of reactor power under normal operation;
- iii) Passive shutdown for postulated accidental conditions;
- iv) Passive means of conduction of core heat by filling up the gas gaps with molten metals;
- v) Passive transfer of reactor heat by heat pipes under normal and postulated accident conditions;
- vi) Passive removal of heat from the reactor core by carbon-carbon composite heat pipes.

8.0 Thermal analysis

A three-dimensional finite element method (FEM) was used for thermal analysis of the CHTR. Figure-4 shows a steady state distribution of the reactor middle plane temperature The temperature is seen to be almost constant within the reactor core and the reflector region. The drops in temperature, as expected, occur in two gas gaps provided to prevent loss of heat in the radial direction. Under postulated accident conditions, neutronic limited power becomes 200% of normal power. Temperature distribution under this condition when molten liquid is filled in the gas gaps is shown in Figure-5. Transient analysis under postulated accident condition and in perfect adiabatic conditions showed that the temperature of the fuel would not reach its design limit for 50 minutes, thereby providing sufficient time for operator action.

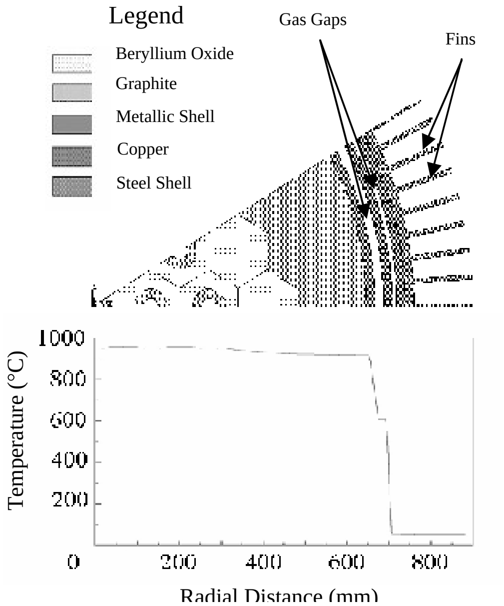


Figure-4: Steady state radial temperature distribution within and outside the core.

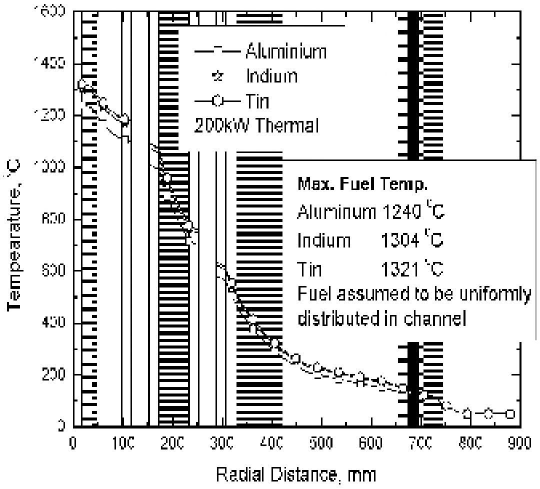


Figure-5: Temperature distribution under postulated accident condition

9.0 Major Research & Development Issues and Critical Technologies for CHTR

This reactor calls for research and development activities in many areas of nuclear engineering. There are requirements of high chemical purity special materials like beryllium oxide, graphite and refractory metals with oxidation and corrosion resistant coatings. The fuel needed is high performance high temperature capable special type of TRISO coated particle fuel. In addition, the reactor design incorporates many passive systems for reactors control and heat removal. Table-2 lists some of the prominent development areas and their current status.

Table-2: Important research & development areas for CHTR

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 fabricated
	Validated codes for simulation of thermal-hydraulic behaviour of Pb-Bi coolant in primary circuit, under natural circulation	
	Compatibility of materials with Pb-Bi coolant	
	Instrumentation and components like electro-magnetic pumps and flow meters for liquid metal coolant	Under development
Development of passive power regulation system	Validated computer codes to simulate operation of passive power regulation system	Experimental set up under procurement
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 graphite and carbon materials	High density isotropic graphite	Under development
Development of high temperature structural materials	Refractory metals	Under development
Development of oxidation- and corrosion-resistant coatings	PyC, SiC, Silicide etc. based coatings development	Under development
Development of codes for design of brittle materials	Validated codes and databases for design of brittle materials	Under development

10.0 Current status and schedule

At present, a feasible design of the CHTR has been established after completing the conceptual design of the reactor and associated systems. Experimental facilities are under various stages of development to carry out various studies related to liquid metals, passive safety and heat removal systems. The manufacturing capabilities for BeO, carbon components, and fuel micro-spheres have been demonstrated. Trials for TRISO coatings have already started. Subsequent to the manufacture of fuel, materials and other systems, an experimental facility for CHTR would be set up around 2011-12.

11.0 References

[1] R.K. Sinha and S. Banerjee, Nuclear Energy to Hydrogen, International conference on roadmap to hydrogen economy organized by INAE, Hyderabad, March 4-5, 2005

[2] P.P. Kelkar, A. Basak, S.S. Jana, and R.K. Sinha, Passive Power Regulation and Shut down System in Compact High Temperature Reactor, INSAC-2005

[3] A. Basak, I.V. Dulera and R.K. Sinha, Passive Accident Condition Heat Removal Systems for CHTR, INSAC-2005