SAFETY DESIGN FEATURES OF THE CHTR

Bhabha Atomic Research Centre (BARC),
India

X-1. Description of the CHTR concept

The Compact High Temperature Reactor (CHTR) is a lead-bismuth cooled beryllium oxide moderated reactor, designed to operate mainly with ^{233}U-Th fuel. The concept of this reactor, which is initially being developed to generate about 100 kW(th), has a core lifetime of 15 years and incorporates several advanced passive safety features to enable its operation as a compact power pack in remote areas not connected to the electrical grid. The reactor, being designed to operate at 1000°C, would also facilitate demonstration of the technologies for high temperature process heat applications, such as hydrogen production by splitting of water. The CHTR concept is described in detail in [X-1].

The CHTR core consists of nineteen prismatic beryllium oxide (BeO) moderator blocks. These moderator blocks have graphite fuel tubes located centrally. Each fuel tube carries fuel inside 12 equidistant longitudinal bores. The fuel tube also serves as a coolant channel. The CHTR fuel is based on tri-isotropic (TRISO) coated particle fuel. Coated particles are mixed with graphite powder as a matrix material and shaped into cylindrical fuel compacts. Fuel bores of each of the nineteen fuel tubes are packed with fuel compacts. Eighteen blocks of beryllium oxide reflector surround the moderator blocks. Centrally, these blocks accommodate passive power regulation system. Graphite reflector blocks surround these beryllium oxide reflector blocks. Cross-sectional layout of the reactor core is shown in Fig. X-1 below.

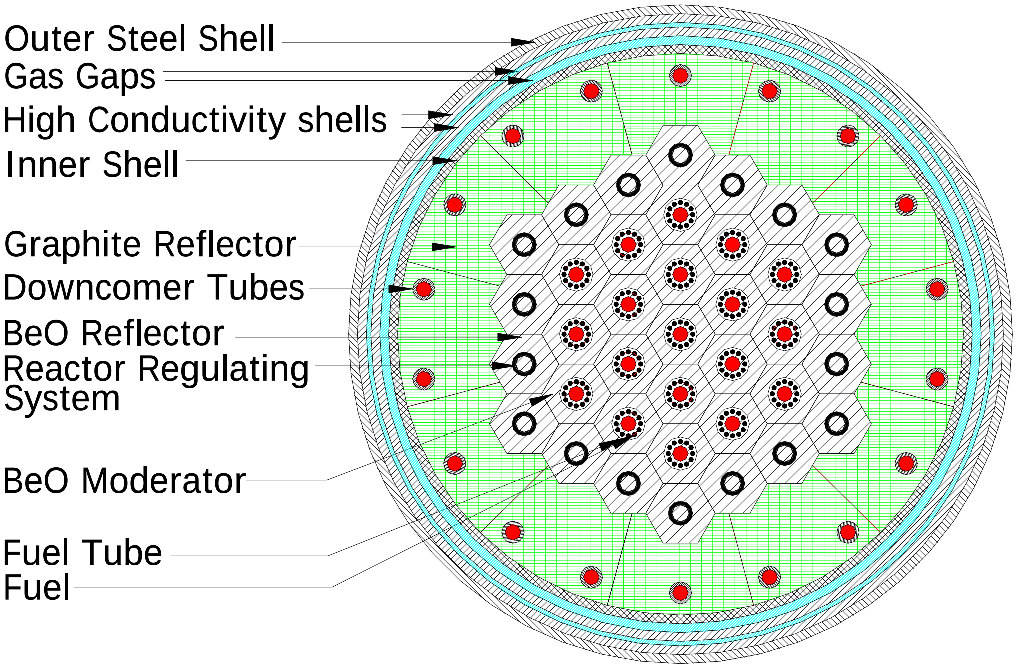

FIG. X-1. Cross-sectional layout of CHTR core.

The core and the reflector part of the reactor are contained in a metallic shell resistant to corrosion against Pb-Bi eutectic alloy coolant, and suitable for high temperature applications. Top and bottom closure plates made of similar material close this reactor shell. Above the top cover plate and below the bottom cover plate, coolant plenums are provided. These plenums have flow guiding blocks made of graphite and having passages for coolant flow to increase the velocity of the coolant between fuel tubes and down-comer tubes. Two gas gaps surround the reactor shell and act as insulators during normal reactor operation, reducing heat loss in the radial direction. A finned outer steel shell is provided, which is surrounded by a heat sink. Nuclear heat from the reactor core is removed passively by the Pb-Bi eutectic alloy coolant, which flows due to natural circulation between the bottom and the top plenums, upward through the fuel tubes, and returning through the down-comer tubes. On top of the upper plenum, heat utilization vessels are located, providing an interface to the systems for high temperature heat applications. A set of sodium heat pipes is provided in the upper plenum of the reactor for passive transfer of heat from the upper plenum to the heat utilization vessels. Three passive systems are provided to remove heat in the case of postulated accident conditions. One of the systems has a set of heat pipes to transfer heat from the upper plenum to the atmosphere in the case of a postulated accident. Another passive system is intended to fill the gas gaps with molten metal in the case of an abnormal rise in the coolant outlet temperature, so as to facilitate conduction flow of the reactor heat to the outside heat sink. To shut down the reactor, a set of seven shut-off rods is included, which fall driven by gravity in the central seven coolant channels. Major design and operating parameters of the CHTR are shown in Table X-1.

TABLE X-1: MAJOR DESIGN AND OPERATING PARAMETERS OF CHTR [X-1]

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
Fuel enrichment by ^{233}U	33.75 weight %
Refuelling interval	15 effective full power years
Fuel burn-up	≈ 68 000 MW·day/t of heavy metal
Moderator	BeO
Reflector	Partly BeO, and partly 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)

ATTRIBUTES	DESIGN PARAMETERS
Primary shutdown system	18 floating annular B_4C elements of passive power regulation system
Secondary shutdown system	7 mechanical shut-off rods

CHTR component layout is shown in Fig. X-2.

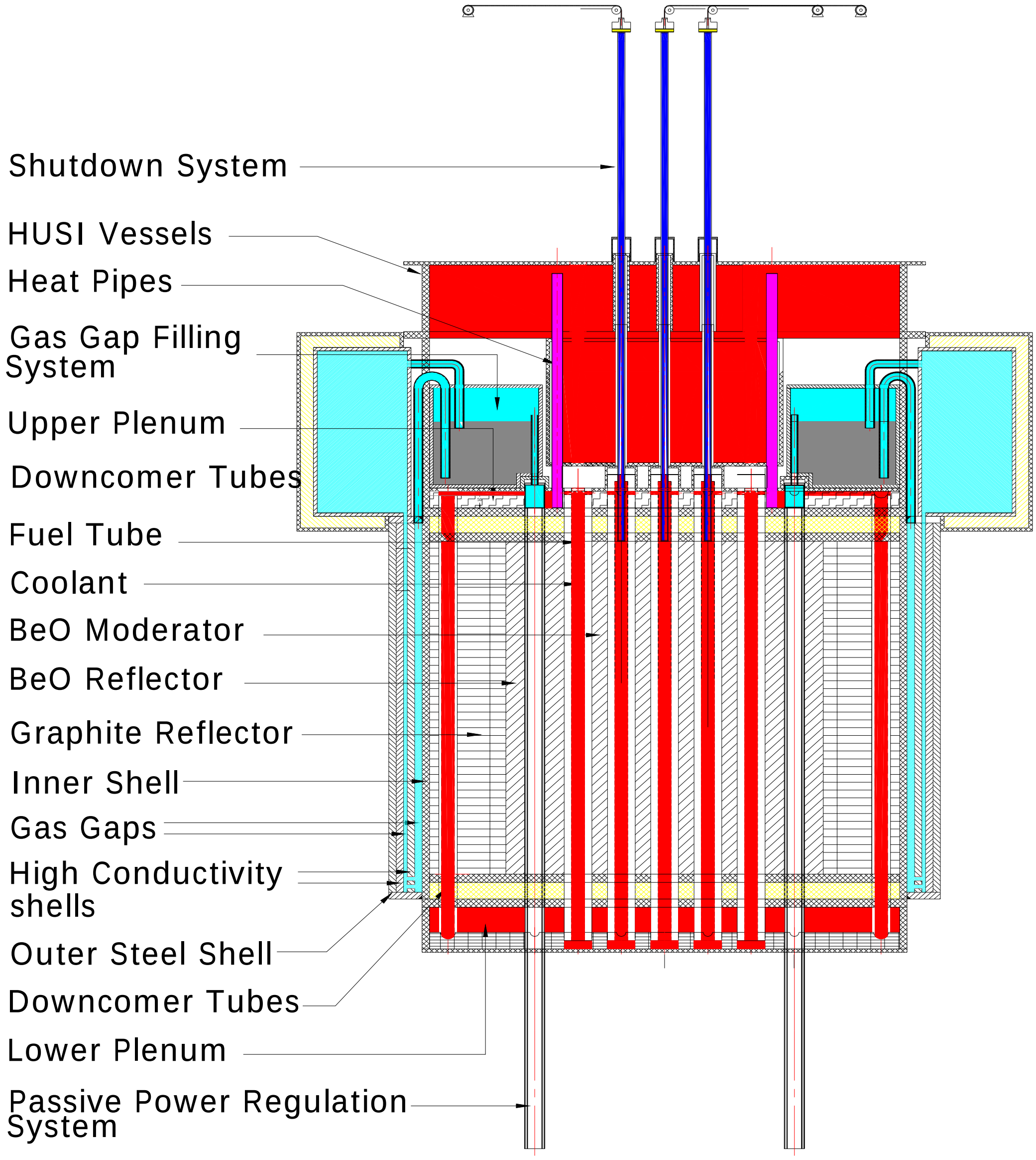

FIG. X-2. Layout of CHTR fuel.

CHTR fuel consists of $^{233}UC_2$, ThC_2, and small amount of gadolinium as burnable poison (provided only in central fuel tube). Thorium and burnable poisons make the fuel temperature coefficient negative, thus making the reactor inherently safe. The fuel is in the form of fuel compacts made of TRISO coated particle fuel embedded in graphite matrix. This type of fuel can withstand temperatures up to 1600°C [X-1, X-2]. A typical CHTR fuel bed consists of a prismatic BeO moderator block with centrally located graphite fuel tube carrying the fuel compacts. Schematics of a fuel particle, a fuel compact, and a single fuel bed are shown in Fig. X-3.

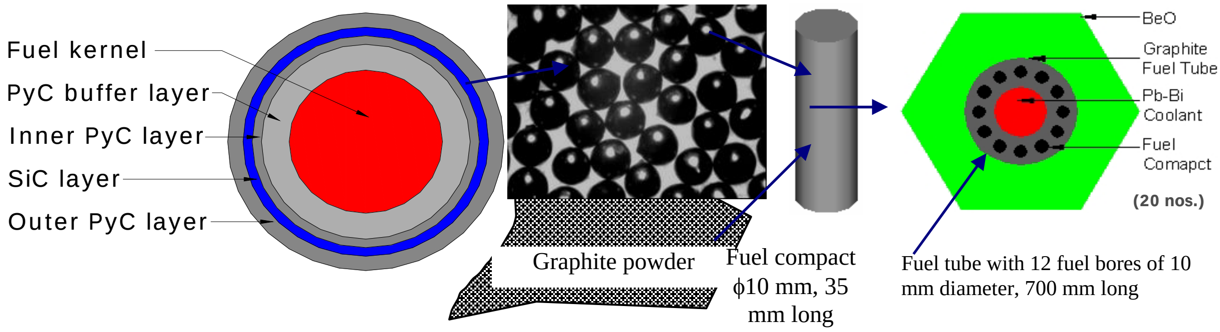

FIG.X-3. Schematic of TRISO coated particle fuel, fuel compact and a single fuel bed.

X-2. Passive safety design features of the CHTR

The *inherent and passive safety features* falling under category A defined in IAEA-TECDOC-626 [X-3] are the following:

- A strong negative Doppler coefficient of the fuel for any operating condition, resulting in a reduction of the reactor power in the case of fuel temperature rise during any postulated accident scenario;
- High thermal inertia of the all-ceramic core and low core power density, resulting in very slow temperature rise of the reactor core components as well as fuel during a condition when all heat sinks are lost;
- A large margin between the normal operating temperature of the fuel (around 1100°C) and the allowable limit of the TRISO coated particle fuel (1600°C), intended to retain fission products and gases and resulting in their negligible release during normal operating conditions. This also provides a “healthy” margin of around 500°C to take care of any unwanted global or local power excursions;
- A negative moderator temperature coefficient results in lowering of the reactor power in the case of an increase in the moderator temperature due to any postulated accident condition;
- Due to the use of lead-bismuth alloy based coolant having very high boiling point (1670°C), there is a very large thermal margin to Pb-Bi boiling, the normal operating temperature being 1000°C. This eliminates the possibility of heat exchange crisis and increases the reliability of heat removal from the core. The coolant operates at low pressure, there is no over pressurization and no chance of reactor thermal explosion due to coolant overheating;
- The high temperature Pb-Bi coolant, which is maintained in inert gas atmosphere, is itself chemically inert. Even in the eventuality of a accidental contact with air or water, it does not react violently and does not cause any explosions or fires;
- Due to above atmospheric melting point of 123°C, even in the case of a primary system leakage, the coolant solidifies and prevents further leakage;
- There is a small thermal energy stored in the coolant, which is available for release in the event of a leak or accident;

- Very low pressure in the coolant allows the use of a graphite/ carbon based coolant channel having a low neutron absorption cross-section, thus improving the neutronics of the reactor;
- A low induced long-lived gamma activity of the coolant, such that in the case of a leakage the coolant retains iodine and other radio-nuclides.
- For Pb-Bi coolant, the reactivity effects (void, power, temperature, etc.) are negative; thus reducing the reactor power in the case of any inadvertent power or temperature increase.

The *passive safety systems* falling under Categories B, C, D defined in IAEA-TECDOC-626 [X-3] are described below.

Passive power regulation system

CHTR incorporates a passive power regulation system (PPRS). This system operates on the principle of an increase of gas pressure with temperature thereby pressurizing 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. This passive system can be classified as category-B passive system [X-3]. It is a safety grade system. A brief description of the system is provided below.

The passive power regulation system consists of 18 different passive power regulation units (PPRU), each of which is centrally housed in the 18 beryllia reflector blocks. Schematic view of a PPRU is shown in Fig. X-4.

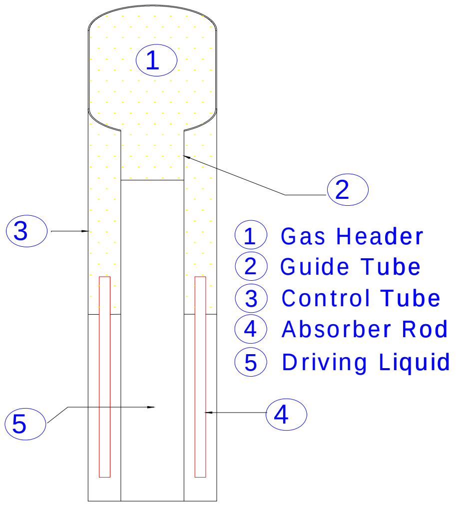

FIG. X-4. Schematic view of PPRS.

The PPRU is tube-in-tube design. The outer tube is a control tube and the inner tube is the driver tube. The driver tube also serves as a guide to the absorber. The boron carbide (B_4C) based absorber is an annular structure; it is housed in the annular space between the control and driver tubes. There is liquid lead-bismuth in these tubes, and the two tubes are in fluidic communication via orifices at the bottom of the driver tube. Free liquid surfaces are maintained in both of the tubes. The volume above the liquid is filled with helium. The absorber floats on the lead-bismuth. A gas header is provided at the top of the driver tube; it is located in the upper plenum, submerged in the coolant. This system operates on the principle of a change in gas pressure with temperature and, therefore, is a category-B passive system [X-3].

When the reactor is critical, the PPRS absorber is located at particular insertion in the core. At this steady state, the gas in the header will be at equilibrium with the coolant temperature in the upper plenum. Any deviation from this equilibrium state will cause the gas to either pressurize or depressurize the driver tube, due to an increase or decrease in temperature respectively. As the control and driver tubes are in fluidic communication, this pressure change will be communicated to the control tube. The net result will be a change in the liquid lead-bismuth levels in both tubes. Since the absorber is riding on the free liquid surface in the annular space between the control and driver tubes, it will also be pushed in or pulled out with pressurization or depressurization, respectively, thereby changing the reactivity. This system is capable of shutting down the reactor.

Passive shutdown system

The CHTR incorporates a passive shutdown system. Under normal operation, this system has a set of seven shut-off rods, made of tungsten, and held on top of the reactor core by the individual electro-magnets, with their magnetic holding power energized by a set of low power batteries. These shut-off rods are passively released under abnormal conditions when the temperature of the coolant or core goes up. These shut-off rods fall in the central bore of the fuel tubes provided for coolant flow. This is a fail safe system, so that in case of a loss of power from batteries, the shut-off rods would fall and shut down the reactor. This passive system can be classified as Category-D passive system [X-3]. It is a safety grade system.

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. This passive system can be classified as Category-B passive system. It is a safety grade system. A brief description of it is given below.

The reactor operates at 100 kW(th) and the lead-bismuth eutectic alloy coolant flowing in the main heat transport system by natural circulation removes the heat generated in the fuel. Lead-bismuth eutectic alloy has a high boiling point (1670°C) at atmospheric pressure. This facilitates a low pressure primary system, which is a safety feature of liquid metal cooled reactors. The main coolant-circulating loop comprises fuel tubes, down-comers and top and bottom plenums. A simplified view of the system discussed is shown in Fig. X-5. The fuel transfers the energy to the coolant flowing upward inside the fuel tubes due to natural circulation. 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. The active heat generation length in the reactor is 700 mm. The buoyancy head developed in the coolant loop is adequate to maintain the required flow rate for normal power level. A computer code, based on the law of conservation of momentum, was developed for this analysis.

Passive transfer of heat to the secondary system

A set of twelve high temperature sodium heat pipes passively transfer heat from upper plenum of the reactor to a set of heat utilization vessels, which are kept directly above the upper plenum. This system can be classified as Category-B passive system [X-3]. It is a safety grade system.

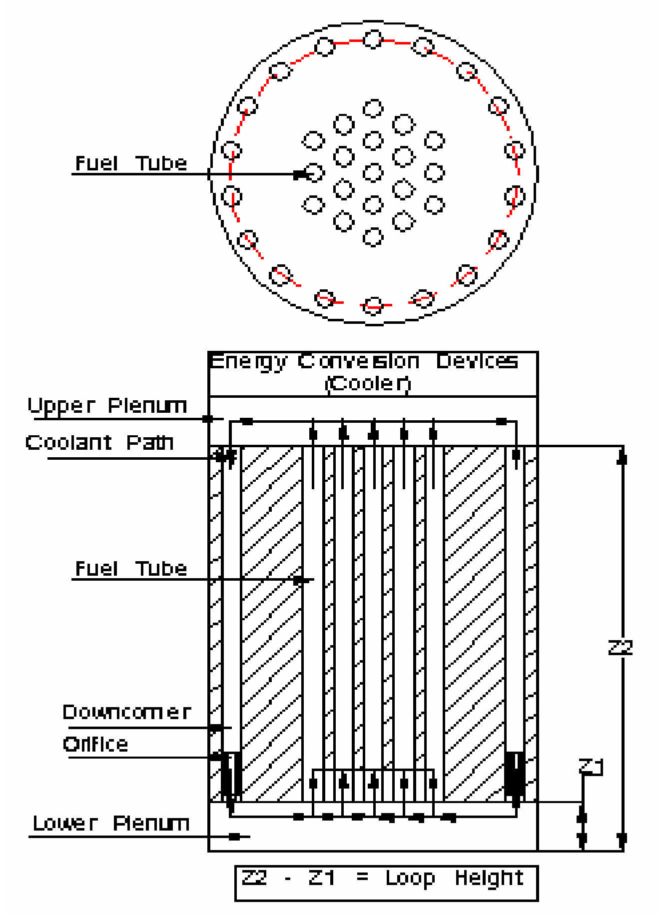

FIG. X-5. Schematic view of CHTR primary circuit loop.

Passive heat removal under postulated accident conditions

The 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 a neutronically-limited power of 200 kW(th) (200% of normal reactor power), 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 sodium heat pipes dissipates heat to the 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 two gas gaps, provided outside the reactor vessel, by a siphon action with a molten metal to provide a conduction heat path from the reactor core to a heat sink provided outside the outer steel shell. Each of these three systems can be classified as Category-B passive systems [X-3]. These are safety grade systems. A brief description of the gas gap filling system is provided below; its schematic view is shown in Fig. X-6.

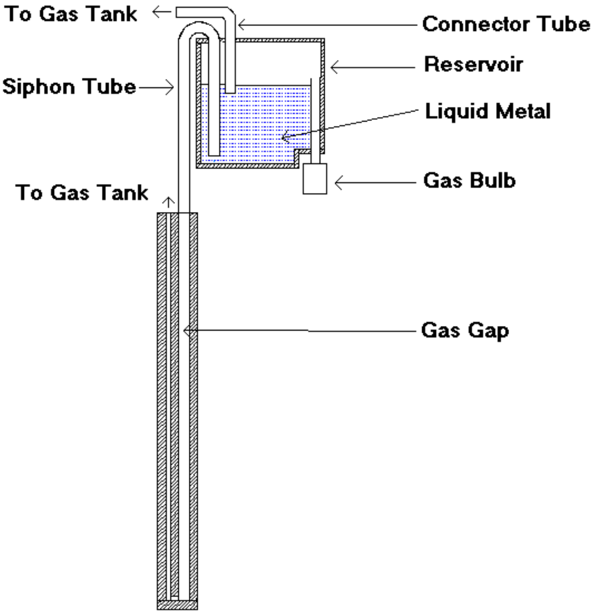

FIG. X-6. Gas gap molten metal filling based passive accident condition heat removal system.

The system consists of a reservoir located above the upper plenum and subdivided into compartments. The liquid metal is stored in the reservoir, which is fitted with siphon tubes and bulbs. One end of the siphon is dipped into the liquid metal and the other opens into the inner gas gap; multiple siphon tubes are employed. The bulb is located immediately downstream of the heat pipes and normally senses a temperature of 900°C. In a case of non-availability of the heat pipes, the coolant immediately senses a temperature of 1000°C. This would increase the pressure of the gas inside the bulb, cause the liquid metal to rise inside the siphon tube and ultimately, start the siphon. The liquid metal would then exit into the inner gas gap and also fill the outer air gap through holes in the inner gas gap wall. The gas inside the gas gap would be pushed into a gas tank. A connector between the liquid metal and the gas tank would handle the decrease in pressure caused by the fall in level of the liquid metal in the reservoir, such that after some time, the pressure in the reservoir and in the gas gaps would be equalised.

The CHTR incorporates the following *active systems*, which are all non safety grade.

Passive shutdown - reset system:

In order to move the shut-off rods to their position of suspension in electromagnets, CHTR employs a motorized and wire rope based active system. This is a back-up system.

Passive gas gap heat removal – reset system:

In order to drain and move the molten metal from the gas gaps to a reservoir, CHTR employs an electromagnetic pump based reset system. This is a back-up system.

De-fuelling and refuelling system:

After the operation of fuel up to a desired burn-up, fuel tubes containing fuel compacts will be replaced by new fuel tubes carrying fresh fuel compacts. This replacement operation will be done using an active system. This is a back-up system.

X-3. Role of passive safety design features in the defence-in-depth

Some major highlights of the passive safety design features in CHTR, structured in accordance with the various levels of defence in depth [X-4, X-5], are brought out below.

Level 1: Prevention of abnormal operation and failure

The CHTR design features contributing to this level are as follows:

(a) Heat removal from the core under normal operating conditions is accomplished through natural circulation of the coolant, which essentially eliminates the hazard of a loss of coolant flow;

(b) The extent of overpower transients and their consequences are limited by:

i) Low core power density;

ii) A highly negative Doppler (fuel temperature) coefficient, achieved through the selection of an appropriate fuel composition;

iii) Use of a burnable poison to compensate for reactivity change with burn-up;

iv) Negative reactivity effects (void, power, temperature, etc.) achieved with the use of the lead-bismuth based coolant;

v) Use of all-ceramic core with high heat capacity and high temperatures margins; and

vi) The resulting low excess reactivity.

Level 2: Control of abnormal operation and detection of failure

The CHTR design features contributing to this level are the following:

i) Increased reliability of the control system achieved through the use of a passive power regulation system. This system inserts negative reactivity in the core when temperature increases beyond the allowable limits;

ii) The use of two independent passively operating shutdown systems;

iii) The use of a high heat capacity ceramic core to prevent fuel temperature from exceeding the design limits for a long time.

The abovementioned design features are expected to result in the reactor operation and safety functions being fully passive and requiring minimum operator intervention.

Level 3: Control of accidents within the design basis

Features of the CHTR that contribute to this level are:

i) The use of two independent shutdown systems, one comprising mechanical shut-off rods and the other employing a temperature feedback gas-expansion based passive shutdown system, altogether resulting in an increased shutdown reliability;

ii) The use of two independent systems to transfer reactor core heat to the outside environment during abnormal conditions, one comprising a gas gap filling system and the other, a heat pipe based system;

iii) The use of an independent system based on carbon-carbon composite heat pipes for the transfer of heat from the reactor core to the atmosphere in the case of a loss of coolant;

iv) The use of a high heat capacity ceramic core to prevent fuel temperature from exceeding the design limits for a long time.

Level 4: Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe accidents

The features important for this level are:

i) Excellent high temperature (up to 1600°C) performance of the TRISO coated particle fuel, ensuring that the probability of a release of fission products and gases is very low;

ii) Large heat capacity ceramic core, resulting in a slow fuel temperature rise with more than 50 minutes being available for a corrective action even when all heat sinks are lost;

iii) The use of a heat sink outside the outer steel shell;

iv) The erection of the reactor in an underground pit with sealed barrier of reinforced concrete and steel covers is foreseen to provide an additional barrier for the prevention of release of radioactive nuclides.

Level 5: Mitigation of radiological consequences of significant release of radioactive materials

Passive design features of the previous levels avoid any significant release of radioactive materials and necessity for evacuation or relocation measures outside the plant site.

X-4. Acceptance criteria for design basis and beyond design basis accidents

X-4.1. List of design basis and beyond design basis accidents

A preliminary list of design basis accidents (DBA) and beyond design basis accidents (BDBA) is the following:

a) Inadvertent withdrawal of one control rod of passive power regulation system so as positive reactivity is inserted;

b) Loss of load accident;

c) Loss of coolant accident; and

d) Air ingress.

A number of inherent and passive safety features in the design of the CHTR prevent the TRISO coated particle fuel from exceeding the limiting temperatures in postulated accidents or abnormal events [X-1]. No further details were provided.

X-4.2. Acceptance criteria

To ensure safety (i.e. to meet allowable radiological consequences during all foreseeable plant conditions) the following fundamental safety functions should be ensured in operational states, in and following a DBA and in and after the occurrence of BDBA conditions for the events a), b), and c) specified in X-4.1:

- Control of the reactor power so as to limit maximum fuel kernel centre temperature by less than 1600°C;
- Removal of heat from the core so as to maintain fuel kernel centre temperature less than 1600°C; and
- Confinement of radioactive materials and control of operational discharges, as well as limitation of accidental releases. This is again ensured by keeping the fuel kernel centre temperature less than 1600°C.

X-5. Provisions for safety under external events

The safety design features of the CHTR intended to cope with external events and external/internal event combinations are described in detail in [X-6].

Combinations of events considered in the design are:

- Earthquake;
- Aircraft crashes;
- Cyclones;
- Flooding.

The protection against earthquake is provided by various structures, systems, and components for CHTR being designed appropriately for high level and low probability seismic events such as the operating basis earthquake (OBE) and the safe shutdown earthquake (SSE) [X-6]. Seismic instrumentation, such as isolators and dampers, are also planned.

For protection against aircraft crashes and cyclones, the reactor will be installed in an underground pit with low exterior profile of the reactor building to reduce a possibility of the aircraft impact and the adverse effects of cyclones. Additionally, the reactor will be first provided with a low leakage thick steel vessel to absorb energy in the case of a postulated aircraft impact.

For protection against flooding, the reactor will be provided with a low leakage thick steel vessel with a reduced number and size of the penetrations to prevent water ingress in the reactor systems. Additional water tight barriers and ducts will be provided for systems communicating to the control room.

X-6. Probability of unacceptable radioactivity release beyond plant boundary

The probability of unacceptable radioactivity release beyond the plant boundary is targeted to be less than 1×10^{-7}/year.

X-7. Measures planned in response to severe accidents

Due to the above mentioned features provided in the reactor, no adverse effect on public domain is anticipated.

X-8. Summary of passive safety design features for CHTR

Tables X-2 to X-6 below provide the designer’s response to the questionnaires developed at an IAEA technical meeting “Review of passive safety design options for SMRs” held in Vienna on 13 – 17 June 2005. These questionnaires were developed to summarize passive safety design options for different SMRs according to a common format, based on the provisions of the IAEA Safety Standards [X-4] and other IAEA publications [X-5, X-3]. The information presented in Tables X-2 to X-6 provided a basis for the conclusions and recommendations of the main part of this report.

TABLE X-2. QUESTIONNAIRE 1 – LIST OF SAFETY DESIGN FEATURES CONSIDERED FOR/INCORPORATED INTO THE CHTR DESIGN

#	SAFETY DESIGN FEATURES	WHAT IS TARGETED?
1.	High negative Doppler (fuel temperature) coefficient	Reduction of the extent of overpower transient so as to keep the maximum fuel (kernel of TRISO coated particle fuel) temperature less than 1600°C
2.	Burnable poison in fuel	
3.	Small excess reactivity	
4.	Pb-Bi coolant - the reactivity effects (void, power, temperature, etc.) are negative	
5.	Negative moderator temperature coefficient	
6.	Low core power density	
7.	TRISO coated particle fuel	Low probability of release of fission products and gases even at very high temperature up to 1600°C
8.	High heat capacity ceramic core	Large thermal inertia ensures slow temperature rise of fuel even in the case when all heat sinks are lost
9.	Use of Pb-Bi eutectic alloy as coolant	Chemically inert to water and air at high temperature
		High boiling point and good thermal properties increases reliability of heat removal from the core
		Operating temperature being much below the boiling point - results in a low pressure system, reducing the possibility of high pressure related accidents as well as facilitating the use of carbon based coolant tubes so as to improve neutron economy
		In the case of a leakage, it solidifies, preventing further leakage as well as retaining the radioactive nuclides present in the coolant
10.	Heat removal from the core by natural circulation	Elimination of the pump failure related initiating events, such as Loss of Coolant Flow
11.	Passive power regulation system	Passive power regulation
12.	Two independent shutdown systems	Redundancy in reactor protection during the transient/ postulated accident conditions
13.	A system of gas gap filling with high conductivity molten metal	Passive means of core heat removal under abnormal conditions and of transfer of heat to a heat sink outside the shell.
14.	Heat pipe based heat removal system during normal operation	Transfer of heat passively from coolant to the heat utilizing system vessels
15.	Variable conductance heat pipes	Heat dissipation from coolant to the outside environment during postulated accident conditions
16.	Carbon-carbon composite heat pipes	Heat dissipation from reactor core to the outside environment during postulated accident conditions
17.	Large capacity heat sink outside the outer steel shell	Absorb neutronically limited power fully in case of postulated accident condition

TABLE X-3. QUESTIONNAIRE 2 – LIST OF INTERNAL HAZARDS

#	SPECIFIC HAZARDS THAT ARE OF CONCERN FOR A REACTOR LINE	EXPLAIN HOW THESE HAZARDS ARE ADDRESSED IN A SMR
1.	Prevent unacceptable reactivity transients	• Passive power regulation and shutdown systems; • Highly negative Doppler (fuel temperature) coefficient; • TRISO coated particle fuel – capable of withstanding very high temperature and retaining fission products; • Large heat capacity all ceramic core, resulting in slow temperature rise; • Negative moderator temperature coefficients; • Three redundant and passive heat removal systems to dissipate neutronically limited power to the atmosphere/ heat sink; • Pb-Bi coolant, ensuring that the reactivity effects (void, power, temperature etc.) are negative.
2.	Avoid loss of coolant	• Low pressure, high density, and high melting point Pb-Bi coolant leaks out very slowly in the case of a break in the circuit and eventually solidifies; • Natural circulation of Pb-Bi coolant in normal operation mode with no piping and joints in the circuit, thus reducing chances of loss of coolant; • High boiling point of Pb-Bi coolant (1670°C)
3.	Avoid loss of heat removal	• Natural circulation of Pb-Bi in normal operation mode • Three redundant and passive heat removal systems to dissipate neutronically limited power to atmosphere/ heat sink under postulated accident conditions;
4.	Avoid loss of flow	• Natural circulation of Pb-Bi coolant in normal operation mode; No piping and joints in the circuit, thus avoiding chances of loss of flow;
5.	Avoid exothermic chemical reactions: Graphite fire (Reaction with oxygen/ water)	Graphite with SiC as outer coating is unlikely to burn Blanket of inert gas on top of the coolant Low pressure, high density, and high melting point Pb-Bi coolant leaks out very slowly in the case of a break in the circuit and eventually solidifies – low probability of ingress of a large quantity of air Water ingress in the core and contact with the graphite is an unlikely event, as water is present only as an ultimate heat sink outside the thick steel vessel with no openings
6.	Polonium activity (specific for lead-bismuth eutectic cooled reactors)	- Inert gas blanket provided on top of the coolant prevents coolant from coming in contact with air – preventing the release of radioactivity; - In case of a leak – coolant will solidify, preventing further leakage

TABLE X-4. QUESTIONNAIRE 3 – LIST OF INITIATING EVENTS FOR ABNORMAL OPERATION OCCURRENCES (AOO) / DESIGN BASIS ACCIDENTS (DBA) / BEYOND DESIGN BASIS ACCIDENTS (BDBA)

#	List of initiating events for AOO / DBA / BDBA typical for a reactor line (heavy liquid metal cooled reactors)	Design features of CHTR used to prevent progression of the initiating events to AOO / DBA / BDBA, to control DBA, to mitigate BDBA consequences, etc.	Initiating events specific to this particular SMR
1.	Inadvertent withdrawal of one control rod of passive power regulation system so as positive reactivity is inserted	High negative Doppler (fuel temperature) coefficient	Nothing in particular specified here
		Passive power regulation and shutdown systems	
		Negative moderator temperature coefficient	
		Pb-Bi coolant, for which the reactivity effects (void, power, temperature, etc.) are negative	
2.	Loss of load accident	Highly negative Doppler (fuel temperature) coefficient	
		Two redundant and passive heat removal systems to dissipate the neutronically limited power to a heat sink	
		Passive power regulation and shutdown systems	
		Large heat capacity of the all-ceramic core results in a slow temperature rise	
		Low core power density	
		TRISO coated particle fuel with high temperature margin to failure	
3.	Loss of coolant accident	High negative Doppler (fuel temperature) coefficient	
		Passive shutdown system	
		Carbon-carbon composite heat pipes provided in the core to dissipate heat	
		Large heat capacity of the all-ceramic core results in a slow temperature rise	
		Low core power density	
		TRISO coated particle fuel with high temperature margin to failure	
4.	Air ingress to the primary coolant system	Graphite with SiC as outer coating is unlikely to burn	
		Blanket of inert gas on top of the coolant	
		Low pressure, high density, and high melting point Pb-Bi coolant leaks out very slowly in the case of a break in the circuit and eventually solidifies – low probability of a large quantity air ingress	

TABLE X-5. QUESTIONNAIRE 4 - SAFETY DESIGN FEATURES ATTRIBUTED TO DEFENCE IN DEPTH LEVELS

#	SAFETY DESIGN FEATURES	CATEGORY: A-D (FOR PASSIVE SYSTEMS ONLY), ACCORDING TO IAEA-TECDOC-626 [X-4]	RELEVANT DID LEVEL, ACCORDING TO NS-R-1 [X-4] AND INSAG-10 [X-5]
1.	High negative Doppler (fuel temperature) coefficient	Reduction of the extent of overpower transient so as to limit the maximum fuel (kernel of TRISO coated particle fuel) temperature by less than 1600°C — A	1, 3
		Mitigation of loss of load accident — A	
		Mitigation of loss of coolant accident — A	
2.	Burnable poison in fuel, minimizing the reactivity margin for fuel burn-up	Reduction of the extent of possible overpower transient so as to keep the maximum fuel (kernel of TRISO coated particle fuel) temperature less than 1600°C — A	1
3.	Small excess reactivity	Reduction of the extent of possible overpower transient so as to keep the maximum fuel (kernel of TRISO coated particle fuel) temperature less than 1600°C — A	1
4.	Pb-Bi coolant - the reactivity effects (void, power, temperature, etc.) are negative	Reduction of the extent of possible overpower transient so as to keep the maximum fuel (kernel of TRISO coated particle fuel) temperature less than 1600°C — A	1
5.	Negative moderator temperature coefficient	Reduction of the extent of possible overpower transient so as to keep the maximum fuel (kernel of TRISO coated particle fuel) temperature less than 1600°C — A	1
6.	Low core power density	Loss of coolant accident — A	1,3
		Loss of load accident	
7.	TRISO coated particle fuel with high margin to fuel failure	Loss of coolant accident — A	4
		Loss of load accident — A	
8.	High heat capacity ceramic core	Loss of coolant accident — A	1,2,3,4
		Loss of load accident — A	

#	Safety design features	Category: A-D (for passive systems only), according to IAEA-TECDOC-626 [X-4]	Relevant DID level, according to NS-R-1 [X-4] and INSAG-10 [X-5]
9.	Low pressure, high density, and high melting point Pb-Bi coolant leaks out very slowly in the case of a break in the circuit and eventually solidifies	Air ingress — A	1
10.	Heat removal from the core by natural circulation	Loss of flow accident — B	1
11.	Passive power regulation system	Reduction of the extent of possible overpower transient so as to keep the maximum fuel (kernel of TRISO coated particle fuel) temperature less than 1600°C — B	2
		Loss of load accident — B	
12.	Two independent shutdown systems	Reduction of the extent of possible overpower transient so as to keep the maximum fuel (kernel of TRISO coated particle fuel) temperature less than 1600°C — One B, and the other D	2,3
		Loss of load accident — One B, and the other D	
		Loss of coolant accident — One B, and the other D	
13.	A system of gas gap filling with high conductivity molten metal	Loss of load accident — A	3
14.	Heat pipe based heat removal system during normal operation	B	1, partially 3
15.	Variable conductance heat pipes, intended to dissipate core heat	Loss of load accident— B	3
16.	Carbon-carbon composite heat pipes, intended to dissipate core heat	Loss of coolant accident — B	3
17.	Large capacity heat sink outside the outer steel shell	Loss of load accident — A	4
18.	Construction of the reactor in an underground pit	External events — A	4

TABLE X-6. QUESTIONNAIRE 5 - POSITIVE/ NEGATIVE EFFECTS OF PASSIVE SAFETY DESIGN FEATURES IN AREAS OTHER THAN SAFETY.

PASSIVE SAFETY DESIGN FEATURES	POSITIVE EFFECTS ON ECONOMICS, PHYSICAL PROTECTION, ETC.	NEGATIVE EFFECTS ON ECONOMICS, PHYSICAL PROTECTION, ETC.
Natural circulation of heavy metal coolant	Saving in cost of the pump and associated components; saving due to the simplified design and maintenance	Higher specific cost of reactor due to lower core power density selected for demonstration, because TRISO particles occupy larger volume as compared to conventional fuel
Thorium fuel cycle with TRISO coating based fuel configuration	Increased proliferation resistance	
Heat pipe based heat transfer to secondary system	Simplified design and maintenance, saving in cost of heat exchanger and associated components	
Passive power regulation system	Simplified design and maintenance, saving in cost with respect to conventional complex mechanism based system	
Passive heat removal based on gas gap filling with molten metal in accident conditions	Simplified design and maintenance, the associated reduction in cost	

References

[X-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Small Reactor Designs without On-site Refuelling, IAEA-TECDOC-1536, Vienna (2007).

[X-2] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Innovative Small and Medium Sized Reactor Designs 2005: Reactors with Conventional Refuelling Schemes, IAEA-TECDOC-1485, Vienna (2006).

[X-3] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Related Terms for Advanced Nuclear Plants, IAEA-TECDOC-626, Vienna (1991).

[X-4] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, Safety Standards Series, No. NS-R-1, IAEA, Vienna (2000).

[X-5] INTERNATIONAL ATOMIC ENERGY AGENCY, Defence in Depth in Nuclear Safety, INSAG-10, Vienna (1996).

[X-6] INTERNATIONAL ATOMIC ENERGY AGENCY, Advanced Nuclear Plant Design Options to Cope with External Events, IAEA-TECDOC-1487, Vienna (2006).