Shaping third stage of Indian nuclear power programme

With high temperature thorium reactors

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Our country has large thorium reserves. Therefore, in long term, our nuclear reactors are expected to predominantly use thorium as fuel. Since thorium is fertile, for its utilisation we need external fissile material in the beginning. The reactor concepts, which do not subsequently need fissile material, are expected to provide sustainability to our nuclear power programme. Additionally, nuclear energy assisted production of energy carrier for transport applications is important for the long term energy security of our country. In order to achieve these goals, BARC is developing nuclear reactors. This article summarises the R & D, in progress in BARC, for these reactors.

Indian Nuclear Power Programme

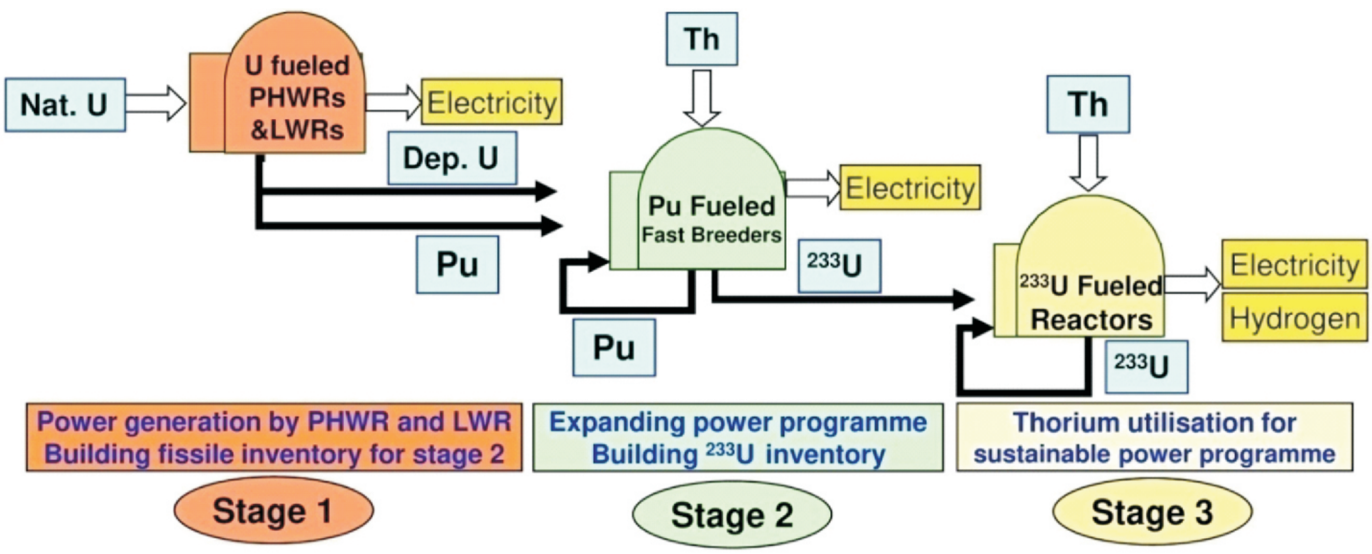
For a large country like India, an optimum mix of diverse energy sources will be required for satisfying the energy demands in future. Environmental concerns limit use of fossil fuel. Nuclear energy, which is a clean source of energy, will have to play a very important role in this objective. The importance of nuclear energy and in particular the role of thorium, as a long term sustainable energy resource for our country, was recognised right at the very inception of our atomic energy programme. Accordingly, Department of Atomic Energy (DAE) formulated and is following a three - stage nuclear power programme (Fig. 1) to efficiently utilise our nuclear resources consisting of modest uranium and abundant thorium. This programme is based on a closed fuel cycle, where the spent fuel of one stage is reprocessed to produce fuel for the next stage. This multiplies manifold the energy potential of the fuel and greatly reduces the quantity of waste.

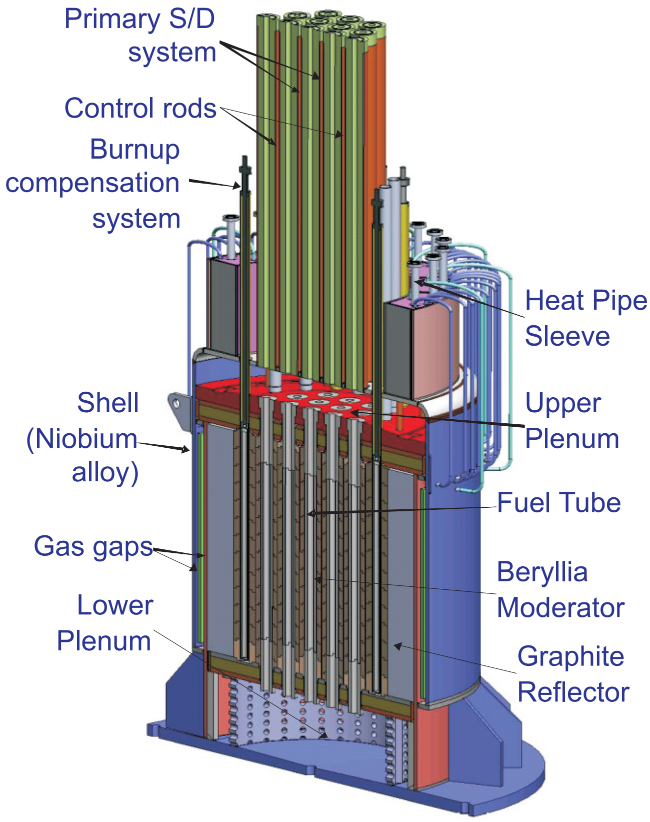
First stage uses natural uranium in Pressurised Heavy Water Reactors (PHWRs) and Light Water Reactors (LWRs, enriched uranium), followed by use of plutonium obtained from the spent fuel of PHWRs in Fast Breeder Reactors (FBRs) in second stage and ^{233}U fuelled systems in the third stage. The first stage, with 18 PHWRs and 4 LWRs in operation and many under construction and planning, has reached a state of commercial maturity. The first commercial FBR of second stage is in an advanced stage of commissioning. When adequate nuclear installed capacity has been built during the second stage, thorium based fuel will be used in FBRs to breed ^{233}U. The third stage of the programme, thus, envisages use of ^{233}U fuelled reactors with thorium as the fertile material.

Importance of third stage of our nuclear power programme

Due to vast thorium reserves in our country, the goal of DAE is to use thorium as the main stay of our long-term nuclear power programme. The reactor systems contemplated and being designed for the third stage will be self-sustaining in Th-^{233}U fuel cycle. It means, after attaining the required level of installed capacity in the third stage, it would be possible to maintain the achieved level of nuclear power programme with thorium alone, without additional demands on uranium or plutonium as fissile material. The ^{233}U required for this purpose would be obtained from operation of Th-^{239}Pu based fast reactors in the latter part of the second stage. The third stage reactors would provide long term energy security to our country. In preparation for the third stage of our nuclear power programme, development of

(1). Three stage Indian nuclear power programme





(2). Compact High Temperature Reactor (CHTR)

technologies pertaining to utilisation of thorium has been a part of ongoing activities in DAE. With the sustained efforts over the years, India has gained experience over the entire thorium fuel cycle-fabrication, irradiation and reprocessing on an engineering scale.

Why India needs High Temperature Reactor (HTR) and Molten Salt Breeder Reactor (MSBR)?

As we have limited reserves of oil and natural gas, our import bills on these is huge and in absence of alternate energy carrier, would continue to increase in future. Their use also has environmental concerns. For the long-term energy security of our country, it has become inevitable that we find an alternative energy carrier for transport applications. Hydrogen is an attractive alternative. While options for production of hydrogen from fossil fuel such as steam methane reforming can satisfy demands during interim periods, nuclear energy assisted hydrogen production, by splitting water, is a long term sustainable and environmentally benign option. Indian HTR programme has this objective.

For India, MSBR is attractive due to its potential to provide breeding for thorium based fuel in thermal or epithermal spectrum of neutron energy. This is mainly because, MSBR being a fluid fuel reactor using thorium based fuel salt, it is feasible to remove intermediate isotope ^{233}Pa, which then decays to ^{233}U, a fissile material, outside the reactor. In a solid fuel reactor, this advantage is lost, as fuel needs to be inside the reactor till it achieves intended burnup. In such a case ^{233}Pa absorbs neutron and ultimately ^{234}U is formed which is not fissile and hence adversely affects breeding ratio. MSBR is, therefore, capable of providing sustainable long term energy security, as is expected from the reactors forming the third stage of our nuclear power programme. Besides efficient conversion of thorium into ^{233}U, MSBR has other advantages also. Some of them are; continuous removal of Xenon and Krypton, resulting in better neutron economy; negative fuel salt reactivity coefficient; sub criticality in case of salt leakage; no violent interaction of salt with water or air; stability of salt under irradiation; online refuelling leading to low excess reactivity; passive decay heat removal; high boiling point of salt resulting in a low pressure system which reduces the risk of a large break and loss of coolant as a result of an accident, thereby enhancing the safety of the reactor; and no significant fuel fabrication. Moreover there is no scenario called 'fuel melt down' and in case of leakage in primary circuit, salt is collected in a non-critical configuration in safety vessel. Solidification of the salt, on leakage, reduces leak and probability of large scale radioactivity release.

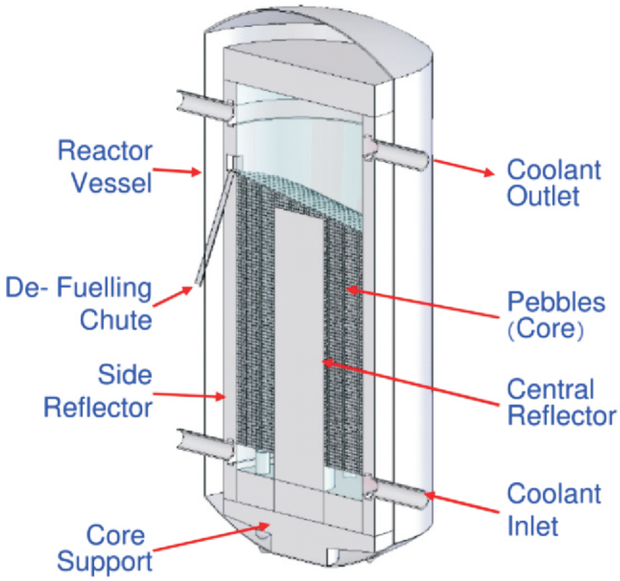
Worldwide status of HTR and MSR development

HTR and MSR both are part of six reactor technologies selected by the Generation IV Forum, an initiative involving 13 countries focused on next generation nuclear power technologies, for further R&D. Majority of the HTRs worldwide, which have been operated or are under design, are gas cooled reactors using high pressure Helium as the coolant. Currently small power (<50 MW) reactors are in operation in Japan and China. Large power HTRs are also under construction in China and under development in USA. Oak Ridge National Laboratory (ORNL) in the United States operated an experimental 7.34 MW reactor.

MSR known as the Molten-Salt Reactor Experiment (MSRE) from 1965 to 1969. This reactor demonstrated the concept of such reactors. Although work on development of MSRs is in progress in many countries, commercial deployments are yet to begin. Besides India, countries where MSR are under development include US, France, China, and Russia. MSRs can be potentially utilised to burn minor actinides which remain radioactive for long time and are of public concern.

Indian High Temperature Reactor Development Programme

BARC is developing a technology demonstrator Compact High Temperature Reactor (CHTR), and a 20 MW_{th} Innovative High Temperature Reactor (IHTR). During the initial developments for HTRs, coolant exit temperature for the reactors was proposed as 1000 °C so as to facilitate hydrogen production from water by Iodine-Sulphur process. As per the studies carried out in BARC for this process, it has been estimated that the high temperature (~ 850 °C) process heat requirement is only about 8% of the overall energy requirement. Balance heat is required at temperatures less than 450 °C. Considering severe challenges and qualification requirements for nuclear reactors at 1000 °C, it was decided to develop the reactors operating at relatively lower temperatures. For CHTR and IHTR, the coolant exit temperatures are 550 °C and 665 °C respectively. The high temperature heat at ~ 850 °C would be supplied through the electrical heaters. CHTR (Fig. 2) is a lead-bismuth eutectic (LBE) alloy cooled, ^{233}U-Th fuelled, beryllium oxide moderated 5 MW_{th} reactor with SS 316L as the structural material with around 5 years long refuelling period. Considering requirements for advanced reactors, the reactor has been provided with several inherent passive features and passive core heat removal systems such as natural circulation of LBE and use of high temperature heat pipes. Studies and developments for this version, called CHTR-B, are in progress.



(3). Innovative High Temperature Reactor

IHTR (Fig. 3) is based on pebble bed fuel configuration with molten fluoride salt as coolant. Earlier conceptual design was done for 600 MW_{th} reactor. In order to demonstrate the concept, it was decided to workout design of a 20 MW_{th} reactor. The reactor, with co-generation capabilities, will also produce electricity for plant load and providing electricity to heaters needed for high temperature segment of the hydrogen production process. Many of the developments carried out for high temperature version of CHTR has applications in IHTR and similar other high temperature applications.

Indian Molten Salt Breeder Reactor

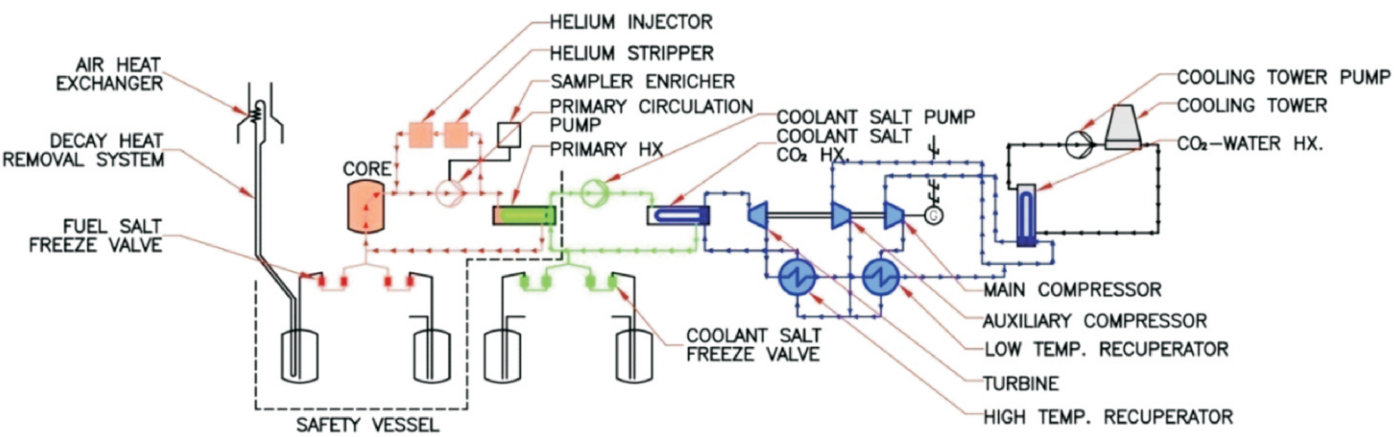
Attractiveness of MSBR in Indian context prompted initiation of R&D in BARC. Earlier, conceptual design of an 850 MW_e reactor was carried out with an aim to identify the R&D areas. Considering the large number of new technologies involved, a 5 MW_{th} demonstration IMSBR is being designed and the required technologies are being developed in BARC. This reactor (Fig. 4) uses $LiF\text{-}CaF_2\text{-}ThF_4\text{-}UF_4$ as fuel salt, which is circulated by pump through the reactor core containing graphite moderator blocks. The heat gained is transferred to the coolant salt (i.e. secondary side) by means of an intermediate heat exchanger. The coolant salt, LiF-NaF-KF, transfers the heat to the super critical CO_2 (SC CO_2) based Brayton cycle (SCBC) for power generation via a salt to SC CO_2 heat exchanger. SCBC based electricity generation system has been chosen as it operates at relatively lower pressure and results in higher efficiency. Ni-Mo-Cr-Ti based alloy has been indigenously developed as material of construction for all components wetted by molten salts. When the reactor is under shutdown, the fuel salt will be transferred to dump tanks from where the decay heat will be removed by passive means. The fuel salt circuit is contained within a nickel lined steel safety vessel. In an improbable case of leakage of fuel salt, it will be contained in this vessel in a subcritical configuration, while being cooled by passive means.

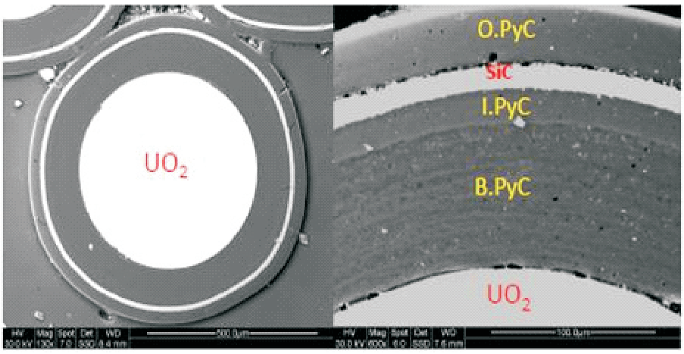
Technology challenges for HTRs and IMSBR

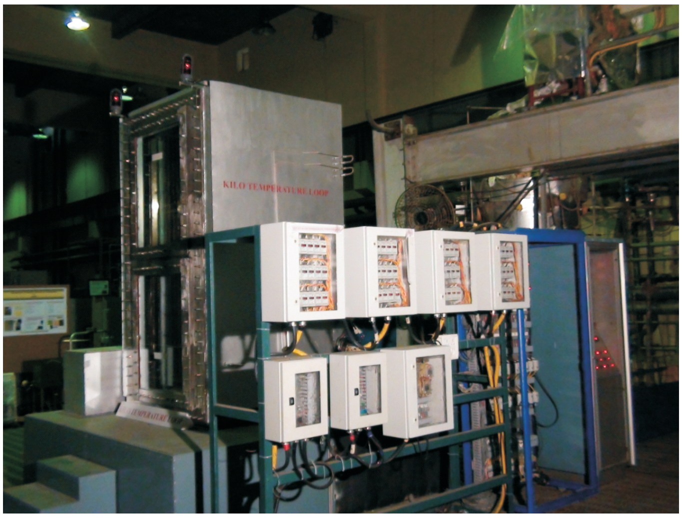
HTRs and MSBR are designed to operate at high temperatures, use different kind of fuel, coolants, and energy conversion systems. Therefore they pose a large number of technological challenges. These challenges are being addressed, mainly in BARC, through detailed R&D programmes. The specific challenges for these reactors have been briefly described in the following paragraphs:

For reactor physics analysis of long life compact CHTR core and pebble based moving fuels for IHTR, new computer codes have been developed. For understanding thermal hydraulics of the coolants, experimental and analytical studies have been carried out. LBE loops have been operated both at 550 and 1000 °C. For compatibility with LBE at high temperatures, Nb based alloy was developed with the help of NFC, Hyderabad. For HTR fuel, technology for TRISO (TRi-ISOtropic) coated particle based fuel was developed. Development of in-core ceramic material like beryllia, carbon-carbon composite etc. and graphite machining was carried out. For graphite, oxidation studies, large scale characterisation to develop design rules, and development of oxidation resistant coatings were carried out. For CHTR, passive heat removal by natural circulation of coolant under normal operation and passive heat transfer from primary to secondary

(4). 5MW_{th} IMSBR Flowsheet







(5). SEM images of TRISO coated particle fuel (Top)

(6). LBE thermal hydraulic studies (Middle)

(7). Graphite oxidation studies (Bottom)

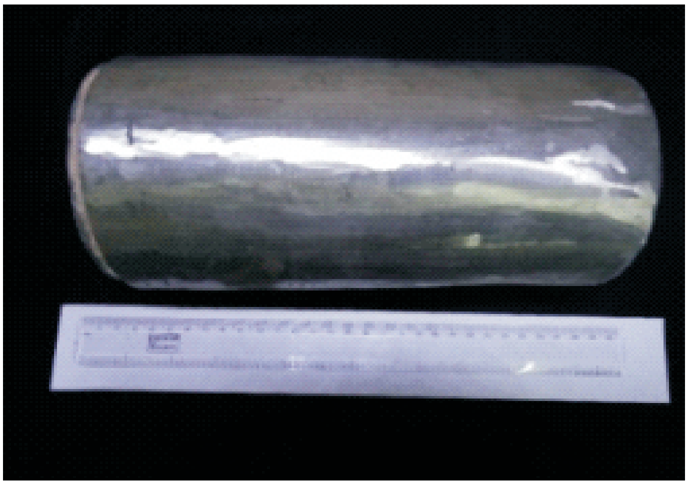
system by high temperature sodium heat pipes was experimentally demonstrated. Studies are in progress for decay heat removal by passive means. For IHTR, development of SCBC based power conversion system and interface with hydrogen production system are in progress. Development of heat exchangers, pump, instrumentation, and other components for the molten salt environment are also in progress.

The reactor physics analysis of fuel circulating IMSBR needs closely coupled neutron transport and CFD codes with capability to account for online reprocessing. Existing computer codes are being modified and new codes are being developed to model the neutronic behaviour of such fluid fuel reactors. Developed codes have been validated against the experimental data from literature. A 3D kinetics code with fuel salt flow and multi-point heat transfer model has been developed. A computational tool is being developed, which can model refueling/reprocessing. To understand behaviour of fuel and coolant salts, chemistry studies such as thermophysical properties, solubility etc. are in progress. Purification facility for coolant salt has been set up, and setting up of similar facility for fuel salt is in progress. For handling of molten fluoride salts, inert gas glove boxes have been setup. Facilities for production of ThF_4 and UF_4 from their respective oxides have been setup. The reactor needs ^{7}Li based fluoride salts. A process is being developed for enrichment of lithium-7 at high throughput rates. An indigenous Ni-Mo-Cr-Ti alloy, which is compatible to molten fluoride salts under reactor conditions, has been developed in collaboration with MIDHANI. It's scaled up production and fabrication of engineering shapes is in progress. R&D is in progress for development of high density isotropic nuclear grade graphite. Design and technology development for pumps, valves, flow meter, off-gas system, dump tanks, helium injector and stripper, intermediate heat exchanger, salt-CO_2 heat exchanger etc. is in progress. Design and studies are also in progress for SCBC components. Facilities for studies on interaction of supercritical CO_2 with Ni-Mo-Cr-Ti alloy and high speed seals are being designed. Instrumentation and sensors are also under development for operation at high-temperature, high-radiation, molten salt environment. Studies are in progress for computational modelling of molten fluoride salts using molecular dynamics. This is expected to reduce experimental work, especially for the salt with fission products. Evolution of safety philosophy and safety studies, batch mode offline reprocessing studies without requiring cooling of fuel salt, reactor control, remote inspection, and qualification of new materials to meet codal design requirements are being initiated.

Current status and way forward

As mentioned above, for CHTR, besides designing the reactor, experimental thermal hydraulic studies, development of TRISO coated fuel on natural urania, BeO, graphite oxidation studies, development of high temperature sodium heat pipes have been carried out. Manufacturing of components for a lower power electrical heated facility of the reactor is in progress. Subsequently this facility will be set up to demonstrate integral behaviour of the reactor. The design of the demonstration IHTR is in progress.

The interface of this reactor with the hydrogen production plant and safety issues arising out of combined operation of IHTR with a hydrogen production plant is being studied. Development of pebble based fuel from TRISO coated fuel particles is being initiated. Due to use of fluoride salts, many developments such as structural material, graphite, salt related components, instrumentation, sensors etc. are similar as those for IMSBR, and are being developed together. This results in overall savings for technology development efforts. The detailed design of the 5 MW_{th} IMSBR is in progress. This will serve as test bed for salts,



(8). Glovebox for handling molten fluoride salts (Top)
(9). Indigenously developed Ni based alloy (Middle)
(10). UF_4 preparation facility (Bottom)

materials, reactors systems, instrumentation, reactor physics and chemistry studies. Operation of this demonstration reactor will help in finalizing the design of the large power IMSBR.

It is planned to demonstrate all the major equipments and systems of this reactor at full scale under actual operating conditions from temperature and salt chemistry point of view. For this purpose, a dedicated facility, Molten Salt Breeder Reactor Development Facility (MSBRDF) is being designed for setting up at Visakhapatnam. Pre-project activities for these facilities are already in progress.

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Further reading

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