Vol. V. No.2 **Editor : G.A. Rama Rao** **April 2006**

Editorial

India consumes about 3% of world energy consumption despite having 17% of the planet's population. With a large part of its one billion plus population without access to modern fuels & energy, India faces a formidable energy challenge. It now seeks to address these challenges in putting in place a commercially sustainable energy agenda and building an energy system, which tackles the current, and long term concerns of Economic, Efficient, and Environment friendly Energy.

Nuclear technology is an important option for the world to meet future energy needs without emitting carbon dioxide and other atmospheric pollutants. In the last forty years we have seen nuclear energy taking its place as a major source of electricity worldwide, on both economic and resource strategy grounds. Today the question of global warming focuses attention on the extent to which nuclear energy offsets it, and may increasingly do so in the future. Nuclear energy now provides over 16 percent of the world's total electricity. It has the potential to contribute much more, especially if greenhouse concerns lead to a change in the relative economic advantage of nuclear electricity, or its ethical desirability.

Since Independence, the Indian Electricity sector has grown manifolds in size and capacity. There is a blend of thermal, hydel and nuclear sources and of late, emphasis is also being laid on non-conventional energy sources - Solar, Wind and Tidal.

With sustainable development as the prevailing ethic, nuclear energy has much to offer in the extent of the resources supplying it and because it is environmentally benign; all wastes are contained and managed.

I am extremely grateful to Shri S.G. Markandeya, the Guest Editor for this volume, for envisioning the theme for this bulletin and judiciously choosing the authors for the contributions.

G.A. Rama Rao

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IANCAS Dr. M.V. Ramaniah Memorial Award to

Dr. C.K. Mathews

INDIAN ASSOCIATION OF NUCLEAR CHEMISTS
AND ALLIED SCIENTISTS (IANCAS)
is happy to confer
IANCAS Dr. M.V. Ramaniah Memorial Award
on
Dr. C.K. Mathews
Bangalore, India

For Lifetime achievement in research and development in the field of Nuclear and Radiochemistry, especially its application to reactor technology. He pioneered the application of mass spectrometry in the nuclear fuel cycle in India encompassing isotopic composition of nuclear fuel materials, burn up measurement, nuclear material accounting and tracer techniques like MAGTRAP and LEADTRAP. Most noteworthy contribution of Dr. Mathews is the building up of a chemistry programme at IGCAR, Kalpakkam which has played a very significant and crucial role in the development of the Indian fast breeder reactor programme. Starting from scratch, he built one of the best Radiochemistry laboratories in the world, and equipped it with a wide range of state-of-theart instrumental methods, many of them developed indigenously for the first time. After mastering the art of purifying, handling and characterising liquid sodium, his team went on to develop on-line monitors for oxygen, hydrogen and carbon in liquid sodium, which are essential for the safe operation of fast breeder reactors. Under his leadership, a wide spectrum of physico-chemical measurements essential for developing the untested mixed carbide of uranium and plutonium, chosen as fuel for driving FBTR, was carried out. Techniques such as Knudsen effusion mass spectrometry, thermal diffusivity, high temperature calorimetry and laser vaporization mass spectrometry were developed. Extensive data thus generated was used to model the behaviour of the fuel under reactor operating conditions as well as in accidental conditions. It is worth recalling that it was an experiment that he set up in a glove box to simulate the operating conditions of the fuel that demonstrated that the carbide fuel pins could be operated safely at adequate linear ratings. Dr. Mathews has authored/co-authored several books and has published over 200 papers in international journals.

March 17, 2006

(V. Venugopal)
President, IANCAS

IANCAS Dr. Tarun Datta Memorial Award to

Dr. A.K. Pandey

INDIAN ASSOCIATION OF NUCLEAR CHEMISTS
AND ALLIED SCIENTISTS (IANCAS)
is happy to bestow
IANCAS Dr. Tarun Datta Memorial Award
on
Dr. A.K. Pandey
Radiochemistry Division
Bhabha Atomic Research Centre
Mumbai, India

For his contributions to the understanding of the synthetic polymer membranes, both for basic and applied research, using radiotracers. He has studied the transport properties of ions and water in Nafion-117 membrane, plasticized polymer inclusion membranes and pore-grafted membranes. Measured selectivity and diffusional mobility of the counter-ions in these membranes have helped in evaluating the extent of physical and electrostatic interactions of ions with the membrane matrix and counter-ions. Dr. Pandey has designed a few membranes with specific applications, integrating selective pre-concentration of various ions and their quantitative determination. He has developed colour changeable optode for Cr(VI) and scintillating optode for -emitting actinides.

March 17, 2006

(V. Venugopal)
President, IANCAS

IANCAS Dr. Tarun Datta Memorial Award to

Dr. Anil K. Pabby

INDIAN ASSOCIATION OF NUCLEAR CHEMISTS
AND ALLIED SCIENTISTS (IANCAS)
is happy to bestow
IANCAS Dr. Tarun Datta Memorial Award
on
Dr. Anil K. Pabby
PREFRE Plant
Bhabha Atomic Research Centre Complex
Tarapur, India

For his work in the field of non-dispersive membrane technology, pressure driven membrane processes, solvent extraction, liquid membranes, extraction chromatography and inorganic ion exchangers. He has obtained a patent on non-dispersive membrane technology which is being examined and explored for the extraction and separation of actinides both in micro and macro quantities. He has been instrumental in the installation of two pilot plants viz. ultrafiltration unit for removing the turbidity as well as activity from fuel pond water, and, reverse osmosis plant for removing alpha-beta activity, nitrate ion from the delay tank stream. In addition to his several publications in peer-reviewed journals, he has contributed several chapters on membrane technology in reputed books/ volumes. He has been a consultant to IAEA, Vienna to develop technical document on nuclear waste processing, an Associate Editor of Journal of Radioanalytical and Nuclear Chemistry, and, serving as an Editor of a Membrane Handbook.

March 17, 2006

(V. Venugopal)
President, IANCAS

IANCAS Prof. H.J. Arnikar Best Thesis Award to

Dr. Tapas Das

INDIAN ASSOCIATION OF NUCLEAR CHEMISTS AND ALLIED SCIENTISTS (IANCAS)

is happy to bestow

IANCAS Prof. H.J. Arnikar Best Thesis Award

on

Dr. Tapas Das

Radiopharmaceuticals Division
Bhabha Atomic Research Centre
Trombay, India

For his work in the field of Radiopharmaceutical development including indigenous production of ^{177}Lu, an important therapeutic radionuclide with high specific activity, and the development of potential ^{177}Lu based Radiopharmaceuticals that await clinical trials for human administration. His work includes development of agents for intravascular radionuclide therapy, agents for targeting tumor and receptors, and bone-pain palliatives. He has designed, synthesized and radiolabeled several ligands and bifunctional chelating agents with ^{177}Lu, $^{186/188}$Re, ^{166}Ho, ^{153}Sm, ^{175}Yb and ^{99m}Tc employing different techniques. Some of these Radiochemical preparations have shown encouraging results in bioevaluation studies and offer good potential towards development into radiopharmaceuticals.

March 17, 2006

(V. Venugopal)
President, IANCAS

Dr. Tarun Datta Memorial Award

Indian Association of Nuclear Chemists and Allied Scientists (IANCAS) invites nominations for the annual Tarun Datta Memorial Young Scientist Award from eligible scientists for their outstanding contributions to the field of Nuclear and Radiochemistry. The Award, carrying a cash prize of Rs.5000/-, a citation and a medal, will be presented to the selected candidate during the Annual General Body Meeting(AGM) of IANCAS.

Eligibility

Citizens of Indian nationality below 45 years of age as on 31st December of the calender year of the Award. The candidate must have made significant contributions in the field of Nuclear and Radiochemistry, or Applications of Radioisotopes for the basic research in any branch of sciences.

It may be noted that the award would be given for research work carried out in India.

How to apply ?

The application should be as per the proforma given on the reverse side of this announcement. Photocopies of the proforma may also be used or downloaded from the web site (www.iancas.org). Applicants should submit the proforma along with a summary (not exceeding 500 words) highlighting the significant research contributions & achievements especially during the last five years. In addition, they should enclose two passport size photographs, proof of age, and reprints of ten best published papers in support of the application and a declaration by the applicant ratified by the Head of the Department, Research Guide or Head of the Institution. The declaration should also bring out clearly the contributions of the co-workers. The application, complete in all respects should reach the General Secretary, IANCAS on or before 30th November of the calender year.

Selection

An expert panel will scrutinise the applications and judge the best research contribution for the award. The awardee has to present her/his work by giving a lecture during the AGM of IANCAS. The awardee will be provided with DA & first class/AC III tier return railway fare, if the awardee cannot get the same from any other source.

It may please be noted that the decision of the expert panel is FINAL and canvassing in any form is a disqualification.

Completed application may please be forwarded to

General Secretary, IANCAS
C/o Radiochemistry Division
BARC, Trombay, Mumbai 400 085

Dr. Tarun Datta Memorial Award

(PROFORMA FOR APPLICATION)

1.	Name in full	
2.	Present office address with telephone, e-mail and FAX	
3.	Date of Birth (attach proof)	
4.	Academic Qualifications (attach certificates)	
5.	Details of employment	
6.	Awards / Recognitions	
7.	Field of specialisation	
8.	Research experience	
9.	Number of publications (Journals only) Attach list	
10.	Invited talks / Session Chairperson in National / International Symposia / Conferences, if any	
11.	Reviews / Books / Chapter contributed to books / Technical Reports, if any	
12.	Popular Science articles, if any	
13.	Citation Index of 10 best papers published (if any)	
14.	Any other contribution(s), academic or otherwise, supporting your candidature	
15.	Signature of the Applicant	
16.	Signature, Name, Designation and full address of the proposer of the nomination with Telephone, e-mail and FAX	

(Please include (i) two passport size photographs, (ii) brief write-up not exceeding 500 words, clearly bringing out significant research contributions, (iii) reprints of ten best published papers, (iv) list of publications and (v) a declaration stating that the work was carried out in India)

DECLARATION

(By Head of the Institute or Head of the Department or Research Guide)

I certify that the research work mentioned by Dr. / Mr. / Ms .... of .... (Name of the Institute) was carried out by him / her. The candidate is mainly responsible for the outcome of this work. I request the Committee to consider the nomination for Dr. Tarun Datta Memorial Award.

Signature and Seal

IANCAS - Prof. H.J. Arnikar - Best Thesis Award

The Indian Association of Nuclear Chemists and Allied Scientists invites applications for the Prof. H.J. Arnikar Best Thesis Award in the field of Radiochemistry and Allied Sciences. The award carries a medal, a citation and Rs.5,000/- in cash. The awardee will be provided return I class/AC III tier fare to attend the award function, which will be held during the Annual General Body meeting of IANCAS, the date and venue of which will be intimated to the selected candidate.

Eligibility

1. *Ph.D. Degree awarded by any of the Indian Universities preceding two years from June of the calender year of the Award e.g. for the calender year 2006, the Ph. D. degree should have been awarded to the candidate between July 2004 to June 2006.*
2. *The work reported in the thesis should be in any one of the following fields*
   - *Radiochemistry*
   - *Nuclear Chemistry*
   - *Nuclear Materials*
   - *Radioanalytical Chemistry*
   - *Isotope Production*
   - *Radiotracer Studies*
   - *Radioactivity Measurement or*
   - *Any Allied Fields wherein Radioisotopes are Used*
3. *Age limit : There is no age limit for this award*

How to Apply?

The nomination should be sent by the Ph.D. Guide along with

- *(a) 3 copies of the synopsis as submitted to the University,*
- *(b) a write up not exceeding 500 words highlighting the significant achievements of the work carried out leading to the award of the degree,*
- *(c) list of publications (journals only) & reprints/preprints of five best papers. It is essential that the list of publications & reprints cover only those papers that are included in the thesis,*
- *(d) A copy of the Ph.D. Degree /provisional certificate from the University.*

Last Date : on or before November 30, of the calender year

The application, complete in all respects, should reach the General Secretary, IANCAS, C/o Radiochemistry Division, Bhabha Atomic Research Centre, Mumbai - 400 085.

Selection

A panel of experts nominated by the Executive Committee of IANCAS comprising members from the Department of Atomic Energy and the Universities will select the best thesis. It may please be noted that the decision of the panel is FINAL and canvassing in any form will be a disqualification. The awardee will be given an opportunity to present his/her work during the Annual General Body Meeting of IANCAS.

Prof. H.J. Arnikar Best Thesis Award

(PROFORMA FOR APPLICATION)

1.	Name and address of the Candidate	
2.	Name and affiliation of the Guide(s)	
3.	Institute where the work was carried out	
4.	Name of the University awarding the degree	
5.	Title of the Thesis	
6.	Year and month of the award	

CERTIFICATE

I hereby confirm that the work pertaining to the Ph.D. Thesis mentioned above of ....

.... was carried out under my supervision

(Signature of Guide)

Non-Fossil Fuel Based Energy Options in India

Guest Editor

S.G. Markandeya

Head, Planning & Coordination Division
Bhabha Atomic Research Centre
Mumbai 400 085

FOCUS

Shri R.K. Sinha

Greenhouse gases are necessary for life on Earth because they keep ambient temperatures well above what they would otherwise be. The main greenhouse gases are water vapour, CO_2, CH_4, N_2O, and chlorofluorocarbons (CFCs). The levels of CO_2 and NO_x in the atmosphere can be influenced by the amount of electricity generated and the fuel used. Of the fossil fuels, coal has the highest carbon content. Oil and natural gas have approximately 80 percent and 60 percent of the carbon content of coal, respectively, on an energy-equivalency basis.

The effect on climate change by greenhouse gas emissions has been a matter of scientific debate for many years. The UN Inter-governmental Panel on Climate Change (IPCC), in its third report, elaborated on the following scientific findings of far reaching consequences for the planet:

> *The Earth's climate system has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities.*
>
> *Carbon dioxide concentrations, globally averaged surface temperature, and sea level are projected to increase under all IPCC emissions scenarios during the 21st century.*
>
> *An increase in climate variability and some extreme events is projected.*
>
> *Inertia is a widespread inherent characteristic of the interacting climate, ecological, and socio-economic systems. Thus, some impacts of anthropogenic climate change may be slow to become apparent, and some could be irreversible if climate change is not limited in both rate and magnitude before associated thresholds, whose positions may be poorly known, are crossed.*
>
> *The projected rate and magnitude of warming and sea level rise can be lessened by reducing greenhouse gas emissions.*

To sum up there is a strong evidence that most of the global warming over the last 50 years is attributable to human activities, particularly by energy consumption in the already developed countries, and that the damaging influences of global warming are likely to progressively escalate, unless timely remedial action is taken.

On account of their adverse environmental impact as well as their limited availability to meet the projected large energy requirements in the future, progressive phasing out of fossil fuel based energy options and deployment of alternate energy options is the sustainable strategy not only for India, but also for the rest of the world. In the case of India, adoption of such strategy is more urgent than many other countries, considering its large population and relatively meagre functional energy resources. Nuclear energy with its very large energy potential can be considered inexhaustible in the foreseeable future, for all practical purposes. This source, along with the renewables, offers the best solution for meeting the long term energy needs of the society for various applications. These applications include electricity, high temperature process heat, hydrogen generation, other non-fossil fluid fuel production, and desalination.

In this context, the articles in this issue of the IANCAS Bulletin provide a broad overview of the prominent non-fossil fuel based energy options in India.

Guest Editorial

Dr. S. G. Markandeya

It gives us great pleasure to bring this long awaited 35th Bulletin of the IANCAS on the theme topic "Non-fossil fuel based energy options in India" which has assumed significant importance in the Indian context particularly due to its rapidly growing population and also due to ever increasing energy demand. The conventionally used fossil fuels, viz., coal, lignite and natural gas are the major energy sources which contribute to about 92 % of the present electricity demand in the country. With the projected ten fold increase in demand of electricity in India in the next 40 to 50 years and knowing the limited fossil fuel reserves in the country, it becomes extremely pertinent to seriously explore every possible non-fossil fuel based option available and at the same time commercially viable. Some of the promising non-fossil fuel options for the country are nuclear (includes fission and fusion both), hydrogen and renewable energy resources such as hydro, wind, solar and biomass. While each of these three major options is an independent and broad topic for discussion in the context of electricity generation, we have attempted in a very modest way to bring out the important salient features of each of these without really dwelling in depth in its theoretical aspects for the benefits of readers of the IANCAS bulletin. We have presented five articles contributed by none other than the well acknowledged experts in the country.

The nuclear being the major option, the first article on "Role of nuclear energy in India's energy mix" undoubtedly will provide the readers a glimpse into the 3-stage nuclear power program carved out in fifties by none other than the great visionary and pioneer of Nuclear energy in India, i.e. Dr. Homi J. Bhabha. Following the well laid path, the Department of Atomic Energy is now poised to take up a very ambitious plan to exploit nuclear energy production to about 275 GWe by the middle of the century. Compare this with the very soon realizable 20 GWe from the mix of PHWRs, LWRs and FBRs by the year 2020 - almost 12 to 13 fold increase in the next 30 years ahead of 2020. No doubt, opening of civil nuclear cooperation with India has a major role to play for the country. The second article in the nuclear series substantiates these plans further and deals with two important innovative reactor designs viz. AHWR and CHTR and the methodologies of their assessment. The Accelerator Driven Sub-critical System has created its own niche in the global nuclear power program and has a great potential to enhance nuclear power production. The third article on ADSS for nuclear power offers the readers a glimpse into the novel design of ADSS system and its promise in the future.

Hydrogen is said to be the fuel for the future, yet the problems associated with economically viable methods for generation, storage and transportation and use as a safe and clean fuel are quite complex. The fourth article on Hydrogen production options gives a glimpse into the hydrogen production technology through various methods such as steam-methane forming, electrolysis of water, gasification or partial oxidation of coal, low temperature and high temperature thermo chemical splitting of water etc. I am sure, the article will enlighten the readers with the rapidly evolving technologies for hydrogen production which will become tomorrow's workhorse.

The renewable energy sources, viz. solar, wind, hydro and biomass, in the Indian context hold undoubtedly significant promise for their individual contributions to the need of the country. The fifth and the last article on renewable energy sources dwells on the evolving technologies, their potential in the country and present extent of exploitation in the Indian context. Besides the solar photovoltaic based plants, the second generation thin film solar cells and the third generation dye sensitised solar cells have a great potential to meet the expected demand at a competitive price per unit of electricity in the future.

This bulletin by IANCAS has been the modest attempt to bring to the readers an update on the important subject of non-fossil-fuel based options for India. I am sure readers of this bulletin will enjoy reading these articles and will get further excited and provoked to explore on the subject on their own.

Role of Nuclear Energy in India's Energy Mix

Dr. R.B. Grover *has been with the Department of Atomic Energy for about three and a half decades. During the first 25 years, he worked in the areas of reactor safety, fuel and core thermal-hydraulics and thermal design of heat exchange equipment. In recent years, he has been working on issues related to technology transfer, energy planning, extra-mural funding and human resource development. Currently Dr. Grover is holding the positions of Director, Strategic Planning Group (SPG), Department of Atomic Energy (DAE) and Director, Knowledge Management Group, Bhabha Atomic Research Centre, DAE. He has also been appointed Director, Homi Bhabha National Institute, a deemed university set up under the aegis of DAE. Dr. Grover is a Fellow of the Indian National Academy of Engineering. He studied mechanical engineering at Delhi College of Engineering, nuclear engineering at BARC Training School and received Ph.D. from Indian Institute of Science, Bangalore.*

Introduction

Linkage between economic growth and energy requirement is well known. Both the primary energy and the electrical energy are needed for growth, but growth rate of electrical energy has been substantially higher than other forms of energy, the reasons being convenience of use and cleanliness at the user end. With information technology driving the present economy, electrical energy has become all the more important. Information technology requires electrical supply that is reliable and is of a much higher quality (in terms of voltage and frequency) than what is presently available to consumers in India. We have done quite well with regard to growth of electrical energy since independence. Power generation in India was only 4.1 TWh in 1947-48 (Shah – 1998) and it will be close to 700 TWh in 2005-06; giving precise estimate being difficult as the extent of electricity generation by captive power plants is not precisely known.

An examination of data (IEA – 2005) indicates that India is the 5th largest producer of electricity in the world. However, while India is amongst the top 10 countries of the world for production of electricity by hydro, coal, oil and gas, it is nowhere near the top 10 with respect to nuclear power generation. For a large country like India, this is an anomaly in need of correction. Claude Mendil, Executive Director, IEA writes, "No single fuel or technology should be canonized, nor should any single fuel or technology be crucified" (Mendil – 2005). It is thus necessary to examine all issues related to nuclear energy and lay down a policy framework to make the necessary transition.

Three-stage nuclear power programme

India has modest reserves of uranium and vast reserves of thorium. Natural uranium consists of two isotopes viz., uranium-235 and uranium-238. While uranium-235 is a fissile material, uranium-238 is not. After irradiation in a reactor, a fraction of uranium-238 gets converted to plutonium-239, another fissile material. The fraction converted depends on several factors and is a parameter of importance in reactor design. Similarly, thorium is not a fissile material, but can be converted to fissile uranium-233 by irradiation in a reactor. India has about 95,000 tons of natural uranium and this contains 0.7% or 675 tons of uranium-235. India's strategic programme as well as the resolve to provide long-term energy security hinges on an effective use of this small quantity of uranium-235 and this is the prime objective of the three stage programme being pursued by the Department of Atomic Energy. The three stages are the following.

Dr. R.B. Grover, Director, Knolwledge Management Group, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085;
E-mail: rbgrover@barc.gov.in

Setting up of natural uranium fuelled, heavy water moderated Pressurized Heavy Water Reactors (PHWRs) in the first stage,

Setting up of Fast Breeder Reactors (FBRs) having desirable growth characteristics (i.e. short doubling time) in the second stage,

Setting up of thorium fuelled reactors in the third stage.

While the first stage of the programme has reached a stage of industrial maturity, we have to carry on with research and development before we can acquire the same level of maturity with regard to the second and the third stage of the programme. It is pertinent to recall that it was after setting up of 6 Pressurized Heavy Water Reactors (PHWRs) that Nuclear Power Corporation of India Ltd. (NPCIL) achieved the confidence to call 220 MWe design 'a standardized design' and went in for expansion of the programme of setting up 220 MWe units and started work on the design of larger sized units (Kakodkar and Grover – 2004).

With regard to the second stage, construction of the Prototype Fast Breeder Reactor (PFBR) (Chetal et al.-2005) has been started in 2004 and standardized design will evolve only after we have operated PFBR for a few years and constructed a few more units. Along with the construction of the reactor, vigorous efforts are being made to develop associated fuel cycle technologies (Baldev Raj – 2005). DAE plans to develop advanced fuels having superior breeding characteristics and high burn-up, and acquire sufficient experience with regard to closing the fuel cycle of fast reactors.

In the early days of nuclear energy, when uranium prices were high, there was worldwide interest in fast breeder reactors and several demonstration reactors were built. These include Dounreay DFR (UK, 15 MWe, shut down in 1977), Phenix (France, 250 MWe), BN-350 (Kazakhstan, 90 MWe shut down in 1999), Dounreay PFR (UK, 250 MWe, shut down in 1994), Monju (Japan, 280 MWe), FBTR (India, 40 MWt) and CEFR (China, 25 MWe under construction). Full scale industrial reactors include BN-600 (Russia, 600 MWe), Superphenix (France, 1200 MWe, shut down in 1998), PFBR (India, 500 MWe, under construction) and BN-800 (Russia, 800 MWe, under construction). Interest in fast reactors declined due to perceived proliferation concerns and availability of uranium at competitive prices. However, rising uranium prices and increasing energy demand has rekindled interest in fast breeder reactors with a closed fuel cycle. Time frame to deploy fast reactors is being decided by nations depending on their energy requirements and fuel resource position.

Generation IV International Forum, a US led multi-nation initiative has selected 6 reactor concepts for detailed study and these include concepts based on closed fuel cycle and fast reactors (Anonymous – 2003). The various concepts are gas-cooled fast reactor (closed fuel cycle), lead-cooled fast reactor (closed fuel cycle), molten salt reactor (closed fuel cycle), sodium-cooled fast reactor (closed fuel cycle), supercritical water-cooled reactor (two options: open thermal and closed fast) and very high temperature gas cooled reactor (open cycle). Thus, the majority of concepts are based on fast reactors and closed fuel cycle.

A study carried out by the French utility EdF envisages industrial deployment of a first series of fast reactors by around 2040 (Carre – 2005). Russian viewpoint (Anonymous – 2005) is that 'mass-scale construction of fast reactors shall not be delayed any longer' as the reserves of both 'cheap and costly uranium will be exhausted between 2030 and 2050'. They advocate finishing development work for the next generation of fast reactors within a decade and start batch production of fast reactors by 2020. The nations are thus deciding time frame for deployment of fast reactors depending upon their energy needs and uranium availability. While other developed nations realize the importance of fast reactors and are pursuing R&D to realize similar objectives, India has to do so earlier than others in view of poor uranium resource position. Thus, on this front India has to pursue independent R&D and protect the intellectual property so developed.

With regard to the third stage, while we have irradiated thorium bundles in PHWRs and set up a facility for reprocessing thorium, industrial scale experience in handling thorium will be achieved only after Advanced Heavy Water Reactor (AHWR) and associated facilities for closing the fuel cycle have been set up and operated for adequate number of years. In addition, research and development on

TABLE 1. Nuclear power programme till 2020

Reactor type and capacities MWe	Capacity MWe	Cumulative capacity, MWe
15 reactors at 6 sites under operation at Tarapur, Rawatbhata, Kalpakkam, Narora, Kakrapar and Kaiga	3,360@	3,326
5 PHWRs under construction at Tarapur (1x540 MWe), Kaiga (2x220 MWe), Rawatbhata (2x220 MWe)	1420	4780
2 LWRs under construction at Kudankulam (2x 1000 MWe)	2000	6780
PFBR under construction at Kalpakkam	500	7280
Projects planned till 2020 - PHWRs (8x700 MWe), FBRs (4x500 MWe), LWRs (6x1000 MWe), AHWR (1x300 MWe)	13,900	21,180

@ includes 50 MWe to be added after MAPS-1 upgradation

accelerator driven sub-critical systems has also been launched and this will enable India to exploit its vast thorium reserves earlier than possible otherwise. Molten salt reactor first studied in 60s led to a proposal to set up 1 GWe Molten Salt Breeder Reactor (MSBR) and molten salt reactors are one of the six systems retained by the Generation IV international forum (David – 2005). This could be another system to enable thorium utilization, but needs to be studied in detail before one can arrive at any conclusion.

To summarize the present status, India has developed expertise in all aspects of PHWRs and associated nuclear fuel cycle and PHWRs are the mainstay of its present nuclear power programme. To kick-start the nuclear power programme, two Light Water Reactors (LWRs) were constructed in the beginning of the programme and they are still in operation. At present, 13 PHWRs are in operation and 5 are under construction. As indicated earlier, one 500 MWe PFBR is also under construction. In addition to indigenous technology, to expedite the growth of nuclear power, India is planning to set up Light Water Reactors (LWRs) in technical cooperation with other countries. Two LWRs being constructed at Kudankulam, in the southern part of India in technical cooperation with Russian Federation is a part of this strategy. Medium term plan is to ensure that nuclear installed capacity by the year 2020 is about 20 GWe[1]. In addition to PHWRs, this would consist of 8 GWe of LWRs and 2.5 GWe of FBRs. Table 1 gives present status and plans till 2020.

Role of nuclear energy

To delineate the role of nuclear energy, one has to look at energy growth scenarios at the global level and the national level. For global scenarios, we will refer to the book titled, “Energy to 2050 – Scenarios for a Sustainable Future” by International Energy Agency (IEA – 2003). They have given several exploratory scenarios and finally given one normative scenario, which aims at meeting three general objectives.

Climate change mitigation,

Energy security and diversification; and

Energy access.

Table 2 gives summary of the results relating to the global situation. We will use this for comparison with a scenario for India.

With a view to determine growth plan for nuclear energy, a group in the Department of Atomic Energy (DAE) studied energy growth scenario in India (Grover and Chandra – 2004). Using available

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[1] This plan was formulated based on discussions at a 3-day seminar on Vision-2020 organized by the DAE in 1995 and includes construction of five fast Reactors of 500 MWe each and import of 8 Light Water Reactors of 1000 MWe each.

TABLE 2. Primary energy in the world – projected growth
Source: IEA (2003)

	2000	2010	2020	2030	2040	2050
Population (million)	6117	6888	7617	8182	8531	8704
Primary Energy-EJ						
Coal	105.6	118.3	135.6	153.5	128.0	99.3
Oil	155.0	165.8	178.5	193.0	191.4	181.3
Gas	86.9	123.2	157.3	206.9	244.2	267.1
Nuclear	8.2	11.4	18.1	39.1	75.3	114.5
Biomass	45.5	52.8	69.3	92.3	117.5	159.0
Other renewables	14.8	25.1	45.6	71.6	122.1	191.8
Total	416.0	496.6	604.3	756.3	878.5	1013.0
Primary Energy - % shares						
Coal	25.4	23.8	22.4	20.3	14.6	9.8
Oil	37.3	33.4	29.5	25.5	21.8	17.9
Gas	20.9	24.8	26.0	27.4	27.8	26.4
Nuclear	2.0	2.3	3.0	5.2	8.6	11.3
Biomass	10.9	10.6	11.5	12.2	13.4	15.7
Other renewables	3.6	5.1	7.5	9.5	13.9	18.9

Note: One of the objectives of the normative scenario reported above is climate change mitigation and one may note peaking of absolute contribution by coal and oil around 2030 and monotonic increase in the contribution by nuclear, biomass and other renewable sources. Exploitation of biomass to make a significant contribution in the Indian case would be difficult as 2 of the 3 main inputs (land mass, water and sunshine) required for biomass production are scarce in India.

GDP forecast, this study developed a scenario for the growth of electrical energy in India and estimates based on this study indicate that even after recognizing that energy intensity of GDP would continue to decline as in the past, the total electricity generation by the middle of the century would be an order of magnitude higher than the generation at present. This calls for developing a strategy for the growth of electricity generation based on a careful examination of all issues related to sustainability particularly abundance of available energy resources, diversity of sources of energy supply and technologies, security of supplies and self sufficiency. Tables 3 and 4 give a summary of results from the study by Grover and Chandra.

To meet the projected demand, the study presents a strategy which incorporates, wherever available, recommendations of various organs of the Government of India. This includes augmenting nuclear installed capacity to 20 GWe by 2020 based on a mix of Pressurized Heavy Water Reactors (PHWRs), Light Water Reactors (LWRs) and Fast Breeder Reactors (FBRs) and realization of full potential of hydro and renewable energy sources. In view of very large energy requirements, it is necessary that pace of addition in nuclear installed capacity is maximized. Considering that India has only modest reserves of uranium, this calls for deploying fast reactor technology, which makes it possible to recycle spent fuel after reprocessing and re-fabrication. Further, to accelerate the growth of fast reactors, it is necessary that R&D, to set up uranium-plutonium metal based FBRs of short doubling time and associated fuel reprocessing technologies, is completed in the next 15 years to ensure that the FBRs set up after 2020 have desirable growth characteristics. By following this route, nuclear installed capacity can reach a figure of 275 GWe by the middle of the century[2]. After accounting

TABLE 3. Primary energy in India – projected growth
Source: Grover and Chandra (2004)

	2002	2012	2022	2032	2042	2052
Population (million)	1040	1200	1330	1420	1470	1500
Primary Energy-EJ						
Coal	6.40	8.1	11	19	31	47
Hydrocarbon	6.02	9.3	13	19	30	41
Hydro	0.79	2.8	4.6	6.0	6.0	6.0
Nuclear	0.23	0.8	2.1	4.4	9.8	19
Renewables	0.03	0.4	1.6	2.0	2.4	2.7
Total	13.46	21.5	32	50	79	116
Primary Energy - % shares						
Coal	47.5	37.6	34.4	38.0	39.2	40.5
Hydrocarbon	44.7	43.2	40.6	38.0	37.9	35.3
Hydro	5.8	13.0	14.3	12.0	7.6	5.1
Nuclear	1.6	3.7	6.5	8.8	12.9	16.4
Renewables	0.2	1.9	5.0	4.0	3.0	2.3

TABLE 4. Cumulative Nuclear Power Installed Capacity

Year	PHWR, AHWR and FBR based on Pu from PHWR			LWR and FBR based on Pu from LWR			Sub Total		Grand Total (GWe)
	Thermal (GWe)	Fast (GWe)		Thermal (GWe)	Fast (GWe)		Oxide (GWe)	Metal (GWe)	
	Oxide	Oxide	Metal	Oxide	Oxide	Metal			
2002	2.40	0.00	0.00	0.32	0.00	0.00	2.72	0.00	2.72
2012	6.06	0.56	0.00	4.32	0.00	0.00	10.88	0.00	10.88
2022	9.96	2.50	6.00	8.00	0.00	3.00	20.46	9.00	29.46
2032	9.40	2.50	33.00	8.00	0.00	10.00	19.90	43.00	62.90
2042	7.86	2.50	87.00	8.00	0.00	26.00	18.36	113.00	131.36
2052	4.06	2.50	199.00	8.00	0.00	61.00	14.56	260.00	274.56

If only the already negotiated 2 GWe LWRs are imported then the installed capacity in 2052 will be 208 GWe instead of 275 GWe.

for contribution by nuclear, hydro and renewable energy sources[3], rest of the demand has to be met by fossil fuels, from domestic sources or by imports. Based on this scenario, it is observed that the cumulative energy import during the next 50 years will be about 30% and the nuclear contribution towards electricity generation will increase from the present 3% to about a quarter of the total.

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[2] Tongia and Arunachalam (1998) have grossly underestimated the growth of installed electricity generating capacity based on plutonium-uranium fast reactors because of their assumptions related to plant capacity factors and a particular interpretation of INFCE data.

[3] Certain authors have commented that installed nuclear capacity in India is lower than installed capacity based on wind mills (Reddy – 2005). However, wind mills operate at very low capacity factors, recorded capacity factor in India being of the order of 12%. When located at ideal sites, capacity factors could be higher (20 to 25%), but this is not applicable to average sites in India, where wind mills are located.

Fossil fuels will continue to dominate the Indian energy scenario. Moreover, though in percentage terms the cumulative imports and the level of imports around the middle of the century could continue to be at the same level as at present, the absolute numbers will be many times larger and will become a major factor with worldwide influence on prices and availability of all fuels.

A comparison of results of the study done by the DAE and the study done by the IEA indicates the following.

> The present hydrocarbon (oil and gas) usage in India is about 2.5% of the worldwide usage and this would grow close to 10% by the middle of the century.
>
> The present coal usage in India[4] is about 6% and could grow to be above 45% of likely world's usage.

One may postulate a scenario different from the one used for generating the above numbers and come up with a different set of numbers, but one cannot escape from the conclusion that increase in the share of nuclear energy in India's energy mix, beyond what is possible based on domestic programme, is desirable to minimize stress on global fossil fuel resources. This is also desirable from global environmental consideration.

It is worthwhile to note that from 1990 through 2004, global nuclear electricity production increased from 1901 to 2619 TWh (IAEA-2005). Installed nuclear capacity rose from 327.6 to 366.3 GWe due to both new construction and uprates at existing facilities, and the global average capacity factor improved from 71.6% to 83.3%.

Fusion

So far we have talked about fission reactors. Another phenomenon that can be utilized to produce electricity is fusion. Fusion powers the sun, and stars, and is potentially an environmentally responsible and intrinsically safe source of essentially limitless power (Smith et al. – 2005). Based on experiments already conducted in various laboratories around the world, scientists have convincingly concluded that fusion could be mastered to produce power. The International Thermonuclear Experimental Reactor (ITER) is a project being developed jointly by an international consortium consisting of European Union, USA, Japan, South Korea, Russia and China. ITER will be located at Cadarache in South of France and aims to develop a plant for demonstrating generation of electricity based on fusion. The design goal of ITER is to produce at least 500 MW of fusion power, with a plasma heating input of around 50 MW. In view of the potential of this technology, India is set to join this international consortium. India already has a sizeable programme in fusion research and a well trained work force of scientists and engineers to be able to make contribution to this project. However, this is a complex technology; an autarchic route is not the preferred path for development of this technology and the decision of the government to join the ITER programme is well advised.

Safety

Safety is a topic that engages the attention of everyone. The nuclear industry all over the world has been conscious of safety and has been making all efforts to enhance safety. If we compare various methods of electricity generation, nuclear industry has the best record. Immediate fatalities for the period 1970-92, normalized to deaths per TWy of electricity generated is 342 for coal, 85 for natural gas, 883 for hydro and 8 for nuclear (Anonymous 2005a). Nuclear industry is the only industry where operators from all over the world have come together and set up an institution called World Association of Nuclear Operators (WANO). This association conducts peer review of all nuclear power plants and is evolving industry-wide procedures and practices to continuously enhance safety. NPCIL is a founder-member of WANO and most of the reactors operated by it have already been subjected to peer review. The very fact that NPCIL joined WANO and offered its reactors for peer review, indicates the level of confidence it has in its operation. NPCIL is not resting on its laurels and is continuously working towards enhancing safety and availability. The first

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[4] In terms of weight, the percent usage is higher as the Indian coal has low calorific value. As per IEA – 2005, India produced 373 Mt of hard coal, 29 Mt of brown coal and imported 31 Mt of hard coal in 2004, while worldwide production was 5508 Mt. India's consumption was thus 7.86%.

step to achieve this is to identify a safety issue and the next step is to resolve it. It is pertinent to quote Gopalakrishnan [2005], who wrote, “As a nuclear engineer and former Chairman of AERB, I am well aware of the Indian and international status in this field. In 1995, when I submitted a comprehensive report to the government on the ‘Safety Status in DAE Installations’, most of the critical safety deficiencies documented by the AERB had been identified prior to that by the DAE managements themselves.” He goes on to say, “To the credit of subsequent managements of the DAE, I am reasonably assured now that most of the safety issues have been resolved within the last decade. The Indian nuclear engineers and scientists, along with the national industries, worked on achieving this without any foreign assistance and often through the development and implementation of indigenous technological solutions.”

From considerations of economics, sustainability and energy security, large-scale augmentation of nuclear generating capacity in India is desirable. It is a safe technology as demonstrated by about 12,000 reactor-years (WNA web site accessed on October 1, 2005) of cumulative commercial operation. As per IAEA database accessed on October 1, 2005, at present 441 reactors are operating in 30 countries and another 24 reactors are under construction. There have been only two major accidents in the history of nuclear power. The first occurred at Three Mile Island, USA in 1979 where the reactor was damaged, but there were no adverse health effects or environmental consequences. The second occurred at Chernobyl, Ukraine in 1986, where the destruction of the reactor by explosion and fire killed 31 people immediately. The just released report by the Chernobyl Forum (IAEA-2005a) says that as of mid-2005, fewer than 50 deaths had been directly attributed to radiation from the disaster. Burton Bennett, Chairman of the Chernobyl Forum explains, “This was a very serious accident with major health consequences, especially for thousands of workers exposed in the early days who received very high doses, and for the thousands more stricken with thyroid cancer. By and large, however, we have not found profound negative health impacts to the rest of the population in surrounding areas, nor have we found widespread contamination that would continue to pose a substantial threat to human health, with a few exceptional, restricted areas.”

World Uranium Situation

After years of flat and declining prices, uranium prices have nearly tripled over the past two years (Kidd – 2005). This has led to speculation about eventual exhaustion of uranium resources and the direction nuclear energy the world over will take in the future. One viewpoint is that the estimated reserves of uranium appear insufficient to ensure a fast and massive increase of nuclear power based on current reactor technology and an early introduction of breeders is necessary (David – 2005). Another viewpoint is that rising uranium prices will lead to a new exploration cycle and the availability of new production from this cycle (Macdonald – 2004). Improving mining technology will allow access to deposits formerly judged difficult to exploit and therefore uneconomic. Secondary uranium sources could also become economical. Rising uranium prices will definitely favour pursuit of closed fuel cycle approach from consideration of sustainability and also economics, an approach which India has always advocated. While extent of rise of uranium prices is difficult to predict, we in India have to plan the future keeping in mind the enormous energy needs necessary for economic development. This calls for multi-pronged approach: step up exploration efforts, particularly to locate uranium resources which are concealed and have no surface manifestation, continue to pursue R&D to develop breeder reactors using advanced fuels having short doubling time and high burn up and develop strategies to become a player in the world civil nuclear trade.

Economics of Nuclear Power

While the nuclear industry continues to provide electricity at competitive rates and several countries in need of additional generation capacity are going ahead with plans to set up nuclear plants, a divergent view is also expressed that nuclear is not cost competitive. Nuclear Energy Agency and International Energy Agency released their joint report titled, “Projected Costs of Generating Electricity: 2005 Update” in early 2005 with the objective to provide reliable information on key factors affecting the economics of electricity generation using a range of technologies (NEA – 2005). The report gives cost ratios of electricity generation[5] from nuclear and coal and also from nuclear and gas. Experts from 19 countries participated in the study. The results indicate the following.

At 5% discount rate, nuclear is cheaper as compared to gas in all the 19 countries.

At 10% discount rate, except Japan and the USA, nuclear is cheaper as compared to gas. USA has offered two gas based plant designs for this study and gas is cheaper in case of only one.

At 5% discount rate, except South Korea and the USA, nuclear is cheaper as compared to coal. In South Korea, out of the 4 comparative evaluations given in the study, coal is cheaper for only one case.

At 10% discount rate, in South Korea, the USA and Germany, nuclear is cheaper as compared to coal. In South Korea, for all the 4 comparative evaluations reported and in the USA for the two cases given, coal is cheaper. For Germany, for 4 cases analyzed, coal is cheaper in case of 2.

There have been several national studies, including by India as reported later, on comparative economics of various methods of electricity generation. In a recent paper, Proust (2005) has done a comparative analysis of all these studies. The studies examined by him include the DIDEME report from France, MIT and University of Chicago studies from the USA, TARAJANNE study from Finland and other studies. He concludes, "All recent European cost studies show that 3rd generation nuclear is competitive with coal-fired plants, and may be up to 20% cheaper than CCGTs for base load electricity generation, even when CO_2 emissions costs are disregarded." He continues, "This EU picture should also apply to the US once the first new nuclear plants will have been successfully built and operated in the country."

Similar studies have been done in India by NPCIL (Thakur and Chaurasia – 2005) as well. While nuclear power cost is location independent, in case of coal, it is very sensitive to distance of the power plant from coal mine as cost of coal transportation is quite significant. The levelised costs of generation at 2005-06 prices for dominant technologies in India using 5% and 10% discount rates have been evaluated (assuming coal fired plant is situated at a distance of 800 km from coal mine) and the results are given in Table 5. The critical discount rate, below which nuclear power is cheaper as compared to coal thermal, is 7.1%.

TABLE 5. Levelised costs (2005-06 constant price)

(Paise/unit)

Discount rate	Nuclear	Coal-fired	Gas-fired (LNG)
5%	152	164	182
10%	218	200	204

The contributions of investment cost, O&M cost and fuel cost in all the cases are shown graphically in Fig 1.

Nuclear power becomes costlier at higher discount rate due to high capital investment compared to that of coal-fired power plants and gas-fired power plants. Greater the investment cost, sharper is the increase in levelised cost with increase in discount rate. However, the contribution of fuel cost is least in the case of nuclear compared to others.

A sensitivity analysis for levelised cost of generation has also been carried out in respect of nuclear and coal. For both nuclear and coal-fired power, levelised costs at critical discount rate have been taken as the base for sensitivity analysis. Critical inputs like base capital cost, O & M cost, fuel price, capacity factor and discount rate have been increased by 1% and the corresponding changes in levelised costs have been observed for both the cases. The results of analysis are shown in Fig. 2.

The analysis shows that nuclear is less sensitive to fuel price as compared to coal. Also, with increase in capacity factor, the economics shifts towards the nuclear at much faster rate. However,

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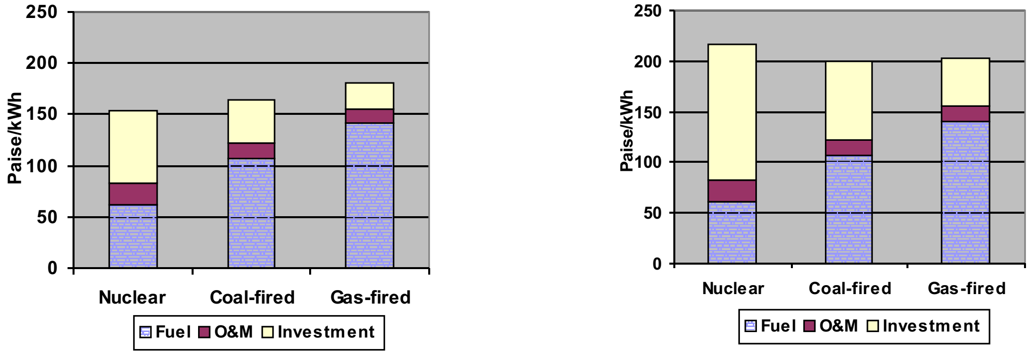
[5] For project appraisal, normally comparison of various technology options is done by calculating levelised costs. In calculating the liveliesed cost of generation, lifetime expenditures are discounted to the present (base year) value by applying applicable discount factor. The levelised cost of generation is the ratio of discounted total lifetime expenditure to expected lifetime net generation.



at 5% discount rate

at 10% discount rate

Fig. 1 Contribution of fuel, O&M and investment cost towards levelised cost of generation

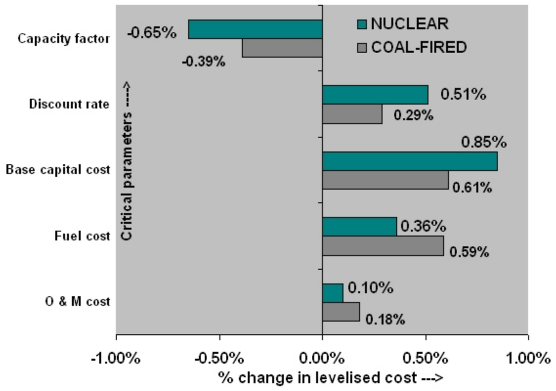


Fig. 2 Sensitivity of levelised cost to the main contributing factors

nuclear is more sensitive to capital cost and discount rate compared to coal-fired power.

As indicated earlier, the cost of generation from coal-fired power plants is location dependent. The variation in the critical discount rate with respect to the distance over which coal has to be transported is shown in Fig. 3.

Several load centres in the country are located away from the coalmines, where nuclear power is an economically attractive option. The cost of additional infrastructure for transportation of coal from mines needed for capacity addition is also quite significant and an additional investment not considered in the evaluation by NPCIL.

With a view to harmonize the output and benchmark with OECD study referred to earlier, the result in respect of nuclear power in India has been dovetailed into OECD study using the assumptions as in the OECD study. The results indicate that the levelised cost of generation of about 30 US $ per MWh compares reasonably well with the levelised cost of generation in other countries (See Fig. 4).

The economic advantage of nuclear power, over thermal, manifests itself during the life of the plant since the escalation in fuel prices has a much lesser impact on the generation cost.

Studies by IGCAR (Bhoje – 2003) indicate that the cost of electricity from fast reactor will also be competitive.

Further Evolution of Nuclear Energy in India

With regard to issues related to energy there is no silver bullet. Every country has to plan its energy infrastructure based on its resource profile, technology base and human resource. Major oil and gas importers including India will become ever more dependent on imports from a few distant, often politically unstable parts of the world. Availability of coal for more than a few decades is also doubtful. Thus it is necessary to reduce dependence on fossil fuels and that can be achieved only by advanced nuclear technology or breakthrough renewable technology, (Mandil - 2005).

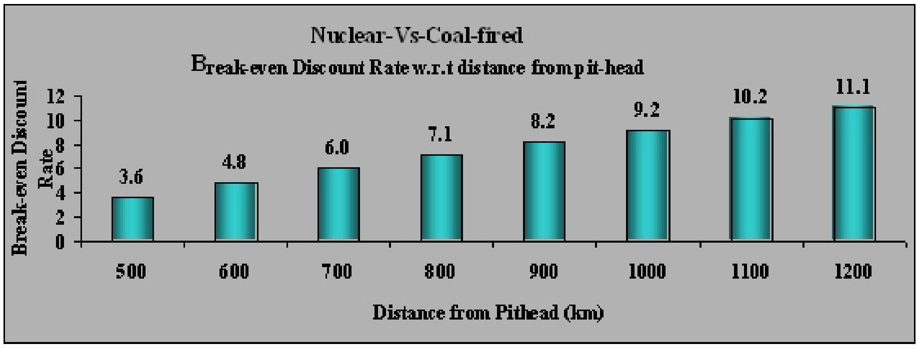


Fig. 3 *Variation of levelised cost with distance over which coal has to be transported*

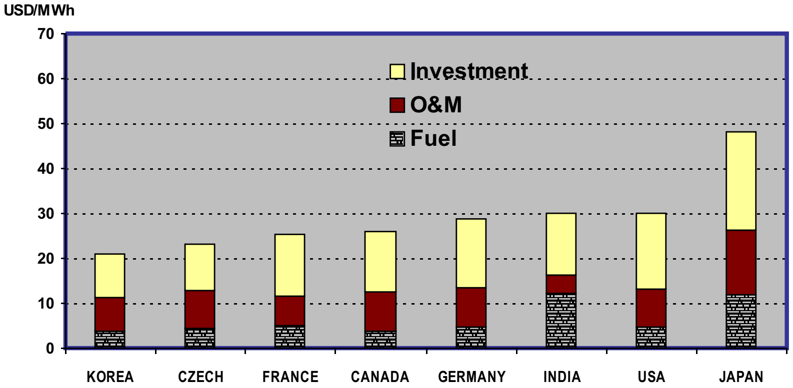


Fig. 4 *Levelised costs of nuclear generated electricity at 5% discount rate*

The growth of nuclear energy in India in the years to come will be determined by several factors including

- success in locating additional uranium resources in the country based on intensification of efforts to explore uranium as planned by the DAE,
- success achieved in domestic R&D
  - with regard to developing fast reactors with advanced fuels (having short doubling time, high burn up) and associated fuel cycle technologies to ensure multiple recycling of fuel,
  - development of technologies for utilization of thorium,
- opening up of civil nuclear cooperation with India.

While opening up of civil nuclear cooperation can lead to immediate gains, long-term outlook will be determined by ongoing R&D in the country. Policy framework has to seek a balance between short-term, medium-term and long-term interests. A country of the size of India cannot plan its economy on the basis of large scale import of energy resources or energy technology. Indigenous development of energy technologies based on domestic fuel resources should be a priority for us in India.

Apart from uranium resource, technology and economics, one more factor is very important and that is selecting and training human resource for nuclear industry, which is knowledge intensive. Here I foresee a problem. World over nuclear power is likely to stage a come back. For India it could be advantageous as it could lead to international cooperation and further improve economics of nuclear power. It could also lead to a problem by opening up lucrative employment opportunities for nuclear scientists and engineers leading to a large scale exodus. This begs the question: can we retain highly skilled manpower by giving them 'Indian salaries' which are much lower than salaries in the developed world!

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Indian Nuclear Power Programme – Past, Present and Future

Shri Dilip Saha *obtained his Bachelor's as well as Master's degree in Mechanical Engg. from the University of Calcutta. After completing orientation course from 15th batch of Training School, he joined Reactor Engineering Division in 1972. Ever since he joined RED he has been involved in research and development work in the area of thermal hydraulics and safety of nuclear reactor systems. Right from its inception, Shri Saha has been involved in the design and development of Advanced Heavy Water Reactor. Currently, he is Head of Reactor Engineering*

Shri Ratan Kumar Sinha *graduated in Mechanical Engineering from Patna University in 1972, standing first in the University. After completing the one year Course of BARC Training School he joined Reactor Engineering Division of BARC in the year 1973. He is a Distinguished Scientist and had been designated as Director, Reactor Design & Development Group and Director, Design Manufacturing and Automation Group of BARC. Shri Sinha has handled several major assignments relating to the Indian research and power reactors. In particular he has specialised in design, development and safety related activities relating to Coolant Channels of Heavy Water Reactors. He is currently guiding the design and development of the innovative Advanced Heavy Water Reactor, and Compact High Temperature Reactor. Shri Sinha has received several awards and honours. He was conferred the first Homi Bhabha Science and Technology Award, for the year 1992, in recognition of his outstanding contributions to nuclear technology. He was elected a Fellow of the Indian National Academy of Engineering in 1998. He was a co-recipient of the VASVIK Award for the year 2000, in the field of Mechanical Sciences and Technology. In the year 2002 he was conferred the first Indian Nuclear Society Award by the then Prime Minister Shri Atal Behari Vajpayee. Shri Sinha is a nationally and internationally recognised expert in the area of nuclear reactor technology. He is a member of several national and international committees.*

Introduction

Nuclear energy has been part of the world's energy mix for more than fifty years. However, over the past twenty years, increased public concern about the safety of nuclear plants had resulted in socio-political constrains on its use. During this period the world was able to cope with an increasing energy demand by relying more on fossil fuel. However, the progressively dwindling world reserve of fossil fuel, a deep rooted concern about global warming arising out of CO_2 emission and increasing oil price have now caused a worldwide renewed interest in nuclear energy. In the opinion of many this is the era of nuclear renaissance.

In India, however, interest in nuclear energy never abated because of the foresight of our predecessors. A blue print of a phased nuclear energy programme with closed fuel cycle, considering the fuel resource position in India was available as early as in 1954. India consistently pursued this phased programme and have now mastered all the aspects of fuel cycle technology.

D. Saha and R.K. Sinha, Reactor Engineering Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085;
E-mail: dsaha@apsara.barc.ernet.in & rksinha@barc.gov.in

India, which accounts for one-sixth of global population, is on rapid economic growth path. A recent study has revealed that we will need to augment our electricity generation ten folds in next four to five decades. This would be a significant fraction of global electricity generation. A large fraction of this energy coming from nuclear power would be of immense benefit, in the context of environment and sustainability concerns, for India as well as for the rest of the world. Nuclear energy is thus an important and inevitable option for India [1]. Our achievements in this area in the past, present activities and future programme to cope with the steeply increasing energy demand are discussed in following sections.

Indian Nuclear Power Programme

India has been pursuing a three stage nuclear power programme that is focused on utilization of the modest amount of uranium and vast amount of thorium available in the country. The three stages are elaborated below.

The first stage of the programme comprises setting up pressurized heavy water reactors (PHWRs) and associated fuel cycle facilities. However, the potential of this stage, if all domestic uranium is used up in PHWRs, is only about 330 GWe-yr [2]. The second stage envisages development of fast breeder reactors using uranium and plutonium obtained from the spent fuel of first stage. The uranium on multiple recycling through the route of Fast Breeder Reactors has the potential to provide about 42,200 GWe-yr. The third stage aims at the development of reactors based on Uranium-233 fuel obtained from irradiated thorium. The Thorium reserves, on multiple recycling through appropriate reactor systems, have a potential of about 150,000 GWe-yr which can meet our energy need for a long time to come.

Achievements of the Past

PHWR Programme

As stated above, the first stage of the programme comprises setting up of pressurized heavy water reactors (PHWR) with natural uranium fuel and heavy water moderator and associated fuel cycle facilities. This stage of the programme has been implemented in a very effective manner. Nuclear Power Corporation of India Limited (NPCIL), which is responsible for the design, construction and operation of nuclear power reactors in India now operates twelve 220 MWe units and one 540 MWe unit. Besides pressurised heavy water reactors, light water reactors were also added to this stage initially to gain operational experience. Two boiling water reactors at Tarapur Atomic Power Station are still operating quite efficiently.

Comprehensive capability in the design, construction and operation of PHWR has been achieved that ranges from exploration of nuclear minerals, mining and ore processing, fuel fabrication, power generation, reprocessing of spent fuel to nuclear waste management. It has also achieved high standards in safety and environment management. To implement the programme, over the years a large infrastructure has been created for R&D as well as production and construction activities.

It is worth mentioning here that our nuclear programme had to flourish in the technology denial regime. The department took up the challenge resulting in indigenous development of critical components and achievement of self-reliance in almost every aspect of PHWR fuel cycle technology.

The first phase has, at present, attained a high level of maturity with standardized design, high capacity factor and construction time less than five years.

Fast Breeder Programme

Significant progress has been made in regard to this stage. The Fast Breeder Test Reactor (FBTR) is in operation at Indira Gandhi Centre for Atomic Research (IGCAR) since 1985 with indigenous uranium-plutonium carbide fuel. It has achieved a very high burn up of 150000 MWd/t without any fuel failure.

Thorium Utilization

A beginning has already been made by introducing thorium in research reactors and in PHWRs for flux flattening. The research reactor, Kamini operating upto a nominal power of 30 kW for the purpose of neutron radiography uses U^{233} fuel produced from irradiated thorium. The reactor has been operating since 1995. The fuel for the reactor is bred, reprocessed and fabricated indigenously.

Present Activities

PHWR Programme

At present, five PHWRs are under construction, four of them 220 MWe units and one 540 MWe unit. A larger PHWR of 700 MWe capacity is being developed. As stated earlier, our PHWR programme has attained a high level of maturity. As a number of units are growing older, they need ageing management and performance enhancing back-fits. Activities in this area include,

(a) Development of techniques for determining residual life of coolant channel based on hydrogen concentration

(b) In-situ property measurement of coolant channel material.

Fast Breeder Programme

Based on the valuable experience gained with liquid metal fast breeder reactor technology, we embarked on the construction of a 500 MWe Prototype Fast Breeder Reactor (PFBR) in October, 2004. Construction of the unit is progressing at a fast pace. A facility to reprocess carbide fuel from FBTR has been commissioned. Fuel with discharge burn up of 100000 MWd/t has been reprocessed successfully. Some important areas of ongoing R&D are:

(a) Development of fuel cycle with shorter doubling time using metallic fuel

(b) Increase of burn up

(c) Fuel reprocessing

Thorium Utilization

Technologies related to utilization of thorium, in the third stage of Indian nuclear power programme need to be mastered before large scale deployment of commercial thorium based reactors becomes necessary. The ongoing fuel cycle related studies include :

Th-U^{233} reprocessing

U^{233} clean up

High temperature fuel development

Partitioning of actinides and fission products

The Future Programme

Technology and related research and development have to be in continuously evolving mode. This is true for nuclear technology as well. One of the reasons is the issue of sustainability. Another important reason is the variation of energy demand and type of energy with time. The impact of this evolving mode on our future power programme is discussed below.

Sustainability

For sustainable development of nuclear energy, besides fuel resource a number of important issues are required to be addressed. It should be economically competitive compared to other sources of energy especially fossil fuel and renewable sources. The issue of heightened public concern about nuclear safety must be addressed. At a minimum, new nuclear plants must maintain or exceed the current level of safety. Other important issues are the long-term disposal of waste, proliferation resistance, environmental impact and crosscutting issues like social and infra-structural aspects.

To address these issues a number of advanced reactor designs as well as fuel cycle technologies are being pursued worldwide. Advanced designs consist of evolutionary designs and innovative designs. A short-term option to address the issues mentioned above is to adopt the evolutionary design that achieves improvements over existing design through a strong emphasis on proven technologies. However, to compete successfully in the long term in highly competitive energy market and to overcome other challenges, innovative designs that incorporate radical conceptual changes in design approaches in comparison with existing practice need to be adopted.

These requirements are now added to the requirement of thorium utilization. The result is the development of the Advanced Heavy Water Reactor (AHWR) which is under pre-licensing safety review by Atomic Energy Regulatory Body. AHWR is a

300 MWe, vertical, pressure tube type reactor cooled by boiling light water and moderated by heavy water. The reactor is fuelled with $(U^{233}\text{-Th})O_2$ together with $(Pu\text{-}Th)O_2$. The main objective behind the development of this reactor is to develop and demonstrate technologies related to thorium based systems well in advance. More details of AHWR are given in a later section.

For breeding fissile uranium-233 from thorium, development of Accelerator Driven Sub-Critical System (ADS) is the latest addition to Indian nuclear power programme. This system promises shorter doubling time of fuel inventory and incineration of long-lived actinides and fission products thus effectively addressing the sustainability issues of availability of fissile material and waste management.

Steep Increase in Demand

India, is on rapid economic growth path. A recent study has revealed that we will need to augment our electricity generation ten folds in next four to five decades. The Department of Atomic Energy has formulated a programme that aims at an installed capacity well above the planned target of 20000 MWe by the year 2020. To meet this target of high installed capacity in a short time there are two options. One is the installation of reactor of higher size that includes importing Light Water Reactors. Two 1000 MWe Pressurised Water Reactors (VVERs) imported from Russia are now under construction. Development of fuel cycle for fast breeder reactors with shorter doubling time by using metallic fuel is another option being pursued.

Non-grid Based Applications

It is necessary to utilize fossil fuel resources to the largest extent possible to meet the sharply increasing energy demand. In this respect high temperature process heat from nuclear reactor can be used for the production of fluid fuel by refining coal and recovery of low grade oil deposits. The most promising application of high temperature process heat is for the purpose of hydrogen generation. High temperature reactor concept can also be applied for the development of compact power pack for electricity generation in remote areas. A Compact High Temperature Reactor (CHTR) is under design now. The CHTR is a ^{233}U-Thorium fuelled, lead-bismuth eutectic alloy cooled and beryllium oxide moderated reactor. This reactor has been designed to have a long core life of 15 effective full power years. This will have several advanced passive safety features to enable its operation as compact power pack in remote areas not connected to the electrical grid. This reactor is initially being developed to generate about 100 KWth power and to operate at 1000°C. CHTR is described briefly in a later section.

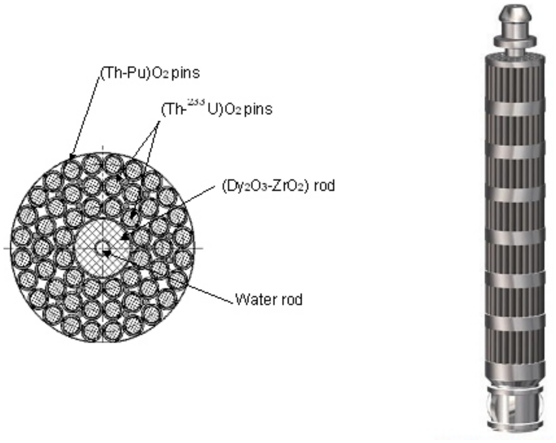

Fig. 1 AHWR Fuel Cluster Assembly

Another important area for non-grid based application of energy is desalination. We are in the fore front of all desalination technologies. Specially designed reactors like AHWR can be effectively integrated with desalination units.

The Advanced Heavy Water Reactor (AHWR) 3

AHWR is a 300 MWe, vertical, pressure tube type reactor cooled by boiling light water and moderated by heavy water. The reactor is fuelled with $(U^{233}\text{-Th})O_2$ together with $(Pu\text{-}Th)O_2$. AHWR is nearly self-sustaining in U^{233}. The design of AHWR is fine tuned towards deriving most of its power from thorium based fuel, while achieving negative void coefficient of reactivity.

The fuel assembly is suspended from the top in the coolant channel of the reactor. The assembly consists of a single long fuel cluster and two shield sub-assemblies. The cluster has 54 fuel pins

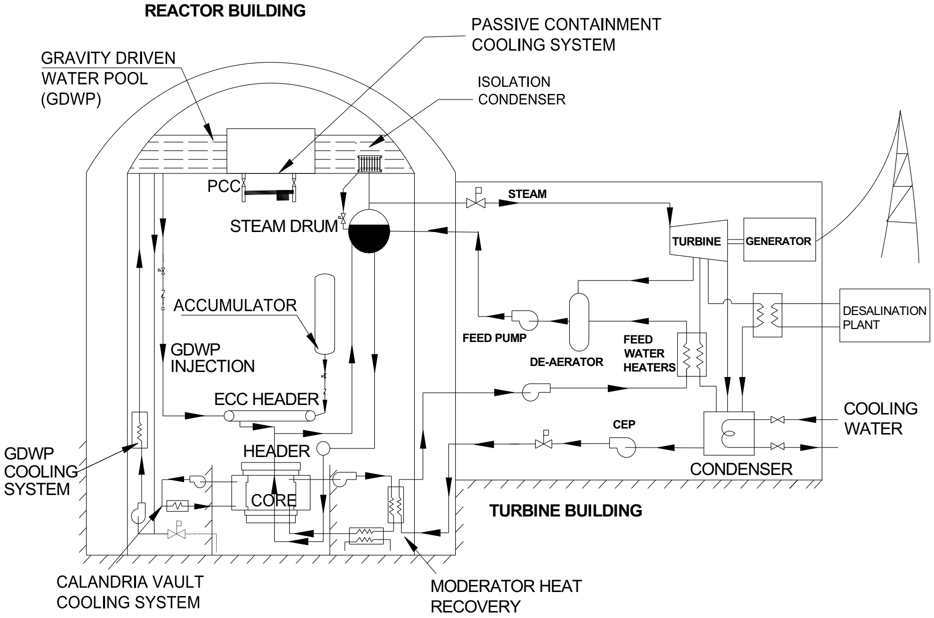

Fig. 2 General Arrangement of AHWR.

arranged in three concentric rings, 12 pins in the inner ring, 18 pins in the intermediate ring and 24 pins in the outer ring, around a central rod containing burnable absorber dysprosium as Dy_2O_3-ZrO_2. The 24 fuel pins in the outer ring have $(Th\text{-}Pu)O_2$ fuel and the 30 fuel pins in the inner and intermediate rings have $(Th\text{-}^{233}U)O_2$ fuel. Fig. 1 shows AHWR fuel cluster assembly. Heat removal from core is achieved by natural circulation of coolant. General arrangement of AHWR is shown in Fig. 2.

The core comprises vertical fuel channels housed in calandria containing moderator. The calandria is located in water filled reactor cavity. The core is connected to four steam drums. A large water pool named GDWP is located near the top of the containment. The GDWP acts as heat sink for a number of systems. Moderator heat is utilized for feed water heating. As shown in Fig. 2, double containment is provided to prevent any release of radioactivity to environment. AHWR incorporates several advanced features to increase its safety, reliability and economics. These are enumerated below:

Natural circulation heat removal under normal operation and shutdown conditions

Low core power density

Slightly negative void coefficient of reactivity

Direct injection of Emergency Core Cooling System (ECCS) water into fuel pins during Loss Of Coolant Accident (LOCA)

Advanced accumulator with fluidic device for ECCS

Gravity driven cooling system ensuring core cooling for three days following LOCA, without operator intervention

Passive containment cooling and isolation

Utilization of moderator heat

Utilization of low grade heat for desalination

Elimination of emergency measure beyond plant boundary

At present AHWR is under pre-licensing review by Atomic Energy Regulatory Board.

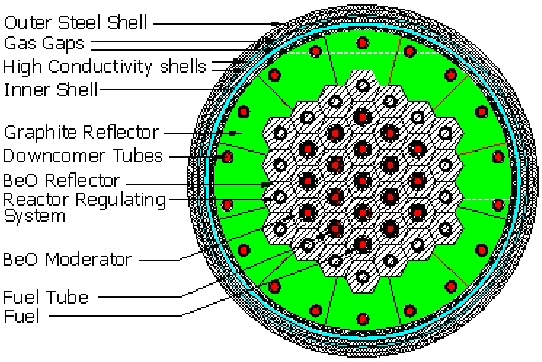

Fig. 3 CHTR core cross-sectional layout

Compact High Temperature Reactor (CHTR) [4]

Compact High Temperature Reactor is a ^{233}U-Thorium fuelled, lead-bismuth eutectic alloy cooled and beryllium oxide moderated reactor. This reactor has been designed to have a long core life of 15 effective full power years. This will have several advanced passive safety features to enable its operation as compact power pack in remote areas not connected to the electrical grid. This reactor is initially being developed to generate about 100 kWth power. The reactor is being designed to operate at 1000°C, to also facilitate demonstration of technologies for high temperature process heat applications such as hydrogen production from water. CHTR would serve as a prototype technology demonstrator reactor in the direction of fulfilling these objectives.

Description of CHTR

The CHTR core consists of nineteen prismatic beryllium oxide (BeO) moderator blocks. These moderator blocks have graphite fuel tubes located centrally. Each fuel tube carries fuel inside 12 equi-spaced longitudinal bores. The fuel tube also serves as coolant channel. The CHTR fuel is based on TRISO (TRI-iSOtropic) coated particle fuel. These particles are mixed with graphite powder as a matrix material and shaped into cylindrical fuel compacts. Fuel bores of each of the nineteen fuel tubes are packed with fuel compacts. Eighteen blocks of beryllium oxide reflector surround the moderator blocks. These blocks centrally accommodate passive power regulation system. Twelve numbers of graphite reflector blocks of variable size surround these beryllium oxide reflector blocks. Cross-sectional layout of the reactor core is shown in Fig. 3.

The core and reflector part of the reactor is contained in a metallic shell resistant to corrosion against Pb-Bi eutectic alloy coolant, and suitable for high temperature applications. This reactor shell is closed by top and bottom closure plates of similar material. Above the top cover plate and below the bottom cover plate, coolant plenums are provided. These plenums have flow guiding blocks made of graphite and having passages for coolant flow to increase the velocity of the coolant between the fuel tube and down comer tube. Two gas gaps surround the reactor shell and act as insulators during normal reactor operation and reduce heat loss in the radial direction. A finned outer steel shell has been provided which is surrounded by heat sink. Nuclear heat from the reactor core is removed passively by the Pb-Bi eutectic alloy coolant, which flows due to natural circulation between the bottom and top plenums, upward through the fuel tubes and returning through the downcomer tubes. On top of the upper plenum, the reactor has been provided with heat utilisation vessels to provide an interface to systems for high temperature heat applications. A set of sodium heat pipes is provided in the upper plenum of the reactor to passively transfer heat from the upper plenum to the heat utilisation vessels. Many passive systems are provided to remove heat in case of postulated accident conditions. One of the systems has a set of heat pipes to transfer heat from the upper plenum to the atmospheric air in the case of a postulated accident. Another passive system has been provided to fill the gas gaps with molten metal in case of abnormal rise in coolant outlet temperature so as to facilitate conduction flow of the reactor heat to outside heat sink. To shut down the reactor, a set of seven shut-off rods has been provided, which fall by gravity in the central seven coolant channels.

Methodology for the Assessment of Advanced Reactors

During the past few years a number of international programmes have been initiated to provide guidance for the medium and long-term development of nuclear energy that covers methodology for the evaluation of innovative reactor systems and fuel cycle. Prominent among them are INPRO initiated by IAEA, GIF, a US initiative and MICANET set up by nineteen European partners.

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was initiated based on a resolution by IAEA General Conference in the year 2000. INPRO has 22 member states as its members including India. As stated earlier, for nuclear energy to play a meaningful role in the global energy supply in the foreseeable future, innovative approaches will be required to address concern about safety, economic competitiveness, waste management and proliferation. Accordingly INPRO takes a longer-term perspective and is the only one that addresses the problems from the point of view of potential users in developing countries.

In 2001-2003, under Phase-1A [5], INPRO produced sets of basic principles (BPs) and user requirements (URs). This phase ended in June, 2003, having established a methodology and guidelines to assess different concepts and approaches. Phase- 1B which began in July, 2003 included the validation of INPRO Methodology through case studies. As part of National Case Study under INPRO, AHWR design was subjected to INPRO criteria and requirements. This study revealed high potential of AHWR design in meeting IAEA requirements for sustainable development of nuclear energy. India has all through out participated very actively in this programme and has been continuing to do so. INPRO is poised to enter the second phase promoting international cooperation in the area of advanced nuclear technology.

Concludung Remarks

The first stage of Indian nuclear power programme has attained a high level of maturity.

We embarked on the second stage with the commencement of the construction of Prototype Fast Breeder Reactor at Kalpakkam. The ongoing and future programme on thorium utilization indicate that we are well on course of the three stage programme with some additionalities. To meet the challenge of high economic growth resulting in high energy demand, the two options we are exercising are the installation of large size reactor and the development of a fuel cycle with shorter doubling time. To address the various issues related to the sustainable growth of nuclear energy we are going for advanced reactors. The case study performed under IAEA INPRO programme revealed high potential of AHWR design in meeting IAEA requirements for sustainable development of nuclear energy.

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Accelerator-Driven Sub-critical Reactor System (ADSS)

***Shri P.K. Nema**, BE (Mech), joined BARC in 1972 as trainee officer. He worked in the design and construction team of Dhruva reactor on the reactor pile-block components in BARC until 1985. In 1985, Shri Nema moved to Centre for Advanced Technology (CAT), now renamed as Raja Ramanna Centre for Advanced Technology, Indore to work on developing first indigenous 450-MeV electron synchrotron accelerator for use as synchrotron radiation source (SRS) named INDUS-1 which was successfully commissioned in 1999.He initiated work in BARC on emerging new technology of Accelerator-Driven Sub-critical reactor Systems (ADSS) for transmutation of actinides waste in the spent fuel, and to achieve higher breeding rate in for the thorium fuel cycle. He is coordinator for the BARC X plan project on ADSS systems developments including a 10-MeV, high current proton linac and lead-bismuth target technologies. These are multidisciplinary projects in which a large number of BARC divisions and expertise require careful interfacing. He is also involved in fabrication of radio frequency quadrupole and drift-tune linac (RFQ & DTL) modules of proton linac. Shri Nema is a member secretary of DAE steering committee on ADS programme, and also of Advanced Technology Advisory Committee of Board of Research in Nuclear Sciences (BRNS). He is a nominated alternate Indian member of the IAEA technical working group on ADS and fast reactors. His areas of special skill include mechanical design and manufacturing of precision components in particle accelerator and their metrology including alignments.*

Introduction

At the rate of present global energy consumption level, known reserves for coal, oil, gas and nuclear would last to a duration of the order of 230, 45, 63 and 54 years respectively [1]. However, newer technological possibilities with nuclear fuel cycles have potential of extending fuel resources rather indefinitely.

Today's nuclear energy is based on using naturally available isotope U-235, which is 0.71 % of the natural Uranium (U), and is fissionable both with thermal and fast neutrons. The workhorse of these energy systems is based on light water reactors (LWRs) using slightly enriched (~ up to 3% in U-235) uranium. Cost-wise, these are as economical in unit electricity cost as other widely prevalent fossil fuel-based thermal power plants. A massive increase of this light water reactor technology (5 to 10 fold), such as to counterbalance effectively global warming due to fossil fuels burning, is facing serious problems of (i) accumulated waste from presently used reactor technology, and of (ii) scarcity of Uranium ores anticipated in coming years.

But, new, more powerful nuclear reactions are possible for better utilization of existing natural resources of nuclear fuel materials. Particularly interesting are fission reactions possible with the use of U-238 or Thorium (Th)-232 in which:

> The naturally occurring species is progressively converted into a readily fissionable energy generating daughter elemental species (e.g. U-238 into Pu-239, and Th-232 to U-233).
>
> The totality of the initial fuel is eventually burnt fully through multiple recycling (at least, so in principle).
>
> The released energy for complete burning of a given quantity of mined natural uranium/thorium is more than one hundred times greater than the one in the case of the classical, U-235 driven nuclear energy systems.

Shri Pramod Kumar Nema, Nuclear Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085;
E-mail: pkn@barc.gov.in

Alternate Nuclear Fission Systems

With the proposed new kind of nuclear energy systems, the natural reserves of U-238 or Th-232 can become adequate for many tens of centuries at an energy consumption level several times higher than today’s primary fossil fuel-based energy production.

This would not be possible, however, without socio-political and public acceptance of nuclear power programme, so that :

Systems must be non-proliferating.

No long-lived radioactive by-products remain, which become liability for future generations; say, after a few centuries of decay in storage.

System should be inherently resistant to runaway nuclear reactions in any case of malfunctioning of engineered systems.

These utilize small fissile fuel inventory per unit of installed power generation capacity.

Basics of Alternate Nuclear Energy Systems

Two neutrons per fission are required within the new basic fuel cycle, one for the breeding to convert fertile species into fissile one, and the other for the fission, in contrast with the ordinary U-235 process, in which only one neutron is necessary.

Once such reactor is charged with nuclear fuel, after a definite burn up time the fuel has to be recycled by addition of /replacement with fresh fuel since:

The fraction of the produced and accumulated fission fragments in the fuel material has affected the operation of the system, and need to be removed.

Radiation damage of the fuel elements with retained fissile mass requires reconstitution of the cleaned up materials.

In practical conditions, this corresponds to the burning of about 10 to 15 % of the charged initial elemental mass of the natural element (Th-232 or U-238), and to a specific thermal energy generation of 100 to 150 GWatt-day/ ton. This may correspond to some 5 to 10 years of uninterrupted operation with the loaded fuel into the reactor core. The fuel cycle is “closed” since the only material inflow is the natural element and the only “outflows” are fission fragments.

Both the above-mentioned two types of new nuclear fuel systems require reprocessing of fuel discharged from reactors. The only remaining waste consists of fission fragments separated from the spent fuel during recycling. The radioactivity of these materials is intense, but limited to some hundreds of years, except for a few long-lived ones in small quantity and may require isolated repository of manageable size.

Actinides as mixture are recovered without individual separation, and are the “seeds” for the next load, after being topped with about 10 to 15 % of fresh breeding element (Th-232 or U-238) in order to compensate for the losses of element. This makes the proliferation resistant nuclear fuel cycle as “closed”.

Proliferation Aspects in New Energy Systems

Of the two systems suggested above, the U-238/Pu-239 breeding reaction is, unfortunately, strongly proliferating, in which the Pu-239 could be chemically separated from the spent nuclear fuel and that is good enough in nuclear purity for using it in an explosive device.

This is not so for the Thorium cycle, since the three main elements of the discharge, if chemically separated, namely Uranium, Neptunium and Plutonium (Pu-238) limit the feasibility of chemical separation and use in an actual explosive device, which has critical mass (CM) of about 30 kg as against 3 kg for Pu-239. Some other physical characteristics also counter the temptation to utilize Th-232/U-233 breeding reactions for nuclear proliferation:

Heat of -decays of about 100 W in 30 kg CM is much larger than the 8 W emitted from the approximately 3 kg of weapon grade Pu-239.

Intense gamma activities due to ~ 2000 ppm of ^{232}U and its decay products make handling and transport of U-233 device virtually impossible. Dose due to Tl-208 (2.6 MeV) in CM is asymptotic after 10^3 days with intensity of about 72 Sv/h (50% lethal radiation dose after 5 minutes).

Prolific spontaneous fission neutrons strongly reduce potential yield of device because of pre-initiation of the chain reaction.

Therefore, the Th-232/U-233 fuel cycle from abundant thorium fuel reserves is considered to be inherently highly proliferation resistant.

Need for Sub-Critical Operation of Reactors

Prompt and Delayed Neutrons in A Reactor

As is well known, the operation of a critical reactor is possible only because of the presence of delayed neutrons, which provide enough time to exercise the control of effective neutron multiplication coefficient k_{eff}. These delayed neutrons, are produced by a few of the fission fragments as against the "prompt" ones that are generated due to fission reaction.

The amount of delayed neutrons, a fraction of all (including prompt ones) neutrons, for a standard LWR with U-235 as fissile fuel is, 0.0070. Over the decades of reactor operations, this much has proven to provide enough margins in controllability of hundreds of operating reactors all over the world.

For Pu-239 and other minor actinides (Np, Am and Cm), and U-233 fuel types is in the range 0.0020 to 0.0026 respectively. This reduced value of delayed neutron fraction makes control of fission reactions rate and thus, the heating in such critical reactor rather difficult, if not impossible.

Operation with New Fuels Breeding in A Reactor

For new nuclear energy systems of the future, the fuel choices would be to utilize U-238/Pu-239 or Th-232/U-233 systems. However, the nuclear characteristics of these fuel types, particularly the smaller value of delayed neutron fraction , do not allow a free run for safe and stable operation of the reactors.

With U-238 or Th-232 as fertile materials loading in a breeder type of reactor, the fuel composition progressively tends to reach a "secular" equilibrium between the many actinides composing the fuel, with rapidly decreasing amounts as a function of the rising of the atomic number.

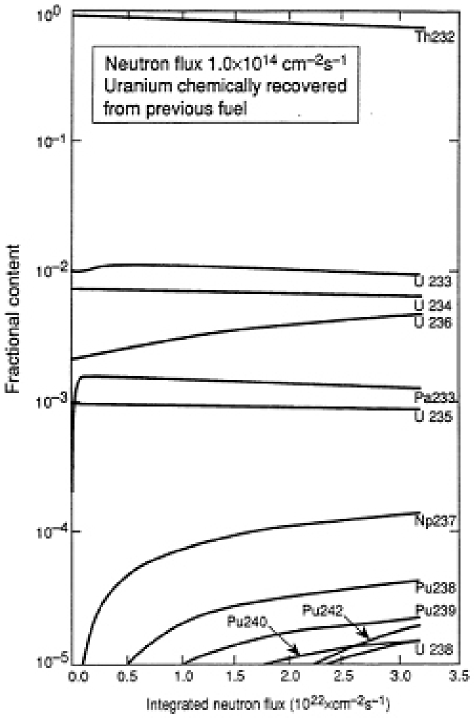

Fig. 1 Th/U breeding

The Fig. 1 [2] shows progress of breeding process in Th-232 in a thermal neutron flux of the order of $1*10^{14}$ cm^{-2}s^{-1}. Such reactor can be operated by first "seeding" with an alternative fissile material, so that gradually the new U-233 fissile isotope concentration grows faster and then stabilises at equilibrium value. Thereafter, the operation progresses with net consumption of the loaded fertile material thorium only.

However, certain constraints have been observed in fuel cycle studies of this type of fertile material utilization in critical reactors operating at equilibrium concentration of the fissile species.

Operation of U-238/Pu-239 System

For fissile/fertile fuel combination of Pu-239/U-238 in a core, their atomic ratio will settle to equilibrium concentration of Pu-239 20 % in a fast reactor. The generation of minor actinides will not be negligible and these isotopes will interfere with the reactivity swings (changes in the effective neutron multiplication factor). The operation produces both Plutonium and minor Actinides (Np, Am, Cm) which show positive void coefficient, that means the fission reactions will accelerate with the depletion/draining of the coolant from the core.

In addition to already small value of , these effects are not very conducive to ensure inherent reactor safety while using this fuel type.

At equilibrium concentration Pu-239/U-238 of about 0.285% in thermal reactor, it does not have an acceptable multiplication coefficient ($k_{inf.}$ 0.7) to sustain critical or sub-critical reactor operation. Such a self-breeding thermal reactor in this type of fuel is not practical.

Operation of Th-232/U-233 System

For Th-232/U-233 fuel the equilibrium concentration in fast reactor is 10%. This will result in a smaller multiplication coefficient compared to that in U-238/Pu-239 fuel, though it would remain very stable (at $k_{inf.}$=1.20) up to 15% mass burn-up of thorium. With the smaller value of k_{inf} in a practical fast reactor, it is difficult to maintain criticality over long burn-up periods. So operational convenience-wise, it will not be a good reactor. For lower fuel costs at higher burn up, one would need an external neutron supply and operate the reactor through the sub-critical regime and as net breeder with reduced fuel doubling time. Shorter fuel doubling time affords the capability to seed next similar ADSS for increasing the installed power generation capacity. Other advantages of using this fuel type in nuclear power generation include high power density (200MW/m^3), no significant Plutonium and MA generation, negative void coefficient and its inherent non-proliferation characteristics as explained previously.

At equilibrium concentration U-233/Th-232 of about 1.3% in thermal reactor, it does have an acceptable multiplication coefficient ($k_{inf.}$ 1.12) to just sustain critical reactor operation. Such a self-breeding U-233/Th-232 thermal reactor in this type of fuel is not practically economical, since only up to 4% of mass burn up would only be possible under the equilibrium concentration. Similar to a fast Th-U reactor, one would need an external neutron supply and operate the reactor through the sub-critical regime. This system would also operate at low power density (10 MW/m^3) and with minimum fissile inventory.

Disposal of Nuclear Fuel Waste

Most of the actinide isotopes remaining in the discharged fuel of conventional light water reactors (LWR) are highly radioactive and have very long half-life. These have been accumulating in the spent fuel over the past fifty years. Such fuel elements have to be safely contained for thousands of years to prevent any harm to the environment. No safe and publicly acceptable way of managing them is yet available. However, in a few countries, the major actinide plutonium (Pu) would be separated by reprocessing the spent fuel, and recycled as mixed oxide (MOX, $U0_2$+$Pu0_2$ mixture) fuel in same LWRs to reduce its inventory in a limited way. The similar disposal schemes for other minor actinides (MA) have not been taken up so far on industrial scale.

Application of sub-critical reactor for MA incineration is dictated by the problems similar to those associated with fuel breeding reactors. The complete incineration of the offending actinides in critical fast or thermal reactors is not practical for reasons of (i) safety concerns due to reduced delayed neutron fraction of MA (Np, Am, Cm) fuel mixtures, (ii) very low burn up possible due limited reactivity swings allowable for safety, and (iii) reduced or almost no self-corrective reactivity feedbacks (like Doppler and void coefficients) under inadvertent high power excursion events with fertile-free MA fuel due to their unfavourable nuclear properties etc. Thus, incineration of MA in known critical reactor systems lacks immediate acceptance by national safety regulators and public in general.

Sub-critical reactor system promises to provide answers to all these problems by fissioning all actinides in specially designed and constructed fast, sub-critical core operating with external neutron supply. The slight sub-criticality of properly designed reactor core still has required excess neutron supply per fission event for incinerating all MA in fast or high flux zones of thermal reactors, and promises much higher fuel burn up per fuel loading cycle than possible with a critical reactor.

When the minor actinides separated from spent fuel in a reprocessing plant are irradiated in such sub-critical reactor system, large fractions of MA are fissioned as a consequence of burn up. The residues of the fission process are fission fragments, most of which loose radiotoxicity in a few centuries. The remaining minor actinides recovered from reprocessing are topped up with fresh MA from spent fuel and re-loaded into sub-critical reactor for another cycle. It has been shown in detailed fuel cycle studies for nuclear waste transmutations [3] that one sub-critical ADS would suffice to incinerate MA produced in 4 to 5 operating 1-GWe LWRs, or those in about 20 fast reactors based on U-238/Pu-239 system.

External Neutrons from Proton Beam

To generate a copious supply of external neutrons, recourse is taken to another type of nuclear reaction than particle capture and fission. When accelerated high-energy (say at 1000 MeV kinetic energy) particle such as a protons strikes heavy target nuclei, the struck target nuclei under go nuclear upheaval called spallation, generating a large number (25-30) of high-energy neutrons per proton. These neutrons can be directed to drive the fission chain reaction in a sub-critical core. Since each fission reaction releases about 200 million electron volt energy, the overall energy produced in the system is several times higher than the input proton energy. Hence, this Accelerator-Driven Sub-critical reactor System (ADSS) is also called an energy amplifier.

Conceptually, an ADSS consists of an accelerator to generate an intense beam of protons. The end of the proton beamline accommodates one or more spallation targets of heavy metal like Lead, Tungsten, etc. Surrounding the spallation target is a reactor core consisting of sub-critical fuel mass mixed with actinide waste as in an incinerator or Thorium as in a breeder. The heat generated by the fission reactions is removed by a primary heat transfer system to a steam generator, steam from which turns the turbine to produce electricity. The reactor fission power can be controlled by changing intensity (current) of proton beam from the accelerator. Turning off the proton beam shuts down the reactor safely.

For given proton beam power on a target, the fission power is directly proportional to the beam power, resulting in the power gain G = [Fission thermal power]/[beam power]. The Gain is related to the value of the neutron multiplication coefficient k_{eff} of the reactor core by a simple expression:

$$G \qquad \frac{\qquad}{1 \quad k_{eff}};$$

2.1   2.4 for Pb - proton collision at > 0.5 GeV

Where,   is a factor based on ratio of fission energy per neutron to the primary particle energy spent per neutron in the target. This factor for proton beam energy > 500 MeV is between 2.1 to 2.4. For deterministic safety, value of neutron multiplication factor may be selected below unity by about 5 to 10 times the delayed neutron fraction of nuclear fuel.

So, for a Th/U breeder reactor at k_{eff} = 1- (5 x 0.0026) = 0.987 for   = 0.0026 for U-233; the power gain of about 160-180 will be possible. Such an energy gain is adequate to not only drive the particle accelerator, but also to feed net power to the connected grid.

ADSS Development Programme

The basic configuration of ADS sub-critical reactor (Fig. 2) as energy amplifier can be applicable either as an efficient breeder or a deterministically safe nuclear waste transmuter depending on the composition of nuclear fuel used. In both cases, it would consist of three basic sub-systems of (i) sub-critical reactor, (ii) spallation target and the (iii) driver accelerator.

The choice of sub-critical reactor type, in principle, is very flexible with regard to the basic options of fuel types and forms, and coolant/moderator selection. Its operation is much less sensitive to reactivity feedback effects of (fuel and coolant/moderator) temperature, neutron spectrum, voiding and modest degree of parasitic neutron captures etc. The optimizations of ADS reactor performance in design and construction can be implemented with much less importance given to the safety against effects of minor reactivity perturbations.

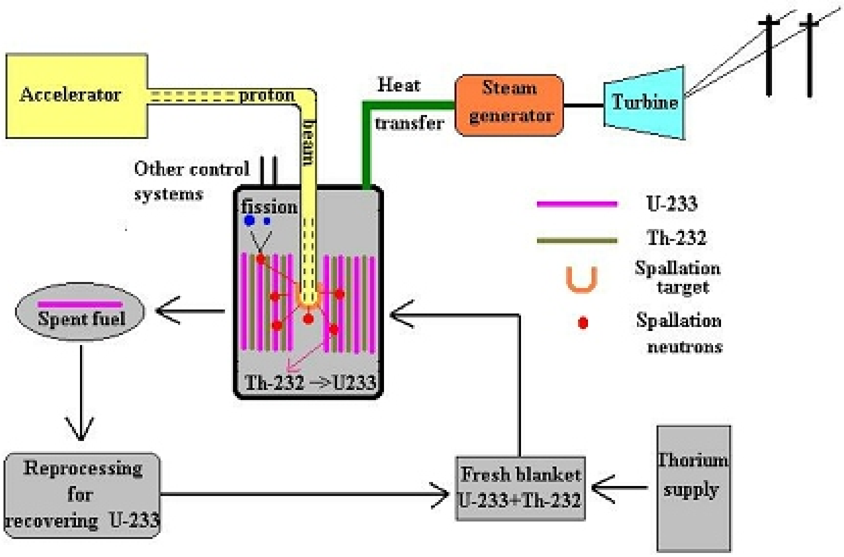

Fig. 2 Schematic of Accelerator Driven sub-critical reactor

The difficult technological aspects of realizing ADS today are the availability of 1-GeV proton beam accelerator and its corresponding spallation target. The requirement of 1-GeV proton energy is dictated by the energetic efficiency for optimum number of spallation neutrons per unit proton beam power. As shown in Fig. 3, it (upper curve) saturates in the proton energy range of 1-1.2 GeV.

The other difficult technological aspects for the spallation target include intense power density of proton beam requiring efficient heat dissipation from beam interaction zone and for maintaining an isolation barrier between ultra-high vacuum of accelerator channel and the coolant vapour environment. This barrier, called beam window, will undergo neutron and charged particle (proton) beam irradiation up to estimated ~100 displacements per atom (DPA) per year with corrosion and erosion effects. These issues need to be resolved for an industrial scale ADS plant.

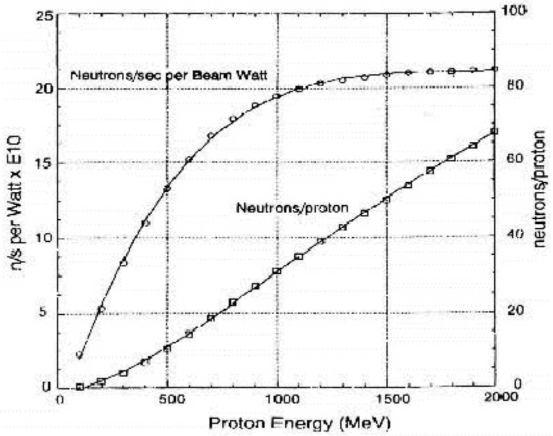

Fig. 3 Energetic cost, i.e. neutrons per sec per watt of beam, of spallation neutrons for various energy of proton beam striking lead target (upper curve).

Nevertheless, developing a realistic ADS presents technological challenges in all its three sub-systems. Therefore, development of these multi-disciplinary sub-systems of accelerator driven sub-critical reactor has been taken up in several countries in Europe and Asia. For Realizing various technological challenges that need to be adequately addressed to, a stage-wise approach has been adopted and R&D on a few identified aspects have been initiated in India. These include ongoing DAE R&D programmes on developing high beam current low energy proton linac and thermal hydraulics test loop of heavy molten metal system for spallation target at BARC, Mumbai. VECC, Kolkta has also initiated developing systems for high current cyclotron accelerator. RR CAT, Indore is expected to provide several key technological inputs to overall ADS programme in near future.

ADDS for Nuclear Power

The outstanding virtues of ADSS, as elaborated previously, lie in its ability to augment nuclear fuel resources both at the front and the back end of fuel cycles. Nevertheless, in its stand-along version as lead-cooled fast reactor sub-systems, it has been showing [4] to be competitive in economics with electricity generating conventional reactors. This is achievable due to (i) better utilization and high possible burn up of cheaper fuel like thorium, (ii) simplicity of design and high level intrinsic safety. The latter is derived from the relaxation of fast acting shutdown and safety reactor systems due to absence of prompt criticality and resulting over power accident scenario. Such theoretical studies were conducted in reference [4] for a 600 MWe ADSS power station along with a cyclotron driver accelerator.

ADSS for nuclear power will be highly desirable for countries like India and Brazil which have rich natural resources of thorium, and because of its externally fed neutron-enhanced potential, which is beneficial in faster rate of in-core breeding. Such reactor system can generate electricity with thorium as well as grow "seeds" of ^{233}U from thorium to light up a similar next power plant. In this way, actinides-free cleaner nuclear waste producing power reactors can proliferate faster than with any other reactor systems.

Summary

ADSS has created its own niche in the global nuclear power programmes with its high neutronic superiority in terms of overall neutron balance and thereby contributing to inherent safety in sub-critical reactor operation. Thorium utilization ADS reactor becomes more efficient breeder and offers extended fuel burn ups in operation with external neutron supply from accelerator beam-driven neutron source. Such reactors are also environmental friendly due to near absence of minor actinides in the spent fuel discharged.

Pu-239 breeder in fast spectrum do not require external neutrons supply due to prolific breeding potential, but such a system is not favoured due to high rate of minor actinides accumulation and tendency for nuclear proliferation. MA incineration schemes with fast neutrons require sub-critical reactor operation due to fuel characteristics, which are not conducive to inherent safety under the conditions of power excursions. The ADS-based nuclear waste incineration schemes are becoming imperative due to large inventory of spent fuel accumulated globally from LWRs operation. The support ratio of having an ADS per 4-5 LWRs have been estimated to plan with the latter for electricity generation in nuclear-waste free energy parks.

In brief, ADSS can be utilized in the transmutation of long-lived actinides and fission products from the spent fuel as well as in establishing self-sustained fuel cycle to utilize thorium reserves for nuclear power generation. Most advanced countries favour developing individual ADS sub-systems to integrate them into an incinerator for the elimination of transuranic elements and long-lived fission products in the spent fuel.

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Hydrogen Production Options– Fuel for Next Generation

***Shri I.V. Dulera**, a mechanical engineer from Regional Institute of Technology - Jamshedpur, joined the Department of Atomic Energy in the year 1987 after completing the 30th Batch of BARC Training School orientation course. Currently he is working as Scientific Officer - G in Reactor Engineering Division of BARC. Initially he was involved in development of remote tooling and systems for carrying out remote rehabilitation work on Indian Pressurised Heavy Water Reactor coolant channels. Currently he is involved in design and development work related to high temperature reactor based nuclear systems and components. He has carried out energy related studies and studies related to growth of nuclear power in India. This includes studies related to non - electricity applications of nuclear power. Currently he is involved in carrying out design and development work related to a High Temperature Nuclear Reactor, which is being designed with an objective to produce hydrogen by splitting water.*

***Shri C.S.R. Prasad** is the Head of Materials Development Section, Chemical Technology Division, BARC. He completed B. Tech. and M. Tech in Chemical Engineering in 1971 and 1980 respectively from Andhra University, Visakhapatnam. He joined Chemical Engineering Division, B.A.R.C., through 17th batch of Training School in 1974. He has been involved in indigenous development of front-end process technologies of nuclear cycle including Fluorine Technology. He has implemented the results of this R&D work to establish large scale production plant, taking care of Project Engineering and Plant Management aspects. His current research interests include design and development of Nuclear based Thermochemical Processes for production of hydrogen from water.*

Introduction

It is well known that the share of transport sector in the total energy consumption in India is significant. This sector is mainly dependent on petroleum-based products. Since Indian reserves of crude oil are rather meager, almost 70% of the crude oil consumed in the country is imported. Due to depleting world reserves of petroleum-based products and the increasing trend of their prices it has become inevitable that India find an alternative energy provider for transport applications. Natural gas is an attractive alternative, but Indian reserves of natural gas are not significant. Over the years hydrogen has emerged as an attractive energy carrier for transport applications. In addition, this could also be utilized for power generation. Thus it is envisaged to form an important component of future energy mix in India. Hydrogen is available in abundance, but is not an energy source like oil, coal, wind, or sun. It is an energy carrier like electricity - a way of transporting useful energy to consumers. It is an especially versatile carrier because like oil and gas, it can be stored in large amounts and can be made from almost any energy source and used to provide almost any energy service and can be either burnt like petrol or easily converted to electricity. The reason hydrogen is not an energy source is that it is not available in nature; the way oil, natural gas and coal are found. It must first be freed from chemical compounds in which it is bound up. Therefore hydrogen production options basically deal with separating hydrogen from fossil fuel, biomass or water. Abundance of hydrogen containing compound, complexities involved and the energy

Shri I.V. Dulera, Reactor Engineering Division and Shri C.S.R. Prasad, Chemical Technology Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085; E-mail: dulera@barc.gov.in & dcrpras@barc.gov.in

required in separation of hydrogen are the key features deciding selection of hydrogen production option. There are broadly three ways to separate hydrogen: using heat and catalysts by reforming hydrocarbons or carbohydrates found in biomass, using electricity with or without heat to split water, or experimental processes, based on sunlight, plasma discharge, or microorganisms. Due to long term sustainability of nuclear and solar energy, they have attracted lot of attention worldwide, for providing required energy for hydrogen separation. They have the potential to sustain long term hydrogen based economy in future. A hydrogen economy is a hypothetical future economy in which the primary form of stored energy for mobile applications and load balancing is hydrogen. In particular it is discussed as a method for replacing the petroleum based hydrocarbon fuels currently used in automobiles. While the hydrogen economy represents a visionary strategy for our future energy security, significant scientific and technical challenges must be overcome to achieve its implementation. The hydrogen economy spans three functional areas: production, storage, and use; each area has its special set of technical challenges. Recent advances in materials science, chemistry, physics, biology, computation, and nanoscience provide considerable promise for breaking through many of these current barriers.

Hydrogen as a Source of Energy

Hydrogen being gaseous can be compared to natural gas as a source of energy. Molecular hydrogen H_2 (two hydrogen atoms) is eight times lighter than natural gas. One kg of hydrogen has about the same energy as about three kg of oil or natural gas [1]. But this advantage is somewhat nullified by lightness of hydrogen resulting in less energy content per unit volume of the gas. This implies requirement of a higher onboard storage capacity. Hydrogen as energy carrier can be either used directly in internal combustion engines or can be used in fuel cells to produce electricity to run hybrid (vehicles which use electricity as well as petrol) or purely electrical vehicles. Fuel cells are not subject to the same thermodynamic limits as fuel-driven engines, because they are not heat engines but electrochemical devices. A hydrogen fuel-cell based car can therefore convert hydrogen energy into motion about 2–3 times as efficiently as a normal car converts oil energy into motion. A good fuel-cell system, based on hydrogen to electricity conversion, is more than 70% efficient, while a typical efficiency of a car engine from oil to output shaft averages only about 15–17%. Both systems then incur further minor losses to drive the wheels. Advantage of hydrogen utilization in cars is especially large because cars run mainly at low loads and in such conditions fuel cells are most efficient where as engines are least efficient. Table 1 compares hydrogen with other fuel resources. The other advantage with hydrogen is that on burning it yields only water. This reduces pollution and protects environment.

Hydrogen Production Technologies

As we know, hydrogen is not found in elemental form. The richest source of hydrogen is water. The other major sources include fossil fuels like petroleum, natural gas, coal, and biomass. Hydrogen is a secondary energy source, since a primary energy source is required to separate it. Hydrogen production technologies in commercial use today are catalytic steam reforming of natural gas, naphtha, and other hydrocarbons; partial oxidation of hydrocarbons; gasification of coal; and electrolysis of water. Newer methods based on biological, photo biological, photochemical, and electrochemical processes are also being developed in laboratories at present. Hydrogen is currently being utilised in India as well as in the world on large scale in fertilizer and petroleum refining industries. It is produced mainly based on steam reforming of naphtha and natural gas. Hydrogen is also produced as a by-product in many chemical industries. Several other methods of hydrogen production such as biomass gasification or pyrolysis, dissociation of methanol or ammonia, thermo-chemical and electrochemical splitting of water, biological photosynthesis, or fermentation etc. are at different stages of development.

Depending upon requirement of hydrogen at a particular location, all these processes can be further classified as production methods for distributed applications where hydrogen is produced at the point of distribution or large size centralized plants with a distribution network up to the point of dispensing. Electrolysis, renewable energy, biomass and

TABLE 1. Comparison of heating values of fuels

Fuels	Lower Heating Value (LHV)		Higher Heating Value (LHV)		Density
Gaseous Fuels	Btu/scf	MJ/kg	Btu/scf	MJ/kg	grams/scf
Gaseous Hydrogen	289	121	331	139	2.51
Natural Gas	983	47.1	1,089	52.2	22.0
Liquid Fuels	Btu/gal	MJ/kg	Btu/gal	MJ/kg	grams/gal
Crude Oil	129,670	42.7	138,350	45.5	3,205
Conventional Gasoline (Petrol)	116,090	43.4	124,340	46.5	2,819
Low-sulfur Diesel	129,488	42.6	138,490	45.6	3,206
Methanol	57,250	20.1	65,200	22.9	3,006
Ethanol	76,330	27.0	84,530	29.8	2,988
Residual Oil	140,353	39.5	150,110	42.2	3,752
Liquefied Petroleum Gas (LPG)	84,950	46.6	91,410	50.2	1,923
Liquefied Natural Gas (LNG)	74,720	48.6	84,820	55.2	1,621
Propane	84,250	46.3	91,420	50.2	1,920
Solid Fuels	Btu/ton	MJ/kg	Btu/ton	MJ/kg	
Bituminous Coal	22,460,600	26.1	23,445,900	27.3	
Coking Coal	24,600,497	28.6	25,679,670	29.9	
Woody Biomass (dry)	16,811,000	19.6	17,703,170	20.6	

Notes: a) The lower heating value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered.

b) The higher heating value (also known gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products.

c) Btu: British thermal units; scf: Standard cubic feet.

biological routes based technologies are expected to play a significant role in the production of low cost and carbon free hydrogen for distributed applications. Coal gasification, and nuclear energy based water splitting on the other hand can play a significant role in centralized hydrogen production. At any given time, depending upon the status of R & D of a particular process, several commercial methods for hydrogen production need to work together so as not to overburden a particular resource.

Steam Methane Reforming

Steam methane (CH_4) reforming is at present the most common and least expensive method of producing hydrogen. Steam methane reforming involves four basic steps (Fig. 1). Natural gas is first catalytically treated with hydrogen to remove sulfur compounds. It is then reformed by mixing it with steam and passing it over a nickel-on-alumina catalyst, making carbon-monoxide (CO) and hydrogen. This step is followed by catalytic water-gas shift to convert it to hydrogen and

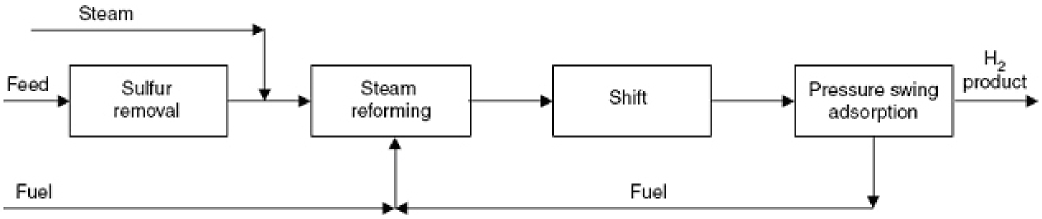

Fig. 1 Steps in steam reforming of natural gas to produce hydrogen

carbon-dioxide (CO_2). Finally, the hydrogen gas is purified with pressure swing adsorption (PSA). The reject stream from PSA forms a portion of the fuel that is burnt in the reformer to supply the needed heat energy. Therefore, CO_2 contained in the PSA reject gas is currently vented with the flue gas. If the CO_2 were to be sequestered, a separations process would be added to capture it. Most of the modern plants use multi-bed pressure swing adsorption (PSA) to remove water, methane, CO_2, nitrogen (N_2), and CO from the shift reactor to produce a high purity product (>99.99%). The reforming reactions can be written as:

$CH_4 + H_2O \quad CO + 3H_2$ - 206 kJ/mol

$CO + H_2O \quad CO_2 + H_2$ (water-gas-shift reaction) +41 kJ/mol

Overall reaction is:

$CH_4 + 2H_2O \quad CO_2 + 4H_2$ – 165 kJ/mol

The reforming reaction is endothermic and requires external heat input. The reaction of natural gas with steam to form CO and H_2 requires about 206 kJ/mol of methane. In practice, gas mixtures containing CO as well as CO_2 and unconverted CH_4 are produced and require further processing. Typically the feedstock is pre-treated to remove sulfur (Figure-1). Alternatively, CO_2 could be removed by chemical absorption followed by methanation to convert residual CO_2. This is a commercially proven, cost effective technology, contributing to about 40-50% of total hydrogen production capacity worldwide. Small and medium scale SMR units (capacity ranging from 50 to 24,000 kg perday) are commercially available for distributed production of hydrogen. Centralized plant capacities are typically 1 million kg per day. The price of natural gas or other feedstock significantly affects the final price of hydrogen produced by this method. As regards energy requirement, the process uses high temperature of 750-800ºC and nickel catalyst to carry out endothermic reforming reaction and medium temperature of 330ºC for exothermic shift reaction. Most common method of providing the required heat is via burning hydrocarbons, which increases CO_2 emissions. Energy requirement is typically 2-2.5 kWh/Nm^3 of Hydrogen and efficiency range is 70-80% [1]. Steam Methane reforming process is used as benchmark for all hydrogen processes for comparing cost and energy requirement.

In India for deployment of small-scale steam methane reformers (SMR) for Compressed Natural Gas (CNG) + H_2 Internal Combustion (IC)-engine trials, Indian Oil Company (IOC) has a reformer pilot plant (for both naphtha and natural gas reforming) of 1 Nm^3/hr capacity. One SMR of 50 Nm^3/hr (35 tonne/year) along with compressor and storage has been procured by IOC. This along with an electrolyser of same capacity has been installed at Indraprastha Gas Limited (IGL) CNG gas station for demonstration of the project on use of 10-30 % H_2-CNG Mixture in vehicles. With the assistance of Department of Science & Technology development work has been initiated for developing skid-mounted reformer for producing hydrogen from methanol. Large number of reformers utilizing various feedstocks can be deployed to produce hydrogen in larger quantity. A phased growth of reformers based on different feedstock could be planned in the country.

Electrolysis of water

Electrolysis is the decomposition of water into hydrogen and oxygen. Electrolysis currently

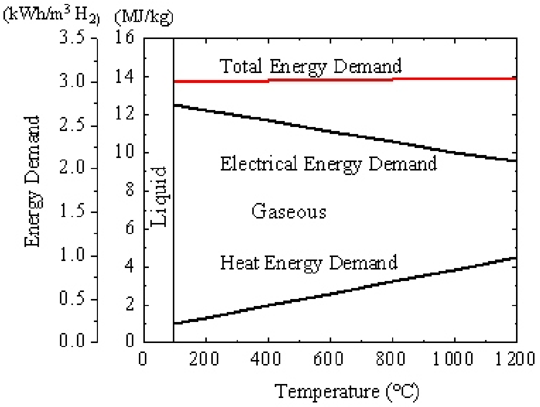

Fig. 2 Electric power needed for electrolysis at different temperatures

comprises about 4% of world's hydrogen production and is used mainly in areas with very cheap electricity, such as those rich in hydro or geothermal resources or in special applications requiring high purity hydrogen such as semiconductor manufacturing. Equation for electrolytic decomposition of water into hydrogen and oxygen can be written as

$$H_2O \quad H_2 + \frac{1}{2} O_2 - 242 \text{ kJ/mol.}$$

This reaction requires electrical energy. Different electrolysis methods exist depending upon the type of electrolytes used. Typical cell voltages are 1.85V-2.05V. The effective electricity consumption, depending on the nature of electrolyte, is approximately 3 - 4.5 kWh/Nm^3 at standard conditions. Cell efficiencies for different electrolytes vary between 70-90 %. Overall energy efficiency depends on both cell efficiency as well as electricity generation efficiency. Water required is of the order of 1 litre/Nm^3 of hydrogen produced. The major factor in the electrolysis route of hydrogen production is the cost of electricity, which is about three to five times more as compared to the cost of fossil fuel feed stock. In view of the high cost of electrolysis, new techniques such as high temperature steam electrolysis are being developed, where about 30% of the energy required could be supplied as heat. Higher temperature (900-1000 C) electrolysis of steam reduces the electrical energy need by 30%. Utilisation of high pressure also results in less consumption of electrical energy. Electric power needed for electrolysis at different temperatures is shown in Fig. 2. The developmental activities include development of electrolysis process, process parameters, and materials for electrolyte, electrodes, catalysts and other cell materials. Following electrolysis based processes are popular and are either being extensively used or are in advanced stage of development:

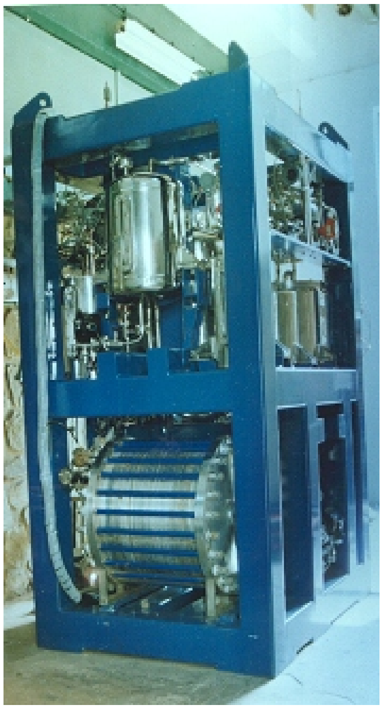

Fig. 3 Compact alkaline electrolyser developed in BARC

(a) Alkaline water electrolysis to demonstrate hydrogen generation at lower temperatures (70 C). NaOH, KOH or NaCl are used as electrolytes. The key factors favouring the alkaline electrolyser are that it eliminates the need for expensive platinum-based catalysts, it is well proven at large scale, and it is usually of lower unit cost than other electrolysers. Compact alkaline electrolyser developed in BARC is shown in Fig. 3

(b) Solid Polymer Electrolyte Water Electrolysis (SPEWE) is used at intermediate temperatures around 120 C. It can operate at high current densities and has compact cell. SPE membranes are commercially used in chlor-alkali industries as well as in electrolysers and fuel cells. Proton exchange membrane contains a proton conducting membrane as the electrolyte material. The membrane material commonly used is called Nafion. It is a fully fluorinated sulphonic acid polymer which is proton conducting. These membranes exhibit exceptionally high chemical stability both in strong oxidising and reducing conditions up to 125 C. SPE electrolyser's function very well with renewable energy systems where the amount of electricity varies greatly. Generally speaking, PEM electrolysers are best suited for small plants, especially plants with varying output, while alkaline electrolysers are advantageous in larger systems, which are connected to the power grid. Much of the technological development, which is currently going on in PEM fuel cells, can be transferred to this type of electrolyser.

(c) High temperature (800-1000 C) steam electrolysis (HTSE): High temperature electrolysis splits steam at a temperature of above 800ºC so that hydrogen and oxygen are produced at the two electrodes. This process uses calcium and yttrium stabilised zirconium oxide membranes. Operation of the cell at high temperatures reduces the amount of electricity needed to produce a kilogram of hydrogen, since about 30% of the energy can be provided as heat rather than as electricity. In addition, at 800-1000ºC there is much lower resistance to the movement of the oxygen ions through the yttria- or scandia-stabilised zirconia electrolyte and all the chemical reactions proceed very rapidly. A high-temperature heat exchanger supplies high-pressure steam superheated to about 550 – 850 °C. In HTSE, steam is introduced at the cathode where hydrogen is released and oxygen ion passes through a conducting ceramic membrane (YSZ) and oxygen gas is liberated at anode. The input steam to the electrolyser is about 50:50 steam and hydrogen. The output from the electrolyser is typically 75% hydrogen and 25% steam by volume. The hydrogen is separated from the steam in a condensing unit. Additional steam is added after removal of about 1/3 of hydrogen to produce a 50:50 gas/ steam for reintroduction to the electrolyser. Electricity consumed is about 2.6 - 3.5 kWh/Nm^3 [1] of hydrogen produced. Nuclear reactor operating in the same temperature range is ideally suited for this purpose. Since the reactor is operating at high temperatures, the efficiency of electricity production is much higher (above 45%). The combination of these effects could result in an overall efficiency of hydrogen production of about 40-45%. Steam and a small amount of hydrogen (to maintain reducing conditions at the nickel-zirconia cathode) are introduced at one edge of the planar cell. Steam diffuses to the interface between the electrode and the electrolyte, where the first reaction takes place.

$$2\,H_2O + 4\,e^- \quad 2\,H_2 + 2\,O_2\text{-}$$

The oxygen ions carry the electrical current through the solid electrolyte to the electrolyte–anode interface, where the second reaction occurs.

$$2\,O_2\text{-} \quad O_2 + 4\,e^-$$

The interconnect plate provides flow channels for the incoming and outgoing steam and hydrogen mixture as well as for the oxygen produced at the anode. The interconnect plate also provides the electrical connection from one cell to the next. Oxygen flows across the lanthanum strontium manganite (LSM) electrode (anode) and the steam/hydrogen mixture flows along the nickel-zirconia cathode on the opposite side of the electrolyte. An experimental stack of ten cells produced more than 60 normal litres of hydrogen gas per hour during extensive tests. Research at the Idaho National Laboratory (INL), in collaboration with Ceramatec, is simultaneously addressing the technical and scale-up issues associated with solid-oxide electrolysis of steam. The research includes an experimental programme aimed at performance characterisation of electrolysis cells and stacks. Results of single-cell tests have demonstrated efficient small-scale hydrogen production, with performance close to theoretical predictions. Based on these preliminary results, high-temperature electrolysis appears to be a viable means for hydrogen production using nuclear energy.

There are many agencies involved in the development of electrolysis-based processes. BARC has developed a few high current density water electrolysers based on indigenously developed advanced electrolytic modules incorporating porous nickel electrodes. This includes a portable electrolyser (1.5 Nm^3/hr capacity), a pilot plant (30 Nm^3/hr capacity) with a 2.5 ton electrolytic module operated at 100 C and 21 Kg/cm^2 and a compact electrolyser (10 Nm^3/hr of hydrogen) with a 1 ton module operated at a current density of 4500 Amperes per m^2 at 55 C. CECRI, Karaikudi has developed a laboratory-scale PEM electrolyser. SPIC, Tuticorin also has developed a PEM water electrolyser of 0.5 NM^3/hr capacity. IOC has imported a 5 NM^3/hr capacity electrolyser and is also procuring another electrolyser of 50 Nm^3/hr capacity along with compressor and storage unit. These will be utilized for demonstration project on 10-30 % H_2-CNG Mixture in vehicles. BARC has a programme to develop PEM electrolyser. BARC also has drafted plans for high temperature steam electrolysers. Electrolysis is best suited for decentralized or distributed hydrogen generation. In the long run electrolysers can use electricity produced from renewable energy sources and also from off peak hour electricity produced by nuclear energy.

Hydrogen as by-product from Industries

Substantial quantities of hydrogen as by product or excess hydrogen which is currently being flared in many chemical industries can be used to meet immediate hydrogen requirement. Chlor-alkali industries and Fertilizer industries are prospective candidates for this category. It is estimated that about 15000 Tonnes of excess hydrogen is available per year from various caustic soda plants in India.

Partial Oxidation of Heavy Hydrocarbons

Partial oxidation of hydrocarbons is another method of hydrogen production. In this process a hydrocarbon fuel reacts with a limited supply of oxygen to produce a hydrogen mixture, which is then purified. Partial oxidation can be applied to a wide range of hydrocarbons including natural gas, heavy oils, solid biomass, and coal. Its primary by-product is carbon dioxide. A hydrogen plant based on partial oxidation includes a partial oxidation reactor, followed by a shift reactor and hydrogen purification equipment. Large-scale partial oxidation systems have been used commercially to produce hydrogen from hydrocarbons such as residual oil, for applications for refineries among other end uses. Large systems generally incorporate an oxygen plant, because operation with pure oxygen, rather than air, reduces the size and cost of the reactors.

Gasification or Partial Oxidation of Coal

Due to large coal reserves in India, this route is a particularly attractive for our country. The key to the efficient and clean manufacture of hydrogen from coal is to use gasification technology, which is a clean coal technology, as opposed to the combustion process used in conventional coal-fired power plants. Coal is initially ground to a fine powder and then mixed with water to create a 50 - 70% solid content suspension, suitable for pumping. Gasification systems typically involve partial oxidation of the coal with oxygen and steam in a high-temperature and elevated-pressure process. This creates a synthesis gas, which is a mixture of mainly CO and H_2 with some steam and CO_2. This synthesis gas (syngas) can be further reacted with water to increase H_2 yield. The gas can be cleaned in conventional ways to recover hydrogen and a high-concentration CO_2 stream that is isolated and sent for disposal. Worldwide gasification of coal is a well-established technology. A typical flow sheet

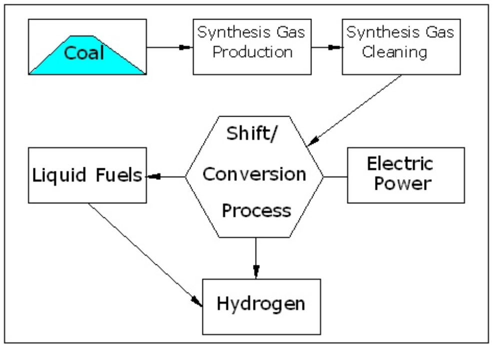

Fig. 4 A typical flow sheet of a coal gasification based hydrogen production system

for such a coal gasification based system is shown in Fig. 4. Gasification can be used to produce syngas from residual oil also. More recently, it has been used to process petroleum coke. These feedstocks also contain variable amounts of water, sulfur, nitrogen, and non-volatile substances that substantially complicate process engineering. When gasifying liquids, it is necessary to remove and recover soot, ash, and any metals that are present in the feed. Feed preparation and handling steps beyond the basic gasification process are needed for coal, petroleum coke and other solids such as biomass.

In India Bharat Heavy Electricals Limited (BHEL) has experience in this field. Integrated Gasification Combined Cycle (IGCC) for Indian coals is under development by many agencies such as National Thermal Power Corporation (NTPC), BHEL, and IOC. NTPC and BHEL have plans to set-up Pressurized Fluidized Bed Gasifier (PFBG) based demonstration plants to produce 95% pure hydrogen at the rate of 7 kg/ hr and 35 kg/hr respectively. Based on the technology developed, commercial scale plants can be set-up in future. Considering large coal reserves in the country, this option ensures supplies of large quantity of hydrogen during the intermediate period. Coal located deep within the earth which cannot be easily mined can be used for Under Ground Coal Gasification (UGCG). Oil and Natural Gas Commission (ONGC), Gas Authority of India Limited (GAIL) and NTPC have initiated work related to UGCG for producing hydrogen or synthetic fluid fuel. In addition to these, IOC also has plans for biomass and residue gasification.

Production from Biomass

In India biomass resources for hydrogen production are - fuel wood, dung, agricultural residues, agro industrial residues, sewage sludge, industrial organic waste etc. The different methods for hydrogen production from biomass are: gasification or pyrolysis of solid biomass, fermentation of liquid manure and biological hydrogen production. In biomass gasification biomass is heated to produce a synthesis gas consisting mostly of hydrogen, carbon monoxide, carbon dioxide and water vapour. The gas is cleaned and steam is introduced to cause the water gas shift reaction. Pressure swing absorption separates hydrogen from the carbon dioxide. This process is similar to coal gasification in many ways. The feedstock is relatively inexpensive. In the pyrolysis method biomass is thermally decomposed at a high temperatures (450-550^o C) in an inert atmosphere to form a bio - oil composed of about 85 % oxygenated organics and 15 % water. The bio-oil is then steam reformed using conventional technology to produce hydrogen.

There are various biological processes by which hydrogen is released or appears as an intermediate product. These processes can be mainly identified as of two types: Photosynthesis (using algae and photosynthetic bacteria) and fermentation (anaerobic decomposition of organic matter). These processes are at different stages of research and demonstration. Fermentative process is presently considered better due to higher hydrogen yield. Being an agricultural country and having variety of climate, India has wide range of biomass available. Therefore, production of hydrogen from biomass holds considerable promise in our country especially to satisfy energy related needs of rural areas. The main advantage of direct hydrogen production from biomass is that renewable energy sources can be utilized without the need of use of electricity, thus leading to higher system efficiency.

Hydrogen production from industrial effluents is another route, which is attractive since it saves environment from the ill effects of these effluents. Hydrogen production from organic industrial waste from distilleries etc. by employing photochemical, electrochemical or biological process can be easily adopted for distributed applications. Continuation of R&D, setting up of pilot scale demonstration plants and setting large-scale production plants can augment hydrogen supplies. In India Murugappan Chettiar Research Centre has operated 125m^3 batch bioreactor using distillery waste to produce hydrogen at the rate of 11,700 litres/hour along with other gases as impurities. The output gas mixture contains 60 %H_2 + 25% CO_2 + other gases.

CSIR (Council for Scientific Research in India) carried out R&D studies on production of hydrogen (upto 100 liter/day) from bioorganic wastes. Pilot plant studies are planned by 2008 with a target to demonstrate continuous production of 100 litres/hour hydrogen. Banaras Hindu University (BHU) has carried out R&D studies for producing hydrogen (36 liter/hour) by photolytic driven process (2 kW Photovoltaic panel) and also photo electro-chemical process for achieving a production-rate of 37 liters/hr m^2. With Department of Science and Technology (DST) assistance work is being done for hydrogen production from bagasse and other biomass material through microbial route. IOC has a Biotics group involved in the area of bioremediation of sludge etc. There are many laboratories in the country working for production of hydrogen from biomass. There is a need to develop the technologies further and also to establish a proper platform for exchanging views to expedite the R & D work to permit these processes to play a significant role for long-term application.

Low Temperature Water Splitting

Photo-catalytic processes involve semiconducting powders spread on water containing solutions, which produce hydrogen on exposure to sunlight. In this case hydrogen and oxygen are produced together and special oxygen suppression agents have to be developed to ensure that only hydrogen is produced. These techniques are still in the early stages of development.

Photo-electrochemical electrolysis processes involving wet photovoltaic systems produce hydrogen through splitting of water in one step. Semiconductors that enable photo electro chemical splitting of water need to become more efficient and less susceptible to corrosion in water.

Hydrogen can also be produced from water using alkali metal sodium. During the reaction, sodium is transformed to sodium hydroxide. However, the reaction is not reversible and sodium can be recovered from sodium hydroxide using solar furnace. Such processes for hydrogen production have not been tried yet. They hold promise for future as viable processes for hydrogen production.

High Temperature Thermo Chemical Splitting of Water

Direct thermolysis of water requires a temperature of >2500 C. In thermo-chemical processes the water splitting process is subdivided into different partial reactions, each running at a lower temperature level. A thermo-chemical process is a sequence of thermally driven chemical reactions in which water and heat are the inputs, and hydrogen and oxygen are the outputs. The chemicals and reagents are recycled in a closed cycle. In the case of a hybrid thermo-chemical process, a combination of heat and electricity is used for splitting water. Overall energy efficiency of 40-57% is reported by investigating laboratories [2]. For long-term hydrogen supplies and large-scale centralized hydrogen production, thermo-chemical splitting of water by getting heat from an external source such as high temperature nuclear reactor or solar concentrators, seems to be the most promising route. Large-scale hydrogen production by this process offers quite attractive concept for future CO_2 - free and efficient energy systems. This process for splitting of water is carried out through multi step chemical reactions at high temperatures in the range of 550-850°C depending on the chemical process adopted. A large number (>100) of thermo chemical cycles have been studied worldwide [2]. Processes like Iodine-Sulfur (I-S), Hybrid-Sulfur, Calcium - Bromine (Ca-Br) and Copper- Chlorine (Cu-Cl) are mainly being pursued for further development. These processes are also being studied from the view of integration with nuclear reactors. High temperature nuclear reactors are well suited for supplying heat to endothermic process steps involved in these processes. BARC is involved in developing technologies related to high temperature reactors. Typically a 600 MWth high temperature reactor would be able to produce 80000 Nm^3/hr of hydrogen besides generating electricity and producing potable water from saline water. BARC has drafted plans for R & D for thermo-chemical processes for water splitting. Besides R & D challenges for high temperature reactor and thermo-chemical processes, a major challenge would be related to integration aspects of nuclear reactor with hydrogen production plant. A few potential thermo chemical processes have been described in the following paragraphs.

Iodine-Sulfur (I-S) Process:

This is a three-step process involving formation and decomposition of hydriodic acid (HI) and sulfuric acid (H_2SO_4). The thermo-chemical reactions of I-S process are given below;

$H_2SO_4 \quad SO_2 + H_2O + 1/2\ O_2$ (850°C)

$I_2 + SO_2 + 2H_2O \quad 2HI + H_2SO_4$ (120°C)

$2HI \quad I_2 + H_2$ (450°C)

If we compare the overall reactions, the net reaction is;

$H_2O \quad H_2 + 1/2\ O_2$

This process is an all-fluid process and has been well studied and fully flow sheeted in laboratories in USA, France and Japan. Laboratory-scale test loops at low pressure have been successfully demonstrated. A laboratory-scale I-S cycle test loop at prototypical pressure and temperature conditions is now under construction by General Atomics, USA; Sandia National Laboratory and Commissariat à l'Energie Atomique (CEA), France. The I-S cycle does require high temperatures, but offers high efficiency conversion of heat energy to hydrogen. Thus economics of scale are favourable for large-scale production of hydrogen from nuclear power. Detailed technical analyses indicate that the I-S cycle coupled to a high temperature reactor could produce hydrogen at a cost not much more than the current cost of hydrogen produced from natural gas, and with no emissions of CO_2. This process has the highest quoted efficiency (57%). This cycle generates hydrogen at high pressure (50 atmospheres) eliminating the necessity of compressing the hydrogen for pipeline transmission or storage. The primary technical issues related to this process include high temperature and corrosion resistant materials development; development of separation and purification technologies; development of membrane reactors; and development of catalysts.

Hybrid-Sulfur Process

Hybrid-Sulfur (HyS) developed by Westinghouse electric in USA is being pursued by Research centre, Jülich; Germany and Savannah Research National Laboratory (SRNL), USA. This is an all fluids, two-step hybrid process in which chemistry involves only S-O-H species. This has been demonstrated in a closed-loop 120 lph bench-scale demonstration facility.

$H_2SO_4 \leftrightarrow H_2O + SO_2 + ½O_2$
(thermochemical; 800-900 °C) (1)

$SO_2 + 2\ H_2O \rightarrow H_2SO_4 + H_2$
(electrochemical; 80-120 °C) (2)

Net Reaction: $H_2O \rightarrow H_2 + ½O_2$ (3)

The presence of SO_2 at the anode of the electrolyser greatly decreases the reversible cell potential needed to split water molecules by electrolysis. Whereas direct electrolysis of water has a reversible cell potential of 1.23V at 25°C, the theoretical potential for SO_2 anode-depolarised electrolysis is only 0.17V per cell. Practical SO_2 electrolysers are expected to operate with only 25% of the electricity needs of conventional water electrolysers. When combined with the endothermic decomposition of H_2SO_4, the net thermal energy requirement for the HyS cycle is much less than that for direct water electrolysis. The overall net thermal efficiency for the plant in SRNL was calculated as around 49% based on thermal input to the process at 900°C. Higher thermal efficiencies, exceeding 50%, seem feasible based on further optimised process flow sheets and the use of higher process operating temperatures. The primary technical issues to be addressed for the HyS cycle include optimisation of system operating conditions (temperature, pressure, acid concentration), selection of electrolyser materials of construction, cell design (including membrane selection and electrocatalyst loadings), and overall durability and performance. Other technical issues are associated with the sulfuric acid decomposition section of the process and the SO_2/O_2 separation system.

Calcium-Bromine (Ca-Br) Process

This is a four-step process. The chemical reactions taking place are shown below;

$2Br_2\ (g) + 2CaO(s) \quad 2CaBr_2\ (s) + ½\ O_2\ (g)$ (672°C)

$3FeBr_2\ (s) + 4H_2O(g) \quad Fe_3O_4\ (s) + 6HBr(g) + H_2\ (g)$ (560°C)

$CaBr_2\ (s) + H_2O(g) \quad CaO(s) + 2HBr(g)$ (760°C)

Fe_3O_4 (s) + 8HBr(g) Br_2 (g) + $3FeBr_2$ (s)
+ $4H_2O$(g)   (210°C)

The four chemical reactions take place in four adiabatic fixed packed bed chemical reactors that contain the solid reactants and products. The chemical reactors operate in pairs, one pair contains the calcium compounds and the other pair the iron compounds. The nuclear reactor transfers heat through a secondary heat exchanger into the gas stream, which traverses through the four chemical reactors. The chemistry of the cycle has been studied extensively. The basic thermodynamics are well documented. The overall cycle has been demonstrated first at the bench scale and finally in a pilot plant. Although this cycle is based on solids, the solid materials remain in fixed beds and only gases are transported. The cycle has been fully flow-sheeted. The reported efficiency for this process is about 40%. This process is being pursued by General Atomics and Argonne National Laboratory, USA.

Copper – Chlorine (Cu-Cl) Process

This process is attractive since it requires process heat at a relatively lower temperature (550 C). This process and other potential processes that operate at lower temperatures have two major advantages related to lower demands on materials and greater flexibility in heat sources. Nuclear reactors suitable for coupling with these processes include advanced supercritical water reactors and sodium-cooled fast reactors. The highest temperature heat for a high temperature reactor then could be used in a cycle to provide electricity, and rejected heat could be efficiently utilised for hydrogen production. Argonne National Laboratory, USA and Atomic Energy of Canada Limited (AECL), Canada are studying this thermo chemical process.

2CuCl (l) + H_2 (g)   2Cu + 2HCl   (430-475°C)

4CuCl (aq) $2CuCl_2$ (aq)+2Cu (s)   30-70°C (electrolysis)

$2CuCl_2$ (s) $2CuCl_2$ (aq)   100°C

$2CuCl_2$ (s) + H_2O(g)   CuO*$CuCl_2$ (s)
+ 2HCl (g)   400°C

2CuCl (l) + ½ O_2 CuO*$CuCl_2$ (s)   530°C

The Cu-Cl cycle consists of five major reactions. Hydrogen is generated at 475°C and oxygen at 530°C. These are the highest temperatures in the cycle. Moreover, these reactions involve the generation of the gas and either a solid or liquid. They can therefore be driven to completion by simple release of the gas, thus minimising recycle flows. There are no competing reactions and, as a result, they are ideal for a cyclic process. The combination of the relatively inexpensive chemicals and a high idealised efficiency of 49% (HHV) is attractive. While this efficiency is somewhat lower than that of the sulfur cycles, the promising chemistry makes the Cu-Cl cycle important.

Conclusions

At present hydrogen is being produced from hydrocarbons, mostly in centralized production plants. A limited network exists to supply this hydrogen in pressurized vessels for a variety of applications. The major producers consume hydrogen within their own production units (e.g. oil refineries, fertilizer plants, large chemical industries). On site hydrogen production based on hydrocarbons or other methods are still in early stages of development. The hydrocarbon based hydrogen production technologies are not environment friendly as they emit CO_2. Coal based hydrogen production is potentially attractive for India, although it is not carbon-free. This technological option is being vigorously pursued internationally and also by Indian industries for centralized production of hydrogen. Different coal gasifiers (moving bed, fluidized bed or entrained bed) can be employed for specific applications. In Indian context, gasifiers suited to high ash content Indian coal needs development. Technologies related to Integrated Gasification Combined Cycle (IGCC) and Under-Ground Coal Gasification (UGCG) for Indian coals are under development. Gas clean up technology to achieve desired hydrogen purity, CO_2 separation and capture, maximizing conversion efficiency, quality of coal are some of the key issues for this technology. This option ensures long-term energy security, if environmental pollution and global warming aspects are also suitably addressed. Both natural gas reforming and coal gasification processes produce CO_2. Their value in meeting the fundamental goals of a hydrogen economy depends on developing safe, effective, and economical methods for CO_2 sequestration. Deep ocean injection, injection into depleted oil/gas wells and saline reservoirs, and injection into hydrocarbon deposits to enhance oil recovery or production of coal-bed methane, are potential sequestration technologies. Most of the hydrogen production techniques from non-fossil fuels such as biomass gasification or pyrolysis, biological, photo catalytic, thermo-chemical methods using nuclear and solar energy etc. are in the early stages of development. Applications that require hydrogen, as an energy carrier may not be attractive unless the cost of energy from hydrogen is comparable to the present day fossil fuel based energy systems. These technologies need to be developed further and demonstrated so that they become technically viable, and cost competitive with the conventional fuels. Further development of these technologies will have to be based on easy and cost effective availability of primary resource to produce hydrogen either in a centralized plant or a on-site production plant. High temperature nuclear reactors have the potential to produce clean hydrogen on a large scale. However, apart from the feasibility of thermo chemical water splitting process, the efficiency, stability of close loop operation, safety, cost, materials etc. are key issues, which need to be addressed. Harnessing the intrinsic potential of these processes for large-scale production of hydrogen is a scientific and technological challenge. Development of high temperature nuclear reactor, and its integration aspects with hydrogen production plant are key issues. Renewable energy technologies need be harnessed in the long run for the production of hydrogen in decentralized manner. This would eliminate cost of long distance transportation of hydrogen. These technologies need to be developed to a level, where the cost of production of hydrogen becomes affordable. A well-coordinated programme for research and development needs to be undertaken to develop and demonstrate renewable energy based hydrogen production. No single production technology is likely to meet the requirement of hydrogen for the new emerging applications in power generation and transport sector. Therefore, suitable policies are required to support further research, technology development, and demonstration of various hydrogen production technologies in a cost effective manner, which should eventually lead to development of hydrogen production network and infrastructure in the country. Research should be undertaken on priority basis to support hydrogen production from nuclear, renewable, and other sources with low or zero CO_2 emission. Research efforts also need to be undertaken for the production of hydrogen based on coal. The final mix of renewable energy, coal, and nuclear energy should provide the basis for ensuring sustainable supply of hydrogen for the new hydrogen economy.

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Electricity from Renewable Energy Sources

***Dr. Bibek Bandopadhyay** after earning his masters in Physics from Visva Bharati, Santiniketan obtained his doctorate from the University of Delhi in 1980. Since then he has worked in the Indian Institute of Technology, Delhi, Department of Science and Technology, Solar Energy Centre and Ministry of Non-Conventional Energy Sources, Government of India in various capacities. His research interests include materials science and solar energy. He has in his credit a book on fine particle magnetism, a number of research papers in national and international journals, contributed chapters in different books apart from various editorial contributions. He has lectured extensively as a guest faculty in the country and abroad. Currently, he is an Adviser to the Government of India in the Ministry of Non-Conventional Energy Sources and heads the Solar Energy Centre, an institution of the Ministry for development and promotion of solar energy technologies.*

Introduction

The sun is the ultimate source of almost all forms of energy that are being utilized from time immemorial. Solar energy is a result of the continuous process of nuclear fusion inside the sun where nuclei of low mass hydrogen atoms 'fuse' together and release energy. In the core of the sun, enormous gravitational pressure makes this to happen at temperatures of around 10 million degree Celcius. Today's principal conventional energy sources, the fossil fuels: coal, oil and natural gas are essentially 'yesterday's sunshine' stored over millions of years and preserved beneath the ground. These are carbon rich energy sources and finite in nature.

Solar energy is also responsible for creation of other energy sources like wind, flowing streams and rivers, photosynthetic production of biomass and thermal gradients in the ocean. These various forms of natural energy like the radiation from the sun, wind, hydro or biomass are renewable in nature and environmentally benign. The magnitudes of all these sources are extremely large. During the last few decades, in various countries of the world, elaborate programmes have been initiated to harness these naturally occurring energy sources for heating, cooling, mechanical work, chemical energy or electricity. The current efforts to derive energy directly from the renewable resources is only a logical extension of the historic role, the sun has played for thousands of year for our energy supply [1]. In this article, we will, however, restrict our discussion only on generation of electricity from a few major renewable sources. The environmental implications would also be discussed.

Solar Power Generation

There are two routes for converting solar energy into electricity. The first is the solar thermal route which collects solar energy as heat through concentrating solar collectors and converts this heat into electricity using a typical thermal power generating unit. The other route is the photovoltaic route in which solar cells convert the radiation from the sun directly to electricity. The output of solar power plants whether thermal or photovoltaic is subject to diurnal, seasonal and weather-related solar radiation changes. These power plants can work in grid interactive mode or as independent power units. In general, if the solar plant is connected with the utility grid, no storage or auxiliary energy supply is needed. However, if it is an independent power unit, necessary storage or auxiliary energy supply will be required.

Solar Thermal Power Generation

For solar thermal power generation, there are three main power conversion technologies:

Dr. Bibek Bandopadhyay, Indian Institute of Technology, Delhi

Central receiver,

Solar line focusing collector and

Solar dish generator.

These concentrating collectors can concentrate only the parallel radiation coming directly from the sun's disk (direct solar radiation). Therefore the collectors are required to follow the sun's path across the sky. The line focusing collector systems require a single axis tracking whereas the central receiver or the solar dish systems require double axis tracking. Table I provides information on various types of systems, the years these were developed, the collector area installed to harness solar energy, and the capacity of plants already installed [2]. Not all the plants are currently in operation. The various power conversion technologies described are still at different stages of development. Solar parabolic trough systems are by far the most commercially mature technology. So far the longest serving solar thermal power plants are the solar electricity generating (SEG) plants with a total capacity of 354 MW based on parabolic trough collectors in operation in Mojave desert, California, USA. The cost of electricity currently being produced by these plants is 8 c/kWh, which is understandably lower than the estimated cost of electricity from a similar power plant to be installed now on commercial basis. Nevertheless, with further maturity of the technology, reduction in its O&M costs, increase in cost of conventional fuels in the days to come, and the environmental problems associated with conventional power generating plants, the cost of electricity is expected to be competitive with that from conventional technologies [3]. Already a number of countries in solar zones, namely Egypt, Morocco, India are planning to set up such plants with a view to getting the technology ready for future use. Further development efforts which are being pursued to make the technology more efficient, reliable and cost effective include amongst others improved anti reflective glass coating that also resists abrasion, high temperature selective coating on receiver tubes with maximum absorptivity and minimum emittance, improved glass to metal seals, and a more efficient design to maximize the energy captured by the receiver.

TABLE 1. Status of Solar Thermal Power Plants

System Developed since	Plant (Numbers, capacity, area)
Parabolic troughs 1973	16 (365 MW) 2263000 sq.m.
Central receivers 1973	6 (16 MW) 117000 sq.m.
Parabolic Dishes (Central PCS) 1977	4 (5.4 MW) 35672 sq.m.
Parabolic Dishes (Stirling) 1977	15 (6.9 MW) 50200 sq.m.
Solar Chimneys 1977	1 (50 kW) 44000 sq.m.

In India, so far experiments have been conducted on a 20 kW solar dish power plant based on concentrating paraboloid collectors and steam engine by BHEL Corporate R&D at Salojipally, Andhra Pradesh, and a 50 kW solar power generating plant based on parabolic trough collectors and steam turbine at Solar Energy Centre near Delhi. Currently, this power plant is being hybridized with a biomass gasifier to study various operational parameters. A 10 kW solar dish Stirling engine has also been installed at Vellore Institute of Technology, Vellore for performance evaluation. These projects have generated good amount of experience in design, installation & commissioning, operation & maintenance of solar thermal power plants in the country. Research and development work on various aspects of solar thermal power generation including development of components have also been undertaken in various organizations resulting in generation of a fair amount of understanding, data, experience and manpower in the field [3]. A 140 MW (nominal power) Integrated Solar Combined Cycle (ISCC) Power Plant with a solar thermal component of 35 MW and a Combined Cycle Power Plant of 105 MW capacity at Mathania village in Jodhpur district of Rajasthan has also been planned.

Solar Photovoltaic Power Generation

Solar radiation can directly be converted to electricity by solar cells. When these cells with similar characteristics are connected and encapsulated, photovoltaic (PV) modules are formed. These modules are the building blocks of solar photovoltaic power generation. The PV modules produce direct current as the sun shines. Photovoltaic power plants can be stand-alone, hybrid or grid interactive. In a stand-alone PV power unit, the electricity produced during the day is stored in a battery bank. A complete PV power system consists of support structures for the modules, interconnecting leads between modules, battery bank, a power conditioner (an assembly of charge controller, inverter and transformer) and a network to which the system is coupled. Stand alone power units can be for individual applications like lighting, communication, refrigeration, homes or remote area electrification. The capacity may range from a few watts to several kilowatts.

In grid interactive mode, photovoltaics can be used in two main ways:

Solar power units on roofs or buildings with capacity upto around 50 kW.

Solar power plants of several hundred kilowatts or several megawatts.

For grid-interactive power plants, normally on-site storage is not required since the excess power available from the plant during the day can be sent to the grid whereas any additional power required can be obtained from the grid. However, depending on requirement, battery storage to some extent can be introduced. Though various kinds of solar cells based on a number of technologies are now available, crystalline silicon solar cells- both single crystal and multicrystal currently dominate the market. There has been a steady growth of production of solar cells over the years (Fig. 1). Out of a total solar cell production of 1200 MW in 2004, these two along with ribbon silicon constitute more than 88 per cent of the market share. These are the so called ‘first generation’ solar cells. The efficiency of these cells ranges between 12 to 16 per cent [4]. Most of the solar photovoltaic power plants installed worldwide are based on these solar cells. A few solar photovoltaic power plants in the megawatt range are indicated in Table 2.

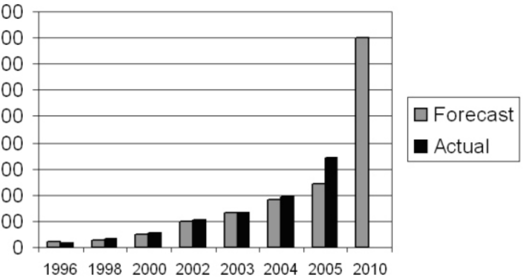

Fig. 1 Photovaoltaic cell/module production

Substantial R&D efforts worldwide are currently being made on the development and fabrication of thin film solar cells that require lesser amount of the expensive semiconductor and also offer simpler techniques for their large scale production. Among these ’second generation solar cells’, the most popular is the amorphous silicon solar cells that offer a stabilized efficiency of around 7% with lesser unit cost than crystalline silicon solar cells.

The current investment costs for SPV plants are in the range of Rs. 300,000 to 350,000 per kilowatt. The electricity cost may range from Rs. 15 to Rs. 28 per unit depending on solar resource availability and the type of plant. Though solar photovoltaics is an expensive proposition, it has been observed that over the years the cost of photovoltaic power has come down with increase in efficiency and rationalization of production techniques. For many years, solar photovoltaics have remained a fascinating area of research and development in many countries of the world. The general trend of research activities includes development of new solar cells and improvement of the performance of the existing solar cells. The particular emphasis is to find out methods for reducing the cost of the material either by using lesser amount or by utilizing an inexpensive new material, to increase the efficiency, making the production techniques simpler and increasing the long term reliability of the modules. Amongst the ‘second generation thin film solar cells’, there are many new developments which promise the above mentioned cherished goals. These include multiple

TABLE 2. Recent Photovoltaic Power Plants

Power plant, Site Year of installation	Capacity	Type of plant	Electricity generation per year
Passau,Germany, 2003	1.7 MW	SA, GC	1700 MWh
Woringen, Germany, 2005	2.3 MW	SA, GC	2300 MWh
Oroville,CA USA, Aug 2004	1.18 MW	BIPV,RM, GC	1400 MWh
Napa, CA. USA, Feb. 2006	1.2 MW	SA, GC	-
Veenendaal, The NL, Jan. 2004	1.21 MW	BIPV,RM, GC	950 MWh
Tudela, Spain, 2002	1.18 MW	SA, GC	1600 MWh
Sinzheim,Germany, 2006	1.4 MW	SA, GC	1300 MWh
Shenzem, China, 2004	1.0 MW	BIPV,RM, GC	823 MWh
Bandau, Germany, Dec., 2004	1.4 MW	BIPV,RM, GC	-

SA: Stand alone, GC: Grid connected, RM: Roof mounted, BIPV: Building Integrated Photovoltaic

cell concepts using a combination of amorphous silicon and microcrystalline silicon cells or heterojunction cells (combination of crystalline silicon wafers with amorphous silicon cells) and compound thin film solar cells (CIGS, CdTe). These solar cells have the potential to reach the goal of US$ 1 (`Rs. 50) per peak watt in not a distant future. Again there are the new ‘third generation cells’ –the dye-sensitized solar cells, organic solar cells and the nano-solar cells, the cost and efficiency goals of which are required to be followed closely [5,6].

Solar photovoltaic power plants have already been found to be suitable for remote area electrification if the electricity demand is less. Because of the remoteness of the locations, inspite of high investment for solar panels and batteries, these plants have even been found to be cost competitive compared to some of the possible alternatives. In India around 30 grid interactive solar photovoltaic power plants of capacities ranging from 25 kW to 200 kW have been set up for voltage support applications in rural sections of weak grid and on public buildings for peak load shaving applications. Stand alone power plants of aggregate capacity of around 2 MW set up in remote areas for electrification have generated rich experience in design, operation and maintenance of such power plants that may provide valuable inputs for remote area electrification. Over one million PV systems have been installed in the country for lighting, water pumping, communications, vaccine refrigeration, telephone exchanges, weather stations etc. The total solar PV modules installed for various applications in the country exceed 160 MW. This puts India as one of the major user of solar PV. The country has also a reasonable manufacturing base for solar cells and modules.

Environmental Implications

Production of electricity from solar energy either through thermal route or through photovoltaic route does not result in release of polluting gases including green house gases. However, as these are material intensive technologies, it is expected that there would be a definite amount of secondary emissions due to production of basic materials and for fabrication of solar cells, thermal collectors, various optical coatings etc. Studies, however, have shown that the proportion of secondary emissions is very small. It has been estimated that carbon dioxide emission for photovoltaic power generation arisen out of these secondary emissions is around 20 gm per kWh, which is a negligible amount when compared to cola based power generation plants. This can also be argued from the fact that the energy pay back period of a solar thermal power plant is less than half a year and that of crystalline silicon based photovoltaic power plant is around 4 years. In other words, the energy required to fabricate such plants is only a fraction of the total projected energy generation in a life span of 25 years. The other primary concern is effect of human health due to use of toxic gases and solvents during manufacture of the above components. The potential impact is primarily at the manufacturing facilities. The completed installed systems do not pose any risk to human health on this count. The newer technologies like use of fewer materials for solar cells or selectively coated collectors based on magnetron sputtering techniques are expected to reduce even this impact to human health at manufacturing site [7]. Solar thermal power generating units, when produce power from solar energy alone, do not contribute to any pollution. However, hybrid plants do emit pollutants in the proportion at which fossil fuels are used.

Batteries are required for storage of electricity for decentralized photovoltaic power generation. Life of batteries ranges fro 3 to 5 years. Disposal of these batteries can be a potential hazard when solar photovoltaics would be extensively used for such decentralized applications unless recycling of batteries is taken care. Studies have shown that the combined effects of improving battery life time to 5 years and enhancing the battery recycling rate to 50 per cent will lead to a much smaller environmental load than expected from the batteries of car industry [8].

Potential in India

India lies in the solar belt of the world. The solar radiation availability ranges from 4 to 7 kWh per sq.m. with around 300 sunny days in a year. This translates to 1500 kWh to 2400 kWh of solar radiation per sqm. per year. The maximum radiation received is in western Rajasthan which has been identified as one of the most suitable sites for solar power generation [5]. India, therefore, has immense potential for producing solar electricity, the quantum of which, however, would depend on maturity and cost effectiveness of the technologies. A parabolic trough collector of ten square meter of area in a site like western Rajasthan can produce high grade heat equivalent to one ton of oil equivalent per year. A photovoltaic module, however, can produce electricity even at lower solar radiation and can find application as a decentralized power unit at any part of the country. The estimated annual average electricity generation from a 100 watt photovoltaic module in Indian condition is 100 units.

Electricity from Biomass

Biomass is a high energy density system with energy content of around 4000 kcal/kg. It is the result of the photosynthetic conversion of solar energy into chemical energy of plant materials. Biomass is the largest renewable energy resource currently in use. But most of this is used in extremely inefficient way. The available biomass feedstock can broadly be divided into forest and agricultural residues and dedicated energy farming. Biomass conversion technologies can be grouped under three headings; conventional steam cycle, co-firing with fossil fuel, and gasification including other advanced cycles.

Conventional steam cycle plants based on combustion of biomass has been the most common biomass power generating practice. The cost of such power projects are in the range of Rs. 30 million to Rs. 40 million per megawatt. In Conventional steam cycle plants, biomass is burned in an excess of air to produce heat that raises high pressure steam in a boiler. The energy stored in the steam is converted into electricity by expanding it through a turbine which in turn drives an electrical generator. The higher the steam temperature and pressure used, the greater is the efficiency of the overall plant. In high pressure, high temperature combustion energy systems, thermal efficiency can be anywhere between 35-40 per cent. These days use of air cooled condensers is more common for reducing water requirement. Studies have shown that conversion of existing coal burning power plants into systems that can co-fire biomass can be a feasible option of utilization of biomass with lower investments.

There are two main combustion technologies such as grate and fluidized bed combustion. The grate firing system is a traditional technology originally developed for coal combustion and the combustion of municipal solid wastes. These systems are inexpensive and reliable though these are designed for a limited number of feed stocks. The fluidized bed combustion technology, on the other hand, is a recent innovation. The advantage of the fluidized bed system is its fuel flexibility. In many countries, therefore, it is now being used for CHP (combined heat and power) plants where various feed stocks like firewood, coal, peat, oil and different combustible wastes are used separately or together. In India, the technology of biomass combustion for power generation is well established. A number of plants have been set up in different parts of the country that are generating power on regular basis. However, it is necessary to develop manufacturing capability of some of the recent developments in fluidized bed combustion techniques.

Biomass gasification has now emerged as a favourable option both for supplying heat and electricity. Biomass gasification is essentially a thermo-chemical conversion process from solid fuel to gaseous fuel. It takes place under controlled condition characterized by high temperature (800-1400 C) and low oxygen supply. The resultant output is producer gas – a mixture of carbon monoxide, hydrogen and methane apart from carbon dioxide and nitrogen with an average calorific value of 1100 kcal/m^3. The producer gas thus developed can be used directly for thermal applications or can be used in internal combustion engines for power generation. Compression ignition (CI) engines, which require use of some diesel for initiating ignition, are being used for a number of years in many locations for generation of electricity using producer gas. In these engines, the average diesel replacement varies between 65 to 80 per cent depending on the extent of variation in the load demand from the engine. During the Second World War, there had been intensive development of biomass gasification to meet the scarcity of petroleum resources for transportation. Gasification systems with 100 per cent producer gas engines (spark ignition engines) have also now been developed in the country. These engines do not necessitate use of diesel for their initial start up. Extensive work has been carried out on fuel type, fuel size, residence time, and moisture content of fuel etc. to optimize the gasification efficiency and reducing problems relating to tar and particulate matter content in gas [9]. These systems of capacities ranging from a few kilowatts to megawatts are now commercially available. The typical costs of biomass-gasifier based electricity generation systems range from Rs. 40 million to Rs. 45 million per megawatt. The cost of generated power ranges between Rs. 2.50 to Rs. 3.50 depending on the purchase price of biomass, plant load factor etc. Gasified biomass can also be used in gas turbines which are very efficient energy conversion devices.

Bagasse based cogeneration is another typical application of biomass based power which is being followed worldwide for ensuring supplying of both steam and electricity in sugar mills. Technologies are now available for generation of steam at high pressure and at high temperature that can not only ensure providing required quantity of heat but also additional electricity than what is required in a sugar mill. This makes the total system energetically efficient and also provides a means for more revenue. Electricity generation from biomass is already significant in many countries of Europe in combined heat and power (CHP) mode.

Environmental Implications

Energy generated in various ways from biomass operates within the earth's natural carbon cycle. As a result it does not contribute to net greenhouse gas build up. Modern biomass systems are clean, efficient and safe compared to their traditional counterparts. One principal aspect of bio energy utilization is its potential for large-scale employment generation. Environmental and social considerations are naturally now spearheading bio energy at the center stage of economic development in many developing countries. With dissemination and adoption of advanced power generation technologies, biomass is expected to account for significant proportions of electricity generation in many countries.

Potential in India

India produces a large quantity of agricultural and forestry wastes. According to an estimate, around one-third of these wastes do not find any productive use. Also there can be biomass plantations in much of our wasteland. All these can be made available for power generation through various biomass power conversion technologies. The existing functional sugar mills can also provide enough bagasse for additional power generation

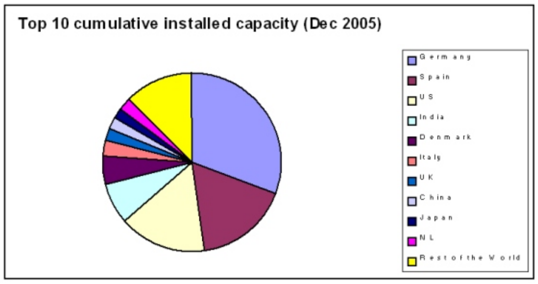

Fig.2 Country-wise installed capacity of wind power.

through cogeneration route [10]. The estimated potential is 70,000 MW.

Wind power

An estimated 1 to 3 percent of the energy from the Sun is converted as the flow of air. Wind energy has been used in the past for a variety of purposes. Currently the major application of wind energy is electricity generation. The kinetic energy of wind is used to drive a wind turbine producing mechanical energy, which is further converted to electrical energy through a generator. Wind turbines can be of horizontal axis configuration or vertical axis configuration. Horizontal axis wind turbines are now being commonly used since these are less expensive than vertical axis wind turbines. The average energy conversion efficiency of horizontal axis wind systems ranges from 25 to 35 percent. The expected lifetime is around 25 years. In the recent years, wind power has been registering a very high growth rate. The total global installed wind power capacity till end 2004 is 48000 MW which represents 30 per cent of installed renewable energy capacity and 1.2 percent of total global power generating capacity. The current cumulative installed wind power capacity is 60000 MW[12]. The country-wise installed capacity is shown in Fig. 2.

The capacity utilization factor (CUF) of a wind turbine is a critical parameter. It depends on availability and velocity of wind at a particular location. For initiating a wind power generation programme, wind resource assessment, therefore, is of paramount interest. The detailed wind data and the state of technological development of wind machines would determine the wind power potential of a country. The power generated from a single machine or a group of machines known as wind farm is normally fed to the utility grid. The stability and the state of the grid will also affect the wind power potential.

Generation of electricity from wind in an efficient manner is an engineering challenge. It demands understanding and technology that can effectively handle the erratic nature of wind and can achieve high performance on partial loads. In grid interactive mode, It also must exhibit low reactive power consumption and low noise levels. In the wind sector during the last three decades, considerable technological advances have taken place in aerodynamic and structural design, mechanical, electrical and control engineering, materials technology, and other related fields. These developments have made this technology one of the fastest growing renewable energy technologies. One of the current developmental challenges is to design and build larger turbines since larger is the turbine, the greater is its cost effectiveness. In mid 1970s, the average turbine size was a mere 10 meters. Today the turbine size has grown to around 80 meters. The largest wind turbine capacity achieved so far is 5 MW. So far only three prototypes have been installed. Recently, a new design of vertical axis wind turbine has been announced. The reported wind to electrical energy conversion efficiency is over 40 per cent in the capacity range of 500 watts to 1 MW. The design and efficiency of this new wind machine promise lower unit cost of electricity produced.

The power in the wind is directly proportional to the area of the machine being swept by the wind and the air density, and more importantly to the cube of the wind speed. This means that when the wind speed doubles, the power in the wind increases by a factor of eight. It is, therefore, of extreme importance both from engineering and economic point of view, to find out a site where the mean wind speed is relatively high. Offshore wind, where the turbines can be taken by ship, is therefore, expected to take off quickly in future. Normally the power density of a 40 kmph wind sweeping through one square meter of intercepted area is equivalent to the power density of the bright sun which is around 1000 Watts per sq.m,.

In the 1980s, globally, the cost of wind electricity was about three to five times than what it is in 2005, The downward trend is expected to continue as larger multi-megawatt turbines are mass-produced and more refined wind data is used to install the wind turbines. The exact cost of producing electricity, however, is dependent on the local wind condition, the technology of the machine, and the mechanism of transmitting the produced electricity.

Environmental Implications

Production of electricity from wind energy is a clean operation. It does not add to environmental pollution of any kind except for acoustic noise that the wind rotors, gear boxes and generators create. The area under wind turbines can productively be used for crop production.

Potential in India

India's wind power potential has been assessed at around 45000 MW assuming 3 percent land availability for wind farms requiring land at the rate of 12 ha per MW in sites having wind power density in excess of 250 Watts per sq.m at 50 m hub height. Considering various other practical aspects, including the international norms of power density of 300 Watts per sq.m or more, the potential for grid interactive wind power may be lesser than 45000 MW. The state wise gross and technical potentials are given Table III. The technical potential of 15000 MW has been estimated assuming 20 per cent grid penetration. This potential, therefore, would increase and approach to gross potential as there would be augmentation of grid capacity [10].

TABLE 3. Wind power potential

State	Gross potential (MW)	Technical potential (MW)
Andhra Pradesh	8275	2110
Gujarat	9675	1900
Karnataka	5520	1310
Kerala	875	610
Madhya Pradesh	5500	1050
Maharashtra	3650	1050
Orissa	1700	1085
Rajasthan	5400	1050
Tamil Nadu	3050	2150
West Bangal	450	450
Total	45195	14775

Hydro Power

Hydroelectric power uses the kinetic energy of moving water to make electricity. This renewable resource is one of the largest producers of electricity (about 20% of total electricity produced) in the world today. Hydropower can come 'on line' quickly to meet sudden increases in electricity demand and respond to emergency energy needs. It is also cheaper compared to electricity produced from fossil fuels, though the initial investment may be a little high. These are the major hydro projects which are in the realm of conventional energy.

From very early times all over the world, small hydropwer from streams, rivulets and canals of small discharge was being harnessed for various day to day activities. The development of these small hydropower had been slowly taking place to meet the energy requirement of local isolated habitaions. The potential of these small power systems are immense. The problems both environmental and social which have recently been encountered with large hydro plants, have reoriented the need of harnessing this natuaral energy source in a managable way for meeting the development objective without any detrimental effect to our environment and society.

Small hydro projects are categorized on the basis of water discharge rates and heads available. The capacity may range from a few kilowatt to several megawatts. In hilly region, most of the small hydro plants are run of the river schemes. There can be snowfed streams or rainfed streams which have varying discharge rates during the year. Hill streams may also carry big boulders. During rainy season, flood discharge may be very high compared to lean period. Further there are possibilities of flash flood of very high intensity. In countries where irrigation network for agriculture has been developed, small hydrpower can be harnessed from irrigation canal drops as small as 2 meters. As the head is small, the discharge to be handled may be large. Keeping in view such large variations, it is essential to carry out a detailed survey for implementing small hydro projects. The success of a project is critically dependent on the accuracy and detailing of the survey. Technologies and procedures to handle these varied situations have been developed over the years. These include development of hydaulic turbines capable of effectively handling various heads and discharge rates, suitable generators and control systems, diversion structures, water conductors, desilting tanks, overflow arrangements, penstocks, anchors and saddle blocks, tail race channels etc.

In India power projects upto 25 MW are considerd as small hydro projects. There is a good manufacturing base with capability of fabricating almost entire range and type of small hydro equipment. However, there are newer developments that include techniques for cost effective civil design and construction. Problems encountered due to silting are also required to be addressed. Now concepts like siphon intake and coanda system are required to be introduced. There is also need to further develop the technology for governors and the quality of automation in plant controls. Development of equipment for ultra low head region has been a continuous subject of investigation. Currently, in India, small hydro projects generally cost between Rs. 50 million and Rs. 70 million per MW depending upon the location and site topography [10,11]. . The capacity utilization factor is a very crucial parameter for arriving at the pay back period of such projects. Further technology development, careful planning based on detailed assessment of the site, and load utilization and management can effectively bring down the pay back period.

Environmental Implications

Hydroelectricity is a clean energy. Its production does not cause emission of greenhouse gasses or other air pollution; neither does it leave behind any waste.

However some recent reports have suggested that in large dams which have been constructed for hydroelectricity, emission of methane has been observed out of decaying submerged plants that grow in the dried up parts of the basin in times of drought. Also it has been increasingly realized that major hydro projects which involve large dams have various detrimental environmental and social consequences. These include submerging of forest and agricultural land, requirement of rehabilitation of prople who live in submerged lands, increasing probability of seismic disturbances due to large volume of water impounded, and problems related to siltation.

The constraints associated with major hydro projects are not encountered in small hydro projects. Experiece gained so far has indicated that these projects can be designed and managed in environment friendly manner. It meets the objective of providing electricity in isolated inaccessible places. The small hydro power, therefore, is environmentally desirable.

Potential in India

In India, the potential of small hydro power is enormous especially in hilly regions of north and north-eastern parts of the country and also in the large irrigation network that has been developed over the years. A data base has been created for potential small hydro sites through information gathered from various sources. Simulation models have been developed that take into account amongst others regional flow duration curves, geological and seismological data and vegetation cover using geographic information system (GIS). The estimated potential is 15000 MW. The available data base includes 4233 sites with an aggregate capacity of 10,324 MW [10,11].

Discussion

In India significant progress has been made in production of electricity from renewable energy. More than 7000 MW is being contributed to our national grid from renewable energy. This constitutes around 6 per cent of total grid power installed capacity in the country. In addition over

160 MW capacity photovoltaic modules have been deployed in the country for powering various systems for domestic, institutional and commercial use.

Under the Electricity Act 2003, the Central Government from time to time is responsible for preparing the national electricity policy and the tariff policy for optimal utilization of all energy resources including renewable energy. The National Energy Policy 2005 contains the broad principles of action. The projected economic growth of the country for meeting its development goals would not only require increased electricity supply, but would also call for clean, reliable and convenient supply system [10,11]. Electricity from renewable energy sources is expected to play an important role in the coming decades to meet the above objective. An analysis of the growth of grid connected renewable power in the country reveals that the achievement has exceeded the set targets. The source wise break up of cumulative installed capacity of grid interactive renewable power upto the end of 2005 is given in Table IV against their potential.

TABLE 4. Installed capacity of grid Interactive renewable power

RE Source	Potential (MW)	Installed capacity (MW)
Solar	-	3 (Grid only)
Biomass	70,000	868
Wind	45,000	4434
Small hydro	15,000	1748

The estimated investment till the end of 2004-05 in renewable power sector in the country is around Rs. 300,000 million. Though various fiscal and financial incentives have been provided by the government, but according to an estimate around 90 per cent of the investment has come from the private sector. The capital investment for renewable power projects are high compared to their conventional counterparts. The electricity produced by the renewable power projects come from ever flowing natural sources. These projects are environmentally desirable compared to their conventional counterparts. It is therefore necessary to calculate the unit cost of renewable energy taking into account the inherent cost of environmental implications. These would naturally lead to providing preferential tariffs for the renewable electricity and also continuing fiscal and financial incentives for setting up such projects. Because of the inherent nature of these energy sources as discussed above, the plant load factor (PLF) for these power projects range from 17 to 70 per cent depending on the resource and location. For making renewable power sustainable, the available resource is required to be utilized optimally. One of the major objectives, therefore, is to increase the capacity utilization factor within the natural constraints of resource availability. This can be achieved by detailed accurate mapping of potentials of various energy sources and ensuring effective electricity evacuation systems. The indigenous design capability is required to be improved further and all products must be manufactured indigenously to suit local requirements and ensure future maintenance. Quality of equipment is extremely important for its reliable and long term operation. It is important to develop standards, specifications and performance parameters for the indigenous products and to make them at par with the best of the world. With immense potential, immediate need to harness new energy sources, rich experience gained on design, development and implementation of a variety of renewable power projects and a pool of trained manpower, India is poised to be one of the leading nations in the world in renewable electricity generation. Concomittant environmental benefits would naturally follow.

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Note: The views expressed in this paper are those of the author in his individual capacity.

NUCLEUS

Project on Clean Air for Asia

India, China, Japan and US Quadripartite Project on CLEAN AIR FOR ASIA

The Atlantic Council of the United States undertook the project on "Clean Air for Asia" along with Confederation of Indian Industry, South-North Institute for Sustainable Development of China and Committee for Energy Policy Promotion of Japan to develop consensus recommendations for economic, environmental and energy policies that would promote cleaner air and reduce air pollution associated with energy use in China and India.

The project was initiated with a visit to China and India in late 2000 to identify areas and issues that were most critical to reducing air pollution in China and India. From the review of legislation and interviews with government and academic experts it was clear that there was a broad appreciation of the need to promote a cleaner environment in conjunction with economic growth through a more efficient and effective development of energy.

Seminars were held in New Delhi and Beijing involving experts from the four countries. The seminars were structured to promote open dialogue by limiting the number of participants to around 40 experts. This approach provided an opportunity for brief statements by many participants on key topics and provided for some discussion in small groups of 8 to 10 experts to provide an opportunity for all to contribute.

The policy paper, published after the compilation of the first phase of the project, observes that China and India are increasingly recognizing the complex linkages between economic development, growing energy requirement and environmental pollution. There is now broad recognition of the need to promote a cleaner environment in conjunction with economic growth through a more efficient and effective development of energy. It also admits that both China and India have programs underway to promote clean air.

Some key policy recommendations of this report include:

> *Both China and India should establish new institutions to develop overall policies and plans on energy and related environmental issues. Environmental regulatory agencies should be strengthened.*
>
> *China and India should further develop and promote economic energy and environmental policies that strengthen the effectiveness and efficiency of energy systems. Such policies should in particular recognize the costs of energy systems and their long-term availability. Government support should be targeted so as to meet social objectives.*
>
> *China and India should complete pricing and structural reforms to help ensure the long-term economic viability of the electric power sector. The two countries should include increased efforts to educate their publics on the need for such policies.*
>
> *Both countries should increase technical and managerial training on the analysis of energy issues, integrating social, technical, and economic impacts.*
>
> *China, India, Japan, and the United States should accelerate the commercial transfer of established technologies as well as official development assistance in the energy sector. Particular attention should be given to clean coal technologies.*
>
> *Efforts should be strengthened in both China and India to accelerate information sharing with enterprises, reduce barriers to trade in goods and services, strengthen intellectual property protection, and improve access to capital.*
>
> *The official development agencies of the United States and Japan and other nations should facilitate and financially support the creation of private-public partnerships with China and India that would lead to the co-development, co-design and co-project implementation of major clean coal technologies.*
>
> *China and India should consider increasing interaction with Japan and the US on rural electricity. The use of renewables in both countries should also be further encouraged.*

[Full report is available from Atlantic Council Web site (www.acus.org./energy)]