3. COMPACT HIGH TEMPERATURE REACTOR (CHTR)

INTRODUCTION

It is generally agreed that in the long term, nuclear energy would emerge as the primary source of energy replacing fossil fuels. It would be expected to satisfy all energy related needs of mankind. Thus, in addition to producing electricity, it would provide necessary energy for producing alternate fuel or energy carrier for transport applications, facilitating production of potable water and satisfy various heating needs of the populations living in colder parts of the country. Small and compact nuclear power packs with very long refuelling periods would supply electricity in areas not connected to the electrical grid of the country. A high temperature reactor has a large potential to satisfy all the above-mentioned needs.

The Compact High Temperature Reactor (CHTR), under development at BARC, is mainly $^{233}$U-Thorium fuelled, lead-bismuth cooled and beryllium oxide moderated reactor. This reactor, initially being developed to generate about 100 kWth 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 system. 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. Hydrogen is being considered world wide as future energy carrier for transport applications. The design guidelines for the reactor includes utilisation of thorium-based fuel, passive reactor safety and passive heat removal features under all operating conditions so as to have very low demands in operator skill and availability.
Compact High Temperature Reactor
Indian Technology Demonstrator HTR

Component Layout of Compact High Temperature Reactor
Description of the CHTR

The reactor core 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). A cross section of the particle fuel is shown below;

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. Schematic of a single fuel bed and cross-sectional layout of the reactor core are shown in the figure.
Above the top cover plate and below the bottom cover plate, plenums provide for core-outgoing and core-incoming coolant respectively. Nuclear heat from the reactor core is removed passively by the lead-bismuth liquid metal coolant which flows due to natural circulation between the plenums, upward through the fuel tubes and returning through the down comer tubes. These plenums have graphite flow guiding blocks to increase the velocity of the coolant between the coolant channel exit and the entry to the down comer tubes of the reactor. The flow-guiding blocks have passages for the coolant to flow from the inner to outer region of the plenum. 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 shell has been provided with fins to improve its heat transfer capabilities. A passive system has been provided to fill the gas gaps with molten metal in case of abnormal rises in coolant outlet temperature thereby providing a conduction path of heat transfer from reactor core to outside heat sink. 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. Appropriate instrumentation like neutron detectors, fission/ion chambers, various sensors and auxiliary systems such as a cover gas system; purification systems, active interventions etc. are being incorporated in the design as necessary. If temperature of coolant increases beyond its design value, a set of seven shut-off rods fall by gravity in the central seven coolant channels to shutdown the reactor.
**IMPORTANT DESIGN PARAMETERS OF CHTR**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power</td>
<td>100 kWth</td>
</tr>
<tr>
<td>Core configuration</td>
<td>Vertical, natural circulation type</td>
</tr>
<tr>
<td>Coolant</td>
<td>Molten lead-bismuth eutectic alloy</td>
</tr>
<tr>
<td>Number of fuel tubes</td>
<td>10 with 35 mm ID and 75 mm OD</td>
</tr>
<tr>
<td>Fuel</td>
<td>$^{235}\text{U}<em>{239}\text{Th}</em>{2}$ based TRISO (TRI-ISOtropic) coated particles made fuel compacts.</td>
</tr>
<tr>
<td>Refuelling period</td>
<td>15 Effective Full Power Years (EFPYs)</td>
</tr>
<tr>
<td>Fuel burnup</td>
<td>680000 MWh/Tonne</td>
</tr>
<tr>
<td>Fuel enrichment</td>
<td>33.75% (2.7 kg $^{235}\text{U} + 5.3$ kg Th)</td>
</tr>
<tr>
<td>Moderator material</td>
<td>BeO</td>
</tr>
<tr>
<td>Reflector material</td>
<td>Partially BeO and graphite</td>
</tr>
<tr>
<td>Lattice pitch</td>
<td>135 mm (triangular pitch)</td>
</tr>
<tr>
<td>Active fuel length</td>
<td>0.7 m</td>
</tr>
<tr>
<td>Total core flow rate</td>
<td>6.7 kg/s</td>
</tr>
<tr>
<td>Coolant inlet temperature</td>
<td>900 °C</td>
</tr>
<tr>
<td>Coolant outlet temperature</td>
<td>1000 °C</td>
</tr>
<tr>
<td>Loop height</td>
<td>1.4 m</td>
</tr>
<tr>
<td>Core height</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Core diameter</td>
<td>1.27 m</td>
</tr>
<tr>
<td>Passive power regulation system/ primary shutdown system</td>
<td>18 floating annular B$_4$C elements of passive power regulation system</td>
</tr>
<tr>
<td>Secondary shut down system</td>
<td>7 mechanical tungsten made shut off rods</td>
</tr>
</tbody>
</table>

**IMPORTANT SAFETY FEATURES OF CHTR**

- A strong negative Doppler coefficient of the fuel for any operating condition;
- High thermal inertia of the all-ceramic core and low core power density;
- A negative moderator temperature coefficient;
- 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;
- There is a very large thermal margin to Pb-Bi (Boiling point 1670 °C) boiling;
- Use of the low pressure Pb-Bi coolant - no over pressurization and no chance of reactor thermal explosion due to coolant emergency overheating;
- 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;
- There is a negligible thermal energy stored in the coolant and available for release in the event of a leak or accident;
- For coolant, the reactivity effects (void, power, temperature, etc.) are negative.
- A low induced long-lived gamma activity of the coolant; in case of a leakage, the coolant retains iodine and other radionuclides.
- No pressure in the coolant allows the use of a graphite coolant channel, improving neutron of the reactor.
PASSIVE SYSTEMS OF CHTR

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

TECHNOLOGY DEVELOPMENT AREAS

Materials Science and Technology
- Carbon, high density and isotropic graphite, and carbon-carbon composites for high temperature structures
- Development of high density BeO of different sizes and shapes
- Liquid metal coolant compatible alloys for high temperature structures
- Oxidation and corrosion resistant coatings for high temperature service
- Molten heavy metal coolant compatibility studies - with carbon based materials, with metallic alloys, with ceramics, and with coatings
- Technology for producing TRISO coated fuel particles and fuel compacts with $^{235}$U – Th fuel

Design, Systems and Components
- Reactor physics design and analysis of compact core
- Reactor physics data generation for materials at high temperatures
- Thermal hydraulics and material compatibility issues related to lead based liquid metal coolants
- High temperature, high heat flux, passive heat removal technologies including development of high temperature heat pipes
- Passive power regulation and shutdown systems
- Rules and methodologies for design of reactor components using brittle materials
- High temperature instrumentation and components for liquid metals

At the current stage, a feasible configuration of the reactor from reactor physics, heat removal and reactor control considerations have been worked out. R & D and technology development for most of the technology development areas have been initiated. For carrying out system studies, verifying the developed computer codes and for material compatibility studies; many experimental facilities are under development. Developmental work related to materials and fuels are being carried out. Analytical studies related to safety and effects of external events are underway.

Future Work and Design of New Reactors

- Experimental facility for CHTR (Initial operation at low temperature – subsequently increase in power to demonstrate high temperature capability)
- Design and development related activities for 600 MW$_{th}$ HTR for hydrogen production as well as a low power compact power pack for supplying electricity in areas not connected to electrical grid.
3.1 PHYSICS DESIGN OF CHTR

The physics design of the CHTR has been carried out with 2.7 Kg $^{233}$U in 8 Kg of fuel (U+Th). A core life of nearly 15 full power years could be achieved with the above configuration. The variation of K-eff with burnup is shown in the figure. Since the initial reactivity (> 100mk) is quite large, it had been decided to add a burnable poison to the fuel. Two options have been analysed respectively, with 180 g Erbium homogeneously mixed in fuel and 40 g Gadolinium only in the central fuel assembly. The effect of both types of burnable poisons can be seen in Figure. The Tables present the total worth of primary and secondary shut-down systems, fuel temperature coefficient and maximum worth of a single control rod when the reactor is in critical state.

When reactor is in critical state, if there is an inadvertent withdrawal of a control rod, a positive reactivity is introduced, resulting in power rise and rise in fuel and coolant temperatures. A negative reactivity feedback is introduced by the rise in fuel temperature and the power stabilizes at about 2 to 3 times the initial power. The variation of relative power, fuel and coolant temperatures with transient time for two types of burnable absorbers are illustrated.

<table>
<thead>
<tr>
<th>Reactor State</th>
<th>$K_{\text{eff}}$ at operating temp (1000 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All CRs IN</td>
<td>0.8501961</td>
</tr>
<tr>
<td>All CRs OUT</td>
<td>1.0488827</td>
</tr>
<tr>
<td>Total Worth of Control Rods</td>
<td>222.8 mk</td>
</tr>
</tbody>
</table>

Worth of control rods in primary shut-down system

<table>
<thead>
<tr>
<th>Shut off rods in coolant channel</th>
<th>$K_{\text{eff}}$ Tungsten without Clad (D=2.0 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 19 channel</td>
<td>0.6599</td>
</tr>
<tr>
<td>Inner 7 channel</td>
<td>0.8634</td>
</tr>
<tr>
<td>Outer 12 channels</td>
<td>0.8810</td>
</tr>
</tbody>
</table>

Worth of Shut-off rods in secondary shut-down system

Control rod worth and fuel temp. coeff. for different burnable absorbers

<table>
<thead>
<tr>
<th>Absorber</th>
<th>Max. Control Rod Worth (mk) at Critical Height</th>
<th>Fuel Temp. Coeff. $(\Delta T/k \degree C)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gadolinium</td>
<td>2.28</td>
<td>$\approx -1.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Erbium</td>
<td>1.74</td>
<td>$\approx -3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Variation of $K_{\text{eff}}$ with burnup for configurations with and without the burnable absorbers
3.2 MODELING OF PERFORMANCE OF TRISO PARTICLES

CHTR uses TRISO coated fuel particles. This study aims to model the behavior of the TRISO particle under irradiation. The TRISO fuel particles consist of a central fuel containing kernel surrounded by four layers, viz. low density pyrocarbon buffer layer, inner high-density pyrocarbon layer, silicon carbide layer and outer high-density pyrocarbon layer. The overall dimension of this particle is ~ 900 μm. The silicon carbide layer acts as the retaining layer for the fission products and no external cladding is needed. There are numerous mechanisms for failure of such particles viz. kernel migration, fission product attack on structural layer, etc. One such mode is by fracture of the silicon carbide layer (pressure vessel failure). Some preliminary modeling of TRISO particles has been initiated, by using FEM to model this pressure vessel failure mechanism. For these calculations, an axisymmetric element capable of modelling creep and irradiation induced swelling was formulated and programmed into a general purpose FEM code. A 0.5-degree sector (to maintain aspect ratio of one) of the TRISO particle was analysed. The dimensions of the particle and the meshing used are illustrated and the results along with comparison with available theoretical solutions for a perfectly spherical particle are presented in the Table.

<table>
<thead>
<tr>
<th></th>
<th>Analytical (MPa)</th>
<th>Soln. Results of developed FEM code (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial stress at ID of SiC layer</td>
<td>-7.94</td>
<td>-7.60</td>
</tr>
<tr>
<td>Radial stress at OD of SiC layer</td>
<td>-14.11</td>
<td>-13.01</td>
</tr>
<tr>
<td>Tangential stress at ID of OPyC</td>
<td>51.34</td>
<td>44.87</td>
</tr>
<tr>
<td>Tangential stress at ID of SiC layer</td>
<td>-47.69</td>
<td>-47.84</td>
</tr>
</tbody>
</table>

Comparison of stresses obtained in the present analysis with the analytical solution
The stresses induced have a statistical distribution due to the variations in kernel diameter, buffer layer thickness, etc. Additionally, the coating strengths also exhibit a Weibull distribution. All these variations need to be combined to estimate the failure fraction as a function of burn-up, using statistical tools, based on Monte Carlo techniques. This study will lead to evaluation of acceptability of the fabrication tolerances for TRISO particles and modeling of other degradation mechanisms.

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3.3 PASSIVE POWER REGULATION SYSTEM (PPRS)

The concept of passive power regulation is one of the important guidelines in the design of CHTR. The coolant temperature is used to passively drive the control rods, to achieve power regulation. The system performance analysis and its response to various anticipated scenarios are discussed.

The PPRS, has a gas header connected to a driver tube, control tube, floating absorber and lead bismuth eutectic. The control tube is concentric and surrounds the driver tube. The gas header, attached to a niobium driver tube acts as a temperature sensor.

The driver tube is housed within a niobium control tube and is filled with Pb-Bi eutectic. The control rod, which is housed in the control tube, is made up of boron carbide and is clad in niobium. The annular space between the driver and control tube is also filled with Pb-Bi eutectic and the control rod is designed to float in it. The system is thus designed to have two free liquid surfaces, one in the driver tube and the other in the control tube. The space above the liquid level is filled with an inert gas like argon. The PPRS gas header, located in the top plenum, is submerged in the coolant. The current location of the gas header ensures that it senses the coolant temperature immediately downstream of the heat removal devices (a set of heat pipes). Under normal operating conditions, the gas header is surrounded by coolant at a temperature of approx. 900 °C. Any condition, which causes the coolant to return at a temperature higher than the normal temperature will cause the gas, in the gas header, to also heat up. Due to this pressure will rise in the driver tube, causing a pressure imbalance between the driver and the control tube. This, in turn, will cause the level of Pb-Bi eutectic in the driver tube to go down and that in the control tube to go up. Since the absorber rod floats on Pb-Bi eutectic, it will also...
rise with the Pb-Bi eutectic level in the core, thus inserting negative reactivity. Depending on the temperature rise that has been sensed, the system will stabilise at a particular value of insertion. The PPRS was analysed using TRAPPOR (TRAnsient Passive POwer Regulation), a computer code developed in-house.

Simultaneously, means to actively control the CHTR are also being explored within the same setup. Analysis has been carried out for two scenarios, one in which the driver tube is pressurised and the other in which the control tube is depressurised.

In addition, work has been done to analyse the upper plenum design of the CHTR. Since the PPRS depends, for its operation, on the temperature signal carried by the coolant, it is important to know the time frame in which coolant will carry the signal to the PPRS header. The analysis showed that the coolant velocities are very low.

Following this analysis the design of the upper plenum has been changed to have channels for flow of the coolant. These channels serve as preferential flow paths and thus reduce the time interval in which the change is sensed. The headers are now submerged in pockets constructed along these channels.

Design of a PPRS test setup, for carrying out experimental analysis under various transients and validation of computer codes, is also underway.

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3.4 THERMAL ANALYSIS OF CHTR CORE UNDER NORMAL OPERATING AND POSTULATED ACCIDENT CONDITIONS

A detailed thermal analysis is essential in design, to ensure fuel integrity under all foreseeable scenarios, without operator intervention. A steady state analysis of the reactor core has been carried out to determine the prevalent temperatures under normal operating conditions, to estimate the thermal stresses. A steady state parametric analysis has also been carried out to estimate and minimise the heat loss from the reactor core, through the gas gaps by all modes, under normal operating conditions.

In the analyses it has been assumed that under postulated accident conditions, the reactor power stabilizes at a peak neutronically limited value of, twice the normal operating power and the entire heat is transferred to an outer heat sink by conduction, through the reactor vessel wall. The maximum fuel temperature has been calculated by a FEM analysis under steady state conditions. This has been followed by a transient analysis, to estimate the available time for safety devices to act. In this analysis it has been assumed that all heat sinks have been lost along with a sudden rise in power. It has also been assumed that an adiabatic boundary condition prevails for all surfaces. The initial temperature distribution has been applied from a steady state analysis and a step increase of twice the reactor power is assumed.

In all the above analyses the thermal contact resistances at all interfaces were assumed negligible. The heat generation in nuclear fuel and moderator has been considered. Appropriate material properties have also been assumed.

The temperature distribution given in the figure, at planes through the top, mid and bottom of the active length shows that the maximum temperature gradient occurs just outside the outermost location of the fuel channel and hence becomes the prime candidate for failure due to thermal stresses.
The variation of total heat loss with respect to inner gas gap shows that increasing this gap beyond 20 mm will not affect any significant economy in core heat.

The temperatures distribution obtained under postulated accident conditions with heat rejection to the outer heat sinks have been obtained by considering aluminium, indium and tin in the gas gaps which yielded maximum fuel temperatures well below the maximum allowable value for the fuel (1600°C).

The results from the transient analysis show that even after fifty minutes have elapsed after overpower, the fuel temperature does not exceed 1510°C, well below the limiting temperature of the fuel.

3.5 PRELIMINARY DESIGN OF GAS-GAP FILLING SYSTEM

One of the basic guidelines of CHTR design is the rejection of the entire core heat to a surrounding heat sink under a condition of heat sink loss and a neutronically limited power of 200 kW. This study aims to design such a system.

The preliminary design of the gas-gap filling system has been completed. A brief description of the system is given in the following paragraphs.

This system consists of a bulb, which is immersed in the liquid metal in the upper plenum, downstream to the heat pipes. This bulb
Communicates with a reservoir, which contains the liquid metal. The reservoir is connected to the inner gas gap by means of siphon tubes.

The bulb senses the temperature increase of the coolant and forces the liquid metal to move up the siphon tube and siphon is started. The liquid metal is conveyed to the inner gas gap by means of the siphon tube. Holes have been provided on the shell separating the two gas gaps at its bottom end so that liquid metal flows into the outer gas gap also. The gas displaced by the liquid metal is pushed into a gas tank.

As the level in the reservoir starts decreasing, the pressure of the gas above the liquid in the reservoir also decreases. This may prevent the flow of the liquid metal after certain time. To avoid such a situation, a vent tube is provided which is connected at one end to the gas tank and the other end is dipped into the reservoir up to a certain depth. When the liquid in the reservoir goes below this level, pressure on both sides becomes equal and this ensures that the siphon process is continued without any break. This system has an advantage that once started this system will stop only when the entire liquid metal has been poured down. To reduce the chances of common mode failure, the liquid metal reservoir is subdivided into four compartments, the capacity of each compartment catering to one quarter of the gas gap volume.

Three probable liquid metals, which can be used to fill the gas gaps, have been considered. These liquids are Indium, Tin and Aluminium which were chosen, due to their ease of availability, low melting points and good thermal conductivities.

Using this principle, the height of the siphon above the liquid level was calculated to be 135 mm for Indium and Tin and 380 mm for Aluminium for a set point of 1000°C. The gas bulb encounters this temperature in the event of a loss of heat sink.

A computer programme FD (Finite Difference) was written for estimating the time taken for filling the gas gaps by solving the one-dimensional momentum conservation equation by using finite difference methodology.

Typical variation of level in reservoir with time
The figure also shows the effect of the vent tube. The line A shows the liquid level in the reservoir, without considering the effect of the vent tube, wherein the pressure in the reservoir keeps decreasing, preventing the complete flow of liquid metal. The case in which the vent tube is incorporated is shown as B. The level in the reservoir falls below that of the excess liquid metal (indicated by the blue line), which implies that the gas-gaps have been filled.

Cases were analysed to get the gas-gap filling time for each of the three liquid metals considered. Different numbers of siphon tubes were also considered. The results are summarised.

<table>
<thead>
<tr>
<th>No. of siphon tubes per reservoir</th>
<th>Indium</th>
<th>Tin</th>
<th>Aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>26.0</td>
<td>25.9</td>
<td>22.8</td>
</tr>
<tr>
<td>6</td>
<td>23.2</td>
<td>23.2</td>
<td>20.4</td>
</tr>
<tr>
<td>7</td>
<td>21.2</td>
<td>21.3</td>
<td>18.6</td>
</tr>
<tr>
<td>9</td>
<td>18.45</td>
<td>18.5</td>
<td>16.1</td>
</tr>
</tbody>
</table>

A parametric analysis to fix the size of the bulb has also been carried out. The results indicate that as the volume of the gas and metal (of the bulb) decreases, the response also becomes faster. This may be accounted by the high heat transfer coefficient of the liquid metal, which makes the effect of decrease in surface area less apparent. A bulb of 5 cm diameter and 5 cm height gives a response time of 2 seconds and has been tentatively selected for use in the present system.

Estimates of the fuel temperatures, by using each of the above metals in the gas gaps, have been obtained by finite element analyses. The maximum fuel temperatures calculated are 1304°C, 1240°C and 1321°C for Indium, Aluminium and Tin respectively, which are much below the maximum allowable temperature (1600°C) of TRISO type fuel.

3.6 APPROACH FOR GRAPHITE COMPONENT DESIGN

A large proportion of CHTR is composed of graphite, a brittle material. Two draft codes, (which are yet to be finalized) are available for graphite component design of HTRs, namely the ASME Section III Division 2 Subsection CE and the KTA 3232, Ceramic internals for HTR pressure vessels, 1992.

In view of the absence of authoritative design rules for nuclear components, a literature survey was carried out to identify the design issues involved. In the design of brittle materials, the usual deterministic design procedures are invalidated by two behavioral characteristics, i.e., the statistical nature of its strength and its large variation. Hence the survival probability in a given stress distribution, is thereby calculated using Weibull statistical design technique. The accurate determination of statistical parameters, a large number of samples need to be tested. The fatigue curves for graphite follow the same pattern as that of metals, when drawn with homologous stress (peak stress divided by mean tensile strength) vs. number of cycles, but with a larger scatter in data.

Following this assessment a code Brittle Design.f90 was written. The failure probability of a given structure was estimated by utilising the stress distribution obtained from a FEM analysis. The effect of multiaxial stresses was incorporated by using the principle of superposition. The failure probability of each element is given by,

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This code has been used to estimate the failure probabilities of graphite reflector and the upper plenum blocks. The failure probability (Ps) of the entire structure is then calculated by,

\[
P_s = \prod_{\text{ELEMENTS}} \exp \left\{ - \int \left( \frac{\sigma_1}{\sigma_0} \right)^m + \left( \frac{\sigma_2}{\sigma_0} \right)^m + \left( \frac{\sigma_3}{\sigma_0} \right)^m \right\} \text{d}V \right\}
\]

<table>
<thead>
<tr>
<th>Where</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_1, \sigma_2, \sigma_3)</td>
<td>Principal stresses (assumed uniform within each element)</td>
</tr>
<tr>
<td>(\sigma_0)</td>
<td>Characteristic strength</td>
</tr>
<tr>
<td>(m)</td>
<td>Weibull modules</td>
</tr>
<tr>
<td>(V)</td>
<td>Volume of component</td>
</tr>
<tr>
<td>(c)</td>
<td>Element number</td>
</tr>
<tr>
<td>(P_s^e)</td>
<td>Survival probability of the (e^{th}) element</td>
</tr>
</tbody>
</table>

The failure probability (Ps) of the entire structure is then calculated by,

\[
P_s = \prod_{\text{ELEMENTS}} \exp \left\{ - \int \left( \frac{\sigma_1}{\sigma_0} \right)^m + \left( \frac{\sigma_2}{\sigma_0} \right)^m + \left( \frac{\sigma_3}{\sigma_0} \right)^m \right\} \text{d}V \right\}
\]

3.7 MODELING, DESIGN, FABRICATION AND TESTING OF HIGH TEMPERATURE HEAT PIPES

The heat pipe is a very effective device for transmitting heat at high transfer rates over considerable distances with extremely small temperature drops. They are simple in construction, easy to control, passive in operation and can be used in any orientation. Heat pipes are used in CHTR to remove heat, under normal operating and accidental conditions, from the primary coolant.

### Development of Computer Codes

A computer code “HPDATA” has been developed to simulate and carry out heat pipe design and analysis under steady state conditions. The heat pipe operation is dependent on various limits to its operation i.e. viscous limit, sonic limit, capillary limit, boiling limit and entrainment limit. This code can calculate the various operating limits for heat pipe operation and the parametric variation of these limits for various heat pipe diameters and wick configurations, by making use of empirical correlations. The code also calculates, the temperature drop between the heat pipe ends and the vapour pressure profile inside the heat pipe.

Variation of sonic and viscous limits with internal diameter of heat pipes

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**Development of High Temperature Heat Pipe Test Facility**

The high temperature heat pipe test set up aims to:

- study performance of heat pipes,
- study startup behaviour of frozen heat pipes,
- study operation under various transients and
- evaluate impact of corrosion by liquid metals under high temperature on heat pipe lifetime and performance
- Serve as a test bed for validating computer codes

The working temperature range for the setup has been selected as 400°C to 1200°C, so as to enable testing of moderate to high temperature heat pipes. With minor modifications, this may also be used for testing of low temperature heat pipes. The heat pipe has three regions - evaporator, adiabatic and condenser sections, which serve as heat input, heat transport and heat output areas respectively. Hence the facility has a means to input heat (by means of a heater), reject heat (to a calorimeter) and means to minimise heat losses (by means of insulation). The setup consists of a heat pipe enclosed in a metallic vessel. To prevent oxidation of the heat pipe material at high temperatures, the vessel is purged with a mixture of argon and helium gas. The portion of the vessel enclosing the condenser section of the heat pipe is cooled by means of silicone oil flowing in a helical coil wrapped around its outer diameter.

The purging gases also play an additional role in regulating the amount of heat removed. Heat losses from the adiabatic region is minimised by alumina based high temperature insulation surrounding the vessel. The evaporator portion of the heat pipe is surrounded by the heater arrangement, which is positioned inside the vessel. The heat pipe test setup is designed to test heat pipes at a maximum power input of 20 kW. In view of the large heat input, high temperatures involved and rapid heating requirement, a RF induction heater is used.

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3.8 THERMAL HYDRAULIC STUDIES ON THE COMPACT HIGH TEMPERATURE REACTOR (CHTR)

The reactor mainly consists of fuel tubes, solid moderator and reflector, coolant, Primary Heat Transfer (PHT) loop and safety & control systems. The flow of the coolant in the loop is maintained by natural circulation. The loop and the core are contained in a high temperature metallic vessel. Annular gas gaps are provided to reduce the radial heat loss during normal operating condition. The solid surfaces of the gaps are coated with low emissive material to reduce the heat transfer rate, further. These two gaps are followed by a high conducting solid wall and then by the outermost shell. External fins are provided to enhance the heat transfer during accidental conditions.

- **Thermal Hydraulic Analysis**

A computer code, HTR-NC, is developed for thermal hydraulic analysis of primary loop of 100 kWt CHTR. Parametric studies on coolant flow rate; temperature variation, pressure drop and power in the loop have been carried out at several stages of development. The results from the analysis have been applied to optimize the down comer tube size and orifice size of the loop. Variation of size of the orifices, which are located at the down comers, with the core height are illustrated. Analysis has also been carried out for 5 MWth CHTR, to optimize the geometry of the primary coolant loop. The variation of core outlet temperature at different chimney height for different fuel tube diameters is also illustrated in the figure.

- **Heat Transfer Analysis**

Steady state thermal analyses have been carried out to find temperature distribution in the geometry of the reactor. The analyses have been carried out for the normal operating and accidental conditions of the reactor. In the normal operating condition the reactor operates at 100 kWth and the coolant temperature rises from 900°C to 1000°C, by taking heat from the fuel tube. Analyses have been carried out for different filling liquid metals and reactor structure materials. It has been found that the maximum fuel temperature is below the maximum allowable temperature (~1600°C). The temperature distribution at the mid cross section of the reactor at normal operating temperature is illustrated in the figure.