Evolving Indian Nuclear Programme – Rationale and perspective

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1 Background

The Indian Department of Atomic Energy (DAE) was established more than five decades ago. Its activities encompass Research and Development in areas relating to nuclear sciences and technologies, industrial scale manufacture of critical raw materials, components, equipment and systems needed for Indian nuclear programme, production of nuclear power, and support of research, academic activities and services associated with nuclear energy and allied subjects within the country. In each of these areas, the required domestic infrastructure, including the human resources have been progressively developed. A capability based on self-reliance has been acquired to take up newer challenges, as and when they arise.

The main drivers of DAE's activities have been: relevance to meet the national needs and priorities, and excellence by global standards. For a large country like India, it is considered strategically important to develop core capabilities in critical areas to reduce vulnerabilities to external pressures. Incidentally, technology denial regimes have been operational through a major part of the DAE's history. The achievements of DAE, in a wide range of fields, have to be viewed from this perspective as well.

2. Reaching global levels of excellence in relevant scientific and technological disciplines – Some recent examples

R&D areas relevant to nuclear power

India is the only country in the world that has accorded a high priority to the use of all the three main fissionable materials, uranium-235, plutonium and uranium-233, to meet the challenge of reaching energy independence through a well calibrated deployment of domestic uranium and thorium resources.

India started with building Pressurised Heavy Water Reactors (PHWRs) in the country in the first stage of its domestic nuclear power programme. The magnitude of research and development in the field of PHWRs is best represented by the number of scientific publications in the area. As can be seen in Figure-1, India has progressively reached world leadership in this area. Nearly 55% of the scientific publications in the field of PHWRs originated from India in the year 2006.

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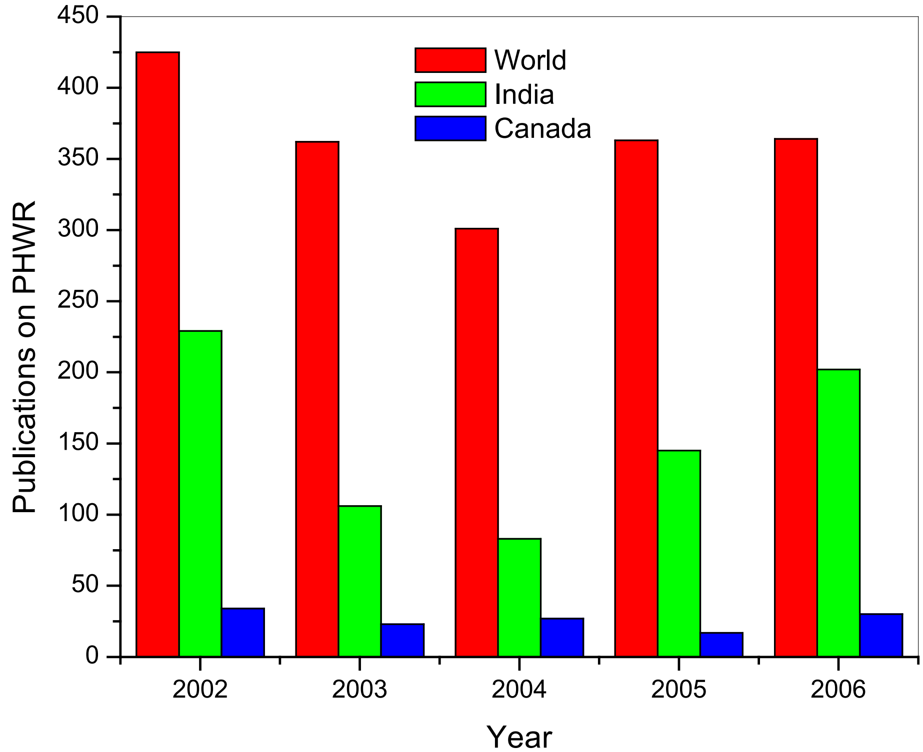

Figure 1: Publications on PHWR

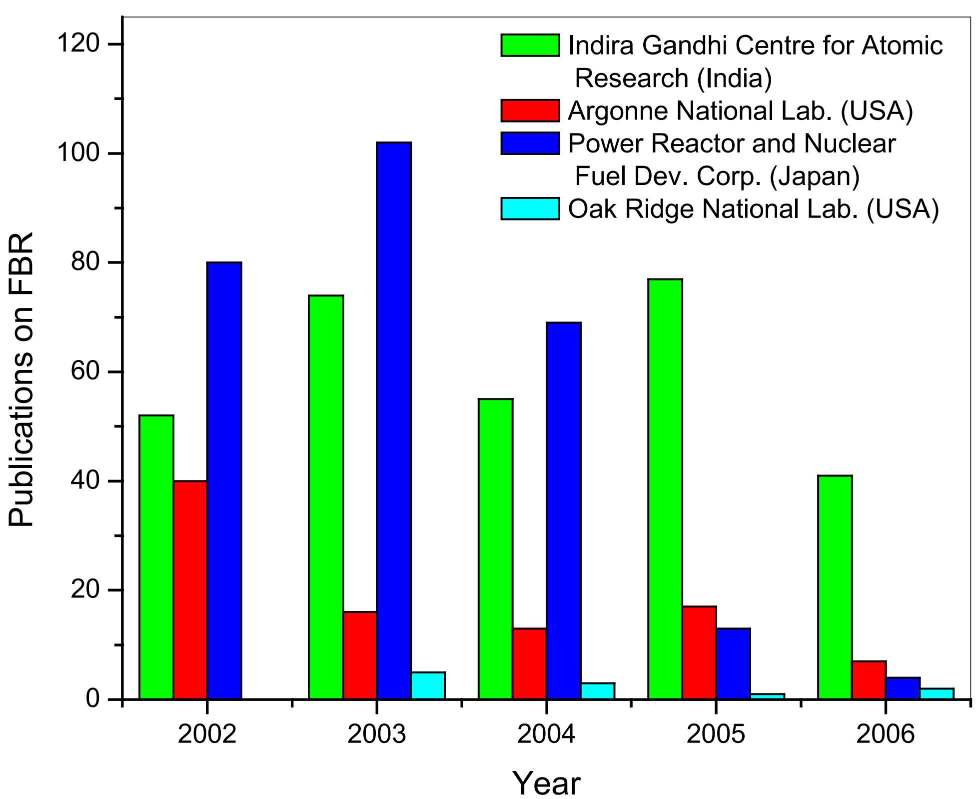

Figure 2: Publications on FBR

We can see similar performance statistics in respect to publications for Fast Breeder Reactors (FBRs) and Thorium. As seen from Figure-2, in the area of FBRs, the Indira Gandhi Centre for Atomic Research (IGCAR) brought out the largest number of publications by any single institution in the years 2005 and 2006 (the latest years for which complete data is available). In the area of thorium research, on the basis of International Nuclear Information System (INIS) database, India stands at the top (Figure-3).

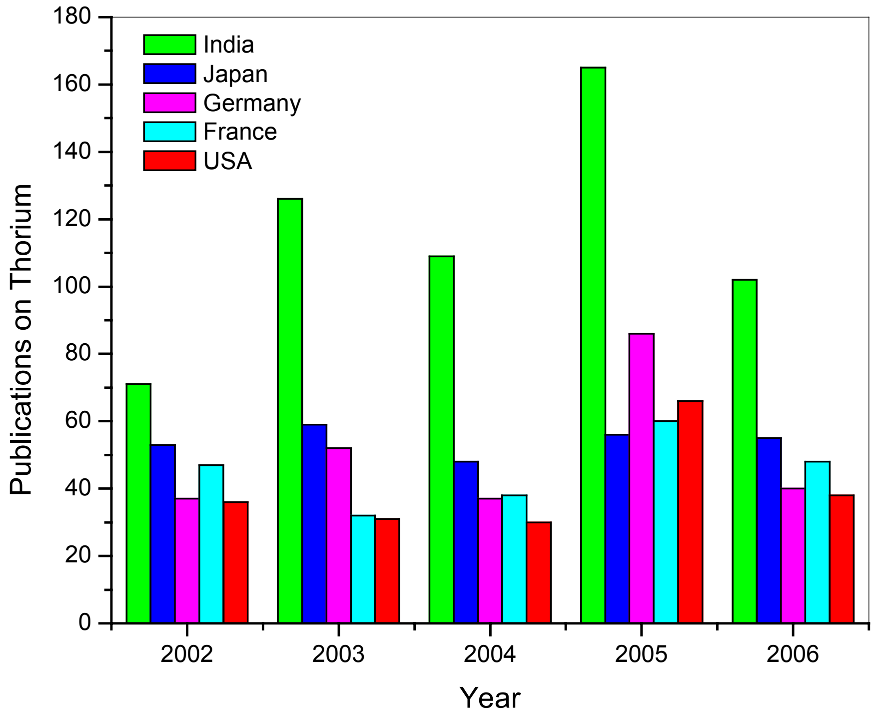

Figure 3: Publications on Thorium

Applications of radio-isotopes

Apart from nuclear power, the programmes of DAE address the conversion of research into societal values for meeting different needs. Large contributions have been made in the field of application of radio-isotopes in industries, health-care, hydrology, food preservation and agriculture. For example, in the field of nuclear agriculture, the mutant ground nut seeds developed at BARC contribute to nearly 25% of total ground nut cultivation in the country. Similarly, in the area of black gram (urad) production, the BARC developed mutant seeds contribute to 22% of the national cultivation. In the state of Maharashtra, this percentage is as high as 95% (Figure 4).

Performance in other cutting edge areas

The Tata Memorial Centre, an aided institution under DAE, was recognised as the outstanding cancer organisation for its excellence in cancer control within and beyond India's border, by the International Union for Cancer Control, Washington DC in 2006.

Figure 4: Application of radio-isotopes to Agriculture

The Giant Meterwave Radio Telescope (GMRT) built by the department for its aided institution Tata Institute of Fundamental Research, has become an international tool for astronomical research. In August 2004, using this facility, the TIFR scientists and their collaborators discovered a new pulsar (Figure-5).

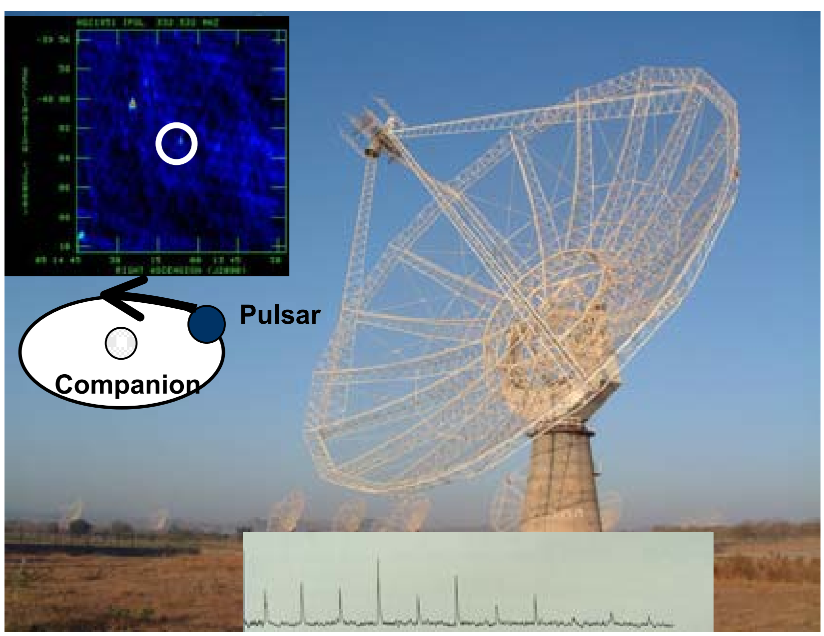

Figure 5: Giant Metrewave Radio Telescope

India has an observer status at CERN along with US, Japan, Russia, Turkey and Israel. We are also partners in contributing to the construction and testing of several important systems of this very large international experimental facility now nearing completion. We have made rapid advances on GRID computing technology as a part of our participation in CERN. Today DAE has surged ahead with its own computing grid that connects four DAE sites with 7 clusters containing 266 processors (Figure-6).

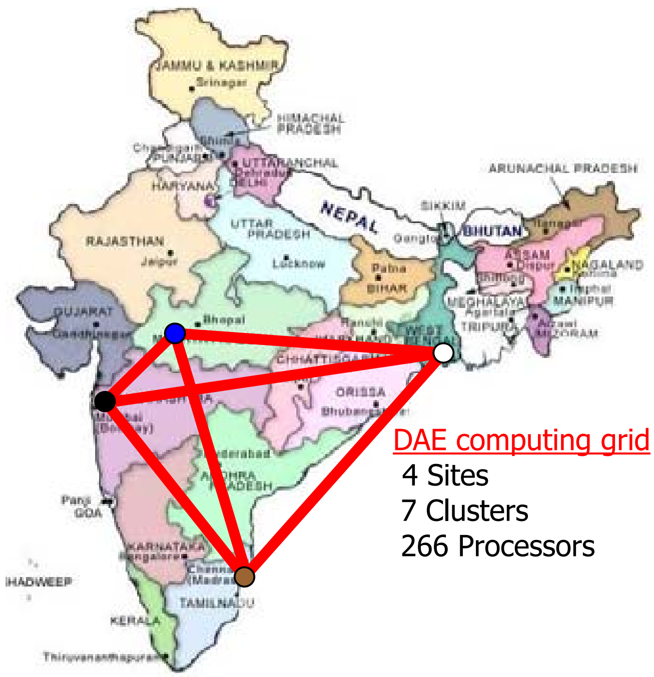

Figure 6: DAE Grid computing

In his testimony at US Senate Committee on appropriations, Subcommittee on energy and water development on April 20, 2008, Seigfried S. Hecker, former director of LANL said "I found that whereas sanctions slowed progress in nuclear energy, they made India self-sufficient and world leaders in fast reactor technology. While much of the world's approach to India has been to limit its access to nuclear technology, it may well be that today we limit ourselves by not having access to India's nuclear technology developments. Such technical views should help to advice the diplomatic efforts with India".

We should thus recognise our strengths and move ahead in addressing India's energy security with a degree of confidence.

3. Three Stage Indian Nuclear Power Programme

The currently known Indian nuclear energy resources comprise 61,000 tonnes of uranium and more than 225,000 tonnes of thorium. An aggressive effort for further exploration of uranium is being pursued. Natural uranium contains only 0.7% of ^{235}U, the only fissionable material available in nature. In principle, however, the entire quantity of uranium (^{235}U and ^{238}U) and thorium available in nature can be converted to fissionable form that can be used for contributing to energy security of the mankind for a few millenniums.

With the above-mentioned perspective, the Indian nuclear power programme is based on closed nuclear fuel cycle, in which the spent fuel of the first stage PHWRs is reprocessed to obtain fissionable plutonium. The choice of PHWRs in the first stage is driven by the fact that in PHWRs, on account of the use of heavy water as moderator and on-power refuelling, more neutrons are available to convert ^{238}U to Pu than in the case of Light Water Reactors (LWRs). In other words, for the same amount of mined uranium, power produced as well as plutonium generated is higher for PHWRs than in the case of LWRs, where the light water moderator absorbs more neutrons and batch-mode refuelling necessitates placing burnable neutron absorbers in the core along with fresh fuel.

For the second stage reactors, based on plutonium, once again, the unique characteristic of plutonium, with the highest value of eta (η) of all fissile materials in the fast spectrum (Figure-7), led to a logical decision to use plutonium based FBRs. Neutron economy does play an important role in deciding the breeding ratio. This consideration favours the use of metallic fuel compared to other forms of fuel in these FBRs for a faster growth. The current Indian programme in the second stage starts with the well proven oxide fuel based FBRs and subsequently, at an appropriate stage, when all the new necessary technologies have been developed and demonstrated, metallic fuel based FBRs will be introduced.

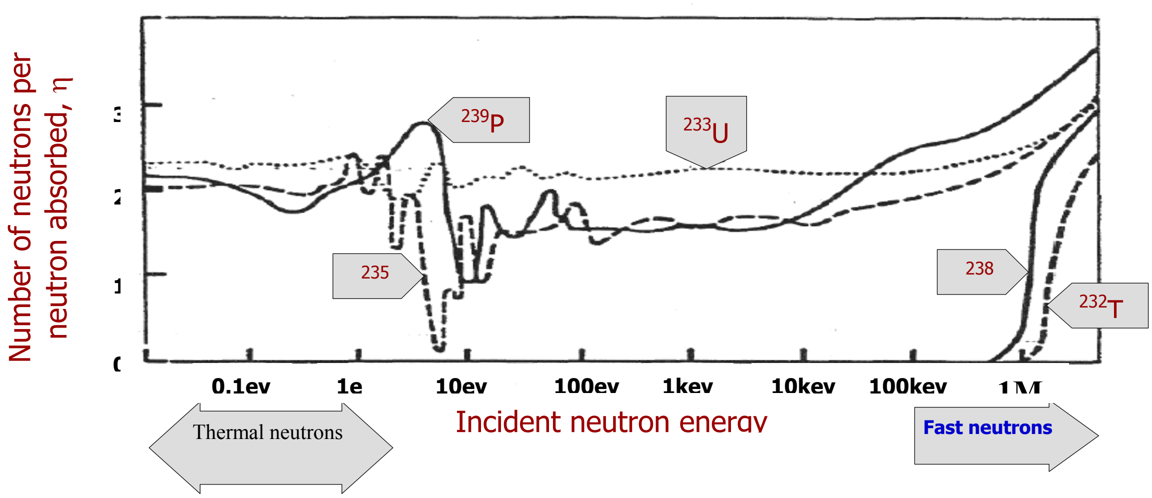

Figure 7: Eta values for various materials

The highest breeding ratio in FBR is achieved with plutonium-uranium based metallic fuel in the core and uranium in the blanket. The introduction of thorium in the blanket of a plutonium-uranium fuelled FBR slightly increases the doubling time, that has an adverse impact on the rate of growth of the installed FBR capacity in the initial part of the second stage. Hence, in the second stage, the introduction of thorium has to be done in a timely manner, starting with its use in the blanket and much later in the core. DAE studies indicate that, it would be most appropriate to introduce thorium in this manner, in the third decade after the launch of metallic fuel based FBRs.

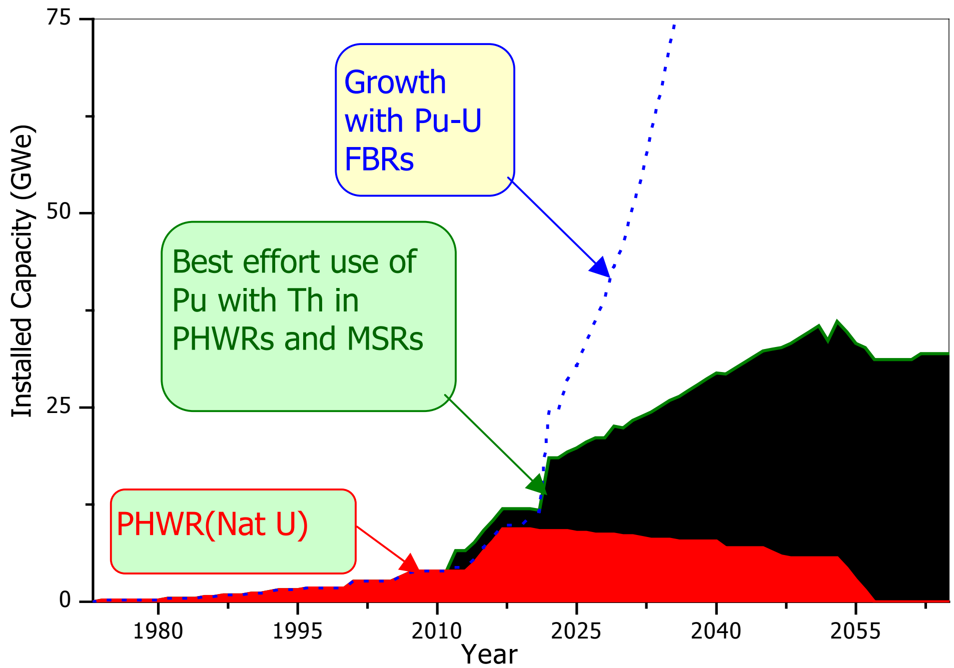

Figure 8: Negative effects of early thorium introduction

Introduction of thorium without going to FBRs is extremely counter productive, since the installed power capacity with thorium and plutonium being used together in thermal reactors will be unable to rise beyond a rather insignificant value, considering the total Indian requirement. This is illustrated in Figure-8. The peak power level achieved briefly, with such premature use of thorium is very low (typically 36 GWe for a brief period) as compared to very high levels reachable through an optimum deployment strategy shown in Figure-9.

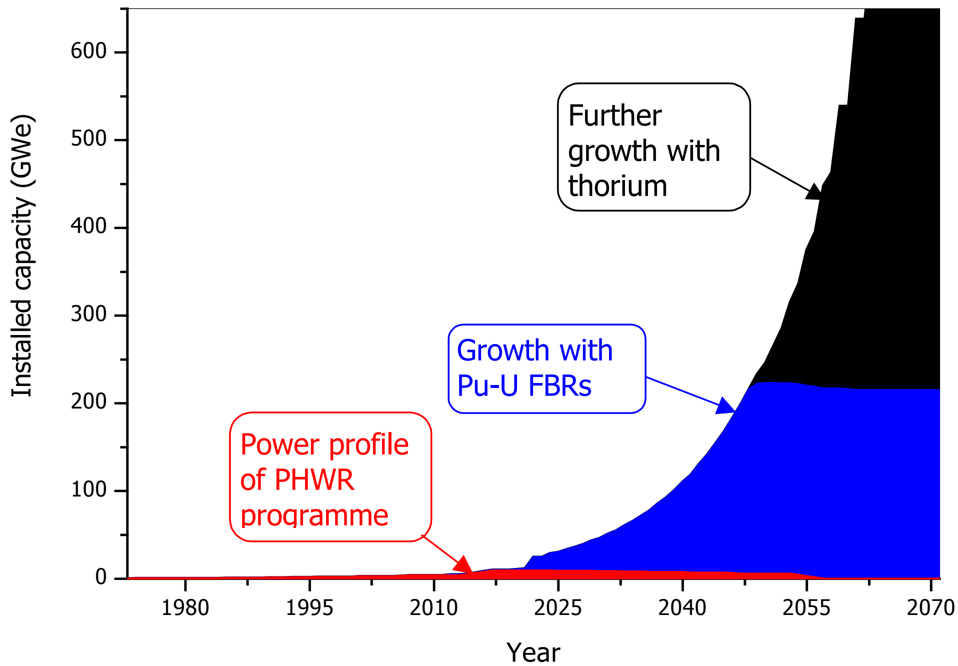

Figure 9: Optimum Strategy for thorium introduction in the third stage

Thorium is an immense source of energy. The Indian resources of thorium, are easily one of the largest and of the best quality available in the world. Studies indicate that once the FBR capacity reaches about 200 GWe, thorium-based fuel can be introduced progressively in the FBRs to initiate the third stage, where the ^{233}U bred in these reactors is to be used in the thorium based reactors. DAE is also envisaging use of Accelerator Driven Sub-critical Systems (ADS) for facilitating an early introduction of thorium.

4. DAE's performance in the three stages

The DAE's performance in each of the three stages has been of world standard. The PHWRs have consistently achieved availability factors of about 90% in the recent past along with an excellent safety record consistent with the best performing reactors in the world. Indeed, in the year 2002, Kakrapar Atomic Power Station (KAPS-1) was adjudged the best PHWR in the world for the period from October 2001 to September 2002. Two of the Station Directors of Nuclear Power Corporation of India Limited (NPCIL) received the prestigious WANO excellence award in the year 2003 and 2007 respectively.

> "At the end of 2002 average annual CANDU/PHWR performance continued to show a gradual improvement, led by the units of NPCIL (India)…" The NPCIL PHWRs showed a major improvement in GCF in 2002, exceeding US light water reactor performance by almost 1%…"
>
> Brian MacTavish, President, COG.

The commercial performance of the Indian PHWRs has been generally at par, if not better, than that of comparable modern reactors in the world. Table-1 illustrates this point for new designs:

Table-1: Commercial performance of Indian PHWRs

	Indian PHWRs (700 MWe)	Global Range
Capital cost $/kWe	1700	2000-2500
Construction period	5 – 6 years	5 – 6 years
UEC $/MWh	60	60 – 70

On account of its excellent performance consistently, NPCIL has been given a 'AAA' grading by CRISIL for ten years in a row.

Currently, the construction activity for a 500 MWe Prototype Fast Breeder Reactor (PFBR) is in full swing. Russia is the only other country with a larger FBR currently under construction/operation. Inspite of being first of a kind in our country, the currently estimated economic parameters of PFBR are fairly attractive, as indicated in Table-2.

Table-2: Important economic parameters for PFBR

	PFBR (500 MWe)
Capital cost Rs/kWe	69840
Construction period	7 years
UEC Rs/kWh	3.22

R&D efforts are currently underway to further improve economics of FBRs

Thorium utilisation has received a high priority right from the early days of the Indian nuclear power programme. DAE has been working on different aspects of utilisation of thorium, and for this purpose irradiation of thorium was carried out in research reactors, in PHWRs as well as in the Fast Breeder Test Reactor (FBTR). Associated aspects of manufacture and reprocessing of thorium based fuels have also been the subject of R&D programmes in DAE.

The Advanced Heavy Water Reactor (AHWR) has been designed to produce most of its power from thorium. The reactor also provides a platform to demonstrate several unique passive safety features which are introduced in this reactor to achieve the highest levels of safety along with superior economics. Technologies thus demonstrated in AHWR will be relevant for future next generation reactors that will meet the further enhanced safety requirements for being built in large numbers in close proximity to population centers. This latter capability is considered important in the third stage of the

Indian nuclear programme, when the deployment of thorium will need to be carried out in a very large population of nuclear reactors. AHWR has been one of the few reactors in the world that have already strived to meet the requirements of innovative next generation nuclear reactors as has been spelt out in several international forums. The AHWR design has reached a level of maturity, and the reactor is ready for launch of construction.

Sometimes, it is asked why the use of thorium has not been taken up in countries where the urgency to multiply fissile resources is not as high as that in India. The main reason seems to be that, while one can start a nuclear power programme with nuclear fuel containing ^{235}U mixed with either ^{238}U (enriched uranium) or with thorium, the real benefit of using thorium accrues only when the fuel achieves rather high levels of burn-up. It is possible to achieve criticality in a nuclear reactor with only with 0.7% ^{235}U (as in natural uranium with heavy water as moderator). In the case of thorium, the required enrichment level to get a reactor critical is nearly 1.8%, for a specific case given in Figure-10, for example. As indicated in this figure, in this case, for thorium based fuel to reach the same level of discharge burn-up, it would need to have a higher enrichment of ^{235}U unless the levels of burn-up exceed about 40 GWd/tonne. In the early period of nuclear power deployment, such high burn-ups could not be readily achieved on account of materials related constraints. Currently, burn-ups higher than 40 GWd/tonne are readily achievable for several LWR designs. Therefore, with these capabilities existing now, it is possible to introduce thorium in current generation reactors where thorium offers several advantages, as listed below:

- Energy advantage (higher burn-ups for similar enrichment)
- Relatively stable core reactivity (depletion of fissile component compensated to a larger extent by generation of fresh ^{233}U)
- Low minor actinide generation (since the mass number of Thorium is 232 as compared to 238 for Uranium-238)
- Proliferation resistance (On account of very high gamma radioactivity associated with daughter product of radiation decay of ^{232}U, that will be always associated with ^{233}U)
- Rapid disposition of plutonium (on account of large neutron absorption cross section of thorium)

In view of these advantages, now there is a growing global interest in thorium. Thus while we are progressing in our development related to thorium on a continuously evolving technological front and large scale deployment of thorium in India will take a while, we are in a unique position to collaborate with other interested countries.

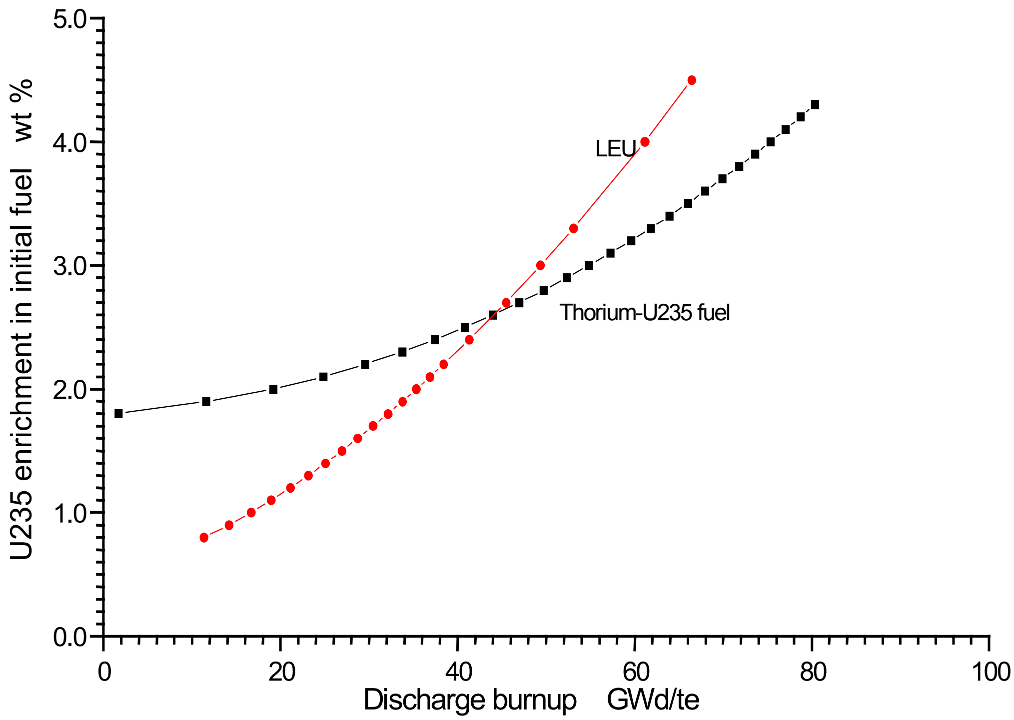

Figure 10: Performance potential of homogeneous mixture of fertile materials with 235U in a PHWR

5. Strategy for Long Term Energy Security

Figure-11 indicates the current Indian energy resources. The units used are in terms of effective electricity generation potential. It is obvious that the total energy content in the currently known Indian nuclear resources is at least twenty times higher than that in other non-renewable resources. This data has been converted to indicate years of depletion for electricity generation, if only a single source is to be used. This information is shown in Table-3. It may be noted that, in this table, the target electricity generation capacity in 2052 is indicated as 7957 TWh. This figure is based on a projection of needs for our growing economy. Similar estimates have also been made by Planning Commission with different GDP growth rates. According to DAE projections, India needs to reach a per capita electricity consumption of nearly 5000 kWh/y by the year 2050. A profile of this growth requirement is included in Figure-12.

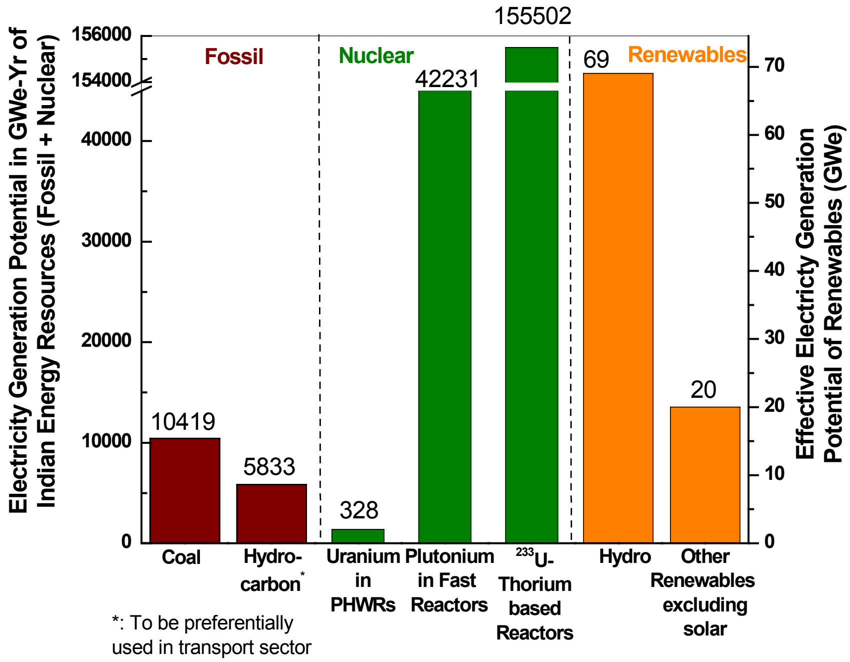

Figure 11: Current Indian Energy Resources

Table-3: Years of depletion for electricity generation by a single source

	Coal	Uranium in PHWR	Plutonium in Fast reactors	^{233}U-Thorium based reactors
Current rate (697 TWh)	130	4.12	211	>1950
2050 rate (7957 TWh)	11.5	0.36	18.5	>170

Figure-12 shows a case, in which best use is made of all available non-conventional, hydro-electric, domestic coal, domestic hydrocarbon as well as domestic nuclear resources (in three stages). It may be noticed that, even after making use of all available domestic resources, it is impossible to meet the required electricity generation requirement profile. One could, of course, stretch the time line beyond 2050, and it would emerge that the exponential growth of contribution of nuclear power should eventually catch up with the requirement a few decades later. However, during the coming few decades, in order to meet the energy requirement driven by the Indian economy, there is a huge energy gap that needs to be filled. DAE has estimated that this deficit would be of the order of 412 GWe in the year 2050. If India is unable to import nuclear reactors or nuclear fuel under international co-operation, India must necessarily go for the import of coal to the tune of 1.6 billion tonne in the year 2050 alone, unless solar capacity grows at even large levels. Depending on external sources for a huge requirement of supply of coal on a regular basis would make a large country like India vulnerable to supply shocks.

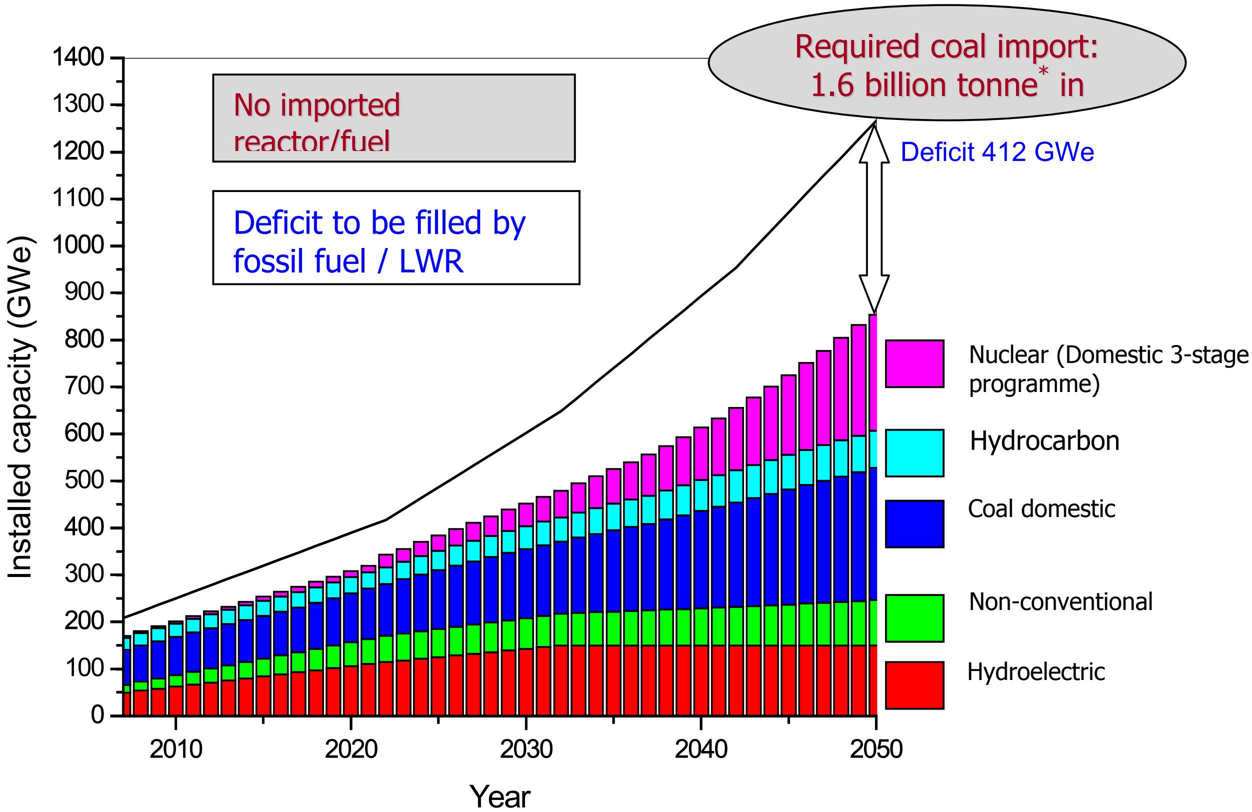

Figure 12: Profile of growth requirement

Another study (Figure-13) shows that the gap between requirement and supply can be easily met if about 40 GWe capacity LWRs* are imported during the period 2012 – 2020. While this 40 GWe additional capacity, on its own, appears to be only a small fraction of the required capacity to meet the deficit, with the use of spent fuel of these LWRs for launching a series of FBRs, the deficit is practically wiped out in the year 2050. One may also note that, on account of exponential nature of the growth, in case the import of these LWRs (40 GWe) is delayed by a decade, the energy deficit in the year 2050 would be 178 GWe and the corresponding requirement for coal import will be 0.7 billion tonne (Figure –14). The latter is approximately twice the annual coal requirement in our country today. With this logic, it is obvious that with the import of LWRs (or, PHWRs, or uranium) as an additionality in the nearer term India can achieve full energy independence in a shorter time. Even much after the imported reactors reach the end of their life, the additional fuel inventory remaining in the country would help in satisfying our future energy requirements for a very long period in a sustainable manner.

* The term LWRs used in the context of international co-operation , is indicative of uranium content in the imported fuel. The imported reactors could be, as well, of other types and direct import of fuel may also be considered.

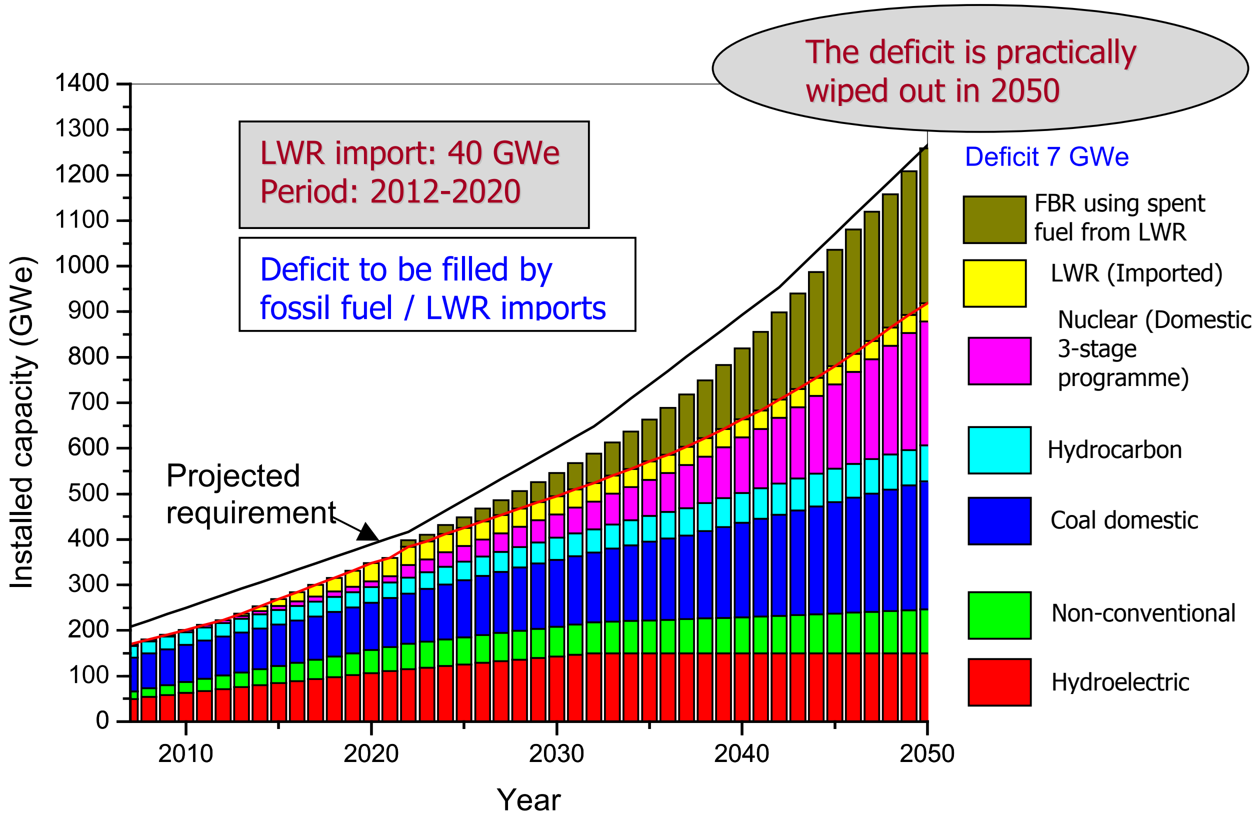

Figure 13: Import of 40 GWe LWR and the multiplier effect

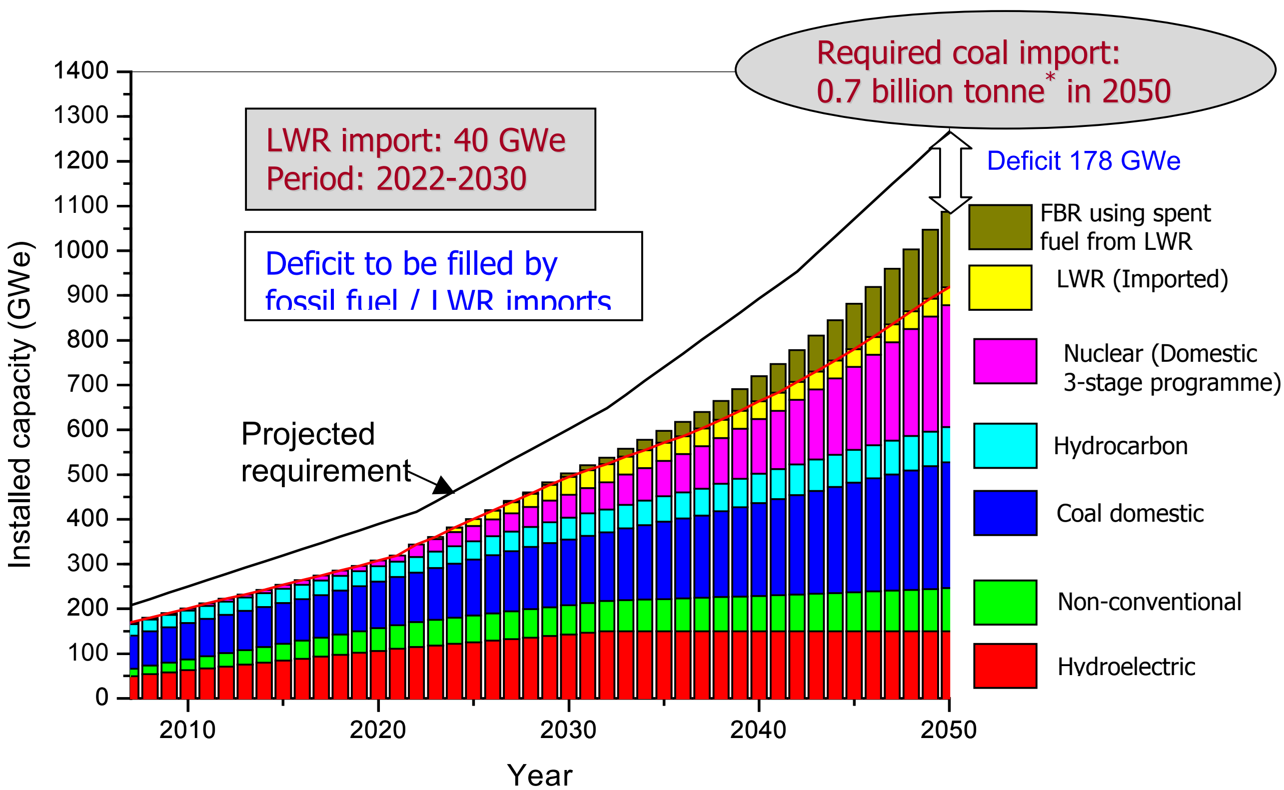

Figure 14: Effect of ten year delay in import of nuclear fuel/reactor

Having stated the rationale behind the benefits of international co-operation to facilitate transfer of nuclear fuel/reactor to India, it must also be emphasised that DAE is leaving no stone unturned for extensive exploration of new uranium deposits in the country and also identify other avenues for securing a supply of uranium. Figure-15 indicates the major areas currently being explored in the country, including the thrust areas in Cuddapah basin in Andhra Pradesh, Mahadek Basin in Meghalaya and North Delhi Fold belt, Rajasthan and Haryana. The technologies to discover deep seated uranium deposits are also under development and deployment. A sufficiently large investment has been made for this purpose. New technologies in drilling and time domain electro magnetic survey are being implemented (Figure-16).

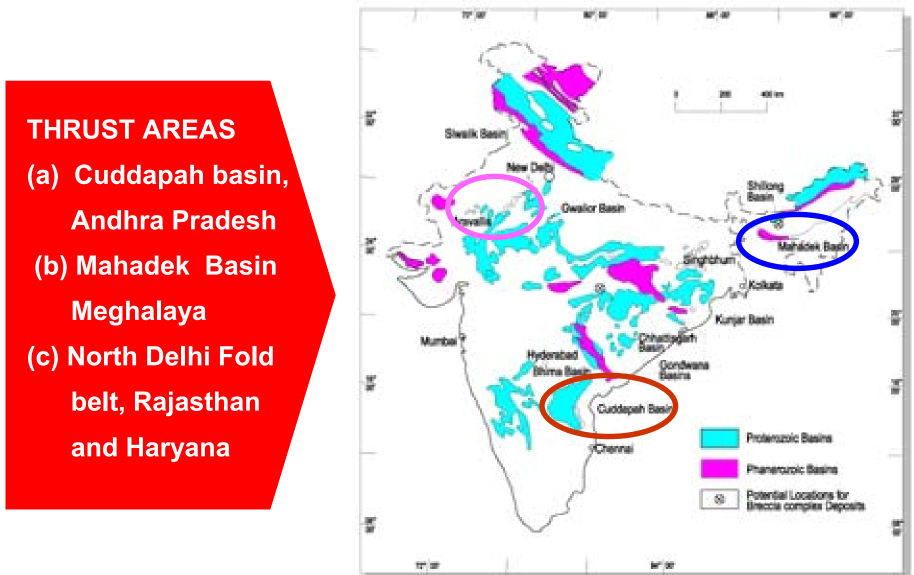

Figure 15: Augmentation of uranium resources

Figure 16: Time Domain Electro Magnetic System being tested at Rohil, Rajasthan

6. **Advanced new technologies: Thorium and beyond**

As discussed earlier, for the successful growth of our nuclear power programme, it is essential to deploy FBRs with short-doubling time. Use of metallic fuels is considered a very attractive approach to get short-doubling time in FBRs.

DAE has launched a programme for the timely development of the required technologies and the characterisation of metallic fuel before its deployment. For the purpose of reprocessing of these fuel materials, without leading to large releases of chemical waste, pyro-chemical technique offers a good solution. With this objective, a new focus on R&D in relevant molten salt technologies has been planned. Incidentally, molten salt is also one of the candidate coolant materials for the large-sized Indian High Temperature Reactor (HTR) for commercial level hydrogen production.

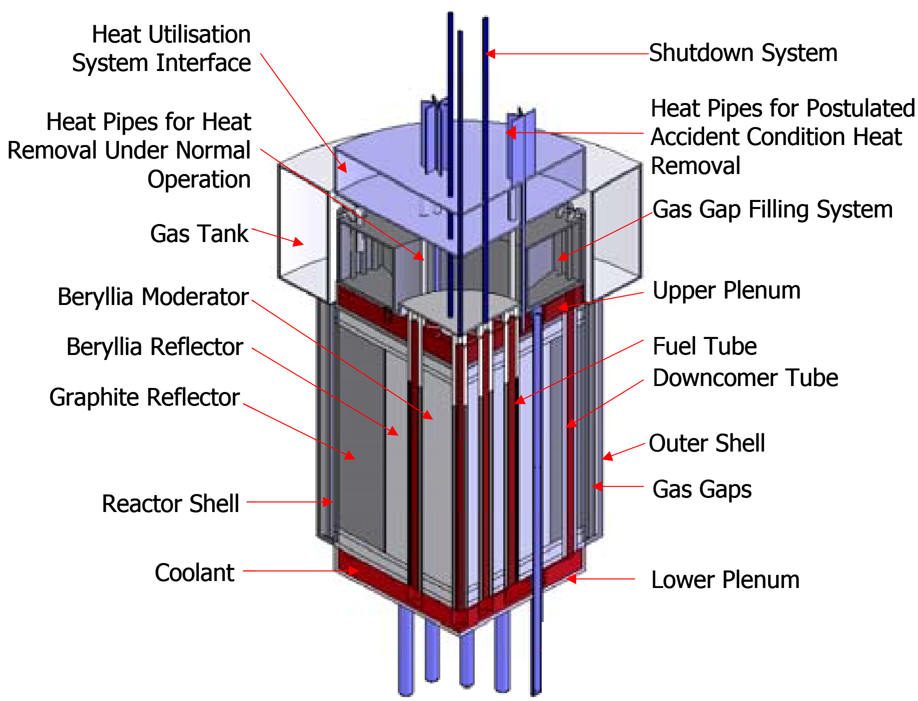

Figure 17: Compact High Temperature Reactor

In the discussion so far, the thrust has been on the use of nuclear energy for meeting the electricity needs. It is, however, well known that the availability of oil and natural gas on a sustainable basis, and at affordable prices, will be severely jeopardised in the context of countries like India with a huge demand and very small domestic availability of these important natural resources. For meeting the requirement of fluid fuel for transport, it is therefore very important to develop alternate solutions that will reduce the dependence on imported oil and natural gas, with commensurate economic benefit in the longer run, and reduced vulnerability to supply shocks. Use of nuclear energy for the generation of fluid fuel is therefore an attractive option that is engaging the attention of researchers all over the world. DAE has focussed its attention on a range of technologies that are important for generation of hydrogen using water-splitting reaction. On one end, small scale efficient units for production of hydrogen using electrolysis have already been developed and deployed in BARC. For large scale production of hydrogen in a commercially viable manner, the high temperature processes for water splitting, having a high efficiency for energy conversion, are being considered. To drive this process, heat at the required temperature, of the order of 800 to 900^{o}C, is needed. With this objective, a High Temperature Reactor programme has been initiated. The most important challenge for such reactors is the development of materials that can survive the aggressive environment for sufficiently long time. The development of the required refractory materials as well as the coolant (expected to be molten salt or molten lead) is in progress. At the same time, high temperature processes for hydrogen generation are being studied in BARC. A Compact High Temperature Reactor (CHTR) (Figure 16) has been designed to serve as a technology demonstrator for the production of high temperature process heat using nuclear energy. This reactor is proposed to be fuelled with the unique thorium – ^{233}U based particle type fuel that has a capability to withstand temperature as high as 1600^{o}C. The reactor is cooled with molten lead-bismuth alloy to deliver process heat at about 1000^{o} C at the exit from the reactor core. This small demonstration reactor with a 100 kWth capacity has a core with a life of 15 years without refuelling.

In the field of nuclear fusion, internationally, a major effort is in hand under the umbrella of the International Thermonuclear Experimental Reactor (ITER) programme. ITER activity has reached a fairly advanced stage and it is planned that the project will be built at Cadarache in France. India has joined a select group of seven partners including the USA, European Union, Japan, Russia, China and South Korea to jointly carry out the work for providing special hardware items and required expertise in some selected special areas of this programme. The Indian contribution to this programme would be approximately Rs. 2500 Crore.

While the main deliverables of DAE have focussed on nuclear related areas, the spin-offs arising out of the DAE's activities have also been contributing substantially to meet several national needs. DAE has made major contributions in the field of development and deployment of water desalination techniques. The work on hydrogen generation has been linked to the development of fuel cells, on which a programme is in an advanced stage. Our capability for high temperature heat removal using natural circulation, and also the capabilities in control and instrumentation, have been used for the design of a solar thermal power generation set up.

DAE runs a broad-based comprehensive scientific programme which includes setting up of large facilities for research thanks to the technological capability that has been built up. DAE's capability in the area of accelerators, super conductivity, cryogenics, radiofrequency (RF)/microwave, plasma technology, laser – photochemical processes etc. is of vital importance in development of future technologies that would make increasing use of these technologies in programmes such as Accelerator Driven Systems and Fusion.

7. Special challenges

The entire saga of the growth of nuclear energy programme in India has an underlying thread of continuing emphasis on self-reliance. This strategy will continue in the future. For a large country like India, we need to preserve our knowledge and protect and enhance our capabilities, while remaining immune to the vulnerabilities. We further need to make sure that the required human resource support for the DAE programmes remains available at the required levels, in terms of numbers as well as quality. In view of this, we have laid further enhanced emphasis on education and training in the recent past. These new initiatives have taken the form of, for example, National Initiative in Undergraduate Sciences, University Grants Commission-DAE consortium for Scientific Research, DAE Graduates Fellowship Scheme (DGFS), DAE-MU CBS, National Institute of Science Education and Research (NISER) etc. It has also been recognised that it is important to promote basic research in a focussed manner, so that strong bridges are built between basic research and technology. Several initiatives in this direction have been already in place. Homi Bhabha National Institute and Board of Research in Nuclear Sciences are two examples.

8. Summary

1. Access to global energy sources would become increasingly difficult and expensive as time progresses.
2. Early availability of domestic/imported uranium (imported reactors) is important for reducing dependence on import of energy resources in the future.
3. We need to sustain the tempo of domestic R&D, focusing on issues and deliverables of a high priority for us.
4. To address the range of the technological and scientific challenges, a holistic approach in the development of required human resource as well as in the management of science and technology is essential.

9. Acknowledgement

I would like to express my thanks to Shri R.K. Sinha, Dr. R.B. Grover and colleagues who have helped me put together this presentation.