International Atomic Energy Agency's Coordinated Research Project

On

Development of Small Reactors Without On-Site Refuelling

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Institute where research was carried out: Bhabha Atomic Research Centre, Mumbai, Pin code: 400 085, India

Chief Scientific Investigator: Dr. R.I.K. Moorthy / Dr. P.D. Krishnani

Progress Report on First Years Work (December 2004 - November 2005)

(First Years Progress Report on IAEA CRP on Development of Small Reactors Without On-site Refuelling)

Requirements of Nuclear Energy Assisted Deliverables in Indian Remote Areas / Villages

R.I.K. Moorthy, P.D. Krishnani, I.V. Dulera, N.K. Maheshwari, and R. Dinesh Babu
Bhabha Atomic Research Centre, Mumbai, India

1.0 Preamble

The project aims to explore the potential of small reactors without on-site refuelling to supply electricity to remote villages, islands, and small-scattered communities in India, which are located in regions not connected to electricity grid. The aim of the project is to arrive at a feasible design of small portable nuclear power packs, having long core life, passive safety and reactor core heat removal features, and not needing skilled man-power for operation. The project involves laying down the specifications of the reactor for the specified task, identification and development of the appropriate reactor concept, its reactor physics analysis and conceptual design of the engineering system. The studies carried out under the project would identify, prioritize, and develop large number of enabling technologies especially related to passive reactor safety & control and passive reactor core heat removal under normal and postulated accident conditions. This report gives a summary of the studies carried out during this calendar year and gives proposed work plan for the next year. Considering vast size of India with lots of regional variations, estimation of electricity and water related requirements were made for different isolated locations in the country. Based on this a broad specification of the nuclear reactor was prepared. Initial reactor physics design and thermal hydraulics design of the proposed reactor was carried out. A large number of enabling technologies were identified.

2.0 Identification of Requirements

2.1 Requirements of electricity

With a landmass of 3.29 million square kilometres and a population of over a billion, India is a mosaic of pluralistic diversity. India is a country of villages. A large portion of the population lives in villages. Many of these villages do not have electricity and potable water. There are large numbers of villages and locations, which are difficult to be connected to the regional electricity grid because of mainly inaccessibility due to their geographical location. These locations in India are predominantly in the hilly regions in north east of the country, islands in the oceans and sea around the country and in the regions located in mountains in north of India. The extension of grid power to these regions is not going to be economical. Therefore for a large and dispersed rural country, decentralized power generation systems wherein electricity is generated at consumer end and thereby avoiding transmission and distribution costs, offers a better solution. Some of these locations, located in hilly regions, are inaccessible during winter for almost 6 months due to severe climatic conditions. In absence of any electricity generating system, many of these locations use diesel oil to produce electricity thereby disturbing the ecology and environment of the region. Therefore, the current studies show that small capacity nuclear power reactors could satisfy energy related needs of such regions.

Studies to estimate requirement of potable water in the remote locations in the country was also done. Islands would benefit the most by nuclear desalination of seawater, since they lack alternate source of drinking water. Some of the hilly regions having saline water lakes would also benefit. In such regions nuclear power reactors are well suited to satisfy all the energy needs such as electricity, potable water, supplying heat for heating in cold climates, and production of alternate fuel for transport applications. For studying the requirements and specifications of a nuclear reactor, three regions were selected based on their geographical locations. As representative examples, Ladakh region, islands, and a cluster of villages were chosen for studying their energy related requirements. These regions are marked with arrows in Figure-1.

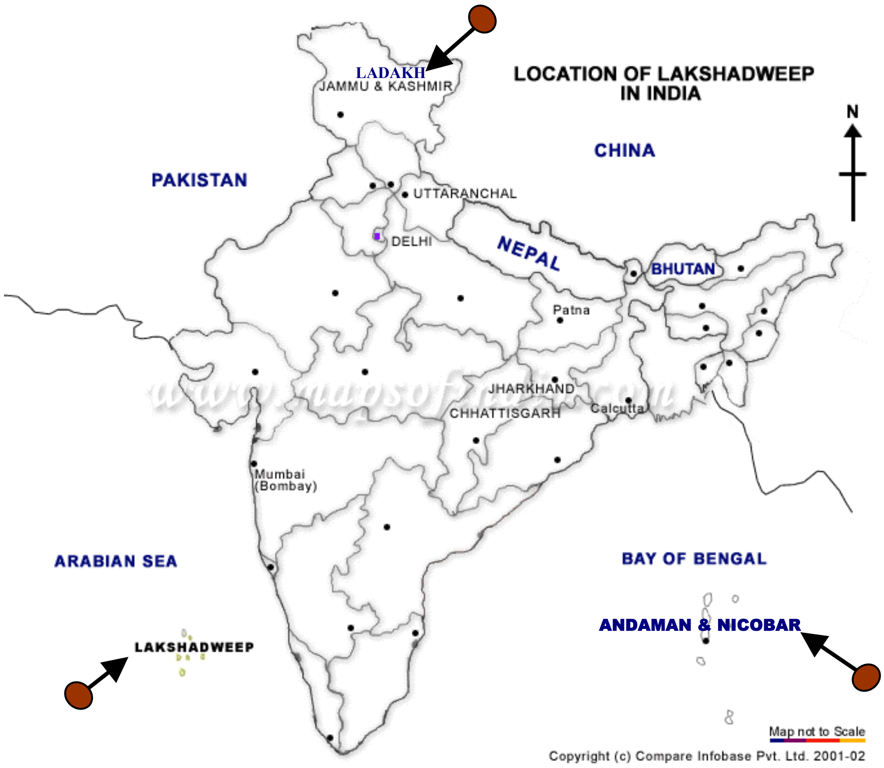

Figure-1: Geographical locations of Islands and Ladakh

2.1.1 Leh, Ladakh Region

This place, called roof of the world, has a population of about 1.18 lakhs. There are 112 inhabited villages. This region is subjected to extremes of the climatic conditions. In winter the temperature reaches as low as –30 °C and in summer the maximum temperature becomes as high as 40 °C. It experiences very poor rainfall. The population of Leh town is 23000 [1], which swells to 40000 in summer due to tourists and return of natives from other places. This region is not connected to the national electricity grid system. Current power generation is by 4.8 MWe hydro and 7.8 MWe Diesel Generator (DG) based installed power plants. Individual DG sets have capacity of 500 kWe each. About 10000 - 12000 litres of diesel is required every day to meet the demand of electricity. Remoteness, inaccessibility, and difficulties in transporting diesel make power generation costly. Some times bad weather disturb supplies. Due to shortage there is curtailment of power supply at times. Diesel generators also pollute the environment of Ladakh. The cost of operating and maintaining DG sets is high. During summer the hydropower contributes up to 70% of the total generation. The hydro power plant is closed for 4 to 5 months during winter, due to freezing of water in the canals. During summer also it is repeatedly shut down for weeks to clear the silts. The down time of machine in case of break down is quite long due to remoteness and in-accessibility. The reported plant utilization factor is very low (≈23%). Considering future growth of population and growing tourism industry there, the studies show that there is a requirement of electricity generating plants with capacities aggregating to about 35 MWe. Since the population is distributed in large number of villages with different geographical locations, the studies show that total requirements can be met by deploying smaller capacity power packs ranging in capacities from 500 kWe to 2 MWe. Due to very cold climate during winter, there is a need to satisfy heating requirements for houses, commercial buildings, waste disposal plants, etc. In addition potable water could be produced from saline water lakes in the region. The studies show that low-grade reject heat, after producing electricity, could be used for these purposes.

2.1.2 Islands

India has two major groups of islands, Andaman & Nicobar islands and Lakshadweep islands. These islands have electricity produced mainly using Diesel Generator (DG) sets. The installed capacities (as in 2003) for these islands are shown in Table-1 [2].

Table-1: In Andaman and Nicobar Islands almost 90% of electricity and in Lakshadweep Islands, 100 % electricity is produced using DG sets

Installed Capacity (In MW) of Power Utilities in the Islands as on 31.1.2003									
State	**Ownership sector**	**Total**			**Thermal**		**Total Thermal**		
			Hydro	**Coal**	**Gas**	**Diesel**		**Wind**	**Nuclear**
Andaman & Nicobar	State	39.30	5.25	0.00	0.00	34.05	34.05	0.00	0.00
	Private	10.00	0.00	0.00	0.00	10.00	10.00	0.00	0.00
	Central	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sub-total		**49.30**	**5.25**	**0.00**	**0.00**	**44.05**	**44.05**	**0.00**	**0.00**
Lakshadweep	State	9.97	0.00	0.00	0.00	9.97	9.97	0.00	0.00
	Private	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Central	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sub-total		**9.97**	**0.00**	**0.00**	**0.00**	**9.97**	**9.97**	**0.00**	**0.00**
Total islands	State	49.27	5.25	0.00	0.00	44.02	44.02	0.00	0.00
	Private	10.00	0.00	0.00	0.00	10.00	10.00	0.00	0.00
	Central	0.00	0.00	0.00	0.00	54.02	54.02	0.00	0.00
Grand total		**59.27**	**5.25**	**0.00**	**0.00**	**54.02**	**54.02**	**0.00**	**0.00**

As per the data shown in Table-1, the Andaman and Nicobar islands currently have about 50 MWe installed capacity. The population of these islands is about 3.6 lakhs [1,3] divided into 39 islands. Considering future growth of population and growing tourism industry in the islands, the studies show that, there is a requirement of electricity generating plants with capacities aggregating to about 75 MWe. Lakshadweep islands have a population of about 61000 [1,3] divided into 10 inhabited islands. The total area of the islands is 32 square km. Currently Diesel Generator based total installed capacity for power generation is around 10 MWe. Considering future growth of population and growing tourism industry in the islands, the studies show that, there is a requirement of electricity generating plants with capacities aggregating to about 15 MWe. Since the population in these islands are scattered, the studies show that, total requirements can be met by deploying smaller capacity power packs ranging in capacities from 500 kWe to 2 MWe. In addition to electricity, there is also a need for potable water in these islands. The same can be produced by desalination of seawater at moderate temperatures. Since the islands have tropic climatic conditions, they do not have heating requirements.

2.1.3 Village/ Cluster of villages

The villages throughout the country vary in size, population, and their surroundings. A big village or a cluster of 4-5 small villages with a total population of around 25000 has been chosen for establishing the requirements. Considering per capita electricity production of around 600 kWhr per year, the installed capacity requirements would be around 1.7 – 2 MWe or around 5 MW(th) capacity. Depending upon the local demands for drinking water and/or heating, proper arrangement can be done to utilise low grade reject heat for these purposes.

2.2 Potable water requirements

To establish potable water requirements for the above-mentioned three regions, an average value of about 100 litres per capita per day (lpcd) was taken as a reference value [4]. For Leh and Ladakh region the requirement is 12000 m^3/day. For Andaman and Nicobar islands, the total water requirement works out to be around 36000 m^3/day. For Lakshadweep islands it is around 6100 m^3/day. For villages with a total population of 25000 and in case of lack of availability of all water resources, the requirement for desalination works out to be about 2500 m^3/day. These overall requirements for electricity and potable water in above mentioned different regions are summarized in Table-2 below;

Table-2: Requirements for deliverables from a small nuclear reactor

Region \ Deliverables	Total Population	Total Electricity demand	Total Potable water demand	Heating	Remarks
Leh, Ladakh	1.18 lakhs distributed in 112 villages	35 MWe	12000 m^3/day	Yes	Multiple units of 500 kWe to 2 MWe capacity
Andaman & Nicobar islands	3.6 lakhs distributed in 39 islands	75 MWe	36000 m^3/day	No	
Lashadweep islands	61, 000 distributed in 10 islands	15 MWe	6100 m^3/day	No	
*** Cluster of villages**	25,000 in 4-5 villages or single big village	2 MWe	2500 m^3/day	Yes/No	Heating/ water requirement will depend upon location

* There are 18000 villages, which cannot be connected to national electric grid. Therefore the requirement for such reactors is very large

3.0 Indian Nuclear Power Programme

India has a three-stage nuclear power programme. The first stage consists of setting up of natural uranium fuelled Pressurized Heavy Water Reactors (PHWRs) which show the maximum neutron economy among the thermal reactors. The plutonium obtained from these reactors would be used in the Fast Breeder Reactors (FBRs), which form the second stage. India has limited uranium but vast thorium reserves, which are one of the world's largest. The third stage of the Indian Nuclear Power Programme is therefore based on the Thorium-Uranium-233 cycle. Extended third stage of the programme envisages utilization of nuclear energy as a primary source of energy so as to provide besides electricity, high temperature process heat for producing transportation fuel and potable water. India has already achieved maturity in the technology related to PHWRs. The second stage started with setting up of a Fast Breeder Test Reactor (FBTR) at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam. FBTR has been running successfully for the past 17 years, utilizing a unique and indigenously developed uranium-plutonium carbide fuel. The construction of a 500 MWe Fast Breeder Reactor (FBR) has already started.

3.1 Objectives for the Nuclear Reactor Concept Under Study

The specification of the reactor should be so as to satisfy all the energy related needs of the region of deployment. These needs include electricity, transportation fuel, potable water and heating in cold regions. Other intended features of the reactor are: compactness and modular construction, non-grid based operation, long life core of around 10-15 years, not requiring on-site fuelling, inherently safe, having passive safety & heat removal features and not requiring large amount of process water for operation. This electricity production capacity was selected as 2 MWe. For designing the reactor a thermal power of 5 MW(th) to produce ≈ 2 MWe electricity was chosen. Besides electricity, the nuclear energy from the reactor is to be utilized for producing potable water at the rate of about more than 2500 m^3/day. As regards production of transportation energy carrier, hydrogen is an environmentally benign option, if produced from water. The process of production could be either high temperature steam electrolysis or one of the low temperature thermo-chemical processes. These two routes demand process heat at temperature around 550 °C. Therefore in order to meet all the objectives, the reactor should be preferably a high temperature reactor with a coolant outlet temperature more than 550 °C.

3.2 Selection of Fuel Cycle and Nuclear Reactor Type

3.2.1 Choice of Thorium Fuel Cycle

The thorium cycle offers certain advantages vis-à-vis uranium cycle. Its half-life is more so it exists in greater abundance than uranium. The fissile isotope used in this cycle (^{233}U) has the best production/neutron absorption rate in the thermal spectrum. Minor actinide production is more limited than in the uranium cycle, which, in the short term, results in lower radiotoxicity. The melting temperature of ThO_2 is very high (3300 °C in comparison to 2700 °C for UO_2). This permits higher powers and burnups. The resistance to proliferation seems slightly better than in UO_2 cycle, for it is above all linked to the difficulty of reprocessing and to the activity of ^{232}U and its decay products.

The drawback with thorium is that it possesses no fissile isotopes and it is therefore necessary to trigger the cycle by using classic U or Pu isotopes. Conversion by reaction (n, 2n) and decay gives ^{232}U and other very energetic gamma emitters. However, it should be noted that this negative point becomes a positive one when considered from the resistance-to-proliferation standpoint. The proportion of delayed neutrons is low for ^{233}U: 270 pcm as against 670 for ^{235}U, which places this fuel on the level of the Pu factor for this type of parameter, and thus results in a certain penalty for accidents of the rapid reactivity insertion type. The accumulation of absorbent ^{233}Pa, parent of ^{233}U, leads to shutdown control problems. Neutron capture of ^{232}Th is three times higher than that of ^{238}U, which ensures a faster conversion than in the ^{238}U- ^{239}U cycle, but necessitates higher fissile igniters to trigger the first cycle. Reprocessing is difficult (but this is a positive point with respect to resistance to proliferation), since ThO_2 is insoluble in nitric acid and the THOREX process uses highly corrosive products.

3.2.1.1 Indian Experience in thorium fuel cycle

A large amount of research and development is going on for utilizing thorium in India. Thorium bundles instead of depleted uranium bundles were loaded in Indian PHWRs of 220 MWe for initial flux flattening from KAPS Unit 1 onwards. A reactor KAMINI, based on ^{233}U fuel in the form of U-Al alloy, was constructed at the Kalpakkam. It is the only operating reactor in the world with ^{233}U as fuel. The reactor power is 30 kW and has very high flux to power ratio. Presently, an Advanced Heavy Water Reactor (AHWR) of 300 MWe power is being designed in India to demonstrate thorium fuel cycle technologies, along with several other advanced technologies required for next generation reactors.

3.2.2 Choice of reactor components and materials

3.2.2.1 Fuel

Considering the defined objectives and relevance of thorium in Indian context, thorium fuel cycle has been chosen for the present reactor development. A metallic fuel has been selected for initial calculations. Metallic fuel is based on ^{233}U, Th, Zr and burnable poison. Zircalloy was selected as clad material.

3.2.2.2 Moderator

Considering the objectives of the reactor and desirable feature of high temperature operation, utilization of liquid moderator like heavy water was ruled out. For solid moderators, graphite would result in a larger core size; therefore a beryllium-based moderator was chosen. India has a beryllium metal plant, which can produce BeO. Therefore BeO was chosen as the moderator material. It was decided to utilize hexagonal shaped BeO blocks.

3.2.2.3 Reflector

Since BeO was chosen as moderator material, BeO was as well chosen for radial reflector material. Later on analysis it was found that part of the reflector even if made of graphite would serve the purpose. Hence partly BeO and partly graphite was chosen as the reflector material.

3.2.2.4 Coolant

As the idea is to develop high temperature reactor, water cannot be considered as coolant that rules out the water based reactor concepts. In order to have passive cooling of the reactor, liquid metal was chosen as coolant vis-à-vis gas. Lead alloy based coolant was chosen vis-à-vis sodium due to its inertness to air and water. In order to have a lower melting point, eutectic alloy of lead (44.5%)

and bismuth (55.5%) was chosen. It was also felt that selection of this coolant would help in providing natural circulation based passive cooling of the reactor core under normal operating conditions.

3.2.2.5 Coolant tube material

In view of reported relative inertness of carbon-based material with molten lead based coolant, graphite was selected as the coolant tube material. This would provide neutron economy as well. In order to make the graphite component impervious and oxidation resistant, it was decided to provide successive coats of pyrolytic carbon and silicon carbide. Silicon carbide is reportedly almost inert to molten lead based coolant.

4.0 Broad Specification and Requirements of the Nuclear Reactor

Based on the criteria as regards operating parameters, fuel cycle, fuel, moderator, reflector, fuel tube material etc. and considering the requirement of higher and passive safety requirement of the reactor, broad specification of the reactor is given below:

a) Fuel to be ^{233}U-Th based metallic fuel with high burn-up and facilitating a long life core of around 10-15 years.
b) The reactor is to have a high coolant exit temperature (> 550 °C) to achieve the maximum possible efficiency as well as have enough energy left after hydrogen and electricity generation for producing potable water. These power-producing concepts shall have less utilization of water to work as well in the arid regions.
c) To minimize water requirement and also to support high temperature power removal from reactor core, either liquid metal coolant or gas, as coolant should be used. A liquid metal-based coolant enables passive cooling of the core. Lead-bismuth eutectic alloy was chosen as coolant.
d) Compact core and high temperature necessitates use of BeO as moderator and BeO and graphite as reflector materials.
e) The temperature range, i.e. inlet and outlet temperature was selected based on requirements of a standard gas turbine as well as a low temperature thermo-chemical process for hydrogen production. Typically a maximum coolant outlet temperature of 600 °C was selected.
f) The reactor should have features to reject entire heat to the atmosphere by natural circulation, conduction and radiation at the neutronically limited peak power level, without fuel damage
g) Some of the inherent safety related features, the reactor should have are:
    - Negative temperature coefficient of reactivity for fuel to ensure self stabilization and limitation of reactor power under abnormal conditions
    - The reactor should have ceramic core structure and fuel elements capable of withstanding high temperature eliminating the possibility of severe accidents.
    - Low ratio of power density to heat capacity resulting in a slow rise of fuel element temperature under abnormal conditions
    - Prevention of over-pressurization of the core under all operating conditions.
    - The coolant should retain the fission products and actinides.

4.1 Expected load variation

The reactor is expected to have base load operation and follow the varying load during the day and night time. It shall have energy storage device to store energy during off peak hours. It can also be thought to provide the system with a hydrogen producing system for hydrogen production during these off peak hours.

A typical rural area load variation curve for the day is shown in Figure-2.

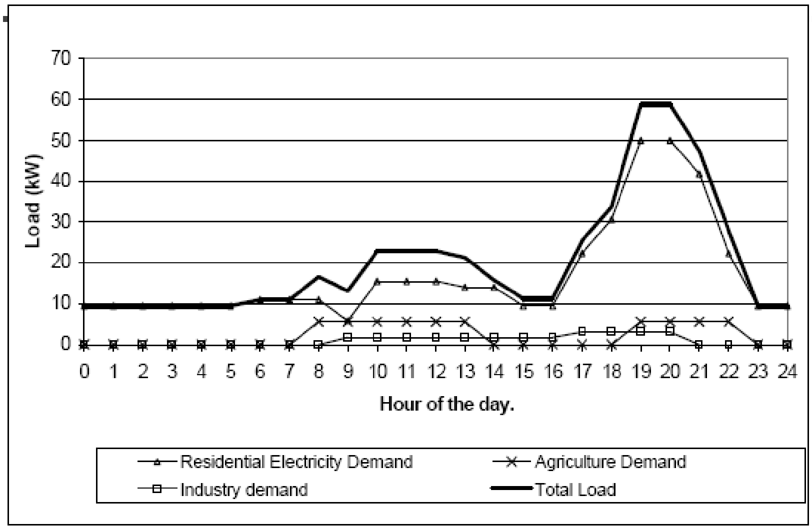

Figure-2: Typical load variation during the 24 hours period in rural area

5.0 Proposed Reactor Core Configuration

Proposed core configuration for this reactor is shown in the Figure-3. As mentioned earlier, the fuel is based on metallic fuel. The metallic fuel consists of about 90% (^{232}Th + ^{233}U) and 10% Zr. Alloy made of these three metals will be made into pellet form having 8-mm diameter. These pellets will be encased in a clad of zircaloy-4. A radial gap between the fuel pellet and the clad is provided to accommodate fuel swelling. This would be filled with a eutectic of approximately 33% Pb, 33% Bi and 33% Sn to improve heat transfer capabilities. There are 12 fuel pins in a fuel assembly. These pins will be incorporated in fuel bores provided in the graphite tube located in BeO moderator block. The central hole provided in the graphite tube acts as the passage for Pb-Bi eutectic coolant. The core of the reactor is based on tri-angular lattice arrangement. It contains 30 annular fuel assemblies, 12 in the inner ring and 18 in the outer ring. These moderator blocks are in turn surrounded by BeO reflector blocks, which also support reactor control devices. There are 7 graphite blocks inside the fuel assemblies and 24 BeO reflector blocks outside the fuel assemblies. Graphite reflector blocks surround BeO reflector blocks. Core height is 100 cm with additional 15 cm as top reflector and 15 cm as bottom reflector. This part of the reactor is contained in a shell of a material having high temperature resistance as well as resistant to liquid metal corrosion.

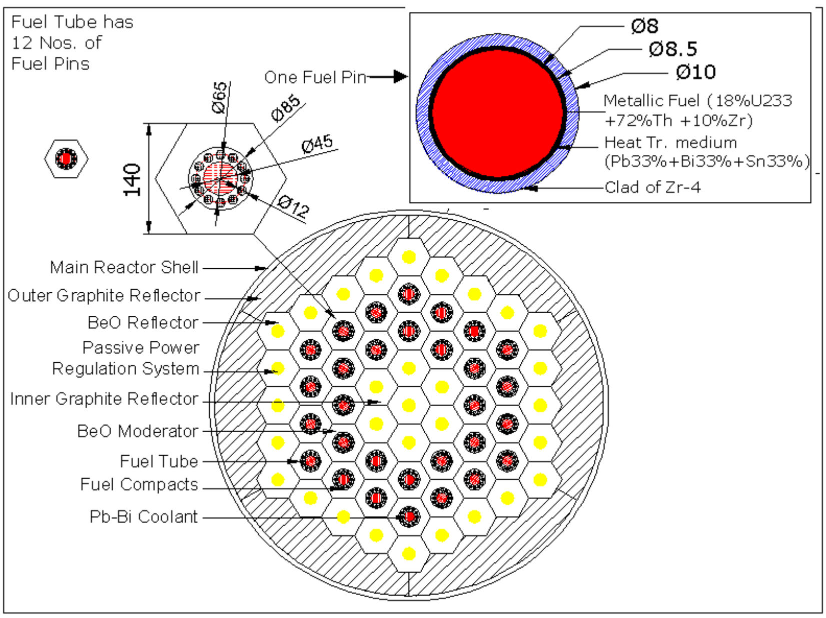

Figure-3: Core cross sectional layout of the reactor

6.0 Reactor physics analysis and optimisation

6.1 Analysis method

A 1-D collision probability code LATTEST [5] was used for lattice calculations. It makes use of first flight collision probability (P_{ij}) method to solve the multi group integral transport equation. In each fuel assembly 12 fuel pins were treated as a ring of fuel about the pitch circle radius conserving its volume. 172-group IAEAGX cross-section library was used for all calculations. 12-group cell-homogenized cross-sections obtained from LATTEST were used in hexagonal mesh diffusion theory code TriHTR [6]. Calculations were performed at a temperature of 575 ^{0}C for fuel and 525 ^{0}C for non-fuel materials for normal operating condition.

To simulate control rods, which are located outside the fuel assembly, a 1-D super cell calculation was carried out by considering a ring of fuel paste (spatially homogenised lattice cell containing fuel) surrounding the control cell. This calculation generates homogenized 12-group cross-section for the control cell.

6.2 Results of analysis

Core simulations were first done to optimise lattice pitch followed by calculation of important parameters like control rods worth, fuel temperature coefficient, height of the control rods at criticality etc. for the case of optimised pitch. The design parameters are given in the Table-3.

Table-3: Broad specification of the reactor

Attributes	Property
Reactor power	5 MW(th)
Core life	Around 15 years
Fuel	Metallic ^{233}U+ ^{232}Th +Zr
Fuel clad	Zircalloy
Moderator	BeO
Reflector material	BeO and graphite
Coolant	Pb-Bi eutectic alloy
Core height	1000 mm
Core inlet temperature	450 ^{0}C
Core outlet temperature	600 ^{0}C
No. of fuel assemblies	30
No. of control locations	31
No. of fuel pins per assembly	12
Fuel pin ID	8 mm
Fuel pin OD	10 mm
Pitch	140 mm
Top reflector height	150 mm
Bottom reflector height	150 mm
Coolant tube OD	45 mm

6.2.1 Fixation of lattice pitch

Calculations were performed for three different lattice pitches 13.5 cm, 14.0 cm and 15.0 cm. Fuel requirement for different pitches are shown in Table-4. Variation of k_{eff} and k_{inf} for 14 cm pitch is given in Figure-4. Requirement of ^{233}U for entire core for a core life of 15 years is 43.195 kg for 13.5 cm pitch, 42.068 kg for 14.0 cm pitch and 42.612 kg for 15 cm pitch. An increase in pitch from

13.5 cm to 14.0 cm reduces ^{233}U inventory by 1.13 Kg. There is no significant gain in fuel inventory for 15.0 cm pitch. So 14.0 cm pitch was considered adequate.

Table-4: Fuel Requirement for Different Pitches

Pitch (cm)	^{233}U content in the alloy (%)	Fuel density (gm/cc)	Fuel requirement For full core	
13.5	20.5	11.65	^{233}U =43.195 Kg.	^{232}Th =146.441 Kg
14.0	20.0	11.63	^{233}U =42.068 Kg	^{232}Th =147.238 Kg
15.0	19.8	11.62	^{233}U =41.612 Kg.	^{232}Th =147.535 Kg.

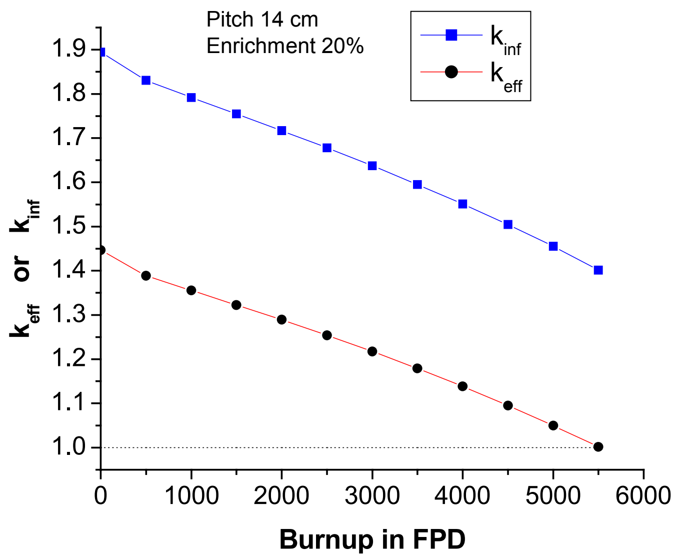

Figure-4: Variation of K_{eff} and K_{inf} with respect to burnup

6.2.2 Fuel inventory

For 14 cm pitch, the requirement of ^{233}U content in the alloy is 20% for a core life of 15 years. Total fuel requirement for the entire core is 42.068 Kg ^{233}U and 147.238 Kg ^{232}Th. At 5500 EFPDs (~ 15 effective full power years), 12.47 Kg ^{233}U and 143.29 Kg ^{232}Th remain in the core whereas 0.58 Kg ^{235}U is produced. Production of ^{239}Pu is negligible.

6.2.3 Introduction of Gd as burnable absorber

As the total control rod worth was much smaller than the total reactivity to be controlled, an effort was made to control the extra reactivity by mixing the burnable poison with the fuel. Different amount of Gd was introduced in different configurations in order to get optimum case with better control and less reactivity penalty. Figure-5 and Figure-6 show variation of K_{eff} with burn up for 160 gm Gd in each of the 12 inner plus 6 outer fuel assemblies and 350 gm Gd in each of the 12 inner plus 2 outer fuel assemblies, respectively. These are for hot operating cases with all control rods out. With 160 gm Gd in (12+6) fuel assemblies, maximum reactivity up to 238 mk can be controlled and the reactivity penalty due to non-burnup of Gd at end of life is 15 mk. Maximum k_{eff} is 1.2086 at 2000 EFPDs. Further optimisation for amount of burnable poison and its distribution is going on. Cold cases with all control rods in with one control rod having maximum worth out were also studied to ensure that maximum K_{eff} is below 0.96 which is required from safety point of view.

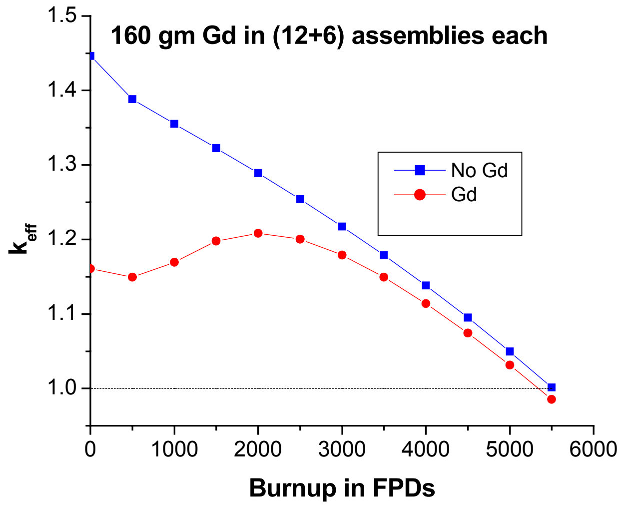

Figure-5: Variation of k_{eff} with burn-up (160 gm Gd)

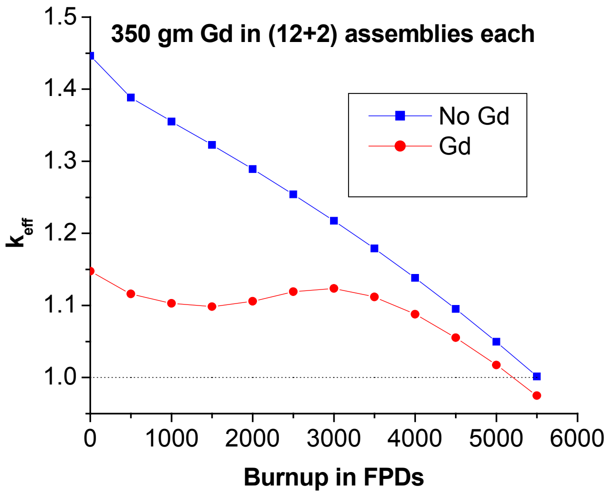

Figure-6: Variation of k_{eff} with burn-up (350 gm Gd)

6.2.4 Estimation of worth of control rods

Control rods worth were evaluated both at cold and hot conditions as shown in the Table-5 and Table-6. Worth of all control rods at hot condition is 310.7 mk and worth of one control rod having maximum worth is 18.3 mk. Corresponding values at cold condition are 291.0 mk and 16.9 mk.

Table-5: Estimation of Control Rods Worth at Hot Condition

Position of Control Rods	Value of k_{eff}
All Control Rods Out	1.20857
All Control Rods In	0.87866
All Control Rods In except one having Maximum worth	0.89305
Worth of all Control Rods = 310.7 mk	
Worth of a Single Control Rod having maximum worth =18.3 mk	

Table-6: Estimation of Control Rods Worth at Cold Condition

Position Of Control Rods	Value of k_{eff}
All Control Rods Out	1.21235
All Control Rods In	0.89616
All Control Rods In except one having maximum worth	0.91000
Worth of all Control Rods = 291.0 mk	
Worth of a Single Control Rod having maximum worth =16.97 mk	

6.2.5 Estimation of fuel temperature coefficient

Fuel temperature coefficient is tabulated in Table-7 for different temperature ranges. At 775 °C it is -1.53×10^{-5} per °C.

Table-7: Estimation of Fuel Temperature Coefficient

Fuel temperature (°C)	Value of k_{eff}	Fuel temperature co-efficient (per °C)
575	0.99998	Reference
675	0.99837	-1.61×10^{-5}
775	0.99692	-1.53×10^{-5}
475	1.00176	-1.78×10^{-5}
375	1.00369	-1.85×10^{-5}

6.2.6 Height of control rods at criticality

At criticality, control rods will be 66 cm in the core plus 15 cm in the bottom reflector. In this condition the worth of one control rod having maximum worth is 8.12 mk.

7.0 Thermal Hydraulic Analysis

The thermal hydraulic analyses were carried out to study natural circulation of the primary loop and effect of providing orifices in the loop. A computer model based on the law of conservation of momentum was developed for the analysis [7,8,9]. The primary loop was simplified for the analysis. They are shown in Figure-7 and Figure-8 for two different kind of down comer system.

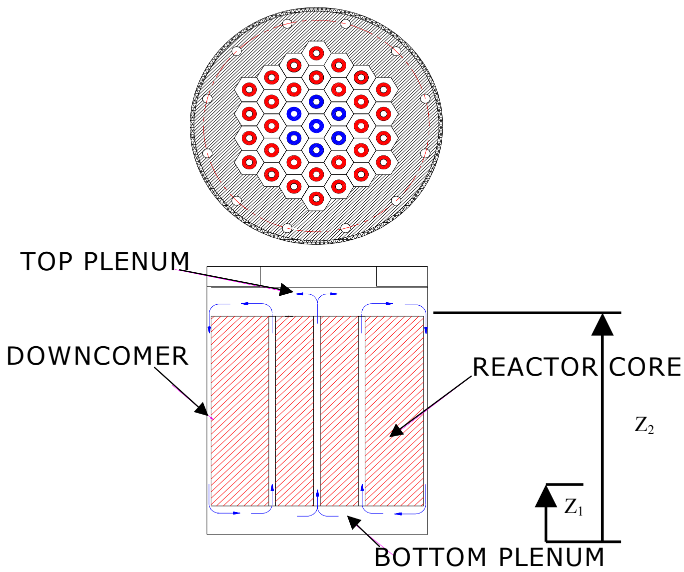

Figure-7: Simplified primary loop for tubular down comers

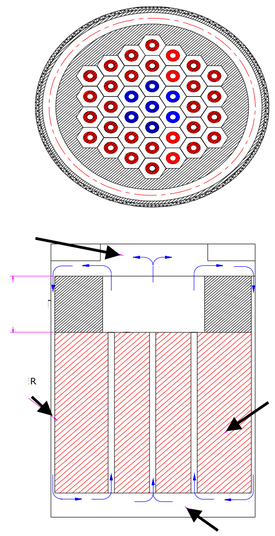

Figure-8: Simplified primary loop for annular down comer

The loop, shown in Figure-7, consists of 30 fuel tubes, a heat sink at the top plenum and down comer tubes. In Figure-8, the down comer is annular, in the graphite reflector zone. Following assumptions were made for the analysis:

1) No heat loss in the loop other than in the heat sink,
2) The viscous heat generation is negligible,

7.1 Cases Analysed

Following cases were analysed:

Case 1: The ID of the riser was varied from 35 mm to 80 mm. 30 tubular down comers were considered (Figure-7).

Case 2: Annular down comer with Inner and outer diameter of 1000/ 1150mm was selected. A chimney height was provided and was varied (Figure-8).

7.2 Results and Discussions

Case 1: For case 1, it was found that, for inlet temperature 450 °C and fuel tube ID 35 mm, the outlet temperature was found to be 735°C, which was higher than desired outlet temperature (i.e. 600°C). The inner diameter of the fuel tube was increased and it was found that for outlet temperature 600°C the required ID of the fuel tube would be 58 mm. This in turn increases the OD of the fuel tube and affects overall inventory of the moderator (BeO) so this type of geometry was not suitable for the reactor. Figure- 9 shows the results of the analysis.

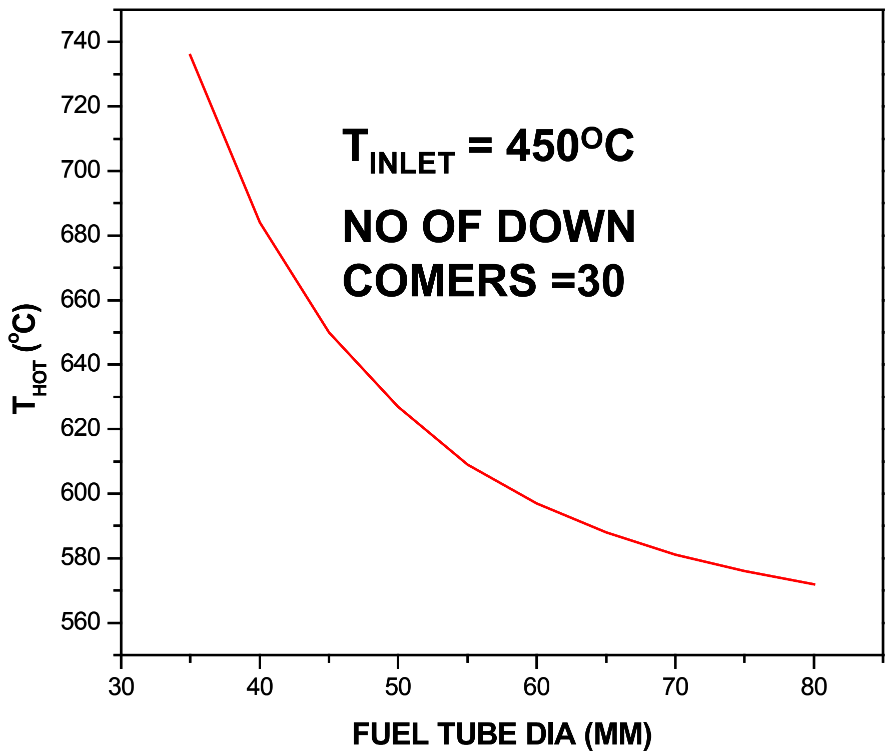

Figure-9: Variation of outlet temperature of the coolant with fuel tube inner diameter

Case 2: For case 2, analysis was carried out to study the effect of chimney height on the natural circulation driving head in the primary loop. The geometry of the down comer was modified from tubular to annular type (Figure-8), to further reduce the hydraulic resistance in the primary loop. Studies were carried out for three different diameters of fuel tube, 35 mm, 40 mm and 45 mm and the required chimney height for outlet temperature 600°C was found to be 2.65 m, 0.7 m and 0.1 m respectively (Figure-10).

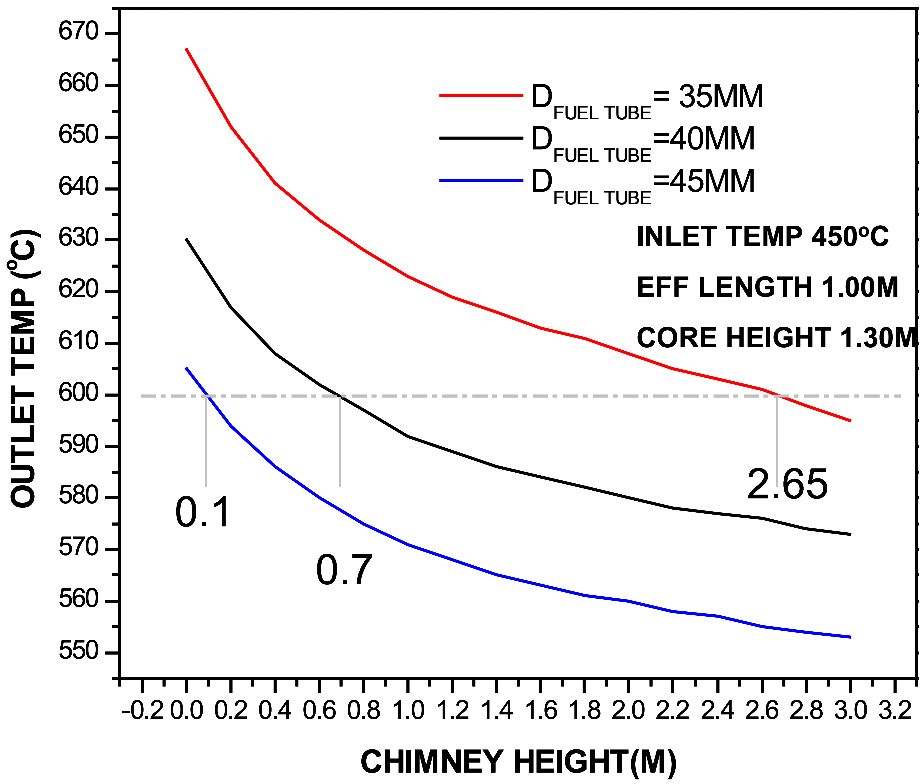

Figure-10: Variation of outlet temperature of the chimney height for different fuel tube inner diameter

Based on these calculations, fuel tube inner and outer diameter of 45 mm and 85 mm were selected so as to have acceptable chimney height of 10 cm.

7.3 Temperature distribution analysis

A 2D heat transfer study was carried out to find out the maximum fuel temperature at normal operating condition. A finite element based code was used for the analysis. Figure-11 shows the result of the analysis. The maximum temperature of the fuel was found to be 862°C.

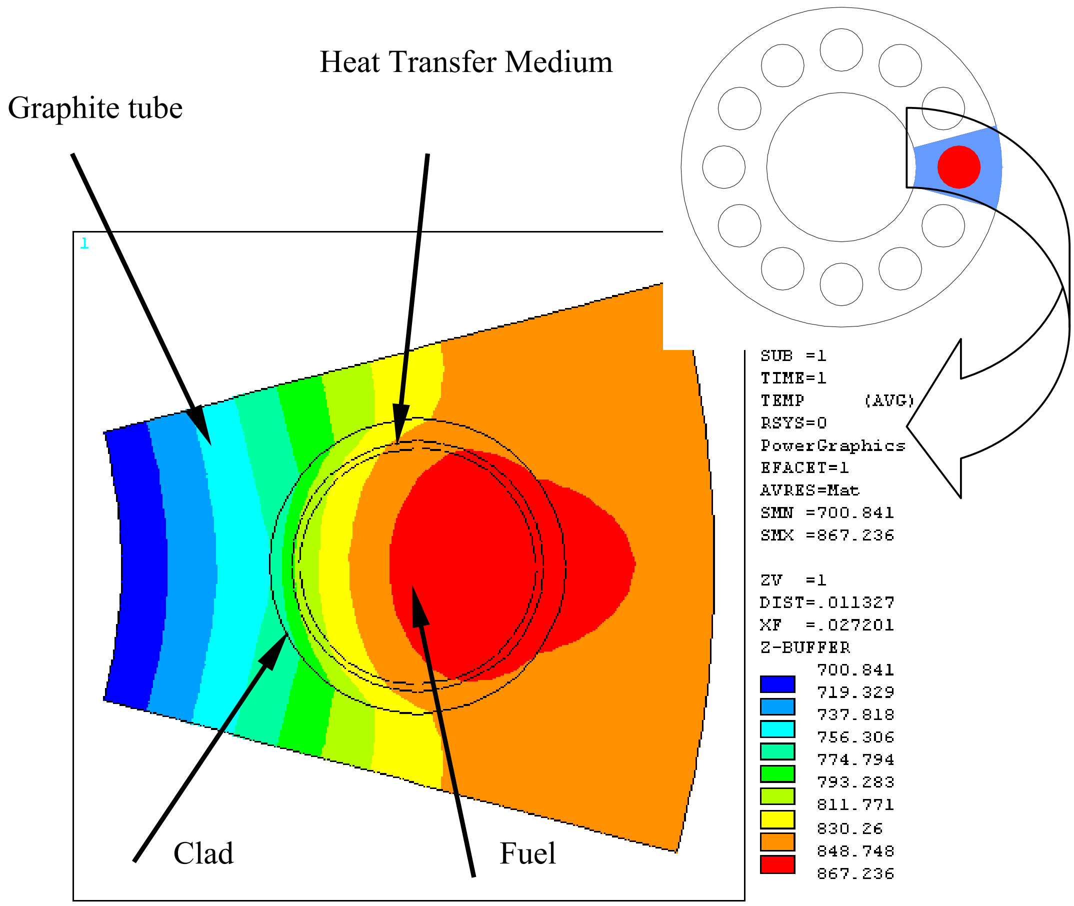

Figure-11: Temperature distribution analysis of fuel tube

8.0 Identification of Enabling Technologies

This reactor concept calls for research and developmental activities to be initiated in many areas. Development of metallic fuel, structural materials, and passive systems are the three main areas for development of enabling technologies. Some of the important enabling technologies are listed below;

8.1 Development of metallic fuel: Thorium and ^{233}U based metallic fuel development is one of the prominent areas of development. Preliminary studies carried out shows feasibility of development of this kind of metallic fuel. Addition of Zirconium to the nuclear metals results in complete solubility in Th-U system in BCC phase.
Status: Preliminary studies carried out, capability exists for fabrication of metallic fuels

8.2 Development of nuclear grade BeO block of hexagonal shape with 140 mm across the flat faces
Status: Manufacture of high density BeO block of hexagonal shape (small size) demonstrated, Facility exists for manufacture

8.3 Development of high-density nuclear grade graphite components such as fuel tube, reflector blocks etc.
Status: Manufacture of high density and long graphite fuel tube demonstrated, Facility exists in the country for such manufacture

8.4 Development of pyrolytic carbon and silicon carbide based oxidation resistant coatings for carbon components
Status: Under development, Know how exists for such development work

8.5 Development of lead based liquid metal coolant technologies with respect to their
i) Thermal hydraulic issues
ii) Compatibility issues with structural materials
iii) Development of corrosion resistant coatings
Status: Experimental loops are under fabrication for carrying out various studies related to thermal hydraulics and material compatibilities

8.6 Development of passive power regulation system
Status: Computer codes developed for simulation studies. Design and development work for experimental set-up under progress

8.7 Development of passive shutdown devices
Status: Technology exists for such development work, work to be initiated

8.8 Development of passive systems for removal of core heat under postulated accident condition and under LOCA. This will include development of high temperature heat pipes, including their manufacture and testing
Status: Computer codes developed for analytical design, simulation and studies, design and development work for manufacture and testing set-ups for heat pipes under progress

8.9 Development of components, sensors and instrumentation for use at high temperature in lead alloy environment
Status: Some components, and sensors are under development

8.10 Development of codes for structural design of brittle components made of BeO and graphite
Status: Preliminary studies and developmental work initiated for code design

9.0 Summary and Conclusions

Typical specifications for a power pack as applicable in the Indian context were evolved based on a survey of the requirements in the different regions. It emerged that a reactor of thermal power of 5 MW and a core life of about 15 years would best fit the requirements. Accordingly, a conceptual design of a 5 MW(th) reactor having a long core life of 15 years has been carried out. This reactor uses ^{233}U, thorium and zirconium based metallic fuel. BeO was selected as the moderator material and BeO along with graphite serve as reflector materials. The reactor physics design of the reactor has been studied with following recommendations and conclusions:

a) A lattice pitch of 14 cm was found to be adequate.
b) Initial k_{eff} is very large necessitating the introduction of burnable poison in the core.
c) Worth of a Control rod appears to be high (8.12 mk at criticality). It need to be reduced either by introducing proper amount of Gd or by reducing initial k_{eff}.
d) Operation of 5500 EFPD corresponding to a burn-up of 1,46,000 MWd/t of heavy metal is feasible
e) To maintain k_{eff}=1 at hot operating condition, all control rods should be 66 cm inside the core. In this situation maximum worth of a control rod is 8.12 mk.
f) Total ^{233}U inventory in the whole core is around 42 kg. At 5500 FPD, unburned ^{233}U is 12.5 kg and production of ^{235}U is 0.6 Kg.
g) Fuel Temperature coefficient at average temperature 775°C is -1.53476 x 10^{-5} per °C, which is quite satisfactory.

The reactor has been designed to have natural circulation of lead-bismuth eutectic alloy coolant to remove reactor heat under normal operation. Maximum temperature seen by the fuel is under acceptable limit. Thermal hydraulics analysis carried out has established feasibility of core cooling by natural circulation.

A large number of enabling technologies needed for this reactor have been identified and are under various stages of development.

10.0 Future work planned for subsequent years

a) Further optimization of design from reactor physics points of view
   i) Optimization of the design from the point of view of burnable poison and variation in enrichment
   ii) Design with alternate fuel (TRISO coated particle based fuel)
   iii) Safety related studies on behaviour of fuel and coolant under various postulated accident conditions
   iv) Coupled neutronics-thermal analysis

b) Further optimisation of design from thermal hydraulics points of view
   i) Optimization of studies related to natural circulation of coolant for reactor heat removal
   ii) Thermal analysis of core under normal operating and postulated accident condition
   iii) Transient thermal analysis under the condition when all heat sinks are lost
   iv) Thermal analysis for loss of heat and analysis for velocity distribution in the plenums

c) Design of system for passive power regulation system and shutdown systems
   i) Design and development of the system
   ii) Development of new/ modification of existing computer codes for design and simulation

d) Design of systems for passive reactor core heat removal under postulated accident condition: Alternate options including heat pipe based systems would be designed and analysed.
   i) Design and development of systems
   ii) Development of new/ modification of existing computer codes for design and simulation

e) Initiation of activities related to studies for development of fuel, structural materials, etc.

11.0 References

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