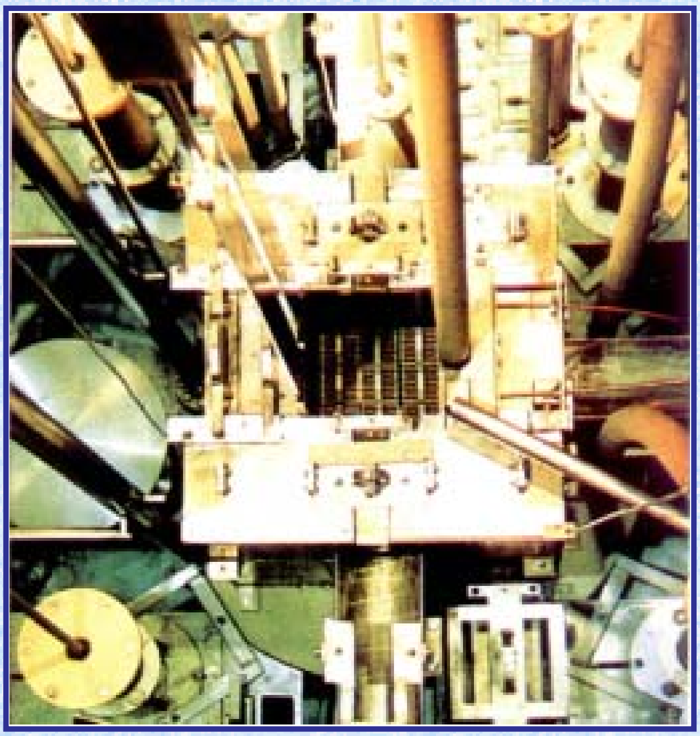
Shaping the Third Stage of Indian Nuclear Power Programme



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Government of India

Department of Atomic Energy

SHAPING THE THIRD STAGE OF INDIAN NUCLEAR POWER PROGRAMME

OUR ENERGY OPTIONS

Energy is essential for the survival and growth of modern human civilisation. A reasonably good correlation exists between the per capita energy consumption and quality of life, as indicated by the UN Human Development Index. This correlation is quite strong in the case of developing countries like India where the energy demand is largely unfulfilled. All available sources of energy, therefore, must be optimally developed and deployed to meet the short as well as long term energy needs of our country.

For a large country like India, a major fraction of energy must come from domestic resources. From a long-term perspective, we have rather limited options in this regard. There are environmental issues, which will be inevitably associated with large-scale deployment of coal. Apart from this, a fact, which is often overlooked, is that the existing reserves of coal in India would be inadequate to meet an enhanced rate of energy consumption, comparable to today's world average per capita level-as needed for an improved quality of life for its entire population, for more than a few decades. Solar and other renewable, and non-conventional energy sources must be deployed to the fullest extent possible. However, to meet the large concentrated energy needs for industries and urban centers, the only sustainable energy resource available to us in India, indeed the entire world in a longer-term time frame, is nuclear energy. Here too, we are in a rather unique situation with regard to the availability of nuclear resources in our country.

We have rather meagre reserves of uranium, the only naturally occurring fissile element that can be directly used in a nuclear reactor to produce energy through nuclear fission. We, however, have nearly a third of the entire world's thorium, which is a fertile element, and needs to be first converted to a fissile material, uranium-233, in a reactor. Our strategies for large scale deployment of nuclear energy must be, and are therefore, focussed towards utilisation of thorium.

THORIUM – OUR PRIORITY IN THE INTERNATIONAL CONTEXT

Thorium, though it possesses a number of superior physical and nuclear characteristics than uranium, is not fissile. Thus, even with much greater abundance as compared to uranium, and also early recognition of its superior characteristics, as an energy source, thorium has lagged far behind uranium.

Saturation in energy demand in industrialised countries and inadequate pick up of development process in the rest of the world has made uranium appear even more attractive today than it was in the past. The early enthusiasm and interest worldwide, which looked at several thorium-based reactor systems in early sixties, has thus not been sustained.

In India, on the other hand, the energy demands are fast growing. With our modest uranium reserves, the large growth in nuclear power capacity can be realised only through efficient conversion of fertile materials into fissile materials and utilising the later to produce energy. A closed nuclear fuel cycle, which involves reprocessing and recycle of fissile materials, is thus inevitable for us and that too, in a relatively shorter time frame than most of the other industrialised countries. With our five to six times larger reserves of thorium, than that of uranium, thorium utilisation for large scale energy production has remained an important goal of our nuclear power programme.

THE THREE-STAGE INDIAN NUCLEAR POWER PROGRAMME

The importance of nuclear energy, as a sustainable energy resource for our country, was recognised at the very inception of our atomic energy programme more than four decades ago. A three-stage nuclear power programme, based on a closed nuclear fuel cycle, was then chalked out. The three stages are:

- Natural uranium fuelled Pressurised Heavy Water Reactors (PHWRs),
- Fast Breeder Reactors (FBRs) utilising plutonium based fuel, and,
- Advanced nuclear power systems for utilisation of thorium.

For carrying out an efficient production of plutonium, the fissile material needed to fuel further growth in nuclear power capacity, a natural uranium fuelled heavy water moderated reactor is the best option.

Thus we started the indigenous development of nuclear power plants based on uranium cycle in PHWRs, in the First Stage. At present we have twelve such reactors under operation, four are under construction, and several others have been planned. We have become self sufficient in all aspects of the PHWR technology. The capacity factors of our operating PHWRs have been close to eighty percent during recent years, an excellent performance even with respect to international standards.

The designs of these reactors have progressively improved taking into account needs for indigenisation, our own operating experience, operating experience in PHWRs outside our country, and progressive evolution of enhanced safety features, as per the practice internationally followed for current generation nuclear power plants. A large volume of R&D has been done in the past to provide support to our PHWR programme. Such support has encompassed practically all the aspects of design, manufacture, construction, commissioning, operation and maintenance of these power plants. Considering the limited size of our nuclear power programme based on PHWRs, there does not seem to be any necessity for seeking major changes in the already matured and standardised designs of our 220 and 500 MWe PHWRs. The required R&D support for currently operating and future PHWRs will, however, continue although the range and volume of these activities to be carried out at BARC is likely to progressively reduce.

As a part of the Second Stage, we started the FBR programme with the Fast Breeder Test Reactor (FBTR), at IGCAR, Kalpakkam (Fig.1). This reactor, operating with indigenously developed mixed (U+Pu) carbide fuel, has already yielded a large volume of operating experience and a better understanding of the technologies involved. This has enabled us to design 500 MWe (prototype) FBR (Fig.2) that will utilise plutonium and the depleted uranium from our PHWRs. Construction of this reactor is due to begin soon.

With the experience gained from the first prototype, improvements and up-gradation in the technology will of course, be an important part of the programme in the coming years. Implementation of further evolutionary and innovative improvements in the reactor design and associated fuel cycle technologies will follow next. Some ideas on the likely future thrust areas for fast reactor programme are brought out in Fig.3 .

In preparation for the Third Stage, development of technologies pertaining to utilisation of thorium have been a part of our ongoing activities. Considerable thorium irradiation experience has been acquired in research reactors and we have introduced thorium in PHWRs in a limited way. With our sustained efforts over the past many years, we already have small-scale experience over the entire thorium fuel cycle. An example is the KAMINI reactor (Fig. on cover), in IGCAR, the only currently operating reactor in the world, which uses ^{233}U as fuel. This fuel was bred, processed and fabricated indigenously. Efforts are currently on to enlarge that experience to a bigger scale.

We are now designing and developing advanced nuclear systems, which will utilise our precious plutonium resources in an optimum way to maximise conversion of thorium to ^{233}U, extract power in-situ from the thorium fuel, and recycle the bred ^{233}U in future reactors.

The Advanced Heavy Water Reactor (AHWR) project, discussed later, provides a focal point for a time bound high intensity development in the efficient utilisation of thorium. The work on AHWR will also help in conserving and further enhancing our R&D expertise related to Heavy Water Reactors. Reprocessing and refabrication of the fuel plays a major part in the utilisation of resources to the full extent. R&D work on the reprocessing and refabrication in the context of AHWR is an important step forward towards large scale thorium utilisation.

In the Accelerator Driven System (ADS), high-energy proton beam generates neutrons directly through spallation reaction in a non-fertile/non-fissile element like lead. A subcritical blanket with lesser fissile requirement will further amplify this external neutron source as well as energy. Development of such a system offers the promise of shorter doubling time with Thorium-Uranium 233 systems, incineration of long lived actinides and fission products and robustness to our approach towards realisation of the objective of large scale thorium utilisation.

CHARACTERISTICS OF THE THORIUM CYCLE

Physical Characteristics

The thermal conductivity of Thorium di-oxide (ThO_2) is higher than that of uranium di-oxide (UO_2). As a result fuel temperatures for thorium fuel will be lower than uranium fuel resulting in reduced fission gas release.The thermal expansion coefficient of ThO_2 is less as compared to UO_2 inducing less strain on the fuel clad. Thus Thorium di-oxide retains dimensional stability at high burn-ups.

It is a very stable oxide and does not oxidise resulting in less release of fission products in the coolant in the event of a clad breach. The fission product release rates for ThO_2 based fuels are one order of magnitude lower than that of UO_2. Fuel deterioration is slower allowing the fuel to reside in the reactor for longer periods of operation.

To summarise, thorium as a fuel material has improved physical properties and has higher radiation resistance than uranium.

Nuclear Characteristics

The nuclear characteristics of thorium have an immense bearing on the selection and development of technologies associated with thorium fuel cycle. Let us have a look at some of these important characteristics.

If one compares the absorption cross section[1] for thermal neutrons, of ^{232}Th vis a vis ^{238}U, (7.4 barns vs. 2.7 barns), it becomes clear that ^{232}Th offers greater competition to capture of the neutrons and as such a lower proportion of the neutrons will be lost to structural and other parasitic materials. Moreover this improves conversion of ^{232}Th to ^{233}U.

^{233}U has an eta[2] value greater than 2.0 and it remains constant over a wide energy range, in thermal as well as epithermal regions, unlike ^{235}U and ^{239}Pu. It makes thorium fuel cycle less sensitive to the type of thermal reactor.

The capture cross section of ^{233}U is much smaller (46 barns) than the other two fissile isotopes (101 barns for ^{235}U and 271 barns ^{239}Pu) for thermal neutrons, while the fission cross section is of the same order (525 barns for ^{233}U, 577 barns for ^{235}U and 742 barns ^{239}Pu). Thus non-fissile absorption leading to higher isotopes with higher absorption cross sections (^{234}U/ ^{236}U and ^{240}Pu respectively) is much less probable. This makes recycling of ^{233}U less of a problem from reactivity point of view compared to plutonium.

One parameter that appears to be disadvantageous in the case of ^{232}Th is the relatively long half life (27 days) of the intermediate product ^{233}Pa compared to the half-life (2.7 days) of the corresponding nuclide ^{239}Np in the case of ^{238}U. As a result, ^{233}Pa builds up to a significantly higher level in equilibrium and a portion of it gets lost by neutron absorption before it decays to ^{233}U.

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1 *The probability of a nuclear reaction is quantified in terms of "cross section". It is measured in terms of "barns"; one barn is defined as 10^{-24} cm^2 – typical nuclear cross sectional area.*

2 *Eta defines the number of fast neutrons emitted in a fission process per neutron absorbed by the fissile nuclei; one neutron is required to continue the chain reaction*

An important isotope of some concern in thorium cycle is ^{232}U. Uranium-232 (^{232}U) is formed via (n, 2n) reactions, from ^{233}Pa and ^{233}U. The half-life of ^{232}U is about 69 years. The daughter products of ^{232}U like ^{208}Tl (2.6 MeV), are hard gamma emitters with shorter half-lives. As a result the radioactivity builds up with time in the bred uranium. This presents several technological challenges in the reprocessing and recycling of bred ^{233}U.

Long-lived minor actinides resulting from the burn-up chain are in much less quantity for thorium fuel cycles, if the reactor operates purely in the U^{233}-Th cycle. Actinides having masses beyond 237 are produced in negligible quantities. This is an important advantage, as the burden of management of long-lived radio-active waste is significantly reduced.

Thorium as Fissile Host

From fuel cycle analysis point of view one can compare the characteristic of the two fertile isotopes, viz., ^{238}U and ^{232}Th, as fissile hosts. For simplicity we assume ^{235}U as the fissile feed. The following conclusions are then arrived at:

- The amount of fissile enrichment required to achieve a given burn-up is higher for lower discharge burn-ups for thorium fuel. But at higher discharge burn-ups[3] , beyond about 50 GWD/t, the initial enrichment required is lower. This is due to the breeding of ^{233}U in thorium system.
- In terms of energy extracted, i.e., fuel utilisation, thorium as fertile host overtakes ^{238}U as host, at about 45 GWD/t. This is because the bred plutonium saturates at about 0.6% at high burn-ups, while ^{233}U saturates to nearly 1.5%.
- In absolute terms, uranium (low enriched uranium, LEU) gives better utilisation up to a discharge burn-up of about 45 GWD/t, while higher burn-ups have to be achieved in thorium cycle to reap its benefits. These burn-up values, though considered high in early days, are now well within the current day water reactor fuel technology.
- There are other advantages of using ^{232}Th that merit consideration. Variation of reactivity with burn-up is smaller in thorium based fuel due to a relatively higher value of fuel inventory ratio (FIR)[4] leading to bet-

3 *Burn-up of a fuel material is defined as the energy extracted for a given mass of the (heavy metal) fuel; it is measured in Mega/Gigawatt (thermal) days per tonne of the fuel.*

ter operational characteristics such as flatter core power distribution that can help reduce the use of burnable or soluble poison. Finally, in thorium based fuel, there is effective utilisation of external fissile fuel whether it is ^{235}U or Pu, added initially. It is for this interesting feature that thorium is getting increasing attention for plutonium dispositioning.

- In terms of operation, multiple recycling[5] of plutonium has adverse effects on reactivity coefficients in thermal reactors, with even void reactivity becoming positive. For fuel dispositioning, employing inert matrix (IM, non-fertile metal alloys containing Pu) fuel also makes the reactivity coefficients so small that poses serious safety issues. As a result, only about one-third to one-fourth of the core can be loaded with such a fuel, bringing down the overall plutonium disposition rate via this route. Thorium as a plutonium carrier enables considerable improvement in both the cases.
- Use of (Th, Pu) MOX in Pressurised Water Reactors (PWRs), improves plutonium burn-up vis-a-vis (Th, U-233) MOX, but the reactivity coefficients turn highly negative which might lead to strong feed back effects. On the other hand, in a PHWR, full core can be loaded with (Th, Pu) MOX fuel without much deterioration in the safety characteristics of the core. Fraction of fissile plutonium burnt is also close to that in the case of IM.

The foregoing discussion brings out the major advantages of thorium utilisation in a Heavy Water Reactor (HWR). The design of the corresponding reactor system should meet the internationally stipulated criteria now being evolved for the next generation nuclear power plants. The Indian AHWR belongs to such class of next generation reactors.

SHAPING THE THIRD STAGE

Current Status

Technologies pertaining to utilisation of thorium have been under development, mainly at BARC, right since the inception of our nuclear power programme. The irradiation of thorium bundles in PHWRs for flux flattening, design, construction and operation of U-233 fuelled Purnima and Kamini reactors and large volume of research activities

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4 *FIR is a ratio of the fissile inventory at a given time in the core life to the initial fuel inventory built in the core.*

5 *Multiple recycling results into built-up of Plutonium - 238, higher isotopes of Plutonium and Americium.*

Fig 1 : Fast Breeder Test Reactor

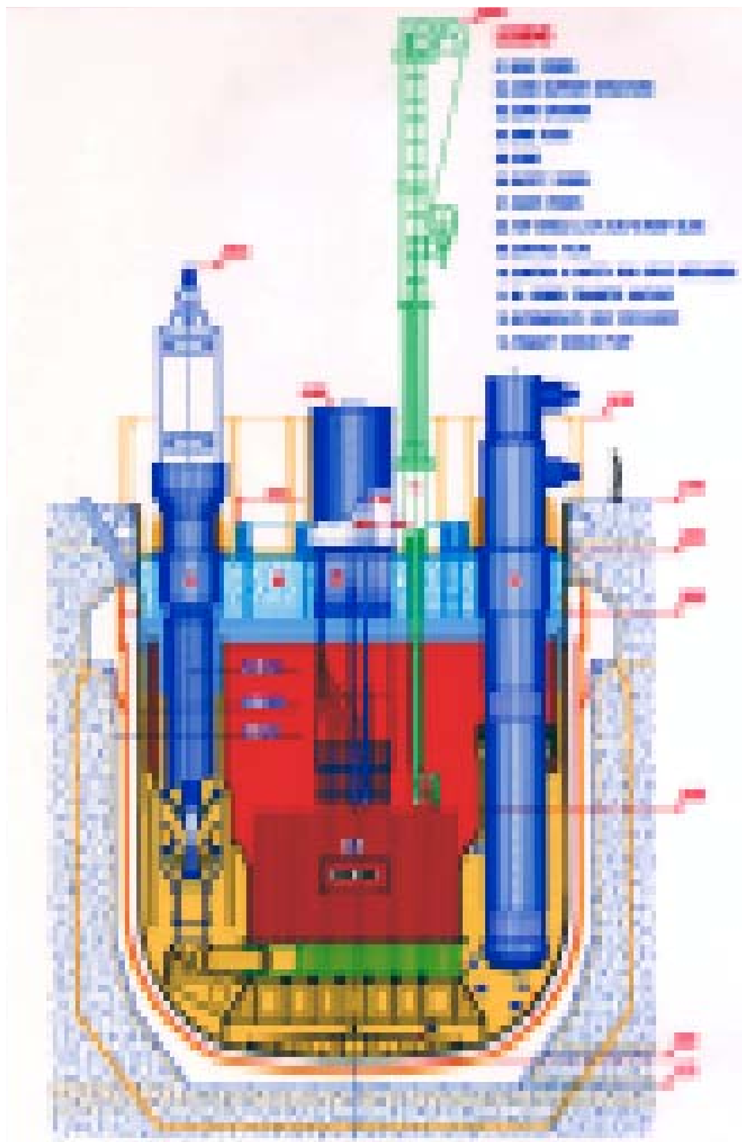


Fig 2 : Prototype Fast Breeder Reactor Schematic

Fig 3: Future Fast Reactor Development Programme

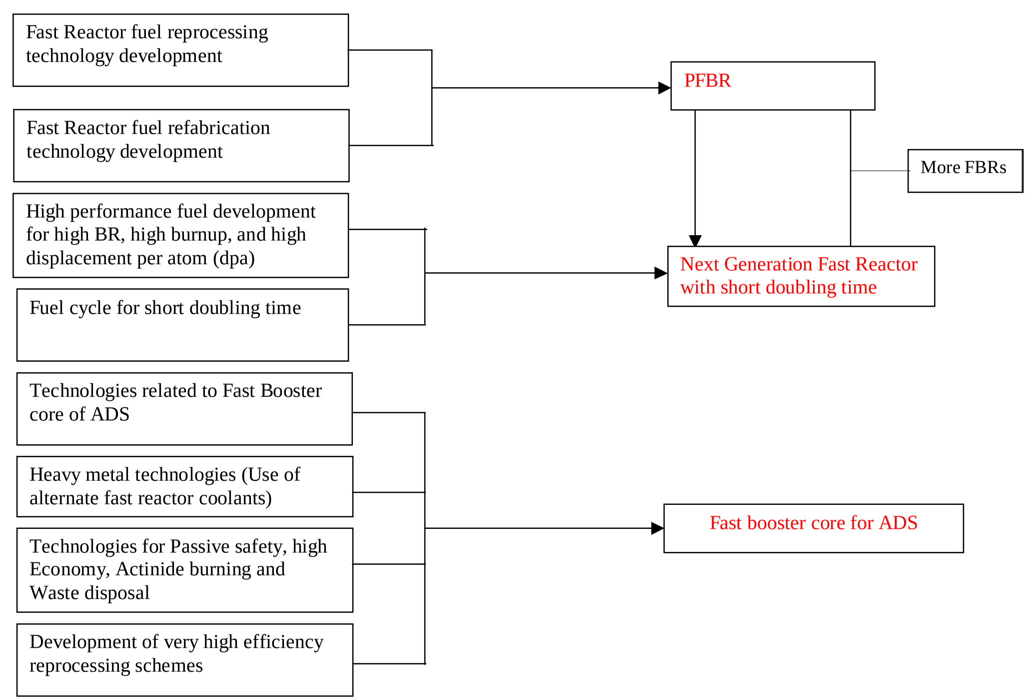


Fig 4: Thermal Reactor based Systems

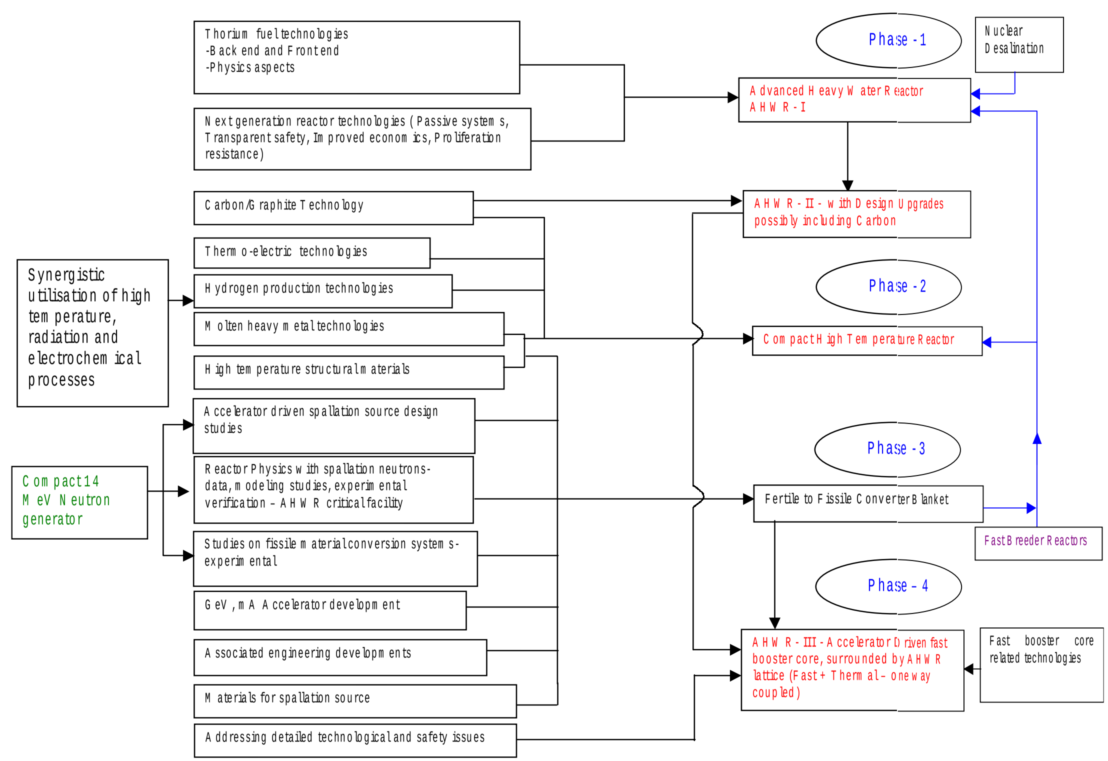
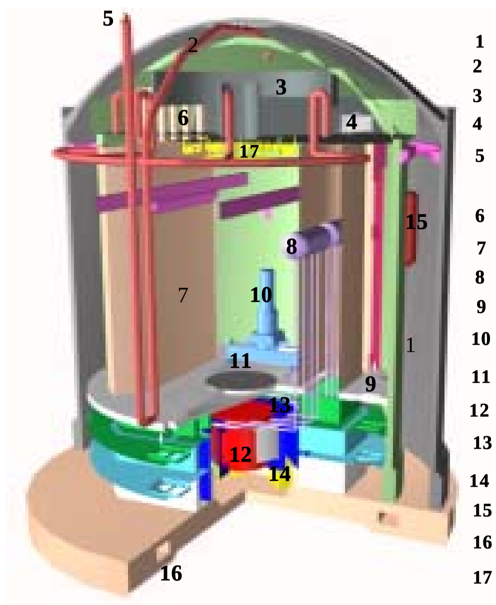


Fig 5 : Advanced Heavy Water Reactor



1 Secondary Containment
2 Primary Containment
3 Gravity Driven Water Pool
4 Isolation Condenser
5 Passive Containment Isolation Duct
6 Vent Pipe
7 Tail Pipe Tower
8 Steam Drum
9 100 M Floor
10 Fuelling Machine
11 Deck Plate
12 Calandria with End Shield
13 Header
14 Pile Supports
15 Advanced Accumulator
16 Pre - Stressing Gallery
17 Passive Containment Cooler

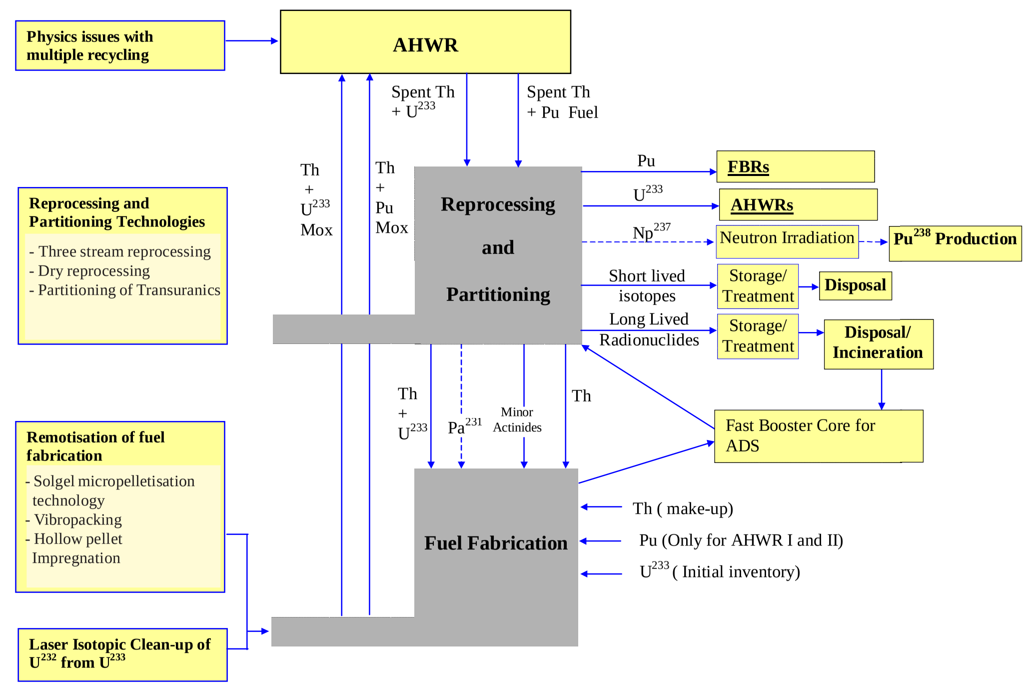
BASIC DATA

FUEL : U-233/THORIUM
MOX + Pu -239/THORIUM
MOX
COOLANT : BOILING LIGHT WATER
MODERATOR : HEAVY WATER
POWER : 235 MW(e)

ADVANCED SAFETY FEATURES

1. -Ve VOID COEFFICIENT OF REACTIVITY
2. SEVERAL ADVANCED PASSIVE SAFETY SYSTEMS
3. LARGE HEAT SINK ALLOWING 3 DAYS GRACE PERIOD

Fig 6: Advanced Fuel Cycle Technologies for Thorium Utilization



including irradiation of thorium fuel in our research reactors, and studies on the fuel cycle technologies related to thorium, have already led India to become one of the top ranking countries in the world in the thorium utilisation field. Some programmes to further develop these technologies for large scale deployment, extending laboratory level studies have been initiated.

Considering the imminent need for large scale expansion of the electricity generating capacity in our country, as well as a need for developing technologies for providing alternative fluid fuels when the hydrocarbon fluid fuel become unaffordable for import, a large thrust to R&D programmes related to the third stage is progressively being given.

Goals of the Third Stage

The third stage of our programme has to necessarily meet the following goals:

i) Utilisation of thorium as fuel on a commercial scale.
ii) Large scale of deployment of nuclear power in the country.
iii) Achieving good economic performance as compared to alternate options for energy generation.
iv) Attaining higher levels of transparent safety, through optimal utilisation of inherent and passive safety features.
v) Utilising the proliferation resistant potential of thorium fuel cycle to the full extent.
vi) Providing for adaptability to non-electrical applications, in particular, desalination and high temperature processing applications, including those for generation of non-fossil fluid fuels.

A Road Map for the Third Stage

To meet these objectives in medium as well as long term time frames, keeping the current international trends in nuclear technology in view, a road map for the third stage of Indian nuclear power programmes has been proposed in Fig. 4. The main products included in this road map, in different time frames, are the following:

Stage 1 : Advanced Heavy Water Reactor (AHWR) (Fig. 5).
Stage 2 : High temperature reactor based power packs.
Stage 3 : Accelerator driven fertile converters.

Stage 4 : Accelerator driven system with a fast reactor sub-critical core together with a mainly thorium fuelled thermal core somewhat similar to that present in AHWR.

ADVANCED HEAVY WATER REACTOR

Introduction

The AHWR, based on both evolutionary and revolutionary design concepts, is being developed in India with the specific aim of utilising thorium for power generation. AHWR is a vertical pressure tube type reactor cooled by boiling light water and moderated by heavy water. It incorporates several advanced passive safety features, e.g., heat removal through natural circulation. The reactor has been designed to produce 750 MW(th) at a discharge burn-up in excess of 20,000 MWd/t. Negative void coefficient of reactivity has been achieved, in spite of using boiling light water coolant. Another design objective is to be self-sustaining in ^{233}U with most of the power from the conversion of thorium fuel while using plutonium as the external fissile feed. Also one has to minimise the external plutonium feed in the equilibrium fuel cycle.

Genesis of Basic Physics Design of AHWR

As discussed above, thorium being a very strong absorber of thermal neutrons, it reduces the fraction of thermal neutron absorption in coolant, moderator and structural materials. It is therefore logical to choose light water as coolant while retaining heavy water as moderator for better neutron economy. When high pressure and high temperature heavy water is used as coolant, several expensive systems and other technological solutions have to be deployed to avoid and recover leakage of this costly fluid, and some constraints in operation and maintenance are imposed to cater to the requirements of radiological protection against associated tritium activity. Use of light water as coolant, as in AHWR, eliminates these costs and constraints. With the achievement of slightly negative void reactivity in the reactor, heat removal in boiling mode can be adopted, thereby affecting a reduction of about 50% in the overall quantity of coolant as well as improvement in steam cycle efficiency.

The afore-mentioned considerations result in a vertical pressure tube type reactor with boiling light water as coolant and heavy water as moderator.

Innovative Engineering Design Concepts

Boiling coolant offers an attractive option for natural circulation, thus doing away with primary coolant pumps. In AHWR, the entire core heat, under both operating and hot shutdown conditions, is to be removed by using natural circulation, without the use of any coolant pump. This choice results in inherent passive safety feature and reduction in overall cost of the primary heat transport system. With natural circulation, the reactor should have lower power densities while assuring sufficient margins in fuel heat fluxes.

With the requirement of low power densities, the neutron flux levels are also low. This offers a better fertile nuclide conversion as well as lower xenon loads. The latter property makes the restart of the reactor, after a trip, an easier task as compared to PHWRs, where xenon poison-out can keep the reactor unavailable for nearly two days.

For inherent safety the reactor should have negative void coefficient of reactivity, which has been achieved by the fuel cluster design as well as providing void tubes in the moderator. This implies that under any postulated scenario, in which there is a tendency towards increase of core power, or a reduction in core flow, as the boiling accelerates and more voids are produced, the reactor power is automatically brought down on account of inherent neutronic characteristics of its core.

The 54-rod circular fuel cluster design with composite [(Th-^{233}U) MOX and (Th-Pu) MOX] fuel with a displacer rod at the center is a very flexible design. Tight packing of the fuel pins offers even distribution of coolant and low local power peaking, which gives sufficient Maximum Critical Heat Flux Ratio (MCHFR) margins. A ferrule type spacer design, while giving minimum resistance to coolant flow, offers an option to reconstitute the plutonium pins, thus enhancing fuel burn-up and power from thorium. A central hole along the displacer rod allows direct injection of Emergency Core Cooling System (ECCS) water into the fuel cluster.

The design specifically takes care of quick replacement of the pressure tube and calandria tube, if required at any time in the future. The overall core structural design aims at a reactor life of 100 years.

The design of AHWR includes several passive features and systems, which do not require operator or automatic control action to get activated. For example, a large pool of water, called Gravity Driven Water Pool (GDWP), located at the top of the reactor building, serves to provide cooling to the reactor core under any postulated event scenario for a minimum period of three days, without there being any need for operator action.

These are only a few examples of several important safety and economy enhancing features of this reactor. This reactor not only fully meets, but exceeds, the safety criteria for an advanced nuclear generating system.

The Implementation of AHWR Project

The design and development of the major systems of AHWR is being carried out under a 9th Plan Project which will yield a detailed project report, design documentation and major experimental facilities as its main outcome. During the 10th Plan, it is proposed to generate confirmatory data supporting validation of the design of the reactor. Also, it is proposed to complete the design of conventional system, using the services of consultants, in the first few years of the 10th Plan, and seek financial sanction for the construction of the first reactor.

It is envisaged that the first AHWR will be constructed and operated as a technology demonstration plant. Based on the experience gained, the design can be optimised even further, and based on further development in materials technology, we could have further enhanced the version of AHWR termed AHWR II.

HIGH TEMPERATURE REACTOR BASED POWER PACKS

It is well known that for India a large fraction of the import bill goes to purchase crude oil and petroleum based hydrocarbon fuels. With continuously increasing demands we have to look for technological solutions for generation of alternate fluid fuels. Most of the technologies for this application need temperatures in the range of 700^{o} C to 900^{o} C. In particular, generation of hydrogen from water using chemico-thermal processes needs high temperatures exceeding 800^{o} C. Keeping this in mind, a programme to design and develop a high temperature reactor system mainly for process heat, and non-grid based electricity generation applications, has been initiated. Using uranium-233 as fuel, a very compact design of core, weighing about 1.5 tonnes, has been worked out. Such a reactor can thus, serve as compact power pack in remote locations. Several new technologies and materials are associated with this reactor system. These include liquid lead based coolant, carbon based structural components, coated particle type nuclear fuel, high temperature resistant alloys, and control systems which can reliably and passively operate under high temperature conditions, preferably without human intervention.

Some of the technologies required for such a high temperature reactor will also be useful for possible implementation in a future version of AHWR, where use of a carbon based moderator, along with heavy water, may be considered to further improve the economic performance of the reactor. Molten lead related and high temperature application specific technologies are important for the accelerator driven systems, discussed below.

ACCELERATOR DRIVEN SYSTEMS (ADS)

Background

Accelerator driven systems throw open several attractive possibilities for extending our nuclear power programme. High energy protons, on colliding with a target of high atomic number element (such as lead, tungsten, uranium etc.) cause detachment of a large number of neutrons from these nuclides in a process known as 'spallation'. These neutrons can provide the required external neutron source which can sustain a significant power level in an otherwise sub-critical blanket (an arrangement similar to a nuclear reactor with not enough fuel to make it critical). Such systems, called 'accelerator driven systems', can be used to produce several times more electrical energy than that required to run the accelerator. Such a system is, therefore, also termed an 'energy amplifier'. The system can also be designed to convert fertile materials, present in the blanket, to fissionable materials. Accelerator driven systems are also eminently suited for transmuting the highly radioactive waste from conventional nuclear power plants to shorter lived radionuclides, which do not require a very long term storage under surveillance.

Milestones towards the Introduction of ADS in the Third Stage

A good beginning has already been made by acquiring the necessary expertise to design and build linear accelerators as well as cyclotrons. The challenges involved in the design of very large accelerators, and coupling them to sub-critical cores, are quite substantial and are a matter of intense R&D effort in several countries. As a part of the roadmap for the third stage of our nuclear power programme (Fig. 6), a set of milestones, have been identified along the way for the development of the technologies relevant for an accelerator driven system.

As a first step, it is planned to develop high-energy neutron source, which can be used in the Critical Facility, due to be constructed soon at BARC, for physics experiments relating to AHWR and PHWR. This will help in quickly validating relevant neutronic data, which can be used for the design of accelerator driven systems. The next step is to develop a spallation neutron source, utilizing molten heavy metal, along with a moderate sized accelerator, and use it in a research reactor core for additional R&D on the coupling of this source with a sub-critical core. This experience can then be used to design and develop an accelerator driven fertile to fissionable material converter, where the basic objective is to produce fissionable material from thorium-232/uranium-238 without generating electricity. The final step will be to build a full-fledged accelerator driven systems, for electricity generation, fissionable material production, and nuclear waste incineration applications. Such systems can then work synergistically with the remaining components of the third stage of our nuclear power programme. A synergetic scenario between AHWR and ADS has been worked out.

The important features of the third stage road map have been summarised in Fig. 4. The figure also brings out the important R&D inputs for different milestones, and the inter-linkages between different phases.

Roadmap for the Development of Accelerator Technologies

The accelerator sub-system that forms the part of ADSS has to be reliable, rugged and stable over long periods of time in order to provide un-interrupted high-energy and high-power proton beam to the spallation target. A two part roadmap for carrying development of accelerator to be part of ADS has been recently drafted by the ADS Coordination Committee. According to its recommendation, the first part comprises three activities:

1. Designing and building of a cyclotron up to about 350 MeV and a beam current of 5mA, with an intermediate injector of a 70-100 MeV stage.
2. Designing and building of a Linac with beam energy up to about 70-100 MeV and a beam current of 10mA with normal/ superconducting operation.
3. Development of different types of superconducting Nb cavities and establishment of cryogenics and superconducting RF technologies.

In the second part, development of a pulsed Linac of about 500 MeV has been contemplated.

THORIUM FUEL CYCLE

One of the major objectives of taking up the design and development of AHWR is to provide a focus for timely development of all technologies relating to large scale thorium utilization for commercial electricity generation.

In order to support fuel cycle of AHWR, several technologies have to be brought to a level of maturity, and some new ones need to be developed. Fig. 6 shows a proposed advanced fuel cycle for the AHWR. It is expected that such a fuel cycle will not only cater to the special challenges associated with re-fabrication of the radioactive fuel thorium, but will also use all the fissionable materials in the fuel cycle very efficiently while minimising the radiological toxicity of the waste stream and enhancing the proliferation resistant potential. A part of the fresh fuel for AHWR, bearing uranium-233, will require to be produced remotely behind lead shields. This requirement follows from the presence of uranium-232, as an impurity along with uranium-233. As mentioned earlier, the former, through its radioactive decay, produces some nuclides with high gamma radioactivity. Many experts in the world view this characteristics as an important feature, which makes thorium cycle resistant to proliferation. We are mainly engaged in developing technological solutions to this issue. Schemes for laser isotopic clean up of uranium-233 as well as several alternative technologies for remote fabrication of this fuel on a large scale, are in progress. Notable among the latter are, sol-gel micro-pelletisation, vibro-packing, pellet impregnation, and advanced agglomeration technologies.

The back-end of the fuel cycle is being developed to work out technologies to cater to the special challenges associated with thorium based fuel. Thorium dioxide, or thoria, is a very inert material and one of the major challenges is to make it dissolve, during the spent fuel reprocessing operations. Encouraging results have been obtained in laboratory experiments done at BARC to find a solution to this problem. Programmes have been identified, as a part of the third stage activities, to reach a desirable goal of using all the fissionable materials in the fuel cycle very efficiently while minimising the radiological toxicity of the waste stream.

CONCLUDING REMARKS

For a large country like India, long term energy security, mainly based on indigenous resources, is an important and inevitable need, from economic as well as strategic considerations. There are several dimensions to sustainable development of energy resources—including not only economic, technological and political, but also global environmental, ecological and social factors. These considerations will dictate the optimum composition of our energy mix, in different time frames in future. As time passes, the actual composition of the mix will be subject to variation with changes in technological and geopolitical environment. Even so, it remains a certainty that thorium based nuclear energy systems will have to be a major component of the Indian energy mix in the long-term.

Research and development in the field of cutting edge nuclear technologies have to be necessarily based on elaborate programmes, and the velocity of such R&D is strongly dependent on the level of inputs of our limited resources to such programmes, in competition with other shorter term priorities. Recognising this, and the fact that India has to be in the lead as far as the development and deployment of thorium utilisation technologies are concerned, an early beginning in this direction has already been made. A strong indigenous R&D infrastructure, including trained scientific and engineering manpower, developed over last several decades, is already available, to a large extent, to help us in reaching further milestones towards the goal of large scale deployment of thorium as a sustainable energy resource for India.

In order to make further continued progress on this path in a focussed and co-ordinated manner, and also to make an optimum utilisation of the resources available to us at any point of time, it is now important to formulate a fairly well laid out roadmap for the third stage of our nuclear power programme. This document has been prepared to serve as the basis for further discussion to enable further and detailing and optimisation of this roadmap.